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Block-Oriented Agent-Based Architecture to Support the Power Distribution System Operation

System Design and Environment Model

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There are no such things as applied sciences, only applications of science.
Louis Pasteur (1822 - 1895)

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Abstract

This thesis proposes the design and evaluation of a block-oriented agent-based architecture to support the power distribution system operation considering the integration of actively managed distributed energy resources. The architecture was designed in alignment with trends enforced by smart/modern grid concepts, such as promoting decentralized management and control, exploiting distributed energy resources in the operational procedures, modernizing the power distribution systems, and increasing the levels of reliability. Nevertheless, instead of promoting solutions to a future smart/modern grid to be, the proposed architecture was devised to gradually attribute smartness to the system operation using the well-defined notions of intelligence of the agent paradigm. This pragmatical directive allowed creating architectural sets of solutions which attain altogether high levels of flexibility, extensibility, and robustness, permitting the smooth transition from actual to future power distribution systems in a way that improvements in infrastructure are established according to a long-term vision.

In the proposed architecture, a block-oriented philosophy of management and control was devised using the agent paradigm to ascribe autonomy to entities responsible to support the operation of particular zones/blocks of the power distribution networks. As consequence, several system capabilities were developed through the application of the agents' autonomy and interaction, including the support to islanded operation and outage management procedures. The agent-based solutions were designed employing explicit representations of goal-directed behaviors interrelated with agent planning. For this accomplishment, BDI agents were modeled using the JASON agent programming language and interpreter, allowing a high-level representation of the agent's reasoning through JASON's syntax. Furthermore, using reference steps of the Prometheus design methodology, the system design is thoroughly described from the abstraction of goals to the coding of agent plans. Once the system design is described, several discussions are provided regarding the transition from the conventional centralized management to the decentralization achieved by the agent-based architecture. At the best of the author's knowledge, this work marks the first application of JASON and Prometheus to power engineering, thereby highlighting their effectiveness in our research area.

Despite the system design matters, it is stated that one of the keys to promote the acceptance of agent-based solutions in the power distribution engineering lies on the development of an environment model, from where the long-term impact of these solutions can be assessed. Therefore, this thesis also proposes the building of a computational environment where the long-term impact of the application of the block-oriented agent-based architecture can be evaluated according to uprisings/downsitting of the power distribution system performance indices. As consequence, it is proposed the concept of an inte-

grated adequacy and security evaluation of power distribution systems with actively managed distributed energy resources, involving power distributed generation units, distributed energy storage devices and controllable loads. Hence, the fundamental concepts behind service adequacy and security were revisited and alternative definitions to these concepts were proposed with focus on the power distribution delivery. Under these definitions, a combined discrete-continuous simulation model capable of providing integrated adequacy and security evaluations is thoroughly described. This simulation model unifies the representation of the long-term failure/repair cycle of system components with aspects of steady-state and dynamic behavior analysis, in a way absent in the state of the art. Furthermore, the simulation model includes several additional developments such as the design of advanced strategies to support load shedding activities, the mathematical disclosure of adverse weather event samplings using a non-homogeneous Poisson process model, the mathematical disclosure of test-functions for the variation of performance indices due to operational/control strategies, and the impact of islanding and islanded operation procedures, droop control schemes, and load shedding strategies on the power distribution system performance indices.

All simulation mechanisms were embedded in a computational artifact-based environment modeling whose infrastructure is supported by CArtAgO, a common framework for agent open environments. Hence, at the best of the author's knowledge, this research also marked the first application of CArtAgO to power engineering modeling and simulation. Therefore, following CArtAgO's agents and artifacts meta model, an artifact model of a general-purpose power distribution system element was devised. Moreover, an artifact-based scheme was developed to integrate the system state transitions of the simulation model with the solutions provided by the agent interactions. These complex schemes permitted an effective evaluation of the impact of the block-oriented agent-based architecture in the performance of the power distribution systems. In fact, simulation experiments indicated that the active management of distributed energy resources achieved by the architecture may allow significant improvements on the power distribution system performance indices, thereby promoting high levels of service adequacy and security to the utilities' customers.

Resumo

Esta tese propõe o projeto e avaliação de uma arquitetura de controlo orientada a blocos e baseada em agentes autónomos para o suporte da operação de redes de distribuição incluindo a integração de recursos ativos distribuídos. A arquitetura de controlo foi projetada de acordo com conceitos fomentados pelo paradigma de redes inteligentes, tais como o controlo decentralizado, a integração de recursos ativos distribuídos em procedimentos de operação, a modernização dos sistemas de energia elétrica e o melhoramento dos níveis de fiabilidade. Todavia, ao invés de abstrair soluções para uma rede no futuro, a arquitetura proposta promove a inserção gradual de inteligência na operação de redes de distribuição a partir de noções do paradigma de agentes inteligentes. Esta pragmática diretiva permite o desenvolvimento de soluções que, quando coordenadas, alcançam elevados níveis de flexibilidade, extensibilidade e robustez, permitindo uma transição suave e continuada em direção a redes de distribuição mais inteligentes estabelecidas sob uma visão de longo prazo.

A arquitetura proposta inclui uma filosofia de gestão e controlo desenvolvida a partir do paradigma de agentes inteligentes de forma a estabelecer autonomia a entidades responsáveis pelo suporte da operação de zonas/blocos particulares das redes de distribuição. Dessa forma, diversas funcionalidades sistémicas são estabelecidas através da autonomia e interação entre agentes, incluindo o suporte a procedimentos de operação em rede isolada bem como de reposição de serviço. As soluções compreendidas na arquitetura empregam uma explícita representação de comportamentos orientados ao objetivo diretamente relacionados com o planeamento dos agentes. Com esse fim, agentes BDI são modelizados utilizando a linguagem de programação e interpretador JASON que, através da sua sintaxe, permite representações de raciocínio em elevado nível. Adicionalmente, o projeto de arquitetura é descrito com base nas etapas de referência da metodologia Prometheus, desde a sua abstração de objetivos primários até a codificação de planos de ação. É também discutida a transição de um paradigma convencional de gestão centralizada até a decentralização alcançada pela arquitetura baseada em agentes autónomos. Por fim, destaca-se que esta tese marca, pelo menos do conhecimento do autor, a primeira aplicação de JASON e Prometheus na área de sistemas de energia elétrica, evidenciando suas características e efetividade.

Além do foco no projeto da arquitetura, enfatiza-se que uma das chaves para aceitação de soluções baseadas em agentes na área de sistemas de energia elétrica está no desenvolvimento de modelos de ambiente, a partir dos quais se faz possível a avaliação do impacto de longo prazo dessas soluções. Por conseguinte, propõe-se um ambiente computacional no qual o impacto de longo prazo da arquitetura é avaliado à luz de índices de performance das redes de distribuição. Por consequência, desenvolve-se o conceito de uma avaliação integrada de aspetos de adequação e segurança de serviço com foco nos sistemas

de distribuição de energia elétrica. Com base nesse conceito, é proposto um modelo de simulação discreta e contínua combinada com o fim de unificar representações de longo prazo de ciclos de avaria e reparação de componentes com representações de aspetos de análise em regime estacionário e dinâmico, sob uma ótica inexistente no estado da arte. Adicionalmente, esse modelo de simulação inclui contribuições para com o desenvolvimento de estratégias de deslastre de carga, a exposição de um algoritmo de amostragem de eventos de condições climatéricas adversas através de processos de Poisson não homogéneos, a exposição de funções teste para a variação de índices de performance devido a estratégias de controlo, bem como o impacto nos índices de performance de estratégias de operação em rede isolada, controlo por emulação de estatismo e deslastre de cargas.

Finalmente, os mecanismos do modelo de simulação são embebidos num ambiente computacional baseado em artefactos estabelecido numa infraestrutura comum para ambientes abertos denominada CArtAgO. Dessa forma, marca-se também nesta tese, pelo menos do conhecimento do autor, a primeira aplicação de CArtAgO na área de sistemas de energia elétrica. Por meio do meta modelo empregado pelo CArtAgO, desenvolve-se um modelo de artefacto para um elemento genérico de uma rede de distribuição. Adicionalmente, um esquema baseado em artefacto é estabelecido de forma a integrar transições de estado do modelo de simulação com a simulação da arquitetura de agentes. Esses esquemas permitem a avaliação efetiva do impacto da arquitetura proposta na performance das redes de distribuição. De facto, as simulações e análises de resultado indicam que a gestão ativa de recursos distribuídos alcançada pela arquitetura pode permitir aperfeiçoamentos significativos dos índices de performance das redes de distribuição, promovendo elevados níveis de adequação e segurança de serviço aos consumidores das empresas de distribuição de energia elétrica.

Résumé

Cette thèse propose le projet et l'évaluation d'une architecture de contrôle par blocs basée sur des agents autonomes comme support pour l'opération des réseaux de distribution de l'énergie électrique considérant l'intégration des ressources distribuées actives. L'architecture de contrôle a été projetée conformément aux concepts suscités par le paradigme des réseaux intelligents, tels que la promotion du contrôle et de la gestion décentralisés, l'intégration de ressources actives distribuées dans les procédures d'opération, la modernisation des réseaux électriques et l'amélioration des niveaux de fiabilité. Cependant, au lieu de proposer des solutions abstraites pour un réseau du futur, l'architecture proposée encourage l'insertion graduelle de l"intelligence dans l'opération des réseaux de distribution à partir des notions du paradigme d'agents intelligents. Cette option pragmatique permet le développement des solutions qui, quand elles sont coordonnées, permettent d'atteindre des niveaux élevés de flexibilité, d'extensibilité et de robustesse, favorisant ainsi une transition douce vers des réseaux de distribution plus intelligents dans une perspective à long terme.

Dans l'architecture proposée, une philosophie de gestion et contrôle a été créée à partir du paradigme d'agents intelligents de manière à conférer de l'autonomie à des entités responsables du support à l'opération de zones/blocs particuliers des réseaux de distribution. Par conséquent, des plusieurs fonctionnalités du système sont réalisées à travers l'autonomie et l'interaction entre agents, y compris le support aux procédures d'opération en réseau isolé ainsi que le rétablissement du service. Les solutions comprises dans l'architecture emploient une explicite représentation des comportements explicitement orientés vers l'objectif et directement lié à la planification des agents. Avec cette finalité, des agents BDI sont modélisés en utilisant le langage de programmation et l'interprète JASON qui, à travers sa syntaxe, permet des représentations d'un niveau élevé de raisonnement. En plus, le projet d'architecture est décrit sur la base des étapes de référence de la méthodologie Prometheus, à partir de l'abstraction des objectifs primaires jusqu'à la codification des plans d'actions. Après la description du système, plusieurs discussions sont effectuées pour une transition d'un paradigme classique de gestion centralisée jusqu'à la décentralisation atteinte par l'architecture basée sur des agents autonomes est discutée. À la fin, il est évident que cette thèse marque, pour le moins de la connaissance de l'auteur, la première application de JASON et Prometheus dans le secteur des systèmes d'énergie électrique, en mettant en évidence ses caractéristiques et son effectivité dans notre domaine de recherche.

Au-delà du projet de l'architecture, il est souligné qu'un des éléments-clés pour l'acceptation des solutions basées sur le concept des agents dans le secteur du système d'énergie électrique est dans le développement des modèles d'environnement à partir desquels il est possible d'évaluer l'impact à long

terme de ces solutions. Par conséquent, l'on propose un environnement informatique dans lequel l'impact à long terme de l'architecture est évalué à la lumière des indices de performance des réseaux de distribution. Pour cela, le concept d'une évaluation intégrée des aspects d'adéquation et de sécurité de service a été développé essentiellement pour les réseaux de distribution. Sur cette base, un modèle de simulation discrète et continue combinée a été proposé dans le but d'unifier la représentation de cycles de panne et réparation des composants avec une représentation des aspects d'analyse dans les régimes stationnaire et dynamique, sous une optique inexistante dans l'état de l'art. En plus de cela, ce modèle de simulation inclut des contributions pour le développement des stratégies de délestage de charge, l'exposition d'un algorithme d'échantillonnage d'événements dans des conditions climatiques défavorables à travers les processus de Poisson non homogènes, l'exposition des fonctions tests pour la variation d'indices de performance due aux différentes stratégies de contrôle, ainsi que l'impact des stratégies d'opération en réseau isolé, le contrôle par émulation du statisme et le délestage de charge sur les indices de performance.

Tous les mécanismes du modèle de simulation sont insérés dans un environnement informatique basé sur des artifices définis dans une infrastructure commune pour environnements ouverts appelée CArtAgO. De cette forme, cette thèse met aussi en évidence une première application de CArtAgO dans le secteur des systèmes d'énergie électrique, pour le moins de la connaissance de l'auteur. Au moyen du métamodèle employé par CArtAgO, se développe un modèle de dispositif pour chaque élément générique d'un réseau de distribution. Additionnelle ment, un schéma basé sur dispositif est établi de manière à intégrer des transitions d'état du modèle de simulation avec la simulation de l'architecture d'agents. Ces schémas permettent l'évaluation effective de l'impact de l'architecture proposée sur la performance des réseaux de distribution. En effet, les simulations et les analyses de résultat indiquent que le niveau de gestion active de ressources distribuées atteint par l'architecture peut permettre des améliorations significatives des indices de performance des réseaux de distribution, en promouvant des niveaux élevés d'adéquation et de sécurité de service pour les consommateurs des sociétés de distribution d'énergie électrique.

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List of Acronyms

A&A	Agents and Artifacts
AC	Alternate Current
ACL	Agent Communication Language
AI	Artificial Intelligence
ANSI	American National Standards Institute
AUML	Agent Unified Modeling Language
AuRA-NMS	Autonomous Regional Active Network Management System
BA	Block Agent
BDI	Belief-Desire-Intention
CA	Client Agent
CArtAgO	Common ARTifact infrastructure for AGents Open environments
CDCS	Combined Discrete-Continuous Simulation
CERTS	Consortium for Electric Reliability Technology Solutions
CHP	Combined Heat and Power
CIM	Common Information Model
CIS	Customer Information System
COMMAS	Conditional Monitoring Multi-Agent System
DER	Distributed Energy Resource
DESIRE	DEsign and Specification of Interacting REasoning
DG	Distributed Generation
DMS	Distribution Management System
E.U.	European Union
EMS	Energy Management System
EPSR	Electric Power Systems Research
EV	Electric Vehicle
FAI	Portuguese Fund for Innovation
FCT	Portuguese Foundation for Science and Technology
FIPA	Foundation of Intelligent Physical Agents
FPI	Directional Fault Passage Indicator
GIS	Geographical Information System
GMDH	Group Method of Data Handling
GOOSE	Generic Object-Oriented Substation Event
GSSE	Generic Substation State Event
HMI	Human Machine Interface

HV	High Voltage
IEC	International Electrotechnical Commission
IEE	Institution of Electrical Engineers
IEEE	Institute of Electrical and Electronics Engineers
IET	Institution of Engineering and Technology
IJEPES	International Journal of Electrical Power & Energy Systems
INESC	Institute for Systems and Computer Engineering
ISAP	Intelligent Systems Applications to Power Systems
JADE	Java Agent Development Framework
JAL	JACK Agent Language
KQML	Knowledge Query and Manipulation Language
LOG	Loss Of Grid
LP	Load Point
LV	Low Voltage
MERGE	Mobile Energy Resources for Grids of Electricity
MV	Medium Voltage
PEDA	Protection Engineering Diagnostic Agents
PROLOG	PROgramming in LOGic
PRS	Procedural Reasoning System
PUCRS	Pontifical Catholic University of Rio Grande do Sul
RBTS-BUS2-F1	Roy Billinton Test System – Bus 2 – Feeder 1
REIVE	Smart Vehicle to Grid
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
TCM	Trouble Call Management
U.S.	United States
UML	Unified Modeling Language
XML	Extensible Markup Language

Chapter 1

Introduction

This chapter introduces the context and motivation of this thesis. Over these elements, the research questions, main hypothesis and objectives of the thesis were established. The challenges of the thesis' topic are discussed and a revised structured of the document is outlined in the end of the chapter.

1.1 Context and Motivation

Electrical power systems are designed to provide electricity with a certain level of adequacy and security. Like most of the systems developed by the human beings, the electrical power systems evolve based on trends motivated by economical, environmental and societal drivers. Recently, such drivers have caused the advent of well-established initiatives especially concerned with these systems as the Modern Grid Initiative [1], the IntelliGrid Initiative [2], and the European Smart Grids Technology Platform [3, 4]. In general terms, these initiatives try to promote on different extends the integration of renewable and distributed energy resources, the deployment of decentralized control and management solutions, the modernization of the electrical power systems, as well as the provision of high levels of reliability. In the past few years, the integration of renewable and distributed energy resources has increased, particulary in what concerns wind power in Europe. Similarly, the deployment of decentralized control and management solutions has also increased, at least in what regards the improvements in automation and control of power distribution systems. All these changes have been achieved due to a gradual modernization process of the electrical power systems which can be observed at contrasting levels around the world. Such modernization has been enforcing improvements on reliability as well. Nevertheless, the deregulation of the power industry has been forcing the electrical power systems to be operated much closer to their technical limits.

The technical challenges of this context embrace several power engineering related fields of expertise as power electronics, communication, information technology, and software engineering. Additionally, the quoted drivers have been influencing power engineering itself in terms of its areas (long-term planning, mid-term planning, short-term or operational planning, operation, control and protection), as well as its structure/organization (generation, transmission, and distribution). In particular, the operation and control of power distribution systems might stand as one of the most promising areas to change. As a matter of fact, most of the interruptions in supply are caused by problems at the power distribution systems [5]. Furthermore, power distribution systems are the main locus for distributed energy resources (DERs) such as power distributed generation (DG) units, distributed energy storage devices and controllable loads. At last, the promoted modernization and decentralization along with the integration of DERs must guarantee the service adequacy and security. This requires revisiting the concepts of service adequacy and security in power distribution systems, re-evaluating power distribution delivery under these concepts, the careful formalization and implementation of local control solutions capable of taking advantage of certain levels of modernization and decentralization, and the development of models to assess how the system performance can be improved by these solutions.

For sure the smart/modern grids are a concept yet to be reached. Also, even if the concept of what is (or what should be) a smart/modern grid matures rapidly, from a pragmatical point of view, it is unfeasible to assume that the power distribution utilities will modify their whole infrastructure overnight. Power system engineers and academia are then responsible to support the quoted formalization and developments in a way that improvements in system infrastructure are enforced in alignment with a long-term vision. Actually, even the capabilities of DERs are still not currently exploited at their most. For instance, power distribution utilities traditionally employ the practice of tripping DG units after the occurrence of a fault. Hence, islanded operation is avoided both for sustaining the operation after a fault or for restorative purposes. Therefore, in order to profit from the benefits DERs can provide to the system operation and to promote the large-scale integration of DERs, operational/control solutions which embrace the full capabilities of DERs to support operation must be developed. Similarly, the impact of these operational/control solutions in the system performance must be evaluated to foster the integration of such strategies into the operational procedures of the power distribution utilities. Finally, these solutions must be designed in order to make it possible their gradual implementation, without requiring great (initial) changes in the infrastructure of the power distribution systems.

Aiming at fulfilling some of these needs, the research questions introduced in the following section were established. Since the concept of what is (or what should be) a smart/modern grid is still under development, we have found advisable to propose solutions which can be gradually applied to actual power distribution systems along with the modernization of these systems. Such research directive aims to aid the modernization of power distribution systems itself, the exploitation of DERs in operation/control schemes, as well as the acceptance of some smart/modern grid ideas by power system engineers and academia.

1.2 Research Questions

Self-healing is ascribed to a system capable of automatically anticipating and responding to power system disturbances, while continually optimizing its own performance [2] to guarantee adequacy and security of supply. Under this definition, the main research questions of this thesis are the following.

1. Is it possible to develop local control strategies to improve the self-healing of power distribution systems by exploiting DER capabilities?

2. How to coordinate these strategies in order to create a control architecture designed to support the

power distribution system operation and to provide an adequate and secure service?

3. How to evaluate the impact of the designed architecture in the performance of the power distribution systems?

In order to approach these questions, the hypothesis and objectives described in the next sections were established.

1.3 Main Hypothesis

The main hypothesis adopted in this work was that "agent-based technology provides the most suitable paradigm to design control architectures capable to support the power distribution system operations in a way to provide a smooth transition from the actual distribution grids to smart distribution grids". This hypothesis was justified using the following statements.

1. The increase in complexity and size of the power distribution systems bring up the need for *distributed intelligence* and *local solutions*, which fall into the scope of agent-based technology.

2. Smart/modern grid design concepts related with entity/device interactions can be tested through agent-based modeling and simulation.

3. Decentralization, autonomy and active management are properties inherent of a system developed under the agent-oriented philosophies. Furthermore, an adequate agent-based modeling can produce flexible, extensible, and robust systems[1.1] [6]. All these features are of most importance to a smooth modernization of power distribution systems.

1.4 Objectives of the Thesis

The overall goal of this thesis is the development and evaluation of a control architecture to support the power distribution system operations under emergency conditions using agent-based technology. The specific objectives of the thesis are enumerated as follows.

1. **Design of an agent-based control architecture to support the operation of power distribution systems under emergency conditions, considering the integration of DERs.** This control architecture must be in alignment with concepts of smart/modern grids, but providing smartness under the well-defined notions of intelligence behind the agent paradigm. Functionalities to support islanded operation and restoration under the presence of DERs must be developed to promote exploiting the DER capabilities in the system operation. Also, the architecture must be conceived following the formalisms of agent-based systems and implemented using an agent programming language based on a strong notion of agency.

[1.1] Conceptually, flexibility is the ability to respond correctly to different (dynamic) situations. Extensibility connotes the ability of augmenting, upgrading or adding new functionality to a system. Finally, robustness stands as a degree of system fault tolerance.

2. **Design of a simulation model for the power distribution system operation in order to evaluate the long-term impact of operational/control solutions.** This requires revisiting and adapting bulk power system adequacy and security evaluation concepts to power distribution system applications. The resulting simulation model must be capable of unifying the modeling of long-term stochastic failure/repair cycles of system components with the modeling of aspects of system steady-state and dynamic behavior analysis. Furthermore, the power distribution standardized systemic and node performance indices must be retrieved as a result of the simulation, in order to enable verifying the impact of operational/control solutions in the power distribution system operation.

3. **Development of an environment model capable of integrating the agent-based architecture with the simulation model of the power distribution system operation.** This requires modeling the power distribution system components using a complex abstraction beyond the notion of a computational object. Furthermore, it demands integrating all system state transitions conceived at the simulation model with all agent reasoning cycles in a coordinated manner, preserving both efficiency and consistency.

The tangible product of the work is an agent-based simulation platform where the developed operational/control strategies can be tested, evaluated and updated. The target group of the work includes researchers, regulators, computational scientists, power distribution systems planners and operators.

1.5 Challenges of the Topic

Despite the challenges of achieving all the contributions outlined in the previous section, we enumerated below three additional challenges which marked considerably the pathway of building this thesis.

1. **Context.** The smart/modern grid paradigm has brought plenty of ideas to the power engineering society. The current context involves discussions where smart/modern grids are enunciated under several frameworks, either general or alongside specific ones such as the micro grid and the multi-micro grid paradigms. As a side effect, similarly to what happened with the advent of the deregulation of the power industry, the number of smart grid related publications increased rapidly, crowding conference proceedings and journals with conventional solutions but elaborated over the under maturing paradigm. For sure, this context imposes several challenges/oportunities to researchers. Among them, we highlight the challenge of developing consistent solutions to smart grids bearing in mind that a clear definition of *smartness* in this context is yet to be provided. In this thesis, we promote *smartness* using the intelligence provided by agency in a well-justified and consistent manner. The participation in projects related to the European Union's Framework Programme for Research at INESC Porto has enlightened different views of smart grids and provided means to achieve such consistency.

2. **Background.** The topic requires extensive knowledge in power system analysis and software engineering. As a researcher with main background in power engineering, assimilating concepts

from computational sciences at the level of devising research was one of the most difficult but gratifying challenges of this work. Although some of the designed models were validated using development suits of more acquaintance to power engineer researchers such as MATLAB [7] and EUROSTAG [8], all the systems were ultimately conceived using computational science tools such as the Unified Modeling Language (UML) and the Agent Unified Modeling Language (AUML), as well as they were implemented using JAVA and JASON/AgentSpeak languages [9, 10].

3. **Technology under development.** Most of the technology we have applied in this work belongs to the state of the art. This comes with a drawback which is the lack of examples and, sometimes, consolidated documentation. At the best of our knowledge, this works introduces the first application of JASON [10] to power engineering. JASON is an open source interpreter for an extended variant of the AgentSpeak language whose version 1.0 and related book date from 2007. Similarly and again at the best of our knowledge, this work marks the first application of CArtAgO [11] (Common ARTifact infrastructure for AGents Open environments) technology to model power engineering environments. CArtAgO is a general purpose infrastructure to execute environments that was registered in 2008, though the bridge to JASON dates only to 2010. Thankfully, the agent-based technology community is open, fast, and productive, allowing discussions and bug solving in an efficient way. Also, the interchange with the department of computer sciences of PUCRS was determinant to achieve the application of these technologies.

4. **Writing the thesis.** Since the topic required deep developments in subjects related to power engineering and computational science, writing this thesis was a great challenge. The main directive was to describe the contributions as precise as possible avoiding confusion with the jargon of both areas, explaining the innovative aspects of the developments in terms of the power engineering solutions, but concurrently making clear to both power engineers and computational scientists the fundamental aspects of modeling and implementation. As consequence, both areas should benefit from the contributions. All the material was thought and re-thought until the final structure converged to the present document. We are confident that readers from both areas will appreciate the work.

1.6 Structure of the Document

Besides this introductory chapter, this document is structured as follows.

Chapter 2 introduces a background and state the art about the main topics approached in the thesis. The chapter begins with a background and state the art on power distributed generation, emphasizing its drivers and technical challenges. Afterwards, power distribution systems are addressed, focusing on the components and systems behind the protection, automation, control and operation activities. The chapter proceeds discussing the state of the art about power distribution system performance evaluation followed by frameworks for future power distribution systems. Hence, the discussions evolve to the definitions of agent and multi-agent systems, emphasizing directly the choices of a reasoning architecture, design concepts, and programming language. Following these discussions, an extensive survey of the applications of agent-based technology to power distribution systems is presented. Finally, the conclusions drawn from the state of the art are summarized in order to highlight the contributions of the thesis.

Chapter 3 describes the proposed block-oriented agent-based architecture developed to support the power distribution system operation. This architecture promotes the concept of a smart distribution grid using *agency* to attain *smartness* and following a block orientation philosophy. This philosophy originated the concept of a block management system, which is featured in the agent-based system specification and architecture design. The agent capabilities are thoroughly presented using descriptors derived from an agent design methodology called Prometheus [12] and, at the same time, showing instructions to JASON/AgentSpeak language implementations. The transition from a pure centralized management to the decentralization achieved by the agents is also discussed. Final remarks regarding the architecture are outlined in the end of the chapter.

Chapter 4 presents the simulation model especially developed to represent the power distribution system operation and to estimate the distributional aspects of the power distribution system performance indices. For this accomplishment, the conceptual framework and initial remarks behind designing the simulation model are discussed. Then, the concept of an integrated adequacy and security evaluation of power distribution systems is described. Hence, we introduce a simulation model which unifies the representation of long-term stochastic failure/repair cycles of system components with the representation of aspects of system steady-state and dynamic behavior analysis, altogether in a combined discrete-continuous simulation approach. The approach includes the modeling of adverse weather conditions, dynamics of DERs, DG islanded operation and load shedding strategies. These developments overpass the state of the art in power distribution system performance evaluation and still possible extensions are described in the end of the chapter.

Chapter 5 presents the interconnection of the agent-based architecture and simulation model described in chapters 3 and 4, respectively, using the CArtAgO technology. The chapter introduces and proposes the concept of modeling power system components as environment artifacts, then allowing conjugating power engineering software component modeling to the creation of agent environments. For this accomplishment, the object-oriented modeling of the power distribution systems utilized in the simulation model is presented. Hence, the artifact modeling of power distribution system components is introduced. At last, the simulation engine developed in chapter 4 is modeled as a major environment artifact, directly connecting the agent reasoning cycles to the simulated system state transitions. Summaries and discussions are outlined in the end of the chapter.

Chapter 6 presents a great series of simulation results and analyzes regarding the developments of the thesis. The chapter begins with general descriptions about the experiments and proceeds with validation tests for the simulation model using a test system well-know by the power engineering society. Afterwards, the main features of our research developments are illustrated through the application of the block-oriented agent-based architecture to an actual feeder from the South of Brazil. Agent simulation interactions are depicted and the impacts of the agent-based solutions in the power distribution system operation are evaluated. Conclusions about the experiments are summarized in the end of the chapter.

Chapter 7 outlines conclusions and final remarks focusing on the main contributions achieved by the work.

Appendix A presents the list the publications achieved during the development of this thesis.

Appendix B enumerates device function numbers for protection relaying.

Chapter 2

Background and State of the Art

This chapter presents a background and state of the art about the main topics approached in this thesis. As emphasized in the introductory chapter, the thesis's topic involves knowledge about several disciplines of power engineering and computational sciences. Hence, the main objective of this chapter is to provide a background and state of art over these two areas, but driving the reader directly to the subjects of interest to our work. Following this reasoning, the contents of this chapter begin with the recent advent of DG, emphasizing its drivers and technical challenges. This advent unveils trends which are already influencing the power industry and are gradually leading the integration of renewable and distributed energy resources in the power distribution systems. Moreover, alongside the integration of energy resources, there is the modernization of the power distribution systems which has been progressively devised by the utilities to improve the service provided to the customers. Such modernization can be found in the complex infrastructure that supports the system operation, control and automation, and protection activities. As consequence, these activities are briefly introduced discussing the impact of the advent of DG. All these trends mark the need for revisiting the conceptual basis behind the power distribution system performance evaluation, a topic explored in detail throughout the document.

The advent of DG and the ongoing system modernization are pictured in the current status of the power distribution system infrastructure and related activities. Nevertheless, these infrastructure and activities might be subjected to changes due to the advent of the smart/modern grid paradigm in the power industry. The smart/modern grid concept is yet to be reached such that its current fundamentals are introduced alongside two frameworks specifically developed to power distribution system applications. Under this context, the agent paradigm is described as a pillar to designing decentralized services and solutions to complex, distributed, dynamic, partially observable and stochastic environments, such as the power distribution systems. Hence, the development of solutions based on agent technology is placed herein as the pragmatic manner of integrating the notion of intelligence in the support of the system operation, contributing to the formalization of an idea of smartness to be embedded in actual networks towards a smart/modern grid to be.

Therefore, in section 2.1, DG is described and contextualized together with its drivers and technical challenges. In section 2.2, power distribution systems are outlined focusing on the components and systems behind their protection, automation, control, operation and performance evaluation activities, as well as their future development frameworks. Hence, agent and multi-agent systems are introduced and their application to power distribution engineering is thoroughly surveyed in section 2.3. At last, in section 2.4, a summary of the conclusions withdrawn from the state of the art is presented and discussed. In this summary, several annotations are enunciated to highlight explicitly the current research gaps in the state of the art and foment the description of the contributions of the work.

2.1 Power Distributed Generation

The organization of the electrical power systems has followed the hierarchical structure shown in Fig. 2.1 over the last 50 to 60 years.

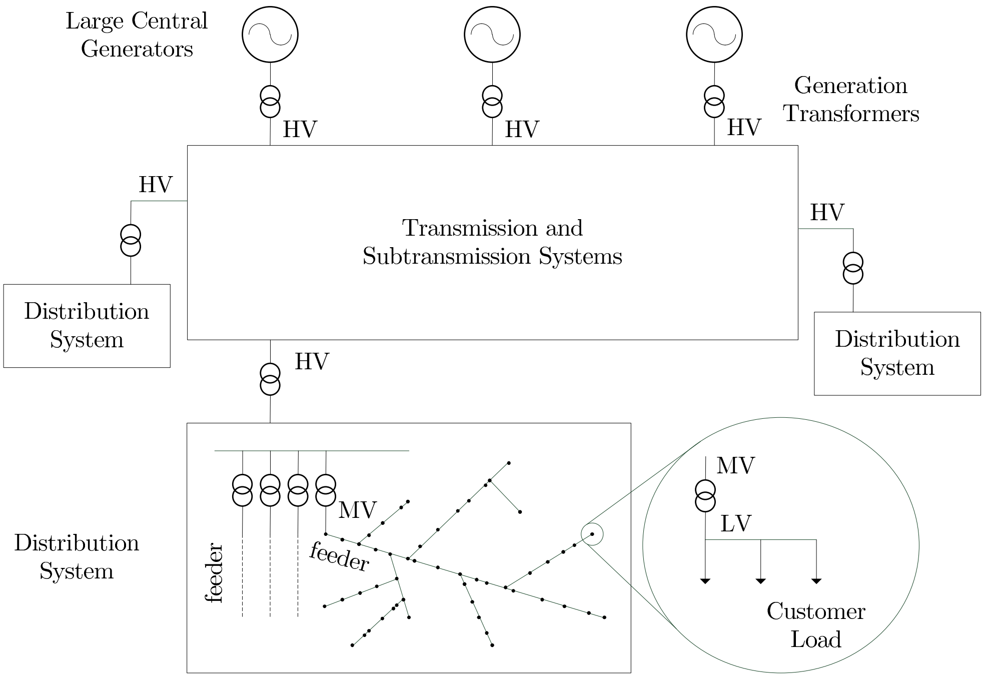


Fig. 2.1: Organization of the conventional electrical power systems.

This structure can be divided in three dimensions: generation, transmission and distribution. In the first dimension, large generations rely mostly on three types of conventional technologies to produce electric energy: hydroelectric units (either run-of-the-river or dams), thermoelectric units based on fossil-fuels (coal, oil or natural gas) or nuclear units. These large generators feed electrical energy through power transformers into high voltage (HV) power transmission systems. Then, in the second dimension, the HV power transmission systems are utilized to transport electrical energy, sometimes over considerable distances, up to power distribution transformers. From these transformers, in the third dimension, medium voltage (MV) and low voltage (LV) power distribution systems carry on the electric energy towards the final circuits of the customers. All these infrastructures are umbrellaed by power system utilities which operate over well-defined geographical territories and under the strict supervision of regulatory bodies [13].

More recently, the interest on DG (also referred in the literature as dispersed generation, decentralized generation or embedded generation) has grown in opposition to employing large blocks of centralized generation. The advent of DG faces considerable challenges and requires significant changes in the way the electrical power systems are regarded. Several definitions of DG can be found in the literature [14–17] and nowadays there is not a unified one. However, it can be loosely established that DG is achieved by the deployment of small-scale generators usually connected to the power distribution systems, as illustrated in Fig. 2.2.

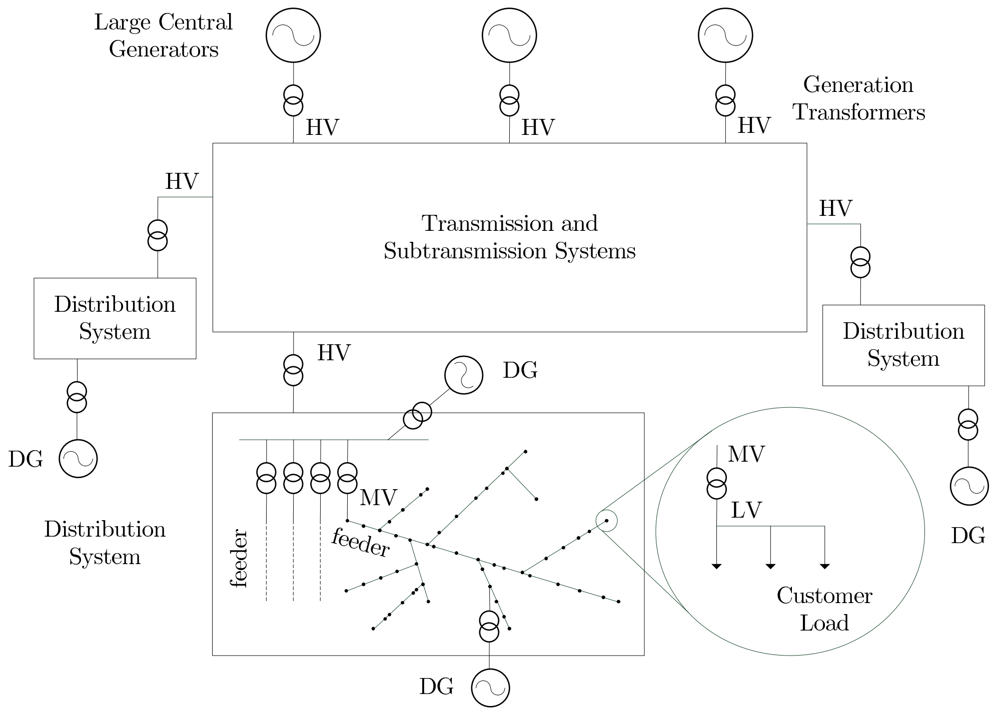


Fig. 2.2: Organization of the electrical power systems with DG units.

There have been series of drivers pushing forward the growth of the interconnection of DG in the power distribution systems. Among them, the three main drivers shown below can be identified [18].

Environmental drivers. The environment concerns have become an important layer of the power industry, especially after the signing of the Kyoto Protocol [19]. The Kyoto Protocol was adopted in Kyoto (Japan) on 11th December 1997, entered into force on 16th February 2005, and sets binding targets to reducing green house gas emissions. These targets foment the DG concept since DG units are envisioned to promote the use of renewable energy resources as well as fossil fuels in high efficiency local combined heat and power (CHP) applications. Furthermore, another driver for the DG comes from the possibility of avoiding the construction of additional transmission circuits and large generation plants, which nowadays face an increasing public opposition due to their environment impacts. Moreover, by providing electric energy closer to the customer loads, DG units contribute to the reduction of the electric energy losses through the power transmission and distribution circuits.

Commercial drivers. DG applications can be commercially attractive due to their reduced construction times and, in general, reduced financial risk in comparison with conventional generation plants. Moreover, incentive and/or market mechanisms have been envisioned to utilize DG in the improvement of service reliability, provision of standby capacity and/or peak shaving, provision of ancillary services, and as an alternative to expansion/reinforcement of the utility infrastructures.

National/regulatory drivers. There has been an increasing concern amongst energy policy makers regarding energy security. The diversification of national energy matrices by using diverse primary energy sources through the DG units may reduce the dependence on fossil fuels, thereby enhancing energy security. Furthermore, DG integration may support competition in energy markets whether energy trading and ancillary service mechanisms are established for them. Hence, it is expected that this competition can, in a long run, reduce the energy prices and improve quality of service.

Nowadays, DG units are considered within the concept of DER. The DERs include not only DG units but also controllable loads as well as distributed energy storage devices [18]. The controlable loads are envisioned as demand-side resources [16] in the sense of providing energy efficiency options (e.g. reduction of peak electricity demand). On the other hand, distributed energy storage devices can be an important supplement to DG due to the three main reasons below [15].

- It can be used for stabilization purposes, allowing DG to run at a constant and stable output level;
- It can provide energy to ride through periods when DG is not available (e.g. considering solar power at night-time);
- It can allow a non-dispatchable DG unit to operate as a dispatchable unit by enabling its output to differ from the power being supplied to the grid.

Distributed energy storage device may involve batteries, flywheels and supercapacitors. Among them, especial attention has been given recently by academia to the possibility of utilizing the batteries of the electric vehicles (EVs) to improve the system service. Under this perspective, the EV can be considered a mobile DER whose utilization depends on the habits of the customer/driver. Although some skepticism may be driven towards the concept of managing EVs towards the betterment of the system, it is a fact that the topic has gained substantial force in the past few years as a research interest of the power engineering society.

Regarding technology, DG units are usually established using energy conversion systems such as reciprocating engines as well as mini hydro, gas, steam, and wind turbines. These technologies allow the production of electric energy in relatively large power rattings and they are usually utilized in DG units connected at the MV levels or, eventually, at the HV levels. Recent technological developments also permit the establishment of DG solutions with power ratings inferior to 100 kWe [20]. These latter DG solutions are mostly connected through power electronic interfaces at the LV levels. Moreover, they are commonly referred as micro sources in the literature, involving technologies for micro turbines, fuel cells, and photovoltaic panels.

In order to accommodate efficiently the integration of DG in the power distribution system infrastructures, several challenges must be overcome. Examples of technical challenges to accommodate the integration of DG are described below [14, 18].

Voltage changes. The voltage rise effect is one of the key factors that can limit the amount of DG capacity to be connected to the power distribution systems. Moreover, voltage imbalances may occur when different feeders originating from the same power distribution substation have different DG integration levels.

Power quality issues. Depending on several matters such as capacity, type of prime mover, interface, location, and so forth, the DG can improve or worsen power quality. Therefore, system analyzes must be devised to verify the impact of DG integration on the power quality and, eventually, to infer possible corrective actions if necessary.

Congestion problems. DG integration may alter significantly the power flows through the power distribution circuits. This may ultimately cause overloadings, especially when large amounts of electric energy are injected into the circuits.

Protection issues. DG integration brought several challenges in system protection. Examples of these challenges are the protection of distribution networks from fault currents supplied by DG, loss-of-grid (LOG) protection, and the impact of DG on the existing system protection schemes.

Stability issues. Whether DG is expected to be able to provide some support services for the power distribution systems, stability becomes a critical issue. For instance, when connected to the utility, the loss of large central generation units may provoke mal-operation of protections (namely sensitive frequency protection schemes), causing undesired trips of DG units in the power distribution systems. Moreover, in case DG islanded operation is desired, stability matters must be thoroughly analyzed to verify the actual feasibility of the islanded operation mode and the proper procedures towards its reconnection with the utility.

System operation. DG has important consequences to the system operation once it may affect the protection, control and automation functions of the power distribution systems. Due to safety reasons, even the policies for isolation might be changed with the integration of DG, requiring additional training to the personnel that works in the field. Simple plans to de-energizing the network for maintenance reasons might be reviewed to take into account the frequency and duration of the DG service interruptions.

Besides the technical challenges, there is also the need for articulating appropriate regulatory policies to support DG integration in the power distribution systems. Moreover, case studies have indicated that some active management of the power distribution systems is required to accommodate a large scale integration of DG units. Such active management would involve managing not only the DG units but also customer loads and storage resources within the integrated concept of DER. Therefore, commercial arrangements are needed to support the active management of the power distribution systems, involving arrangements such that [18]

- to recover the cost of implementing active management directly through price control mechanisms;
- to establish an incentive scheme that would reward companies for connecting DG, such as the one recently developed in the United Kingdom [21];
- to establish a market mechanism, outside of the regulatory framework, which would create a commercial environment for the development of active networks.

This work focuses strictly on the technical matters, establishing the integration of DERs in the operational procedures devised by the power distribution utilities.

2.2 Power Distribution System Operation and Control

The power distribution system operation and control play a key role in enabling the system to adapt to changing situations in order to achieve the utility business goals. The developments in the system operation and control have followed the availability of enabling technologies (e.g. power electronics, communications, microprocessors) as well as the evolution of their associated methodologies. From the humble fuse to today's microprocessor based relay, protection gear and methodology have progressed to the point where protection can be looked upon as a fast method of control [22]. Nowadays, modern automation can improve the utilization and economy of operation, serving as an umbrella term covering from a large slice of the entire utility control process to the deployment of a simple local automatic control action. Furthermore, besides all possible automatisms, there is also the human intervention and decision making which exist either in a manual switch action devised by a crew staff or in a higher level deliberation remotely devised by an operator in a control room.

The system operation and control intrinsically involves the protection, automation and management activities. These activities impact on the system service delivered to the customers and how such service must be modeled and evaluated. Aside from these technical issues, following the advent of DG, several concepts and frameworks have been proposed to the so-called future of the power distribution systems. All these topics cover a broad extend of the science and technology behind power engineering, such that this section was clearly not intended to approach the entire scope of their matters. Conversely, we stress that the aim of this section is to provide knowledge background over the topics of interest of our work and to improve the readability of the document as a whole.

Following this reasoning, the general operation states and modes of the the power systems are described in section 2.2.1. Then, in section 2.2.2, the central control and management of the power distribution systems are outlined with focus on the features of modern integrated distribution management systems (DMSs). Such central control and management are supported by automation and protection infrastructures which are geographically widespread along the coverage areas of the power distribution utilities. Therefore, power distribution system automation is summarized in section 2.2.3 and some protection practices towards the interconnection of DG are presented in section 2.2.4. Once these activities are described, the state of the art in power distribution system performance evaluation is discussed in section 2.2.5, emphasizing the application of simulation methods to estimate standardized performance indices.

Finally, frameworks to future power distribution systems are drawn in section 2.2.6, enabling further discussions about the contributions of the work.

2.2.1 Power System Operation States and Modes

Power system operational and control decisions must be continuously undertaken to maintain the service adequacy and security. Such decisions depend upon the power system operation conditions, which can be summarily described by three sets of equations as follows.

1. A set of differential equations which represent the physical laws governing the dynamic behavior of the power system elements, including the different regulation blocks installed in the generation units.

$$\mathbf{h}(\mathbf{x}, \mathbf{u}) = 0 \qquad \text{[in steady state]} \tag{2.1}$$

   where $\mathbf{x}$ stands for dependent (state) variables and $\mathbf{u}$ denotes independent (input, control, structural) variables.

2. A set of algebraic equalities corresponding to the power flow equations.

$$\mathbf{f}(\mathbf{x}, \mathbf{u}) = 0 \tag{2.2}$$

3. A set of algebraic inequalities which represent the operational restrictions of the system such as the limits on system frequency, current and voltage.

$$\mathbf{g}(\mathbf{x}, \mathbf{u}) \leq 0 \tag{2.3}$$

The operation conditions can be encoded into states in terms of the degree with which adequacy and security are achieved. The operation states were first classified in [23] and, since then, they have been approached in different ways according to the purposes of their application. For instance, in [23] the operation states were classified in normal, emergency, and restorative. In [24] (apud [25]), the alert state was included in this classification. In [26, 27], the emergency state was further sub-divided in emergency and "in extremis" states. Furthermore, in [28] (apud [25]) three main possible crises were identified for the emergency state: the viability, integrity and stability crises. The *viability crisis* is characterized by constraint violations lasting from few seconds to many minutes. The *integrity crisis* is assigned in case of system islanding and/or service interruption. The *stability crisis* is a transitory emergency condition in which system integrity is at risk, lasting for a few seconds. Finally, in [29] operation states were categorized in nine non-disjoint states named adequate, inadequate, partially adequate, marginally adequate, stable, unstable, secure, not secure, and system collapse. These states were utilized in an integrated evaluation of bulk power system adequacy and security.

Another categorization of power system operation states can be performed through well-being analysis, commonly used in adequacy performance evaluations. In this sort of evaluation, power systems are represented by system states and their transitions, where generation capacities, components and loads have their own set of states. Each system state has an associated power system condition categorized as healthy, marginal or at risk, depending upon some adequacy and/or security criteria. In the *healthy* state, the total generation capacity is adequate to supply the total demand and system constraints are respected. Additionally, there is sufficient margin such that the "loss" of a system element, specified by some criteria, will not result in a system constraint violation [30]. In case there is not sufficient margin to guarantee a system constraint will not be violated, the state is called *marginal*. At last, in the *at risk* state, load can be curtailed and system constraints are violated.

An operation state transition can be caused by several factors such as changes in the load demand, generation, component status, or disturbances. By taking into account the literature discussed above, the power system operating conditions can be encoded in three states as follows.

Normal state. The generation is adequate to supply the load demand as well as service requirements are respected ($\mathbf{h}(\mathbf{x},\mathbf{u}) = 0$, $\mathbf{f}(\mathbf{x},\mathbf{u}) = 0$, $\mathbf{g}(\mathbf{x},\mathbf{u}) \leq 0$). This state can be further subdivided in two substates named secure state and alert state.

- **Secure state.** No credible event can result in a system transition out from the normal state. This state is analogous to the adequate-secure-stable state in [29], and includes the healthy state of the well-being analysis.

- **Alert state.** One or more credible events can result in a system transition out from the normal state. This state corresponds to the marginally adequate-stable state in [29], and includes the marginal state of the well-being analysis.

Emergency state. The generation is adequate to supply the load demand but one or more service requirements are violated ($\mathbf{h}(\mathbf{x},\mathbf{u}) = 0$, $\mathbf{f}(\mathbf{x},\mathbf{u}) = 0$, $\mathbf{g}(\mathbf{x},\mathbf{u}) \nleq 0$). This state corresponds to the inadequate-stable state in [29], and it is included into the at risk state of the well-being analysis.

Restorative state. Only a fraction of the customers are supplied ($\mathbf{h}(\mathbf{x},\mathbf{u}) = 0$, $\mathbf{f}(\mathbf{x},\mathbf{u}) \neq 0$, $\mathbf{g}(\mathbf{x},\mathbf{u}) \leq 0$ or $\mathbf{g}(\mathbf{x},\mathbf{u}) \nleq 0$). This state corresponds to all other states in [29] and it is also included into the at risk state of the well-being analysis.

A summary of the operation states, modes and their transitions is shown in Fig. 2.3. The process of determining whether the system is in the secure normal state (or not) is called security assessment [31]. In case the system is in its alert state, system operators have to proceed with preventive control actions in order to bring the system to the secure state. If the system transits to the emergency state, corrective and emergency control actions have to be performed pursuing the normal operation state. Also, in case the system transits to the restorative state, restorative control actions are utilized aiming the normal operation state as well. The normal operation mode is herein considered the operation at the normal state, while the emergency operation mode is characterized by the emergency and restorative states.

A set of operational/control actions towards a given goal defines an operational/control strategy. Since operational/control strategies are designed to improve the system operation, they must be technically evaluated in terms of how they achieve such target, which is a topic discussed in section 2.2.5. For now, observe that the practice of assessing the power system operation states and modes is clearly useful to the system analysis and real-time operation. Nevertheless, it depends on the degree of monitoring deployed in the power system infrastructure. Historically, control systems have been implemented on

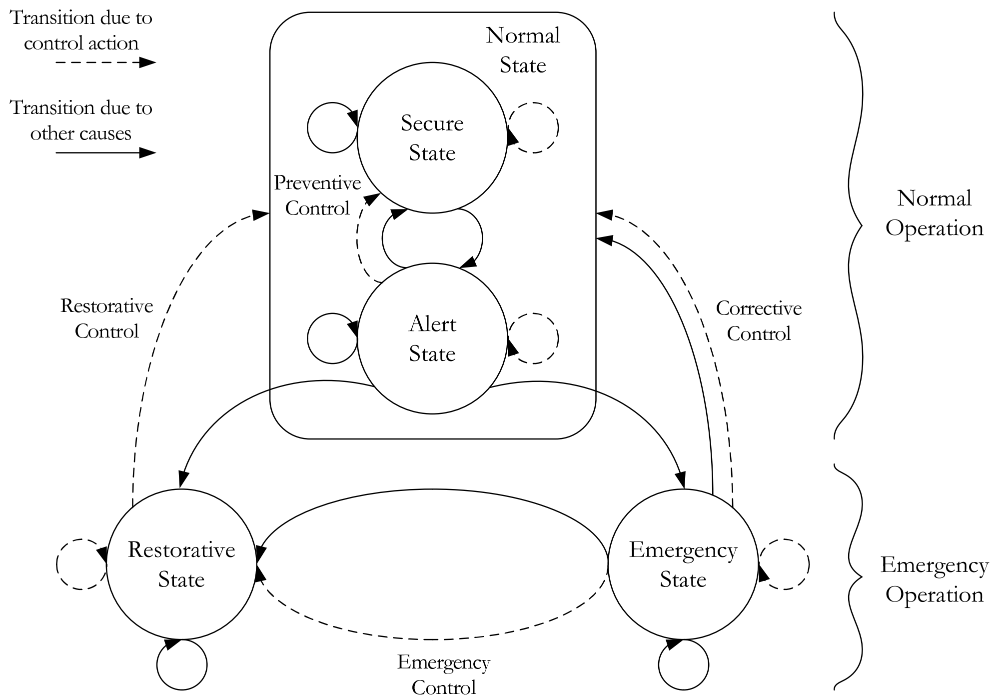


Fig. 2.3: Power system operation states.

bulk power systems where it was economical to monitor a large amount of the incoming and outgoing points of the network. Advances in computation technology and power system modeling enabled fast applications to be fed with real-time data from supervisory control and data acquisition (SCADA) systems [32] aiming at providing additional decision-making information to the system operators. Conversely, power distribution systems occupy the lower end of the control hierarchy, and the level of control is restricted by the specific structure of the power distribution networks and the penetration of real-time monitoring and control facilities. The SCADA system implementations in power distribution systems have historically controlled around 10% of the utility's switching devices and have been generally limited to circuit breaker applications at the larger HV/MV (primary) substations [33]. The adoption of the power distribution system automation concepts, where control is extended to substations and primary feeders, can substantially increase the reach of real-time control.

2.2.2 Power Distribution System Central Control and Management

Power distribution system operations are deliberated at central control rooms with the aid of distribution management systems (DMSs). The DMS acts as a decision aid system to assist the control room and field operating personnel with the monitoring and control activities. Currently, the manner in which power distribution systems are operated is influenced by the lack of remote control and real-time monitoring, demanding considerable manual intervention for decision making and restoration [33]. Therefore, although the described abstract encoding in operation states might be of interest, the power distribution system context requires more tangible perspectives where decisions are deliberated in a customer-oriented approach rather than reasoning about supplying blocks of load, and taking into account the monitoring and control limitations of the networks. These decisions require the usage of support systems and information outside traditional SCADA such as

- operating diagrams and geographical maps showing the location of the network and devices;
- inventory of device spares;
- trouble call systems to identify probable location of faults from customer calls;
- crew and job management methods to track and dispatch the correct resources and skills;
- mobile communications and data systems to allow command and data interactions between the control center and field.

Manual operations are performed by crews consisting of workers specially trained to work on either overhead or underground systems. They are placed on regional service centers that serve as home bases for trucks and equipment [34]. Crews are responsible for locating faults, performing switching actions, repairing damaged equipment, performing routine maintenance and constructing new facilities. A common scenario occurs when an operator receives a trouble call from customers with service interruption. The operators first identify the circuit associated with the customers and dispatch a crew to locate the fault. Once the fault is located, the crew reports back and awaits further instructions. Typically, the operator directs the crew to isolate the fault through the opening of disconnect switches and to re-energize the network as much as possible. If possible, the crew may also be instructed to close tie switches and restore more customers before beginning the repairs. After the switching actions are accomplished, the crew repairs the damaged equipment and returns the system to its normal state/configuration.

This scenario of operation exemplifies a set of coordinated activities to be managed by operators and field personnel. Before the advent of the integrated DMSs, power distribution utilities have been managing their systems by focusing on four key functional dimensions. All these functional dimensions must work in a coordinated manner synchronizing the control center and field operations [33].

Operations. This function is responsible for the daily running of the network with the primary objective of maintaining continuity of supply. Traditional SCADA systems are then placed at the top of the operation and control hierarchy. For the remainder of the network, paper maps or large wallboards are used to manage operations.

Assets. This function involves the activities such as inventory control, construction, plant records, drawings, and mapping. The major application to be introduced to facilitate this activity is the geographical information system (GIS), previously known as automated mapping facilities management system.

Engineering. An engineering department carries out all the design and planning activities for network extensions. Towards modernization, computational tools for network analysis and planning can be used to permit system operation audits of short-term solutions and to search for system reinforcements alternatives at minimum cost.

Business. The business function covers all accounting and commercial activities within the power distribution utility. It involves the operation in the sense of obtaining customer information in order to respond to trouble calls. Such information is maintained in a customer information system (CIS) or customer relationship management system.

Each of the functional dimensions above have especial applications to aid their management processes. The existing DMSs are extensions of these applications lumped in packages to be used in a control room. The evolution path and level of functional integration vary depending on the priorities of each power distribution utilities. However, the concept of sharing data models and interfacing different data sources is generally pursued aiming at creating an integrated system that serves the needs of the operator. The resulting modern DMS for system control and automation is comprised of four main functions, each with the ability to be fully integrated with the other and the possibility of operating independently. Fig. 2.4 illustrates these functions as described below.

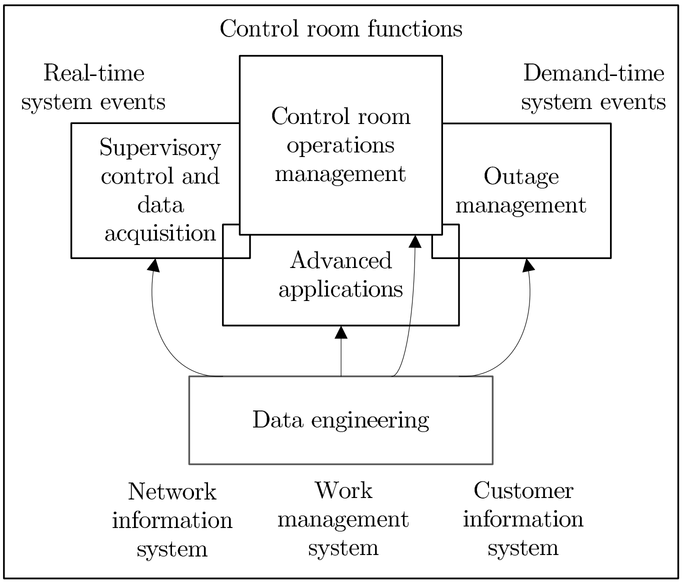


Fig. 2.4: High level DMS functions (adapted from [33]).

Control room operations management. This is an umbrella function covering the facilities provided to the operator in the control room through the operator's console, usually referred as human machine interface (HMI). The typical subfunctions involve a control room graphics system for network diagram display, an interface with SCADA, switching job management systems, and access to advanced applications (e.g. trouble call management (TCM) systems, outage management systems, data engineering applications).

SCADA. This provides the monitoring and control of the power distribution system in real-time. Traditional SCADA system extends down from the HV/MV distribution substation to MV feeder circuit breaker with displays limited to substation single schematics. Under the concept of an integrated

DMS, traditional SCADA systems have been extended to include the control of feeder devices outside the substations and the representation of the entire MV network in the form of a connectivity model.

Advanced applications. Applications to system analyzes that rely on MV network connectivity databases may support the assessment of the impact of switching actions in the operation conditions in terms of, for instance, component loadings and node voltages. The consequences of any network configuration on fault levels can also be determined with basic applications which are familiar to planning engineers. As privatization emphasizes the business issues, applications that concentrate on meeting the contract constraints respecting the technical limits will be required.

Outage management. Outage management spans a number of functions and can encompass the entire process from taking a customer's call, diagnosing the fault location, assigning and dispatching the crew to confirm and repair the fault (job management), preparing and executing switching operations to restore the service, and closing the outage by completing all required reports and statistics about the incident. During this process, additional trouble calls from customers should be coordinated with the declared fault if appropriate or another incident is initiated.

Besides these four functions, the DMS is also supported by other separate applications within the corporate information technology systems such as network information systems (including GIS), work management systems and customer information systems. These separate applications feed the DMS with data to support all the functionalities from graphic displays to outage management.

Notice that the modernization of the DMSs must regard the ongoing integration of DERs in the power distribution systems. Indeed, depending upon the level of integration of DERs, data and information models for the DERs must be embedded in the DMS data engineering processes to ensure that the DMS functions are performed adequately. For instance, DER data might be of utmost importance to analyze the "as-built" and "as-operated" network conditions. Besides this plain example, even the authorizations for physical access of DER facilities might be a subject to be embedded in the work management systems of the utility. For this accomplishment, the design itself of the control processes might consider real-time monitoring of the devices nearby and within the DER facilities. Finally, the control room operators and field personnel must be trained and act taking into account the impact of their decisions on the individual operation of the DERs.

2.2.3 Power Distribution System Automation

Power distribution system automation involves the set of technologies that enable a utility to monitor, coordinate and operate the power distribution system components in a real-time and non real-time mode from local, remote or central locations. Local automation is achieved at the device level while remote and central automation are usually controlled from the primary substations and control room, respectively. The main elements of the a power distribution automation systems are illustrated in Fig. 2.5. These elements might be in the control room, primary substations, and along the power distribution feeders.

The control and monitoring front end of the control room is given by the SCADA. From the control room, decisions can be passed down towards the HV/MV substations through a communication media

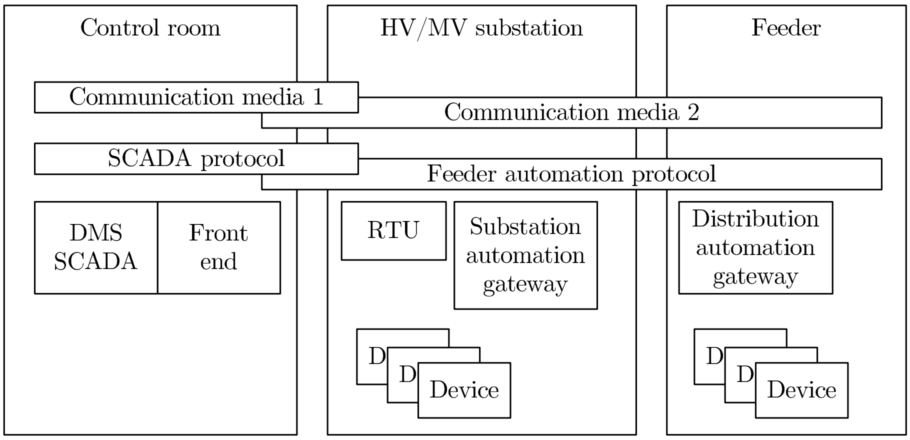


Fig. 2.5: Components of power distribution system control and automation systems (adapted from [33]).

following the SCADA protocol. In the HV/MV substations, remote control can be achieved following two strategies. The first one is obtained by hardwiring the control and monitoring circuits to a remote terminal unit (RTU) that exchange information with the control room through the SCADA protocol. The second one is achieved through substation automation, where a local area network within the substation is established between the communicating protective relays and a small computer based gateway to manage the data within the substation. This substation automation gateway provides a communication interface back to the control room using the SCADA protocol, supports software based internal substation interlocking and automation applications, and provides a HMI for local operation [33]. Finally, through the power distribution feeders, automation can be established by distributed control activities which can be invisible to the control room, integrated in the substation automation by the exchange of information with a substation gateway, or even converse directly with the control room using a distribution automation gateway. Recently, some authors (e.g. in [35]) have been utilizing the term "feeder remote unit" to refer to a terminal unit installed at the feeders to allow the communication of a local process with a master or central system.

The design of substation automation systems is standardized by the International Electrotechnical Commission (IEC) through the IEC 61850 [36]. Summarily, this standard splits the communications within the substation in three levels (see Fig. 2.6): the process level including the input/output devices (sensors and actuators), the bay/unit level including the intelligent electronic devices (IEDs) [37], and the substation level including the substation computer, operator's desk and the interfaces outside the substation. The term IED describes a general device that has versatile protection functions, advanced local control functions, monitoring abilities and the capability of extensive communications directly to a SCADA system.

The IEC 61850 standard breaks the protection and control functions in units named logical nodes. Each logical node has data objects defined under the object-oriented context. Hence, services that act upon the logical node's data objects are defined covering from the traditional control/read/write commands to the grouping of data objects, the reporting and logging of data, as well as the transmitting

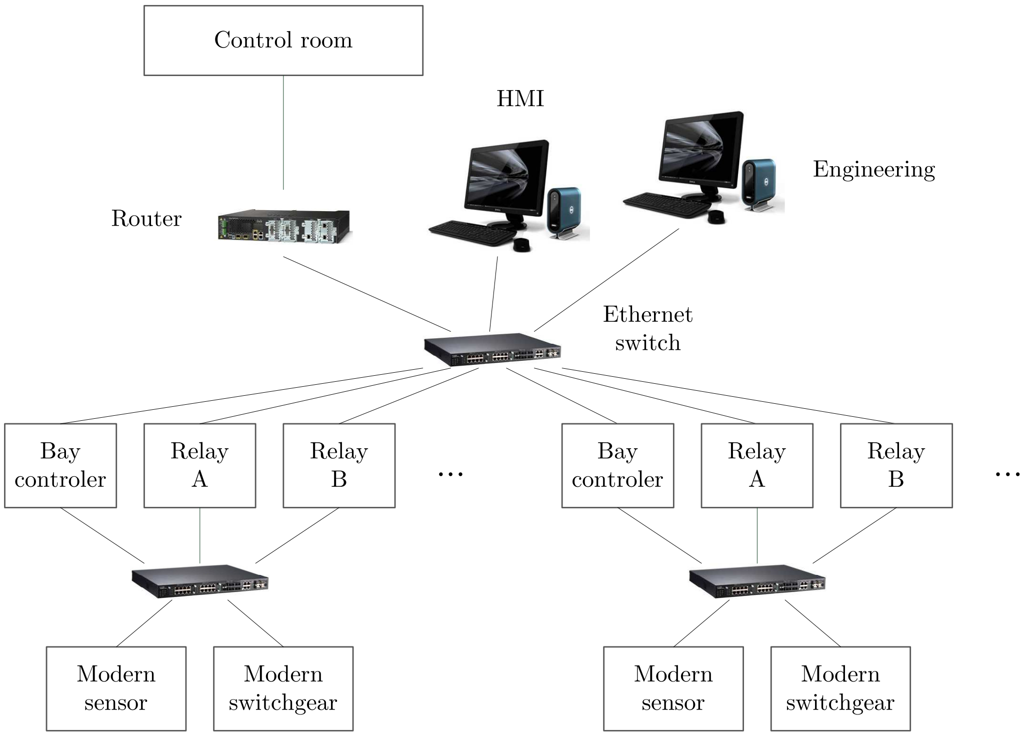


Fig. 2.6: Substation automation topological scheme (adapted from [38]).

of fast messages with generic object-oriented substation event (GOOSE) and generic substation state event (GSSE) mechanisms [39]. Logical nodes for DERs were recently designed in the IEC 61850-7-420 [40] and additional extensions of this standard are envisioned to be proposed [35, 41, 42]. These extensions are required since the ongoing integration of DERs implicates that monitoring, control and protective devices from the DER infrastructure become an integral part of the power distribution automation. The extensions of IEC 61850 to distribution automation have recently begun [35] and some authors (e.g. in [43, 44]) have been discussing the conceptual coupling of the IEC 61850 with the IEC 61499 [45], an open standard to distributed control and automation based on the concept of function blocks. The allocation of the logical nodes into physical devices is a choice of the device manufacturer and typically depends on substation technology and operation conditions.

Aside from technology and standard matters, there are two main approaches to integrate automation functions to the power distribution system infrastructures: the *top-down* approach or the *bottom-up* approach [46]. The top-down approach is the harsh approach in which a large scale fully-integrated automation system is installed to automate most or all of the functions performed by various individual devices in the power distribution system. The bottom-up approach is evolutionary in the sense that automation devices to perform only a particular function are gradually installed and/or a small part of the system is automated at a time. While the the top-down approach is expensive and requires major modifications in the utility operation, the bottom-up approach allows utilities to adjust to changes at a more measured pace and to install automated systems for the most immediate needs, which in turn might be dependent on the geographic location of the utility feeders, operation philosophies, and financial situation.

Some authors have speculated that most of the utilities would embark on large scale distribution automation. However, many utilities found difficulties in justify distribution automation based on hard cost-benefit numbers [47]. Therefore, need-based automation must be promoted to justify changes in the operational procedures and infrastructure. Also, there is nowadays the opportunity of improving the system service with the adequate utilization of DERs in the operational/control procedures. This opportunity, allied with the advent of advanced metering infrastructures [48] promoted under the smart/modern grid paradigm, opens the way for bidirectional communication-based automation and control solutions distributed along the power distribution feeders.

2.2.4 Power Distribution System Protection

Below the operational, control and automation layers of the power distribution system infrastructure, there are the protection systems. Power distribution system protection plays a crucial role in preserving the service continuity to the customers by isolating affected parts of the system during short circuits and abnormal operation conditions. Most of the protection infrastructure was created assuming the load and short circuit currents are unidirectional. As consequence, power distribution system protection is normally based on overcurrent relays with settings selected to ensure discrimination between upstream and downstream relays. Hence, a fault on a downstream feeder must be cleared (at most) by the relay at the source end of the feeder. In case the downstream relay fails to clear the fault, relays on the immediate adjacent upstream sections should operate. Examples of protective devices are the lightning arresters, fuses, and relays with associated circuit breakers, reclosers, and so forth.

A large number of protection challenges arose with the advent of DG integration and interesting reviews about the topic have been established in the technical literature [49, 50]. Nonetheless, it is a fact that DG units have been progressively integrated and the existent variety of published studies indicate the awareness of the power system protection communities about the existing challenges. For sure, DG owners need to be concerned with abnormal operation conditions imposed by the utility system such as overexcitation, overvoltage, unbalanced currents, abnormal frequency and shaft torque stress caused by breaker automatic reclosing. On the other hand, utilities must be concerned with the possible damage DG integration may incur to their equipment/assets. Typically, protection requirements to connect a DG to the utility system are established by each individual utility or by national grid codes. Mostly, utility's requirements cover small generators and the integration of large generators is usually reviewed on a case-by-case basis [51].

Usually, DG interconnection protection is established at the point of common coupling between the utility and the DG facility, as shown in Fig. 2.7. The DG protection must detect generator internal short-circuits and abnormal conditions. On the other hand, DG interconnect protection must protect the utility from damage caused by the connection of the DG and the DG from damage caused by the utility system. General DG interconnection protection methods and practices shown in the literature are summarized below alongside their associated relay functions [14, 49, 51, 52].

Detection of loss of parallel with the utility. The most universal means of detecting loss of parallel

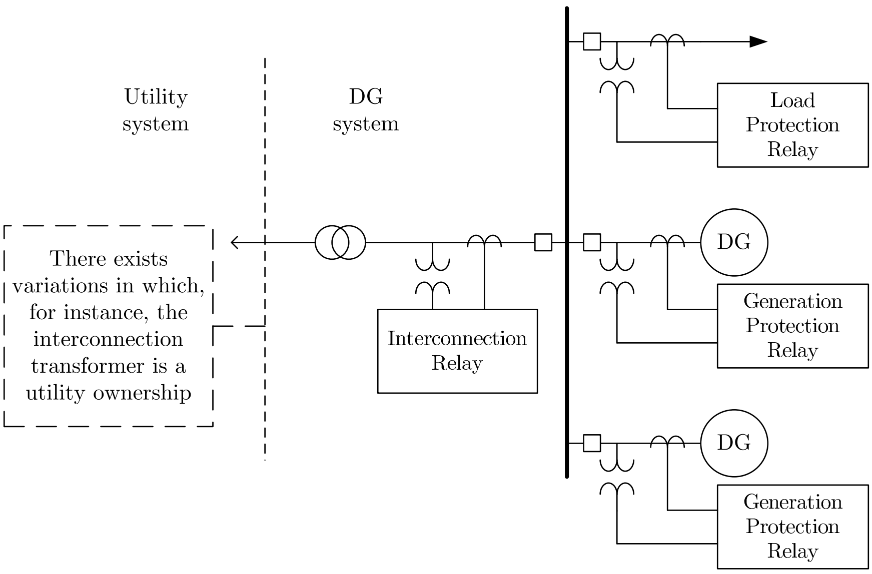


Fig. 2.7: General interconnection protection scheme.

operation with the utility is to establish an over/underfrequency (R81O, R81U) and over/undervoltage (R59/R27) window within the DG should operate. Rate of change of frequency (R81R) and vector shift (VS) relays can be used as well [50]. If the local load and generation production are near a balance, transfer trip[2.1] (TT) using reliable means of communication may be necessary. An instantaneous overvoltage relay (R59I) that responds to peak voltage can be used to avoid non-sinusoidal overvoltage due to resonant conditions, for instance, in islands operating near their maximum capacity with pole top capacitors, synchronous or induction generators, as described in [51]. Actually, TT may be enforced and the loss of parallel relays used as back protection [52]. Whether anti-islanding is required, the separation must be quickly enough to allow the utility breaker to automatically reclose.

Fault backfeed detection. Distance relays (R21) and/or directional overcurrent relays (R67) (eventually) with supervised restraint/controlled overcurrent relay (R51V) are applied for phase fault backfeed removal. Ground fault backfeed removal depends on primary winding connection of interconnection transformers. For grounded primary transformer winding, neutral overcurrent relay (R51N) may be applied. For ungrounded interconnection transformers, neutral overvoltage/undervoltage relays (R59N, R27N) provide detection for supply ground faults. Also, some authors (e.g. [52]) describe backfeed protection against faults on adjacent feeders or the transmission system. In the substation, directional overcurrent protection devices (R67,R67N) are needed in place of nondirectional (R50,R50N,R51,R51N) phase and neutral protection to prevent incorrect operation.

[2.1] Transfer trip is a communication system with transmitter at the utility end keyed by any opening of the feeder breaker, whether manually, remotely by SCADA or automatically by protective relays. The signal is sent by a communication link such as microwave radio, fiber optics or telephone pairs to a receiver at the DG location. Hence, the receiver will trip the interconnect breaker at the DG site. Protective relays at the DG intertie point are also needed as backup protection for the transfer trip scheme in order to detect the faults on the utility system.

Detection of damaging system conditions. Protection against unbalanced currents and phase-phase faults [14] using negative sequence overcurrent relay (R46) as well as protection against phase reversals caused by inadvertent "phase swapping" after power restoration using a negative sequence voltage relay (R47) are applied.

Abnormal power flow. Directional power relay (R32) is demanded to trip the DG if power inadvertently flows into the utility system for a predetermined time in violation of an interconnection contract.

Synchronization. When the utility system is re-energized after a service interruption, the DG units can be automatically resynchronized, usually with synchrocheck relay (R25) (e.g. checking magnitude, phase, and frequency difference of voltages) at the main incoming breaker to supervise reclosing.

The update in a HV/MV substation scheme as well as the functions of interconnection relaying are shown in Fig. 2.8. Relay numbered functions, following the American national standards institute (ANSI) definitions, are summarized in Appendix B.

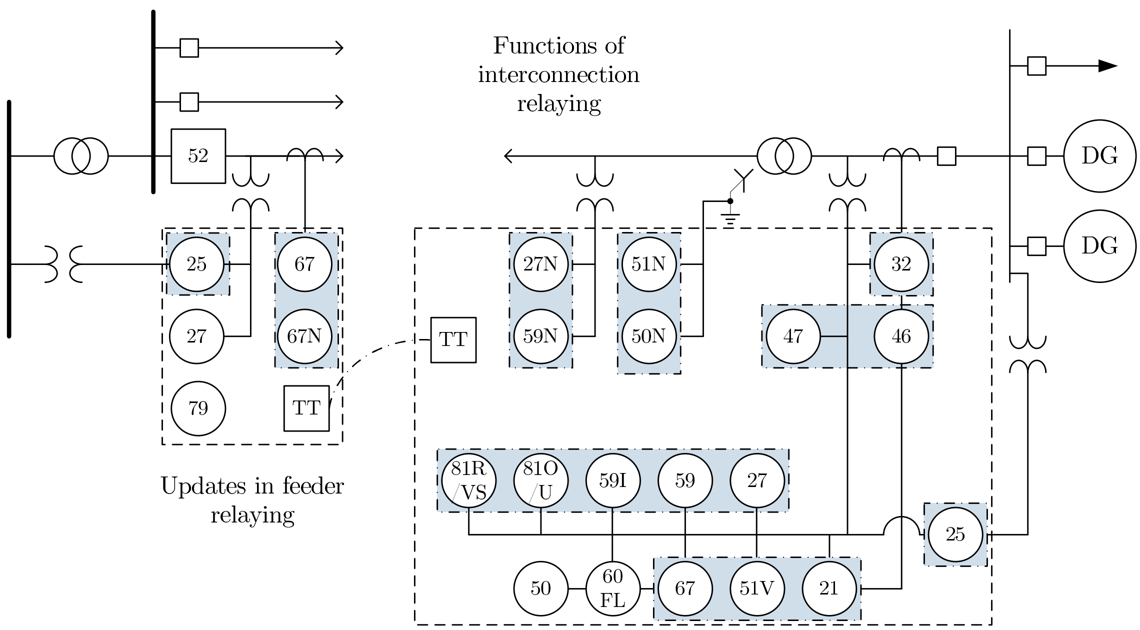


Fig. 2.8: Functions of feeder and interconnection relays.

The relay functions shown above can be utilized depending upon the DG application. Also, several other relay functions might be used, such as voltage transformer fuse failure (R60FL) and (R50) instantaneous current relays, according to the preferred design of the utility and/or DG owners.

2.2.5 Power Distribution System Performance Evaluation

The operation, control, and protection activities have impact on the system service delivered to the customers and how this service must be evaluated. Despite of the possible techniques and methods that can be applied to the system evaluation, it is important to emphasize that aspects from both adequacy and security of the system operation must be regarded in the evaluations alongside proper performance index estimation. Power system performance evaluations can then be classified as follows [30].

1. Adequacy evaluation: this relates to the ability of the installed generation and transmission facilities to serve the total system requirements.

2. Security-constrained adequacy evaluation: this relates to the ability of the generation and transmission system to avoid load curtailment under failure events.

3. Security evaluation: this relates to the ability of the system to operate under stable conditions when a major change in the system occurs.

The integrated evaluation of adequacy and security aspects, covering the three items above altogether, is a non-consolidated topic in power engineering. Also, even the separate classification above is sometimes misused by the power engineering academia. For instance, at the discussions of [53], J. Endrenyi verifies the misusage of the classification of security evaluation to the work in [53] once dynamic behavior analyzes were not actually performed. Aside from these issues, in the past few decades, adequacy evaluation and probabilistic transient stability have been subjects of interest (see bibliography surveys in [54–57]) to the power engineering society. Recently, some efforts have been directed to researching security-constrained adequacy evaluation and security evaluation techniques [58]. For instance, security-constrained adequacy evaluation and security evaluation approaches can be found in [53,59–61], where probabilistic information about the system operation states is quantified. In [62], a security-constrained adequacy evaluation is considered by using scenarios characterized by base system configurations (system topology, equipment and load level) and associated set of generation dispatches and voltage profiles. Scenario divisions were adopted in developing security assessment solutions as well in [20, 63]. In [30], adequacy issues, voltage stability and transient stability are discussed altogether for composite generation and transmission bulk power system performance evaluation and considering well-being analyzes. Transient and voltage stability are also approached in [64], without well-being analysis, but with a more accurate modeling of dynamic aspects of generators. In [58], self-organizing maps are utilized to accelerate the evaluation of some adequacy and security aspects and, in [65, 66], adequacy and security concepts are introduced in a bulk power system evaluation approach.

We emphasize that none of the works quoted above are associated to power distribution systems. As a matter of fact, the definitions enumerated in this section are clearly tuned for bulk power system performance evaluations. Power distribution systems are assessed according to system and/or customer service interruption performance, subjects not even mentioned in the three enumerated items. Indeed, in the power distribution system context, the term adequacy assessment/evaluation is generally utilized to refer to the evaluation of system and/or customer service interruption performance indices. Nevertheless, the increasing concerns about quality of service, the promotion of smart/modern grid concepts and the ongoing integration of DERs require clearer meanings for adequacy and security of supply in power distribution systems. Therefore, in order to formalize the evaluations of interest in our context, it was found required *to revisiting and adapting bulk power system adequacy and security evaluation concepts to* *power distribution system applications*. This topic is explicitly tackled in chapter 4 as a contribution to the research area.

For now, let us attain to the fact that quantifying the performance of a power distribution system evolved into evaluating a set of standardized indices that are well recognized throughout the industry. Of course, this does not imply that the utilities cannot develop their own measures to set specific business goals within their organization. However, the referred indices are of great importance since they indicate the annual average system performance in terms of customer interruption frequency and duration. Hence, these indices are weighted by the number of customers or energy supplied and are either presented on a system-wide or customer basis. Also, the performance indices can be applied to the entire system or separated coverage areas as long as consistency is maintained between the data used in the analyzes and the interpretation of the associated indices.

The standard customer indices are the failure rate λ [interruptions/year], the unavailability or annual outage time U [h/year] and the mean time to repair $r = {}^{U}/_{\lambda}$ [h/interruptions] at the customer point of connection. The system-wide power distribution performance indices are defined as follows [34, 67].

System Average Interruption Frequency Index. This index measures how many sustained interruptions an average customer will experience over the course of a year.

$$\text{SAIFI} = \frac{\text{n}^{\text{o}} \text{ of customer interruptions}}{\text{n}^{\text{o}} \text{ of system customers}} = \frac{\sum_i \lambda_i N_i}{\sum_i N_i} \qquad \left[\frac{\text{interruptions}}{\text{year}}\right] \tag{2.4}$$

where λ_i is the failure rate and N_i is the number of customers at the point of connection i.

System Average Interruption Duration Index. This index measures how many interruption hours an average customer will experience over the course of a year.

$$\text{SAIDI} = \frac{\text{Total customer interruption durations}}{\text{n}^{\text{o}} \text{ of system customers}} = \frac{\sum_i U_i N_i}{\sum_i N_i} \qquad \left[\frac{\text{h}}{\text{year}}\right] \tag{2.5}$$

where U_i is annual outage time at point of connection i.

Customer Average Interruption Duration Index. This index measures how long an average interruption lasts.

$$\text{CAIDI} = \frac{\text{Total customer interruption durations}}{\text{n}^{\text{o}} \text{ of customer interruptions}} = \frac{\sum_i U_i N_i}{\sum_i \lambda_i N_i} \qquad \left[\frac{\text{h}}{\text{interruption}}\right] \tag{2.6}$$

Average Service Availability Index. This index measures the customer weighted availability of the system.

$$\text{ASAI} = \frac{\text{Total customer service durations}}{\text{Total customer year durations}} = \frac{\sum_i 8760 N_i - \sum_i U_i N_i}{\sum_i 8760 N_i} \tag{2.7}$$

where 8760 is the number of hours in a calendar year.

Average Service Unavailability Index. This index measures the customer weighted unavailability of the system.

$$\text{ASUI} = \frac{\text{Total customer interruption durations}}{\text{Total customer year durations}} = \frac{\sum_i U_i N_i}{\sum_i 8760 N_i} = 1 - \text{ASAI} \tag{2.8}$$

Energy Not Supplied. This index measures the total energy not supplied by the system.

$$\text{ENS} = \text{Energy not supplied by the system} = \sum_i P_i U_i \qquad \left[\frac{\text{MWh}}{\text{year}}\right] \tag{2.9}$$

where P_i is the load connected to the point of connection i.

Average Energy Not Supplied. This index measures the average customer total energy not supplied.

$$\text{AENS} = \frac{\text{Energy not supplied by the system}}{\text{n}^{\text{o}} \text{ of system customers}} = \frac{\sum_i P_i U_i}{\sum_i N_i} = \frac{\text{ENS}}{\sum_i N_i} \qquad \left[\frac{\text{MWh}}{\text{customer.year}}\right] \tag{2.10}$$

Regarding the evaluation itself of power system performance indices, several methods have been proposed in the literature. Among them, the analytical and Monte Carlo simulation [68] approaches stand out. Summarily, in the analytical approaches, the system states are modeled as a composition of states (failure, repair, high, low, and so on) of components, generators, and loads. Hence, by enumerating and evaluating these system states, performance indices are estimated. On the other hand, the Monte Carlo approaches are further sub-divided in non-sequential, sequential, pseudo-sequential, and population-based. In the non-sequential approaches, the states of components, generators and loads are sampled to obtain non-chronological system states which are evaluated to estimate performance indices. In the sequential approaches, the failure and repair cycles of components and generators are simulated alongside load transitions. Then, the system operating cycle is obtained by combining all these effects and performance indices are estimated through state evaluation following a chronological sense. The pseudo-sequential approaches retain some flexibility and accuracy of the sequential Monte Carlo approaches while reducing the computational effort. At last, the population-based approaches utilize population-based meta heuristics to search for system states that are prone to contribute to the estimation of performance indices.

Most of these approaches estimate single-valued performance indices, which provide arguably poor information regarding the power system operation performance. At the present time, *the sequential Monte Carlo simulation is the only realistic option available to investigate the distributional aspects associated with system index mean values* [69]. Quite recently, cross-entropy methods have been used to optimize failure and repair rates of generators, then improving the efficiency of the sequential Monte Carlo approach [70]. Nevertheless, the technique has the drawback of distorting the estimated probability distribution of the performance indices. Another recent advance regards the mix of population-based methods with the sequential Monte Carlo approach for the evaluation of generation systems. This approach increases considerably the efficiency of the sequential Monte Carlo simulation keeping the possibility of estimating the probability distribution of the performance indices (see publication 4 in Appendix A). Also, a hybrid approach can be found where the analytic method and the sequential Monte Carlo simulation are mixed to reduce the computational burthen of the latter. This approach provides fast estimations and non-orthodox interpretations of the probability densities of the performance indices (see publication 3 in Appendix A).

Non-sequential, pseudo-sequential and sequential approaches have been extensively applied for composite generation and transmission performance assessment (e.g. [71–75]). On the other hand, only some power distribution systems applications can be found in the literature (e.g. [76–81]). In fact, some applications of performance evaluation of power distribution systems considering DG can already be found in [82–84]. In [85], systemic and customer reliability indices are evaluated for power distribution systems with micro grids. Also, voltage sag indices are studied in [86] and a customer security assessment is presented in [87] for power distribution systems with large scale integration of wind power.

At the best of the author's knowledge, only in [29, 88, 89] a fully sequential Monte Carlo simulation is considered alongside bulk power system static and dynamic aspects and aiming the integrated evaluation of adequacy and security issues. Static and dynamic aspects are also considered in [90] with some advantages regarding the emergency control measures but considering a non-sequential Monte Carlo representation. *An integrated adequacy and security performance evaluation of power distribution systems with DERs was not found* in the literature. The current alternatives proposed in the literature for the long-term simulation of the power distribution systems to estimate performance indices still have several limitations, namely in: the evaluation of adequacy and security aspects of the power distribution systems, modeling and cross-comparison of different control strategies, the associated simulation of load transitions and different schemes of protection, coupling of steady-state analysis, and the representation of the dynamic behavior of DERs to allow the assessment of islanded operation and islanding procedures. All these topics are approached at different extends in chapter 4.

2.2.6 Frameworks for Future Power Distribution Systems

All the systems, activities and infrastructures described in the previous sections represent the current status of the power distribution systems. However, it is important to point out that the power industry has been passing through an interesting phase which may incur on changes and transformations. Nowadays, a great amount of ideas have been inundating the power industry all covered by the term *smart grid*. These ideas manifest themselves in the large amount of novel products and solutions delivered to the market under the quoted term, as well as the increase of the number of smart grid related academic publications. Besides these manifestations, the concept of a what is (or what should be) a smart grid is yet to be reached and different ideological views coexist in the technical literature. Nevertheless, some convergence about the concept can already be found, even if we compare the European Union (E.U.) and United States (U.S.) views.

In the *Strategic Deployment Document for Europe's Electricity Network of the Future* [3, 4], a smart grid is defined as follows.

> *Smart grid is an electricity network that can intelligently integrate the actions of all users*

connected to it – generators, consumers and those that do both – in order to deliver efficiently sustainable, economic and secure electricity supplies. A smart grid employs innovative products and services alongside intelligent monitoring, control, communication, and self-healing technologies to

- *better facilitate the connection and operation of generators of all sizes and technologies;*
- *allow consumers to play a part in optimizing the operation of the system;*
- *provide consumers with greater information and choice of supply;*
- *significantly reduce the environmental impact of the whole electricity supply system;*
- *and deliver enhanced levels of reliability and security of supply.*

Over the definition above, several strategic research areas were established to develop the smart grid paradigm in Europe. Regarding the power distribution system level, some of the research areas are the following [3, 4].

- Distributed control systems, autonomous self-controlling and self-healing grids;
- Applications of dynamic islanding using DERs and intelligent switching;
- Tools for the integration of active demands (including EVs) in the system operations;
- Flexible MV and LV network control strategies with increasing automation and making the best use of novel equipments;
- Assessment of reliability, redundancy and self-healing;
- Advanced integrated communication and control systems to gathering a wide set of information from the field. They must interact with local and remote devices to enable rapid analysis and initiation of automatic corrective actions.

On the other hand, in the U.S. smart grid vision, herein represented by the modern grid initiative conducted by the National Energy Technology Laboratory for the U.S. Department of Energy, a smart grid is defined as below [91].

The smart grid vision generally describes a power system that is more intelligent, more decentralized and resilient, more controllable, and better protected than today's grid.

Moreover, seven main characteristics are identified as key factors to promote the modernization of the U.S. power systems [1].

Self-heals. The modern grid will perform continuous self-assessments to detect, analyze, respond to, and as needed, restore grid components or network sections.

Motivates and includes the consumer. The active participation of consumers in electricity markets brings tangible benefits to both the grid and the environment, while reducing the cost of delivered electricity.

Resists attack. Security requires a system-wide solution that will reduce physical and cyber vulnerabilities and recover the system rapidly from disruptions.

Provides power quality for 21st century needs. The modern grid will provide the quality of power desired by today's users, as reflected in emerging industry standards.

Accommodates all generation and storage options. The modern grid will seamlessly integrate many types of electrical generation and storage systems with a simplified interconnection process analogous to "plug-and-play".

Enables markets. The modern grid will enable more market participation through increased generation paths, more efficient aggregated demand response initiatives and the placement of energy storage and resources within a more reliable power distribution system.

Optimizes assets and operates efficiently. The modern grid's assets and their maintenance will deliver desired functionalities at minimum cost.

From the technical point of view, by reviewing the E.U. and U.S. conceptual documents about smart/modern grids, it becomes clear the convergence of the paradigm over the ideas of modernizing the grid, increasing the system reliability through self-healing strategies, increasing the participation of DERs in the operational procedures, integrating information and communication technology solutions, and decentralizing automation and control decisions. Regarding specifically the power distribution systems, there are frameworks developed under similar trends and which are currently considered under the scope of the smart/modern grids. The next sections emphasize two of these frameworks: the U.S. CERTS micro grid Framework and the E.U. micro and multi-micro grid framework.

2.2.6.1 The CERTS Micro Grid Framework

The consortium for electric reliability technology solutions (CERTS) of the office of power technologies of the U.S. Department of Energy developed the CERTS micro grid framework. The consortium was established in 1999 and the white paper on the micro grid framework dates 2002 [92]. In summary, the framework assumes an aggregation of customer loads and micro sources operating as a single system. The majority of the micro sources must be power electronic based to provide the required flexibility and to ensure controlled operation as a single aggregated system. This control flexibility allows the micro grid to relate itself to the bulk power system as a single controlled unit increasing local reliability and security.

The typical structure of the CERTS micro grid framework is shown in Fig. 2.9. It comprises a radial distribution network with three LV feeders (A, B and C) and some customer loads. Also, it has micro sources (either micro turbines or fuel cells) connected to the network through power electronic interfaces. The point of common coupling is on the primary side of the transformer and it defines the separation between the micro grid and the main utility grid.

The CERTS micro grid framework assumes three critical functions:

Micro source controller. A power and voltage controller, coupled with the micro source, provides fast response to disturbances and load changes without relying on communications.

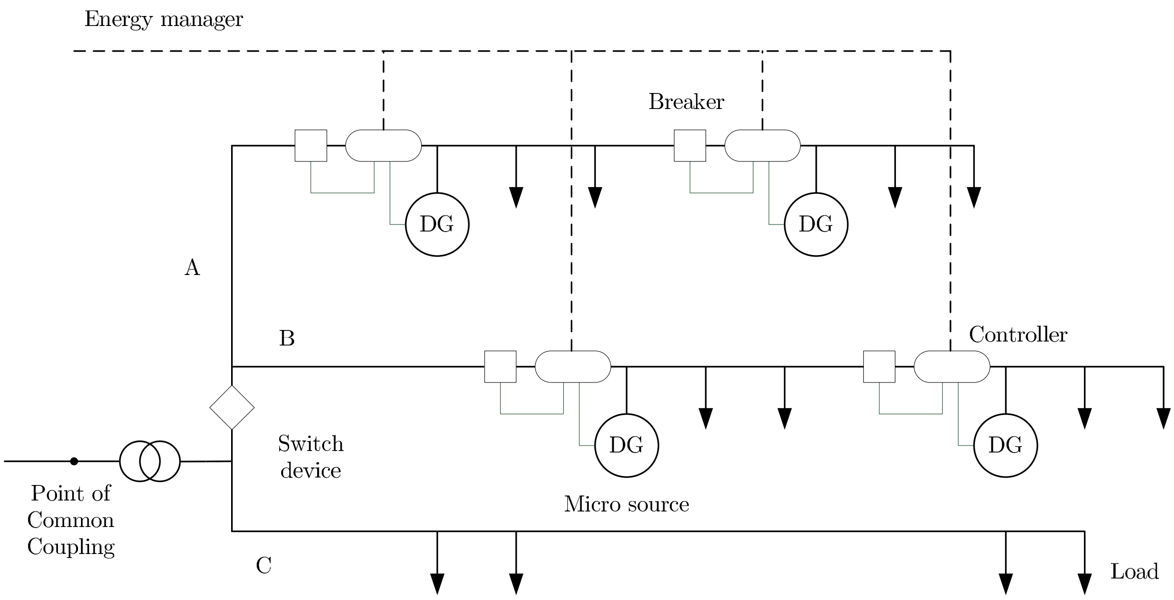


Fig. 2.9: The CERTS micro grid architecture (adapted from [92]).

Energy manager. A manager provides operational control through the dispatch of power and voltage set points to each micro source controller. The time response of this function is measured in minutes.

Protection. Micro grid protection requires unique solutions since the sources are interfaced using power electronics.

The main operations of the micro grid depend on micro source controllers which are responsible to regulate power flow through the feeder, to regulate the voltage at the interface of each micro source and to ensure that the micro sources are able to pick up a share of the load as the demand changes, especially in islanded mode. The ability of the system to transit to islanded mode smoothly and to automatically reconnect to the main utility grid is another important function. The micro source controller is then able to respond quickly (in milliseconds) using only local values for voltage and current to control the micro source during most events. Consequently, fast communications among micro sources are not required since each inverter is able to respond to load changes in a predefined manner without data from other locations.

The energy manager is in charge of the micro grid operation through the dispatch of set points to the micro source controllers, according to the operational needs of the micro grid and some criteria such as:

- ensuring that local needs for heat and power are met by the micro sources;
- ensuring that the micro grid satisfies operational contracts with the bulk power provider;
- minimizing emissions and/or system losses;
- maximizing the operational efficiency of the micro sources.

Finally, a protection coordinator must respond to both system and micro grid faults. For a fault on the main utility grid, the micro grid should isolate itself rapidly in order to preserve the most sensitive loads. Whether the fault occurs within the micro grid, the protection systems should isolate the smallest possible section of the feeder in order to eliminate the fault.

2.2.6.2 The E.U. Micro and Multi-Micro Grid Framework

Almost simultaneously, in Europe, the first major effort devoted to micro grids was initiated with the Fifth Framework Program (1998-2002), which funded the research and development project entitled “MICROGRIDS – Large scale integration of micro generation to low voltage grids”, contract n° ENK5-CT-2002-00610. The E.U. micro grid concept [20] developed in the MICROGRIDS project is illustrated in Fig. 2.10.

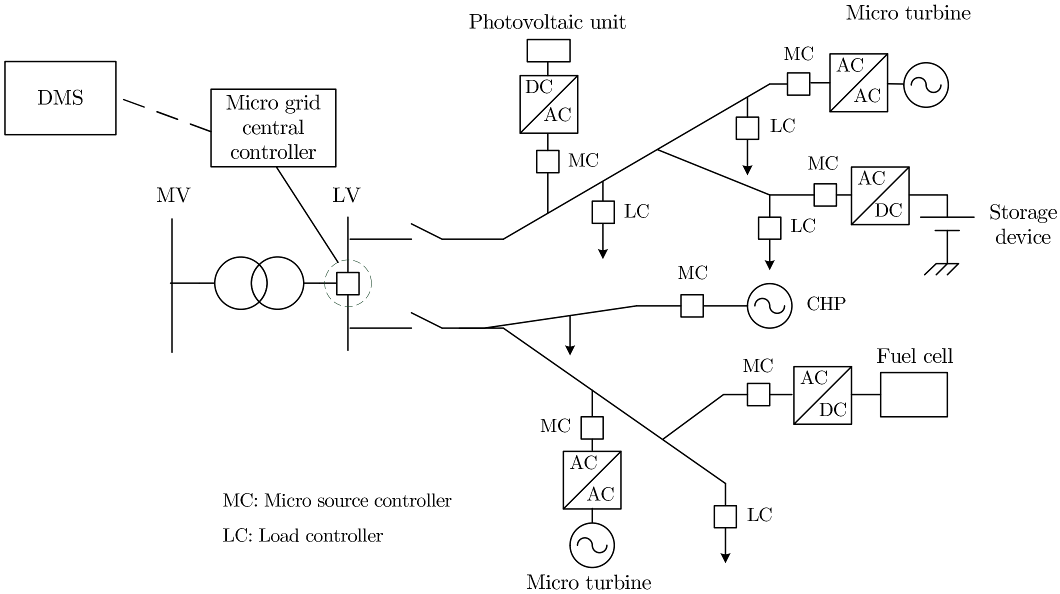


Fig. 2.10: The E.U. micro grid architecture (adapted from [20]).

The figure above illustrates a micro grid composed of a LV network connected to the secondary winding of a MV/LV distribution transformer, including its customer loads (some of them interruptible), both controllable and non-controllable micro sources (such as micro turbines, photovoltaic generators, etc.), distributed energy storage devices, and a hierarchical type management and control scheme supported by a communication infrastructure used to monitor and control micro sources and customer loads. In this concept, each micro source is connected to the grid through a power electronic converter which is operated using one of the two types of control modes below.

PQ inverter control mode. This is composed of a current controlled voltage source that injects a given active and reactive power set point into the network;

Voltage source inverter control mode. This is established to emulate a synchronous machine where the load is fed with pre-defined values for voltage and frequency according to a specific control strategy.

The micro grid normally operates interconnected to the main utility grid. Otherwise, the micro grid may be islanded operated in case of contingencies in the upstream system or if maintenance actions are occurring. A micro grid central controller, to be housed in MV/LV substations, is then responsible to controlling the micro grid in a hierarchal manner. At a second level, controllers located at loads, groups of loads and micro sources exchange information with the central controller and local control devices. It is also established that the central controller can communicate with the DMS, contributing to improve the management and operation of the MV power distribution system through contractual agreements that can be devised between the micro grid and the operator. In another perspective, a micro grid might be managed by another controller under the the multi-micro grid concept.

The multi-micro grid concept is an extension of the micro grid concept consisting of a MV network with micro grids, controllable loads and DG units connected to the feeders, as illustrated in Fig. 2.11. In this proposal, micro grids, MV controllable loads and DG units can be considered as active cells, for

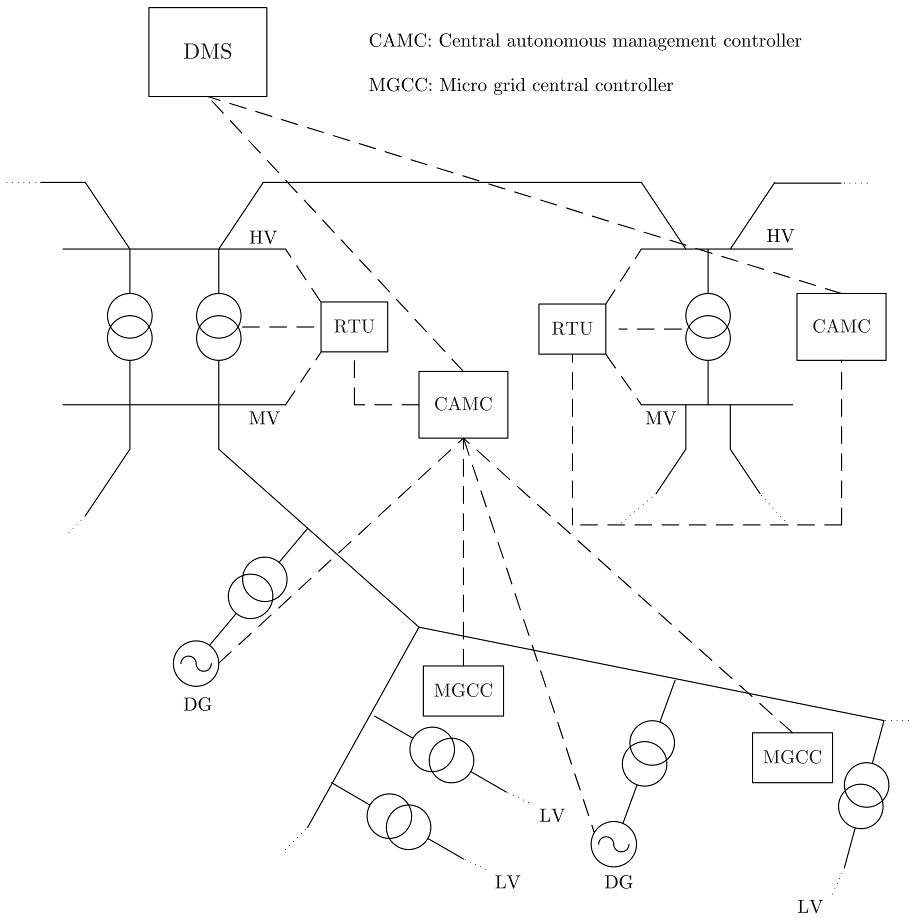


Fig. 2.11: The E.U. multi-micro grid architecture (adapted from [93]).

control and management purposes. The technical operation of such a system requires the transposition of the micro grid concept to the MV level, where all these active cells should be controlled by a central autonomous management controller to be installed at the MV side [93] of the HV/MV transformer. The central autonomous management controller is supposed to interface with the DMS and provide functions to the secondary frequency control, coordinated voltage support and state estimation, as well as to operate under the responsibility of a distribution system operator.

Regarding particularly the frequency control, the central autonomous management controller reacts to frequency changes, in a way similar to regular automatic generation control. Therefore, in case of frequency variation, the requested change in generation production is derived from the system frequency through a proportional-integral controller. Then, an economical allocation algorithm distributes this change among the DG units and micro grids which desire to participate in frequency regulation. Each of the micro grid central controllers also allocate the generation production change among its subordinate micro source units according to their own regulation capabilities. All these activities are called if the multi-micro grid passes through an islanding process after the disconnection from the HV/MV link.

The U.S. CERTS micro grid and the E.U. micro and multi-micro grid frameworks promote smart/modern grid ideas to the power distribution systems. The hierarchical structure applied by both resembles the control architecture utilized in the HV transmission system operation, which increases the prospects for acceptance by utility engineers, researchers, scholars, and practitioners. Nevertheless, the hierarchical control structure seems of interest only for networks which already acquired a large scale integration of DERs. For instance, let us take the case of the multi-micro grid framework which is developed to operate both MV and LV networks in a coordinated manner. Notice that the functionalities for islanded operation would achieve their purpose only for networks with enough DER integration to supply all the non-controllable loads in case of faults outside the network. Also, for practical applications, these frameworks might require extensive alterations in infrastructure and operational procedures to accomplish functionalities which would be put forward quite rarely. As a matter of fact, while service interruption on MV and LV networks might be somehow common on an annual basis, the service interruption of HV/MV transformers might occur only in rare events of major black outs. This is, arguably, in contradiction with the bottom-up philosophy of updating the power distribution system automation infrastructure according to local and immediate needs. Also, there were not found extensive discussions on how to achieve the multi-micro grid paradigm, while DERs are gradually integrated in a distributed manner through the networks. Finally, it was not found either a clear definition about which sort of intelligence/smartness is fostered by these architectures.

2.3 Agent-Based Systems applied to Power Engineering

After reviewing the ideological views of the smart/modern grid concept, agent technology was enlighten as the correct vector to promote actual decentralization, autonomous operation and active management in the power distribution system operation. As a mater of fact, an adequate agent-based modeling can produce flexible, extensible, and robust systems, which are features of most importance to a smooth modernization of power distribution systems. Moreover, the agent paradigm can provide a well-established notion of intelligence/smartness to be progressively applied along with the modernization of the power distribution systems. Therefore, this research utilizes agent modeling and simulation extensively to achieve its purposes. As consequence, a didactic review about agent and multi-agent systems is provided in section 2.3.1 in order to facilitate the task of undertanding/verifying the contributions of the work. Furthermore, an extensive survey about the applications of agent technology to power engineering is provided in section 2.3.2. This survey is presented and discussed highlighting the applications more directly related to the scope of the power distribution systems.

2.3.1 Agents and Multi-Agent Systems

This section introduces a background and state of the art of agent-based systems emphasizing the concepts, methodologies, and component elements approached in the research. The section is organized as follows. In section 2.3.1.1, the definitions and properties of agents, intelligent agents, and agent environments are presented. In section 2.3.1.2, the agent architectural model applied in this work is described. Agent communication and interactions are discussed in section 2.3.1.3. After that, in sections 2.3.1.4 and 2.3.1.5, aspects of designing agent-based system are outlined and the choices of a building methodology and programming language are justified. At last, in section 2.3.1.6, a background of the chosen programming language and associated interpreter is provided, allowing accurate discussions about the research developments in the next chapters.

2.3.1.1 Basic Concepts and Definitions

“Intelligent agents are 99% computer science and 1% artificial intelligence (AI)” [94]. Typical definitions of an agent declare that “agent is someone who acts on behalf of another”. However, in the context of engineering and computation, the term agent is used as a shorten for *software agents*, though in turn some software agents may act mirroring the agents from the typical definitions as well.

As expected from a relatively young area of research, there is not an universal consensus about the definition of an agent. Nevertheless, it is probably fair to state that most researchers, if asked to provide their definition, quote the properties [12] drawn from the sentence below.

> An *agent* is some entity placed into an *environment*, and that is able to autonomously react to changes in this *environment* [95].

This definition implies that agents have *sensors* to sensing the environment and *effectors/actuators* to modify the environment. The two concepts that capture the interface between an agent and its environment are the *percept*, an item of information received by some sensor, and the *action*, which is something that the agent does. Hence, the key issue lies in between the sensing and acting activities, where the agent decides how to proceed based on the percepts collected via input sensors. The relationship between an agent and its environment is illustrated in Fig. 2.12.

Environments can be classified as physical environments or software environments. In the first case, we can refer to the application of robots such as the Curiosity Rover which recently landed on Martian

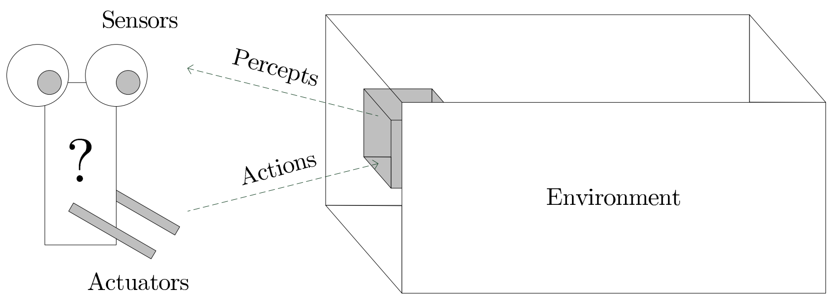


Fig. 2.12: Agent and environment.

surface (August 6, 2012) [96]. In the the latter case, we can refer to the internet, where software agents are placed aiming at achieving a great variety of goals. The well-defined separation of agents and their environments means that agents are inherently distributable. Regarding properties, environments can be categorized as follows [97].

Fully observable or **Partially observable.** If an agent's sensor gives access to the complete state of the environment at each point of time, then the environment is considered fully observable. Otherwise, it is considered partially observable.

Deterministic or **Stochastic.** If the next state of the environment is completely determined by the current state and the action executed by the agent, then the environment is considered deterministic. Otherwise, it is considered stochastic.

Episodic or **Sequential.** In an episodic environment, the agent's experiences are split into atomic episodes, each consisting of the agent perceiving and then performing a single action. The next episode does not depend on the actions taken in the previous ones, and the choice of actions in each episode depends only on the episode itself. On the other hand, in sequential environments, current actions may affect all further decisions.

Static or **Dynamic.** If the environment can change while the agent is deliberating, then the environment is considered dynamic for the agent. Otherwise, it is considered static.

Discrete or **Continuous.** The distinction between discrete and continuous environments can be applied to the state of the environment, to the way the time is handled, and to the perceptions and actions of the agent. All these features can be either discrete or continuous in the environment modeling.

Single agent or **Multi-agent.** Single agent environments are those where only one agent is situated. Multi-agent environments are those where more than one agent is situated.

Clearly, the most complex environments are those partially observable, stochastic, sequential, dynamic, continuous and multi-agent. In real world applications, agents have at best partial understanding and control of the environment. Furthermore, the spheres of influence of the agents can overlap, as illustrated in Fig. 2.13.

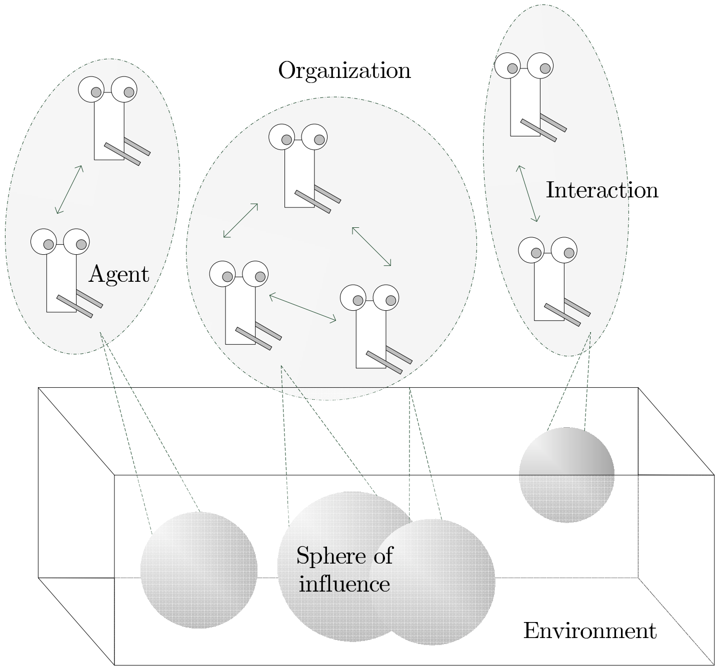


Fig. 2.13: Typical structure of a multi-agent system.

From the definition of agent, we can also derive that agents are provided with autonomy. Hence, it is important to understand that autonomy can vary from a broad spectrum [10]. At one extreme, conventional text processors only compute/make what the user wants and, therefore, are provided with little or no autonomy. At the other extreme, human beings ultimately can believe or do what they want. Modern views look in between these two extremes, where the main interest lies on delegating goals to agents, which in turn decide how to act to achieve this goals. From this perspective, autonomy means to be able to make independent decisions about how to achieve delegated goals.

Regarding intelligence, agents are distinguished from intelligent agents as follows (see [98] for discussions).

An *intelligent agent* is an agent which exhibits proactive, reactive, and social behaviors.

Therefore, besides situatedness and autonomy, intelligent agents are provided with proactivity, reactivity, and social abilities. These properties can be formalized as follows.

Proactiveness. This means that the agent exhibit some goal-directed behavior. As consequence, if a particular goal was delegated to the agent, then the agent is expected to at least try to achieve this goal [10].

Reactivity. This means to be able to respond to changes in the environment in a useful time. Designing a system which simply responds to environmental stimuli in a reflexive way is not hard [10]. However, implementing a system that achieves a balance between goal-direted behavior and reactive behavior can be a considerably difficult task.

Social ability. This means that agents interact with other agents (and possibly humans) via communication. This stands beyond passing data through software/hardware entities. Often, agent interactions are framed in terms of communication acts with standard semantics that are defined in terms of their effects on agent's mental states. Also, agent interactions are often viewed in terms of human interaction types such as negotiation, coordination, cooperation and teamwork [12].

The concept of an intelligent agent is a natural development of other trends of AI and computer science. As consequence, some differences among the ancestors are of interest to be clarified (see [95] for discussions).

Agents and **AI.** The discipline of intelligent agents has emerged largely from research in AI. Nevertheless, it is important to distinguish the broad intelligence that is the ultimate goal of the AI community, and the intelligence sought in agents. The only intelligence requirement generally devised for agents is that they should make an acceptable (reasonable) decision about which actions to perform in their environment (in time for this decision to be useful). The application and exploitation of agent technology is primarily a computer science problem. However, AI technology can contribute significantly to building agents.

Agents and **Expert Systems.** Expert systems do not interact directly with any environment. In general, they do not obtain their information via sensors, but through a user acting as a middle man. In addition, expert systems are not usually required to operate in anything like real time. Finally, we do not generally require expert systems to be capable of cooperating with other agents.

Agents and **Objects.** Agents are identical to (active) objects in important aspects: they encapsulate both state and behavior, and communicate via message passing. The most obvious difference between the "standard" objects and agents is that in traditional object-oriented programs there is a single thread of control. In contrast, agents are process-like, concurrently executing entities. Also, differently from objects, agents are rational decision-making system capable of reactive and proactive behavior, and of interleaving these types of behaviors as the situation demands. At last, the object-oriented community has not addressed issues like cooperation, competition, negotiation, and so on.

An agent-based system means one in which the key abstraction is that of the agent. Hence, a single agent system refers to an agent-based system with only one agent, then comprising a single agent environment. Similary, a multi-agent system refers to an agent-based system with more than one agent, then comprising a multi-agent environment. Each agent has internal sets of structures and mechanisms which allow it to reason about itself and the environment. These sets of structures and mechanisms define the agent's architecture. The next section describes the belief-desire-intention (BDI) architecture and its associated procedural reasoning system (PRS), both approached in this work.

2.3.1.2 The BDI Architecture and The Procedural Reasoning System

There are four groups of agent architectures: logic-based, reactive, BDI and layered-based. Among them, the BDI model is the best known and best studied model of practical reasoning agents [99]. The BDI model originated in the theory of human practical reasoning developed by a philosopher named Michael E. Bratman [100, 101]. Since then, it has been used in several applications, including factory process control systems, business process management and fault diagnoses in space shuttles [99]. Summarily, the main idea behind the BDI model lies in representing computer programs considering they have *mental attitudes* such as beliefs, desires and intentions. Although at first glance this can be seen as the mere introduction of pure semantics to the context, this sort of representation provides abstraction mechanisms which are quite practical and useful in designing agent-based systems for real world applications.

In the BDI model, the *beliefs* of an agent are the information collected about the environment. The *desires* (options) represent the objectives or *states of affair*[2.2] the agent would like to accomplish. Hence, the *intentions* are the desires to which the agent has committed at some extend. In terms of implementation, intentions are manifested by means of executing one or more *plans*, which are courses of actions and may include the triggering of additional plans. At this point, it is important to distinguish desires from goals as well. The *goals* are desires that have been chosen to be actively pursued by the agent in a way that its set of goals is consistent. This means that, for instance, the agent should not have concurrent goals of standing and sitting, though they could both be desirable. Another central concept regards *events* which are triggers that may activate plans, update beliefs or modify goals, and are generated internally or externally to the agent.

Using this concepts, the *practical reasoning* of the BDI model implies in deliberating (to adopt intentions) and means-end reasoning (to decide how to act in order to achieve the adopted intentions). In the architectural point of view, the PRS, originally developed at the Standford Research Institute, was perhaps the first agent architecture to explicitly embody the BDI model, and has proved to be one of the most durable approaches to developing agents to date [10]. This architecture is shown in Fig. 2.14.

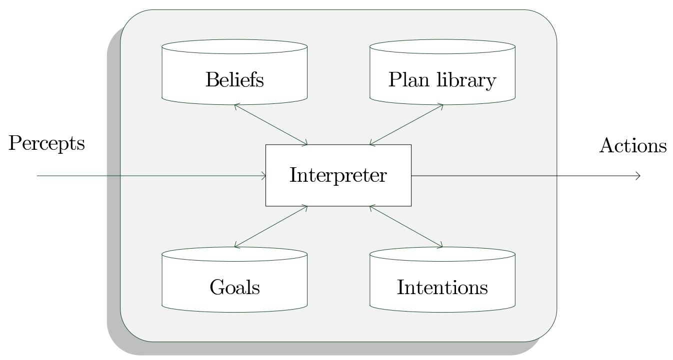


Fig. 2.14: The PRS agent architecture.

In the PRS agent architecture, beliefs, goals, plans and intentions are managed by an agent interpreter which is responsible to updating beliefs from observations made of the environment, generating new desires (tasks) on the basis of new beliefs, and selecting from the set of currently active desires some subset to act as intentions. Hence, the interpreter must select an action to perform on the basis of the agent's

[2.2] In philosophy, a state of affairs, or (also known as) a situation, is a way the actual world must be in order to make some given proposition about the actual world true [102].

current intentions and knowledge [103]. A PRS agent starts up with a collection of plans, top-level goal, and initial beliefs. These beliefs are represented as atomic formulas of first-order logic. The top-level goal is put onto an *intention stack*, which is responsible to store all goals pending achievement. The agent then searches through a plan library to see which plans have the goal on top of the intention stack as post-condition. Of these, only some will have their pre-condition satisfied, according to the agent current beliefs. The set of plans that achieve the goal and have their pre-condition satisfied, become the possible options for the agent. At this point, the process of selecting a particular plan may rely from meta-level plans to simple utility ordering. The chosen plan is then executed possibly involving pushing further goals onto the intention stack, and son on. Whether a particular plan to achieve a goal fails, then the agent is able to select another plan to achieve the associated goal from a set of candidate plans [10].

This research makes extensive use of an extended version of the AgentSpeak language [9], an agent-oriented language created aiming at modeling the key features of the PRS. This extended edition and its interpreter are described in section 2.3.1.5. For now, observe that the PRS architecture addresses only the internal reasoning of an agent. However, alongside these mechanisms, agents are also required to be able to communicate and interact with each other in order to devise some social ability.

2.3.1.3 Agent Communication and Interactions

One of the key aspects in agent-based systems is communication. Agent communication has its origins in the speech-act theory which states that messages represent actions or communication acts. In general, a speech act is defined by a performative (e.g. achieve, ask-one, tell) and a proposition content (e.g. "the switch is closed"). Hence, different pairs performative/content compose different speech acts. Examples of speech acts and their associated pairs performative/content are shown in Table 2.1.

Table 2.1: Examples of speech acts

Content	Performative	Speech act
"The switch is closed"	`achieve`	"Close the switch"
"The switch is closed"	`ask-one`	"Is the switch closed?"
"The switch is closed"	`tell`	"The switch is closed"

The first agent communication language with a broad uptake was the Knowledge Query and Manipulation Language (KQML). The syntax of KQML is based on a balanced parenthesis list. The initial element of the list is the performative and the remaining elements are arguments in pairs keyword/value. The KQML language has the reserved keywords shown in Table 2.2 and a large list of performatives.

Table 2.2: KQML reserved parameter keywords [104]

Keyword	Meaning
:content	Information about which the performative expresses an attitude
:force	Whether the sender will ever deny the meaning of the performative
:in-reply-to	Expected label in a reply
:language	Name of the representation language of the content parameter
:ontology	Name of the ontology, e.g. set of term definitions, used in the content parameter
:receiver	Actual receiver of the message
:reply-with	Whether the sender expects a reply, and if so, a label for the reply
:sender	Actual sender of the message

In Table 2.2, two parameters deserve especial attention: (content) language and ontology. The content language must provide syntax (grammar) while ontology must provide semantics (lexicon). Two agents who wish to communicate should share a common ontology about the domain of discourse. This ensures agents ascribe the same meaning to the symbols used in their messages.

One example of KQML message is shown below.

```
(tell
  :sender stock-server
  :content (PRICE IBM 14)
  :receiver joe
  :in-reply-to ibm-stock
  :language LPROLOG
  :ontology NYSE-TICKS)
)
```

In this message, the sender is to be identified as `stock-server`, the performative is `tell`, the content is `(PRICE IBM 14)`, the receiver of the message is to be identified as `joe`, the expected label of this reply is `ibm-stock`, the language is called `LPROLOG`, and the ontology is to be identified as `NYSE-TICKS`. In this communication message the agent `stock-server` tells the agent `joe` that the price of the artifact IBM is 14 [no units provided].

Regarding communications, it is important to quote the Foundation of Intelligent Physical Agents (FIPA) [105]. FIPA is an Institute of Electrical and Electronics Engineers (IEEE) Computer Society standards organization that promotes agent-based technology and the interoperability of its standards with other technologies. FIPA has proposed four content languages: the FIPA Semantic Language (FIPA-SL) [106], the FIPA Constraint Choice Language (FIPA-CCL) [107], the FIPA Knowledge Interchange Format (FIPA-KIF) [108], and the FIPA Resource Description Framework (FIPA-RDF) [109]. The FIPA standard for agent communication [110] was released in 2002 and differs from the KQML language both in the set of performatives and semantics.

FIPA also specifies interaction protocols for requests, queries, request-when, contract net, iterated contract net, brokering, recruiting, propose, and subscribe. As an example, Fig. 2.15 illustrates the FIPA subscribe interaction protocol. In this protocol, the initiator begins the interaction with a subscribe message containing the reference of the objects of interest. The participant processes the subscribe message and makes a decision whether to accept or refuse the query request. If the query request is accepted, notifications and result information might be sent back to the initiator. The interaction finishes either with a failure message from the participant or with a cancel message from the initiator. The latter is skipped in the figure since it belongs to the FIPA cancel meta-protocol, also approached in the FIPA subscribe interaction protocol specification.

As stated previously, this research applies an extended edition of AgentSpeak and its interpreter, which in turn process communication following performatives and semantics similar to the KQML. By these means, either simple or sophisticated human-like interactions (e.g. negotiation, cooperation, coordination and teamwork) can be achieved through agent reasoning alongside agent communications. Nevertheless, besides the individual aspects of agent reasoning and communication, an agent-based system must be thought as a whole following design principles and methodological procedures. Practical issues of choosing

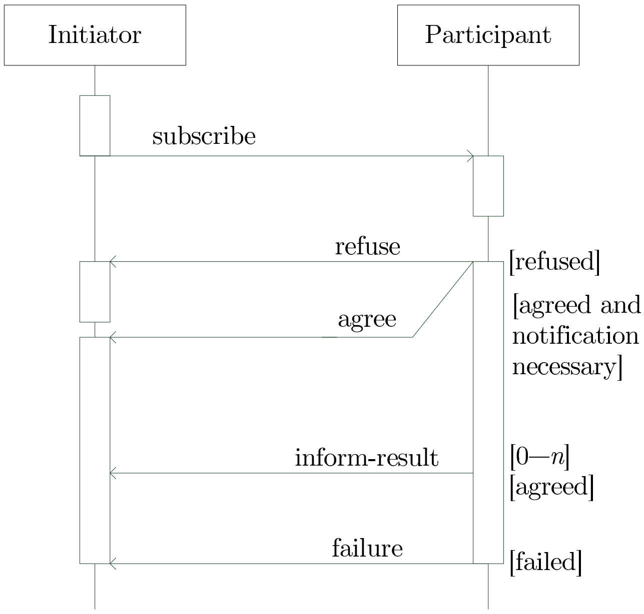


Fig. 2.15: FIPA subscribe interaction protocol (adapted from [111]).

a methodology to support designing an agent-based system are discussed in the next section.

2.3.1.4 Designing Agent-Based Systems

A large number of methodologies have been proposed to designing agent-based systems. However, only some of them are described with great detail in the literature and, at the same time, offer modeling tools to support their application. Among those, we can quote the methodologies Gaia [112], Tropos [113], MaSE [114], Passi [115], and Prometheus [12]. Although discussing the particular features of each of these methodologies is out of the scope of this document, some practical aspects of choosing a methodology to aid the designing of an agent-based system must be highlighted.

Firstly, the methodologies are intrinsically related to their originating software engineering (SE) approaches, such as agent orientation (AO), object orientation (OO), knowledge engineering (KE) and requirement engineering (RE). Also, the availability of modeling tools is quite important to support the design and simplify the transition from abstract specification to implementation. An analysis of the existing agent-oriented tools has shown that the choice of tools in the area of agent technology is somewhat limited [116]. In fact, most tools evolved in the context of a specific project or product. As a direct consequence, usually only a single and highly tailored tool (if any) is made available.

A modeling tool might be already associated to a development environment, which in turn may be related to a programming language and its agent architectural model. Due to this context, it is important to examine the methodologies alongside their associated software engineering approaches, modeling tools, development environments, languages and agent architectures. Fig. 2.16 surveys the interrelation among these elements. For the sake of clarity, elements without relation to a modeling tool are not shown in the

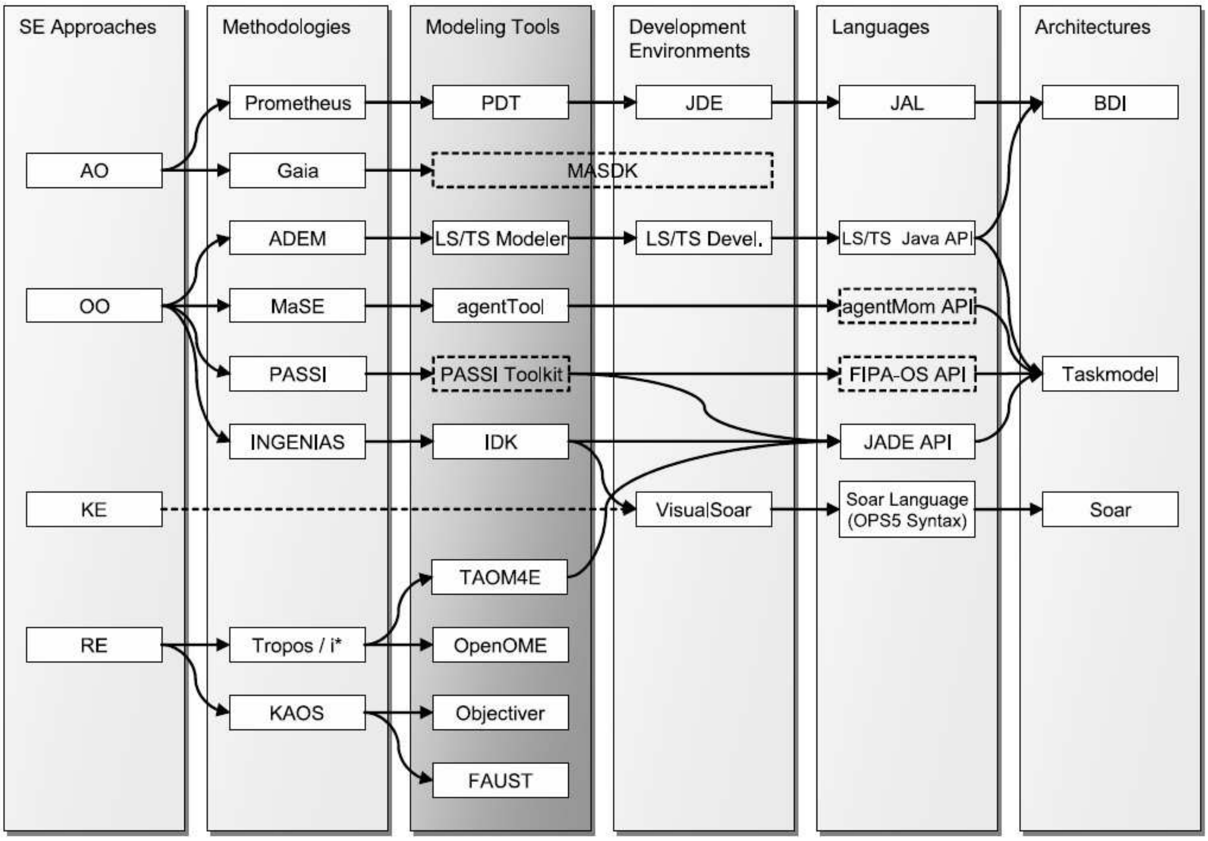


Fig. 2.16: Methodologies for designing agent-based systems and their connection to other elements [116].

figure.

In Fig. 2.16, observe that only the methodologies named Gaia and Prometheus have originated from agent-orientation approaches. Among these two, only the Prometheus methodology is directly related to the BDI architecture. In fact, the Prometheus methodology showed to be the most interesting one to our work due to its level of maturity, extensive documentation, general purpose, and availability of a software design tool, named Prometheus design tool (PDT). As consequence, several concepts of the this methodology were implicitly or explicitly applied in this work, particularly in what regards the development of goal mappings and description schemas [12].

The Prometheus methodology consists of three phases: system specification, architectural design and detailed design. These phases involve a great variety of stages which are briefly described herein and summarized in Fig. 2.17. The first phase of the methodology, the system specification phase, focuses on identifying the goals and basic functionalities of the system, along with percepts and actions. The main steps of this phase include the following.

1. Identification of system goals and sub-goals.

2. Development of use case scenarios.

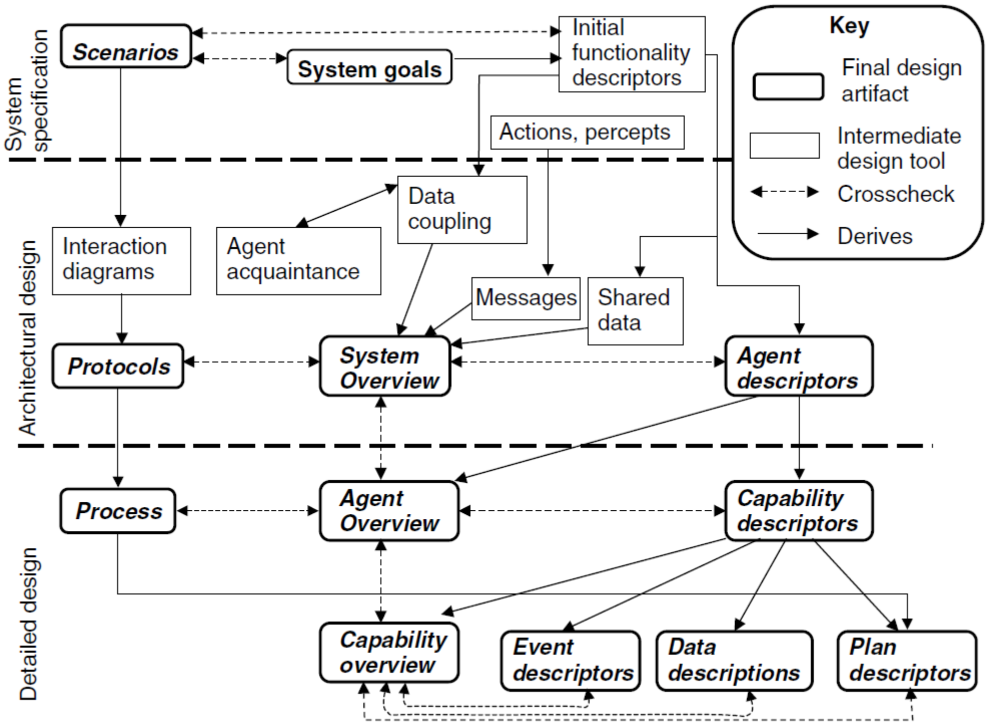


Fig. 2.17: The Prometheus methodology to building agent-based systems [12].

3. Identification of the agent system's interface with the environment in terms of actions, percepts, and external data.
4. Identification of the main functionalities.
5. Identification of the data read and written by the functionalities.
6. Preparation of functionality schemas (name, description, actions, percepts, data used/produced, interaction with other functionalities, and goals).

Using the knowledge produced in the first phase, the architectural design phase consists of identifying the agent types[2.3] of the system and their interactions. This phase is performed according to the stages listed below.

1. Grouping of functionalities using data coupling and agent acquaintance diagrams.
2. Defining agent types, their possible number of instances, and life-cycle.
3. Creation of agent descriptors.
4. Creation of a system level overview diagram describing the overall structure of the system.

[2.3] Agents are instances of agent types in runtime. For example, an agent type might model a robot. In runtime, multiple robots can exist and interact all being instances of the same type.

5. Development of interaction protocols from use case scenarios via interaction diagrams.

In the last phase, a detailed design is produced by looking at the internal issues of each agent type and the tasks to be accomplished within the overall system. The detailed design phase is composed of the following stages.

1. Development of process diagrams.
2. Production of agent overview diagrams showing the internal issues of agent types in terms of capabilities, events, data and plans.
3. Refinement of the capabilities.
4. Introduction of plans to handle events.
5. Defining details of events (external, between agents, between capabilities and within agents).
6. Defining details of plans (relevance, context, subgoals).
7. Defining details of data.

All these phases are usually presented in a sequential fashion for pedagogical purposes but, like most software engineering methodologies, the Prometheus methodology foresees revisiting earlier stages as the design advances. Also, the methodology is not intended to be followed strictly such that the designer is responsible for finding a balance between committing with practicality and the methodological stages. Regarding practicality, it is important to foresee aspects of representation and how they will be implemented. Therefore, programming languages and development environments might be taken into account when designing an agent-based system.

2.3.1.5 Programming Languages and Development Environments

Some agent programming languages are already available in the literature and source codes with their applications have been wide-spreading within the agent community. Besides, these languages and their development environments have been improving considerably such that new updates can be found with high frequency. The requirements for an agent programming language can identified as follows [10].

- The language should support delegation at the level of goals;
- The language should provide support for goal-directed problem solving;
- The language should lend itself to the production of systems that are responsive to their environments;
- The language should cleanly integrate goal-directed and responsive behavior;
- The language should support knowledge-level communication and cooperation.

There are already some agent programming languages in the literature which satisfy the requirements above. However, the process of choosing an agent programming language is more complex than the sole fulfilling of a list of requirements, involving the interrelations discussed in section 2.3.1.4. From Fig. 2.16, once the Prometheus methodology and PDT were chosen to support the design, one might expect that the JACK Agent Language (JAL) [117] would be selected straightforwardly. Nevertheless, JACK has the great drawback of not being open source. Hence, in order to examine deeply the alternatives, Fig. 2.18 provides a survey similar from the presented in section 2.3.1.4, but now focusing on the elements interrelated with the agent programming languages and development environments which are associated to agent oriented approaches.

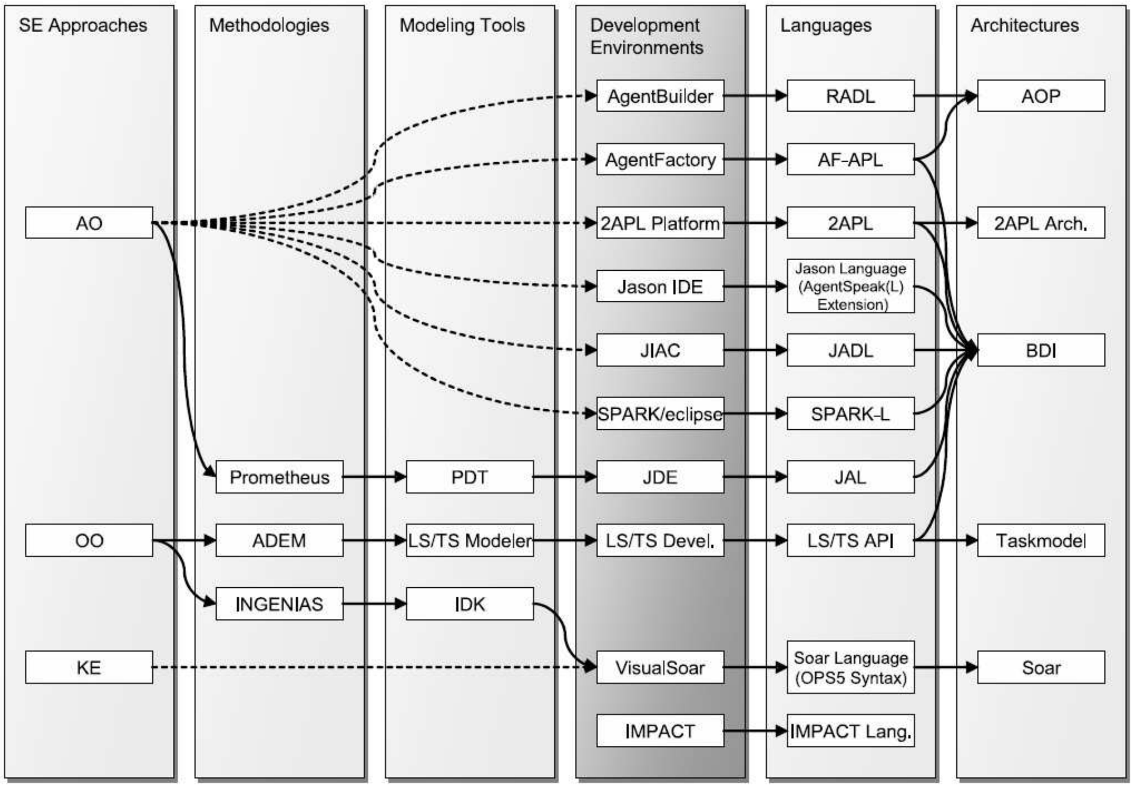


Fig. 2.18: Agent programming languages and their connections with other elements [116].

In Fig. 2.18, some languages that are based on the BDI model and are provided with associated development environments can be identified. As it will be shown in section 2.3.2, the Java Agent Development Framework (JADE) [118] is the most utilized middleware in the power system academia. Therefore, since we are interested in well-defined BDI agents, one alternative would be to utilize JADEX [119], an add-on which allows BDI modeling in conjunction with JADE. The application of JADEX in our research area would already constitute a contribution and, following this reasoning, an agent-based architecture to DG islanded operation in active power distribution systems using JADE was completely implemented from scratch (see publication 9 in Appendix A). Nevertheless, the gradual contact with other technologies led JADEX to be considered not the best alternative to our ambitions.

As a matter of fact, during the development of the thesis, we have identified the need for establishing a complex environment modeling whose feasibility was only reached by using the CArTAgO technology [11], a novel and sophisticated common artifact infrastructure to model agent open environments. The CArtAgO is meant to be integrated with existing agent programming languages aiming at extending their notions of environment and allowing agents running on different platforms to interact within the same environment. However, nowadays only two agent platforms are complectly bridged with CArtAgO: JADEX and JASON. Among these two, JASON is the standard instance utilized in the CArTAgO documentation, code examples and publications. In fact, JASON is an open source interpreter of an extended version of AgentSpeak, which in turn is a logic-based agent-oriented programming language that applies the BDI model. If well-utilized, JASON allows a high-level representation of the agent's reasoning through AgentSpeak and, at the same time, a sophisticated use of legacy code and object-oriented programming implemented in JAVA. This separation is not present in JADEX which utilizes the well-known JAVA language and extensible markup language (XML). Moreover, differently from JADEX, JASON belongs to the group of theoretically-rooted agent-oriented programming languages, outlining a strong emphasis on rigorous formal semantics [120]. Furthermore, similarly to JADEX, JASON can use the JADE infrastructure as well and some authors state daringly that JASON provides a far more elegant coding than other agent programming languages (e.g. JAL and JADEX) (see [121] for discussions). Despite issues about elegance, JASON has also disadvantages in comparison with JADEX. One of the main disadvantage of utilizing JASON is the steep learning curve, which is worsened by the understandable lack of available tutorials, documentation, and examples, an opinion shared by the authors of [120].

2.3.1.6 The JASON Programming Language and Interpreter

This section introduces the JASON programming language and interpreter. As it will be stated in section 2.3.2, the description of designing and implementation issues are commonly avoided by the power engineer researchers which adventure themselves in the agent technologies. Although the main focus of these works are the power engineering solutions, agents are a discipline of the computational sciences and, therefore, some of these details are of great relevance to differentiate the developed models and applications. Moreover, it is unfeasible to follow the evolution in the agent technologies unless the power engineering academia enforces a strong interaction with the computational sciences. For this reason, in order to introduce the reader to the quoted details and provide at least a "flavor" of how the solutions are actually materialized, a brief explanation of the JASON programming language and interpreter is presented. Of course, the JASON programming language and interpreter involve several complex issues which were skipped for the ease of the reader. For extensive information, we strongly recommend the reference [10].

JASON is an open source interpreter of an extended edition of AgentSpeak. In JASON/AgentSpeak, an agent has a *belief base* which is a collection of literals, where each belief is represented by *predicates* in symbolic form such as

```
closed(switch-ABB-X01)[source(dms),source(percept)]
```

which means that "the switch-ABB-X02 is closed". The existence of the literal above in the agent's belief base only means that the agent currently believes that `closed(switch-ABB-X02)` is true. Hence, it might be the case that the `switch-ABB-X02` is actually open. The annotation `[source(dms),source(percept)]` means that the sources of this information were both an agent named `dms` and an environment sensor.

The agent's belief base can be used to derive further knowledge in a process called theoretical reasoning. Such process is modeled through JASON rules, such as

```
inconsistency(status,Comp) :- closed(Comp)[source(A)] & open(Comp)[source(B)]
```

which concludes that there is an inconsistency in the status information of the component `Comp` since contradictory status information were delivered by sources `A` and `B`.

Moreover, there are two sorts of goals in JASON/AgentSpeak: the *achievement goal* and the *test goal*. An achievement goal explicitly represents a state of affair the agent wants to achieve, whilst a test goal verifies if the agent believes a literal (or conjunction of literals). The achievement and test goals are denoted by the operators "!" and "?", respectively. For instance, the literal

```
!enabled(alarm-PSL-X02)
```

means that the agent has the goal of achieving a state of affair where it believes that `enabled(alarm-PSL-X03)` is true. On the other hand, the test goal

```
?current_value(comp-LIN-X04,Imag)
```

unifies `Imag` with the electrical current the agent believes is flowing through the component `comp-LIN-X04`. The term `Imag` is syntactically regarded as a variable subjected to unification since starts with a capital letter.

Agent plans are then composed of three distinct parts: the triggering event, the context and the body. The *triggering events* are changes in beliefs and goals that can trigger the execution of plans, *contexts* represents logical conditions which define if a plan is applicable or not (i.e. candidate for execution), and *bodies* are sequences of formulae determining a course of action. The different types of triggering events and context literals are shown in Table 2.3 and 2.4, respectively.

Table 2.3: Types of triggering events

Notation	Description
$+\ell$	Belief addition
$-\ell$	Belief deletion
$+!\ell$	Achievement goal addition
$-!\ell$	Achievement goal deletion
$+?\ell$	Test goal addition
$-?\ell$	Test goal deletion

Table 2.4: Types of literals in plan context

Notation	Description
ℓ	The agent believes ℓ is true
$\sim\ell$	The agent believes ℓ is false
not ℓ	The agent does not believe ℓ is true
not $\sim\ell$	The agent does not believe ℓ is false

The syntax of the plans follows the structure

```
@plan_label triggering_event :  context <- body
```

One example of an agent plan is shown below.

```
@plan_example ⟵ plan label
+!isolated ⟵ triggering event
   :  ~ energized & ~ black_start_mode ⟵ context
   <- !open(neigh_switches);  ↖       // (achievement goal: open neighboring switches)
      ?isolation_data(Data); ⟵ body  // (test goal: retrieve isolation data)
      .send(dms,tell,Data).   ↙       // (internal action: send information to dms)
```

This simplified plan was labeled as `@plan_example` and is activated by the triggering event `+!isolated`, which in turn refers to addition of the achievement goal `!isolated`. This plan becomes a candidate for execution only if the agent believes the literals `energized` and `black_start_mode` are false. Once its chosen for execution, the sequence of formula {`!open(neigh_switches)`;`?isolation_data(Data)`;`.send(dms, tell,Data)`.} is executed as an attempt to achieve the goal.

The reasoning cycle of the agent operates according to the scheme shown in Fig. 2.19. In the scheme, rectangles represent the main architecture components, namely the belief base, set of events, plan library and set of intentions. On the other hand, rounded boxes denote customizable functions for the belief update (BUF) and belief revision (BRF). The diamonds are customizable selection functions for social acceptance ($\mathcal{S}ocAcc$), messages ($\mathcal{S}_{\mathcal{M}}$), events ($\mathcal{S}_{\mathcal{M}}$), options ($\mathcal{S}_{\mathcal{O}}$) and intentions ($\mathcal{S}_{\mathcal{I}}$). Finally, circles show interpreter additional internal functions. The cycle is composed of the ten steps enumerated below. Observe that some elements in Fig. 2.19 are labeled with the step number to which they belong.

1. Perceive the environment.
2. Update belief base with the perceptions of the environment.
3. Receive communication messages from other agents.
4. Select socially acceptable messages.
5. Select an event to be handled.
6. Retrieve relevant plans from the plan's library that can be unified with the selected event.
7. Determine the applicable plans by verifying which of the plans' contexts are a logical consequence of the agent's belief base.
8. Select one applicable plan.
9. Select an intention for further execution.
10. Executing one step of the intention.

The JASON programming language and interpreter involve several complex functionalities (establishment of rules, libraries of internal actions, customization options, environment classes, plan patterns, and so forth) that were skipped for the sake of conciseness. The basic concepts presented in this section are intended to give background in understanding how the agent-based architecture of this work was implemented using JASON.

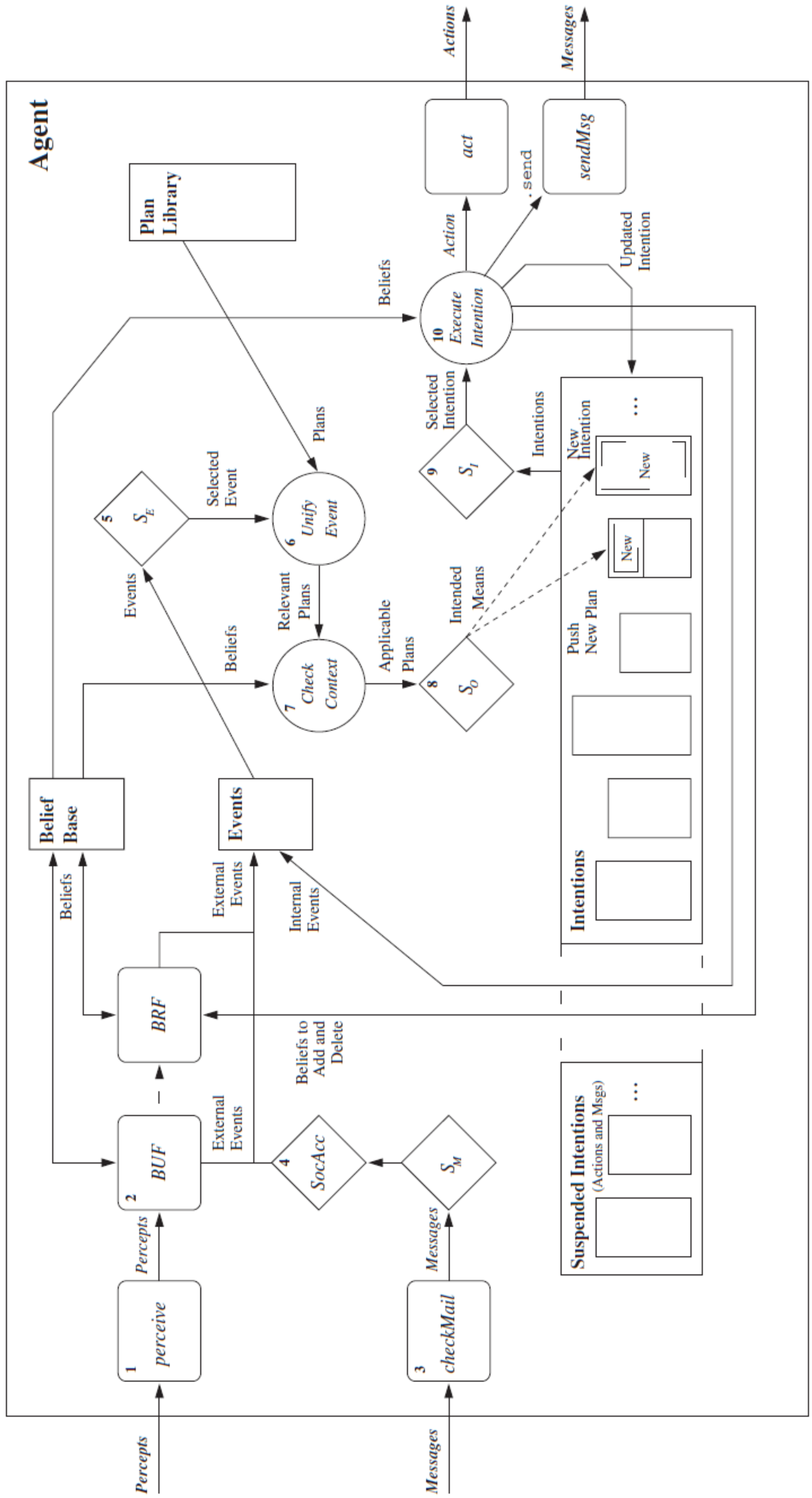


Fig. 2.19: The JASON reasoning cycle [10].

2.3.2 Applications to Power Engineering

Once the aspects of interest about agent-based systems were presented, this section surveys, analyses and discusses the application of agent-based technology to power engineering. Hence, in section 2.3.2.1, the developed survey is described, highlighting the size/range of the survey and main sources of information. Then, in section 2.3.2.2, discussions and analyzes about the state of the art are developed, emphasizing the works related to this research.

2.3.2.1 Description of the Survey

Recently, a representative literature survey on agent-based systems applied to power engineering was published [6] by the IEEE Power Engineering Society's Multi-Agent Systems Working Group, created in June 2005. The related publications were sought and categorized based upon their applications in protection, modeling, simulation, distributed control, monitoring and diagnoses. The survey included publications dated from 2001 to 2005 of the Intelligent Systems Applications to Power Systems (ISAP) conference proceedings as well as publications dated from 1998 to 2007 covering some IEEE transactions and some Institution of Electrical Engineers (IEE) journals. Hence, a similar survey was developed considering publications dated from 2001 to 2011 of the ISAP conference proceedings plus the publications dated from 1998 to 2011 of the IEEE Transactions on Power Systems, IEEE Transactions on Power Delivery, Institution of Engineering and Technology[2.4] (IET) Generation, Transmission & Distribution, Electric Power Systems Research (EPSR) and International Journal of Electrical Power & Energy Systems (IJEPES). Table 2.5 summarizes the outcomes of the survey emphasizing the functional separation between power generation & transmission engineering and power distribution engineering[2.5]. Naturally, additional conference proceedings and journals were sought for the sake of completeness.

Table 2.5: Bibliographic survey of multi-agent systems applied to power engineering problems

	ISAP 2001–2003	ISAP 2005–2007	ISAP 2009–2011	IEEE/IEE IET Journals	EPSR/IJEPES Journals	Total
Gen. & Trans.	5 [122–126]	15 [127–141]	15 [142–156]	39 [6, 157–194]	3 [195–197]	77
Distr.	1 [198]	5 [199–203]	6 [204–209]	8 [210–217]	3 [218–220]	23
Total	6	20	21	47	6	100

Table 2.5 outlines in totality 100 publications, from which 23 were directly conducted aiming at power distribution system applications. In comparison with classical power engineering research fields such as reliability modeling, these figures suggest that the marriage between agent technologies and power engineering is far from being mature. This conclusion was expected given how agent-based systems have been maturing conceptually during the past few years, the interdisciplinary requirements to building practical applications under the agent paradigm, and the innovative character of applying such paradigm in power engineering solutions. On the other hand, although some overlapping work can be found, these figures also indicate that consistent research efforts have been made to exploit the agent paradigm to improve power engineering. These efforts cover from specific solutions proposed to improve the protection

[2.4] In 2006, the IEE merged with the Institution of Incorporated Engineers to form the IET.
[2.5] Differently from [6], papers related with the application of ant colony optimization algorithms as an approach for power system optimization problems were not included in the survey. The same applies to the direct application of reinforcement learning algorithms or other meta-heuristics.

of small industrial systems [198] until abstract frameworks devised to manage entire bulk power systems [161]. Among these solutions, some must be highlighted due to their, at least partial, closeness to this thesis.

2.3.2.2 Analyzes and Discussions

Most probably, the application of agents to power system protection and primary control is the best starting point in what regards examining the evolution of academia in understanding the actual potential of agent technologies to power engineering. As highlighted in [6], Wooldridge's classical definition of an agent (see section 2.3.1.1) does not clearly distinguish agents from a number of existing softwares and hardware systems. Hence, under the quoted definition, controller devices or protective relays could be considered agents in the sense that they exhibit a certain degree of autonomy, they are situated in an environment (the power system), and they react to changes (voltage and/or current signals) in the environment. The same reasoning applies, for instance, to an excitation system of a synchronous generator, a buck-boost transformer or a capacitor bank placed in a distribution feeder. Thus, following this crude definition, the term *agent* can be misapplied as a wrapping concept over control devices and protective relays, thereby originating multi-agent systems from interactions employed in legacy control and protective schemes. Although this can be arguably viewed as beneficial in providing different abstractions and ways of understanding existing systems, we share the harsh belief of some authors (e.g. [6]) which state that renaming existing or new systems built over existing technologies as *agents* offers almost nothing in terms of concrete engineering benefit.

Not surprisingly, one of the first research contributions [157] about agents to bulk power system protection applies a cooperation of agents abstracted over a wide range of equipments/components such as *line agents*, *bus agents*, *current transformer agents*, *potential transformer agents*, *circuit breaker agents*, *current transformer data collector agents*, and so forth, without an explicit representation of goal-directed behaviors for all of them. In power distribution systems, one example is the control and protection scheme described in [199] where a network split in zones, as proposed in [221], is managed by *monitoring agents*, *communication agents*, *breaker agents* and *relay agents*, which similarly lack goal-directed behavior. Also, in several further works, model validation through computer simulations (if any) did not imply that the agents were provided with data encapsulation, code encapsulation, separated threads of control, or the ability to run autonomously without being evoked externally (e.g. [217, 222]). Despite these issues, those works should not be seen with criticisms since they provided contributions to their respective fields. In fact, possible misconceptions might be merely faced as a consequence of the academic knowledge of the epoch in which the studies were performed.

More specifically to the applications of agent-based technology to power distribution system protection, the literature analysis had identified that the number of contributions/publications in this field of research is still limited. As one of the exceptions, we can refer to the multi-agent system applied to the overcurrent protection of a 6.6 kV industrial system proposed in [198]. The work focuses on using overcurrent *relay agents* and fuzzy sets [223] to search for an optimum protection capability scheme. Although agent simulation itself is not performed in sensu stricto, the idea of providing adaptive protection through agency, the cooperation among *relay agents*, and concerns regarding communication protocols are already discussed in the context of improving the protection schemes of power distribution systems. These concepts are present in more recent contributions such as [201, 224].

In [201], a coordinated protective scheme for distribution feeders is proposed using *feeder agents* and overcurrent *relay agents*. The scheme dictates that *relay agents* must update fault currents and maximum load currents using exchanged information whereas network topology changes are identified. For this accomplishment, source impedance information is fed downstream the primary substations while maximum loading information is fed upstream the loads. Object-oriented programming in C++ and agent communication language (ACL) are utilized. A small test system is used to illustrate the proposed rules and the resulting relay settings update seems promising, though more information could be exhibited about how the agents actually perform their reasoning. Also, it seems that more interactions and information would be necessary to achieve a practical usage of the scheme. For instance, the scheme does not seem directly extendable for distribution feeders with DG units since time settings are not even mentioned.

In [224], the coordination of relays in power distribution systems with DG units using a multi-agent solution is proposed. Similarly to the previous works, it consists of applying the abstraction of a *relay agent*, but considering those along with *DG agents* and *equipment agents* to aid protective coordination. In summary, each *relay agent* takes sensory information, such as DG connection status, in order to choose among a list of settings. Then, some protection coordination is achieved through message exchange. The major drawback of the methodology is that agent message conveyance is required right after fault currents are identified. Besides demanding fast communications which are unfeasible to legacy systems, the idea of establishing agent interactions while the system devices are directly subjected to fault currents is, at least arguably, controversial. As a matter of fact, in case time constraints and backup protections were not adequately set, equipment life cycle might be jeopardized. Nevertheless, it is important to emphasize that some authors have been stating that while the cost of communications may not be justifiable to achieve sole protection functions, there will be situations where such cost might be justifiable if the same infrastructure is applied to provide other functions. This point of view is clearly exhibited, for instance, in the fault isolation scheme proposed in [217] where a wavelet-based fault direction identification technique is applied and *relay agents* interchange logical signals to locate the fault and activate circuit breakers.

Apart from devising protective schemes, agent-based systems have been applied to post-fault diagnosis as well. The first found work in the area refers to the ARCHON project [225, 226] whose main outcome is a general purpose architectural framework to facilitate cooperation among computational systems for industrial applications. As a practical deployment of the framework, the ARCHON approach was used to integrate reasoning systems within a control room including an *alarm analysis agent*, *breaker and relay supervision agent*, *black-out area identifier agent*, and even a *system restoration agent*, having as target the provision of useful information to the operators regarding contingency situations. Although some authors state that the resulting post-fault diagnosis application was not truly flexible or scalable [173], the general framework itself is considerably well thought in terms of deriving design concepts to structure interactions among problem solving entities (called agents in ARCHON's context) for industrial applications. Unfortunately, recent power engineering applications or even quotations about the ARCHON framework were not found in the power engineering literature, a fact that might be explained by the lack of dissemination of ARCHON framework's features in power engineering journals and conference proceedings.

Almost ten years ahead, the protection engineering diagnostic agents (PEDA) proposed in [173, 183, 227] were introduced. In this research, a post-fault diagnose assistant system to protection engineers was developed through the integration of several protection analysis tools. The integration was performed by wrapping analysis tools in agents named *protection validation and diagnoses agent*, *incident and event identification agent*, *fault record interpretation agent*, *fault record retrieval agent*, *collation agent* and *engineering assistant agent*. Despite of the straightforward (but well justified) aspect in how the authors defined the agent types, the work stands as one of the few where some multi-agent system design concepts were applied, namely the task decomposition stage of the DESIRE [228] methodology. Codding was performed using ZEUS [229] and at least one agent descriptor with functional task and exchange resource information is provided, what we believe should be a practice to be adopted in exhibiting research material in this area. The work itself is discussed in the context of bulk power system applications. Nevertheless, with the ongoing increase of feeder automation, it could be adapted/extended to distribution feeder applications. Other related system that could be exploited on distribution feeder automation is the conditional monitoring multi-agent system (COMMAS) currently applied to plant monitoring [230] and transformer monitoring [148, 177].

Regarding power distribution system restoration, we initially instantiate the multi-agent system introduced in [231, 232]. This work resembles a previous research developed by the same authors in the context of bulk power system restoration [169] and consists of abstracting *feeder agents* and *load agents* to perform restoration functions according to the following directives.

1. Once a service interruption is assigned, load agents have to isolate their respective loads and send a message to their service feeder agents.

2. The feeder agents receive the messages from the load agents and handle the restoration using rules extracted from operator's experience.

The proposal has the merit of being one of the earliest in the area. However, decision-making about the restoration procedures is still centralized on the feeder agents while the role of the load agents is basically to notify the feeder agent about service interruptions. In addition, discussions about software modeling and the practicality of implementing one agent per secondary transformer in actual power distribution systems are neglected. Decisions about restoration are also centralized in the solutions proposed in [206, 222], where *global agents* [222] and *restoration leader agents* [206] were envisioned to wrap reconfiguration and decision-tree algorithms, respectively. The latter solution [206] is assumed to follow the BDI agent architecture but beliefs, desires and intentions are not explicitly described in the agent restoration mechanisms.

A decentralized multi-agent solution for power distribution system restoration was proposed in [216] where three agent types are abstracted: the *generator agent* (to model primary substation sources), the *load agent* and the *switch agent*. Service restoration is then achieved through interactions among these entities without the figure of a higher level entity managing the switch actions and taking into account the available transfer capacity of switches. The work is clearly JADE-oriented and the agents are described according to their initial knowledge and behaviors. Also, the simple UML class diagram of the application is presented making easy understanding the author's implementation. Further improvements are introduced in [233] with a small update to consider rules for load shedding and a DG agent. Although engineering aspects about the actual implementation of the proposed solution are not discussed, these publications succeed on describing simple behaviors and rules to aid the restoration processes in power distribution systems. Furthermore, the provided small case study is well described, so that we recommend its implementation to power system researchers interested in achieving some proficiency on implementing agent behaviors in JADE.

In concise terms, the contributions in [206, 216, 222, 231–233] would seem more realistic in case, for instance, the load agents explicitly represented an aggregation of customers, as well as requirements for monitoring and main hypothesis about infrastructure were clarified. Conversely, other contributions such as in [211–214, 234] introduce fair hypotheses also offering discussions about the practicality of their proposed solutions. As a matter of fact, the authors in [211] present an interesting application of agency to condition assessment and fault management, though much more focused on engineering solutions for power distribution system automation than in agent modeling itself. The concept is composed of three main aspects as follows.

1. A software object for secondary substations which encapsulates a set of object classes representing the substation hardware and following the concept of logical nodes from the IEC 61850 [36].

2. Functionalities based on token (permission to act and execute local functions) message conveyance between neighboring substations. The basic procedure implies that, when a substation receives a token, it executes the required function, attaches the result, and conveys information to downstream substations. After processed at the last secondary substation, the token is sent back to the primary substation.

3. An information access model which, in summary, hierarchically defines that a permission to execute a given function is conveyed from the control center to the primary substation, and further downstream the secondary substations.

Hence, fault location and isolation are obtained by sending a token from a primary substation downstream secondary substations to verify fault indicators and to open normally closed switches around the faulted section. Power is restored by closing the circuit breaker at the primary substation and passing tokens upstream towards alternative supply primary substations. The proposed concept was extended to include state estimation in [212] and has a reduced engineering complexity in the sense that all secondary substations in a feeder are copies of a common secondary substation type. Furthermore, it provides local management at the secondary substation level as well as it reduces the information and communication saturation since, for the developed functions, the control centers "see" a primary substation area as a single entity. Regarding communication issues and validation tests, the authors verified the reduction in number of hops for fault management in comparison with a totally centralized control approach, and they tested the approach using a small but very illustrative prototype implementation.

Another agent-based approach much more focused on finding engineering solutions to power distribution system automation than in agent modeling itself is provided in [234]. The authors introduce an hierarchical automation architecture based on the concept of *intelligent logical nodes*, which is envisioned as an extension of the logical node (see IEC 61850 [36]) concept applied to substation automation. Although the rules for fault location and power restoration can be found in previous works, the approach itself is very interesting in the sense that it establishes a direct integration of the IEC 61850 and IEC 61499 [45] into the so-called intelligent logical nodes. Concisely, the integration dictates that for each logical node, an intelligent logical node is implemented as a composite function block of the IEC 61499 with a database, service interpreter and intelligence (the part responsible for decision making and negotiation). The agents communicate via services of the IEC 61850 and computer validation tests were carried out using a MATLAB [7] model interfacing with function block models through custom-design user datagram protocol sockets.

Following a different approach, a multi-agent system for fault location, isolation and power restoration is described in [213]. The approach is directed to underground power distribution systems and assumes three software agent types located at the secondary distribution substations. They are the *agent expert* that must handle emerging situations, the *agent inter* that provides connection with the physical environment, and *agent com* that is responsible for communications. Also, a *terminal agent* performs some activities at the primary distribution substations. All these agents have specific rules to be applied in three operation states called: steady-state, fault isolation state and restoration state. The research has continued in [214] where the engineering complexity [211] was reduced in considering only two agent types: the *primary substation agent* and the *secondary substation agent*. Hence, the resulting structure resembled the one proposed in [211, 212], though fault isolation and power restoration are achieved differently by using some JADE-oriented implementations of agent behaviors. The applications in [214] are sound and the rules behind the agent behaviors consolidate the idea of employing neighborhood interactions as in [211, 216]. The economic feasibility of these solutions were verified in [219].

In order to close (for now) the discussions about the agent-based solutions to power distribution system restoration, we quote the actual application of the IntelliTEAM II automatic restoration system developed by the S&C Electric Company [235]. In the approach, the basic unit of operation is a line segment bounded by *intelligent switching points*. The combination of the line segment and intelligent switching points is called a *team* and a so-called virtual agent manages internal team information sharing and restorative tasks. Also, a *contract agent* that works across multiple teams back to a common load source is applied to avoid safety problems and a *return to normal agent* is utilized to handle backing to normal configuration after a network failure is repaired. Current implementations usually rely on peer-to-peer wide area communications provided by a 900 MHz UtiliNet spread spectrum radio system that transports data using a connection-less mesh architecture, thus allowing each radio in the network to act both as a repeated radio and a data transceiver for an automated switch. Even though agency is not dealt specifically in the abstraction (e.g. by recurring on a reasoning model), it is a fact that the company have been installing the automation solutions since 2003 with success, assigning both interest and economic feasibility to providing distributed restorative functions for power distribution systems. Applications in the field have reported [236] automatic restoration cases which endured less than 10 seconds, which is an impressive result.

Up to this point, we have outlined agent-based applications specifically leaned to power distribution system protection, diagnoses, fault isolation, fault location and power restoration. However, other activities such as voltage control, power flow management and market operation were also approached under the agent paradigm either in a sole way or within broad conceptual frameworks. As one example of the latter, let us take the “cell” concept introduced in [237], where a network cell is viewed as a self-managing entity of protection, voltage control and power control activities. Summarily, the concept produces a system structure which is envisioned to evolve in analogy with a biological cell division process from a whole distribution network as a single cell to a final distribution network probably composed of thousands of cells. Hence, the resulting theoretical framework was recently utilized up to a certain degree in [238] where an agent-based converter interface for active distribution networks is proposed. The converter was named *smart power router* and it was applied to interfacing different cells of a power distribution system. The work uses an operation structure quite similar to the proposed in [239], where each agent is considered an autonomous actor handling the three issues: management (performs the object functions for voltage regulation, power management, or state estimation), coordination (defines control set points for the object functions) and execution (activates control actions). Aspects of reasoning modeling were not derived and the focus was strictly on the control functions which were further improved with optimal power flow computations [240]. Nevertheless, interesting results were provided and the solutions were verified under a laboratory setup specifically configured for the application.

One of the most important aspect of analyzing the introduction of the cell concept in [237] is to verifying that utilities have the pragmatic (and reasonable) perception that it is impossible to transform a distribution network in an active distribution network overnight. It is therefore necessary to abstract the current situation so that the evolution to active distribution networks happens in a controlled manner aiding network designers to plan their modifications and extensions in alignment with a long-term vision [237]. These concerns were also raised in developing the autonomous regional active network management system (AuRA-NMS) [202], though the resulting solutions were centralized in primary substation equipments and mostly tailored for regional-scale applications. Concisely, the AuRA-NMS is composed of functionalities wrapped in agents, namely the *power flow management agent*, *voltage control agent*, and *automatic restoration agent*. Also, an additional agent named *arbitration agent* was envisioned to avoid conflicting actions by imposing priorities, though more information could be given about its reasoning. These agents were deployed within an agent platform running across several ABB COM6xx computers [241] placed at primary substations. The functionalities were approached as follows.

1. Power flow management: A constraint satisfaction problem formulation was applied to power flow management [208] where DG control signals (100%, 90%, 80%, and so forth, of rated power) represent the domain of discrete variable values. Hence, potential solutions to maximize DG access are checked while power flow and contractual (e.g. “last-in, first-off”) limits impose the constraints to the problem. A solver is utilized to find multiple ranked solutions to a given problem supporting operator’s requirements for graceful degradation. Thus, if the preferred solution does not mitigate thermal excursions due to model error or measurement error, the next ranked solution can be implemented. Optimal power flow arrangements were under trials as well but concerns regarding algorithm non-convergence seem to deviate the authors from this solution. They state (and we agree) that from operator’s perspective optimality plays second fiddle to robustness, thus suboptimal but robust solutions are preferable instead of those which strive for optimality.

2. Voltage control: A case-based reasoning approach was used [218] to avoid problems associated

with the non-convergence of power flows or optimal power flows. The idea was to apply a set of preenumerated solutions created over a representative set of voltage excursions aiming at providing solutions to similar but different voltage excursions. The authors considered as control measures the change of tap positions, DG power factor set points and DG active power outputs. A constraint programming arrangement was also considered but issues regarding to search space size and computation time seems to drive the authors towards the case-based reasoning approach as main solution, though such statement was never explicitly mentioned in [208].

3. Automatic restoration: Researchers at the University of Cardiff developed a reconfiguration approach to minimize the number of disconnected customers based on the knowledge of fault location and pre-fault loadings [242]. No further information was found about this functionality up to April 2012.

The work provides interesting discussions about operator's requirements for active management of distribution systems and manifests explicit goal-driven concerns in the solutions design, mostly in the sense a control engineer would be able to set control goals for an area under the AuRA-NMS. The research project was well planned and executed producing further contributions and extensions [208,218,242,243].

Note that all these agent-based solutions and active management applications did not rely on a market operator to devise real-time operation, which is reasonable since the great majority of the customers connected to the power distribution systems pay a pre-specified tariff for the electric energy without any sort of real-time selling/buying activity. As a matter of fact, achieving operation through a market interactive customer per household seems unfeasible in the short/mid-term given that even different payments for different levels of power quality are far from being popular. Despite of these issues, some authors have also studied market operations to power distribution systems under the agent paradigm. In this context, the market-based control concept to supply-demand matching in electricity networks [244], called PowerMatcher, must be quoted. The objective of the concept is the optimal use of devices (named agents) which sell/buy electricity on a market exchange and are categorized as stochastic operation, shiftable operation, external resource buffering, electricity storage and user-action. The resulting application is sound and field test implementations are shown in [245], though the authors are not clear about how agent-based simulations were actually performed.

A market operation control concept is also explored in a micro grid concept in [246] where the agents are assigned to a power system as well as to micro grid entities such as the micro grid central controller, the production units and the consumption units. This work has continued in [138,139,205,210,247–249] where JADE-oriented behaviors, technical discussions and test cases are presented. In architectural terms, the main difference from the multi-micro grid paradigm lies in the fact that, in these works, the micro grid communicates directly to a technical operator and a market operator, while in the multi-micro grid paradigm proposed in [93] the micro grids interact with a controller placed nearby the primary substation. The multi-agent system developed for resource schedule in multi-micro grids shown in [220] also shares such a difference.

Another set of market-based solutions over a broad framework is obtained through the Infotility GridAgents [250] software platform deployed at the Consolidated Edison Company of New York's power distribution system. In summary, the GridAgents were initially designed by Infotility for energy transactions based on real time pricing signals. Recently, the GridAgents framework sells a set of default decision support solutions to power systems split in the activities of Resource (pull information and write data from meters, EMS, sensors, databases), Interface (display modifications), Task (EMS functions) and Broker (market/contract operator). For distribution network control, the developments are a set of plug-in modules with embedded solutions such as to compute optimal DER response to price signals, inclusion of business rules, physical constraints, and artificial intelligence learning routines to optimize operation and/or response over time. The most interesting feature of the framework is the integration with internet-based systems through a web services gateway via blackboard agents.

Finally, the literature analysis also showed that the design of voltage control schemes for distribution feeders using agent-based technology is a recent and rare research topic to be found. In a set of exceptions, we initially quote the broad hierarchical control framework for transmission and distribution networks described in [251]. This framework employs a hierarchical control architecture in which actions follow a chain of command from a top layer (control center) to bottom layers (power distribution systems and loads). As consequence, interactions are performed by a central *EMS agent* and layered *relay agents*, all implemented in JADE. The key aspect of the approach is a reactive load control optimization algorithm to improve voltage profiles in power distribution systems. However, a *top feeder relay* attributed to each distribution feeder is envisioned to solve the optimization problem and to coordinate bottom controllers, which in turn simply corresponds to delegating centralized voltage coordination decisions to an entity at the primary substation level instead of relying on functions (or operators) at a control center. This sort of delegation was also exhibited in the previously described voltage control of AuRA-NMS [218], but the latter approach is much more connected to the actual practice of operation mainly in the sense it focuses on pre-enumerated solutions which can be thoroughly analyzed by operators and experts instead of relying on an algorithm designed to strive for optimality.

The straightforward delegation of voltage coordination functions is avoided in [252] where RTUs are placed at DG sites and near capacitors to aid control by the voltage regulators. The harsh drawback of the work is that the authors stated in the publication abstract that the RTUs coordinated together compose a multi-agent system, but actually agent modeling and interactions are not described in the contents of the document. Conversely, agent interactions through the contract net protocol are explicitly applied in the multi-agent reactive power dispatch of DG units proposed in [215]. Nevertheless, the authors did not considered utility voltage regulators or shunt capacitors and they did not revealed a proper simulation model to validate their work, as also identified in [253]. At last, we refer to the well described coordination mechanisms for voltage control introduced in [253] which considers the following agents: *load tap changer control agent*, *voltage regulator control agent*, *DG control agent* and *shunt capacitor control agent*. In this approach, each agent type has an internal architecture where control rules/equations are wrapped into modules named perception, interpretation, expert-based decision-maker, and execution. Decision-making is performed using expert-based pre-specified lookup tabled rules whereas *load tap changer control agents* and *voltage regulator control agents* receive information from the other agents regarding updated and forecasted set points, as well as solution proposals (or requests) enforced due to voltage violations which can (or cannot) be solved locally. All agents are implemented in JADE whilst sensors and actuators are modeled in MATLAB [7] Simulink. The work stands out in the sense that the objectives of the agents (minimize voltage deviations, injected reactive power and tap/switch operations) are explicitly defined by the authors, which combined with the module design indicates some goal-oriented behavior is considered in the modeling and implementation.

2.4 Summary and Discussions

An extensive review was presented about the current status of power distributed generation as well as power distribution system operation and control, focusing on aspects from operation states and modes, central control and management, automation, protection, performance evaluation and future frameworks. The discussions enlighten the infrastructures and operational activities behind the utility's system operation and control. All these infrastructures and activities might be subjected to changes and transformations fostered by smart/modern grid concepts. Aside from speculations and self-interests, it was found clear the opportunity for developing solutions towards a more modern grid where DERs might be promoted and integrated in the operational activities, reliability might be improved through self-healing strategies, innovations on information and communication technology might be considered, and decentralized services alongside autonomous operation can be enforced. Nevertheless, current frameworks focus considerably on developing solutions assuming a brand new future comprised of modern infrastructures and the large scale integration of DER in the power distribution systems. After analyzing carefully the current context and initiatives we concluded that

> *instead of developing frameworks for future power distribution systems where modernization and the large scale integration of DERs are assumed achieved, it is more pragmatical to concern with the gradual attribution of smartness to the system using a well-defined notion of intelligence such as the notion employed by the agent paradigm.*
>
> Annotation A

An extensive survey about the applications of agent systems to power engineering brought up several insights and conclusions regarding how power engineers have been exploiting agent technologies to their end means. As previously stated, in comparison with classical power engineering research fields, such exploitation is far from being mature due to, for instance, the interdisciplinary requirements to build practical applications under the agent paradigm and the innovative character of applying such paradigm in power engineering solutions. The existing applications are fragmentally distributed among several research areas and, differently from what we expected in the beginning of the survey, the research activities have not been booming recently, even with the rise of smart/modern grid trends.

Applications to power distribution engineering are even more fragmentally distributed. Also, common ground is missing in what regards how solutions in protection, monitoring, diagnoses, voltage control, power flow management, fault location, fault isolation and power restoration can be integrated to support DMS functions. As one of the main conclusions of the survey, we identified that

> *there is a lack of an agent-based architecture specifically designed to support distributed feeder applications aligned to the trends enforced by the smart grid paradigm.*
>
> Annotation B

Without such an architecture, integrating solutions from different areas that influence distribution feeder operations can become a task full of complexities. This point is particularly interesting since one of the main justifications for applying agent systems lies in designing extendable solutions with reduced complexity. In fact, several of the surveyed works are quite extendable mostly in the sense of accommodating new agent instances of a designed agent type. However, it is not a straightforward task to accommodate interactions of agent types developed under different contexts. As an example, let us consider the voltage control mechanisms in [253] and the IntelliTEAM II [235] restoration mechanisms. It would be advisable to avoid the change of device tap positions at the same time restoration switch procedures are enforced and this could be obtained, for instance, by prioritizing goals. Nevertheless, since goal-directed behavior and agent planning are not explicit in IntelliTEAM II, one cannot straightforwardly choose which *team* plans to disable in order to prioritize a goal in [253]. With this simple example, we illustrate that

> *the lack of explicit representation of goal-directed behaviors interrelated with agent planning makes difficult to conjugate in a common framework the agent solutions proposed in the literature.*
>
> Annotation C

As a matter of fact, the great majority of works which perform some sort of validation through computer simulations applies the middleware JADE to aid implementation. The JADE platform focuses on implementing the FIPA reference model providing communication infrastructure, platform services such as agent management, and a set of development and debugging tools. On the other hand, it intentionally leaves open much of the issues of internal agent concept, which in turn can be considered through add-ons as in JADEX [119]. Hence, in order to develop agent systems, it is necessary to consider the intra-agent as well as inter-agent structures, being the BDI model one of the main options to enable viewing an agent as a goal-directed entity that acts in a rational manner. Nevertheless, the only application of BDI models in the power distribution system environment is found in [206], and even in this work beliefs, desires and intentions are not properly described. As conclusion, it is crucial that

> *some agent architectural models, such as the BDI model, are included in the agent systems developments, thereby avoiding the sole use of the middleware JADE by exploring other alternatives such as JADEX or JASON.*
>
> Annotation D

Another issue that jeopardizes the possibility of conjugating agent developments in power distribution engineering is the lack of deployment of designing tools and software engineering methodologies. The surveyed works do not describe their designing, with the few exceptions of the very closed applications of the ARCHON framework and the PEDA agents. Usually, agent types are chosen according to the convenience of the designer without proper clarifications. Once design matters are not described, the design itself cannot be extended directly which is a frustrating dichotomy for those interested in customizing a set of distributed solutions to their particular applications. Therefore, *power engineering academia should be aware that the description of software engineering design matters are of utmost importance to guarantee their proposed agent systems can be actually extended in different contexts and applications. Also, the usage of well established and documented agent design methodologies, such as Prometheus, is appreciated to foster proper discussions about the virtues and drawbacks of each development.*

Annotation E

Finally, none of the surveyed works provides one of the most important issue for the practical implementation and acceptance of agent-based technology in power distribution engineering. In order to justify altering the power distribution system infrastructures and providing alternative distributed functionalities

it is necessary an environment model which emulates the system operation to evaluate the long-term impact of the agent-based solutions according to standardized (and regulated) power distribution system performance indices.

Annotation F

The absence of such environment simulation is understandable since this would require a simulation model which considers altogether aspects from power distribution system planning and infrastructure, the long-term failure/repair cycle of the system components, topology changes caused by protective and control network actions, DER impact on system steady-state and dynamics, control strategies such as for islanding and load shedding, and so forth, in a way never conceived in the state of the art.

The following chapters explore the Annotations A–F to derive the contributions of the work and to address the research questions listed in the introductory chapter.

Chapter 3

Block-Oriented Agent-based Architecture to Power Distribution System Operation: A JASON Approach

This chapter presents a block-oriented agent-based architecture specifically designed to support the power distribution system operation in a decentralized manner. This architecture was conceived to approach, as effectively as possible, the issues raised in Annotations A–E of section 2.4. The main idea behind the developments lies in building architectural solutions to support distributed feeder applications. These solutions are in turn aligned to trends enforced by smart/modern grid concepts, such as promoting decentralized management and control, integrating DERs in the operational procedures, modernizing the power distribution systems, and increasing the levels of reliability. Nevertheless, instead of promoting solutions to a future smart/modern grid to be, the proposed architecture was devised to gradually attribute smartness to the system operation using the well-defined notions of intelligence of the agent paradigm. This pragmatical directive allows creating architectural sets of solutions which attain altogether high levels of flexibility, extensibility, and robustness. Such features are of major importance to the gradual implementation of decentralized solutions in the power distribution system operation, permitting the smooth transition from actual to future distribution systems in a way that improvements in infrastructure are established according to a long-term vision.

The proposed agent-based solutions were developed employing explicit representations of goal-directed behaviors interrelated with agent planning. For this accomplishment, BDI agents were modeled using the JASON agent programming language and interpreter, whose choice was justified in section 2.3.1.5. The design itself was undertaken using as reference the steps of the Prometheus methodology introduced in section 2.3.1.4, but following a proposed block-oriented philosophy of management and control. The agent capabilities are thoroughly described showing details about JASON implementations. At last, the transition from the conventional centralized management to the decentralization achieved by the agent-based architecture is discussed providing indications for actual deployment.

This chapter describes in detail the proposed architecture and discusses its implications. In chapter 4, a simulation model to evaluate the impact of operational/control solutions on the power distribution system performance indices is presented. Hence, in chapter 5, the proposed architecture is bridged to an environment model designed to embody the simulation mechanisms introduced in chapter 4. This chapter is organized as follows. In section 3.1, the application of a block-oriented philosophy to power distribution system management and control is defined and justified. In section 3.2, the agent-based system specification and architecture design are presented following conceptual steps of the Prometheus methodology and exploiting the block-oriented philosophy. In section 3.3, a series of agent capabilities are designed alongside their associated agent plans. Hence, in section 3.4, the transition towards the block-oriented agent-based architectural philosophy is discussed and indications for actual deployment are provided. Finally, in section 3.5, remarks regarding the architecture are outlined to close the chapter. The developments presented in this chapter were initiated from the works introduced in publications 9 and 5 of Appendix A.

3.1 The Block-Oriented Philosophy

Power distribution systems are considerably complex and dynamic. While some groups of feeder sections do not change their main source of supply in a lifetime, others can change it seasonally through network control actions remotely devised to achieve, for instance, scheduled maintenance or, more rarely, outage management. These changes impact on how system protective, monitoring, control and operational decisions must be undertaken, making intricate the task of managing the power distribution systems. As described in the previous chapter, power distribution systems are managed hierarchically by a DMS which, at a higher level, commands remotely some protective and control devices at lower levels. However, the size and complexity of the power distribution systems impose limitations to the extent with which the DMS can manage the system. As a consequence, crew personnel are commonly dispatched to identify and solve local problems in the field. Therefore, the increase in size and complexity of the power distribution systems bring the need for distributed intelligence and local solutions, a statement which corroborates with the ongoing evolution of power distribution system automation, and which is enforced by the concept of building a smart/modern grid.

One of the major concerns in designing a local solution is to evaluate its level of compatibility with the current infrastructure and the future solutions to be. Also, the resulting set of local solutions should be evaluated as whole, in the sense of its ability to accommodating novel functionalities. Since it is unreasonable to assume that power distribution utilities will modify their infrastructure overnight to address smart/modern grid trends, architectural sets of solutions must be devised assuring that local solutions can be gradually implemented, following a long-term vision which enforces flexibility, extensibility and robustness. The block-oriented philosophy of management and control is proposed with such intend, aiming its further connection with the agent paradigm.

The block-oriented philosophy of management and control is defined herein as the one in which *a certain degree of autonomy is ascribed to at least one entity responsible to support the management* *and control of particular parts of the power distribution system*[3.1]. The application of a block-oriented philosophy where management and control activities are partitioned in blocks is justified below.

1. Customer interruptions are caused by a wide range of phenomena including equipment failure (e.g. transformers, overhead lines, underground cables, circuit breakers, surge arresters, insulators, bushings), action of animals (e.g. squirrels, mice, rats, gophers, birds, snakes, fire ants, large animals in general), severe weather (e.g. wind storms, lightning storms, ice storms, heat storms), natural disasters (e.g. earthquakes), trees (e.g. falling branches/trunks, branch intruding, branch contacting) and human factors (e.g. schedule interruptions, operational errors, vehicular accidents, dig ins, mischief and vandalism). Most commonly, these causes exhibit their patterns in geographic zones rather than on entire feeders. Therefore, it is more pragmatic to direct investments towards the troublesome zones (where the problems are) instead of investing on entire feeders or even entire power distribution systems. This point of view already originated research efforts in which reliability is retrieved distinctively according to the block/zone under analysis, as in [254, 255].

2. Different customers may be interested (or even require) different levels of service reliability. In fact, while the one-hour interruption cost of a residential customer might be virtually zero, the same one-hour interruption might incur in enormous costs to an industrial client. Longer interruptions are even worse to an industrial client since they are inclined to cause lost of production or ruined inventory. As an example, in the Canadian interruption cost survey examined in [34], it is verified that large customers in some industrial activities might incur on millions of dollars per interruption hour. Hence, identifying and providing the exact reliability which satisfies each customer is always a recurrent challenge for the power distribution utilities. Stepping ahead towards local management strategies to specific blocks of the power distribution systems aids to improve differentiating the service reliability of the interested customers.

3. Actual power distribution feeders are already segmented for protection and control purposes. This allows reducing the service interruption durations by separating faulted sections and, when it is possible, to feed non-faulty interrupted sections using alternative feeders or other sources of supply. Power distribution system automation has evolved from substation automation towards feeder automation. Hence, block-oriented solutions where functions are deployed at specific blocks of the feeders are the natural step further to power distribution system automation.

4. In terms of philosophical choice, current trends, namely the smart grid paradigm, foster the development of decentralized architectures with enhanced intelligent and active demand side solutions. As a matter of fact, one of the six deployment priorities of the *Strategic Deployment Document for Europe's Electricity Network of the Future* [3] is named *Active Distribution Networks* where the implementation and communication of multiple intelligent elements at multiple nodes is envisioned to support the power distribution system operation. The coupling of a block-oriented philosophy with the agent paradigm is conceptually aligned with this deployment priority, allowing to address-

[3.1] Although this definition might seem daringly abstract at first glance, the terms "certain degree" and "particular part" will be shown to be quite appropriate whilst the reader is guided throughout the document.

ing other priorities such as the establishment of self-healing features promoted by the U.S. Modern Grid Initiative [1].

5. It is not expected that utilities will change their control and protection schemes at once in order to cope with the smart/modern grid philosophies. Actually, it is more reasonable to expect utilities will deploy network reinforcements as well as improvements on protection, monitoring, control and operation according to the necessity of particular blocks/zones of some feeders. Besides, one should not assume an homogeneous integration of DERs among power distribution systems, among feeders, or even in a particular feeder. Therefore, the necessity (and opportunity) for complex operational/control architectures will not be evenly distributed as well. As consequence, in order to go through the necessary changes to create smart/modern grids, one should employ an automation philosophy based on local solutions that cooperate to provide an adequate and secure service. Also, the extend and complexity of these solutions must be flexible in a way they can be redefined according with the ongoing integration of DERs and the tightening of quality of service requirements.

The statements above suggest as proper solution a decentralized architecture in which the power distribution system is divided into blocks for management and control purposes. The blocks should be abstracted in such a way that their number, capabilities, and disposition on the system can vary according with the gradual integration of DERs and with the necessities of the power distribution utilities. The implementation of block functionalities might follow plug-and-play philosophies as much as possible to support the smart/modern grid concepts. Furthermore, in order to ensure security, flexibility, scalability, tolerance to failures, and graceful degradation, each block must have some degree of reactiveness and autonomy. At last, aiming at designing complex operational/control strategies through the interaction among blocks, one can additionally assign them social ability, situatedness (in an environment), and proactiveness (in pursuing its goals). Such assignments characterize *agency* to the blocks and indicate the agent paradigm as basis to the development of management and control solutions to smart/modern grids.

Therefore, an architecture in which agents are responsible for the management and control of networks blocks of the power distribution systems is proposed. Note that such philosophy differs from previous works in which functionalities of the power distribution system operation are clustered in general frameworks where agency is studied, or in which devices (e.g. relay, switches) and/or entities (e.g. loads, DMS) are directly abstracted as agents. For sure, agents must be designed to act to improve the system service. Moreover, they might communicate with each order to share information about the system conditions. Nevertheless, instead of pursuing blindly the innumerable manners of interactions that can be established under the philosophy, we recurred to the application of methodological procedures of the design and specification disciplines of agent-based systems. As identified in the state of the art survey, building agent-based systems without the deployment of proper design methodologies is, unfortunately but arguably, a common practice to the power engineering academia. Similarly, there is a lack of applications of design methodologies to justify how frameworks for smart grid, multi-micro grid and micro grid operation and control were conceived. To avoid following this pathway, design directives from the Prometheus methodology were utilized herein to guiding the system specification and architecture design. Since outlining all stages and diagrams of the methodology is out of the scope of this document, the next section focus on the description of the goal mapping, functionalities, and agent types directly derived from the methodological stages. These results originated the agent capabilities which are further presented in detail alongside indications for JASON implementations.

3.2 System Specification and Architecture Design

The first step in building any complex system is to formalize the reasons for which this system must be built. However, specifying *goals* over the power distribution system operation can be a slippery task. In fact, despite achieving acceptable *states of affair*, the goals should agree with the mission of the power distribution utility as an enterprize, respect standards and regulations, follow inner policies, foster sustainability, and protect the interests of customers and stakeholders. All these features vary with the business administration and life cycle of the power distribution utility. Therefore, it is not reasonable (and useful) to our purposes to stipulating as an objective the approach of all possible goals of a power distribution utility. Assuming this task is possible, most certaintly some of the stipulated goals would not fit in the inner processes and infrastructure of certain power distribution utilities and the research would decay into producing unsuitable generalizations, feeding the architecture design with poor directives. On the other hand, the choice of a particular power distribution utility to devise a case study would lead to excessive particularizations, where some of the concepts we intended to approach about the smart/modern grid paradigm would be distorted by particular views or current intentions of a business administration.

Since one of the main research purposes behind building the system lies in showing how the trends quoted in the beginning of this chapter can be approached using the notion of intelligence provided by a block-oriented agent-based architecture, goals were obtained, featured and refined by focusing on these trends and their resulting implications. Following this reasoning, we present how a goal mapping can ultimately originate agent capabilities and plans to be deployed aiming at supporting the power distribution system operation. Hence, the interested designer might customize his application to his goals and plans of interest, or even develop his own goal mappings to his particular interests following an analogous procedure.

Bearing these issues in mind, a goal overview diagram was developed to our framework as characterized in the system specification stage of the Prometheus methodology. This diagram maps goals and subgoals elicited from decision makers to withdraw knowledge about the purposes of building the agent-based system, and to drive the design of agent capabilities and plans. The goals and subgoals were elicited from discussions with coordinators and/or members of the research areas in planning & forecasting, smart grid and power distribution systems at INESC Porto, and mind organizations of the author. Although the description of the elicitation processes is out of the purview of this document, we emphasize that the Prometheus methodology provides only guidelines for building a goal map such as "highlighting words/phrases" in eliciting descriptions of goals or asking "how this goal may be achieved?" to retrieve subgoals. These guidelines showed to be useful but sometimes short due to the size and complexity of our framework. Therefore, looking for alternatives with more conceptual formalisms, our research leaned to the disciplines of cognitive mappings [256].

Summarily, a cognitive mapping involves building a cognitive map to structure and organize concepts around a given framework. In the topological point of view, a cognitive map is a directed graph whose nodes represent concepts and arrows denote relations between concepts. These relations are signed positive or negative depending upon the sort of influence a concept has to the other. All these concepts are then elicited and organized up to a graph diagram where top nodes represent abstract objectives and bottom nodes denote tangible directives or potential options. A generical scheme of a cognitive map is illustrated in Fig 3.1.

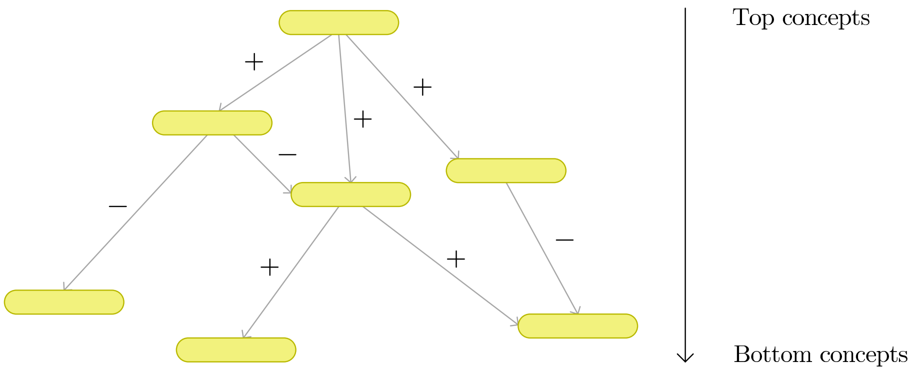


Fig. 3.1: General scheme of a cognitive map[3.2].

Even though a direct association with cognitive mapping is not exhibited in the documentation of the Prometheus methodology, the guidelines for building a goal overview diagram resemble considerably those utilized in building cognitive maps. However, the formalisms behind cognitive mappings are arguably more mature and several extensions are already available in the literature regarding their connection with fuzzy logic [257] or neutrosophic logic [258, 259]. Additionally, several elicitation mechanisms and guidelines are provided and discussed in the literature. Therefore, the elicitation process employed in this work followed the guidelines and directives of building cognitive maps using [260] as main reference, but considering the goals as node concepts of the end-means map diagram. The main directives approached at this stage can be summarized in the following steps.

1. Identification of *anchor-concepts* around the problem/framework to be structured, where brainstorming sections raised several concepts to be addressed in supporting the power distribution system operation such as the minimization of customer interruptions or the design of reconfiguration/restoration solutions.

2. Building of concept hierarchies, where abstract goals and subgoals were retrieved from the *anchor-concepts* by the inquire "why this goal must be achieved?" and "how this goal may be achieved?", respectively. For instance, one might inquire "how to minimize customer interruptions?" and retrieve the concept "provide DG islanded operation" from the answer.

3. Building the cognitive/goal mapping by connecting the conceptual relations enlightened during the inquires devised in the previous step. These connections may be signed positive or negative indicating if a concept acts positively or negatively on the other, respectively.

[3.2] Arrow directions are inverted from the common cognitive mapping notation to couple with the goal overview notation of the Prometheus methodology.

It is important to mention that there are other sets of directives to building cognitive mappings such as the weighting of relations and the description of end-means alternatives. However, these directives are not directly useful to this work since our aim is strictly the structuring of concepts to foment the other stages of the Prometheus methodology. After devising extensively the three steps enumerated above, a cognitive mapping for our framework arose. The main goals of the developed goal/cognitive mapping are depicted in Fig. 3.2.

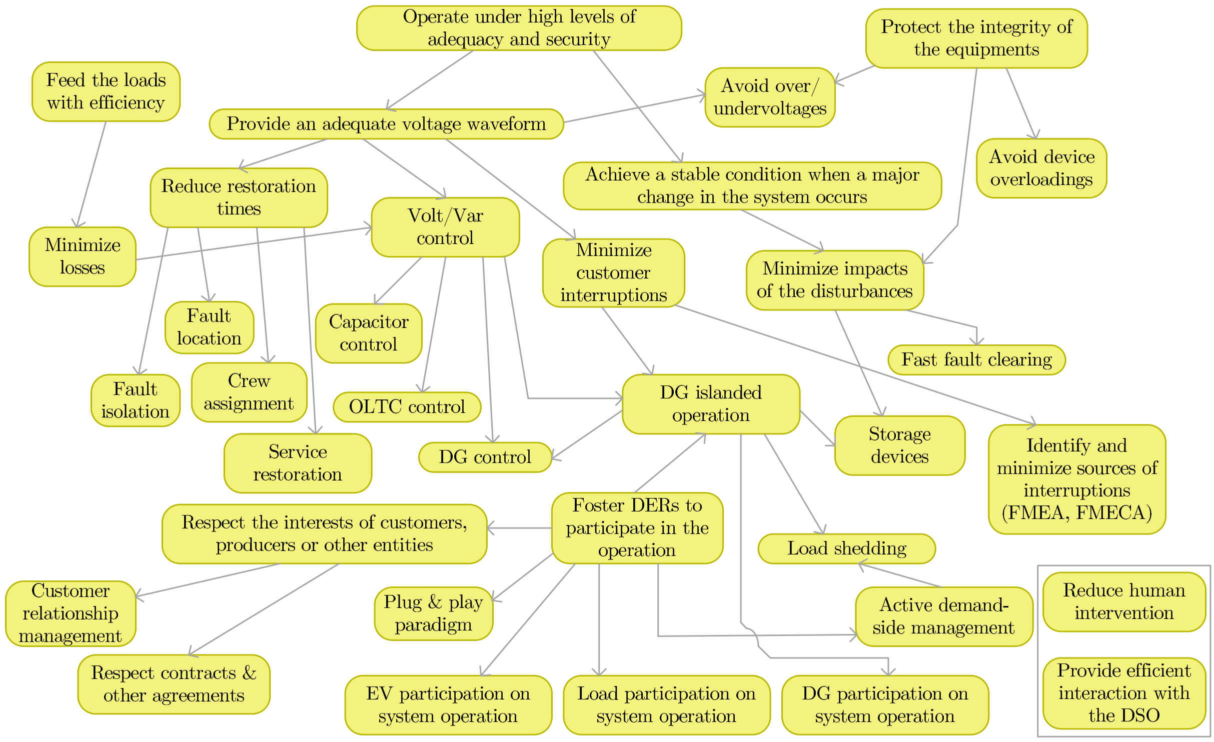


Fig. 3.2: Main goals from goal overview diagram of the agent-based architecture.

In the figure, the main goals represent the abstract (top) concepts of the mapping while potential options were removed for the sake of visibility and generality. Also, concepts were organized in such a way that only positive influences are established, causing that influence signals were removed from the scheme as well. It must be stressed that the mapped goals are not supposed to range all the possible purposes of the power distribution utilities or even of a particular utility. On the contrary, they were devised with focus on enlightening critical matters to our purposes. Hence, the set of goals includes technical matters such as to `protect the integrity of the equipments` and to `operate under high levels of service adequacy and security`, as well as smart grid matters such as to `foster DERs to participate in the operation`. Moreover, it includes design objectives such as to `reduce human intervention` and to `provide efficient interaction with the DSO`. As an example of interpretation of the goal overview diagram, one can derive that in order to `provide an adequate` `voltage waveform` (including the provision of any voltage waveform)[3.3], one alternative might be to `reduce restoration times`. On the other hand, in order to `reduce restoration times`, one alternative might be to provide fast `fault location`, so that potential options (i.e. operational/control schemes) might be developed with this intent. Other discussed alternatives to `reduce restoration times` might be to improve `fault isolation`, `crew assignment` and the `service restoration` as a whole. As expected, some sub-goals suggest that an (agent) abstraction might be assigned to the blocks of the power distribution system. For instance, when eliciting a basic scenario of service restoration the following description arose.

> *When a sustained fault occurs in a distribution feeder, fault isolation is achieved by isolating the faulted block from the remaining network. Then, service restoration is endeavored to connect as many blocks as possible to alternative supplies, aiming at minimizing the number of customers under service interruption.*

The sub-goal `DG islanded operation` pointed also to the block-oriented paradigm during discussions through the following description.

> *In order to minimize customer interruptions and foster the exploitation of DER capabilities, DG islanded operation procedures might be employed. Given the spatial distributed signature of the DG units and their restricted capacity in supplying feeder's customers, DG islanded operation is expected to be achieved only in certain blocks of the network.*

Description of basic scenarios and operational schemes were documented to support the understanding of how the mapped goals might be achieved in the system operation. Discussions about the semantic and necessity of these goals were significantly useful to sharp the devising of agent functionalities and capabilities.

Hence, once the goal/cognitive mapping was devised, several functionalities of interest were established in the scope of the architecture design stage, as illustrated in Fig. 3.3. These functionalities are chunks of behaviors originated from grouping related sets of goals and associated percepts, actions, or data. In the figure, the main functionalities are exhibited with self-explainable names and alongside some associated goals. Clearly, there are several manners of grouping (and ungrouping) functionalities and the reader might consult reference [12] for guidelines and discussions. Among the functionalities, there are the strictly technical ones which refer to the management and control of the feeders and require data about the power distribution utility infrastructure, such as the `outage management`, `protection management`, `voltage management`, and `congestion management` functionalities. In addition, we recall that, due to the matters enumerated in section 3.1, a block-oriented philosophy of management and control should be utilized to support the power distribution system operation. This suggests that an entity responsible to the management and control of the block must be able to provide a service in which these technical functionalities are cooperatively tackled with other entities. Hence, such service was established as a general functionality and named `block management service` (BMS).

[3.3] One might verify that the provision of an adequate voltage waveform implies on delivering an undistorted sinusoidal voltage with constant amplitude and frequency. Under this reasoning, this research adopts the convention of R. E. Brown [34] where a service interruption itself is considered a voltage waveform problem. As a direct consequence, the reduction of restoration times leads to less service interruption durations, which in turn improves the provision of adequate voltage waveforms.

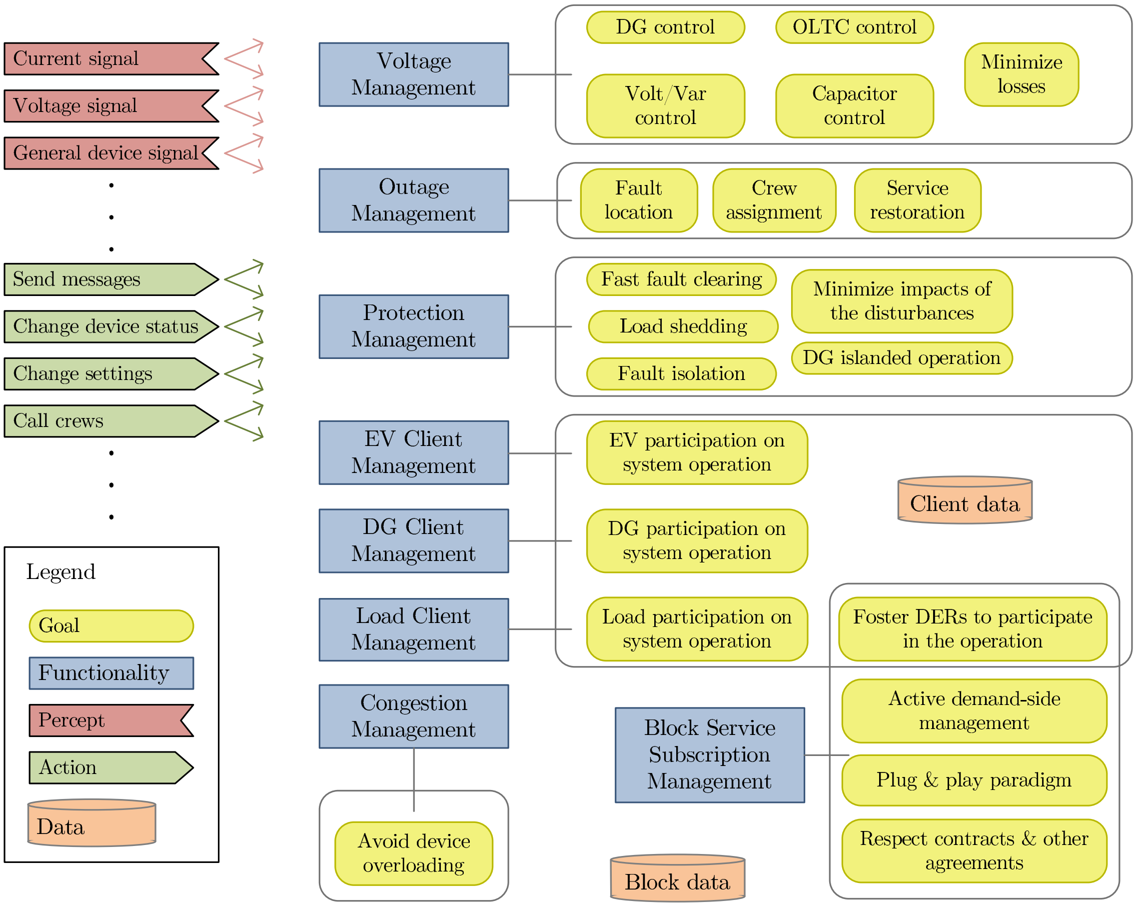


Fig. 3.3: Main functionalities from the role overview diagram of the agent-based architecture.

Aiming at reducing data requirements and ensuring decentralization, it is desirable that the entity responsible to the management and control of the block does not encapsulate information about the entire utility infrastructure. On the contrary, it is of interest that only the utility infrastructure data related to the assigned block is encapsulated by the entity. Also, primary actions and percepts might be restricted, as much as possible, to the usage of the components within or nearby the block infrastructure. This implies that interactions with other entities are necessary to share updated information about the system conditions in a timely manner. In order to manage and authenticate other entities with which interactions can be pursued, a `block subscription management` functionality should be included to the BMS. Observe that the referred other entities might be responsible for other blocks or even behave as DER's representative actors. In turn, these DER's representative actors might provide `client management` functionalities using, eventually, private data from the DER.

All these reasonings suggest that an agent type named `block agent` (BA) must be established to take the responsibility of providing the BMS. On the other hand, a general agent type named `client agent` (CA) might be established as a DER's representative actor and an agent type might be defined to the DMS as well in order to verify possible interactions with the BAs. Aiming at pursuing the mapped goals and enforcing decentralization, each BA might be responsible to feeding and sharing information with its neighboring BAs, inner CAs and, eventually, with the DMS through the utility communication system. Hence, agent plans related to searching for clients and neighbors as well as information flow schemes must be designed. In addition, the following BMS directives were envisioned at this stage as guidelines to designing BA capabilities.

1. The power distribution networks can be segmented in blocks which have particular features and can be separated by power switching elements (sectionalize and tie switches). Hence, blocks can incorporate monitoring, protection & control devices, lines, transformers, poles & points of connection, customer loads, capacitor & reactor banks, on-line tap changers, DG units, EV charging stations and even micro grids. One agent is assigned to the management and control of each block "giving life" to a BA, which might be embedded in device apparatus running, for instance, a JAVA virtual machine nearby the block infrastructure. Hence, a communication network which allows BAs to communicate with inner entities and among themselves is assumed. The set of block monitoring, protective and control devices trace the possibilities of perception and action of the BA. Discussions about the block segmentation are outlined in section 3.4.

2. Using the available devices and schemes, the BA must provide an adequate and secure service to its assignee and cooperate with other entities. Also, it must protect the integrity of the utility's and customers' devices, as well as respect contracts and regulations. In summary, the BA must strive to accomplish the abstracted goals and subgoals mapped in Fig. 3.2.

3. BAs should characterize the operation state of their assignee. For this accomplishment, the monitoring of node voltages and component currents (magnitude & direction) is needed at least at some block ends. Using these measurements, a network model, plus the information conveyed from inner entities, the BA might estimate its loading and infer the proximity to an inadequate operation state. Also, equipment rating and voltage constraints may be evaluated. Stressed operation conditions might be identified and reported to the DMS. In case the operation condition differs significantly from the usual conditions or even from the designed conditions, this could suggest inadequate operation or that some equipment is damaged. Eventually, protection resetting and control actions might be taken to solve these issues. All this information can be further utilized in the restoration procedures.

4. As formerly described, certain blocks of the feeders are prone to recurrent problems. BAs might have an historical knowledge base to assist interruption failure mode analysis in order to support specifying the crew assignment (safety, equipment, size, expertise) of its assignee. Local weather monitoring, if available, is an excellent source of information to infer the probability of failure of components. Local diagnoses using live cable testing technology (though immature [34]), overhead line infrared inspection, and other equipment damage monitoring scheme may also provide useful information to crew assignment. Multifunction digital relay can provide immediate detection of relay failure (self-diagnostics) [51], ability to interrogate relay information from remote locations (communication capabilities) and information on the cause of the interconnection relay operation (oscillographic monitoring).

5. BAs should monitor the outages of DERs. These outages should be included in the feeder protection design and can ultimately impact on resetting relays and/or enabling alternative control and protection schemes.

6. Voltage problems are by nature local and they are solved using automatic voltage regulators, capacitor banks, transformer tap changers, and so forth. BAs might infer over the automatism of these devices to mitigate voltage problems. Similar inferences can be applied to overloading problems.

7. Block monitoring might identify and categorize modes of operation (`grid connected`, `islanded operation`), energization status (`energized`, `de_energized`) and topology (`connected`, `isolated`) aiming at leading its further actions such as the enabling of control and protection schemes.

8. In order to support outage management (including outage alert, fault location, fault isolation, service restoration), the following remarks must be taken into consideration.

   (a) Directional fault passage indicators (FPIs) might be installed at the limits of each block to support fault location. The FPI schemes must be devised considering conventional DMS strategies in case of FPI misoperations. FPI backfeed information may be checked through message conveyance to support outage management.

   (b) The BA which identifies the fault was into its assignee (using the FPI information) might mark its assignee as `faulty` and convey this information to its neighbors (which, in turn, may repass this information to the others) to support outage management.

   (c) Once a BA identifies its assignee as `interrupted`, the BA might isolate its assignee and start looking for power in its neighbors. At the same time, it manages activities such as service restoration through black start using cold load pick up information when available.

By utilizing these architecture design guidelines plus brainstormed scenarios, schemas and descriptors, the agent capabilities and plans of actions were abstracted as presented in the next section.

3.3 Agent Capabilities and Plans of Action

Following the Prometheus methodology, a description of the detailed design of the agent-based architecture would demand the specification of each percept, action, data, event and message to be utilized in the system operation. Actually, at some extreme, a detailed design would also require refining each project decision after prototype implementations and field applications, two topics which are out of the scope of this thesis. As a matter of fact, in case we entry into the resolution of the devices placed in the utility infrastructure, the design might become excessively particularized to certain sorts of networks and operational procedures. For instance, in examining the attribute fields of the IntelliTEAM instructions sheets [261], one might incur in several attributes which can be interpreted herein as percepts or actions but which do not aggregate significant semantic value to our framework. Examples of these attributes are daylight savings time automatic changeover, calendar timeclock time/data, cabinet heater temperature, serial number, padmount configuration, switch visual disconnect contacts, and so forth. Therefore, we have chosen to focus our developments and descriptions about this stage upon the agent capabilities and plans which originated the actual code developed in JASON, alongside their main associated percepts, actions, data, events and messages. This focus corroborates with the computational modeling of the power distribution system components and their conveyance to environment artifacts, a topic explored in detail in chapter 5.

By definition, the referred agent capabilities are nested functionalities related to agent types and characterized by a set of associated plans. For our real world application, agent plans must be employed respecting the complexity and dynamism of the power distribution systems. Hence, simple but effective rules must represent the main contents of the plans. At this point, excess of complexity in plan designing is not considered to be directly related to high agency intelligence. On the contrary, it is a signal of immoderate particularization in abstracting the architecture. Also, excess of complexity might lure utility engineers towards disbeliefs imposing difficulties in the acceptance of the block-oriented philosophy. In fact, in order to promote the application of the philosophy within the utilities, certain conservative directives might be of interest. For instance, in pilot projects and first field implementation stages, we expect that conservative utility engineers would require the plans to be approved by the DMS staff before any action, reporting of all activities to be sent back to the DMS, and even the possibility of overriding simple decisions. These directives might be of great relevance to gathering data about the operation of network blocks of interest, testing protection and control settings derived from system planning, tuning and validating the BA's plans, as well as improving the degree of acceptance/confidence in the decentralized solutions provided by the block-oriented agent-based architecture. The transition from the conventional centralized management towards the decentralization achieved by the agent-based architecture is discussed in section 3.4.

The following subsections describe the agent capabilities and their associated plans. Obviously, we have not defined as an objective to deal with all possible issues of each of the functionalities raised in section 3.2. This would decay in providing the referred immoderate particularization and somehow contribute to the fragmentation of agent applications to power distribution engineering discussed in section 2.4. Conversely, the capabilities and plans were designed aiming at their balance between addressing critical matters to our purposes and providing generality alongside the possibility of encapsulating existing schemes from the literature or currently being utilized in the field. Hence, the plans presented in this section are called *meta plans*[3.4] in the sense they abstract a more fragmented lower level set of plans implemented in JASON. Each meta plan originated twenty five low level plans in average and they are introduced into forms similarly to those proposed in the Prometheus methodology, but enhanced by JASON's syntax. Therefore, as an example, if the meta plan applies some predefined interaction protocol, the messages of this protocol are directly included in the fields *incoming messages* and *outgoing messages* of the meta plan's description form. On the other hand, as another example, if the execution of the meta plan incurs in updating information on a physical HMI, then the literal `hmi_update(·)` can be established in JASON to represent the action of updating the HMI, where the notation "`(·)`" means a lumped set of entries which are skipped for the sake of straightness. Since one of the fields of the meta plan's description form refers to their related *actions*, the literal `hmi_update(·)` is then placed in this field

[3.4] The *meta plans* presented in this document must not be confused with the *meta-level plans* of the PRS agent architecture. While *meta-level plans* are plans which are capable of modifying the agent's intention structures at run-time in order to change the focus of the agent's practical reasoning [10], the *meta plans* introduced herein compose abstract plans which represent a set of low level plans coded in JASON.

to indicate the update of the HMI as one of the meta plan's actions. At last, pieces of code are outlined to complete the description of the meta plans and to show how they were implemented in JASON.

3.3.1 Managing Client Subscription

In order to cope with a plug-and-play paradigm, DER's representative agent types must be able to establish and unestablish interactions with a BA at the point of connection according to the desires of the DER owner and interests of the BA. The nature of these interactions suggests that at least some sort of subscription is necessary by the DER's representative agent type to the services the BA provides. In addition, the establishment of standardized electronic contracts/agreements including the DER owner's preferences and offered flexibilities as well as the BA wished flexibilities might be of great interest for both parts. For instance, the possibility of interrupting some loading of a customer cooperative at specific periods of time can increase the flexibility of the power distribution system operation. Nevertheless, following a devised agreement, this customer cooperative should be able to cease offering this flexibility if the representant so desires. The same concept applies to other DERs such as DG units or even prospected micro grids, EV charging stations, as well as groups of entities represented by an agent type.

The capability *Managing Client Subscription* deals directly with the subscription of DER's representative agent types to BMSs through the Meta plans 1–3. The client flexibilities are addressed in the next capability.

Meta plan 1: Subscribe to a BMS

Description: Subscription to a BMS formulated by a CA.
Context: The CA desires to subscribe to a BMS.
Functionality: `client management`.
Trigger: `+cl_subscr_on`.
Incoming messages: [←BA] Refuse, agree and failure messages (FIPA-like Subscription Participant).
Outgoing messages: [→BA] Subscribe message (FIPA-like Subscription Initiator).
Percepts: `cl_subscr_on`.
Actions: `hmi_update(·)`.
Used data: Client data.
Produced data: Log (i.e. record) of the attempts and subscription data.
Procedure:
- Fulfill a client concept schema containing at least the agent ID, electrical point of connection, electronic contract/agreement (if any), and particular data specific to the type of DER.
- Send a subscribe message (client candidate) to the possible BA service provider.
- Handle the responses looking forward to achieving the subscription (`cl_subscr_block(·)`).

The Meta plan 1 allows a DER's representative agent type to assign itself as a client candidate to a BA service provider. Whether a BMS is recognized, this meta plan can be triggered by the user (DER owner or other representant) at will through the percept `cl_subscr_on` (`@metaplan01_01`). Thus, the client candidates' preferences/flexibilities (client data) are encapsulated in a client concept schema and a subscribe message is sent aiming at reaching a BA service provider (`@metaplan01_09`). The interaction follows a FIPA-like Subscribe Interaction Protocol [111] and the client schema might contain at least the agent ID, some data about the type of DER, and electrical point of connection allowing the BA to verify if the client candidate is connected to the network block. Results from the interactions are saved in a log and might be displayed in a HMI. In case the subscription is achieved, information about the subscription is also saved and the subscription belief `cl_subscr_block(·)` is added to the CA's belief base (`@metaplan01_12`). The subscription is altered or terminated using Meta plans 2 and 3, respectively.

```
@metaplan01_01   +!cl_subscr_on :  true   <- +cl_subscr_on; ?cl_subscr_on.

@metaplan01_09   +cl_subscr_on :  acceptableBlockschema(Count,blockschema(·))
   <- ...; !sendmsg(BA,tell,subscribe(Count,clientschema(·));
      +subscribe(Count,clientschema(·))[sent(BA)].

@metaplan01_12   +agree(SubId,subscribe)[source(BAx)]
   :  subscribe(Count,clientschema(·))[sent(BA)] & BA == BAx & ...
   <- ...; hmi_update(·); +cl_subscr_block(Count,BA,clientschema(·)).
```

Meta plan 2: Update/change subscription

Description: Request update or change to a subscription/contract agreement.
Context: The DER's representative agent type desires to update or change the subscription agreement with a BMS.
Functionality: `client management`.
Trigger: `+cl_subscr_update(·)`.
Incoming messages: [←BA] Refuse, agree and failure messages (FIPA-like Request Participant).
Outgoing messages: [→BA] Request message (FIPA-like Request Initiator).
Percepts: `cl_subscr_update(·)`.
Actions: `hmi_update(·)`.
Used data: Subscription data.
Produced data: Log of the attempts and updated subscription data.
Procedure:
- Send a message requesting the update/change of the subscription agreement.
- Handle message responses.

Meta plan 3: Terminate a subscription to a BMS

Description: Request formulated by a CA in order to terminate a client subscription to a BMS.
Context: The DER's representative agent desires to terminate the subscription to a BMS.
Functionality: `client management`.
Trigger: `+cl_subscr_off`.
Incoming messages: [←BA] Refuse, agree and failure messages (FIPA-like Request Participant).
Outgoing messages: [→BA] Request message (FIPA-like Request Initiator).
Percepts: `cl_subscr_off`.
Actions: `hmi_update(·)`.
Used data: Subscription data.
Produced data: Log of the attempts and updated subscription data.
Procedure:
- Send a request message aiming at terminating the subscription.
- Handle message responses.

Meta plan 2 outlines the update or change of a subscription contract/agreement clause between the

DER's representative agent type and the BA service provider (@metaplan02_01). On the other hand, Meta plan 3 describes how subscriptions are terminated through requests of DER's representative agent types (@metaplan03_01). Meta plans 2 and 3 are triggered by the user (DER owner or other representant) using the percepts cl_subscr_update (@metaplan02_08) and cl_subscr_off (@metaplan03_09), respectively, employing a FIPA-like Request Interaction Protocol [262], and using the performative tell for the sake of simplicity and didactics. Also, these plans might produce updates to subscription data as well as updates to a HMI (@metaplan02_13,@metaplan03_12). Hence, the belief cl_subscr_block(·) can be updated in Meta plan 2 or even excluded from the belief base in Meta plan 3.

```
@metaplan02_01   +!cl_subscr_update(U) : true   <- +cl_subscr_update(U); ?cl_subscr_update(U).

@metaplan02_08   +cl_subscr_update(U)   :  cl_subscr_block(Count,BA,clientschema(·))
   <- ...; !sendmsg(BA,tell,subscribe_update(Count,clientschema(·));
      +subscribe_update(Count,clientschema(·))[sent(BA)].

@metaplan02_13   +agree(SubId,subscribe_update)[source(BAx)]
   :  subscribe_update(Count,clientschema(·))[sent(BA)] & BA == BAx & ...
   <- ...; hmi_update(·); +cl_subscr_block(Count,BA,clientschema(·)).

@metaplan03_01   +!cl_subscr_off :  true   <- +cl_subscr_off; ?cl_subscr_off.

@metaplan03_09   +cl_subscr_off :  cl_subscr_block(Count,BA,clientschema(·))
   <- ...; !sendmsg(BA,tell,unsubscribe(Count,clientschema(·));
      +unsubscribe(Count,clientschema(·))[sent(BA)].

@metaplan03_12   +agree(SubId,unsubscribe)[source(BAx)]
   :  unsubscribe(Count,clientschema(·))[sent(BA)] & BA == BAx & ...
   <- ...; hmi_update(·); -cl_subscr_block(Count,BA,clientschema(·)).
```

Service subscription interactions are basic to agent systems. Electronic contract negotiation represents a broad research area in agent systems and several forms of interactions are available in the literature. The BA service subscriptions and electronic contract negotiations might be devised as complex as of interest for both parts, bearing in mind the increase in complexity may result in an increase in costs of field implementation of the solutions.

3.3.2 Managing Client Flexibilities

In addition to subscription and electronic contract negotiations, further interactions might be of interest to support the power distribution system operation. For instance, in case a plan is directly dependent on a flexibility which can be provided by a subscribed CA, interactions can be devised to require this flexibility and even avoid a subscription to be terminated if so desired by the CA. This suggests the need for a capability named *Managing Client Flexibilities* which materializes the usage of a DER's flexibility through Meta plan 4.

Meta plan 4: Activate/deactivate provided flexibility

Description: Handle requests formulated by a BA service provider in order to activate/deactivate a DER flexibility.
Context: The DER is requested to provide a given flexibility.
Functionality: `client management`.
Trigger: Message from BA.
Incoming messages: [←BA] Request message (FIPA-like Request Initiator).
Outgoing messages: [→BA] Refuse, agree and failure messages (FIPA-like Request Participant).
Percepts: -
Actions: `hmi_update(·)`.
Used data: Subscription data.
Produced data: Log of the attempts and activation/deactivation data.
Procedure:
if *activation/deactivation of flexibility is consistent with subscription agreement* **then**
- Activate/deactivate flexibility.
- Confirm activation/deactivation to the BA.

else
- Refuse request informing the reasons.

Meta plan 4 abstracts a wide range of possible low level plans for the flexibilities that the DERs might provide. Once a requirement for the activation of a flexibility is received, then the triggering event `+cl_flex_on`(F) is produced causing the request to be dealt depending upon the clauses of the subscription agreement (`@metaplan04_05, @metaplan04_06`). A similar reasoning is implemented for the deactivation of a flexibility. The list of flexibilities include DER disconnection and reconnection, DER start-up and shutdown, acceptance in load shedding schemes, as well as protection and control settings update (in case they are internal to the DER facility).

```
@metaplan04_05   +cl_flex_on(F)
  :  cl_subscr_block(Count,BA,clientschema(·)) & acceptableCondition(F)
  <- ...; !activateFlex(F).

@metaplan04_06   +cl_flex_on(F)
  :  cl_subscr_block(Count,BA,clientschema(·)) & not acceptableCondition(F)
  <- ...; !sendmsg(BA,tell,refuse(Count,cl_flex_on(F)).
```

One may observe that this meta plan generalizes a series of activities produced in the surveyed works, where DER operational actions (e.g. disconnection of a customer load or change of a DG unit setpoint) are requested to be performed directly or indirectly by a higher level entity. Examples of these activities are employed in the micro grid control [138,139,205,210,246–249], the multi-micro grid hierarchical frequency control [63,263,264], the multi-micro grid coordinated voltage control [93], the AuRA-NMS power flow management and voltage control [208,218], and the smart power router optimization for voltage control, power management and state estimation [238].

3.3.3 Managing Block Service Subscriptions

Following Meta plans 1–3, the BA must be able to authenticate and handle subscriptions and negotiations with clients to improve its ability to support the power distribution systems operation. Also, as outlined in the previous section, knowledge about neighboring blocks are of utmost importance to guarantee a proper cooperation among BAs. This revels the need for a *Managing Block Service Subscriptions* capability in which subscription interactions with clients and other BAs are devised. This capability is achieved through Meta plans 5–6.

Meta plan 5: Broadcast the BMS

Description: Broadcast the BMS to possible neighboring BAs and CA candidates.
Context: Broadcast of the BMS is desired by operators or crew personnel.
Functionality: `block subscription management`.
Trigger: `+bk_serv_broadcast`, message from DMS.
Incoming messages: [←DMS] Request message (FIPA-like Request Initiator).
Outgoing messages: [→DMS] Refuse and agree messages (FIPA-like Request Participant); [→CA,BA,DMS] Inform message.
Percepts: `bk_serv_broadcast`.
Actions: `hmi_update(·)`.
Used data: Block data.
Produced data: Log of the attempts and subscription data.
Procedure:
- Fulfill a BMS concept schema containing at least the agent ID and data specific to the BMS.
- Broadcast the concept schema to other BA service providers.

Meta plan 5 is called by operators or crew personnel through the percept `bk_serv_broadcast`, which triggers the broadcast of a message declaring the provision of a BMS. These messages convey a block concept schema containing at least the agent ID and data specific to the BMS (`@metaplan05_01`, `@metaplan05_02`).

```
@metaplan05_01   +!bk_serv_broadcast :  true   <- +bk_serv_broadcast; ?bk_serv_broadcast.

@metaplan05_02   +bk_serv_broadcast :  true
   <- ...; .broadcast(tell,blockservice(Count,blockschema(·));
      +broadcasted(blockservice(Count,blockschema(·)).
```

Hence, in Meta plan 6, the BA attempts a subscription (`@metaplan06_01`,`@metaplan06_09`) to a neighboring BMS through the percept `bk_subscr_on` following similar procedures from those employed in Meta plan 1, but leaving the handling of responses to further meta plans. The subscribe message might contain at least the agent ID, electrical boundary points of connection, and particular data specific to the block in order to allow other BAs to verify neighborhood properties. Since network blocks may have more than one neighbor, Meta plan 6 is called for a list of possible neighboring BMS providers.

```
@metaplan06_01   +!bk_subscr_on(BA) : true   <- +bk_subscr_on(BA); ?bk_subscr_on(BA).
```

Meta plan 6: Create a subscription to a neighboring BMS

Description: Request formulated by operators or crew personnel in order to individually create a neighboring block subscription to a BMS.
Context: Subscription to neighboring BMS are desired to be created by operators or crew personnel.
Functionality: `block subscription management`.
Trigger: `+bk_subscr_on`, message from DMS.
Incoming messages: [←DMS] Request message (FIPA-like Request Initiator).
Outgoing messages: [→BA] Subscribe message (FIPA-like Subscribe Initiator), [→DMS] Refuse and agree messages (FIPA-like Request Participant)
Percepts: `bk_subscr_on`.
Actions: `hmi_update(·)`.
Used data: Subscription data.
Produced data: Log of the attempts and subscription data.
Procedure:

- Fulfill a block concept schema containing at least the agent ID, electrical point of connection, electronic contract/agreement (if any), and particular data specific to the block.
- Send a subscribe message (neighbor candidate) to the possible BA service provider.

```
@metaplan06_09   +bk_subscr_on(BA) : blockservice(Count,blockschema(·)) & ...
   <- ...; !sendmsg(BA,tell,subscribe(Count,neighschema(·));
      +subscribe(Count,neighschema(·))[sent(BA)].
```

Meta plan 7 handles interactions with client and neighbors (`@metaplan07_11`,`@metaplan07_21`, `@metaplan07_26`,`@metaplan07_27`) which were triggered by incoming messages produced in Meta plans 1–5, 6 and 8. Once changes in the subscribed CAs are identified, aggregated information is updated and sent to other entities using the Meta plan 9 to be described in the next subsection.

```
@metaplan07_11   +subscribe(Count,clientschema(·)[source(A)]
   :  acceptableClient(clientschema(·))
   <- ...; -subscribe(Count,clientschema(·))[source(A)];
      +agreed(subscribe(Count,clientschema(·))[source(A)]);
      !sendmsg(A,tell,agree(SubId,subscribe));
      +bk_subscr_client(Count,clientschema(·)).
```

```
@metaplan07_21   +subscribe(Count,neighschema(·)[source(A)]
   :  acceptableNeighbor(neighschema(·))
   <- ...; -subscribe(Count,neighschema(·))[source(A)];
      +agreed(subscribe(Count,neighschema(·))[source(A)]);
      !sendmsg(A,tell,agree(SubId,subscribe));
      +bk_subscr_neighbor(Count,neighschema(·)).
```

```
@metaplan07_26   +agree(SubId,subscribe)[source(BAx)]
   :  subscribe(Count,neighschema(·))[sent(BA)] & BA == BAx & ...
   <- ...; hmi_update(·); +agreed(subscribe(Count,neighschema(·))[sent(BA)]).
```

Meta plan 7: Block service subscription responder

Description: Identifies subscription messages and request messages for updates either from clients or neighbors. Client and neighbors are authenticated according to their respective concept schema.
Context: The BA is able to provide the service to a client or neighbor according to the terms of the subscription contract/agreement.
Functionality: `block subscription management`.
Trigger: Subscribe and request message.
Incoming messages: [←CA,BA] Subscribe and request messages (FIPA-like Subscription Initiator, FIPA-like Request Initiator).
Outgoing messages: [→CA,BA] Refuse, agree and failure messages (FIPA-like Subscription Participant, FIPA-like Request Participant).
Percepts: -
Actions: `hmi_update(·)`.
Used data: Block data, client data, subscription data, activation/deactivation data.
Produced data: Log of the attempts and updated data.
Procedure:

if *subscription/update/termination/flexibility activation/flexibility deactivation is accepted* **then**
- Authenticate/unauthenticate client (`bk_subscr_client(·)`) or neighbor (`bk_subscr_neighbor(·)`), if applicable.
- Update information about the inner entities: active power capacity/load, reactive power capacity/load, type of the DER entity, flexibilities, and so forth, if applicable.
- Send updates about aggregated information to the neighboring BAs using Meta plan 9.

else
- Send a message denying the subscription/request, eventually informing the reasons.

```
    +bk_subscr_neighbor(Count,BA,neighschema(·)).

@metaplan07_27   +refused(SubId,subscribe)[source(BAx)]
   :  subscribe(Count,neighschema(·))[sent(BA)]  & BA == BAx & ...
   <- ...; hmi_update(·); +refused(subscribe(Count,neighschema(·))[sent(BA)]).
```

At last, in Meta plan 8, a BMS subscription termination can be requested by operators or crew personnel (`@metaplan08_01`,`@metaplan08_02`). This meta plan follows similar procedures from those employed in Meta plan 3 but leaving the handling of responses to Meta plan 7.

```
@metaplan08_01   +!bk_subscr_off(BA) : true   <- +bk_subscr_off(BA); ?bk_subscr_off(BA).

@metaplan08_09   +bk_subscr_off(BA) : true
   <- ...; !sendmsg(BA,tell,unsubscribe(Count,neighschema(·));
    +unsubscribe(Count,neighschema(·))[sent(BA)].
```

Among the purposes behind the designing of Meta plans 5–8, there are the participation of DERs in the system operation, the supporting of the plug and play paradigm as well as the system expansion activities. Once the subscription capabilities are devised, the natural evolution of the system caused by the connection/disconnection of DERs, acquiring/losing of alternative DER flexibilities, building/disregarding

Meta plan 8: Terminate a subscription to a neighboring BMS

Description: Request formulated by operators or crew personnel in order to individually terminate a neighboring block subscription to a BMS.
Context: Subscription to neighboring BMS are desired to be terminated by operators or crew personnel.
Functionality: `block subscription management`.
Trigger: `+bk_subscr_off(·)`, message from DMS.
Incoming messages: [←DMS] Request message (FIPA-like Request Initiator).
Outgoing messages: [→BA] Unsubscribe message, [→DMS] Refuse, agree and failure messages (FIPA-like Request Participant).
Percepts: `bk_subscr_off(·)`.
Actions: `hmi_update(·)`.
Used data: Subscription data.
Produced data: Log of the attempts and subscription data.
Procedure:
- Send a request message aiming at terminating the subscription.

alternative or ring connections, devising/disregarding of main feeder or lateral structured connections, and so forth, can be seamless accommodated by the architecture.

3.3.4 Information Sharing

The electrical coupling among blocks yields that actions which directly affect electrical variables into a block will affect electrical variables in other blocks as well. Hence, autonomy must be employed with responsibility in the sense that actions can confer at the same time benefits to one block and drawbacks to others. Aiming at guaranteing a successful cooperation, it is imperative that the BAs have a certain degree of knowledge about the electrical system upstream and downstream their assignees. The capability *Information Sharing* allows knowledge sharing through the Meta plan 9.

Meta plan 9: Information management

Description: After receiving updates about clients or neighbors, the BA groups and filters relevant data to be conveyed to other BA neighbors. It can be activated by operators or crew personnel.
Context: Information updates about clients or neighbors are received; update provision is required by operators or crew personnel.
Functionality: `block management service`.
Trigger: `+info_man`, messages from BA/DMS, events from other Meta plans.
Incoming messages: [←BA] Inform message; [←DMS] Request message (FIPA-like Request Initiator).
Outgoing messages: [→BA] Inform message; [→DMS] Refuse and agree messages (FIPA-like Request Participant).
Percepts: `info_man`.
Actions: `hmi_update(·)`.
Used data: Aggregated information data.
Produced data: Log of the attempts.
Procedure:
Rules enumerated in this subsection.

The information flow employed in Meta plan 9 is triggered by the receiving of updates from clients or neighbors (`@metaplan09_07`), or even by operators and crew personnel in the field (`@metaplan09_01`) through the percept `info_man`. Since power distribution systems are mostly operated using a radial topology, one can represent a set of neighboring blocks connected to each other as vertices of a graph tree[3.5]. Consequently, blocks with only one neighboring block are defined as *end blocks* and are deemed to begin the information flow among neighboring BAs (`@metaplan09_02`) in case nothing else is specified. The message recipient then processes, updates and stores aggregated data in order to properly resume feeding its neighbors (`@metaplan09_04`,`@metaplan09_09`, `@metaplan09_10`) with updated information. Fig. 3.4 illustrates how the sharing of information among BAs is schematized.

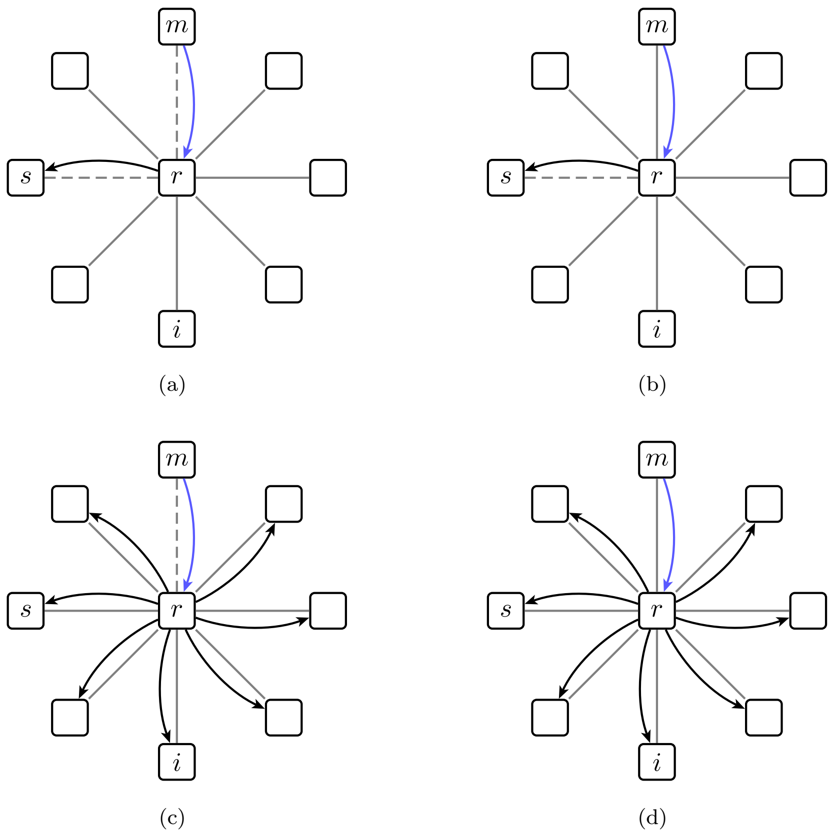
```
@metaplan09_01   +!info_man :  true   <- +info_man; ?info_man.

@metaplan09_02   +info_man :  end_block & ...   <- ...; !informAggregatedInfo(ToName,Type)

@metaplan09_04   +!informAggregatedInfo(ToName,Type) :  ...
  <- ...; ?received_info(DataRec(·))[recipient(ToName)]; ?inner_info(DataInn(·));
     !aggregateAll(DataRec(·),DataInn(·),Data(·)); !sendmsg(ToName,tell,info(Data(·)));

@metaplan09_07   +info(Data(·))[source(BA)] : neighbor(BA)
  <- ...; !informAggregatedInfoToList(S,Type).

@metaplan09_09   +!informAggregatedInfoToList([],Type) :  true   <- true.

@metaplan09_10   +!informAggregatedInfoToList([ToName|S],Type) :  true
  <- !informAggregatedInfo(ToName,Type); !informAggregatedInfoToList(S,Type).
```

Aiming at formalizing the information flow scheme, let us consider a BA_r with n neighbors in $\mathcal{N}_r \doteq \{\text{BA}_j, \forall j = 1, \dots n\}$. Without loss of generality, let us consider the total DER generation capacity as the subject of the information exchange. The information flow rules can be enumerated as follows.

1. Assume $\text{BA}_m \in \mathcal{N}_r$ sends an information message to BA_r regarding the system downstream their common neighboring switch.
   (a) If neighboring information messages regarding the subject have already been received from all BAs in $\mathcal{N}_r - \{\text{BA}_m\}$ except BA_s, then BA_r must send an information message to BA_s (see Fig. 3.4(a)–3.4(b)). This message includes data encapsulated by BA_r regarding its own client's generation capacity and the total generation capacities sent by all BAs in $\mathcal{N}_r - \{\text{BA}_s\}$.
   (b) If all BAs in $\mathcal{N}_r - \{\text{BA}_m\}$ have already sent at least one information message regarding the subject to BA_r, then BA_r must send a message to BA_i (see Fig. 3.4(c)–3.4(d)) containing the total generation capacity received from the BAs in $\mathcal{N}_r - \{\text{BA}_i\}$, $\forall \text{BA}_i \in \mathcal{N}_r - \{\text{BA}_m\}$.
2. In all other cases the incoming information is processed and stored for further action.

As an example, let us take the disposition of BAs and information flow shown in Fig. 3.5. In this figure, starting from null aggregated information about downstream/upstream capacity, (i) the end block

[3.5] A tree is a graph in which any two vertices are connected by exactly one simple path.



A solid line indicates at least one information message was conveyed from m to r, whilst a dashed line points out the contrary.

Fig. 3.4: Information flow scheme among neighboring BAs.

BA_1 sends capacity information to BA_2. Following rule 2, this information is processed and stored for further action. Hence, (ii) the end block BA_3 sends capacity information to BA_2. Since BA_4 is the only neighbor who still did not send any capacity information, then (iii) BA_2 aggregates the total capacity received plus its inner capacity information and sends the resulting aggregation to BA_4, as specified by rule 1a. After a while, (iv) BA_2 receives capacity information from BA_4, which is an end block. As consequence, following rule 1b, (v) BA_2 sends to BA_1 the aggregated capacity received from BA_3 and BA_4 plus its inner capacity information. Similarly, (vi) BA_2 sends to BA_3 the aggregated capacity received from BA_1 and BA_4 plus its inner capacity information, closing the cycle of information. In Fig. 3.5(b), (i) a client of BA_3 sends updates about its available capacity information. Such update is stored, processed and conveyed (ii) towards BA_2, and then after (iii) to BA_4 and to (iv) BA_1 analogously, following the rule 1b.

Note that starting from a null information about a subject, this scheme requires from each BA only one message to be sent to each neighbor and only one message to be received from each neighbor, guaranteeing that all BAs have updated information. Moreover, the information rules are independent of the network

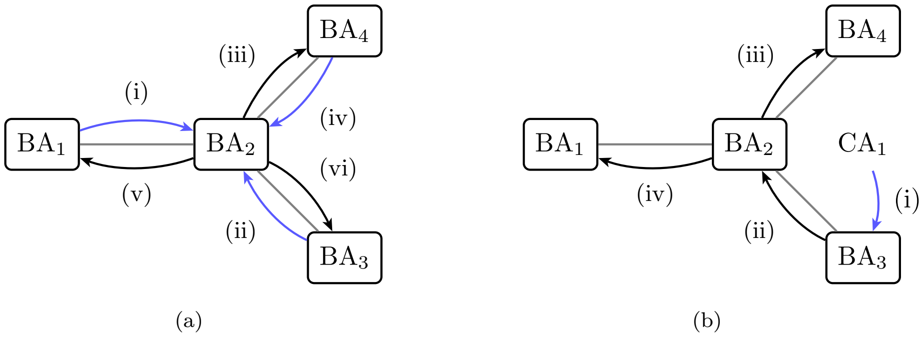


Fig. 3.5: Example of application of the information flow scheme.

configuration in such a way that, if reconfiguration procedures are identified in an individual block, the information flow scheme is straightforwardly performed taking into account the updated neighboring relations. Also, the chain of information can be used to derive the network configuration itself. Finally, in this capability, neighboring BAs are able to ask each other if one believes a proposition is true. This is particularly useful to create information flow mechanisms in which one BA verifies the operation conditions of the other. For instance, one BA can ask if the other believes it is `energized` by triggering the goal `!sendmsg(BA,askOne,energized,R)`, where the variable `R` is unified with the message reply.

3.3.5 Adverse Condition Alerting

As described in section 3.1, different network blocks are prone to different sorts of causes of interruption. The *Adverse Condition Alerting* capability decentralize alarming/alerting functions to assist crew assignment through Meta plans 10 and 11.

Meta plan 10: Enable alarms/alerts caused by adverse conditions

---

Description: Once adverse conditions are identified, the BA enables alarms/alerts to aid crew assignment.
Context: Abnormal weather or other environmental conditions are identified.
Functionality: `block management service`.
Trigger: `+sensor_info(·)`.
Incoming messages: [←DMS] Crew assignment message.
Outgoing messages: [→DMS] Alarm message (enable).
Percepts: `sensor_info(·)`.
Actions: `set_visual_alarm(·)`, `hmi_update(·)`.
Used data: Block data, condition data.
Produced data: Log of the operations and conditions.
Procedure:
- Using encapsulated data, evaluate possible and most common problems of this context.
- Set and send alarms/alerts for crew assignment to a crew center or TCM/DMS.

In summary, Meta plans 10 and 11 deal with enabling and disabling alarms/alerts which suggest the block is more propense to a service interruption. The nature of the alarms/alerts varies according to the list of causes and failure modes of the block. High wind speeds and lightnings are common

Meta plan 11: Disable alarms/alerts caused by adverse conditions

Description: Once adverse conditions have ended, the BA disables alarms/alerts.
Context: Abnormal weather or other environmental conditions have ended.
Functionality: `block management service`.
Trigger: `+sensor_info(·)`.
Incoming messages: [←DMS] Crew assignment message.
Outgoing messages: [→DMS] Alarm message (disable).
Percepts: `sensor_info(·)`.
Actions: `set_visual_alarm(·)`, `hmi_update(·)`.
Used data: Block data, condition data.
Produced data: Log of the operations and conditions.
Procedure:
- Account and save information about the adverse condition (duration, intensity, and so forth).
- Reset alarms/alerts and send such information to a crew center or TCM/DMS.

examples of environmental conditions which can be sensed in order to triggering alarms/alerts. These alarms/alerts may activate visual signaling in the field as well as be directed towards the TCM[3.6]/DMS or crew centers (`@metaplan10and11_01`, `@metaplan10and11_04`). Information about the adverse conditions can be utilized to facilitate establishing crew assignment or to schedule additional crew support.

```
@metaplan10and11_01   +!sensor_info(weather,State,·) :  State == 1 & not crew_assignment
   <- ..., set_visual_alarm(enabled); !informCrewCenter(·).

@metaplan10and11_04   +!sensor_info(weather,State,·) :  State == 0 & crew_assignment
   <- ..., set_visual_alarm(disabled); !informCrewCenter(·).
```

Meta plans 10 and 11 are general plans which can be extended to approach several phenomena of interest. As a matter of fact, they are exhibited in their general form to enlighten that this capability may encapsulate diagnosis agents of condition monitoring multi agent systems developed in the literature, such as the COMMAS [135,230], or be implemented to converse to alarm agents in control rooms, such as those developed in the ARCHON project [225, 226]. Given an improved diagnosis, crew assignment can be established more efficiently. Actually, sometimes a simple sort of alarm may be considerably useful to avoid interruptions or to reduce their associated impact. As an example, alarms/alerts may be received in case of thermal protection or loss of field of synchronous generators. In the specific case of loss of field, an operator would be expected to restore the field or initiate a controlled shutdown [14]. Hence, alarms/alerts may be sent to the BA in order to prepare for an imminent contingency. For instance, in DG islanded mode, preparation for loss of generation or even of a load customer would involve verifying the implications in other meta plans, requesting connection of storage units or diesel units (under isochronous control), changing the settings of control units, and so forth. At last, knowledge based system for diagnoses and data interpretation can be implemented, analogously to the research works employed to retrieve and interpret information from SCADA [173], but decentralized in the BAs to avoid local problems such as the historical replay of alarms, provision of nuisance alarms, and conveyance of broken data. Web

[3.6] The acronym TCM stands for trouble call management as defined in section 2.2.2.

serviced local weather information was already applied by the Infotility GridAgents [250] in the context of optimizing DER productions.

3.3.6 Dealing with Device Problems

All monitoring, protection, control, communication, and interface devices are prone to fail sometime. The capability *Dealing with Device Problems* allows the BA to handle these failure possibilities through the Meta plan 12.

Meta plan 12: Handle problems in devices

Description: Once a device failure is assigned, then activate contingency plans, verify how other plans will be affected by the failure and report to the DMS.
Context: Device failure beliefs based on internal reasoning, messages or percepts.
Functionality: `block management service`.
Trigger: `+operation_failed(·)`, messages from other actors, beliefs from meta plans.
Incoming messages: [←BA,DMS] inform messages.
Outgoing messages: [→BA,DMS] inform messages.
Percepts: `operation_failed(·)`, `hmi_update(·)`.
Actions: -
Used data: Block data, contingency plan data.
Produced data: Log of the operations and conditions.
Procedure:
- Activation of contingency plans (if any).
- Verify how other plans will be affected by the failure.
- Gather information about the problem and report to the DMS.

This Meta plan 12 is triggered by messages from other actors, beliefs produced in other meta plans, or when a device executes the general action `operation_failed(·)` where information about the failure is provided if possible (`@metaplan12_01`). This general action can be caused by operation malfunction or induced by periodical device self-diagnostics and communication (pooling) tests during operation.

```
@metaplan12_01   +operation_failed(·) :  true
  <- ..., !evaluatePlanDependencies(·); !sendmsg("dms",tell,operation_failed(·)).
```

Besides the general action `+operation_failed(·)`, the goal failures are tackled in JASON according to the definition of contingency plans, a feature which copes interestingly with this capability. For instance, the goal of sending a message to a recipient is triggered by the event `+!sendmsg(Receiver, Performative,Msg)` as shown in `@metaplan12_07`, where the literal `prob_com_fail(P)` models in a plan context the probability of failure to sending the message. This plan sends the referred message if a uniformly distributed random number sampled at $[0, 1]$ is superior to the probability of failure `P`. Otherwise, the contingency plan `@metaplan12_08` is triggered where, in this example, the failure is reported to the DMS alongside timestamp information.

```
@metaplan12_07   +!sendmsg(Receiver,Performative,Msg) :  prob_com_fail(P)
  <- ..., .random(M); M >P; .send(Receiver,Performative,Msg).
```

```
@metaplan12_08  -!sendmsg(Receiver,Performative,Msg) :  true
   <- ..., ?cdcstime(Year,TimeInstant);
     .send("dms",tell,fail(sendmsg(Receiver,Performative,Msg),Count,timestamp(Year,TimeInstant))).
```

Furthermore, after the evaluation of the failure, the DMS can deactivate current plans and send alternative contingency plans to be included in the plan library of the BA in order to solve current problems in the field or to be prepared for conditions not envisioned during the design. This update process brings flexibility, extensibility and robustness to the architecture and it can be performed straightforwardly by removing a plan using the message goal

```
!sendmsg(BA,untellHow,"@metaplan12_11")
```

and sending to the BA a new plan using the message goal

```
!sendmsg(BA,tellHow,"@metaplan12_11_updated").
```

Moreover, if the BA wants to achieve a given state of affair but it did not succeed in this endeavor using its current plan library, the BA can ask directly the DMS about how to proceed through the message goal

```
!sendmsg("dms",askHow,"!open(neigh_switches)")
```

or about a belief which somehow could not be retrieved due to a device failure as in

```
!sendmsg("dms",askOne,current_value(comp-LIN-X04,Imag)).
```

Clearly, each of the possible failures (or sets of them) might have contingency plans which in turn could result in enabling protection & control schemes besides informing the DMS about the current condition and the plans compromised by the failures.

3.3.7 Updating Settings According to Operation Condition

The operation condition of the block must be under surveillance to guarantee the proper operation of the protective and control systems. This unveils the capability *Updating Settings According to Operation Condition* as a requisite to support the power distribution system operation. This capability is attributed to the BAs through Meta Plan 13.

Meta plan 13 handles the settings update of protective and control devices and is triggered by signals provided by sensors (`@metaplan13_05`), operators or crew personnel in the field. The operation condition is built through the sensory data and depends on the sensor devices installed in the power distribution system. Some of these sensors already allows by default the specification of alarm messages which can be used to verify operation condition window shifts. Once a shift is assigned, beliefs related to conditions

Meta plan 13: Update settings according to operation condition

Description: Once the operation condition has shifted, then the resetting of protective and control devices may be devised.
Context: Operation condition window shift (even out of the designed) is identified.
Functionality: `protection management`, `voltage management`, `congestion management`.
Trigger: `+sensor(·)`.
Incoming messages: [←BA,DMS] inform message, [←DMS] Request message (FIPA-like Request Initiator).
Outgoing messages: [→BA,DMS] inform message, [→DMS] Refuse and agree messages (FIPA-like Request Participant).
Percepts: `sensor(·)`.
Actions: `change_setting(·)`, `hmi_update(·)`.
Used data: Library of operation conditions and associated settings.
Produced data: Log of interactions, operations and conditions.
Procedure:
- Update beliefs (e.g. `condition(·)`, `voltage(·)`, `energized(·)`).
- Resetting of protective and control devices (if necessary) and inform the neighbors about this activity using Meta plan 9.
- Gather information about the operation condition and send reports to the DMS.

(e.g. `condition(·)`, `voltage(·)`, `energized(·)`) are updated and the resetting of protective and control devices may be enabled through the action `change_setting(·)`.

```
@metaplan13_05   +shift_condition(·) :  true
  <- ..., !updateRelaySettings(condition(·)); !updateControlSettings(condition(·));
      !informAggregatedInfoToList(ListOfNeighNames,Type).
```

The BA "understanding" of a window shift in the operation condition can be implemented through the application of JASON rules. For instance, the BA "understanding" about an adequate service regarding voltage constraints is directly modeled through the JASON rules shown below.

```
undervoltage(Node_code,Volt_value) :- voltage(Node_code,Volt_value) & (Volt_value<0.95).

overvoltage(Node_code,Volt_value) :- voltage(Node_code,Volt_value) & (Volt_value>1.05).

adequate_voltages :- (not undervoltage(_,_)) & (not overvoltage(_,_)).
```

Note that the option of requesting, instead of enabling directly the resettings, would also provide some autonomous feature to the devices in blocking setting alterations based on, for instance, DMS directives. However, devices are not considered as agents in our design, such that interactions of this kind are skipped from the meta plans in order to assume a more suitable abstraction through the modeling of environment artifacts, as explained in detail in chapter 5. The settings are defined in the power distribution system planning process and their changes during the operation must be reported to the DMS to avoid functional inconsistencies. Also, resetting activities are informed to the neighbors through Meta plan 9 and are subjected to the approval of the DMS.

The information about the operation condition is particularly useful to infer about the proximity of an inadequate state. As discussed in section 3.2, operation conditions out of the designed or usual could suggest inadequate operation or that some equipment is damaged. Hence, once stranded operation conditions are identified they are directly reported to the DMS. Also, similarly to the previous subsection, Meta plan 13 is exhibited in its general form to enlighten that other solutions proposed in the literature can be compatible with this capability if transposed to the block level. Examples of other solutions are introduced in the relay agent-based schemes employed in [201,217,224] and the voltage control employed by the AuRA-NMS [218]. Nevertheless, some cautions must be mentioned before striving to integrate other solutions within the capability. For instance, regarding the protective activities, we emphasize that concepts from self-adapting protection should be placed carefully to avoid being discredited by protection engineers. This is the prime motive for choosing a conservative approach where pre-specified settings are utilized according to operation conditions foreseen in the design/planning phases and subjected to the approval of the DMS.

Analogously, one could encapsulate in this capability a series of control actions associated to sets of surveyed operation conditions, as developed for the case base reasoning in [218]. Pre-specified solutions would then be established for most probable and worst situations and, for other cases, the BA must report the problem and ask for alternative plans from the DMS. Actually, in a further extreme, even some state estimation analysis with a block network model could be used to assign voltage and current values to each of the devices of the block, as discussed in [211]. Then, optimization software functions could be applied to find the most suitable alternative to avoid undervoltages/overvoltages and device overloadings. However, this would require several sensors at the utility system which might be unreasonable for short or even mid-term applications. Therefore, problem mitigation strategies obtained during the design and/or planning processes are promoted herein as more pragmatic solutions.

3.3.8 Dealing with DER Stochastic Behavior

Similarly to the devices, the DERs are also prone to failures. The capability *Dealing with DER Stochastic Behavior* allows the BA to handle DER failures through Meta plans 14–15.

Meta plan 14 allows the BA to handle DER out of service situations. Once the event of a DER out of service condition is assigned through the percept `sensor(·)` or message from the associated CA (`@metaplan14_03`), protective and control device resetting may be activated to account for the event through the action `change_setting(·)`. For instance, note that the power flow constrained by a relay R32 (see Appendix B) can be considerably affected by the failure of a DER. Thus, R32 resetting (or even disabling) might be of interest to avoid unnecessary block interruptions. Similarly, block LOG[3.7] protection of an entire zone can be disabled for the cases in which its associated DERs are out of service. This would again avoid unnecessary block interruptions forthcoming from breaker actions caused by temporary or permanent faults in other blocks of the system. Other relay settings such as for overcurrent protection might be covered by this plan all in coherence with the belief `condition(·)` updated in Meta plan 13.

[3.7] The acronym LOG stands for loss of grid as defined in section 2.1.

Meta plan 14: Handle DER out of service conditions

Description: Once the DER out of service condition is assigned, if necessary re-arrange relays and control settings as well as convey this information to the other BAs.
Context: DER out of service condition is identified.
Functionality: `protection management`.
Trigger: `+sensor(·)`, message from CA.
Incoming messages: [←CA] Inform message.
Outgoing messages: [→BA,DMS] Inform message.
Percepts: `sensor(·)`.
Actions: `change_setting(·)`, `hmi_update(·)`.
Used data: Block and client data, library of operation conditions and associated settings.
Produced data: Log of the operations and conditions, updated block and client data.
Procedure:

- Confirm this information with the DER interconnection relays (if applicable).
- Monitoring of the operation condition and resetting of protection and control devices if necessary (e.g. R32) using pre-specified solutions.
- Update aggregated information and send it to the neighbors following Meta plan 9.

Meta plan 15: Handle DER back to service

Description: Once DER (re)connection/back to service is requested, the BA handles reconnection allowances and settings update.
Context: DER back to service is desired.
Functionality: `protection management`.
Trigger: Message from CA.
Incoming messages: [←CA] Request (FIPA-like Request Initiator).
Outgoing messages: [→CA] Refuse, agree and failure messages (FIPA-like Request Participant); [→BA,DMS] Inform message.
Percepts: `sensor(·)`.
Actions: `change_setting(·)`, `hmi_update(·)`.
Used data: Block and client data, library of operation conditions and associated settings.
Produced data: Log of the operations and conditions, updated block and client data.
Procedure:

- Handle the reconnection allowances.
- Resetting of protective and control devices if necessary (e.g. R32).
- Update aggregated information and send it to the neighbors following Meta plan 9.

```
@metaplan14_03   +down_transition(·)[source(CA)] : true
  <- ..., !updateRelaySetting(condition(·)); !informAggregatedInfoToList(ListOfNeighNames,Type).
```

On the other hand, in Meta plan 15, the DER back to service situations are dealt. The additional issue of this meta plan incurs in handling reconnection allowances where more than one DER is not supposed to reconnect at the same time since this can cause undesired transients in the power distribution systems. In summary, the BA proposes the reconnection instant to the DMS which, if approved, is conveyed in the form of an allowance to the CA. Otherwise, a novel proposal is created up to achieving the reconnection. The reconnection processes might require to block (or postpone) device operations (capacitors banks, automatic voltage regulators, scheduled/"known" load increase) and smooth relay settings. In DG islanded operation, storage units with droop and/or inertial control or synchronous machines with isochronous control, for instance, might also be applied to smooth the reconnection.

```
@metaplan15_03   +up_transition(·)[source(CA)] : down_transition(_)[source(CA)]
  <- ..., ?cdcstime(Year,TimeInstant); !propose_reconnection(·).
```

3.3.9 Supporting Islanded Operation

Islanded operation can be enforced to reduce service interruptions in blocks (or sets of blocks) with high level integration of DERs. This brings out the interest in a capability to *Supporting Islanded Operation* which is described in Meta plan 16.

Meta plan 16: Support islanded operation

Description: Islanded operation is supported by preparing settings for isolation.
Context: LOG protection is available.
Functionality: `protection management`.
Trigger: Internal message (periodical).
Incoming messages: [←BA,DMS] inform message.
Outgoing messages: [→BA,DMS] inform message.
Percepts: -
Actions: `change_setting(·)`, `hmi_update(·)`.
Used data: Block data.
Produced data: Updated block data.
Procedure:
- Prepare to isolate its associated network block or other blocks by linking breaker actions through transfer trip or using fast LOG protection settings.
- This information is shared with the block neighbors using Meta plan 9.

Meta plan 16 is applied periodically using updated information from power flow in/out of the block (`condition(·)`) and updated information from the sharing rules of Meta plan 9. The main objective is to evaluate the ability of its assignee alongside each of the downstream systems to operate in islanded mode if necessary (`@metaplan16_01`,`@metaplan16_06`). For instance, let us take again the block disposition shown in Fig. 3.5 assuming without loss of generality that all blocks can operate in islanded mode, BA_1 connects with the HV system, and system capacity is the subject of the assessment. In this example, the meta plan proceeds as follows.

1. BA_1 evaluates if there is enough capacity in its block and downstream (BA_2,BA_3,BA_4) to work in islanded mode in case of the HV/MV substation is interrupted. If not, BA_1 sets its block to be tripped from the system to guarantee it will not jeopardize the chances of the downstream system to operate in islanded mode. Also, BA_1 verifies the possibility of its block to operate in islanded mode by itself.

2. BA_2 evaluates if there is enough capacity in its block and downstream (BA_3,BA_4) to work in islanded mode in case BA_1's block is interrupted. If not, BA_2 sets its block to be tripped to guarantee it will not jeopardize the chances of BA_3 and BA_4 to operate in islanded mode. Also, BA_2 verifies the possibility of its block to operate in islanded mode by itself.

3. BA_3 and BA_4 verify, individually, the possibility of their blocks to operate in islanded mode by themselves.

```
@metaplan16_01   +!support_islanded_operation :  true
  <- +support_islanded_operation; ?support_islanded_operation.

@metaplan16_06   +support_islanded_operation :  prior_conditions(C) & C == 1
  <- ..., !retrieveIslandingLoad(MW_load,Mvar_load);
    !retrieveIslandingCapacity(MW_load,Mvar_load); !verifyIslading(MW_cap,Mvar_cap).
```

The tripping schemes might be approved by the DMS and are established according to the possibilities of the LOG protection devices. Of course, in the assessment of the possibility of islanded operation, other issues are taken into consideration such as the existence of DER interfaced with synchronous machines or inverters capable of emulating a synchronous generator (e.g. voltage source converter). The rules above were implemented to exemplify how decentralization and the survivor of downstream islands can be favored (see publication 9 in appendix A for application and result analyzes). However, cases that favor upstream islandings may be enforced as well and they might be convoluted with the establishing of block priorities or the application of load shedding schemes. Moreover, we recall that only the survivor of the entire network is taken as an islanding possibility in the multi-micro grid framework. This constitutes a quite particular situation embodied by the rule 1 above, where the service interruption of the HV/MV substation is assigned and the DERs are able to supply the entire loading of the network. Conversely, this capability may embody several other interruptions and island formations where, perhaps more pragmatically, DERs may be able to supply only a portion of the feeder loading.

Observe that to secure the DG islanded operation of one or more feeder blocks, it may be necessary to constraint the power flow (e.g. using R32,R32N) at some components. Hence, inner production control or inner load shedding (e.g. using R81U,R81O) actions might be used, in case those are covered in contracts with the DERs. In fact, it is already a common practice to trip DG units if power inadvertently flows in violation to interconnection contracts. Also, load shedding schemes already exist in some industrial installations [51]. In case the design requires, the BA might be able to manage distributed energy storage devices (fixed or mobile) to assure a safe operation. Moreover, AI techniques might be useful in aiding to choose the amount of loading to be controlled/shed, a topic explored in chapter 4. Again, all these actions may ultimately impact on resetting relays and/or enabling alternative protection and control schemes.

3.3.10 Managing Outages

Outage management is an essential function to the power distribution systems. The capability *Managing Outages* was attributed to the BA to provide support to this function, as materialized in Meta plans 17–21.

Meta plan 17 allows the BA to create a fault log, starting from a signal provided by neighboring FPIs (`@metaplan17_01`,`@metaplan17_02`,`@metaplan17_04`). If the fault is cleared and the block succeeds energized, the log is saved with relevant data such as the power which was temporarily interrupted and the differences ($\Delta P, \Delta Q$) between the power flow before and after the interruption suggesting, eventually, the existence of a permanent service interruption in an inner customer. If ($\Delta P, \Delta Q$) are superior to a given threshold, the fault record is sent to the TCM/DMS informing the possibility of inner service

Meta plan 17: Fault logging

Description: Once a fault is identified, a log entry is created to track the outage management up to its end.
Context: A fault in the block, either permanent or temporary, is assigned by a FPI device.
Functionality: `outage management`.
Trigger: `+signal_fpi(·)`.
Incoming messages: -
Outgoing messages: [→DMS] Inform message.
Percept: `signal_fpi(·)`.
Action: `hmi_update(·)`.
Used data: Outage management data.
Produced data: Outage management updated data.
Procedure:
∟ - Account and save relevant information about the failure.

interruption. On the other hand, in case the fault is followed by an entire block service interruption, the fault record is similarly sent to the TCM/DMS, the fault condition is managed by further plans and the log is kept running up to the service is completely restored to its normal connection and energization status condition.

```
@metaplan17_01   +signal_fpi(Year,TimeInstant,·)
   :  not fault_log(Counter,timestamp(Year,TimeInstant),·)
   <- ..., !create_fault_log(Year,TimeInstant).

@metaplan17_02   +!create_fault_log(Year,TimeInstant) :  true
   <- +create_fault_log(Year,TimeInstant); ?create_fault_log(Year,TimeInstant).

@metaplan17_04   +create_fault_log(Year,TimeInstant) :  energized(false,·)
   <- ..., +fault_log(Counter,timestamp(Year,TimeInstant),·).
```

In case the BA believes its assignee is completely de-energized, then activities are devised to isolate the block aiming at supporting the service restoration. Hence, the Meta plan 18 handles the isolation of the network block by opening the neighboring switches (`@metaplan18_02`,`@metaplan18_03`,`@metaplan18_04`). The energization belief comes from percepts `sensor(·)`, which are associated to voltage transformer devices $[V \approx 0]$. If the isolation is well-successful, the BA marks its assignee as `isolated(true,·)` and conveys this information to the neighboring BAs. Whether the isolation procedure failures for any reason, crews are called and a report is sent to the DMS, as specified in Meta plan 12.

```
@metaplan18_02   +!isolate_itself   :  energized(false,·)
   <- ..., !open_list_switches(ListOfIDs); update_logger(·); hmi_update(·).
@metaplan18_03   +!open_list_switches([]) :  true <- true.

@metaplan18_04   +!open_list_switches([ToName|T])) : true
```

Meta plan 18: Isolate block

Description: Actions are taken to isolate the block aiming at supporting the service restoration.
Context: The block is assigned de-energized.
Functionality: `outage management`.
Trigger: `+sensor(·)`.
Incoming messages: [←BA,DMS] Inform message.
Outgoing messages: [→BA,DMS] Inform message.
Percepts: `sensor(·)`, `energized(·)`, `isolated(·)`.
Actions: `open_switch(·)`, `hmi_update(·)`.
Used data: Outage management data.
Produced data: Outage management updated data.
Procedure:

- Open neighboring switches.
if *successful* **then**
  - Mark topology status as `isolated(·)`.
  - Inform neighbors.
else
  - Proceed according to Meta plan 12.

```
<- ...  !open_switchID(ToName); !open_list_switches(T).
```

Hence, the cooperative support to fault location among BAs is attributed to Meta plan 19, which is triggered whether the fault current was sensed or the fault current was not sensed but the block is de-energized. In either of these cases, the BA establishes if its assignee was in the current path (`current_path(·)`) and conveys relevant information to neighboring BAs, such as its energization status and if the fault current crossed or not its assignee. If the block is assigned de-energized and the FPI information indicates the fault occurred in the block, then the BA assign itself as faulty `faulty(true,·)` and direct crew efforts to the block. Also, it informs the DMS and the other BAs about its `faulty(true,·)` condition using Meta plan 9.

```
@metaplan19_04  +!fault_location : fault_was_here(Res) & Res == -1
  <- ..., !sendmsg(ListNeigh,tell,fault_man(energized(false,·),faulty(false,·),
current_path(false,·));

@metaplan19_05  +!fault_location : fault_was_here(Res) & Res == 0
  <- ..., !sendmsg(ListNeigh,tell,fault_man(energized(false,·),faulty(false,·),
current_path(true,·));

@metaplan19_06  +!fault_location : fault_was_here(Res) & Res == 1
  <- ..., !sendmsg(ListNeigh,tell,fault_man(energized(true,·),faulty(false,·),
current_path(true,·));

@metaplan19_07  +!fault_location : fault_was_here(Res) & Res == 2
  <- ..., !sendmsg(ListNeigh,tell,fault_man(energized(false,·),faulty(true,·));
```

Meta plan 19: Support fault location

Description: Verify current path and convey relevant information to other BAs.
Context: Fault current was flagged by a neighboring FPI or the block is de-energized.
Functionality: `outage management`.
Trigger: `+sensor(·)`.
Incoming messages: [←BA,DMS] Inform message.
Outgoing messages: [→BA,DMS] Inform message.
Percept: `sensor(·)`.
Action: `updade_logger(·)`, `hmi_update(·)`.
Used data: Outage management data
Produced data: Outage management updated data.
Procedure:

if *FPIs assigned the fault was outside the block or the block is de-energized* **then**
- Verify if the block was in the current path or not.
- Send its statuses (`energized(·)`,`faulty(·)`,`current_path(·)`) to the neighboring BAs.

else if *FPIs assigned the fault was within the block* **then**
- Assign its assignee as faulty (`faulty(true,·)`).
- Send its statuses (`energized(false,·)`,`faulty(true,·)`,`current_path(true,·)`) to the BAs following Meta plan 9.
- Call crews and send a report to the DMS.

Once the BA believes its assignee is isolated, nonfaulty, and a neighboring block is faulty, then the BA endeavors in activities to acquire electric energy from neighboring blocks (`@metaplan20_09`), as outlined in Meta plans 20. These activities may also be called by operators and crew personnel through the goal `!requestnergy(·)` and involve initially the requesting of power from neighboring BAs. The amount of power to be requested is obtained through the saved monitoring information `(condition(·))`, the amount of disconnected generation production, and cold load pick up information (`@metaplan20_10`,`@metaplan20_11`). If the neighbor is energized and agrees with the reconnection, then the protective and control devices are reset to account for the cold load pick up and the neighboring switch is closed. Once the alternative connection is established, the BA sends updated information to the DMS and to its (old and new) neighbors. Then, the BA awaits for the re-energization of the neighbor that customarily supplies the block. Whether this re-energization is assigned, the BA reconnects to its customarily neighbor and disconnects from the alternative neighbor. This decentralized process allows the reconfiguration of the network for restoration purposes by applying the autonomy of the BAs in managing their assignees.

```
@metaplan20_09   +!acquire_energy :  isolated(·) & faulty(false,·) & ...
   <- ..., !request_energy(ListNeigh).

@metaplan20_10   +!request_energy([]) :  true <- true.

@metaplan20_11   +!request_energy([H|T]) : true
   <- ...; ?totalAmmount(Data(·)); !sendmsg(H,tell,request(Count,connection,Data(·)));
       !request_energy(T).
```

Meta plan 20: Acquire electric energy from other blocks

Description: Procedures are devised to acquire electric energy from other blocks.
Context: BA believes its assignee is isolated, nonfaulty, and a neighboring block is faulty.
Functionality: `outage management`.
Trigger: `+isolated(·)` | `+faulty(false,·)` | `+faulty(true,·)[source(BAneigh)]`.
Incoming messages: [←BA,DMS] Inform message, [←BA] Refuse, agree and failure messages (FIPA-like Request Participant).
Outgoing messages: [→BA,DMS] Inform message, [→BA] Request message (FIPA-like Request Initiator).
Percepts: `isolated(·)`, `faulty(·)`.
Actions: `change_setting(·)`, `open_switch(·)`, `close_switch(·)`, `updade_logger(·)`, `hmi_update(·)`.
Used data: Outage management data.
Produced data: Outage management updated data.
Procedure:

- Request power from neighboring blocks.
- **if** *participant agrees* **then**
  - Resetting of protective and control devices for cold load pick up.
  - Close the neighboring switch.
  - Send updated information to neighbors.
- **if** *all participants refuse* **then**
  - Resetting of protective and control devices for cold load pick up.
  - Start black start procedures (if possible) using Meta Plan 21.
- **if** *the context persists* **then**
  - Schedule a new attempt.
- Request the reconnection with the customary neighbor when its re-energization is assigned.

```
@metaplan20_12   +request(Count,connection,Data(Pload,Qload,·)))[source(BA)]
   :  energized(true,·) & Pload < Plim & Qload < Qlim & ...
   <- ...; -request(Count,connection,Data(Pload,Qload,·));
       +agreed(request(Count,connection,Data(Pload,Qload,·)));
       !sendmsg(BA,tell,agree(request(Count,connection,Data(Pload,Qload,·))));
       !close_switchID(ToName).
```

Whether the BA receives information of faulty condition from more than one block, then this meta plan becomes idle and such inconsistency is reported to the DMS, which in turn can resume the process when the inconsistency is resolved. Also, observe that an energized neighbor might not agree with the alternative connection. The motive is that connection allowances are dependent on a power limit in providing alternative supply. In our implementation, this limit is fixed as defined in a planning process, though the meta plan is general and might include further reasonings to compute variable power limits according to operation conditions. If the total request is not accepted, the BA may disconnect inner customers in case this procedure is covered by the CA subscription. If the neighbors refuse all possible alternative connections, the BA still has the possibility of starting back-start procedures whether there are available DER capacity and technology to these activities, as described in Meta plan 21, always respecting the operation adequacy and the safety of crew personnel.

Meta plan 21 encapsulates procedures to restore an individual block using its inner DER generation capacity and technology. This meta plan may be triggered by the previous meta plan or by operators

Meta plan 21: Handle black start

Description: Black start procedures are enforced in case the connection to an alternative block was not possible.
Context: Enough inner generation capacity and technology, `energized(false,·)`, `faulty(false,·)`, `isolated(true,·)`.
Functionality: `outage management`.
Trigger: Goal achievement from Meta plan 20, message from DMS.
Incoming messages: [←DMS] Inform message, [←CA] Refuse, agree and failure messages (FIPA-like Request Participant).
Outgoing messages: [→DMS] Inform message, [→CA] Request message (FIPA-like Request Initiator).
Percepts: `energized(·)`, `faulty(·)`, `isolated(·)`.
Actions: `change_setting(·)`, `open_switch(·)`, `close_switch(·)`, `call_crew(·)`, `updade_logger(·)`, `hmi_update(·)`.
Used data: Outage management data.
Produced data: Outage management updated data.
Procedure:
- Resetting of protective and control devices for cold load pick up.
- Disconnect as much customer load as possible.
- Connect storage units to smooth frequency deviations during energization.
- Start-up of DERs interfaced with synchronous generators or inverters capable of emulating synchronous generators.
- Load increase/reconnection.

and crew personnel, and may embody all the strategies developed in the context of the multi-micro grid paradigm [63, 263, 264] but focusing on the block operation. In our coding, the black start involved the resetting of protective and control devices for cold load pick up, disconnection of customer loads, connection of distributed energy storage units, start-up of DERs and load increase/reconnection.

```
@metaplan21_01   +!black_start :  true   <- +black_start; ?black_start.

@metaplan21_02   +black_start :  energized(false,·), faulty(false,·), isolated(true,·)
   <- ...; !updateRelaySettings(condition(·)); !updateControlSettings(condition(·));
       !disconnect_loads(·); !startup_DERs(·); !reconnect_loads(·).
```

At last, there is the case in which the block (or a set of them) is kept energized due to a successful islanding procedure. Once the neighboring block is ultimately energized by an utility point of supply, the BA can request the alternative connection to the neighboring BA (`@metaplan22_02`), as specified in Meta plan 22.

```
@metaplan22_02   +info(Data(utility_mode,·))[source(BAneigh)]
      :  energized(true,·) & islanded_mode(true,·)
   <- ..., !request_connection(BAneigh).
```

The reconnection between two blocks under islanded mode was not allowed in our implementation. If the alternative connection is agreed, the device R25 is authorized to unify the two blocks. None of these

Meta plan 22: Handle island reconnection

Description: In islanded mode, request and handle the connection with a block in utility mode.
Context: `energized(·)` & `islanded_mode(·)`.
Functionality: `outage management`.
Trigger: Beliefs from other meta plans.
Incoming messages: [←BA,DMS] Inform message, [←BA] Refuse, agree and failure messages (FIPA-like Request Participant).
Outgoing messages: [→BA,DMS] Inform message, [→BA] Request message (FIPA-like Request Initiator).
Percepts: `energized(·)`, `islanded_mode(·)`.
Actions: `updade_logger(·)`, `hmi_update(·)`.
Used data: Outage management data
Produced data: Outage management updated data.
Procedure:
- If pre-specified criteria is met, authorize reconnection with R25.

considerations about islanding and black start procedures were considered in the restoration processes in [211–214, 234].

3.4 Towards the Block-Oriented Agent-Based Philosophy

The previous section presented the design of the block-oriented agent-based architecture to support the power distribution system operation. Once the design matters are described, it is important to discuss the transition from a centralized management towards the decentralization achieved by the agents. Firstly, we highlight that the separation of a network in management and control blocks must follow the goals of the utility as well as practical issues regarding the availability of protective, monitoring and control devices already installed or in stock, the operational procedures, as well as the interests of the involved entities. Although this statement at first glance seems to make the idea of a block separation too case-dependent for an objective discussion, the transition path towards the block-oriented management and control paradigm comes directly from establishing priorities over goals such as those listed in the former sections. Hence, candidate systems, feeders, or zones for the block-oriented philosophy are those which demand improvements in service, either due to the interests of the utility or to the interests of the DER owners and customers. Moreover, as formerly described, power distribution feeders are usually already separated in sections for protection and control purposes. This existing separation splits the network in blocks with different degrees of reliability, establishing and positioning protection, monitoring and control devices, as well as dividing the entities affected by operational deliberations. Therefore, one natural separation of a network is given by the usage of feeder sections to define the management blocks.

As identified in section 3.1, advanced control functions must be employed in certain zones of the grid where necessity and opportunity arise. For instance, assume a power distribution feeder with high level integration of DG units. Whether DG islanded operation is of interest for the utility and/or DG unit's owners, the block abstraction can be utilized to support DG islanding and load-following in the blocks aiming at improving the utility reliability. Hence, the block separation in this case would be driven by the exploitation of the benefits that DG islanded operation can provide taking into account service and power quality constraints, therefore considering the possibility of overlapping current section division employed by sectionalize switches. Then, in a different stage, when the necessity and opportunity arise again, the management blocks can be re-organized or even further separated aiming again at improving the utility service but over a different perspective. This results in a continuous application of the abstraction using the flexibility provided by the agent design.

In order to exemplify a block separation, let us take the power distribution feeder shown in Fig. 3.6. In this figure, a MV primary power distribution feeder is illustrated emphasizing a circuit breaker and automatic recloser device at the substation bus, eight laterals indicated by capital letters from A to H, three normally closed sectionalize switches, one normally open tie switch separating an alternative supply feeder from section H, seven lateral fuses and twenty transformer fuses. Plain fuse saving operation is utilized and the sectionalize switch at lateral A was installed instead of a lateral fuse due to the high fault currents at the proximity of the substation. In case some customer calls a TCM/DMS to inform a service interruption, crew personnel is sent to the customer household/facility to investigate the causes of the interruption and, eventually, restore the service by manual switching actions. Depending upon the time to call, cause of interruption, feeder distance and availability of crew personnel, service restoration might take several hours.

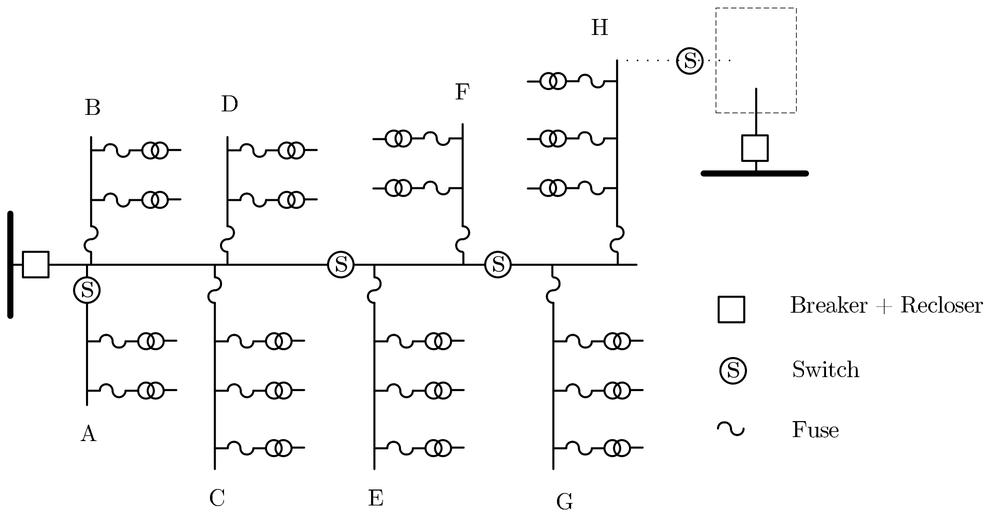


Fig. 3.6: Example of a power distribution feeder.

Assuming the interest on improving the service interruption time durations, one might integrate decentralized outage management capabilities to this system using the block-oriented philosophy. Hence, a possible block separation to this intent is exhibited in Fig. 3.7, where the feeder is segmented in three blocks grouping laterals A–D, E–F, and G–H, as well as it is upgraded with BA embedded device apparatuses, measuring devices, controllable switches and FPIs, all herein lumped at the indicated black squares. Under this arrangement, once a fault occurs at a lateral, then the associated BA may identify a significant change in its power flow exchange and proceed to informing the TCM/DMS. This might avoid long times to call caused, for instance, by interruptions of empty households/facilities. On the other hand, if the fault occurs at the feeder trunk, the restoration of some blocks might be achieved automatically using the meta plans described in section 3.3.10, diminishing considerably the interruption time durations.

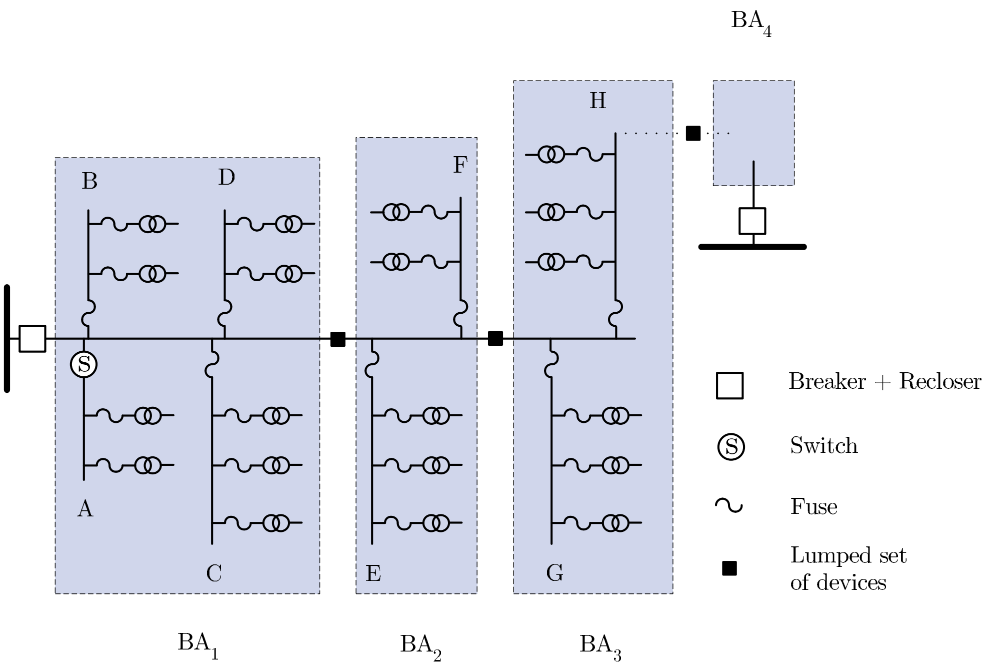


Fig. 3.7: Example of block separation of a distribution feeder for outage management purposes.

In a further stage, assume the connection of DG units in laterals B and H, named DG_B and DG_H, respectively, to the feeder exhibited in Fig. 3.7. In order to improve the service, a designer might consider reducing the reach of the recloser at the substation and the installation of another recloser mounted in the beginning of the trunk to restrict the number of disconnections of DG_B due to LOG caused by temporary faults. With the same purpose, in case temporary faults are uncommon in lateral B, a fuse clearing strategy may be established in this lateral. Similarly, solutions to avoid temporary faults across feeder aiming at reducing LOG protection actuation should be devised. Moreover, several concerns regarding resetting substation, network, and interconnection protection are of interest herein to achieve an adequate accommodation of the DG technologies.

Once the DG units are integrated, a simulation analysis may reveal that DG_B is able to supply the lateral B islanded from the utility system with high success rates of islanding and respecting the operational constraints. Similarly, it can be verified that, at some periods, the DG_H might be able to supply adequately laterals E–H, and in other periods, only laterals G–H. Therefore, the block separation illustrated in Fig. 3.8 can be established to support islanded operation and to interrelate this support with the outage management capability. In fact, using the rules described in section 3.3.9, the success rate of the islanding procedures can be improved once LOG protection might disconnect laterals E–F from laterals G–H in case the DG_B is not able to supply all customers of laterals E–H. On the other hand, if lateral B is operating in an islanded mode either achieved through direct islanding or black start procedures, it can be reconnected to a utility served block using the outage management capability described in section 3.3.10.

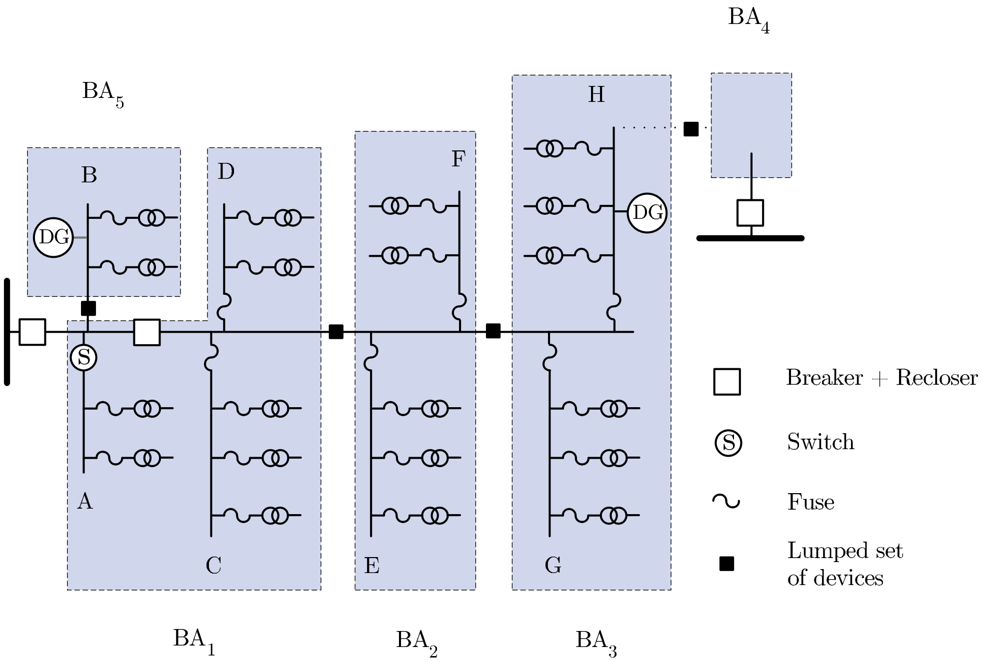


Fig. 3.8: Example of block separation of a distribution feeder for outage management and islanded operation purposes.

This example illustrates how capabilities can be enforced according to the desires of a designer. Regarding actual deployment in the field, the BAs must be embedded in device apparatuses running operation systems near the blocks' infrastructure. Similarly, CAs should be embedded in modules close to the DER's infrastructures though an interface might be provided towards the locus of the DER's representative actor. The interactions between BAs and other entities depend upon the usage and gradual modernization of the utility communication systems. Relevant information regarding these interactions must be accessible in the HMI of the BA's physical module to aid local operations performed by utility personnel (e.g. time setting update, firmware update, re-initialization). In turn, these personnel must be trained to maintain and understand the procedures deployed by the BMSs. This training is crucial to guarantee the safety of the utility staff in the field, where simple decisions such as installing visual signals to indicate "live" lines might protect the life integrity of the staff and equipment.

Observe that the BA activities can be as subjected to DMS authorizations as desired by the operators. In fact, we stress that the architecture is not designed to substitute the DMS. On the contrary, it is designed to aggregate, improve and complement the DMS functions with alternative possibilities, where the block disposition and agent capabilities vary according to the gradual modernization of the power distribution systems. Hence, agent capabilities can be deployed to support the system operation, but always having the conventional procedures in place at least in the form of contingency plans. Such argument is particularly relevant since it is unreasonable to assume that the utilities will modify their infrastructure and operational procedures consolidated throughout the years overnight. Moreover, this argument impacts on guiding the modernization of the DMS functions themselves since upper ontologies [265] are still maturing to the support of power engineering applications either in control rooms or in local sites.

Under the block-oriented philosophy, the DMS remains the greatest *maestro* of the management of the power distribution systems. However, instead of centralizing in the DMS control room the operational decisions about all geographically distributed feeders, the DMS functions should interact with widespread BMSs to improve the utility service. Following this reasoning, the modernization of the DMS should be driven by the concept of providing means of managing the power distribution systems following a higher level abstraction, where goal priorities must be emphasized in real time and ultimately affect how the BMSs should locally behave. At last, the evolution of the DMS can also benefit from agent technology through the development of ontologies to integrate applications in the control room which allows higher level analysis of the system operation, as somewhat envisioned in the projects ARCHON [225, 226] and PEDA [173, 183, 227].

3.5 Summary and Discussions

This chapter proposes a block-oriented agent-based architecture aiming at supporting the power distribution system operation. For this accomplishment, a block-oriented philosophy of management and control is developed and justified under the scope of the power distribution delivery. In the philosophy, a certain autonomy is ascribed to agent entities in order to aid the management and control of particular blocks of the power distribution systems. These agents interact and cooperate with each other to improve the utility service as a whole, decentralizing functional activities over the system operation. Hence, distributed feeder applications can be enforced providing a common ground to accommodate future protection, monitoring, and control solutions. Moreover, DER integration, improved reliability, decentralization and modernization are promoted by the architecture in alignment to the smart/modern grid paradigm, as a direct contribution to the gap highlighted in Annotation B.

The architecture has the pragmatic directive of avoiding the development of solutions to a speculated future smart/modern grid to be, as emphasized in Annotation A. Instead, solutions are devised to gradually attribute smartness to the system operation using the well-defined notions of intelligence of the agent paradigm. Indeed, the design and reach of the block-oriented agent capabilities can vary according to the interests of the utility, customers and DER owners. Such extensibility was achieved through an adequate agent design, taking into account the features of the current power distribution systems. Other features obtained through the agent design are the flexibility retrieved from the agent reactiveness and goal-oriented reasoning, as well as the improved robustness by considering the possibility of employing conventional DMS procedures, at least in the form of contingency plans. The progressive modernization through agent technology seems, arguably, more realistic than other approaches such as the multi-micro grid, where functionalities are only useful after rare events (e.g. HV link interruption) as well as depend upon great changes in infrastructure, operational procedures, and DER integration. On the other hand, a multi-micro grid might be absorbed by the architecture modeling as a very particular case, where an entire power distribution systems is represented as a unique block, DERs and micro grids are clients of the block management and control, and some hierarchical functionalities to islanded frequency control, voltage coordination and state estimation are considered.

The design and implementation of the developed approach provide an explicit representation of goal-oriented behaviors interrelated with agent planning. This aids conjugating in a common framework agent solutions built to different activities and under different contexts, as a contribution to the gap emphasized in Annotation C. The intra agent reasoning is also explicit by the application of the BDI model, which enables viewing agents as goal-directed entities that act in a rational manner. The BDI model is embodied by the JASON agent programming language and interpreter, whose syntax is used directly in the design, as a contribution to the gap mentioned in Annotation D. Moreover, it can be identified in discussing Annotation E the lack of provision of agent design matters by the power engineering academia. To avoid following this path, the architecture was devised using concepts of the agent design methodology Prometheus as well as cognitive mapping, then permitting further variations, extensions, particularizations and discussions in the future. At the best of the author's knowledge, this work marks the first application of JASON and Prometheus to the power engineering society, and they should both be exploited in the future under the great variety of power engineering problems yet to be tackled by our society.

The resulting architecture provides structured solutions to feeder applications, an area in between the systems approached in the substation level standard IEC 61850 [36] and the industrial level standard IEC 61499 [45]. Therefore, it should benefit from the ontological developments of these standards. Moreover, the agent capabilities described herein "only" illustrates how the methodological approach and the block-oriented philosophy can improve the system operation. Hence, different agent capabilities could be designed depending upon the interests of the involved entities, following that the proposed architecture opens the way to a large number of capabilities to be envisioned aiming at improving the system operation through areas such as forecasting and scheduling. Also, it drives the rethinking of how the modernization of network automation and DMS functions must evolve in the next years.

Finally, notice that all the developed solutions must ultimately be tested, verified and evaluated through environment interactions in order to be technically accepted towards their practical field implementations, a concern placed in Annotation F. Environment modeling is a fundamental matter to agent-based system, though it is mostly overlooked in the power engineering literature. An advanced environment modeling is proposed in this thesis in chapters 4 and 5.

Chapter 4

Environment Modeling: Simulating and Evaluating the Power Distribution System Operation

All the developments in the previous chapter were directed to designing a block-oriented agent-based architecture to support the power distribution system operation. However, as emphasized in Annotation F of section 2.4, the key to justify altering the system infrastructure and to promote the acceptance of agent-based solutions in power distribution engineering lies in the development of the environment model. As formerly discussed, the environment model must be able to emulate the system operation aiming at evaluating the long-term impact of the agent-based solutions according to the power distribution system performance indices. This requires unifying the representation of long-term stochastic failure/repair cycle of system components with the representation of aspects of system steady-state and dynamic behavior analysis, altogether in a simulation model. This sort of modeling is absent in the state of the art and was considered one of the main topics of the research.

Therefore, the conceptual basis and design of the environment modeling is presented in this chapter, highlighting the aspects of simulating and evaluating the power distribution system operation. Differently from the previous chapter where power distribution engineering and agent-based system issues are discussed altogether, this chapter focuses specifically on power distribution engineering matters. The next chapter then presents how the developed simulation model can be utilized to create a proper computational environment where agents can be situated and interact with each other.

This chapter is organized as follows. In section 4.1, the conceptual framework and initial remarks behind building the simulation model are devised, emphasizing the complexities and challenges brought by the current context. In section 4.2, adequacy and security evaluation concepts are discussed and adapted to power distribution system applications. In section 4.3, the proposed combine discrete-continuous simulation model is thoroughly described, emphasizing the modeling of the long-term failure/repair cycle of system components, the representation of adverse weather effects, the analyzes of steady-state and dynamic aspects, the state evaluation procedures and performance index estimation. The developed algorithm derived from the simulation model is summarized in section 4.4. At last, in section 4.5, final remarks and discussions close the chapter. The developments of this chapter are partially presented in publication 1 of Appendix A.

4.1 Conceptual Framework and Initial Remarks

Power distribution systems must deliver to the customer circuits the electrical energy received from DERs and mainly from transmission substations. This involves a wide range of activities such as system protection, system automation and control, devising of operational and system studies, expansion planning, and so forth. Fig. 4.1 outlines these activities according to their related timeframes.

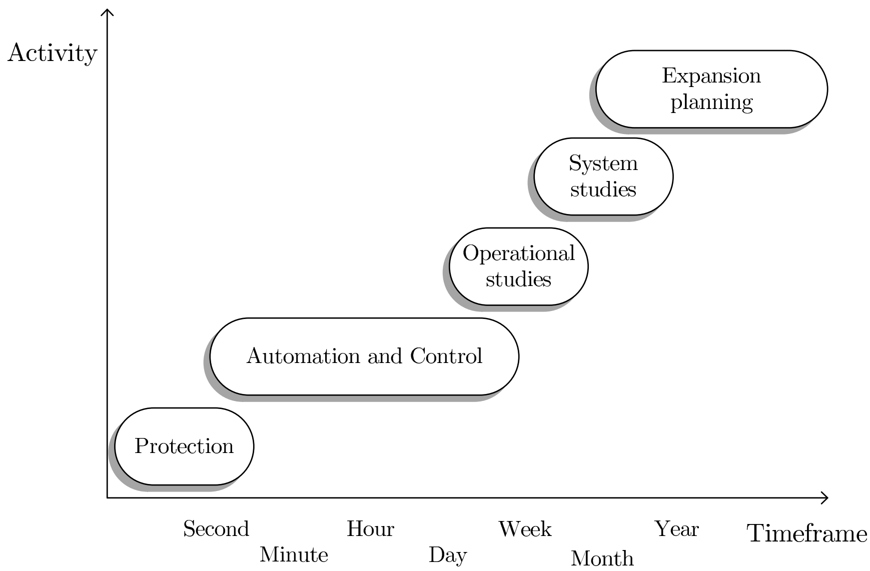


Fig. 4.1: Activities *versus* timeframe.

In the left-hand extreme of the figure, there are the protection activities which must be executed as fast as possible to assure the integrity of the utility's assets. At the other extreme of the figure, there are the planning activities which must be executed in a timely and well-thought manner to guarantee consistency with the business goals of the utility. Due to the differences in timeframe, the process analyzes of these activities involve distinct assumptions, following that modeling and data gathering efforts are directed to the main phenomena of interest in each particular timeframe. For instance, the long-term failure/repair cycle of system components might not be of great interest to operational studies, where steady-state conditions and pre-established configuration scenarios are usually assessed. On the other hand, they are determinant to evaluate the predicted reliability of the system. Conversely, the electrical parameters of the network might not be of great interest to evaluating the predicted reliability of the system. On the other hand, they are required to performing steady-state and dynamic behavior analyzes aiming at assessing system operation scenarios.

Conventionally, the analysis of service reliability and the estimation of performance indices occur in the planning processes. In this activity, either pushed by regulation or by its own's intend of providing a better service, utilities verify several alternatives to improve the service reliability such as the installation of protective devices, the increase of the level of automation and control (including the devices placed at the DG facilities), the establishment of alternative operational schemes, the establishment of different reconfiguration/restoration procedures, and so forth. At most, different network configurations are considered and performance indices are estimated using some analytical approach or, more rarely, a simulation approach. Hence, data requirements involve the failure and repair rates of components, topology and unifilar diagrams, locus of protective and control devices, and some operational rules. Once a set of alternatives is chosen, case studies are performed to assess in a more detailed way the short-term and transient effects of the alternatives in the shorter timeframe activities.

The performance assessment processes described above are typical and function adequately in the utilities. Nevertheless, the ongoing integration of DERs and the perspective of promoting the participation of DERs in the operation brought novel complexities to evaluating the system performance. One compelling example lies in designing and allowing DG islanded operation. Whether well-successful, DG islanded operational procedures can avoid the interruption of the islanded customers given the occurrence of a failure event. However, in order to evaluate the impact of these procedures in the performance indices, modeling (and data requirements) must cover all the way from year to second timeframe representations. This includes modeling not "only" the long-term failure/repair cycle of system components, but also steady-state aspects (e.g. voltage profiles and line currents) and some dynamic behavior aspects to assess the response of DERs to frequency and voltage variations. Clearly, other compelling examples can be found where operational procedures might be improved by DER integration but the evaluation of such improvements imposes challenges in modeling and data requirement. About this matter, we can quote the applications of DERs to black-start procedures and to increasing the load transfer capabilities during restoration (see publication 2 in Appendix A).

Therefore, to evaluate the impact of the integration of DERs in the operational procedures, modeling demands unifying the quoted representations allowing a distinct form of performance evaluation where the phenomena of interest are considered altogether in a wider timeframe. The unification of timeframe representations is even more required to assess agent-based operational solutions, where the resulting combination of interactions is non-conventional, decentralized, and sometimes difficult to foresee. To our purposes, the challenge lies in designing a simulation model where the long-term effects of the failure/repair cycle of system components are represented alongside aspects of steady-state and dynamic behavior analysis. However, before going through such designing blindly, the complexities of this context require revisiting the concepts behind evaluating the system service of power distribution systems.

4.2 Integrated Adequacy and Security Evaluation of Power Distribution Systems

A power system is deemed adequate according to its ability to meet the demand regarding operational constraints, and taking into account planned and unplanned component outages (adapted from [29]).

On the other hand, a power system is deemed secure according to its ability to withstand disturbances, taking into account the operational constraints. Power systems are designed to provide an adequate and secure service. Hence, protection and control must guarantee service adequacy under normal operation conditions. In case of disturbances, protection and control must stabilize the system and minimize the impact of the disturbance.

Adequacy and security concerns are interdependent and part of the same problem. However, power engineers often decouple adequacy and security aspects to facilitate the power system analysis. The main implication of this decoupling is to adopt certain assumptions in what, for instance, system steady-state and/or dynamic issues would not affect the adequacy performance. This is the case of bulk power system generation adequacy evaluation, where only the generation capacity to serve the total load is taken into consideration. In power distribution systems, where the presence of DERs was limited in the past, similar assumptions are applied to adequacy studies and they are generally considered sufficient to characterize the system service. Nevertheless, when the number of DERs connected to the system increases, aspects related to system steady-state and dynamics might be of great importance to evaluate the predicted service of a power distribution system.

Essentially, the principles of evaluating the service adequacy of power distribution systems are marked by the absence of the integration of DERs in the operational procedures aligned to the weakly meshed structure and radial operation assumptions. These hypotheses allow the abstract understanding of the network as a set of series components (e.g. lines, cables, transformers) where the fundamentals of series systems [5] can be applied to characterize a well-successful service. The fundamentals of series systems define that *system elements are said to be in series from the reliability point of view if they must all be operating for system success or only one needs to fail for system failure*. Such concept provides the basis of the analytical approaches to compute the service adequacy, in which the failure rate and unavailability of each point of connection are computed based on the failure rate and unavailability of the components. Using this information, the system-wide performance indices are straightforwardly computed through (2.4)–(2.10) in section 2.2.5. Also, even the simulation models utilize the same principles, in the sense that service interruptions are accounted by sampling different system states where a set of components might be operating or not.

Note that these principles are quite practical to assessing conventional power distribution systems. Assuming a worst-case loading scenario, if the steady-state node voltage profiles and component currents are considered acceptable, the service reliability at the points of connection can be estimated using the fundamentals of series systems and alternatives can be built to support decision-making on system expansions and/or improvements. However, this decoupling of service reliability analysis with other analyzes is not completely possible when DERs are integrated in the operational procedures. For instance, let us take again the example of allowing DG islanded operation. The successful rate of DG islanding procedures depends considerably upon features of the operation conditions which can be only obtained through steady-state and dynamic behavior analyzes. Nevertheless, all these features are neglected in the conventional principle of evaluating the service adequacy of power distribution systems. This illustrates that, to the purposes of evaluating the predicted service adequacy, the principals of series systems might be insufficient to assess the long-term impact of the solutions, either based on agency or not, which depend upon steady-state and dynamic behavior information about the operation conditions.

On the other hand, most of the principles commonly used to bulk generation and transmission system evaluation cannot be applied directly to power distribution system assessment. Although the system covered by a power distribution utility can be abstracted as a power system in sensu stricto, the proximity to the end customer connections leans the evaluation much closer to local/punctual customer service assessments rather than the abstractive conceptualization of operation state classifications. Local customer service information can be further aggregated to provide systemic knowledge on the system service, as provided by the system-wide performance indices.

Nevertheless, concepts from service adequacy and security can provide important information regarding the assessment of power distribution systems, mainly with the increasing concerns about quality of service, the promotion of smart/modern grid concepts and the ongoing integration of DERs. As a matter of fact, from the pure definition of adequacy, the service continuity must be evaluated along with operation constraints, which at the level of the customer connection may involve any aspect of the voltage waveform. This principle unifies the evaluation with the modern notions of power quality [34] in which all the phenomena related to local voltage waveform (e.g. interruptions, spikes, noises, flickers, sags, swells, undervoltages/overvoltages, harmonic distortion, frequency variation, etc.) are subjects of matter. Similarly, from the pure definition of security, the system service must be evaluated according to its ability to withstand disturbances, which in turn requires that dynamic behavior aspects are considered to assess the effects of operational decisions as well as protective and control actions. Clearly, DERs can improve and/or jeopardize system operation over several dimensions. By means of evaluation methodologies which consider well-defined service adequacy and security aspects, the actual impact of DER integration and modern operational solutions on the system operation can be properly assessed.

Following this reasoning, we classify the service at the customer point of connection as *adequate* according to the voltage waveform at the point of connection, taking into account planned and unplanned component outages. By extension, any system composed of adequately served customer points of connection would provide an adequate service. If the voltage waveform is nonexistent, the point of connection is not energized featuring a service interruption. On the other hand, the service at the point of connection is classified as *secure* according with its ability to withstand a given set of disturbances. Analogously, any (sub-)system composed of securely served points of connection would provide a secure service.

The following definitions can be derived from the discussions above.

1. Power distribution system adequacy evaluation (classical): assessing the ability of the system to provide a continuous service in terms of interruptions in its points of connection.

2. Power distribution system adequacy evaluation (alternative): assessing the ability of the system to provide an adequate service in terms of voltage waveform in its points of connection, taking into account planned and unplanned component outages.

3. Power distribution system security evaluation: assessing the ability of the system to operate under stable conditions given a set of disturbances.

From these suggested definitions, power distribution system adequacy evaluation (alternative) covers the standard reliability assessments where failure rates, average annual outage times, and average outage durations are estimated for the points of connection. In addition, this evaluation also deals with voltage waveform aspects when the customer points of connection are energized. Finally, the power distribution system security evaluation covers topics such as system frequency and voltage stability.

Clearly, the definitions above were conceived to be general over the scope of power distribution engineering. Of course, only the aspects of interest were approached in our developments. For sure, the current context requires evaluation models which deal with adequacy and security aspects in an integrated way. On the other hand, for efficiency purposes, modeling must be restricted to the phenomena of interest and feasibility of the simulation as a whole. The proposed combined discrete-continuous simulation model focuses on customer interruption evaluations, undervoltage/overvoltage steady-state aspects through alternate current (AC) power flow computations, as well as DG islanding frequency stability evaluations through dynamic simulation, involving year to second timeframe representations. Fast transient representations were considered out of the scope of the work.

4.3 Combined Discrete-Continuous Simulation Model

Simulation models can be categorized as discrete-event, continuous-time, or the combination of both. A pure discrete-event simulation model concerns the representation of a system by scheduling and/or sampling a sequence of events, which are assigned to specific time instants making possible discrete state transitions. The sequential Monte Carlo simulation approaches cope with this definition, where the operating cycles of the system components are combined to compose operation/system states, which in turn are subjected to evaluation. Conversely, in a pure continuous-time simulation model, state transitions are never abrupt but continually evolve over time. Typically, continuous simulation models involve differential equations to represent continuous state variables. Power system dynamic simulation usually applies this concept by solving a set of differential equations through numerical integration, although some event scheduling is common in terms of, for instance, machine setpoint changes, switch opening/closing, relay based protective/control actions, etc. A combined discrete-continuous simulation model [266] utilizes both discrete-event and continuous-time representations. The challenge in developing such a model is to couple these representations in a unique simulation process.

The complexity of modeling the power distribution system operation naturally leads to a combined discrete-continuous simulation approach. In fact, the three fundamental types of interaction between discretely changing and continuously changing state variables are inherent to a detailed modeling of the system operation.

1. A discrete event may cause a discrete change in the value of a continuous state variable (e.g. a component transition to the failure state may cause breaker actions, which in turn may lead to a sudden change in a node voltage).

2. A discrete event may cause the relationship governing a continuous state variable to change at a particular time instant (e.g. a DG transition to the failure state may cause the abrupt uncoupling between the DG continuous state variables and the remaining system state variables).

3. A continuous state variable achieving a threshold value may cause a discrete event to occur or to be scheduled (e.g. underfrequency relay based load shedding).

The interactions above influence the simulation modeling and how the system states must be composed and evaluated. Indeed, since the transition from a current system state to the next system state is dependent on the evaluation of the current system state, sequential Monte Carlo procedures of generating subsequent system states covering a year of operation followed by their post-evaluation are not possible. This leads to a coupling between state composition and state evaluation introducing complexities to the simulation modeling, namely in the application of parallel computation to distribute simulation tasks. Furthermore, these interactions require handling, in the state composition, events that were established or scheduled during state evaluation.

Therefore, the proposed approach employs a combined discrete-continuous simulation model in which system states are evaluated as long as they are obtained. Similarly to the sequential Monte Carlo simulation, the failure/repair cycles of the system components are merged with a load state representation to create a synthetic operating cycle of system states. However, additional transitions are considered involving the interactions enumerated in this section altogether. Discrete and continuous state variables are then updated over time and the evaluations provide means of accounting and measuring phenomena of interest to performance evaluation.

The simulation procedure tracks its clock using the *next-event time advance* mechanism. This design implicates that a simulation clock is initialized to zero and the time instant of the next state transition event of each system element is either sampled (if it follows a stochastic modeling) or determined (if it follows a deterministic modeling). The clock is then advanced to the time instant of the most imminent (first) of these events, at which a system state is characterized and evaluated. As formerly stated, this evaluation might result in triggering or scheduling other events. At last, the imminent event triggers the state transition of its associated element followed by an update of the time instant of its next state transition event. The process continues until the convergence of performance index estimates. The resultant sequence of system states creates a synthetic operating cycle which is illustrated in Fig. 4.2.

In the left-hand side of the figure, the operating cycles of a system component, DG and customer load are illustrated. In the example, the component and DG begin the snapshot of the operating cycle in the *up state*, meaning they are operating[4.1]. On the other hand, the customer load begins its demand requirement at a value closer to the unit. At this point (t_i), the time instants of the next state transition events of these elements (i.e. component, DG, customer load) were already either sampled or determined. Then, the clock steps forward to the time instant of the most imminent event (t_{i+1}), which in the example refers to the failure of the DG. As consequence, a system state is characterized in $[t_i, t_{i+1})$ and the evaluation of this state might cause the triggering or scheduling of other events (e.g. switch openning/closing, relay action). After the state evaluation, the DG transit to the *down state*, meaning it will be under failure in

[4.1]Due to the mix of power engineering disciplines enforced by the proposed modeling, the term *state* is utilized under several circumstances to model the power distribution system operation. To avoid misconceptions, let us clarify that the system elements might have discrete states to represent their failure/repair cycle (e.g. up state, down state). Also, they might have discrete states to model their operational status (e.g. on, off, open, close). As it will be described later on, DG units and customer loads may have several discrete states regarding their possible production and demand values, respectively. On the other hand, each element may have associated continuous state variables (e.g. voltage, frequency) which advance with time alongside the discrete variables, either at the state composition or state evaluation. The term *system state* herein means the entire set of constant features composed at the end of a given interval, including externalities such as the weather effects. As consequence, there may be also several inner systemic states related to the continuous state variables which evolve, in our approach, through numerical (time) integration. All the described variables are updated when necessary to create a consistent evolution of states with time. The next sections will clarify the modeling of these variable in the developed approach.

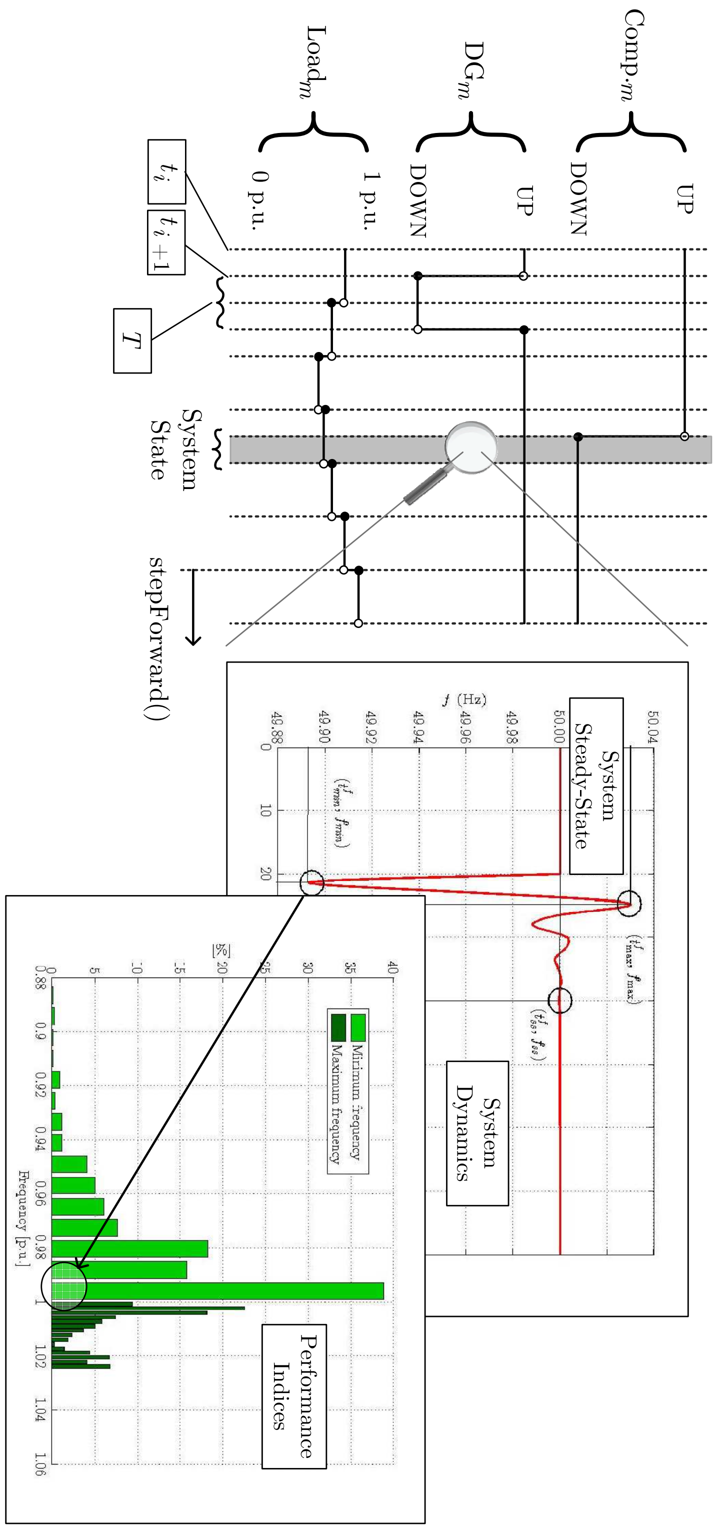


Fig. 4.2: Operating cycle in the combined discrete-continuous simulation approach.

the next system state. The duration (T) of the down state of the DG is sampled and the time instant in which the DG will come back to the up state is computed ($t_{i+1} + T$). This completes a step of the system operating cycle produced by the approach.

Note that a system state is evaluated in each step of the operating cycle. In turn, this evaluation might require several sorts of analyzes depending on the phenomena under assessment. In the discussed example, it might be of interest to quantify how undervoltage/overvoltage events are associated to the DG failure/repair cycles. For this accomplishment, a fast and robust power flow processor must be utilized, in order to verify the system voltage profiles, eventually for all chronological system states. Actually, the impact of DER integration on system voltage profiles is a major topic usually approached only through scenarios specifications. The simulation model provides means to verify the impact of DER integration on the voltage profiles respecting the chronological sense of the operation and allowing the consistent development of time-based (e.g. yearly, monthly) performance index estimates.

Similarly, it might be of interest to feature the system customer interruption frequencies and durations. About this matter, let us take the failure of a series component placed in the trunk of a feeder. This event might ultimately cause breaker actions which in turn would de-energized the feeder and interrupt the service. Since fast transients are not under consideration, a rule engine can be utilized to address the protection coordination modeling and a topology processor may be applied to differentiate nodes regarding their electrical islands. If an electrical island is computed de-energized, all its customer are interrupted and the individual occurrences and durations of these interruptions must be accounted. At last, whether the failure of the series components cause a DG islanding, additionally to the rule engine, topology and power flow processors, a dynamic behavior simulation is required to verify whether (and under which circumstances) the DG islanding process occurs. This can provide useful information related to frequency and duration of DG islanding processes, besides allowing gathering data from the islanding processes themselves. As an illustrative instance, in the right-hand side of Fig. 4.2, the DG islanding process in a state evaluation is highlighted, where the minimum and maximum electrical frequencies are stored to further provide estimated information about the DG islanding processes.

All these analyzes allow evaluating aspects from service adequacy and security of the power distribution systems in an integrated manner. Moreover, they provide consistent information regarding how the system behaves, building means of accounting and measuring phenomena of interest. The next sections presents details of the modeling and evaluation stages in our simulation model.

4.3.1 Stochastic and Deterministic Modeling

DG units may be represented according with their failure/repair stochastic cycle, as well as their generation power regarding the availability of natural resources, such as water inflows, wind speed, solar irradiations, and so forth. In our approach, the two-state Markov model [267] was used to represent the stochastic cycle of network components and DG units. Network component and DG state residence times are assumed to be exponentially distributed, and are sampled using the equations below [268].

$$T^{up} \leftarrow -\frac{1}{\lambda} \ln U \tag{4.1}$$

$$T^{down} \leftarrow -\frac{1}{\mu} \ln U \tag{4.2}$$

where T^{up} is the residence time of the component/unit in the up state, T^{down} is the residence time of the component/unit in the down state, λ is the failure rate of the component/unit, μ is the repair rate of the component/unit, and U is a uniformly distributed random number which is sampled at $[0, 1]$.

Load patterns can also be modeled by aggregated and/or multi-level non-aggregated Markov models, as shown in [73]. Nevertheless, since a combined discrete-continuous simulation approach which follows chronology has been adopted, a deterministic load model consisting on 8760 peak load percentage levels [269] was utilized, each associated to one hour of the year. These percentage levels are then applied to the customer loads during simulation following a chronological order, though the model implementation is also prepared to consider customer loads with different load percentage levels. Since the development of stochastic models for generation productions was considered out of the scope of this work, a similar approach is utilized to determine generation productions.

Regarding resolution, it is important to emphasize that the frequency of updates of load patterns or generation productions can be chosen as greater as of interest. However, the smaller the resolution the greater the number of transitions to be assessed in a synthetic year of operation. Also, these updates might depend on the sort of evaluation under consideration. For instance, if only service interruption indices are subjected to evaluation, these updates are only necessary when the interruptions are assigned, in order to account consistently the energy not supplied by the utility. Moreover, all these patterns refer to steady-state conditions for adequacy evaluations. When security aspects are included, generation productions and customer loads may react in a responsive manner to frequency and voltage variations.

4.3.2 Adverse Weather Representation

Although the number of simulation approaches which represent chronology alongside adverse weather modeling is still limited in the literature, it is undeniable that weather effects have major influence on the power distribution delivery, mainly when the infrastructure relies on overhead lines. The developed approach employs a model for adverse weather characterized by high wind speeds over the stochastic representation of the system components. Despite an improved adherence to the actual operation, this modeling allows representing operational solutions specifically designed to adverse weather conditions. The fundamentals of this model were introduced in [270, 271], so that the reader might recur to these references for basic information. In this section, only the concepts withdrawn/adapted to our approach and the developed variations are presented. Also, mathematical formulations and algorithmic details not covered in the quoted references are outlined for the sake of completeness.

Adverse weather conditions are generally more common during certain seasons making the failures caused by weather not uniformly distributed over the year. As consequence, the failure/repair cycle of a set of components considerably affected by weather effects may not be accurately modeled by the two-state Markov model from the previous section. However, in case the components are deemed affected by adverse weather and weather data is provided, the transition rates in (4.1) and (4.2) can be dynamically updated to account for adverse weather conditions. For this accomplishment, a time-dependent failure rate can be written as follows.

$$\lambda(w(t)) = \lambda_a(w(t)) + \lambda_n(w(t)) \tag{4.3}$$

where $w(t)$ is the wind speed at time instant t, $\lambda_a(w(t))$ denotes the failure rate during adverse weather (high wind speed) and $\lambda_n(w(t))$ is the failure rate during normal weather conditions. These two failure rates can be defined with the expressions below.

$$\lambda_a(w(t)) = \begin{cases} \lambda_{wind}(w(t)) & \text{if } w(t) \geq w_{crit} \\ 0 & \text{otherwise} \end{cases} \tag{4.4}$$

$$\lambda_n(w(t)) = \begin{cases} \lambda_{norm} & \text{if } w(t) < w_{crit} \\ 0 & \text{otherwise} \end{cases} \tag{4.5}$$

where w_{crit} is the critical wind speed from which the failure rate of the component is increased and λ_{norm} is the constant failure rate during normal weather conditions.

Now, let $\mathcal{T}_{tot}$ be a time period of analysis where utility service and weather data are provided. Note that, by using (4.4) and (4.5), the mean value of $\lambda(w(t))$ at the end of the time period can be computed as follows.

$$E\left(\lambda(w(t))\right) = \frac{\mathcal{T}_a}{\mathcal{T}_{tot}} E(\lambda_{wind}(w(t))) + \frac{\mathcal{T}_n}{\mathcal{T}_{tot}} \lambda_{norm} \tag{4.6}$$

where $\mathcal{T}_a$ denotes the total duration in adverse weather condition and $\mathcal{T}_n$ represents the total duration in normal weather condition. If we consider F_a and F_n the proportion of failures occurring in adverse and normal weather conditions, respectively, and assuming the time durations in the failure state are negligible in comparison with the time durations in the operating state, by definition we have

$$\frac{\mathcal{T}_a}{\mathcal{T}_{tot}} E(\lambda_{wind}(w(t))) = \frac{\mathcal{T}_a}{\mathcal{T}_{tot}} \left(\frac{n_a^f}{\mathcal{T}_a^{up}}\right) \approx \frac{\mathcal{T}_a^{up}}{\mathcal{T}_{tot}^{up}} \left(\frac{n_a^f}{\mathcal{T}_a^{up}}\right) = \frac{n_a^f}{n_{tot}^f} \left(\frac{n_{tot}^f}{\mathcal{T}_{tot}^{up}}\right) = F_a E(\lambda(w(t))) \tag{4.7}$$

$$\frac{\mathcal{T}_n}{\mathcal{T}_{tot}} \lambda_{norm} = \frac{\mathcal{T}_n}{\mathcal{T}_{tot}} \left(\frac{n_n^f}{\mathcal{T}_n^{up}}\right) \approx \frac{\mathcal{T}_n^{up}}{\mathcal{T}_{tot}^{up}} \left(\frac{n_n^f}{\mathcal{T}_n^{up}}\right) = \frac{n_n^f}{n_{tot}^f} \left(\frac{n_{tot}^f}{\mathcal{T}_{tot}^{up}}\right) = F_n E(\lambda(w(t))) \tag{4.8}$$

where n^f denotes the number of failures; the subscripts $(\cdot)_a$,$(\cdot)_n$ and$(\cdot)_{tot}$ mean adverse weather, normal weather and both weather conditions, respectively; and the superscript $(\cdot)^{up}$ points out the variable refers to the up state[4.2].

Power distribution utilities usually keep records of the failures per year and their association with weather effects, thereby F_a, F_n, $E(\lambda(w(t)))$ can be estimated from statistics. Similarly, $\mathcal{T}_a$ and $\mathcal{T}_n$ can be retrieved from weather data so that (4.7) and (4.8) can be used to estimate the values of $E(\lambda_{wind}(w(t)))$ and λ_{norm}, respectively. On the other hand, the failure rate during high wind speeds can be modeled as

[4.2] The approximations shown in (4.7) and (4.8) mark one of the conceptual differences between the employed formulation and the formulation in [270, 271]. The latter considers these expressions are equalities, overlooking the assumption that the time durations in the failure state are negligible. Other difference lies on the definitions of the time periods $\mathcal{T}_a$ and $\mathcal{T}_n$, which are considered average values in [270, 271] and absolute values herein.

a function of the wind speed as follows [270, 271].

$$\lambda_{wind}(w(t)) = \left(1 + \alpha\left(\frac{w(t)^2}{w_{crit}^2} - 1\right)\right)\lambda_{norm} \tag{4.9}$$

with average value

$$E(\lambda_{wind}(w(t))) = \left(1 + \alpha\left(\frac{E[w(t)^2 \mid w(t) \geq w_{crit}]}{w_{crit}^2} - 1\right)\right)\lambda_{norm} \tag{4.10}$$

and allowing (4.4) to be rewritten as below

$$\lambda_a(w(t)) = \begin{cases} \left(1 + \alpha\left(\frac{w(t)^2}{w_{crit}^2} - 1\right)\right)\lambda_{norm} & \text{if } w(t) \geq w_{crit} \\ 0 & \text{otherwise} \end{cases} \tag{4.11}$$

in which α is a scaling parameter retrieved from (4.10) once $E[w(t)^2 \mid w(t) \geq w_{crit}]$ can be estimated through statistics, similarly to the $E(\lambda_{wind}(w(t)))$ and λ_{norm} values.

Therefore, once an adverse weather condition is assigned $(w(t) \geq w_{crit})$ at a given instant t, the resident time in the up state can be sampled rewriting (4.1) as

$$T_a^{up} \leftarrow -\frac{1}{\lambda_a(w(t))}\ln U \qquad \text{if } w(t) \geq w_{crit} \tag{4.12}$$

and conversely, under normal weather conditions, (4.1) can be re-written as

$$T_n^{up} \leftarrow -\frac{1}{\lambda_{norm}}\ln U \qquad \text{if } w(t) < w_{crit} \tag{4.13}$$

where T_a^{up} and T_n^{up} denote the resident time in the up state in adverse and normal weather conditions, respectively.

Note that the characterization of adverse weather condition cycles demands, to our purposes, sampling the occurrence, intensity and duration of high wind speeds. High wind speed intensity variations $(\Delta w^2(t) = w(t)^2 - w_{crit}^2(t))$ and durations (T_w) can be modeled through Weibull distributions as shown in [270, 271], as well as estimated through statistics. Hence, they can be sampled using the expressions below [272].

$$T_w \leftarrow (-scp_{T_w}\ln U)^{\frac{1}{\text{shp}_{T_w}}} \tag{4.14}$$

$$\Delta w^2 \leftarrow (-scp_{\Delta w^2}\ln U)^{\frac{1}{\text{shp}_{\Delta w^2}}} \tag{4.15}$$

where scp_{T_w} and $scp_{\Delta w^2}$ are the scale parameters of the Weibull distribution for the high wind intensity variations and durations, respectively; shp_{T_w} and $shp_{\Delta w^2}$ are the shape parameters of the Weibull distribution for the high wind speed intensity variations and durations, respectively.

Regarding the occurrences of high wind speeds, we stress that high wind events varies from year to year, and they are usually more likely to occur during specific periods of each year. Therefore, the rate of occurrence of high wind events cannot be accurately estimated by a constant rate value over the year duration. Nevertheless, it is fair to assume that, to our purposes, there are not simultaneous occurrences of high wind events and the number of occurrences counted in disjoint intervals are independent from each other. Under these hypotheses, the counting of high wind events in a given time interval can be modeled by a Poisson process. Once the rate of occurrence varies with time within the year, the resultant process consists of a non-homogeneous Poisson process [68] over a year of operation. Hence, from the weather data, annual wind speeds can be split in $\mathcal{Q}$ time periods $[t^-_{\nu_k}, t^+_{\nu_k})$ of interest (e.g. months, trimesters) and the rate of occurrence of high wind speeds $\nu_k(t)$ can be estimated for each of these time periods, $\forall k = 1, \dots, \mathcal{Q}$. The union of these rates of occurrence composes a piecewise time-dependent function as shown below.

$$\nu(t) = \begin{cases} \nu_1(t) & \text{if } t \in [t^-_{\nu_1}, t^+_{\nu_1}) \\ \vdots & \vdots \\ \nu_k(t) & \text{if } t \in [t^-_{\nu_k}, t^+_{\nu_k}) \\ \vdots & \vdots \\ \nu_{\mathcal{T}}(t) & \text{if } t \in [t^-_{\nu_{\mathcal{T}}}, t^+_{\nu_{\mathcal{T}}}) \end{cases} \tag{4.16}$$

Once $\nu(t)$ is provided, the composed sampling algorithm for adverse weather can be established as presented in pseudocode 1.

$\nu_{max} \leftarrow \max \nu(t), \forall t \in [0, 8760)$ h; `// Initialize maximum rate of occurrence of adverse weather`
$t \leftarrow t_{init}$; `// Initialize time instant of the sampling`
$i \leftarrow 0$;
while $t < 8760$ **do**
  $U_1 \leftarrow U(0,1)$; `// Sample uniformly distributed random number`
  $U_2 \leftarrow U(0,1)$; `// Sample uniformly distributed random number`
  $t \leftarrow t - \frac{1}{\nu_{max}} \ln U_1$; `// Advance with time`
  if $U_2 \leq \nu(t)/\nu_{max}$ **then**
    $U_3 \leftarrow U(0,1)$; `// Sample uniformly distributed random number`
    $U_4 \leftarrow U(0,1)$; `// Sample uniformly distributed random number`
    $T_w \leftarrow (-scp_{T_w} \ln U_3)^{\frac{1}{\mathrm{shp}_{T_w}}}$; `// Sample high wind speed duration`
    $\Delta w^2 \leftarrow (-scp_{\Delta w^2} \ln U_4)^{\frac{1}{\mathrm{shp}_{\Delta w^2}}}$; `// Sample high wind speed intensity variation`
    $\mathcal{TA}(i) \leftarrow t$; `// Save time instant of the adverse weather event`
    $\mathcal{DA}(i) \leftarrow T_w$; `// Save duration of the adverse weather event`
    $\mathcal{IA}(i) \leftarrow \Delta w^2$; `// Save intensity variation of the adverse weather event`
    $i \leftarrow i + 1$;
$t_{init} \leftarrow t$; // Observe that the last elements of $\mathcal{TA}$, $\mathcal{DA}$ and $\mathcal{IA}$ refer to an event for the next year.

Pseudocode 1: Adverse weather sampling using a non-homogeneous Poisson process model.

At last, regarding the repair time durations, we assume that overhead components are not repaired during high wind speed conditions for crew safety reasons. Therefore, in adverse weather conditions, the resident time in the failure state is sampled using (4.2) but starting from the instant the adverse weather is finished, resulting in the expressions below.

$$T_a^{down} \leftarrow -\frac{1}{\mu}\ln U + \mathfrak{T} \qquad \text{if } w(t) \geq w_{crit} \tag{4.17}$$

$$T_n^{down} \leftarrow -\frac{1}{\mu}\ln U \qquad \text{if } w(t) < w_{crit} \tag{4.18}$$

where $\mathfrak{T}$ is the remaining duration of the adverse weather condition, T_a^{down} represent the resident time in the down state in adverse weather conditions, and T_n^{down} denote the resident time in the down state in normal weather conditions.

4.3.3 Electric Steady-State and Dynamic Modeling

Even in recent publications, the segmentation of timeframe representations to system analysis purposes is promoted using as justification the processing time and digital storage constraints of computer technologies [273]. However, our research goes in the opposite direction by showing that the current computer technologies are fairly able to support some unifications of timeframe representations aiming a more accurate modeling and evaluation of the power distribution systems. For this accomplishment, the modeling of the long-term stochastic failure/repair cycle of system elements was established as described in sections 4.3.1 and 4.3.2. The failure/repair cycles originate system states which can be associated to electric steady-states and, eventually, to some dynamic behavior. Hence, the characterization of the electric steady-state and dynamic behavior of system states is performed in a state evaluation process, as shown in section 4.3.4, where further state transitions may be assigned and/or scheduled. The state evaluation allows updating discrete and continuous state variables to create a consistent operating cycle of system states. Therefore, in this section, the electric steady-state and dynamic modeling of our approach are presented alongside details about DER dynamic and load shedding representations.

Summarily, the power system conditions can be described by a set of differential equations $\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x})$, algebraic equations $\mathbf{g}(\mathbf{x}) = \mathbf{0}$ and algebraic inequations $\mathbf{h}(\mathbf{x}) \leq \mathbf{0}$, as introduced in section 2.2.1. These equations and inequations represent the dynamic models of generators and loads (including the prime movers, control loops, rotational inertia equation, excitation systems, etc.), as well as the network model. In our formulation, the HV systems are modeled by infinite nodes with constant voltage and frequency, while network components are represented by their equivalent $\pi-$models. For steady-state analysis, the load demands and DG unit's productions are modeled using constant complex powers $S_l = P_l + jQ_l$ and $S_g = P_g + jQ_g$, respectively. The power flow method applied to steady-state analysis was the forward-backward sweep method presented in [274] merged with the efficient improvements and convergence verifications developed in [275].

In case dynamic simulation is required, as common practice in power system dynamic analysis, network component transients as well as stator transients of synchronous and induction machines are neglected. Additionally, loads are represented by their equivalent admittance ($y_l = S_l^*/\|V_l\|^2$) which is computed using the steady-state voltage V_l at the connection node. These load admittances are then added to the main diagonal of the network admittance matrix to create the network model

$$\begin{bmatrix} \mathbf{I_g} \\ \mathbf{\Delta I_r} \end{bmatrix} = \begin{bmatrix} \mathbf{Y_{gg}} & \mathbf{Y_{gr}} \\ \mathbf{Y_{rg}} & \mathbf{Y_{rr}} \end{bmatrix} \begin{bmatrix} \mathbf{V_g} \\ \mathbf{V_r} \end{bmatrix} \tag{4.19}$$

where $\mathbf{I_g}$ denotes a vector of injected currents at the generation nodes; $\mathbf{\Delta I_r}$ represents a vector of variations in the injected currents at the other nodes; $\mathbf{V_g}$ and $\mathbf{V_r}$ are vectors of voltages associated with generation and other nodes, respectively; as well as $\mathbf{Y_{gg}}$, $\mathbf{Y_{gr}}$, $\mathbf{Y_{rg}}$, and $\mathbf{Y_{rr}}$ are network admittance sub-matrices associating nodes with each other.

By manipulating the matrix equation in (4.19) we have

$$\mathbf{I_g} = \underbrace{\left(\mathbf{Y_{gg}} - \mathbf{Y_{gr}}\mathbf{Y_{rr}^{-1}}\mathbf{Y_{rg}}\right)}_{\mathbf{Y_h}} \mathbf{V_g} + \underbrace{\mathbf{Y_{gr}}\mathbf{Y_{rr}^{-1}}}_{\mathbf{K_h}} \mathbf{\Delta I_r} \tag{4.20}$$

Note now that (4.20) can be represented in the dq system reference frame as follows.

$$\mathbf{I_g^{dq}} = \mathbf{Y_h^{dq}}\mathbf{V_g^{dq}} + \mathbf{K_h^{dq}}\mathbf{\Delta I_r^{dq}} \tag{4.21}$$

where

$$\mathbf{I_g^{dq}} = \left[\Re\{\mathbf{I_g}\}_1, \Im\{\mathbf{I_g}\}_1, \ldots, \Re\{\mathbf{I_g}\}_{n_g}, \Im\{\mathbf{I_g}\}_{n_g}\right]^T \tag{4.22}$$

$$\mathbf{V_g^{dq}} = \left[\Re\{\mathbf{I_g}\}_1, \Im\{\mathbf{I_g}\}_1, \ldots, \Re\{\mathbf{I_g}\}_{n_g}, \Im\{\mathbf{I_g}\}_{n_g}\right]^T \tag{4.23}$$

$$\mathbf{\Delta I_r^{dq}} = \left[\Re\{\mathbf{\Delta I_r}\}_1, \Im\{\mathbf{\Delta I_r}\}_1, \ldots, \Re\{\mathbf{\Delta I_r}\}_{n_o}, \Im\{\mathbf{\Delta I_r}\}_{n_o}\right]^T \tag{4.24}$$

$$\mathbf{Y_h^{dq}} = \begin{bmatrix} \{\mathbf{G_h}\}_{11} & -\{\mathbf{B_h}\}_{11} & \cdots & \{\mathbf{G_h}\}_{1n_g} & -\{\mathbf{B_h}\}_{1n_g} \\ \{\mathbf{B_h}\}_{11} & \{\mathbf{G_h}\}_{11} & \cdots & \{\mathbf{B_h}\}_{1n_g} & \{\mathbf{G_h}\}_{1n_g} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \{\mathbf{G_h}\}_{n_g1} & -\{\mathbf{B_h}\}_{n_g1} & \cdots & \{\mathbf{G_h}\}_{n_gn_g} & -\{\mathbf{B_h}\}_{n_gn_g} \\ \{\mathbf{B_h}\}_{n_g1} & \{\mathbf{G_h}\}_{n_g1} & \cdots & \{\mathbf{B_h}\}_{n_gn_g} & \{\mathbf{G_h}\}_{n_gn_g} \end{bmatrix} \tag{4.25}$$

$$\mathbf{K_h^{dq}} = \begin{bmatrix} \{\mathbf{\Theta_h}\}_{11} & -\{\mathbf{\Psi_h}\}_{11} & \cdots & \{\mathbf{\Theta_h}\}_{1n_o} & -\{\mathbf{\Psi_h}\}_{1n_o} \\ \{\mathbf{\Psi_h}\}_{11} & \{\mathbf{\Theta_h}\}_{11} & \cdots & \{\mathbf{\Psi_h}\}_{1n_o} & \{\mathbf{\Theta_h}\}_{1n_o} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \{\mathbf{\Theta_h}\}_{n_g1} & -\{\mathbf{\Psi_h}\}_{n_g1} & \cdots & \{\mathbf{\Theta_h}\}_{n_gn_o} & -\{\mathbf{\Psi_h}\}_{n_gn_o} \\ \{\mathbf{\Psi_h}\}_{n_g1} & \{\mathbf{\Theta_h}\}_{n_g1} & \cdots & \{\mathbf{\Psi_h}\}_{n_gn_o} & \{\mathbf{\Theta_h}\}_{n_gn_o} \end{bmatrix} \tag{4.26}$$

$$\mathbf{G_h} = \Re\{\mathbf{Y_h}\}, \mathbf{B_h} = \Im\{\mathbf{Y_h}\} \tag{4.27}$$

$$\mathbf{\Theta_h} = \Re\{\mathbf{K_h}\}, \mathbf{\Psi_h} = \Im\{\mathbf{K_h}\} \tag{4.28}$$

in which n_g is the number of generation nodes and n_o is the number of other nodes.

The dynamic model of each unit is initialized using the voltage, current and frequency obtained through a previous saved continuous state. For synchronous and asynchronous machines, a stator electric model is built for each unit according with the equation below.

$$V_{unit}^{dq} = E_{unit}^{dq} - Z_{unit}^{m} I_{unit}^{dq} \tag{4.29}$$

where V_{unit}^{dq}, E_{unit}^{dq} and I_{unit}^{dq} are 2×1 vectors with the connection node voltage, transient internal voltage, and terminal (injected) current, respectively, at the dq unit reference frame. The variable Z_{M}^{unit} denotes a 2×2 matrix with entries given by stator impedance parameters.

The expressions in (4.21) and (4.29) can be combined as follows

$$\mathbf{I_g^{dq}} = \left(\boldsymbol{\Upsilon} + \mathbf{Y_h^{dq} Z_M}\right)^{-1} \left(\mathbf{Y_h^{dq} E^{dq}} + \mathbf{K_h^{dq} \Delta I_r^{dq}}\right) \tag{4.30}$$

where $\boldsymbol{\Upsilon}$ is the unit (identity) matrix, $\mathbf{Z_M}$ is a block diagonal matrix with elements Z_{M}^{unit} converted to the dq system reference frame, and $\mathbf{E_{dq}}$ is a vector with entries E_{dq}^{unit} converted to the dq system reference frame.

The dynamic simulation is then performed using a partitioned approach which alternates between the solution of the differential equations and the algebraic equations, and was successfully applied in works specifically related with dynamic analysis [276,277]. In summary, according with a numerical integration rule: (a) the continuous state variables are estimated and the variables E_{dq}^{unit} and Z_{M}^{unit} are updated; (b) the terminal node currents are updated using (4.30); and (c) terminal voltages are updated using (4.29). These steps are repeated until a new steady-state is achieved or other event is assigned. In case the network configuration changes or a generation unit is disconnected, the matrix variables in (4.30) are updated. If necessary, the dynamics of other components can be added, involving the change of $\mathbf{\Delta I_r^{dq}}$ depending on, for instance, terminal voltage and/or system frequency information.

At last, it is important to mention that the dynamic modelings were coded from scratch in JAVA language. Numerical integration was implemented using the fourth-order Runge-Kutta method from the (open source) Flanagan's JAVA Scientific Library [278].

4.3.3.1 DER Dynamic Modeling

Several DER dynamic models were tested during the course of this research and, about this matter, the interested reader might consult publication 9 in Appendix A where the islanding of a power distribution system with different sorts of DERs is modeled and simulated using the commercial software EUROSTAG [8]. Nevertheless, the evaluation of the individual operation of different sorts of DERs is out of the scope of this work and the references [20,63] already provide extensive information about this topic, at least for the micro grid and multi-micro grid paradigms. The main objective in implementing DER dynamic models herein is to show how the combined discrete-continuous simulation approach is capable of supporting the integrated adequacy and security evaluation of power distribution systems. Moreover, the integrated evaluation allows verifying the advantages of applying the developed agent-based architecture to aid the power distribution system operation.

Therefore, regarding power distributed generation, we focused on implementing a CHP system connected through a synchronous generator since this is a well-known technology which can provide inertia to the system and support DG islanded operation. For this accomplishment, the synchronous generator forth-order model was utilized [279, pg.456] alongside the single reheat tandem-compound steam turbine [280, pg.427], governor [280, pg.437] and IEEE DC1A exciter [280, pg.363] models. Although a significant amount of time was spent in implementing the equations of these models in JAVA language as well as validating them with EUROSTAG, these are well-known models thoroughly described in the literature and their fundamentals were skipped from this document for the sake of straightness.

On the other hand, DG islanding frequency decays are deemed to be improved with the connection of another form of DER: the energy storage devices. In association with the proper controls (e.g. droops), these devices might smooth frequency variations during islanding procedures by injecting power into the system when frequency decreases. Additionally, overlying the possibility of connecting energy storage devices to the power distribution systems, there is nowadays the future prospects of the increase in sales of EVs. From the point of view of the utility, the EV stands as a different customer load that must be absorbed by the utility business. At the same time, the battery of the EV represents an energy storage device whose availability depends upon the habits of the customer driver. Hence, in our approach, the EV constitutes an interesting form of energy storage that influences the loading of the system in steady-state conditions as well as it requires a dynamic model to verifying its impact on the islanding procedures.

Regarding the loading increase caused by the connection of EVs in the system, EV load profiles were retrieved from the non-homogeneous Poisson process-based stochastic model developed under the scope of the Master's thesis shown in [281]. On the other hand, regarding dynamic modeling, a general model for a lumped set of EVs connected via droop control was implemented. The main concept behind this model is to reduce smoothly the battery chargings according to frequency variations using a proportional gain. The schematic of this model is shown on Fig. 4.3.

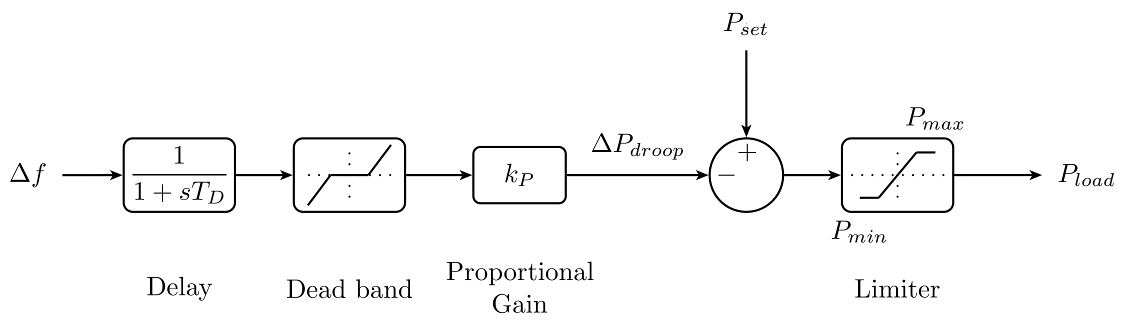


Fig. 4.3: Schematic for the droop control of a lumped set of EV batteries.

In this simple model, the frequency deviation signal (Δf) passes through a block which models the delay caused by measuring the frequency. The delayed signal passes through a dead band block to prevent the charging from being disturbed by minor frequency changes. The resultant signal is multiplied by a proportional gain (k_P) to determine the contribution (ΔP_{droop}) of the droop to reducing a pre-specified charging set point (P_{set}). At last, the altered signal ($P_{set} - \Delta P_{droop}$) is limited at $[P_{min}, P_{max}]$ composing the charging load (P_{load}) of the EVs. Observe that if the limit P_{min} is chosen negative, this means that the EVs can inject electric energy into the system, a process usually referred as vehicle-to grid in the literature.

The EV battery droop control model was initially developed and implemented using the commercial software EUROSTAG, under the framework of the European project MERGE [282]. About this matter, implementation and simulation results can be found in publication 7 in Appendix A. Afterwards, the model was implemented in JAVA language and validated using the EUROSTAG implementation as reference. It is also important to emphasize that this individual modeling was not created in this work, in the sense that a similar schematic was adopted in [283] at the low voltage level and in [284] at the high voltage level. Our application at the medium voltage level uses the model to represent a set of EVs which are lumped in a charging station, as developed in project MERGE.

Finally, customer loads that participate in the power distribution system operation can also be considered DERs. One of the applications on this area refers to allowing the interruption/shedding of certain customer loads to increase the probability of well-successful DG islandings, thereby improving the service continuity in the DG islanded area. With this purpose, the conventional underfrequency relay based load shedding was implemented as part of the set of possible discrete events in the dynamic simulation. Additionally, an advanced load shedding scheme based on a neural network application was developed, as described in the next section.

4.3.3.2 Advanced Load Shedding Modeling

In order to verify the impact of load shedding strategies on the DG islandings, an advanced load shedding scheme was also designed to the simulation model. Besides improving the modeling adherence to the actual operation where load shedding schemes can already be found in industrial installations with LOG protection, the modeling of load shedding schemes can be applied to evaluating/promoting the DG islanding of network blocks or even entire power distribution system. The developed advanced load shedding scheme relies on a polynomial neural network to forecast the minimum value of the frequency in case of islanding. The polynomial neural network is built using the Group Method of Data Handling (GMDH) approach [285]. Essentially, the GMDH is a modeling approach to synthesize polynomial representations that embody the inherent complexity of highly nonlinear systems. It employs a flexible neural network architecture whose structure is developed through learning. Hence, the number of layers of the neural network is not pre-specified but a result of the GMDH learning algorithm procedure.

In order to describe the general steps of the GMDH algorithm, let us consider $\mathcal{O}$ observations of m independent input variables $\mathbf{\Phi}^{(k)} = \{\phi_1^{(k)}, \phi_2^{(k)}, \dots, \phi_m^{(k)}\}$, $\forall k = 1, \dots, \mathcal{O}$. Similarly, let us take their associated output observations $\psi^{(k)}$, $\forall k = 1, \dots, \mathcal{O}$. Note that, by using the set of observations, it is possible to create a rough quadratic predictor through regression for each pair of input variables (ϕ_i, ϕ_j),$\forall i \neq j \in \{1, \dots, m\}$ following the expression below.

$$\widehat{\psi}_h = \mathcal{A}_h + \mathcal{B}_h\phi_i + \mathcal{C}_h\phi_j + \mathcal{D}_h\phi_i\phi_j + \mathcal{E}_h\phi_i^2 + \mathcal{F}_h\phi_j^2 \tag{4.31}$$

where $\mathcal{A}_h$, $\mathcal{B}_h$, $\mathcal{C}_h$, $\mathcal{D}_h$, $\mathcal{E}_h$, and $\mathcal{F}_h$ are the estimated parameters of the h-th polynomial, and $\widehat{\psi}_h$ is the estimate of the dependent variable ψ of the h-th polynomial, $\forall h = 1, \dots, 0.5m(m-1)$.

The resultant $0.5m(m-1)$ polynomials produce estimation variables $\widehat{\psi}_h$ which are trimmed according to some selection criterion. The standard selection criterion is the root mean square error r_h and only the estimates with associated errors below a pre-specified limit are kept. The minimum error r_{min} of the data set is saved and the selected $\widehat{\psi}_h$ variables constitute a new data set for repeating the estimation and selection steps producing further higher level variables. The process finishes when r_{min} stops decreasing. Hence, the best fitted polynomial is retrieved backwards following the network path of the best estimators. Making the necessary algebraic substitutions, a complex polynomial in the form of the Kolmogorov-Gabor polynomial is obtained.

$$\widehat{\psi} = \mathcal{KG}(\mathbf{\Phi}) = a + \sum_{i=1}^{m} b_i \phi_i + \sum_{i=1}^{m}\sum_{j=1}^{m} c_{ij}\phi_i\phi_j + \sum_{i=1}^{m}\sum_{j=1}^{m}\sum_{r=1}^{m} d_{ijr}\phi_i\phi_j\phi_r + \dots \tag{4.32}$$

where a, b_i, c_{ij}, d_{ijk} and so forth are the coefficients of the polynomial, $\mathcal{KG}(\mathbf{\Phi})$ is the polynomial function and $\widehat{\psi}$ is the resultant estimate.

Therefore, in the proposed approach, a Kolmogorov-Gabor polynomial is generated to model the relation between local information and the minimum frequency values in case of islanding. The set of local information can be rich or poor according to the availability of system sensor devices. Aiming at limiting the information requirements, we have established that at least the total active generation capacity per technology, total active generation production per technology and active power imbalance in the island must be provided. This does not imply that reactive power is unimportant for these matters or, more generally, that this set of information is sufficient to assure the best usage of the GMDH for all cases. On the contrary, it refers to the minimum amount of variables judged to provide adequate results in our particular simulated forecastings. From the point of view of engineering, a designer might devise simulations for its particular network in order to verify which are the local data available and, at the same time, of interest to forecast the frequency decays. Hence, the developed simulation model has a role in providing chronological operation state instances and operating cycle behavior data to support the establishment of forecasting alternatives to the particular network.

The load shedding approach itself is established as follows. Given local information, suppose that the estimated Kolmogorov-Gabor polynomial model points out that the value of the minimum islanding frequency would be inferior to the threshold of the DG underfrequency relay based protective devices. Then, the rate of change of frequency relays of the participating customer loads are turned on, following a priority order, aiming to perform their load sheddings in case of islanding. The choice of how much to be shed is devised iteratively by testing the Kolmogorov-Gabor polynomial model over different power imbalance values, given by the current power imbalances minus the total shed loadings. In field applications, this process might be repeated in pre-specified periods aiming at updating relay statuses cyclically and avoiding unnecessary shedding occurrences. For the purposes of our simulations, training and test data sets are obtained by emulating the operation through the simulation approach assuming all DG underfrequency relay based protective devices are turned off, allowing retrieving data information regarding the islanding processes. The pseudocode 2 summarizes the GMDH-based advanced load shedding approach.

There are already in the literature a few applications of neural networks to estimate the frequency decays after disturbances in isolated systems. Nevertheless, these approaches rely on neural networks to forecast frequency decays as *black boxes*, raising concerns regarding applicability and interpretation. On the other hand, the polynomial neural network applied herein has the interesting feature of providing as a

```
cap ← total generation capacity per technology;
pro ← total generation production per technology;
imb ← total power imbalance;
acc ← total shed loadings starting at zero;
APC ← list of available participant customers sorted by priority;
M ← number of elements of APC;
RES ← {empty};                                   // Empty list
flag ← false; i ← 0;
while flag is false & i < M do
    Δf_i ← KG(cap, pro, imb − acc);   // Kolmogorov-Gabor polynomial function application
    if Δf_i ≥ Δf_threshold then
        RES(i) ← APC(i);   // Take and store the i-th participant customer from APC
        acc ← total loading associated to the RES entries;
        i ← i + 1;
    else
        flag ← true;
Turn on the rate of change of frequency relays of the customers in RES;
```

Pseudocode 2: GMDH-based advanced load shedding approach.

result the explicit expression of the polynomial which relates input to output variables. This polynomial can be easily manipulated and analyzed to ascertain the limits of its applicability in a practical problem. Moreover, at the best of our knowledge, none of these works have a combined discrete-continuous simulation model to produce training and testing datasets. The association of saved chronological system states of interest with the setting of load shedding strategies provides means of evaluating more accurately how these strategies influence the system operation.

Finally, it is important to mention that the GMDH model was implemented with the support of the (open source) libraries of the wGMDH Weka project [286], whose distribution dates 2010.

4.3.4 State Evaluation Procedures

As previously stated, the combined discrete-continuous simulation approach produces system states which are subjected to evaluation. In each state evaluation process, electric steady-state and dynamic behavior analysis may be applied to characterize the system state. This characterization allows updating system discrete and continuous state variables following a chronological order in order to build a synthetic operational history of the system. For efficiency and consistency purposes, the evaluation procedures vary according to the transition which produced the system state. These procedures are illustrated in Fig. 4.4 and described in the followings.

1. Protective actions are performed by changing (or scheduling the change of) the status of the protective devices (e.g. breaker, switch, fuse) depending on the component under state transition.

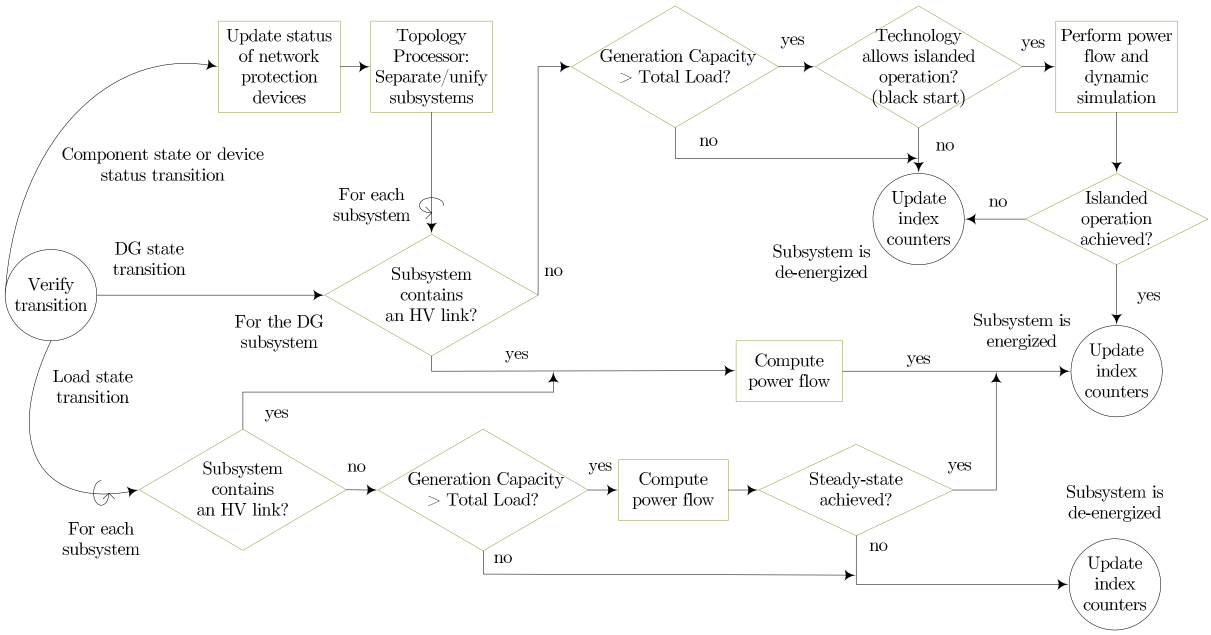


Fig. 4.4: Evaluation procedures in the combined discrete-continuous simulation approach.

For instance, a component state transition to the down state may trigger breaker actions or fuse operations. Also, it may cause scheduling the opening of disconnects or the closing of connections to alternative supplies. All the interrelations among transitions and protective actions are obtained straightforwardly through a rule engine which creates dependency schemes encapsulated in the computational objects which model the protective devices.

2. A topology processor is applied to verify possible network unifications or separations in subsystems (islands). Subsystems composed of at least one HV link are considered energized and a power flow is computed to assess its steady-state. Otherwise, the evaluation goes to the next step.

3. The subsystems capability to operate in islanded mode is assessed. For this accomplishment, the generation capacity to meet the load is verified. Furthermore, islanded operation is assigned only for subsystems with DERs interfaced with synchronous machines or inverters capable of emulating a synchronous generator. If one of these conditions is not met, the subsystem and its elements are assumed de-energized. Otherwise, the evaluation continues to the next step.

4. Steady-state and dynamic analyzes are performed following the modeling introduced in subsection 4.3.3. Only if frequency and voltage stabilization are achieved, the subsystem is considered energized. State discrete and continuous variables are updated at the end of these procedures.

In case of a load transition, if the subsystem contains an HV link, then a power flow is computed and the subsystem is considered energized. If the subsystem does not contain an HV link, a power flow is computed for the islanded subsystem only if there is enough generation capacity to supply the load. As an approximation, in order to meet the load in islanded mode, DG unit's productions are increased/decreased from the previous operation state following a merit order. Losses are then compensated by the unit at a chosen reference node. In case the subsystem does not have capacity to supply its load demand and network losses and, therefore, steady-state is not achieved, then the subsystem and its elements are considered de-energized. Otherwise, they are considered energized. Finally, in case of a DG state transition, if the subsystem contains at least one HV link, a power flow is computed to assess the subsystem steady-state. Otherwise, steps 3 and 4 are considered, but including the verification of the existence of a DER with black start capabilities in case the subsystem is de-energized and the DER transits to the up state. Note that dynamic simulation is not performed in case of load transitions. Hence, it is assumed the subsystems in islanded mode are able to perform load-following perfectly.

All these evaluations can be used to retrieve chronological information to assess the system operation. The information is aggregated in terms of performance indices which can measure adequacy and security aspects of the service provided by the utility.

4.3.5 Performance Index Estimation

The actual impact of operational solutions in the power distribution system operation can be measured using the uprising/downsitting of performance indices. As a matter of fact, the main principle behind evaluating any process with stochastic nature lies in counting and measuring phenomena of interest. In the power distribution system operation, examples of phenomena of interest are the occurrences of customer interruptions, steady-state undervoltages/overvoltages, and underfrequency/overfrequency relay actions. Given a sequence of system states in a certain period of time, the counting and measuring of phenomena of interest can be modeled by test functions $G(\cdot)$. For instance, in order to quantify the frequency of interruptions an average customer might experience in a particular year of operation, we can define the test function

$$G_{\text{SAIFI}}(y_u) = \frac{\text{n}^{\text{o}} \text{ of customer interruptions in } y_u}{\text{n}^{\text{o}} \text{ of system customers}} \tag{4.33}$$

where y_u stands for the sequence of system states in year u. Note that the sole value $G_{\text{SAIFI}}(y_u)$ "only" represents a possible instance of the SAIFI in a particular year of operation. On the other hand, the whole simulation allows collecting several possible instances of $G_{\text{SAIFI}}(y_u)$ and to estimate statistics about its behavior.

In a general form, the unbiased estimation of an unknown quantity $\mathcal{I}$ can be obtained by the expected value equation

$$\tilde{E}\left[\mathbf{G}\right] = \frac{1}{n}\sum_{u=1}^{n} G(y_u) \tag{4.34}$$

in which $G(y_u)$ is the test function evaluated at y_u, n represents the number of simulated years, and $\mathbf{G}$ is a continuous random variable which maps $G(y_u)$ values.

Since for each n there is an estimate $\tilde{E}\left[\mathbf{G}\right]$, it is also convenient to define $E_n\left[\mathbf{G}\right] \triangleq \tilde{E}\left[\mathbf{G}\right]$ as the n-th element of the sequence $\{E_n\left[\mathbf{G}\right]\}$ of estimates for $\mathcal{I}$. Hence, for large n, the variance σ^2 of $\mathbf{G}$ can be estimated by

$$\sigma^2 \approx \mathcal{S}^2 = \frac{1}{n-1}\sum_{u=1}^{n}\left(G(y_u) - E_n\left[\mathbf{G}\right]\right)^2 \tag{4.35}$$

Also, by the central limit theorem [68], the distribution of any sequence of $E_n\left[\mathbf{G}\right]$ values tend to the normal distribution $\mathcal{N}\left(\mathcal{I}, \sigma^2/n\right)$. Consequently, for large n, the estimate variance tends to σ^2/n and the random variable $Z = \frac{E_n[\mathbf{G}]-\mathcal{I}}{\mathcal{S}/\sqrt{n}}$ follows the normal distribution $\mathcal{N}\left(0,1\right)$. Therefore, the approximate $(1-\zeta)$ confidence interval for $\mathcal{I}$ is given by

$$\left(\underbrace{\tilde{E_n}\left[\mathbf{G}\right] - z_{1-\zeta/2}\frac{\mathcal{S}}{\sqrt{n}}}_{\text{Inferior limit}}, \underbrace{\tilde{E_n}\left[\mathbf{G}\right] + z_{1-\zeta/2}\frac{\mathcal{S}}{\sqrt{n}}}_{\text{Superior limit}}\right) \tag{4.36}$$

where $z_{1-\zeta/2}$ is the $(1-\zeta/2)$ quantile of the standard normal distribution $\mathcal{N}\left(0,1\right)$. For instance, the 95% $(\zeta = 0.05, z_{0.975} = 1.96)$ confidence interval of $\mathcal{I}$ is given by

$$\left(\tilde{E_n}\left[\mathbf{G}\right] - 1.96\frac{\mathcal{S}}{\sqrt{n}}, \tilde{E_n}\left[\mathbf{G}\right] + 1.96\frac{\mathcal{S}}{\sqrt{n}}\right) \tag{4.37}$$

The normalized measure of the dispersion of a probability distribution is given, in statistics, by the ratio of the sampled standard deviation over the sample mean, called coefficient of variation. Hence, the accuracy measure of the estimator $\tilde{E}\left[\mathbf{G}\right]$ is given by

$$\beta = \frac{\sqrt{V(\tilde{E}\left[\mathbf{G}\right])}}{\tilde{E}\left[\mathbf{G}\right]} \times 100\% \tag{4.38}$$

and the convergence of the estimate of $\mathcal{I}$ is assigned when a pre-specified minimum threshold for the coefficient of variation value is achieved.

Following these definitions, the conventional system-wide performance indices can be estimated using as test functions the equations introduced in section 2.2.5. Moreover, the conventional customer performance indices at a particular point of connection i can be estimated through the following test functions.

$$G_{\lambda_i}(y_u) = \text{n}^\text{o} \text{ of interruptions in } y_u \tag{4.39}$$

$$G_{U_i}(y_u) = \text{total interruption duration in } y_u \tag{4.40}$$

$$G_{r_i}(y_u) = \frac{G_{U_i}(y_u)}{G_{\lambda_i}(y_u)} \tag{4.41}$$

In the proposed approach, the impact of the deployment of an operational solution can be directly attained through its effect on the performance indices. This effect can be verified since an operational solution might influence the sequence of generated system states in order to improve the service adequacy and security. The influence can be modeled as follows. Let y_u and y_u^{new} be the sequence of system states in year u without and with the addition of a given operational solution, respectively. Also, let us define N, $\rho(\cdot)$ and $\varrho(\cdot)$ as the number of customers of the system, the number of customer interruptions given a sequence of system states, and the total customer interruption duration given a sequence of system states, respectively. By these definitions, the impact of an operational solution in the system-wide performance indices can be estimated using the test functions below.

$$\begin{aligned}\Delta G_{\text{SAIFI}}(y_u) &\triangleq G_{\text{SAIFI}}(y_u^{\text{new}}) - G_{\text{SAIFI}}(y_u) = \frac{\rho(y_u^{\text{new}})}{N} - \frac{\rho(y_u)}{N}\\ &= -\frac{\text{n}^{\text{o}} \text{ of avoided customer interruptions in } y_u}{\text{n}^{\text{o}} \text{ of system customers}}\end{aligned} \tag{4.42}$$

$$\begin{aligned}\Delta G_{\text{SAIDI}}(y_u) &\triangleq G_{\text{SAIDI}}(y_u^{\text{new}}) - G_{\text{SAIDI}}(y_u) = \frac{\varrho(y_u^{\text{new}})}{N} - \frac{\varrho(y_u)}{N}\\ &= -\frac{\text{total avoided customer interruption durations in } y_u}{\text{n}^{\text{o}} \text{ of system customers}}\end{aligned} \tag{4.43}$$

$$\begin{aligned}\Delta G_{\text{CAIDI}}(y_u) &\triangleq G_{\text{CAIDI}}(y_u^{\text{new}}) - G_{\text{CAIDI}}(y_u) = \frac{G_{\text{SAIDI}}(y_u^{\text{new}})}{G_{\text{SAIFI}}(y_u^{\text{new}})} - \frac{G_{\text{SAIDI}}(y_u)}{G_{\text{SAIFI}}(y_u)}\\ &= \frac{G_{\text{SAIDI}}(y_u^{\text{new}})G_{\text{SAIFI}}(y_u) - G_{\text{SAIDI}}(y_u)G_{\text{SAIFI}}(y_u^{\text{new}})}{G_{\text{SAIFI}}(y_u^{\text{new}})G_{\text{SAIFI}}(y_u)}\\ &= \frac{G_{\text{SAIFI}}(y_u)\Delta G_{\text{SAIDI}}(y_u) - G_{\text{SAIDI}}\Delta G_{\text{SAIFI}}(y_u)}{G_{\text{SAIFI}}(y_u)\left(G_{\text{SAIFI}}(y_u) + \Delta G_{\text{SAIFI}}(y_u)\right)}\end{aligned} \tag{4.44}$$

$$\begin{aligned}\Delta G_{\text{ASAI}}(y_u) &\triangleq G_{\text{ASAI}}(y_u^{\text{new}}) - G_{\text{ASAI}}(y_u)\\ &= \left(1 - \frac{G_{\text{SAIDI}}(y_u^{\text{new}})}{\text{n}^{\text{o}} \text{ of hours of } y_u^{\text{new}}}\right) - \left(1 - \frac{G_{\text{SAIDI}}(y_u)}{\text{n}^{\text{o}} \text{ of hours of } y_u}\right)\\ &= -\frac{\Delta G_{\text{SAIDI}}(y_r)}{\text{n}^{\text{o}} \text{ of hours of } y_u}\end{aligned} \tag{4.45}$$

$$\begin{aligned}\Delta G_{\text{ASUI}}(y_u) &\triangleq G_{\text{ASUI}}(y_u^{\text{new}}) - G_{\text{ASUI}}(y_u)\\ &= \left(1 - G_{\text{ASAI}}\left(y_u^{\text{new}}\right)\right) - \left(1 - G_{\text{ASAI}}\left(y_u\right)\right)\\ &= -\Delta G_{\text{ASAI}}(y_u)\end{aligned} \tag{4.46}$$

$$\begin{aligned}\Delta G_{\text{ENS}}(y_u) &\triangleq G_{\text{ENS}}(y_u^{\text{new}}) - G_{\text{ENS}}(y_u)\\ &= -\text{ avoided energy not supplied in } y_u\end{aligned} \tag{4.47}$$

$$\begin{aligned}
\Delta G_{\text{AENS}}(y_u) &\triangleq G_{\text{AENS}}(y_u^{\text{new}}) - G_{\text{AENS}}(y_u) \\
&= \left(\frac{G_{\text{ENS}}(y_u^{\text{new}})}{N}\right) - \left(\frac{G_{\text{ENS}}(y_u)}{N}\right) \\
&= \frac{\Delta G_{\text{ENS}}(y_u)}{N}
\end{aligned} \tag{4.48}$$

Similarly, the impact of an operational solution in the customer performance indices can be estimated through the following test functions.

$$\Delta G_{\lambda_i}(y_u) \triangleq G_{\lambda_i}(y_u^{new}) - G_{\lambda_i}(y_u) = - \text{ n}^{\text{o}} \text{ of avoided interruptions in } y_u \tag{4.49}$$

$$\Delta G_{U_i}(y_u) \triangleq G_{U_i}(y_u^{new}) - G_{U_i}(y_u) = \text{total avoided interruption durations in } y_u \tag{4.50}$$

$$\begin{aligned}
\Delta G_{r_i}(y_u) &\triangleq G_{r_i}(y_u^{new}) - G_{r_i}(y_u) \\
&= \frac{G_{U_i}(y_u^{new})}{G_{\lambda_i}(y_u^{new})} - \frac{G_{U_i}(y_u)}{G_{\lambda_i}(y_u)} \\
&= \frac{G_{U_i}(y_u^{new})G_{\lambda_i}(y_u) - G_{U_i}(y_u)G_{\lambda_i}(y_u^{new})}{G_{\lambda_i}(y_u^{new})G_{\lambda_i}(y_u)} \\
&= \frac{G_{\lambda_i}(y_u)\Delta G_{U_i}(y_u) - G_{U_i}(y_u)\Delta G_{\lambda_i}(y_u)}{G_{\lambda_i}(y_u)\left(G_{\lambda_i}(y_u) + \Delta G_{\lambda_i}(y_u)\right)}
\end{aligned} \tag{4.51}$$

Observe that the test functions $G_{\text{CAIDI}}(y_u)$ and $G_{r_i}(y_u)$ share an important semantic distinction from the others. As a matter of fact, most of the test functions approached in this section refer to a metric which is evaluated in a year basis. As an example, a sequence of states y_u might produce a $G_{\text{SAIFI}}(y_u)$ value which in turn can be interpreted as a possible instance of the SAIFI at the end of a year. Conversely, though the CAIDI is usually utilized as a metric to assess years of operation, this index refers to customer average interruption durations. Hence, the occurrences of $G_{\text{CAIDI}}(y_u)$ values should be evaluated in an interruption basis. Such distinction is of importance to highlight that, conceptually, the probability distribution and coefficient of variation of $G_{\text{CAIDI}}(y_u)$ must be estimated using interruptions as sampling basis. However, the probability distribution and coefficient of variation of $G_{\text{CAIDI}}(y_u)$ might be of great interest if estimated using sampled years, depending of course upon the purposes of the analysis. A similar reasoning can be applied to the test function $G_{r_i}(y_u)$.

Finally, alternative indices can be estimated following the general deductions devised in this section. In our approach, besides the failure rate λ [interruptions/year], unavailability U [h/year], and mean time to repair r [h] at the points of connection, also the frequency λ_v [occurrence/year], annual duration U_v [h/year], and mean time to solve r_v [h] inadequate delivered voltage conditions ($voltage < 0.95$ p.u. or $voltage > 1.05$ p.u.) are estimated. Following a security perspective, other indices (related with frequencies, annual durations, mean times) are accounted, for instance, regarding the interruptions which are avoided by DG islanded operation procedures. Frequency stability issues associated with islanding dynamics (see Fig. 4.2) are also observed during the sampling of system states.

4.4 General Algorithm Procedure

After presenting the combined discrete-continuous simulation model emphasizing the stochastic and deterministic behavior of system elements, the adverse weather representation, steady-state and dynamic analysis matters, state evaluation and performance index computation, the developed algorithm procedure can be described in resemblance to the sequential Monte Carlo simulation as presented below.

1. Initialize all the computational objects which model the power distribution system and the simulation approach.

2. Initialize clock and iteration counter: $t_i \leftarrow 0$, $i \leftarrow 0$.

3. Initialize the elements as follows.

   (a) Initialize the state of customer loads and generation productions with their associated profiles at time $t = 0$.

   (b) Initialize the component statuses with pre-specified values (on, off, open, close, etc.).

   (c) Sample the initial state of the weather condition. For this accomplishment, note that usually the probability of normal weather is significantly greater than the probability of adverse weather. Therefore, the weather condition can be assumed at the normal state for initialization purposes.

   (d) Sample the initial state of components and DGs. Similarly, observe that the probability of residing in the up state is usually considerably greater than the probability of residing in the down state. As consequence, components and DGs can be assumed in the up state for initialization purposes.

4. Generate the adverse weather events for a year of operation using pseudocode 1 in section 4.3.2.

5. For each component, DG, and customer load the following rules are performed.

   (a) Sample the resident time T in the current state. In case of deterministically modeled elements, this duration is given by the resolution of the profile (e.g. 1 hour). On the other hand, for the stochastically modeled elements, the rules below must be applied.

      i. If the element is in the up state and normal weather state, sample the time duration in these states using (4.13).

      ii. If the element is in the down state and normal weather state, sample the time duration in these states using (4.18).

      iii. If the element is in the down state and adverse weather state, sample the time duration in these states using (4.17).

The sampling of time durations of elements in the up state immediately after the occurrence of an adverse weather state are performed in a further step. Hence, in the first iteration of the algorithm, all components are marked with a flag (†) to identify that time durations in the up state and adverse weather state are yet to be sampled. Moreover, as stated in section 4.3.2, the transition to the up state is only characterized in normal weather conditions due to crew safety reasons. At last, assuming that the stochastically modeled elements are initialized in the up state and normal weather state, only item 5(a)i should be performed in the first iteration of the algorithm.

(b) Update the time instant of the next state transition.

6. Obtain the time instant t_{i+1} associated to the most imminent transition, covering the possibility of a component state transition, DG state transition, load/production state transition, component status transition and weather state transition. If more than one element is assigned to transit at t_{i+1}, take one indiscriminately. The occurrence of simultaneous events is addressed in the next step.

7. Once the next transition is assigned, the following procedures must be applied.

   (a) If $t_{i+1} \neq t_i$, then step forward the clock to t_{i+1} and evaluate the system state at $[t_i, t_{i+1})$ using the procedures described in section 4.3.4. During the evaluations, measure the phenomena of interest assuring a consistent timeframe unification of discretely changing and continuous changing state variables.

   (b) If $t_{i+1} = t_i$, go directly to the next step.

8. Perform the transition associated to t_{i+1} as described below.

   (a) In case of a component status transition, perform straightforwardly the change of the status of the component.

   (b) In case of a weather transition to the normal state, perform straightforwardly the weather transition guaranteeing that all components have their time transition instants referred to the normal weather state.

   (c) In case of a weather transition to the adverse state, perform the state transition followed by the sampling of the wind speed duration and wind speed intensity variation using (4.14) and (4.15), respectively, and guaranteeing that all components have their time transition instants refereed to the adverse weather state. Moreover, using (4.12), sample the time duration in the up state and adverse weather state for the marked (†) components.

   (d) In case of a component, DG, or load/production state transition.

      i. In case of a load/production state transition, perform the transition followed by the update of the time instant of its next state transition (e.g. 1 hour).

      ii. In case of a DG state transition, and since adverse weather effects are assumed only for components, perform the transition followed by the procedures detailed in items 5(a)i [or 5(a)ii] and 5b.

iii. In case of a component state transition in normal weather state, perform the transition followed by the procedures detailed in items 5(a)i [or 5(a)ii] and 5b, in similarity to the previous item.

iv. In case of a component transition to the down state in the adverse weather state, perform the transition followed by the procedures detailed in items 5(a)iii and 5b. Then, mark the component with a flag (†) to identify that a time duration in the up state and adverse weather state is yet to be sampled.

9. If a year is covered by the simulation approach, go to step 10. Otherwise, return to step 6.

10. Gather the state evaluations and compute the performance index test functions $G(y_u)$ at the end of the year y_u. Also, estimate the performance indices and their correspondent coefficient of variation.

11. Verify if the coefficients of variation are inferior to a pre-specified tolerance. If not, repeat step 4 and return to step 6. Otherwise, finish the simulation approach.

Note that the description above kept hidden aspects from implementation for the sake of generality and clarity. However, it must be mention that there are plenty of complexities in implementing and synchronizing the described algorithm procedures. For instance, if a rigorous control of the generation of random numbers is not employed, then the sequence of sampled system states cannot be replicated, the simulations results cannot be repeated, and the impact of operational solutions cannot be genuinely assessed. In fact, even one misplaced temporal event can jeopardize the entire simulation providing indices which are, sometimes, absurd. Hence, the success of the implementation is attributed, in part, to the continuous development of object-oriented computational models to the elements of the simulation approach. This continuous development allowed both devising consistent add-ons/improvements for extension purposes and revisiting system states at particular instants of the simulation for testing/debugging purposes. Moreover, these computational models are important to preserve the conceptual meaning of emulating the system operation, where concise representations of the system elements are instantiated within computational artifacts. All these issues are discussed in depth in chapter 5.

4.5 Summary and Discussions

This chapter presented in detail a novel approach to evaluate the power distribution system operation based on a combined discrete-continuous simulation model. Hence, this simulation model can be encapsulated in an environment platform to allow evaluating operational solutions devised to improve the power distribution system delivery. In determining the conceptual framework and practical matters of designing the simulation model, the representation of the long-term failure/repair cycle of system components was established as a requirement, aiming at estimating the standardized power distribution system performance indices. In order to verify the actual impact of DER integration in the power distribution delivery, the representation of steady-state and dynamic aspects was established as a requirement as well. Therefore, the design of the simulation model demanded the unification of representations permitting a distinct form of performance assessment where the phenomena of interest are considered altogether in a wider timeframe. For this accomplishment, the fundamentals of service adequacy and security were revisited and adapted to power distribution system delivery.

In establishing alternative definitions for power distribution system adequacy and security evaluations, the assessment was leaned to the aspects of the voltage waveform at the customer points of connection. This is consistent with modern concepts of power quality in power distribution delivery and differs from the operation state classifications devised in bulk power system applications. In addition, to our purposes, it was identified that only an integrated adequacy and security evaluation would suffice. Also, for the sake of efficiency and feasibility, modeling was rigorously restricted to the phenomena of interest. Hence, in narrowing the timeframe representations, we have chosen to approach the long-term failure/repair cycle of system components alongside steady-state aspects through AC power flow analysis as well as DG islanding frequency stability through dynamic behavior analysis. Of course, the reader might verify that the proposed concept of applying a combined discrete-continuous simulation model to evaluate the power distribution system operation is general, either to other phenomena of interest or timeframe representations. For instance, future works might include in the wider timeframe the modeling of causes of failures/interruptions. In a narrower timeframe, future works might even link this causes with the sampling of actual short-circuit events alongside a more accurate modeling of the network and protection activities. The combined discrete-continuous simulation model includes also the representation of adverse weather conditions composed of high wind events, a GMDH-based advanced load shedding developed scheme, series of state evaluation procedures, and performance index test functions. These developments sum value to the contributions and accuracy to the evaluations.

Finally, as previously highlighted, aspects from implementation were skipped from this chapter for the sake of generality and clarity. Nevertheless, the intention of unifying representations in a simulation approach is only rigorously achieved if the implementation copes with this directive. This implies that an explicitly computation model might be constructed for the fundamental concepts behind the power distribution delivery and the simulation approach. For instance, an explicit computational model of an operation/system state is of interest to rigorously cope the implementation with the mathematical modeling of test functions of sequences of system states. Also, an explicit computational model of a breaker is of interest to unify its status with the temporal sequence of sampled events. All these issues allow abstracting the simulation model from a mere tool to extract performance indices about the system operation. Distinctively, they permit utilizing the simulation model to emulate properties of the system operation, where operational solutions can be designed and properly evaluated.

The conveyance of the simulation model in a mechanisms to representing the system operation was utilized to build an environment where agents can be situated and interact. This conveyance along with several issues of computational modeling are approached in chapter 5.

Chapter 5

Environment Modeling: A CArtAgO Technology Application

In chapter 3, a block-oriented agent-based architecture aiming the support of the power distribution system operation was presented. In describing this architecture, detailed notions about the computational modeling of the environment were avoided for the sake of straightforwardness. On the other hand, in chapter 4, a simulation model designed to evaluate the long-term impact of operational/control solutions on the power distribution systems was described. The intention of applying this simulation model within the computational modeling of the environment aiming at assessing the impact of agent-based solutions was briefly outlined, but the actual procedures behind this intention were skipped as well. Therefore, this chapter represents the counterpart of chapter 4 where the systems and mechanisms of the simulation model are embedded within an environment representation. It is a crucial chapter which completes the environment modeling by interconnecting the agent-based architecture and the simulation model mechanisms using the state of the art artifact-based model employed by CArtAgO, a general-purpose infrastructure to develop and execute agent environments.

It must be noticed that the computational modeling of the environment is a fundamental part of defining an agent-based system, though it is somehow overlooked by the power engineering academia. Hence, after analyzing carefully the literature of the field, the bridge between JASON and CArtAgO was found as the missing piece to allow both agent programming with strong notions of agency and, at the same time, environment programming endogenously integrated to our system design. As a matter of fact, the notion of artifacts employed by CArtAgO proved to be effective and practical to model entities in the power distribution engineering context. As consequence, CArtAgO was utilized in this research marking, at the best of the author's knowledge, the first application of this solution to power engineering modeling and simulation.

Therefore, this chapter presents the environment modeling from the computational perspective, but focusing on introducing how the environment was conceived and how the interactions with the modeled agents were simulated. Hence, details about UML[5.1] diagrams were avoided and the descriptions

[5.1] UML is a standardized modeling language which includes a great variety of graphic notation techniques to create visual were placed herein directing the discourse towards readers which might not be very familiar with object-oriented modeling. Following this reasoning, the chapter is organized as follows. In section 5.1, the conceptual framework and initial remarks are outlined emphasizing the distinctions of reasoning about time and time durations within the developed simulation model mechanisms and in an environment simulation. In section 5.2, the object-oriented modeling of the power distribution systems and simulation model mechanisms are provided. Then, in section 5.3, the artifact-based infrastructure created to the environment modeling is described focusing on the procedures to create artifacts and their interactions with agents. In section 5.4, implementation issues are summarized involving the whole system infrastructure. Lastly, in section 5.5, summary and discussions finalize the chapter.

5.1 Conceptual Framework and Initial Remarks

The notion of environment is a primary concept in agent and multi-agent systems. In summary, the environment is the computational or physical place where agents are situated. As consequence, the environment provides the basic ground for defining agent perception, action and interaction [11]. Moreover, even the fundamental principles behind the agent abstraction are connected to the concept of environment. The obvious example is the concept of reactivity, which means responding to changes in the environment. Another example lies in the concept of goal-directed behavior, which is straightforwardly related to the states of affair the agent might envision to achieve about the environment.

Since agent-based systems are normally utilized to develop complex distributed systems, verifying and validating such systems are very hard tasks [10]. As consequence, computational models to real-world (and virtual) environments are of major importance to evaluate how effective the agents can achieve their targets. The modeling itself of an environment depends, however, upon its desired accuracy and objective. At one extreme, an environment model might have the minimum amount of features to allow verifying some agent interactions. At the other extreme, it might represent accurately all the artifacts of the real-world where the agents are designed to be situated. Depending upon the domain, implementation and applied technology, once the interactions between agents and environment are consolidated, the actual deployment of the agents might be reached by "simply" changing the implementation of the methods[5.2] that interface the agents with the environment. Therefore, the closer the environment modeling is from representing the artifacts of the real-world, the closer it is from supporting the actual deployment of the whole agent-based system.

The combined discrete-continuous simulation model presented in the previous chapter is able to represent and evaluate the impact of operational/control solutions on the power distribution system operation. Nevertheless, there are subtle but sharp distinctions between representing agent-based solutions within a general environment modeling and within our simulation modeling. Similarly to the former argument, these distinctions are directly related to the purposes of the representation. In our simulation modeling, the operational/control solutions are represented according to how they impact on the phenomena of

models of object-oriented software systems.

[5.2]Up to this chapter, the term *method* was applied in reference to its scientific meaning: a body of techniques to investigating phenomena and acquiring knowledge. Conversely, in this chapter, the term method is utilized under the context of object-oriented programming, meaning a subroutine/procedure associated with a *class*, which in turn is a construct to create instances of itself.

interest aiming at estimating performance indices and retrieving system behavior patterns. On the other hand, in an environment modeling to the power distribution system operations, the purpose lies in representing the entity and artifact interactions, which in turn may enable the operational/control solutions. This focus on mimicking inner issues of the entity and artifact interactions is more directly related to the emulation (instead of the simulation) of the power distribution system operation.

Indeed, both purposes are of great interest leading, however, to different representations. Due to these differences, one of the main concerns when designing and verifying the modeling presented herein was *which time is it?* or *which time is the subject of matter?*. These questions refer to distinctions in how time can be understood in our work. In devising an environment modeling, the explicit notion of time is sometimes not present and the focus is leaned to the agent reasoning cycles and their resulting interactions. Moreover, even if an event generator with an explicit representation of time is applied, the understanding of time itself may differ from that approached in a simulation model designed for stochastic evaluations. Hence, three sorts of manners of understanding time can be identified in our developments. The first one relates to the time which advances from the point of view of the modeled system operation or, more generally, the conventional concept of time when emulating the system operation. The second one relates to the time instants produced by the combined discrete-continuous simulation model using as main step procedure the next-event time advance mechanism. Finally, the last one relates to the actual time to which both the author and readers are subjected, and from which computer running elapsed time durations are retrieved to verify the efficiency of the simulations/emulations. The last one refers to a straightforward concept, at least in our context. The others must be differentiated carefully to avoid misconceptions.

In a simulation modeling to the purpose of performing stochastic evaluations, the time advances with the intention of sampling different system states given a constant set of subjects of evaluation such as the infrastructure (e.g. lines, transformers, DG units, protective devices, and so forth) and the operational procedures. These subjects of evaluation must be constant to guarantee consistency in estimating the performance of the system operation. As consequence, given data from an actual system, if an event is sampled to an instant of time, say $t = (392 \text{ years}, 2967.32 \text{ h})$, that does not mean we are evaluating the operation of the actual system more than 392 years ahead in the future. Clearly (or at least hopefully), the infrastructure and operational procedures will change in the next 392 years. The existence of this event only implies that a temporally connected sequence of system states was obtained up to covering more than 392 years, aiming at estimating performance indices about the operation of the actual/current system. Conversely, in the conventional concept of time approached in emulating the system operation, the infrastructure and operation procedures might change during the time advance mechanisms. Nevertheless, since the emulation of the the system operation is usually utilized in much shorter-term analyzes, these changes are commonly disregarded. This second understanding of time is employed within the state evaluations of the combined discrete-continuous simulation model where, for instance, dynamic behavior analyzes might be of interest to assess the system operation states.

Aiming at illustrating the implications of these distinctions, let us take the connection of a novel (client) DER to the utility network. From the point of view of verifying agent and artifact interactions in the system operation, this connection might trigger interactions conceived in the design of the agent-based architecture. However, though these interactions demand testing and verification, the entry of a novel DER can jeopardize the estimation of performance indices about the system operation. From this example, we can conclude that, sometimes, the requirement of keeping constant the subjects of evaluation imposes limitations in applying the sole simulation approach to our purposes. On the other hand, as previously emphasized, the aim of evaluating the impact of the agent-based solutions according to the power distribution system performance indices is legitim and of major importance.

Therefore, an effective environment modeling to our ambitions must be able to emulate the aspects of the system operation covered by the agent/artifact interactions allowing their testing and verification. At the same time, it must be able to embody those interactions which can be considered subjects of evaluation in a simulation engine to estimate consistently the performance of the system operation. Clearly, the development of an environment with such features comprehends complex tasks. Among them, we emphasize the task of designing the artifacts of the environment conjugating the two described purposes. For this accomplishment, an object-oriented computational modeling of the power distribution system elements as well as the simulation approach was undertaken. This modeling is presented in the next section allowing the further description of the environment artifacts.

5.2 Developed Object-Oriented Modeling

Object-oriented modeling is a modeling paradigm where concepts are represented by *objects* that have their own *attributes* and associated procedures called *methods*. It is a consolidated paradigm to address the complexity of domains by considering them as a set of related objects. Object-oriented modeling is a computational science discipline not usually covered in the power engineering graduate and postgraduate education. As a matter of fact, power engineering academia has been directing significant efforts on improving the mathematical modeling of physical phenomena and the solution algorithms to the analysis and simulation of power systems, while computational modeling matters are somehow overlooked in the academic publications. However, the power engineering society has growingly diverting attention towards object-oriented modeling, at the point that recent standards utilize UML diagrams to formalize the data exchange and interoperability of several applications/activities within the power utilities (e.g. [36, 287]). Concomitantly, the power engineering academia has also presented fragmented but actual contributions on object-oriented representation for power systems, including works on operation and control data exchange [288], network topology [289], Monte Carlo simulation [75], reliability assessment [290], power flow [291, 292], state estimation [293] and dynamic simulation [294].

Aiming at features such as flexibility, extensibility, easy maintenance and upgrade, modern DMSs adopt the open system/architecture approach where softwares and applications are mainly developed upon object-oriented programming [293]. This permits a direct correspondence between real objects (i.e. the system elements) and programmable objects, easing the usage of a single element/object database for all the DMS functions (with no need of conversion names and numbering of elements), the representation of system topology changes, and the inclusion of additional elements. Moreover, regarding the representation itself of power system elements, it is important to highlight the advent of the common information model (CIM) [287]. The CIM is an abstract model representing the objects of an electrical power system in the form of UML diagrams, enabling a seamless integration of energy management system (EMS) applications independently developed by different software vendors and/or the integration of EMSs with other systems. The CIM was conceived to EMS applications and extensions towards DMS applications were proposed by the academia (e.g. [295]) as well as they are under development into the scope of the IEC 61968 [296], a series of standards to define the information exchange between power distribution systems. In comparison with the power transmission systems, the power distribution systems have a much larger amount of data and more applications to support its routine operations and controls [295], some of them described in section 2.2.2.

One might observe that, to our purposes, it is of great interest the understanding of object-oriented modeling to abstract the system elements and simulation mechanisms. Nevertheless, it is not of our direct interest to utilize CIM objects since they were conceived to EMS applications including a large number of data and attributes that are out of the scope of this work. Hence, future developments might foresee the integration of the approaches developed herein to corporative enterprize and CIM-based systems. However, it was found more pragmatical, to our purposes, the development of an application specific object-oriented modeling from scratch to both system elements and simulation mechanisms. Therefore, after analyzing the application specific abstractions of the literature (e.g. [287, 291, 292, 297]), we have created the abstract model shown in Fig. 5.1, based on the work conceived for the power transmission systems in [297], but embedding information regarding the data files of the power system simulation software EUROSTAG [8] and the ELIPSE[5.3] Power DMS Platform [298].

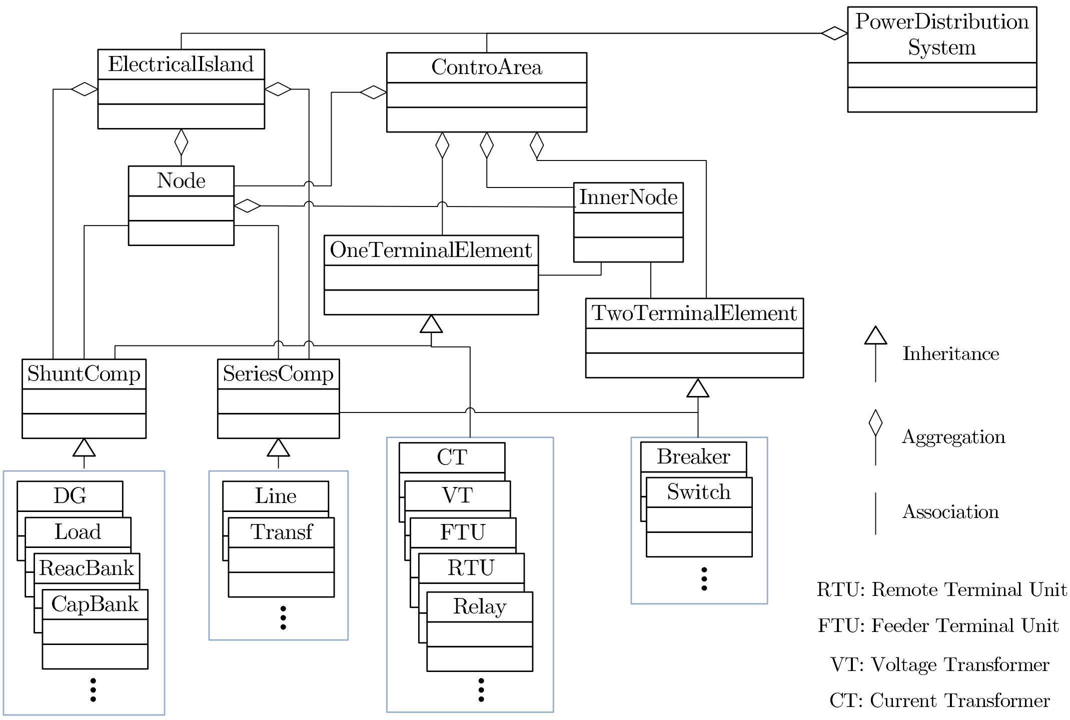


Fig. 5.1: UML class diagram for the power distribution system elements.

[5.3] The author would like to thank Eng. Tiago Santos and Eng. Felipe Kober for the discussions and material provided as courtesy of the PowerSysLab®.

In the diagram, a class hierarchy about the main classes and relations utilized to model the power distribution system elements is exhibited. In object-oriented modeling, a *class* defines a type of object. In turn, an *object* is an instantiation of a class, while a class hierarchy exhibits an abstract model of a system comprised of object types. Hence, in our approach, a power distribution system is conceived by a class named *PowerDistributionSystem* and the squared arrows out of this class indicates the concept of *aggregation*. Then, one must interpreter from the diagram that a power distribution system aggregates electrical islands, which are by definition composed of a set of connected elements. Following the single line diagram sense, these electrical islands aggregate node, shunt connected component and series connected component classes. Moreover, the node class is connected through a solid line to the series and shunt component classes, indicating *association* and physical connection in the object-oriented sense and single line diagram sense, respectively. Such association manifests itself in the existence of node objects in the list of attributes of the shunt and series component objects. In reciprocity, there are series and shunt component objects in the list of attributes of the node objects as well. Particular types of series connected components are the transformers and lines, whilst types of shunt connected components are the DG units, loads, reactor banks and capacitor banks. These subclasses inherit the attributes of the series and shunt components, in a relationship process called *inheritance*. All these classes, when instantiated, encapsulate data regarding the element they represent, including the common data utilized in steady-state and dynamic behavior analysis. For instance, the DG objects encapsulate several subobjects which contain from general data to specific control parameters. Regarding this issue, most of the control parameters were retrieved from the data sheets of EUROSTAG. Hence, from the described class relationships, the object-oriented correspondence of electrical island elements in a single line diagram is illustrated in Fig. 5.2.

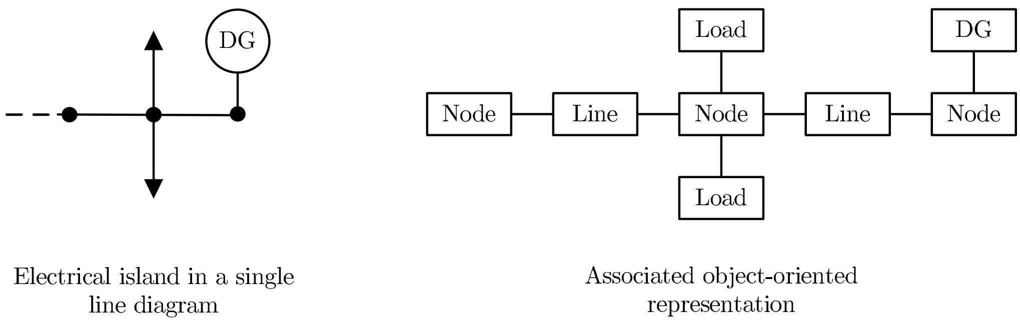


Fig. 5.2: Object-oriented correspondence of electrical island elements in a single line diagram.

In establishing a single line diagram for steady-state and dynamic behavior analysis purposes, the concept of a “node” is usually an abstract representation of actual poles (or underground notable points) with racked or nearby devices. Sometimes, information at the resolution of the pole and its connected devices are of interest, mainly when evaluating topological and control procedures. This unveils the need for encapsulating data over the protective, monitoring and control devices which, in our approach, are lumped in the node class concept, as illustrated in Fig. 5.3. In this figure, instruments that can directly change the connectivity of the network (e.g. breaker, switch) are considered two terminal element types

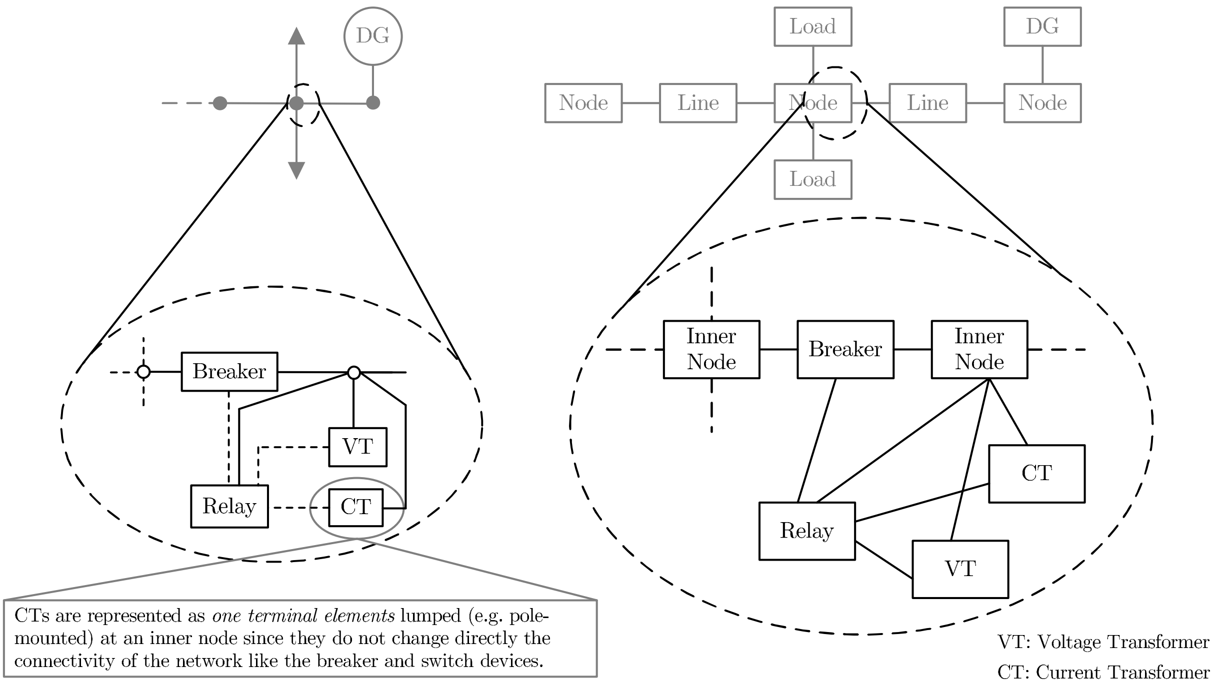


Fig. 5.3: Object-oriented correspondence of system elements in a single line diagram.

whilst others are regarded as one terminal element types. Therefore, the class hierarchy includes a more general concept named control area, which might aggregate the nodes of the electrical islands plus inner nodes, as well as lumped protective, monitoring and control devices. Furthermore, a control area class aggregates classes for one and two terminal elements, from which the shunt and series component classes inherit attributes and methods. The control area class may overlap several electrical islands or integrate the entire set of elements of the power distribution system. For the sake of clarity of the diagram, additional associations (e.g. between relays and breakers) shown in Fig. 5.3 were hidden in the class diagram of Fig. 5.1.

Once the power distribution system elements are formalized in a class hierarchy, system information can be read from data files and encapsulated in a computational object. This object is then subjected to different operation conditions created by a simulation engine that embodies the mechanisms and applications described in chapter 4. The main classes of the simulation engine are exhibited in Fig. 5.4, where a class named *CDCSapproach* is emphasized at the top of a diagram. This class abstracts the simulation model as an *aggregation* of a state composer, a state evaluator and an index composer. Summarily, the state composer is responsible for sampling, transiting and constituting operation states using as information the stochastic and deterministic models of the power distribution system elements. In turn, the state evaluator is responsible to evaluate operation states. The resultant state evaluations are then conveyed to the index composer which must keep track of the estimation of performance indices.

Certainly, all these classes depend upon a series of additional developments. These developments are outlined in the right-hand side of the figure, where several supplementary classes are illustrated. For

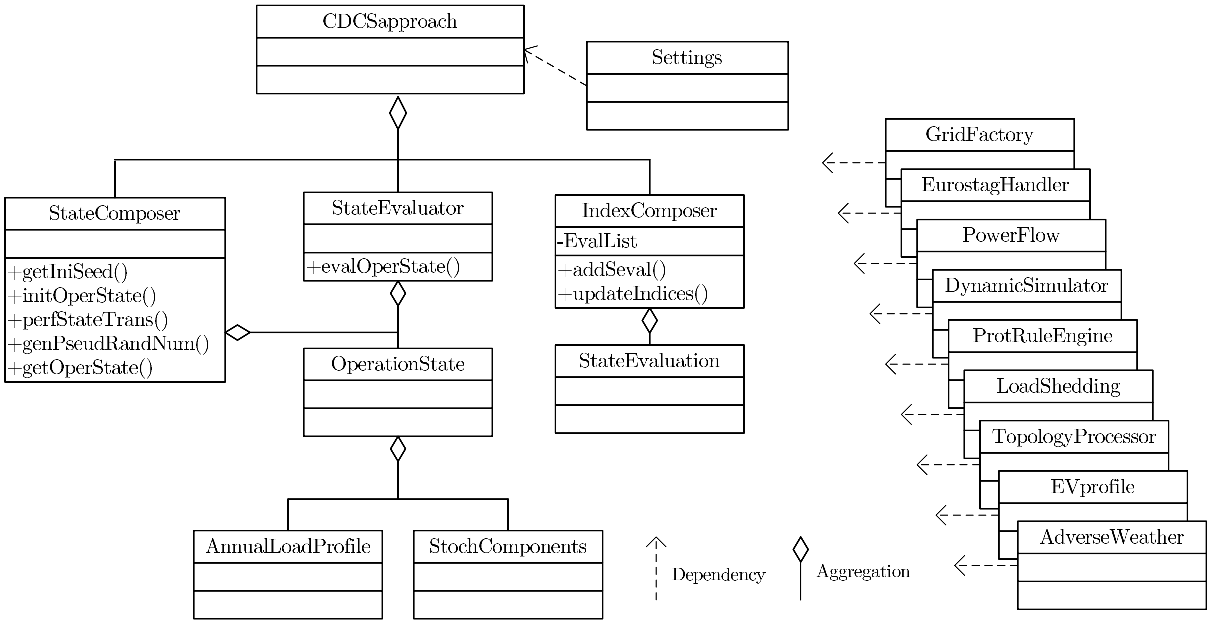


Fig. 5.4: Object-oriented modeling of the combined discrete-continuous simulation approach.

instance, a grid factory was designed in an especial class which is able to interpreter different data files and build a complete or partial power distribution system object. Also, topology processor and protection rule engine classes were developed with the aim of assigning electrical islands to a power distribution system object. Power flow and dynamic behavior analysis were encoded in separated classes using subclasses to specify control blocks and models. Particularly, an EUROSTAG handler was implemented to control the EUROSTAG software, which in turn was utilized to produce steady-state and dynamic behavior analyzes. These analyzes describe the behavior of the real world and were applied in the validation of the operation conditions obtained in the state evaluations. The modeling of EV integration, load shedding schemes and adverse weather were also designed in separate projects and then embedded in the simulation platform. All these classes allow the complete representation of the simulation mechanisms and applications described in chapter 4.

5.3 Developed Artifact-Oriented Approach

The modeling described in the previous section involves the representation of the system elements and simulation mechanisms as objects in a computational framework. Therefore, to our purposes, an overall simulation platform might be conceived in a way that AgentSpeak agents interact through speech-act based communication as well as with a shared environment developed according to the object-oriented modeling. Such strategy is possible using JASON's infrastructure which provides support to the implementation of environment models coded in the JAVA language. Hence, an environment model named *PowerDistrSysEnv* was established by extending JASON's environment class, as illustrated in Fig. 5.5.

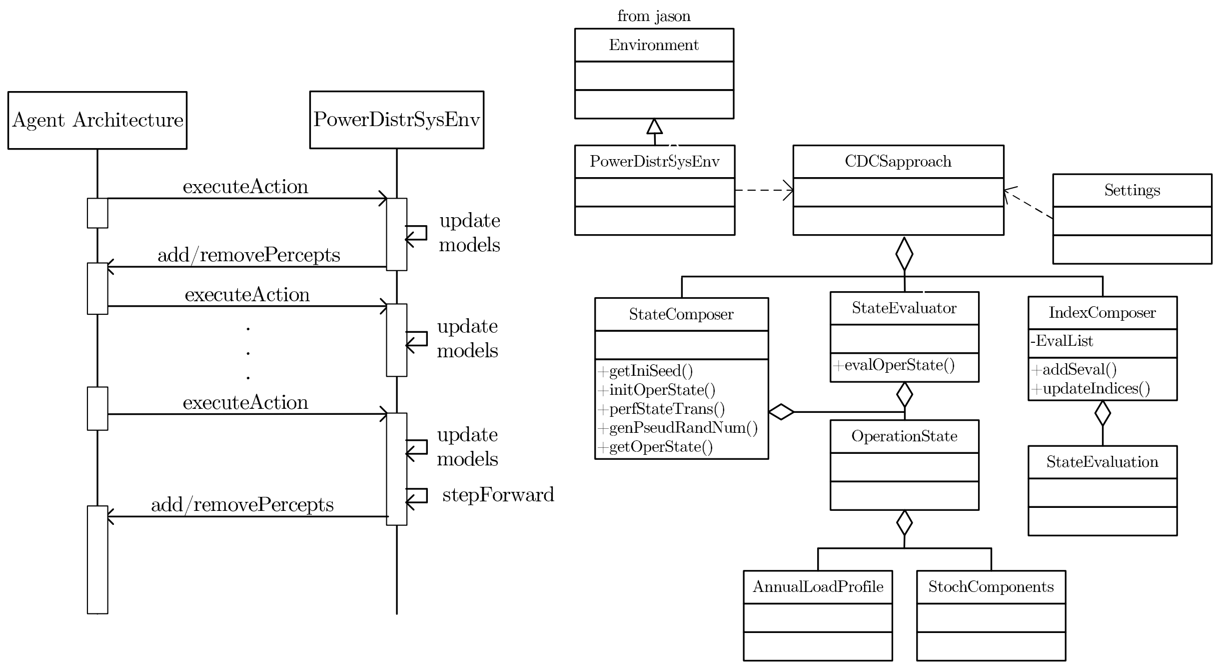


Fig. 5.5: Diagrams for the environment modeling and its interaction with the agent architecture.

In Fig. 5.5, the developed environment class is emphasized alongside its dependence/usage of the simulation mechanism modeling described in the former section. The interaction between agents and environment is then obtained as follows. In the whole simulation, each agent follows a JASON's reasoning cycle (see Fig. 2.19) where the environment's *executeAction* method is invoked by the agents to act upon the power distribution system elements and/or the simulation mechanisms. This invoking may cause the models to be updated and *percepts* to be added or removed via *addPercept* or *removePercept* method invocation, respectively, from a list of percepts to be sensed. In case a novel percept is identified, its correspondent literal ℓ is added to the agent's belief base, as well as the triggering event $+\ell$ is added to the agent's event queue. Depending upon the contexts of the agent's plan library, the triggering event $+\ell$ may (or may not) cause *intentions* to be pursued and, eventually, more interactions with environment. These intentions might also lead to actions in the environment, which in turn may result on additional model updates regarding the power distribution system elements (e.g. status of components) and simulation mechanisms. Once all *intended means* of interest are finished, the agents assign themselves as `idle` and the environment is allowed to step forward up to the next state transition instant by the developed environment's *stepForward* method invocation[5.4]. This method then utilizes the combined discrete-continuous simulation model, including its time advance mechanisms. All these schemes allow simulating the system operation embodying the agent and environment interactions in accordance to the framework

[5.4]Up to the development of this thesis, events to address the idling of agents were not found in JASON infrastructure. After discussing the scheme with JASON's developers (and perhaps influenced by our discussions), we have been informed that fully-fledged events to address this issue were prepared to help the interested programmers and developers. These pre-defined events might be available in JASON's software distribution in the future with adequate documentation.

discussed in section 5.1.

This approach was tested, implemented and validated using a small system where a capability to support islanded operation was enforced. Hence, the reader might recur to publication 5 in Appendix A to illustrative results about this research. Under this first application, it was verified that the sole undertaken of one capability development demanded already a complex managing of the percept updates associated to each agent. Due to JASON's environment infrastructure, this management was centralized in a unique environment object, a strategy which somehow seems not perfectly linked (in modeling terms) with the idea of decentralizing services and resources to support collective and individual activities. Furthermore, one might notice that not all modeled objects might be directly subjected to agent actions or have percepts to be perceived. This revels the need for an abstraction beyond the concept of a computational object aiming at the modeling of computational environments to agent-based systems.

As a matter of fact, the application mentioned above was led by the classical AI notion of environment used to identify the external world that is perceived and acted upon by the agents so that to fulfill their goals. There exists, however, a modern view of environment as a *first-class abstraction* of agent system engineering where to encapsulate services and resources to aid the agent activities. This modern view is employed in the agents and artifacts (A&A) meta model of CArtAgO, a "one of its kind" common artifact infrastructure for agent environments. The A&A meta model is the first (and quite recent) general-purpose computational/programming model to environment programming [11]. In this meta model, *artifacts* are conceived as general resources and tools, organized in workspaces, to be shared and exploited by agents working in the same environment. Hence, from the point of view of designing and implementing agent-based systems, the artifacts are basic modules to structure and organize the environment, providing a general-purpose programming and computational model to shape functionalities available to agents. On the other hand, from the agent point of view, artifacts are first-class entities structuring a world that the agents can (re-)create, dispose, act upon, share, use, and perceive at runtime (see [11,299] for discussions). Clearly, our artifact modeling may ultimately take advantage of the developed object-oriented modeling, but now focusing specifically on the agent system design matters, as illustrated in Fig. 5.6.

In the figure, one might observe the explicit separation of the agent, artifact and object-oriented modeling layers. Summarily, the agent modeling layer aggregates the agents (e.g. BA, CA)[5.5] designed in chapter 3 and implemented in JASON, whilst the object-oriented modeling layer is comprised of the computational objects (e.g. switch, node, line) described in section 5.2. Hence, in the artifact modeling layer, there are the artifacts which interact directly with the agents and may encapsulate several data in the form of computational objects. Also, they provide sets of operations and observable properties to the agents. These *operations* are computational processes which may be triggered by agents or other artifacts, whilst the *observable properties* are the variables whose value can be perceived by the agents which are observing their associated artifact. The execution of an operation can also produce *signals* carrying information to be perceived by agents as a manner to model non-persistent observable events inside the artifact. Artifacts may have also hidden matters necessary to implement inner functionalities and they can be linked together to enable one artifact to trigger the execution of operations over another artifact. Finally, artifacts may be equipped with an instruction manual [300], a machine-readable document to be consulted by agents, containing a description of the functionalities provided by the artifact and how to

[5.5] BA and CA stand for block agent and client agent, respectively, as designated in section 3.2.

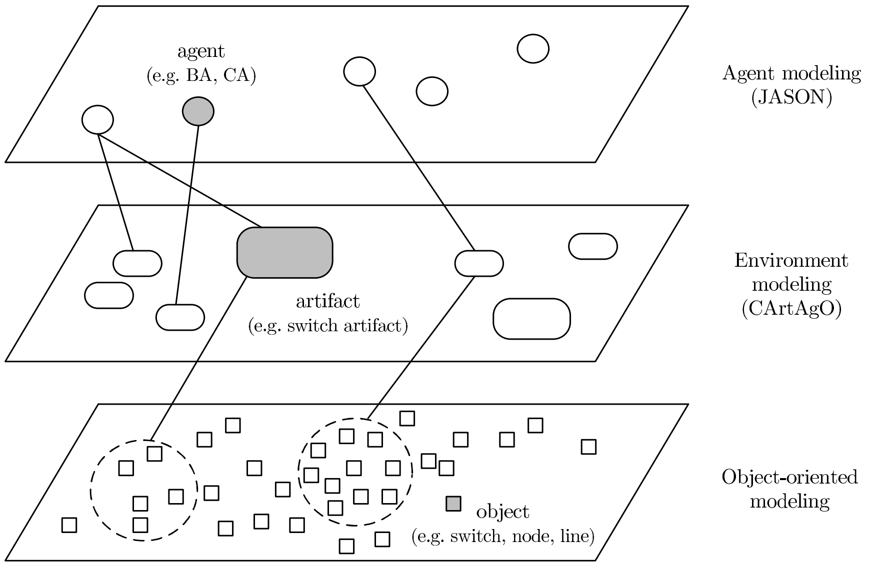


Fig. 5.6: Modeling layers emphasizing the differences between the agent, environment, and object-oriented representations.

exploit such functionalities. By using CArtAgO, it is possible to implement/program artifacts in terms of JAVA classes and basic data types, without the need of a special-purpose language.

The integration of artifact-based modeling achieved through CArtAgO with AgentSpeak agents implemented in JASON is shown in Fig. 5.7.

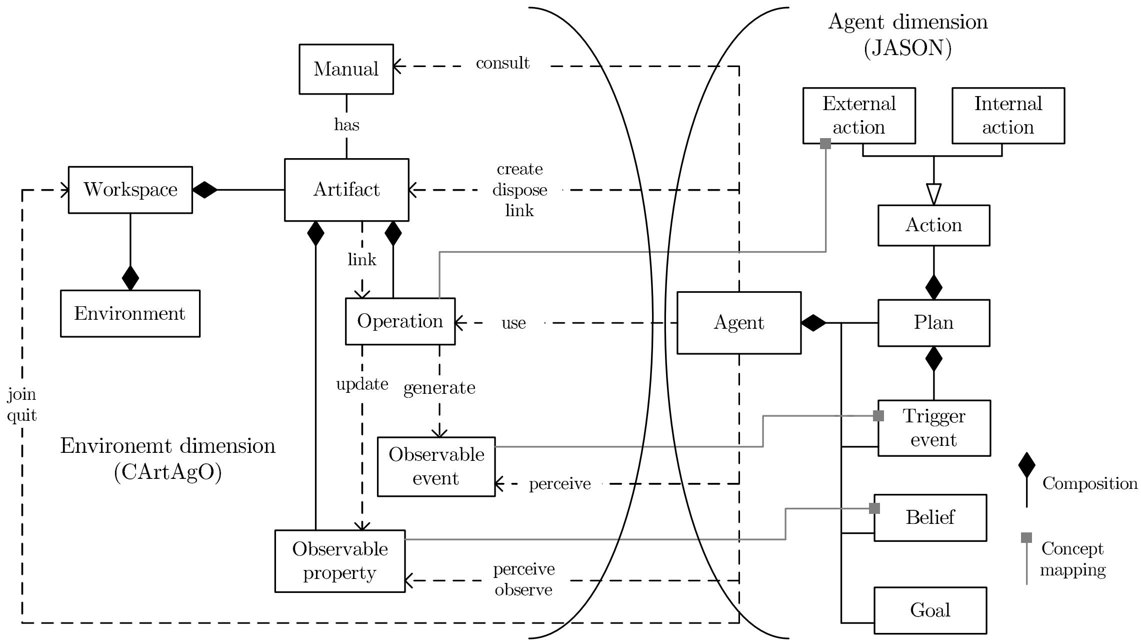


Fig. 5.7: Synergy between JASON's and CArtAgO's infrastructures (adapted from [300]).

This figure shows the synergy between the agent dimension and artifact dimension employed by JASON and CArtAgO[5.6], respectively, where concept mappings are marked through filled squared end connections. These mappings are achieved by linking the external actions of the agents to the artifact operations. Also, the concept (and practical) mappings involve linking the observable properties and events of the artifacts to the beliefs and triggering events of the agents, respectively. This implies that an agent can perform an action if there is (at least) one artifact providing this action as an operation at runtime. Moreover, it results that the set of observable properties of the artifacts that an agent is observing are directly represented as dynamic beliefs in the agent's belief base. Hence, the interaction makes possible coding plans that react to changes in the observable properties of the artifacts or that are selected on the basis of contextual conditions including the observable properties of multiple artifacts [300].

Once the object-oriented modeling of the power system elements is adequately devised, artifacts can be modeled and implemented from these objects to dynamically interact with AgentSpeak agents following the A&A meta model. Such strategy allows creating artifacts only for the elements that are supposed to interact with the agents, keeping the object-oriented representation intact for other simulation purposes. Therefore, the developed conveyance of power distribution system object types to power distribution system artifact types was achieved by utilizing the CArtAgO infrastructure, as schematized in Fig. 5.8.

```
/**
 * This class abstracts an artifact model for a general-purpose power distribution system element.
 */
public class ElementArtifact extends Artifact {                           // Declaration of artifact class

   /**
    * Power distribution system element.
    */
   Element myElement;                                 // Declaration of element object as an artifact attribute
   ⋮
   /**
    * Artifact initialization.
    */
   @OPERATION void init(Element myElement) {
      this.myElement = myElement;
      defineObsProperty(myElement.attribute.name,myElement.attribute.value);
      ⋮                                                  // ↪ Definition of artifact observable property
   }
   ⋮
   /**
    * General operation.
    */
   @OPERATION void generalOperation(...)  {                          // Definition of artifact operation
      ⋮
   }
   ⋮
}                                                                             // End of artifact class
```

Fig. 5.8: Artifact scheme of a general-purpose power distribution system element.

[5.6] The interaction between JASON agent programming and the artifact-based environment programming designed through CArtAgO is referred as JaCa in http://cartago.sourceforge.net/.

In the scheme, an artifact model is structured for a general-purpose power distribution system element. More specifically, an object type named *Element* is converted to an artifact type named *ElementArtifact*, where one of the artifact's attribute refers to the object type itself. Then, some of the object's attributes are mapped in observable properties while different operations might utilize the object's methods. For instance, in a outage management capability (see section 3.3.10), it is of interest to act upon the opening or closing of switch devices. Hence, in the A&A meta-model for power distribution system elements, this can be achieved by creating an artifact to represent the switch device, mapping the switch status as an observable property and establishing operation(s) to control its opening of closing. Using the described scheme, a simplified switch is modeled as shown in Fig. 5.9.

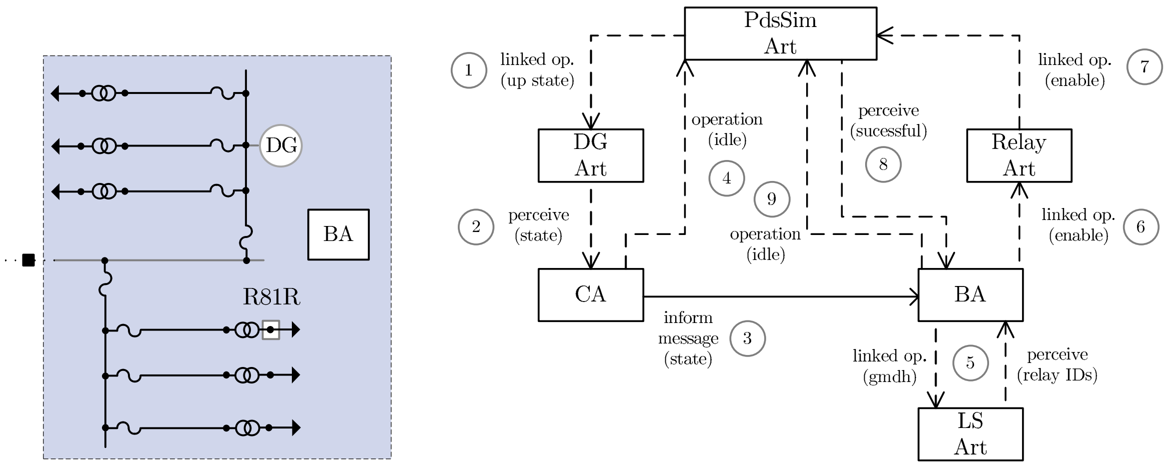
```
/**
 * This class abstracts an artifact model for switch element in a power distribution system.
 */
public class SwitchArtifact extends Artifact {                          // Declaration of switch artifact

   /**
    * Power distribution system element.
    */
   Switch mySwitch;                                  // Declaration of switch object as an artifact attribute
   ⋮
   /**
    * Artifact initialization.
    */
   @OPERATION void init(Switch mySwitch) {
      this.mySwitch = mySwitch;
      defineObsProperty("status",myElement.iStatus);
      ⋮                      // ↪ Definition of switch status as an observable property of the switch artifact
   }
   ⋮
   /**
    * This operation perfoms a change in the status of the switch artifact.
    */
   @OPERATION void changeStatus(...)  {                           // Definition of switch artifact operation
      ⋮
      ObsProperty prop_status = getObsProperty("status");                        // Get observable property
      if (prop_status.intValue() == 1) {
         prop_status.updateValue(0);                 // Change observable property to 0 (i.e.  to switch off)
      } else {
         prop_status.updateValue(1);                 // Change observable property to 1 (i.e.  to switch on)
      }
      ⋮
   }
   ⋮
}                                                                             // End of artifact class
```

Fig. 5.9: Artifact scheme of a switch element of a power distribution system.

This allows converting a switch element object type to an artifact available as a resource/tool to agent interaction. As a consequence, any agent observing the artifact will have the current status of the switch in its belief base and may act upon this status through an artifact operation.

Following this reasoning, artifacts were established for each of the elements necessary to verify sets of agent capabilities established for analyzes. This includes the sensing devices, monitoring devices, switches, FPIs, relays, HMIs, visual alarms, DG units and so forth. All these artifacts are created in runtime by an agent named `gaia` whose goals involve strictly to "give life" to the agents and to build the system artifacts using the object components devised by the whole simulation platform. Moreover, besides all these artifacts, an additional artifact was modeled to manage the algorithm mechanisms of the combined discrete-continuous simulation approach described in chapter 4. This important artifact, named *PdsSimArt*, encapsulates an object of the class *CDCSapproach* shown in Fig. 5.4 and provides a series of operations to link the system state transitions and evaluations to the operations of the element artifacts with which they are associated. Therefore, each state transition and evaluation might ultimately produce update values to the system model, which in turn are conveyed to update values to observable properties of the element artifacts causing the agents to respond accordingly. On the other hand, agent actions are performed through operations in the artifacts, which in turn might create additional transitions to be handled by the combined discrete-continuous simulation approach. At last, it must be emphasized that the developed scheme allows again the environment to step forward the time only when the agents assign themselves as `idle`. Nevertheless, this scheme was achieved through operations in the *PdsSimArt* artifact instead of through "plain" environment method invocations in JASON.

As a practical example, let us consider the network block illustrated in Fig. 5.10(a). This network block is assumed to be managed and controlled by a BA, which in turn is designed to improve the system operation through the support of block islanding activities. For this accomplishment, one of the plans involves verifying the customer loads that might be shed in case of islanding and enabling the rate of change of frequency relays of these customer loads (as modeled in section 4.3.3.2). This plan might be activated under several contexts such that after the state transition of the DG unit. Therefore, assuming the transition of the DG unit to the up state, the A&A interactions behind this plan can be summarized as illustrated in Fig. 5.10(b).



(a) Example of network block (b) Example of A&A interactions

Fig. 5.10: Example of A&A interactions within the whole simulation platform.

In Fig. 5.10(b), the artifacts associated to the DG unit and relay are emphasized. Furthermore, the DG unit is represented by a CA which is a client of the service provided by the BA. Also, the advanced modeling mechanisms described in section 4.3.3.2 are encapsulated in an artifact named LSArt. Hence, at a given point of the time advance mechanism, the interactions begin with the transition of the DG unit to the up state. This state transition is identified within the *PdsSimArt* artifact, which performs the transition itself of the DG artifact through a (1) linked operation. As consequence, this linked operation changes the observable property "state" of the DG artifact, such that this change is (2) perceived by the CA. The CA faces the change as an event that triggers a plan where the state transition is (3) informed to the BA. Once this plan is finished, the CA (4) assigns itself as `idle` to the *PdsSimArt* artifact. On the other hand, using its beliefs regarding the operation conditions, the BA (5) verifies the relays that should be enabled using the load shedding artifact. Then, the BA enables the relay artifacts through (6) linked operations. As consequence, the relay artifacts convey the (7) enabled condition back to the *PdsSimArt* artifact through linked operations as well. Finally, the BA (9) assigns itself as `idle` after (8) perceiving that the enable operations were successfully performed. Once the BA and CA are both `idle`, the *PdsSimArt* artifact steps further to the next transition of the combined discrete-continuous simulation model.

5.4 Implementation Packages

In order to test and verify the developments of the research, a simulation platform written in AgentSpeak and JAVA languages was implemented. This simulation platform was structured using the package organization shown in Fig. 5.11.

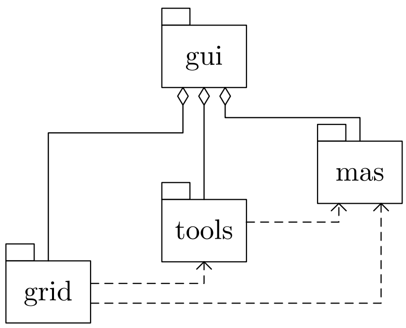


Fig. 5.11: UML package diagram for the simulation platform.

In summary, the platform is composed of four packages as follows.

Gui package. This package is composed of JAVA classes related to a graphical user interface. The package has only JAVA classes which aggregates several objects from other packages.

Mas Package. This package aggregates JAVA classes and AgentSpeak files associated to the agents and their behaviors. Therefore, they include the agents designed in chapter 3 as well as the artifacts developed under the CArtAgO infrastructure. Moreover, a JASON handler was built to start up the JASON infrastructure in a separate JAVA thread.

Tools Package. This package has classes associated to the power system analysis and simulation mechanisms utilized in our developments and illustrated in Fig. 5.4.

Grid Package. This package aggregates the classes which abstract a power distribution system and its elements, some of them illustrated in Fig. 5.1.

All these packages were implemented using Eclipse [301], a free and open source software development environment.

5.5 Summary and Discussions

This chapter completed the environment modeling by describing the interconnection of the agent-based architecture (from chapter 3) with the simulation model mechanisms (from chapter 4) using the artifact-based infrastructure provided by CArtAgO. While the description of mathematical modeling issues of power system related phenomena is a common practice in the power engineering academia, computational modeling issues are generally disregarded. On the other hand, computational modeling issues are of major importance to define agent-based applications either in the power engineering context or in other contexts. Hence, reasoning about the emphasis to be established herein, we focused the discourse objectively on the environment conception and how it interacts with the developed agents, avoiding extensive details about UML diagrams and organizing the discussions for a reader which may not be familiar with object-oriented modeling.

In providing initial remarks regarding the chapter, it was clarified the distinctions of the different types of time representations approached in the developed environment. Then, the classes designed to represent the power distribution system elements in our computational framework were straightforwardly outlined. These classes embody data utilized in power system dynamic simulation tools (e.g. EUROSTAG) and a DMS platform (ELIPSE Power DMS Platform). Moreover, they were structured in such a way that a direct correspondence between the object-oriented and single line diagram representations can be established, easing their application in tools specifically developed to power distribution system analysis (e.g. power flow, dynamic behavior analysis, topology analysis). As a matter of fact, several tools were conceived and implemented within the simulation mechanisms of the power distribution system operation. Using these tools, additional classes to model the simulation mechanisms themselves were created by separating the major simulation algorithm responsibilities, namely the composition of operation states, their evaluation, and the estimation of performance indices. All these quoted classes comprise the object-oriented representation of the elements and mechanisms introduced in chapter 4.

Using the whole object-oriented modeling, a general-purpose artifact scheme is devised to represent artifacts in a power distribution engineering environment context. The scheme is based on the modeling of artifacts only for the power distribution system elements which must be perceived or acted upon in runtime. Of course, additional artifacts were allowed to model resources and tools which might be built, disposed, shared, used, perceived and acted upon by the agents designed in chapter 3. Hence, the synergy between AgentSpeak agents with artifacts is described and an additional artifact to encapsulate the simulation mechanisms is derived, closing the description of the environment modeling. Therefore, by addressing annotation F, the resulting environment models the system operation in order to evaluate the long-term impact of the agent-based solutions according to performance indices, then providing a common infrastructure (through CArtAgO) to different agent platforms which in turn might be developed to different purposes. Finally, we highlight that reasoning cycle time durations and communications delays were neglected, in the same way they were disregarded in the developments of chapter 4. The representation of communication media and time-stamped reasoning activities altogether in the environment simulation were considered out of the scope of this research and compose the list of topics for future works.

Chapter 6

Simulations and Result Analysis

This chapter presents quantitative and qualitative result analysis regarding the research developments of this thesis. The chapter is organized as follows. Section 6.1 introduces general remarks about the series of simulation experiments devised to highlight the applicability of the developed solutions. Then, assuming a standard framework of operation and control, section 6.2 exhibits case studies elaborated over a consolidated test feeder in order to validate the main stochastic and deterministic models utilized in the combined discrete-continuous simulation approach. Hence, under the developed framework, section 6.3 shows a large set of simulation results associated to the application of the block-oriented agent-based architecture with environment modeling to an actual feeder from the South of Brazil. Finally, section 6.4 outlines conclusions and final remarks.

6.1 General Remarks about the Experiments

The experiments devised in this chapter aim at illustrating the application and evaluation of the block-oriented agent-based architecture in the support of the power distribution system operations. Since the experiments involved stochastic evaluations, special attention was paid concerning the seed[6.1] control of the uniformly distributed random numbers generated within the simulation platform. As consequence, all experiments can be repeated at will, allowing also the controlled replication of each state transition and the fair comparison of performance index estimates. Moreover, a large series of validation studies were gradually undertaken during the implementation of the whole simulation platform in order to assure the validity and accuracy of the developed models. Hence, about this particular matter, we have chosen to exhibit application results of the combined discrete-continuous simulation model in the performance assessment of a consolidated test system, thereby validating the main stochastic/deterministic transitions employed by the simulation approach. Such experiments produced already a large set of results whose initial figures are summarized in publication 8 in Appendix A. Furthermore, under the developed framework, a large set of results is presented regarding the application of the block-oriented agent-based architecture with environment modeling to an actual power distribution feeder from the South of Brazil.

[6.1] A seed is an integer used to initialize a pseudorandom number generator.

This second set of results involves from plain stochastic evaluations to simulations with agent and artifact interactions. Although the basic figures regarding adequacy and security evaluation of this actual network were presented in publication 1 in Appendix A, this second set of results is also completely novel.

The operational/control strategies applied in our framework were evaluated according to their impact on the power distribution system performance indices. Therefore, for the ease of the reader, the units of these performance indices were summarized in Table 6.1.

Table 6.1: Performance indices and their respective units

System Index	Unit	Load Point Index	Unit
SAIFI	interruptions/year	λ_i	interruptions/year
SAIDI	h/year	U_i	h/year
CAIDI	h/interruption	r_i	h/interruption
ASAI	-	λ_{v_i}	occurrence/year
ASUI	-	U_{v_i}	h/year
ENS	MWh/year	r_{v_i}	h/occurrence
AENS	MWh/customer/year	-	-

In all experiments, the convergence of the simulations was assigned for β values (see section 4.3.5) inferior to 5% for the system-wide performance indices. Hence, it is important to highlight that such convergence criteria does not implicate that the load point (LP) indices have reached the same coefficient of variation threshold. At last, the numerical results presented herein were enhanced with information concerning the computation time (τ) of the simulations, which in turn were performed on a personal computer with an Intel Core i7 3.40 GHz processor and 8 GB of random-access memory.

6.2 Standard Framework Application

Under a standard framework of operation and control, this section presents the application of the combined discrete-continuous simulation approach for a well-known test feeder providing both a brief system description and performance evaluation results.

6.2.1 Description of the Test Feeder: RBTS-BUS2-F1

The validation of the system operating cycle generated by the stochastic and deterministic models of the combined discrete-continuous simulation approach is addressed herein through a series of case studies developed over a consolidated test feeder called Roy Billinton Test System – Bus 2 – Feeder 1 (RBTS-BUS2-F1) [302], whose single line diagram is illustrated in Fig. 6.1. The RBTS-BUS2-F1 was specifically designed for reliability performance assessments, following that only reliability analysis information (data and results) is provided within its data set. This test feeder is composed of a main supply source representing a primary substation (indicated as SUB in Fig. 6.1), 1 feeder breaker, 1 alternative supply source, 19 nodes, 4 sections at the main feeder (trunk), 7 primary laterals, 7 secondary transformers, 7 lateral fuses, 3 sectionalize switches (called disconnects in the data sheet), 1 tie switch with the alternative supply source, and 652 customers distributed over 7 points of consumption. The component reliability information (failure and repair rates) and customer information (point of consumption and load demand) are disclosed in [302].

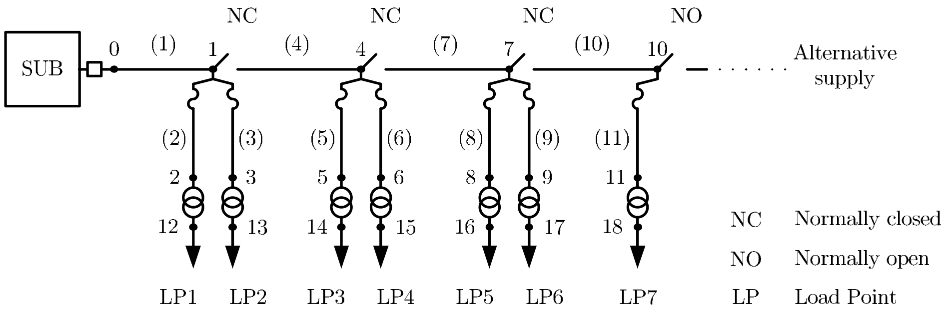


Fig. 6.1: Roy Billinton Test System – Bus 2 – Feeder 1.

6.2.2 Framework Application and Performance Evaluation

In the RBTS-BUS2-F1, the standard framework of operation and control involves the individual operation of the breaker, fuse, sectionalize and tie switch devices, the repairing of components (lines and transformers) under failure state, managing sectionalize switches to isolate components under failure state, and managing the tie switch to restore the service using the alternative supply source. Under this framework, the developed set of performance evaluations consists of eight case studies, named A, B, C, D, E, F, G, and H. These cases were assessed not only by the combined discrete-continuous simulation (CDCS) model, but also using the classical analytical technique (see [268] for details) for validation purposes. Cases A, C, E, and G assume constant average load levels throughout the simulated years. Cases B, D, F and H apply a peak load normalized version of the annual load curve of the IEEE Reliability Test System 79 [269] as load factor[6.2] for each of the LPs. The RBTS-BUS2-F1 is a reliable system which required the simulation of at least 11500 years of operation in order to guarantee β values inferior to 5%. Since the purpose of these analyzes is to verifying the simulation model, we reduced even more the β values by simulating 50000 years of operation for each case. A summary of the case studies devised for the RBTS-BUS2-F1 is shown in Table 6.2.

Table 6.2: Summary of case studies elaborated over the RBTS-BUS2-F1

Case ID	LP demand	Device operations
A	Constant	breaker
B	Variable	breaker
C	Constant	breaker and fuses
D	Variable	breaker and fuses
E	Constant	breaker, fuses, sectionalize switches
F	Variable	breaker, fuses, sectionalize switches
G	Constant	breaker, fuses, sectionalize switches and tie switch
H	Variable	breaker, fuses, sectionalize switches and tie switch

Cases A and B assume the representation of the main breaker protection, neglecting fuse, sectionalize switch and tie switch related operations. The numerical results of these cases are shown in Table 6.3, emphasizing the performance index estimates as well as the inferior (Inf.) and superior (Sup.) limits of

[6.2] Originally, the annual load curve of the IEEE Reliability Test System 79 has 8736 hour entries representing a year with 364 days. Hence, the last 24 hour entries were repeated in the end of the data array to compose 8760 hour entries for a year with 365 days. Such update is demanded to guarantee a fair comparison with the results provided by the classical analytical technique.

the confidence intervals.

Table 6.3: System-wide performance indices for cases A and B

Index	Case A Analyt.	Case A CDCS	Case A β (%)	Case A Inf.	Case A Sup.	Case B Analyt.	Case B CDCS	Case B β (%)	Case B Inf.	Case B Sup.
SAIFI	0.62500	0.62750	0.56647	0.62053	0.63447	0.62500	0.62750	0.56647	0.62053	0.63447
SAIDI	23.56462	24.22581	1.74586	23.39684	25.05477	23.56462	24.22581	1.74586	23.39684	25.05477
CAIDI	37.70339	38.60686	-	-	-	37.70339	38.60686	-	-	-
ASAI	0.99731	0.99723	0.00484	0.99714	0.99733	0.99731	0.99723	0.00484	0.99714	0.99733
ASUI	0.00269	0.00277	1.74586	0.00267	0.00286	0.00269	0.00277	1.74586	0.00267	0.00286
ENS	85.89303	88.30306	1.74586	85.28148	91.32464	52.77073	54.21846	1.75021	51.77417	56.66276
AENS	0.13174	0.13543	1.74586	0.13080	0.14007	0.08094	0.08316	1.75021	0.08030	0.08601
					$\tau = 27.15$ min.					$\tau = 27.23$ min.

One might highlight that the performance indices approximated by the analytical technique fall within the confidence interval provided by the simulation model. Also, the performance indices SAIFI, SAIDI, CAIDI, ASAI, and ASUI are equal for both cases. This result is consistent with the fact that the failures in the components and the actuation of the breaker device are, in this sort of analysis, independent of the loading of the system. As a matter of fact, a customer interruption is assigned herein either if the loading is at its maximum value or its minimum value. Clearly, if the seed of the uniformly distributed random number utilized to sample the state transitions was not controlled, the failure/repair cycle of components could not be repeated and the quoted equality in results would not be obtained. Since only the breaker operations are considered in these cases, all customers in the system experience the same interruptions. As consequence, the system indices SAIFI, SAIDI, CAIDI coincide with the LP performance indices λ, U, r, respectively.

On the other hand, in cases C and D, the main breaker and fuse operations are represented altogether. Similarly to the former cases, numerical results are shown in Table 6.4.

Table 6.4: System-wide performance indices for cases C and D

Index	Case C Analyt.	Case C CDCS	Case C β (%)	Case C Inf.	Case C Sup.	Case D Analyt.	Case D CDCS	Case D β (%)	Case D Inf.	Case D Sup.
SAIFI	0.24799	0.24816	0.81719	0.24418	0.25213	0.24799	0.24816	0.81719	0.24418	0.25213
SAIDI	4.16345	4.20658	2.09700	4.03369	4.37948	4.16345	4.20658	2.09700	4.03369	4.37948
CAIDI	16.78856	16.95136	-	-	-	16.78856	16.95136	-	-	-
ASAI	0.99952	0.99952	0.00101	0.99950	0.99954	0.99952	0.99952	0.00101	0.99950	0.99954
ASUI	0.00048	0.00048	2.09700	0.00046	0.00050	0.00048	0.00048	2.09700	0.00046	0.00050
ENS	15.17440	15.50172	1.46306	15.05720	15.94624	9.32281	9.51669	1.46807	9.24286	9.79052
AENS	0.02327	0.02378	1.46306	0.02309	0.02446	0.01430	0.01460	1.46807	0.01418	0.01502
					$\tau = 27.08$ min.					$\tau = 27.38$ min.

In comparison with the previous cases, the fuse operations allowed the reduction of the SAIFI index by around 60.45%. This result was expected since, in cases C and D, the failures at the feeder laterals are dealt by fuse operations rather than by the substation breaker, thereby interrupting less customers per interruption in average. Moreover, the other performance indices have also improved in consequence of the reduction of the average customer interruption frequency of the feeder. Again, the performance indices approximated by the analytical technique are consistent with the confidence intervals provided by the simulation model. Also, the average customer interruption indices in cases C and D are perfectly equal, whilst the indices associated to the energy not supplied by the feeder are distinct. This outcome was similarly anticipated once these two cases are differentiated only by their annual load curves.

Considering the aforementioned breaker and fuse operations, cases E and F include also the representation of the sectionalize switch operations. Furthermore, cases G and H include, additionally to the sectionalize switch operations, the application of an alternative supply source with normally open tie switch in the end of the feeder. These two sets of cases provide the results shown in Table 6.5 and 6.6, respectively, where one can verify that the SAIFI values have not changed in comparison with cases C and D. Such equality would not be verified if, at some point of the simulation, customers served due to the sectionalize and/or tie switch operations were interrupted. However, these particular cases showed to be quite rare for the RBTS-BUS2-F1 feeder, such that their occurrences were not found within the 50000 synthetic years of operation. Regarding other performance indices, the operation of the switches and alternative supply source allowed the reduction of the average interruption duration (SAIDI) and service unavailability (ASUI), besides reducing the energy not supplied (ENS) by the feeder.

Table 6.5: System-wide performance indices for cases E and F

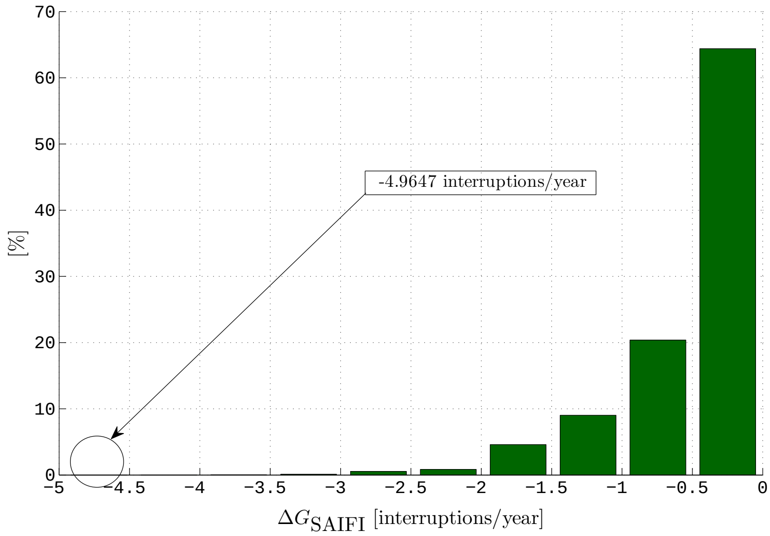
Index	Case E					Case F				
	Analyt.	CDCS	β (%)	Inf.	Sup.	Analyt.	CDCS	β (%)	Inf.	Sup.
SAIFI	0.24799	0.24816	0.81719	0.24418	0.25213	0.24799	0.24816	0.81719	0.24418	0.25213
SAIDI	3.69572	3.73823	2.34015	3.56677	3.90969	3.69572	3.73823	2.34015	3.56677	3.90969
CAIDI	14.90252	15.06403	-	-	-	14.90252	15.06403	-	-	-
ASAI	0.99958	0.99957	0.00100	0.99955	0.99959	0.99958	0.99957	0.00100	0.99955	0.99959
ASUI	0.00042	0.00043	2.34015	0.00041	0.00045	0.00042	0.00043	2.34015	0.00041	0.00045
ENS	14.04514	14.37011	1.55872	13.93110	14.80912	8.62901	8.82500	1.56320	8.55462	9.09538
AENS	0.02154	0.02204	1.55872	0.02137	0.02271	0.01323	0.01354	1.56320	0.01312	0.01395
					τ = 30.02 min.					τ = 30.10 min.

Table 6.6: System-wide performance indices for cases G and H

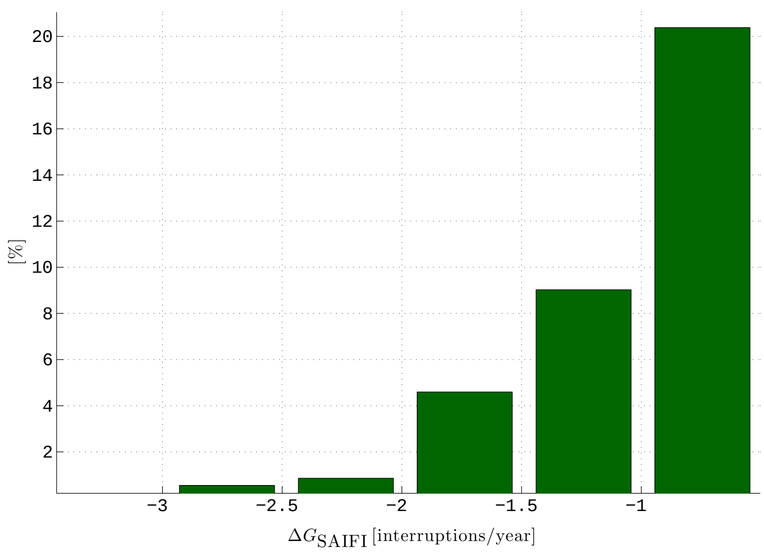
Index	Case G					Case H				
	Analyt.	CDCS	β (%)	Inf.	Sup.	Analyt.	CDCS	β (%)	Inf.	Sup.
SAIFI	0.24799	0.24816	0.81719	0.24418	0.25213	0.24799	0.24816	0.81719	0.24418	0.25213
SAIDI	3.62069	3.65640	2.39113	3.48504	3.82776	3.62069	3.65640	2.39113	3.48504	3.82776
CAIDI	14.59995	14.73427	-	-	-	14.59995	14.73427	-	-	-
ASAI	0.99959	0.99958	0.00100	0.99956	0.99960	0.99959	0.99958	0.00100	0.99956	0.99960
ASUI	0.00041	0.00042	2.39113	0.00040	0.00044	0.00041	0.00042	2.39113	0.00040	0.00044
ENS	13.27364	13.49644	1.65125	13.05965	13.93324	8.15502	8.29087	1.65532	8.02188	8.55985
AENS	0.02036	0.02070	1.65125	0.02003	0.02137	0.01251	0.01272	1.65532	0.01230	0.01313
					τ = 30.05 min.					τ = 30.88 min.

The performance indices shown in the former tables represent average values obtained through an analytical technique and the simulation model. Although they reflect in average the system performance, these values by themselves provide, arguably, poor information to assess the power distribution feeder. However, differently from the analytical technique, the simulation model is based upon building time-sequential synthetic operating cycles. As consequence, the impact of operational/control solutions in the power distribution system operation can be verified through the uprising/downsitting of the performance indices over the synthetic years of operation. Furthermore, the probability distributions of the uprising/downsitting of the performance indices can be obtained using an explicit representation of the state evaluations within the computational modeling. Following this reasoning, using case B as base case, Fig. 6.2–6.4 exhibit the impact of fuse, sectionalize switch and tie switch related strategies utilized in case H.

In summary, Fig. 6.2–6.4 show the estimated probability distribution of the variation of the SAIFI, SAIDI and ENS indices achieved through the operational/control strategies utilized in case H. This sort of information unveils that, for instance, despite of the absolute average reduction of 0.3793 interruptions/year, the strategies considered in case H avoided more than 0.5 interruption/year in roughly 20% of the simulated years. This implies that an average customer in this feeder might experience less 0.5 interruption/year thanks to the operational/control strategies in around 20% of the years of operation.

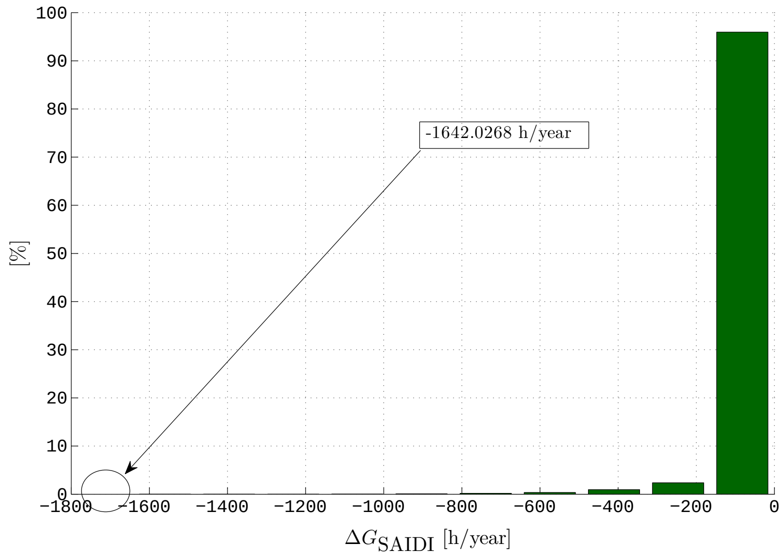


(a) Estimated probability distribution of $\Delta G_{\mathrm{SAIFI}}$ (10 bins).

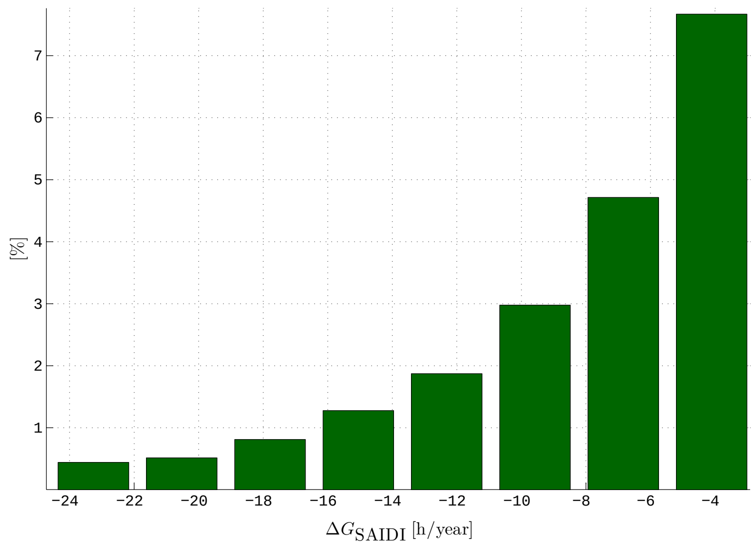


(b) Estimated probability distribution of $\Delta G_{\mathrm{SAIFI}}$ focused at a given interval (10 bins).

Fig. 6.2: Impact of fuse, sectionalize switch and tie switch strategies on the SAIFI of case B.

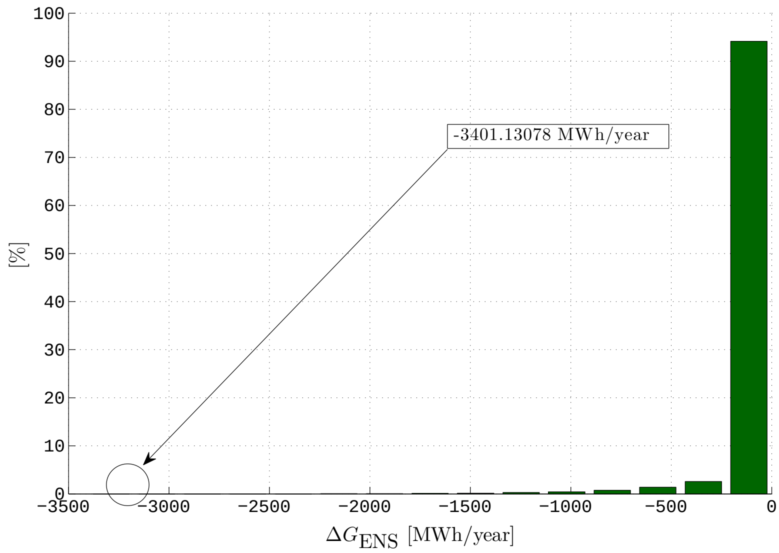


(a) Estimated probability distribution of $\Delta G_{\mathrm{SAIDI}}$ (10 bins).

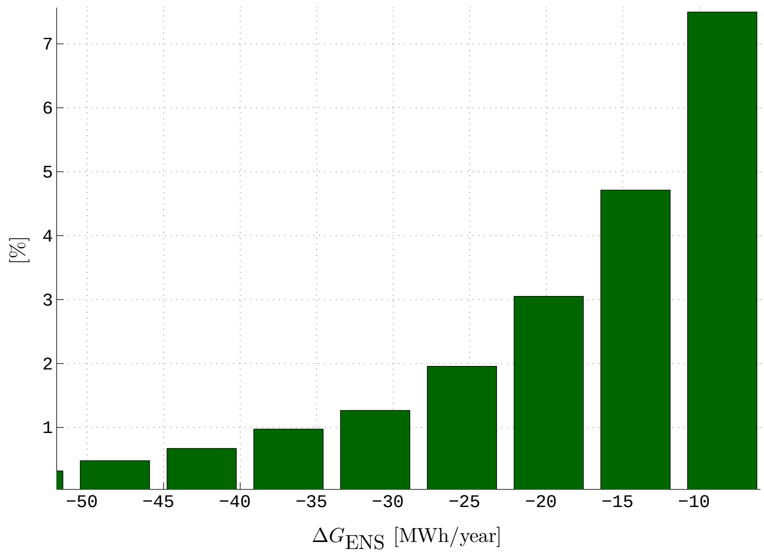


(b) Estimated probability distribution of $\Delta G_{\mathrm{SAIDI}}$ focused at a given interval (600 bins).

Fig. 6.3: Impact of fuse, sectionalize switch and tie switch strategies on the SAIDI of case B.



(a) Estimated probability distribution of ΔG_{ENS} (15 bins).



(b) Estimated probability distribution of ΔG_{SAIDI} focused at a given interval (600 bins).

Fig. 6.4: Impact of fuse, sectionalize switch and tie switch strategies on the ENS of case B.

Hence, similar analyzes can be established for the estimated average interruption durations and energy not supplied by the feeder. For example, it can be verified that the strategies in case H avoided more than 6 hours and 10 MWh of system average customer interruption durations and energy not supplied, respectively, in around 4.8% of the simulated years. These sorts of improvements may avoid a series of penalties to the utility that provides electric energy through the feeder. In fact, depending upon the rules specified by regulatory bodies, severe penalties may be established for high customer interruption frequencies and durations. Also, the energy not supplied might be intrinsically related to a diminishing in the utility's revenue. Therefore, in analyzing the penalty reductions and revenue increase due to the operational/control strategies, a power distribution engineer might quantify its interest on the adoption of these strategies and their required payback.

Once all system-wide performance indices are presented, for the sake of completeness, Fig. 6.5–6.7 show the LP performance indices for cases A–H. As expected, it was verified that the LP indices also tend to their analytically computed values with the increase of the number of simulated years. This completes the performance evaluation of the test feeder and validates the main stochastic and deterministic state transitions produced in the simulation model.

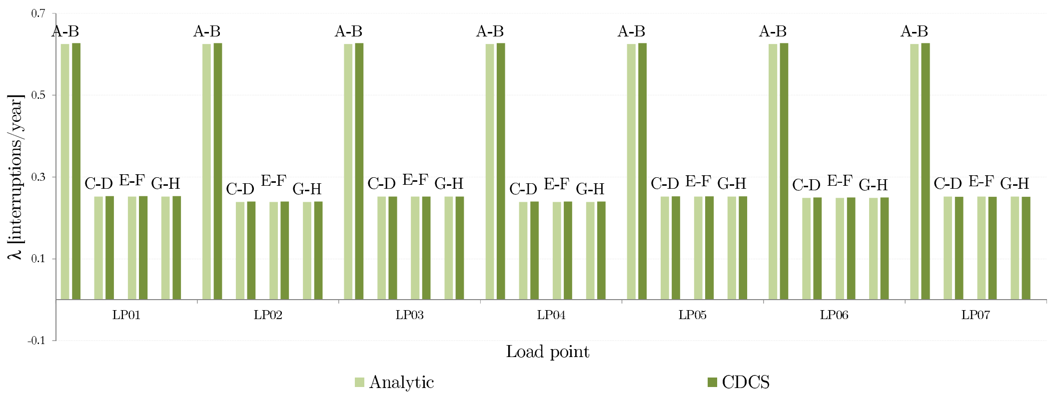


Fig. 6.5: Failure rate of the LPs for cases A–H.

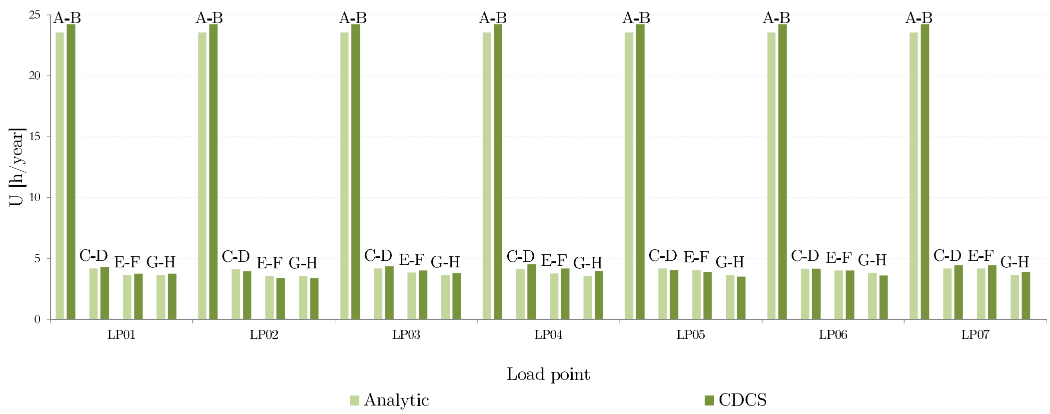


Fig. 6.6: Unavailability of the LPs for cases A–H.

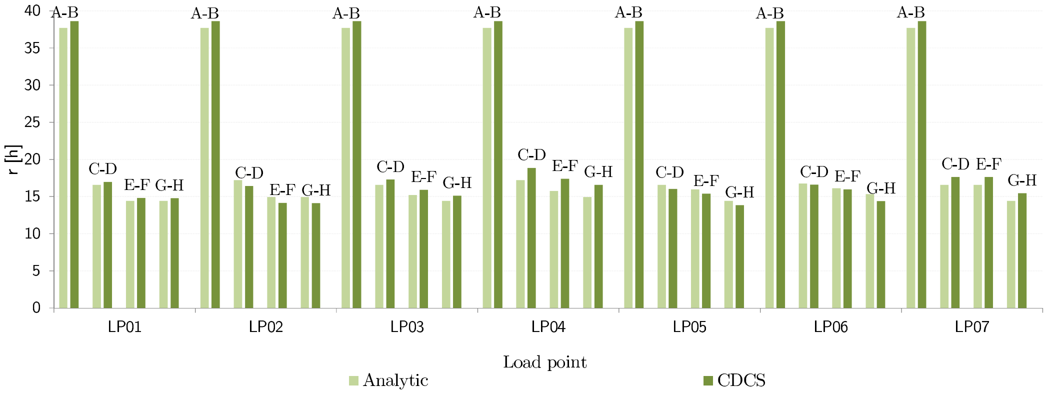


Fig. 6.7: Mean time to repair of the LPs for cases A–H.

The combined discrete-continuous simulation model goes beyond the sole reliability analysis by unifying the representation of the long-term stochastic failure/repair cycle of system components with the representation of aspects of system steady-state and dynamic behavior analysis. As consequence, various additional analyzes can be performed concerning, for instance, the impact of DG integration on the network load transfer capabilities or the impact of DG islanded operation on the performance indices. Nevertheless, since the RBTS-BUS2-F1 only provides data for plain reliability assessments, several information would have to be hypothesized to perform these sorts of analyzes. Therefore, results utilizing the quoted unification of representations are provided for an actual power distribution feeder from which a large variety of data was obtained and organized. Finally, under the scope of a block-oriented management and control philosophy, one must emphasize that the simulation approach is utilized herein as the mathematical basis of a computational environment modeling designed to evaluate the agent capabilities. Case studies focused "only" on the quoted impacts of DG interconnection can be found in publications 8, 1 and 2 in Appendix A.

6.3 Developed Framework Application

This section addresses the application and evaluation of the block-oriented agent-based architecture to an actual power distribution feeder from the South of Brazil. For this accomplishment, section 6.3.1 provides a brief description of the actual feeder utilized in the simulations. Then, in section 6.3.2, the developed framework is verified over the operation of the described feeder, focusing on the interactions and performance evaluations behind the client and block subscription activities, the sharing-handling-alerting-updating of data and information, the support to islanding and islanded operation procedures, and the support to outage management.

6.3.1 Description of the Actual Feeder: CAX1-105

The actual power distribution feeder utilized in our framework, called CAX1-105 by the local utility personnel, is exhibited in Fig. 6.8. The feeder covers the wide area of 166.33 km^2 providing electricity

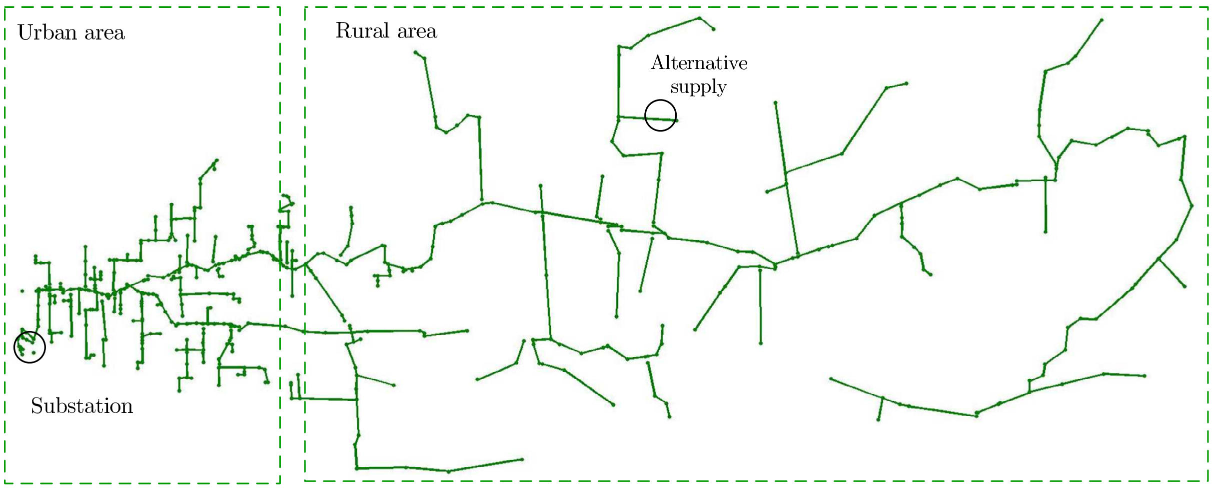


Fig. 6.8: Actual power distribution feeder from the South of Brazil (CAX1-105).

for 9780 registered clients (5.36 + j1.84 MVA peak). The service area is split into an urban area (on the left-hand side of the figure) and a rural area (on the right-hand side of the figure). Most of the clients dwell at the urban area which is small, reliable, and well-serviced. In contrast, the rural area supplies only 1865 registered clients (1.03 + j0.34 MVA peak) and is characterized by its large extension and lower quality of service in certain periods of the year. The network is composed of 547 nodes (associated to 1 substation bus and 546 network nodes), 546 lines, 215 secondary transformers (with lumped loads), 1 capacitor bank, 1 substation breaker, 10 sectionalize switches, 1 tie switch and 41 lateral fuses. All network and customer information is disclosed in [303].

6.3.2 Framework Application and Performance Evaluation

Similarly to the RBTS-BUS2-F1, a series of case studies were devised to the CAX1-105, named I, J, L, M, N, O, and P. In all these cases, the simulation platform which includes all developments of chapters 3–5 is utilized. Particularly, in the first case named case I, the presence of agents to support the system operation is disregarded. Hence, the results associated to case I are equivalent to those obtained through the sole application of the combined discrete-continuous simulation model. As a matter of fact, the only difference from the sole application of the simulation model lies on the elapsed time duration of the simulation which is slightly longer in this case due to the initialization of the JASON and CArtAgO infrastructures. Case I is introduced in this subsection whilst other cases are presented in further subsections.

Regarding application data, the data set of the CAX1-105 includes large amounts of reliability data, customer data and electrical parameter information. Nevertheless, it does not include weather information. On the other hand, the system interruptions of this feeder are well-known to depend upon high wind speed events, such that the proportions of failures in adverse weather and normal weather conditions are 0.31 and 0.69 [304], respectively. As consequence, aiming at illustrating the adverse weather modeling related to high wind speed events, examples of wind speed data were obtained from the National

Renewable Energy Laboratory [305], where wind speed time series from a certain geographical location were retrieved with an update window of 10 minutes. Considering an average annual duration of adverse weather of 48 h [302], a critical wind speed (w_{crit}) of 23.14 m/s was computed from the time series. Using this critical wind speed value, the total durations in adverse weather and normal weather conditions were retrieved. Hence, assuming that all components are subjected to the same weather conditions, the scaling parameter α of each component was computed, as described in section 4.3.2. Moreover, without loss of generality, by assuming that the rates of occurrence of high wind speed events exhibit a monthly variation (in resemblance to the work in [271]), these rates can be retrieved as illustrated in Fig. 6.9.

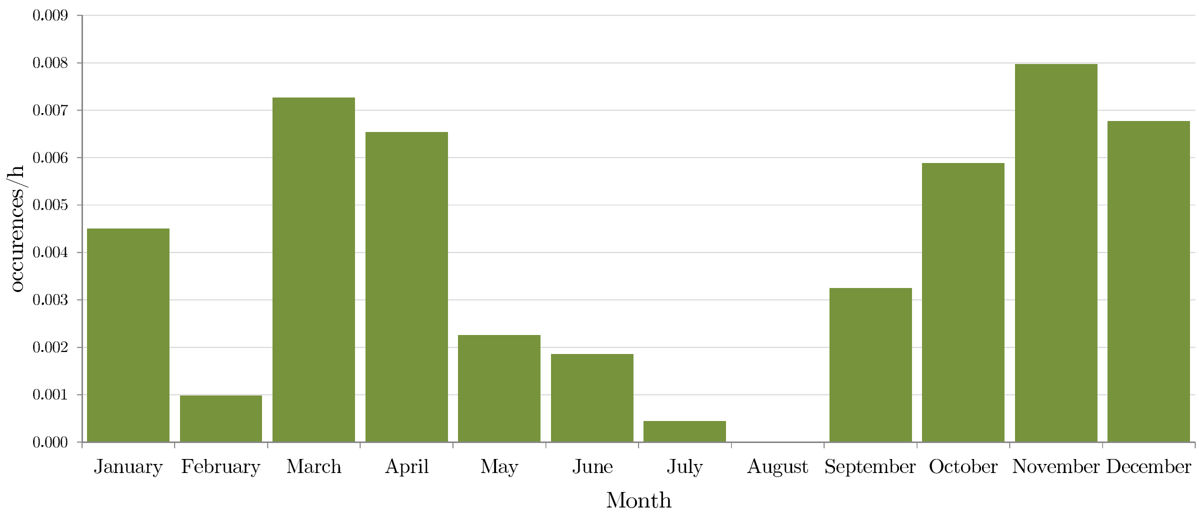


Fig. 6.9: Rates of occurrences of high wind speed events.

The union of the rates of occurrence of high wind speed events composes the piecewise time-dependent function required to sample these events following a non-homogeneous Poisson process. However, to characterize the high wind speed events themselves, high wind speed durations (T_w) and intensity variations (Δw^2) must also be sampled. As consequence, the Weibull distribution function of the high wind speed duration was estimated ($scp_{T_w} = 78.0126$ min., $shp_{T_w} = 0.8952$) as shown in Fig. 6.10. Similarly, Fig. 6.11 illustrates the Weibull distribution function ($scp_{\Delta w^2} = 105.5825$ m^2/s^2, $shp_{\Delta w^2} = 0.9485$) estimated for the high wind speed intensity variation.

Using these models, the performance indices of the actual feeder were obtained through the simulation platform. Although cases without and with adverse weather effects may not be directly comparable in the sense that they provide different state transitions throughout the synthetic years of operation, the average customer interruption durations are expected to be higher with the adverse weather modeling due to the imposition that components are not repaired during adverse weather conditions. This result was indeed verified as shown in Fig. 6.12, where the convergence of the SAIDI index is exhibited for case I and for a general case without adverse weather representation.

Hence, the performance indices of case I are summarized in Table 6.7. The result analysis unveiled that the CAX1-105 feeder is not as reliable as the RBTS-BUS2-F1 test feeder, at least in terms of the

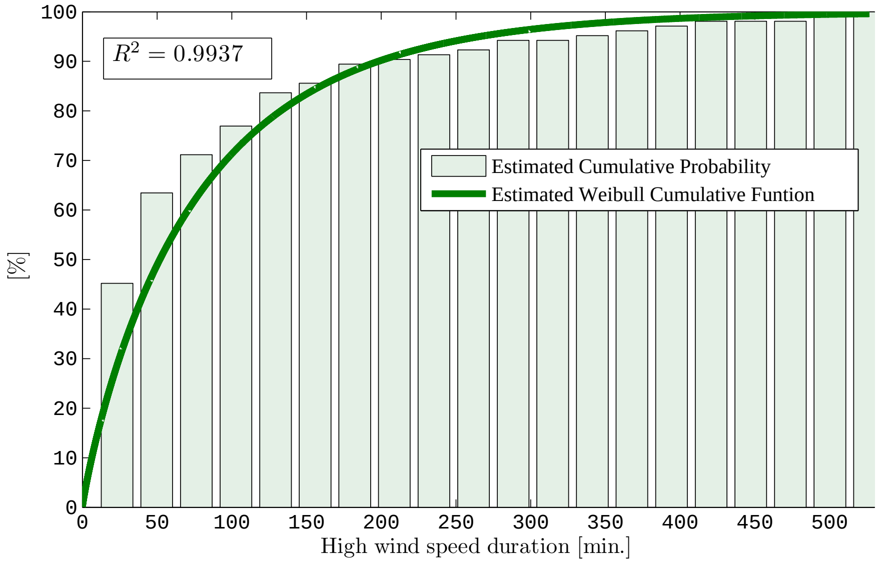


Fig. 6.10: Estimated Weibull cumulative function of high wind speed durations.

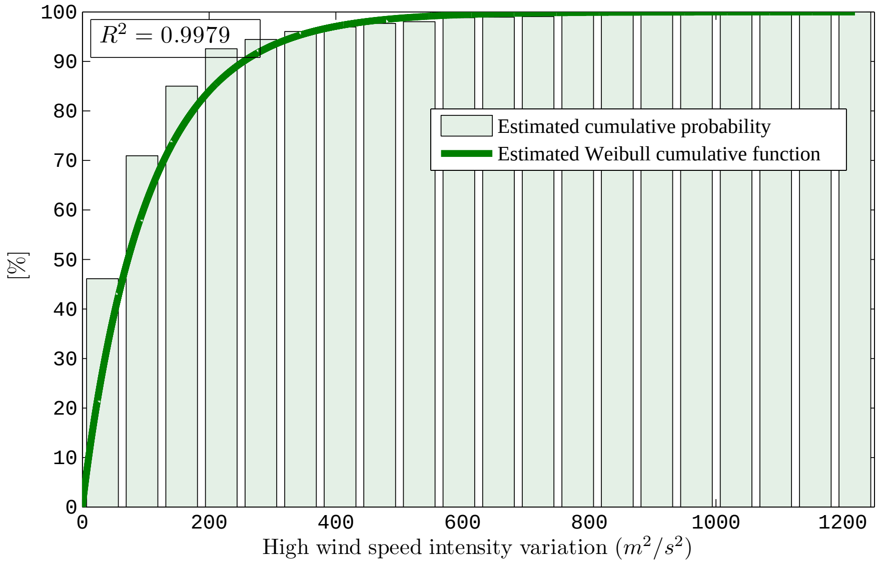


Fig. 6.11: Estimated Weibull cumulative function of high wind speed intensity variations.

average customer interruption frequencies. In fact, more interruption samples were obtained for each simulated year and the entire process achieved β values inferior to 5% right after 199 synthetic years of operation. As consequence, aiming at retrieving even more interruption samples from the simulation platform, the performance indices of this case were obtained for 650 years of operation, a number which was utilized also to assign convergence for all cases from I to P. Such requirement of a constant number of

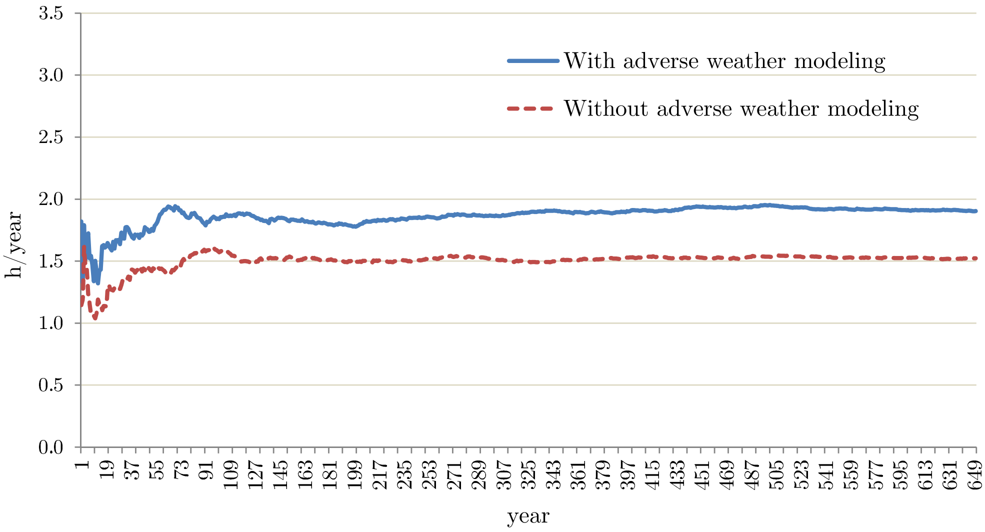


Fig. 6.12: Convergence of the SAIDI index for cases with and without adverse weather modeling.

Table 6.7: System-wide performance indices for case I

Case I					
Index	CDCS	β (%)	Index	CDCS	β (%)
SAIFI	1.38252	2.73949	ASUI	0.00021	2.33991
SAIDI	1.90332	2.33991	ENS	9.01143	2.44778
CAIDI	1.37670	-	AENS	0.00092	2.44778
ASAI	0.99978	0.00050	-	-	-

τ = 34.46 min.

simulated years for all cases aligned with the seed control guarantees the fair comparison of case studies and the consistent estimation of the probability distributions of the uprising/downsitting variations in the performance indices.

6.3.2.1 Client and Block Subscription Activities

The results shown in the previous subsection are an outcome of a large effort to creating synthetic system operating cycles through the representation of the long-term stochastic failure/repair behavior of system components where the adherence to the reality is pursued, for instance, by modeling the adverse weather effects. These synthetic operating cycles are an integral part of our environment modeling whose design involved the application of the A&A[6.3] meta model employed by CArtAgO and its interaction with agents implemented in JASON under the scope of a block-oriented management and control philosophy. Therefore, aiming at supporting the power distribution system operation through the block-oriented agent-based architecture, several block dispositions can be established depending upon the interests of the designer/operator. To illustrate the applicability of our architecture, the block separation exhibited in Fig. 6.13 was devised.

In this block disposition, the CAX1-105 was divided in 5 blocks separated by the sectionalize switches

[6.3] The acronym A&A stands for agents and artifacts, as defined in section 5.3.

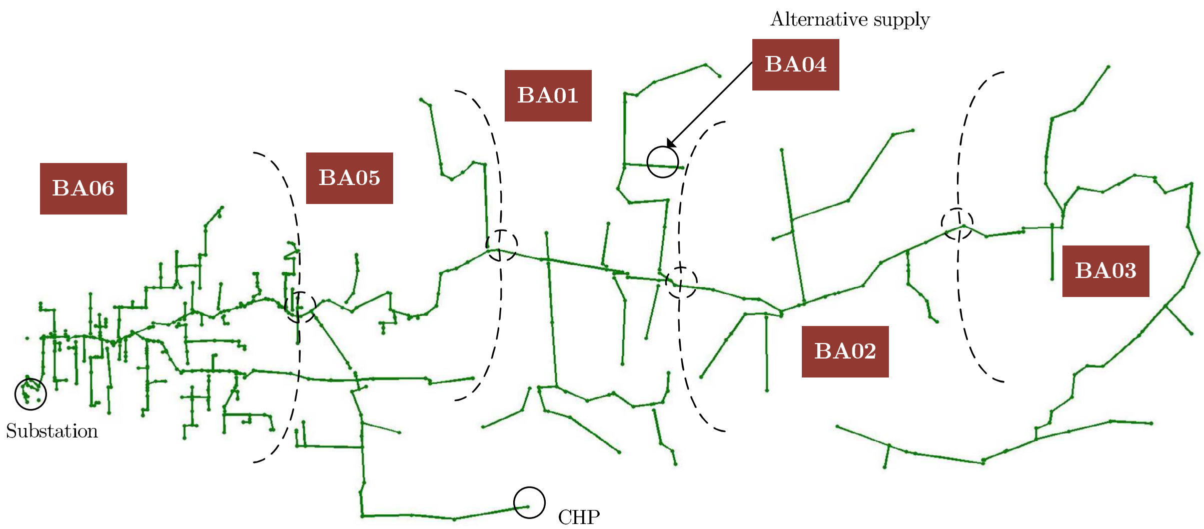


Fig. 6.13: Block separation of the actual feeder (CAX1-105).

placed at the main feeder (trunk). Furthermore, one additional block was considered at the interconnection with the neighboring feeder to aid in the outage management activities. Each block has a numbered code and an associated BA, such that BA01 is assigned to block 01, BA02 is assigned to block 02, and so forth. Moreover, the feeder itself was enhanced with the interconnection of a CHP unit (1.2 MVA) at block 05 assuming its failure rate and mean time to repair specified at 8.6381 interruptions/year and 77.74 hours [306], respectively. Moreover, 17 customers were considered controllable in the sense that, if requested, they may reduce 20% of its loading during 2 hours/day at most. Besides, this same 17 customers were regarded interruptible since they were equipped with rate of change of frequency relays (R81R). Hence, if enabled, these relays can shed the customer loads at once in case the derivative of the frequency ($^{df}/_{dt}$) crosses a threshold, thereby supporting islanded operation procedures. Also, the load demand of these 17 customers was increased, totalizing additional 264.49 kW peak to the rural area. Lastly, one EV charging station of 150 kW peak was integrated in block 01 regarding the possibility of employing the EV droop control strategy described in section 4.3.3.1. This EV charging station is associated to a parking area with maximum capacity of 50 EVs (3 kW each [263]). The EV annual load profiles were obtained from the non-homogeneous Poisson process-based stochastic model developed and parameterized under the scope of the co-oriented Master's thesis shown in [281].

Under the devised block disposition, the simulation platform automatically creates one agent to manage each block (BA01–BA06), DG unit (CA01), controllable/interruptible load (CA02–CA18), and EV charging station (CA19). Moreover, in order to stress the simulation platform, CArtAgO was utilized to building one artifact for each system element including the substation, nodes, lines, secondary transformers, loads, DG units, sensors, protective devices, HMIs, and so forth. Regarding this particular matter, CArtAgO was able to support all these artifacts without loss of efficiency.

Therefore, once all agents and artifacts are built, the A&A interactions can be performed through the simulation platform in runtime. As a matter of fact, according to our architectural philosophy, the

BAs must be able to provide management and control services where subscriptions/negotiations can be authenticated and handled. As consequence, once the BAs are created and initiated, they follow protocols to broadcast themselves as service providers, as specified by Meta plan 5 (see section 3.3.3). This leads to message conveyances as illustrated in Fig. 6.14, where a BA sends a literal with its associated block schema to the nearby neighbor and client candidates.

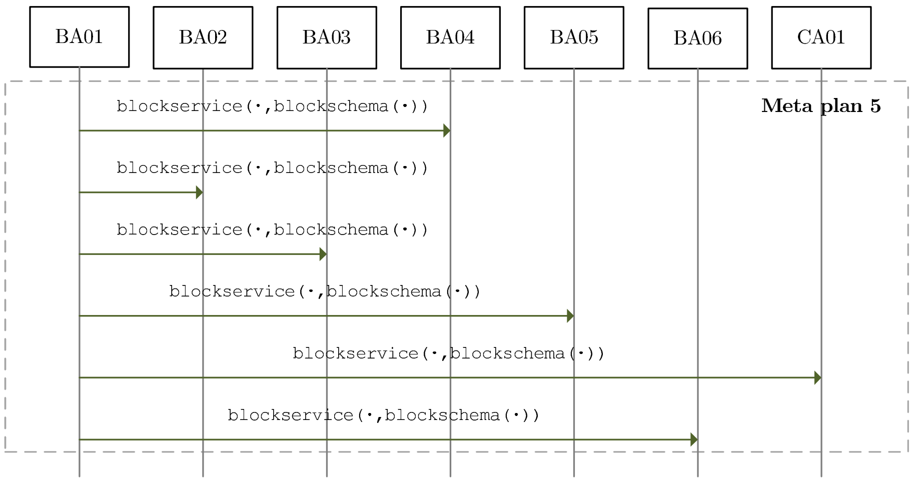
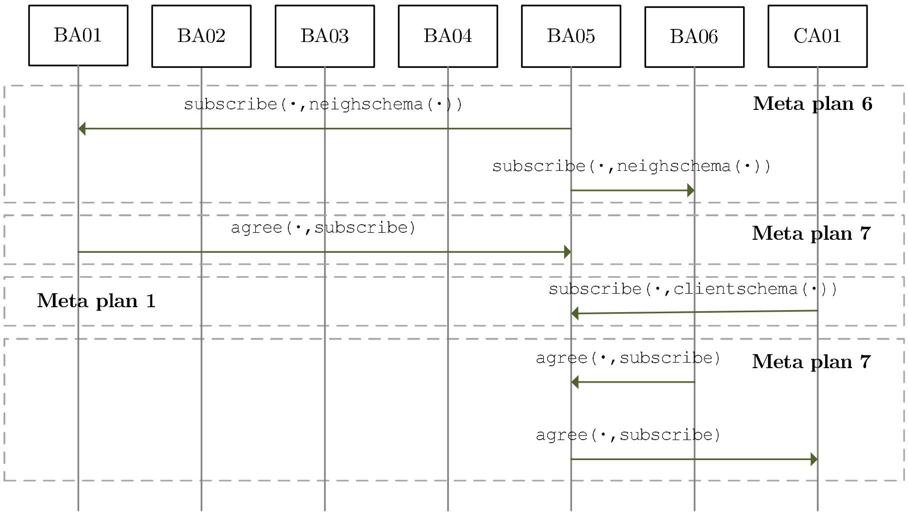


Fig. 6.14: Broadcast of the management service provided by BA01.

In Fig. 6.14, the broadcast of the service provided by BA01 is marked by the conveyance of a `blockschema(·)` containing specific data about the service. As a direct consequence of the BMS[6.4] broadcasts, following Meta plans 6, the intention of creating a subscription to a neighboring BMS might be put forward through a series of subscribe messages which are conveyed towards the BMS providers. Similarly, following Meta plan 1, CAs attempt to subscribe to BMSs through subscribe messages filled with client concept schemas containing at least the agent ID, electrical point of connection, electronic contract/agreement (if any), and particular data specific to the type of DER. These subscribe message conveyances are depicted in Fig. 6.15, where CA01 attempts (and succeeds) a client subscription to BA05, which in turn attempts (and succeeds) neighboring subscriptions to BA01 and BA06. All subscribe messages are responded using Meta plan 7, as also illustrated in Fig. 6.15, eventually leading to updates in the agent's belief bases and actions to be performed at artifacts such that the agent's associated HMIs. Meta plans 2, 3 and 8 provide analogous interactions when subscription updates and terminations are desired.

One might observe that the subscription activities themselves do not impact on the service interruptions. As a matter of fact, by defining a case J where only subscription activities are performed over the enhanced feeder, the resultant performance indices must be the same from case I, with the exception of an aggravation of the ENS and AENS indices due to the load increase on the controllable/interruptable customers and the integration of the EV charging station. Indeed, such aggravation can be verified in Table 6.8, where the performance indices of the enhanced feeder are presented.

[6.4]BMS stands for block management service, as defined in section 3.2.



Meta plans 2, 3 and 8 provide analogous interactions.

Fig. 6.15: Interactions regarding the subscription of clients and neighbors of a BMS.

Table 6.8: System-wide performance indices for case J

Case J					
Index	CDCS	β (%)	Index	CDCS	β (%)
SAIFI	1.38252	2.73949	ASUI	0.00022	2.33991
SAIDI	1.90332	2.33991	ENS	9.09917	2.44677
CAIDI	1.37670	-	AENS	0.00093	2.44677
ASAI	0.99978	0.00050	-	-	-

$\tau = 34.52$ min.

Although the subscription activities do not affect directly the performance indices, they allow DER's representative agent types to establish and unestablish interactions with a BA at the point of connection according to the desires of the DER owner, interests of the associated BA, and following a plug-and-play paradigm. Furthermore, these activities permit BAs to establish and unestablish neighboring relations in order to cooperate to improve the system operation as a whole. Once the main subscriptions are devised, each BA accumulates beliefs referred to the quoted relations and data associated to its neighbors and clients. Therefore, by handling of novel/updated subscriptions, the natural changes in the system infrastructure can be accommodated including the interconnection/disconnection of DERs, improvements in DER technology, acquirement/loosing of alternative DER flexibilities, building/disregarding alternative or novel network connections, and so forth.

6.3.2.2 Sharing, Handling, Alerting and Updating Activities

Due to the possible physical/electrical connection among blocks, actions within one block might have great influence on the operation of other blocks. As consequence, each BA must acquire a certain degree of knowledge about the electrical system upstream and downstream its assignee. This is achieved by information flow schemes, such as those discussed in section 3.3.4. Hence, assuming the client and neighboring relations are established, an information sharing about a certain subject, for instance DER capacity, is performed through Meta plan 9 as depicted in Fig. 6.16.

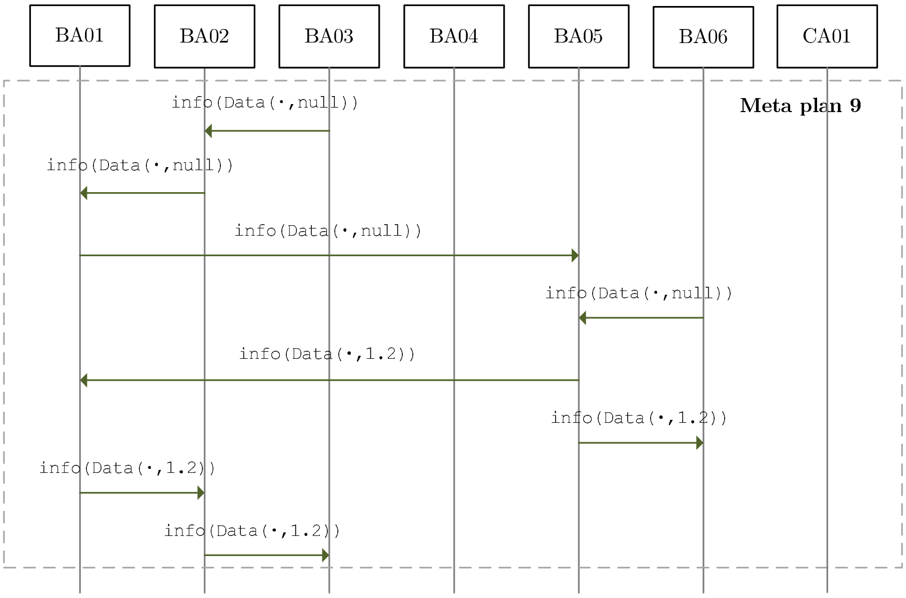


Fig. 6.16: Example of information flow scheme among BAs.

Following the rules described in section 3.3.4, BA03 begins the interaction since it is assigned to an end block. For this accomplishment, BA03 conveys its (null) inner DER capacity to BA02 through an inform message. Then, BA02 aggregates this information with its own, and conveys the (null) DER capacity of blocks 02 and 03 towards BA01. Similarly, BA01 aggregates this information with its own, and conveys the (null) DER capacity of blocks 01–03 towards BA05. At this point, BA06 (which is assigned to an end block) sends its (null) DER capacity to BA05 through an inform message. Since BA05 has one DER client, it aggregates its client's DER capacity (1.2 MVA) to the null value provided by BA06 and sends the resultant value to BA01. Also, once BA05 processes the inform message from BA01, it aggregates its client's DER capacity (1.2 MVA) to the null value provided by BA01, and send the resultant value to BA06. This process continues in such a way that, after receiving the inform message from BA05, BA01 conveys the aggregated DER capacity (1.2 MVA) towards BA02, which in turn conveys the same value to BA03. Hence, as an outcome, using the information flow scheme, each BA acquires knowledge about the DER capacity upstream and downstream its assignee. The only exception is BA04, which was not included in this interaction since block 04 is not physically connected, in normal operation, to the other blocks.

Similarly, various sorts of data/information are shared among the BAs. During the operation, the information sharing is usually triggered within other meta plans to report about updated beliefs and performed actions. For instance, one might recall that, DERs under active management should be utilized to improve/support the system operation. Hence, their availability, interests and provided flexibilities must be under surveillance to guarantee a proper coordination among BAs. Therefore, the failure/repair states of the DERs must be handled, as specified by Meta plans 14 and 15, and such state information must be shared with the neighboring BAs. In fact, one example of handling state transitions is provided in the end of section 5.3, where a DG unit returns to service triggering interactions with relay artifacts. The interactions behind these sorts of handling and sharing activities are illustrated in Fig. 6.17.

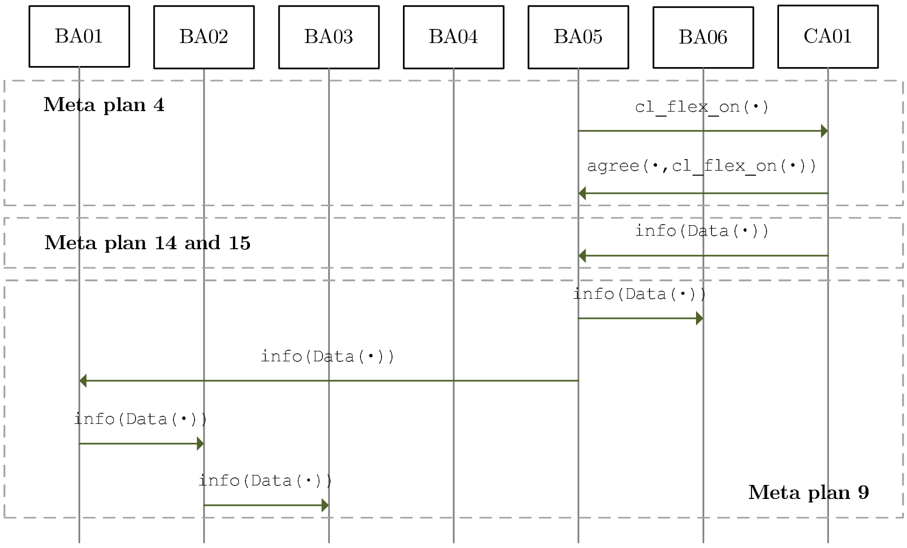


Fig. 6.17: Handling and sharing information regarding the DER stochastic behavior.

In the referred interactions, the CA01 informs BA05 about the state transition of the CHP unit. The provision of this information was previously requested as a flexibility through Meta plan 4. Hence, the state transition is handled through Meta plans 14 and 15, where the operation condition is revisited and the protection/control devices are reset if necessary using pre-specified solutions. As a matter of fact, in the CAX1-105 feeder, after a failure of the CHP unit, aiming at avoiding unnecessary interruptions, a directional power relay (R32) nearby the CHP network lateral is disabled and a request to disabling the customer rate of change of frequency relays is conveyed to the neighboring BAs using the information flow schemes. Moreover, the data already shared with the BAs (e.g. DER capacity) is updated to avoid misbeliefs and following the information flow schemes as well.

Several other interactions were established in the architecture, for instance, in case of device problems (Meta plan 12), operation condition change (Meta Plan 13) or adverse weather alerting (Meta plans 10 and 11). As a practical example, it was established for a given set of operation conditions that customer load reductions could be requested from inner clients or even from clients of other BAs. For this accomplishment, the controllable loads were sorted following a priority order from which the load reductions are called sequentially. Also, due to the information flow scheme, each BA has aggregated information about the possibilities of load reduction available upstream and downstream its network block. This information is constantly updated such that the interruption of a controllable customer load caused by a blown lateral fuse is informed from the associated CA to the BA service provider. In turn, the BA service provider aggregates and conveys this information towards its neighbors according to the information flow scheme. These interactions were employed in case the operation condition assigns inadequate voltages within the blocks, composing case L. The results obtained through these interactions are shown in Table 6.9.

Table 6.9: Inadequately delivered voltage condition indices for case I, J and L

Node	Block	Case I			Case J			Case L		
		λ_v	U_v	r_v	λ_v	U_v	r_v	λ_v	U_v	r_v
N432	02	1.99874	3.98921	1.99586	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
N479	03	2.98917	5.96816	1.99659	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
N518	03	2.99714	23.9455	7.989451	0.56310	2.1924	3.89346	0.02469	0.04713	1.90899
				$\tau = 34.86$ min.			$\tau = 34.92$ min.			$\tau = 47.66$ min.

Table 6.9 shows the inadequately delivered voltage condition indices, defined in section 4.3.5, for different nodes of the CAX1-105 feeder in cases I, J and L. Since block 03 is the last block of the feeder, the worst results in terms of voltage conditions were verified in this block. Also, in comparison with case I, the frequency, annual duration and mean time to solve the inadequately delivered voltage conditions have improved considerably in case J. This improvement represents mainly the impact of the integration of the CHP unit on the CAX1-105 feeder where, considering the failure/repair cycle of this unit, a reduction of 81.21% was obtained for the frequency of inadequate voltage conditions at node N518. Hence, the operational/control strategies employed in case L diminished even more (99.18%) this index, improving the *service adequacy* provided by the utility. This sort of analysis was only possible by conjugating all agent interactions with an environment modeling which embeds simulation mechanisms able to unify the representation of long-term stochastic cycles with steady-state analysis. At last, since the state transitions associated to the service interruptions were not altered, one might notice that the system-wide performance indices of case L are equal from those found in case J.

6.3.2.3 Supporting Islanded Operation Activities

Once the BAs have information regarding their inner and outer clients, they might be able to support islanded operation procedures, as discussed in Meta plan 16. Due to the devised block disposition and DG features (technology, capacity, location, and so forth), LOG protection was established in between blocks 05 and 06. As consequence, a fault in the main feeder of block 06 can be isolated at this same block, allowing the other blocks to change altogether to islanded operation mode. Hence, immediately after the isolation, BA06 must strive for outage management whilst the other BAs have to change settings to islanded operation mode. Moreover, if the islanded operation mode must be prolonged and the total loading approximates to the maximum capacity of the CHP unit, controllable loads are requested to reduce the loading of the blocks through piecewise demand reductions sequentially performed using the priority order of case L. All these strategies comprise case M, whose results are shown in Table 6.10. The CHP unit was represented using the synchronous generator forth-order model with parameters shown in [63], whilst the governor-steam turbine and IEEE DC1A exciter parameters are given in [280].

In Table 6.10, one can verify that the islanded operation procedures improved the performance of the system in comparison with case L. However, despite the narrow view provided by the performance index mean values, the environment modeling also allows observing how the islanded operation strategies affect the performance indices over the synthetic years of operation. This provides valuable information regarding the actual impact that islanded operation strategies can have on the system operation performance.

Table 6.10: System-wide performance indices for case M

Case M					
Index	CDCS	β (%)	Index	CDCS	β (%)
SAIFI	1.32179	2.70907	ASUI	0.00021	2.31154
SAIDI	1.85176	2.31154	ENS	8.85768	2.45156
CAIDI	1.40094	-	AENS	0.00090	2.45156
ASAI	0.99979	0.00049	-	-	-
				$\tau = 49.81$ min.	

In fact, the environment modeling permits verifying the variation of the system average interruption frequency estimated over each year of operation, as depicted in Fig. 6.18.

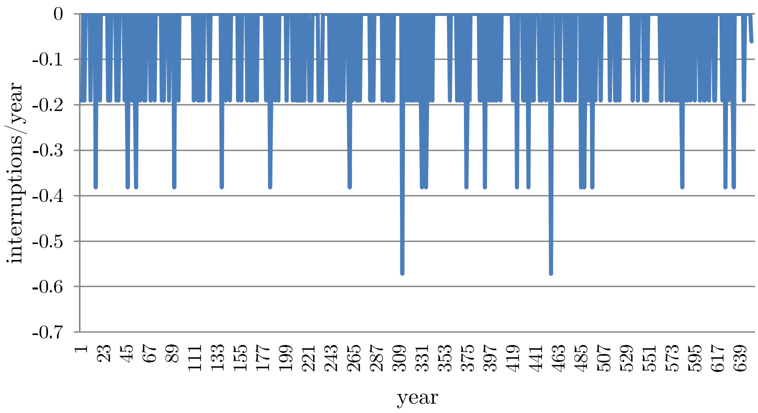


Fig. 6.18: Impact of islanded operation strategies on the SAIFI of case L over each simulated year.

In Fig. 6.18, one might observe that the improvements on the system average interruption frequencies can be discretized in steps of 0.1906953 interruptions/year, meaning {0.1906953, 0.3813906, 0.5720858, etc.}. This outcome is consistent with the fact that only the customers of the rural area might be subjected to the islanded operation mode. As a matter of fact, each successful islanding procedure avoids 1865 customer interruptions, leading to improvements on the SAIFI index given by

$$\Delta G_{\text{SAIFI}}(y_u) = -\frac{\text{n}^{\text{o}} \text{ of avoided customer interruptions in } y_u}{\text{n}^{\text{o}} \text{ of system customers}} \tag{6.1}$$

$$= -\frac{1865(\text{n}^{\text{o}} \text{ of avoided interruptions due to islanded operation in } y_u)}{9780} \tag{6.2}$$

$$= -0.1906953(\text{n}^{\text{o}} \text{ of avoided interruptions due to islanded operation in } y_u) \tag{6.3}$$

where y_u stands for the sequence of system states in year u. Therefore, in a synthetic year of operation, the variation on the SAIFI index due to islanded operation strategies is obtained through the product of the number of associated avoided interruptions by a factor of -0.1906953 interruptions/year. Hence, using the sampled variations of the SAIFI index, the probability distribution of the $\Delta G_{\text{SAIFI}}(y_u)$ values can be retrieved analogously to the exposed in section 6.2, as shown in Fig. 6.19. Similarly, the estimated probability distributions of $\Delta G_{\text{SAIDI}}(y_u)$ and $\Delta G_{\text{ENS}}(y_u)$ are presented in Fig. 6.20 and 6.21, respectively. Clearly, these understandings of the impact of the islanded operation strategies in a synthetic year operation can only be reveled using an environment modeling which encompasses the long-term failure/repair cycle of system components with aspects of steady-state and dynamic behavior analysis.

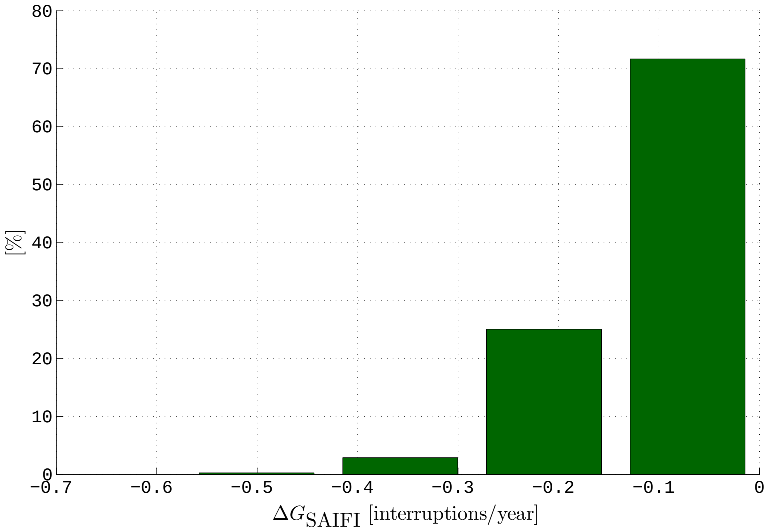


Fig. 6.19: Impact of islanded operation strategies on the SAIFI of case L (5 bins).

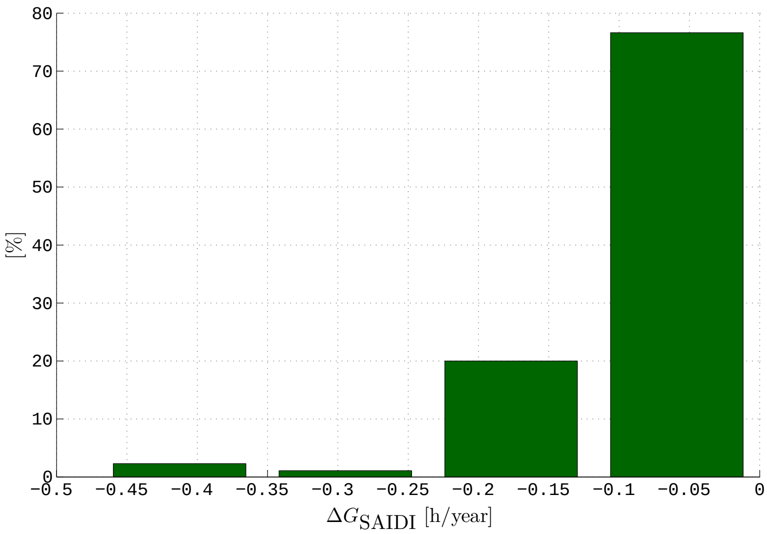


Fig. 6.20: Impact of islanded operation strategies on the SAIDI of case L (4 bins).

The estimated probability distributions unveiled that, in more than 20% of the synthetic years of operation, improvements of at least 0.20431 h/year and 0.6017 MWh/year were reached to the system average interruption durations and energy not supplied, respectively, due to the islanded operation strate-

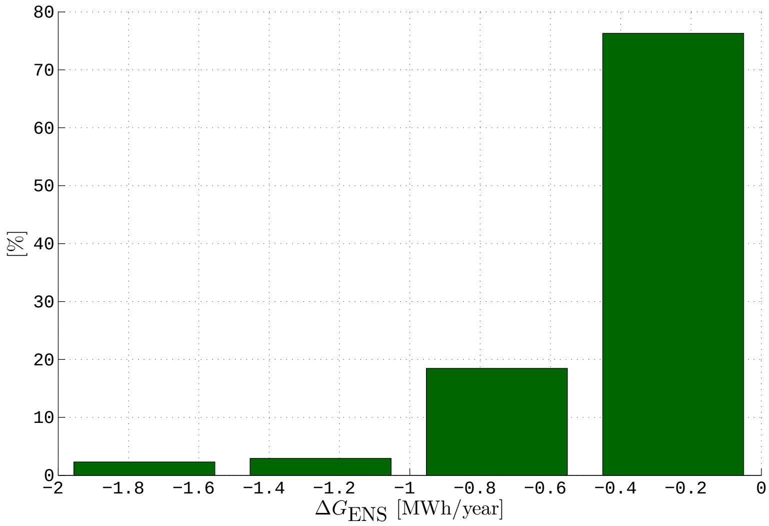


Fig. 6.21: Impact of islanded operation strategies on the ENS of case L (4 bins).

gies. Furthermore, the system average interruption frequencies were improved on 184 of the 650 synthetic years of operation. Until the convergence of the simulation, more than 5705599 operation states were evaluated. Within these state evaluations, 664 islandings were attempted from which 210 (31.63%) were successful and 454 (0.6837%) were unsuccessful. This assessment highlights that, in average, more than one islanding attempt is performed per year. Moreover, the low successful rate of islanding attempts shows that there exist margin for improvements in the system performance through islanded operation strategies. In fact, by storing and evaluating the object data of the islanded operation procedures, the islanding conditions could be verified and analyzed. Examples of organized information about islanding conditions retrieved from the object-oriented modeling are exhibited in Fig. 6.22–6.24, where the interconnection relays were disabled in the dynamic behavior analyzes to increase the number of illustrative samples.

After careful examination, it was verified that some of the islandings were unsuccessful due to a slight threshold crossing detected on the DG interconnection underfrequency relay (R81U), which was set to trip a circuit breaker in between the CHP unit and the utility network if the frequency decays below 48 Hz for a time duration greater than 0.5 s [14]. As consequence, operational/control strategies to smooth frequency variations might diminish the actuation of this relay, leading to an increase on the successful rate of the block islanding attempts. Therefore, aiming at smoothing frequency variations, droop control strategies were regarded for the EV charging station installed at block 01, as modeled in section 4.3.3.1. For this accomplishment, EVs were considered to charge at nominal power immediately after their network connection, such that the charging set point (P_{set}) assumes the value 1 p.u.(MW) of the total EV connected load. Furthermore, the model applies a time delay (T_D) of 0.1 s [284], dead band (f_{band}) of 0.01 p.u.(Hz), proportional gain (k_P) of 32 p.u.(MW)/p.u.(Hz), minimum power (P_{min}) of -0.2 p.u.(MW), and maximum power (P_{max}) of 1 p.u.(MW). One might observe that the minimum power was chosen to be negative, meaning that the EVs are allowed to inject electric energy into the

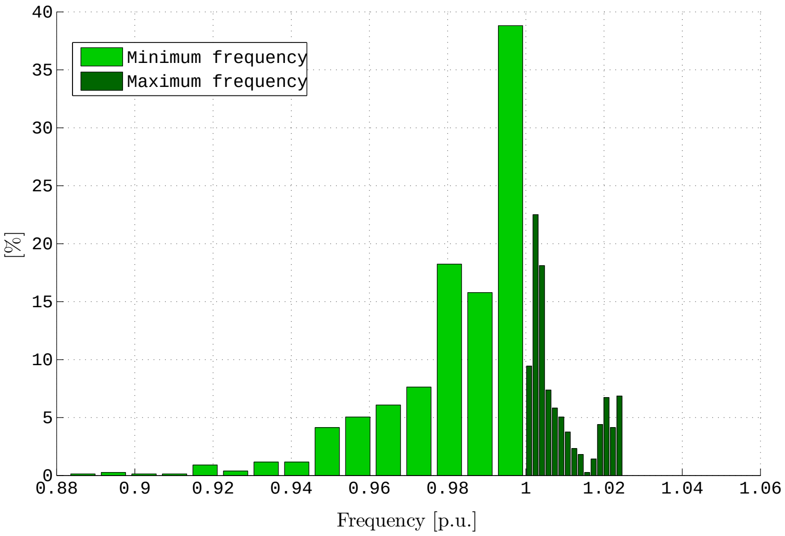


Fig. 6.22: Estimated probability distributions of the maximum and minimum islanding frequencies of case M (15 bins each).

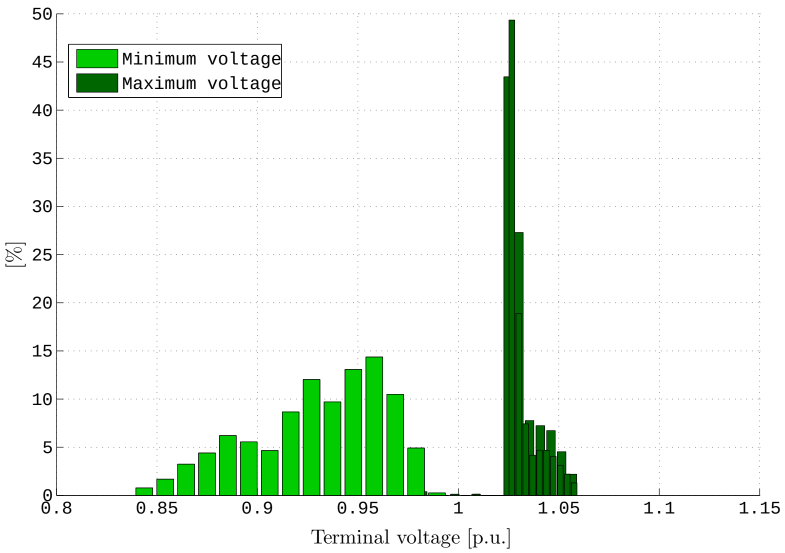


Fig. 6.23: Estimated probability distributions of the maximum and minimum islanding voltages of case M (15 bins).

system, a strategy called vehicle-to-grid in the literature.

Once these parameters are stipulated, the impact of the EV droop control strategies on the block islanding attempts can also be verified. Following this reasoning, Fig. 6.25–6.27 illustrate the dynamic behavior analyzes of the block islandings with and without considering the EV droop control strategies. These analyzes (including the EV droop control model) were validated using an EUROSTAG imple-

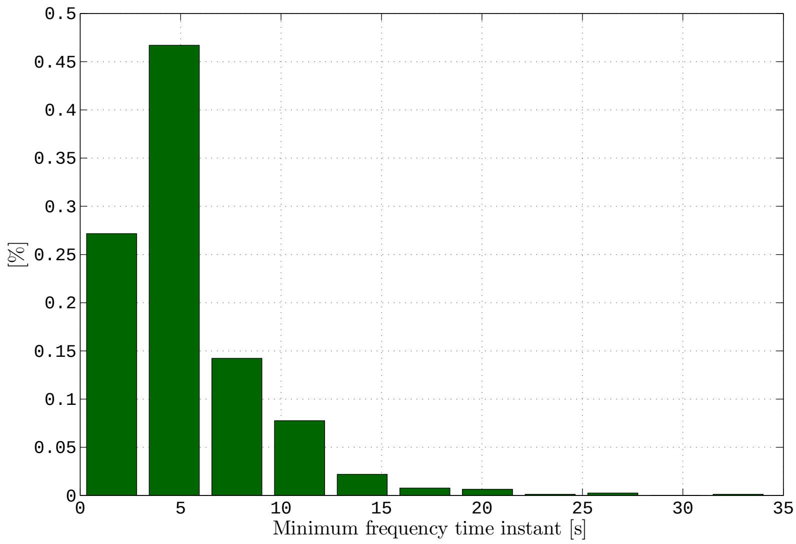


Fig. 6.24: Estimated probability distributions of the time instant of the minimum islanding frequency of case M (12 bins).

mentation designed under the scope of the European project MERGE [282], whose results are described in [263].

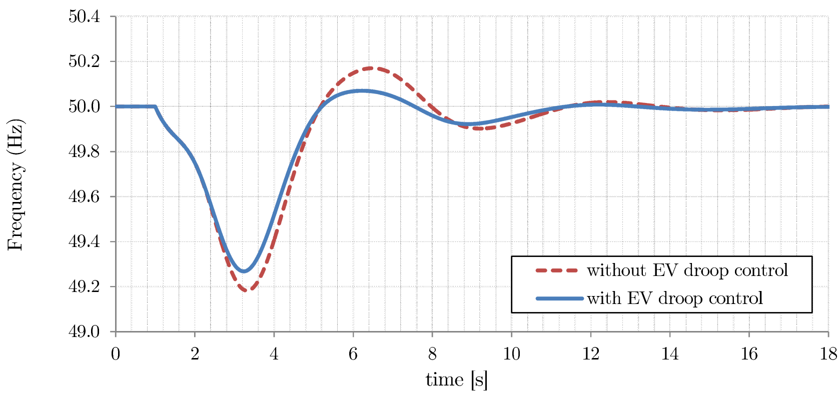


Fig. 6.25: Impact of EV droop control on the block islanding frequency.

In Fig. 6.25, one might verify that the integration of the EV droop control strategies lead to the smoothing of the block islanding frequency behavior and the increase/reduction of the minimum/maximum frequency value during islanding. Similarly, a smoothing of oscillations can also be observed in the CHP mechanical power in Fig. 6.26. The EV dynamic load begins its demand reduction immediately after the frequency decays below 49.75 Hz at around $t = 2$ s, as shown in Fig. 6.27. This result is consistent with our dead band design, such that the EV load ceases its dynamic behavior some instants after the frequency deviation lies again within the dead band at around $t = 4.2$ s. All these results show outcomes

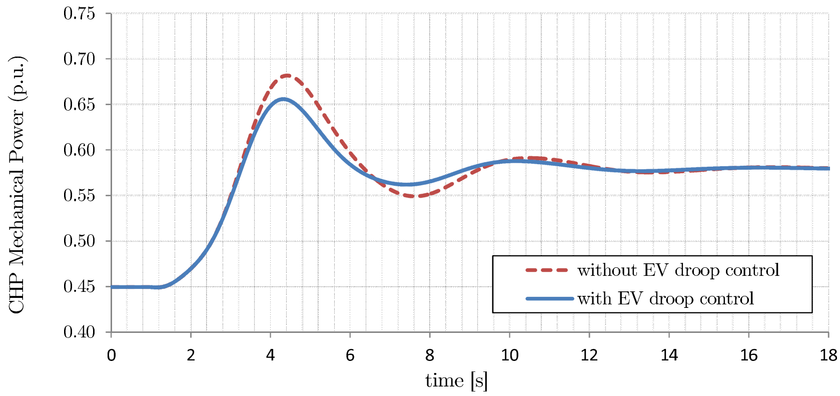


Fig. 6.26: Impact of EV droop control on the CHP mechanical power.

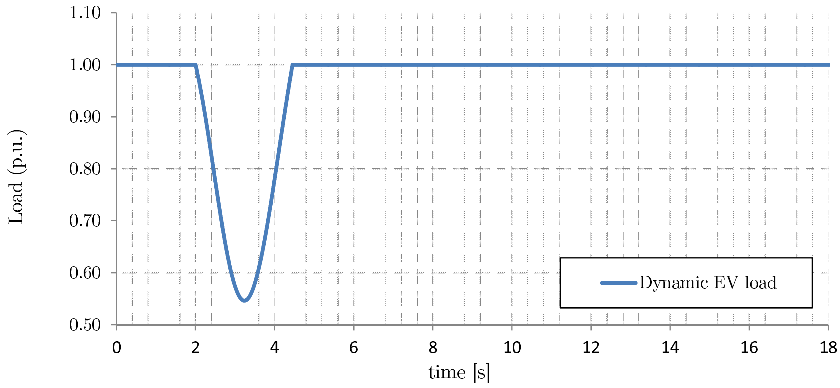


Fig. 6.27: Dynamic loading provided by the EV droop control.

of interest from having EV (or other responsive load) participating actively in frequency control. In particular, since improvements on the frequency deviations were found, the representation of EV droop control strategies on the block islandings were considered in a case named N. The performance indices of this case are presented in Table 6.11.

Table 6.11: System-wide performance indices for case N

Case I					
Index	CDCS	β (%)	Index	CDCS	β (%)
SAIFI	1.31123	2.70543	ASUI	0.00021	2.30895
SAIDI	1.84424	2.30895	ENS	8.81607	2.45177
CAIDI	1.40649	-	AENS	0.00090	2.45177
ASAI	0.99978	0.00048	-	-	-
					τ = 49.91 min.

The result analyzes of case N indicate that the EV droop control was indeed able to aid the islanding procedures, leading to improvements on the system average interruption frequency, duration, and energy not supplied. During the simulation of the synthetic years of operation, the variation of the system average interruption frequency due to the EV droop control strategies was obtained as depicted in Fig. 6.28. In this figure, a series of years of operation with avoided interruptions can be verified again through a discretization factor of −0.1906953 interruptions/year. As expected, the reduction of the minimum frequency decays diminished the number of triggerings of the DG interconnection underfrequency relay, leading to an increase on the successful rates of the block islanding attempts. In fact, among the 664 islanding attempts, 246 (37.05%) were successful and 418 (62.95%) were unsuccessful, which represents an increase of 17% on the islanding successful rates in comparison with case M.

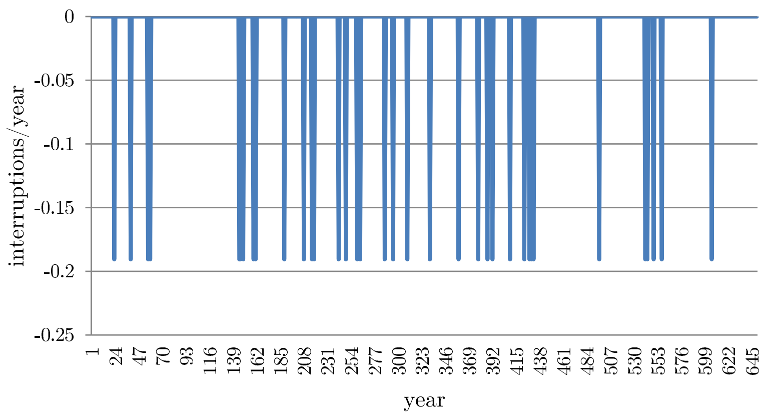


Fig. 6.28: Impact of EV droop control strategies on the SAIFI of case M over each simulated year.

These analyzes show how EV droop control strategies can improve the successful rate of the block islanding procedures. However, the results also disclose that there still exist margin for improvements on these procedures. As consequence, aiming at increasing even more the probability of successful islandings, load shedding schemes were also considered. For this accomplishment, the CAs distributed over blocks 01, 02, 03 and 05 were allowed to be requested to enabling/disabling their rate of change of frequency relays (R81R). One might notice that this scheme is more complex than the one introduced in the end of section 5.3, where a BA is assumed to enable directly a relay artifact. On the contrary, CAs are requested herein to enable their rate of change of frequency relays but they might refuse the request according to its own desires. Hence, due to practical and illustrative matters, it was specified that the CAs would refuse enabling their rate of change of frequency relays if at least one interruption was assigned to their associated customer load at the same year. Furthermore, LOG protection was also considered in between blocks 02 and 03, in such a way that BA05 is able to link the trip of the circuit breaker in between blocks 05 and 06 with the trip of the circuit breaker in between blocks 02 and 03, disconnecting/interrupting block 03 entirely if necessary.

The decision making about which customer loads should be interrupted in case of islanding is supported by the GMDH-based approach described in section 4.3.3.2, and whose implementation is encapsulated in a load shedding artifact, as illustrated in Fig. 5.10(b). The GMDH training and test data sets were retrieved by utilizing the simulation model but with a different random seed and assuming that the DG interconnection relays are disabled. Hence, the GMDH model was trained using data distinct from those retrieved through the original random seed, but yet maximizing the number of data samples. The comparison between the simulated and estimated values of maximum frequency decays is illustrated in Fig. 6.29, where satisfactory estimations were obtained with a mean square error of 0.6211%.

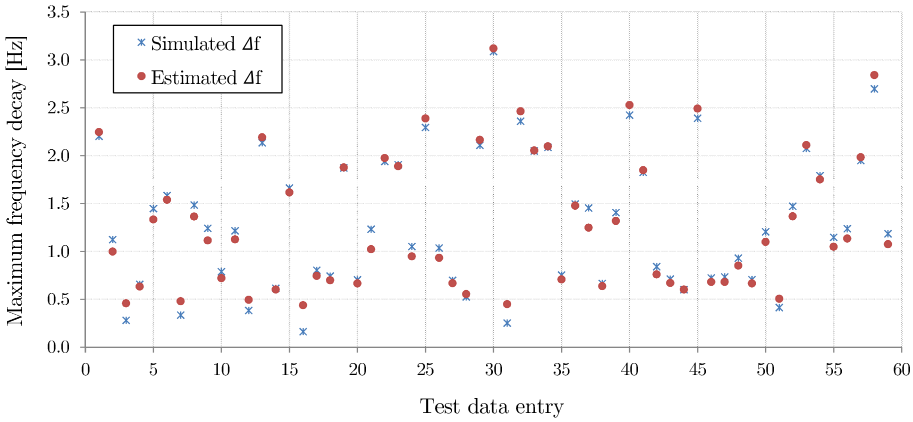


Fig. 6.29: Comparison between simulated and estimated values of maximum frequency decays.

Therefore, over case N, case O was built comprising the representation of the devised load shedding strategies on the system operation of the CAX1-105 feeder. The result analyzes of this case showed that, using the load shedding strategies, the successful rate of islanding attempts can be improved considerably. As a matter of fact, in the 664 islanding attempts, 588 (88.55%) were successful and only 76 (11.45%) were unsuccessful, thereby representing an increase of 139.02% in the successful rate of the block islandings in comparison with case N. This outcome implies that major betterments can be observed on the variation of the system average interruption frequencies, as exhibited in Fig. 6.30.

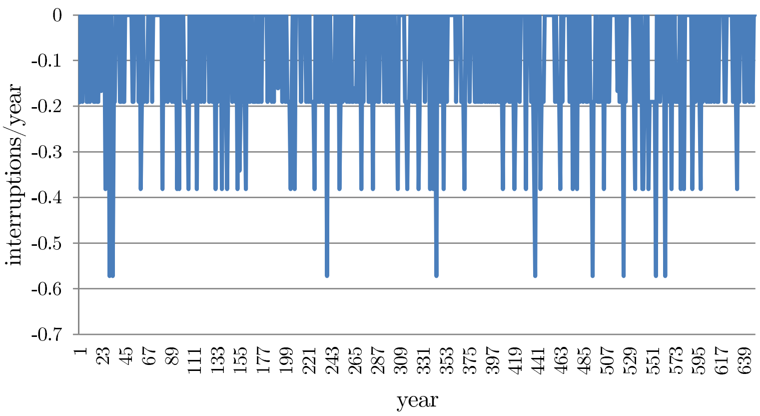


Fig. 6.30: Impact of load shedding strategies on the SAIFI of case N over each simulated year.

In the figure above, one can notice that a great amount of customer interruptions were avoided by using the load shedding strategies. Moreover, the multiplication factor of −0.1906953 interruptions/year was not perfectly reached for all years of operation. This result was expected since some additional customers associated to the controllable loads and block 03 were individually interrupted through load shedding actions, thereby allowing the block islandings to be successful. The other performance indices were also significantly improved in comparison with case N, as shown in Table 6.12.

At last, Fig. 6.31–6.33 exhibit the estimated probability distributions of the impact of the load

Table 6.12: System-wide performance indices for case O

Case I					
Index	CDCS	β (%)	Index	CDCS	β (%)
SAIFI	1.21089	2.64055	ASUI	0.00020	2.29960
SAIDI	1.79950	2.29960	ENS	8.73084	2.48205
CAIDI	1.48609	-	AENS	0.00089	2.48205
ASAI	0.99979	0.00047	-	-	-
				$\tau = 61.32$ min.	

shedding strategies on the performance indices of case N. In these figures, one might observe that the advanced load shedding strategies reduced considerably the system average interruption frequencies in the sampled years, as already verified in Fig. 6.30. Moreover, in the estimated probability distributions of the variations of the SAIDI and ENS indices, negative values can be found. This outcome was indeed anticipated since, in some of the synthetic years of operation, the adoption of the load shedding strategies increased (though slightly) the customer interruption durations and energy not supplied. This increase occurred when the GMDH model produced unnecessary sheddings looking forward to achieve well successful islandings. Such phenomenon is quite reasonable once the GMDH model is not supposed to be perfect in estimating the maximum frequency decays of the block islanding procedures. Furthermore, this phenomenon is also verified in the system average interruption frequency values, though it is not visible in Fig. 6.30 and 6.31 once its associated impact ranges at most 0.001738 (17/9780) interruptions/year.

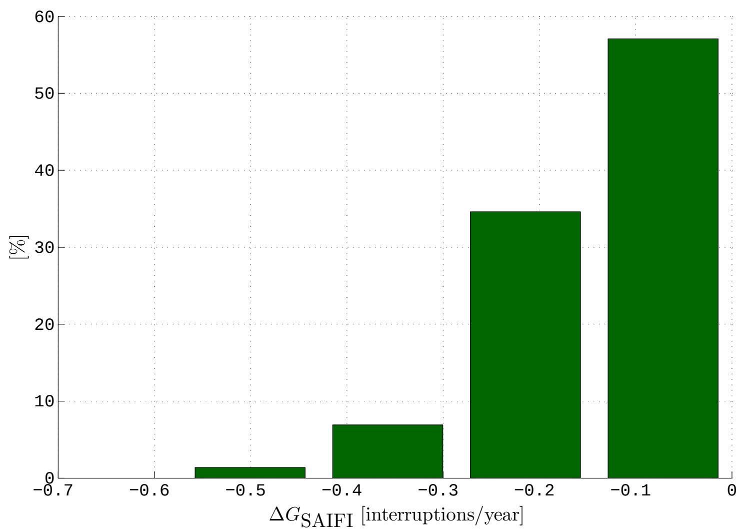


Fig. 6.31: Impact of load shedding strategies on the SAIFI of case N (4 bins).

Finally, it is important to emphasize that the system-wide performance indices have improved considerably through the block islanding, load shedding and EV droop control strategies. Since only 19.07% (1865/9780) of the feeder customers are straightforwardly affected by these strategies, this implies that an even greater service improvement was achieved for the LP indices of blocks 01, 02, 03 and 05. The successful rate of the islanding attempts reached the value of 88.55% for a case where several strategies are performed in conjunction. Therefore, by definition, the *service security* of the customers at blocks

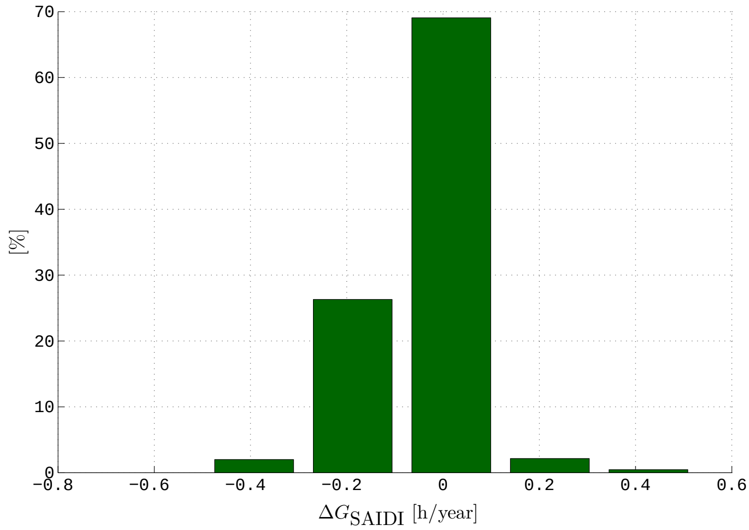


Fig. 6.32: Impact of load shedding strategies on the SAIDI of case N (5 bins).

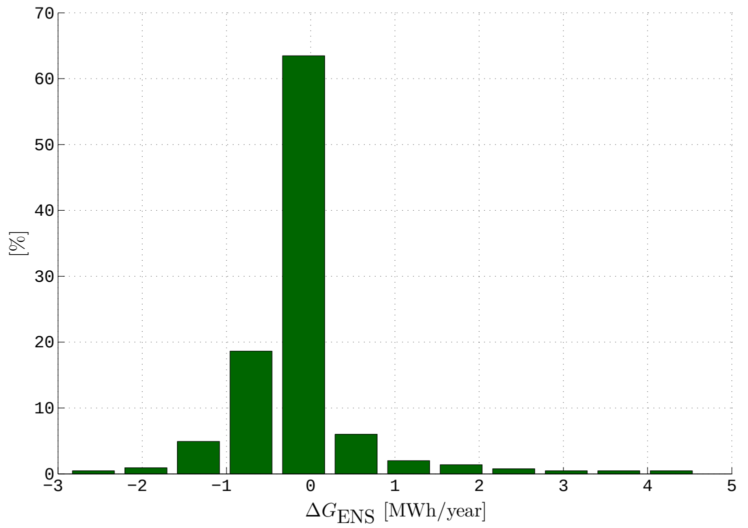


Fig. 6.33: Impact of load shedding strategies on the ENS of case N (12 bins).

01, 02, 03 and 05 have improved 88.55% by using the designed strategies, in reference to the faults at the main feeder (trunk) of block 06.

6.3.2.4 Supporting Outage Management Activities

The operational/control strategies devised in the former subsection aimed at reducing the frequency of customer interruptions through block islanded operation procedures. Nevertheless, all system elements are prone to failures and some interruptions might be inevitable during the operation of the power distribution feeders. As consequence, once customer interruptions are detected, outage management functions must be performed as efficiently as possible to reduce the customer interruption durations and energy not supplied. Hence, under the scope of the block-oriented agent-based architecture, outage management activities can be performed automatically, as described in section 3.3.10.

In order to support the outage management functions, FPI artifacts were assumed in between the network blocks of the CAX1-105 feeder. Furthermore, Meta plans 17–21 were activated within the simulation platform. During the years of operation, the very first outage at the main feeder (trunk) is assigned to block 06 followed by islanding procedures which were unsuccessful. In this scenario, all network blocks became de-energized and the FPI artifacts assigned the fault within block 06. Hence, following Meta-plan 17, the DMS was informed about the block interruptions and a log entry was autonomously created by each BA to track the outage management activities of their assignees. Afterwards, the BAs isolated their assignees and began conveying information to support fault location as specified by Meta plans 18 and 19, respectively. In particular, once the BA06 verified that the fault occurred within its assignee, BA06 sent a report to the DMS and called crews to its location. Moreover, after the fault location became a collective belief, following Meta plan 20, BA01, BA02, BA03 and BA05 started requesting electric energy from their neighbors aiming a state of affair where their assignees are energized.

After a series of request interactions, BA01 was the first one to receive authorization to connect its assignee to a neighboring block, since its assignee's neighbor (block 04) is directly served by an alternative supply source. Nevertheless, the authorization came with the imposition that additional loading would not be provided by the alternative supply source. Such imposition was established since the loading of block 01, even after disconnecting some interruptible customers, was enough to nearly reach the transfer capacity limit in between blocks 04 and 01. As consequence, BA01 reset its protective/control devices to cold load pick up and the switch in between blocks 04 and 01 was closed. Immediately after the re-energization, BA01 sent inform messages to the DMS and its neighbors about the updated energization condition. Furthermore, it responded the upcoming requests for reconnection with refuse literals due to BA04's recent imposition. Since BA05 did not succeed in reconnecting its assignee to block 01, it attempted black start procedures through the CHP unit, as specified by Meta plan 21. The black start procedures were well successful but, some minutes afterwards, the CHP actually failed before the outage management activities were finished. Therefore, in this scenario, blocks 02, 03, 05 and 06 were found de-energized just before the failed component finished repairing. The only exception was indeed block 01, which was re-energized through a connection with block 04.

The scenario described above summarizes one over the several sorts of interactions performed within the outage management capability. Hence, from the point of view of evaluating the impact of these interactions on the system operation, a hypothesis must be made regarding their time duration. As consequence, without loss of generality, it was assumed that these interactions lead to a power restoration 4 times faster than the actual (sometimes manual) power restoration of the CAX1-105 feeder. This hypothesis is conservative/moderate since the power restoration of the CAX1-105 feeder, involving the managing of sectionalize switches to isolate components under outage and managing the tie switch to restore the service using the alternative supply source, usually takes 60 minutes in average. Therefore, the representation of the outage management capability in case O comprises case P, whose performance indices are provided in Table 6.13.

Table 6.13: System-wide performance indices for case P

Case I					
Index	CDCS	β (%)	Index	CDCS	β (%)
SAIFI	1.21089	2.64055	ASUI	0.00012	2.47030
SAIDI	1.09387	2.47030	ENS	5.69767	2.87680
CAIDI	0.90336	-	AENS	0.00058	2.87680
ASAI	0.99987	0.00030	-	-	-

In this table, one might verify the significant impact of the outage management strategies on the system average interruption duration and energy not supplied of the CAX1-105 feeder, accounting reductions of 39.22% and 34.75% for each of these indices, respectively. Such outcome indicates that large benefits can be noticed on the variations of these indices over each simulated year, as depicted in Fig. 6.34 and 6.35. In fact, the result analyzes highlighted that improvements on the SAIDI and ENS indices were achieved in 544 (83.69%) of the 650 years of operation. Moreover, in these figures, one may observe that the outage management strategies avoided more than 3 hours and 12 MWh of system average interruption durations and energy not supplied, respectively, in some sampled years. Therefore, it can be concluded that even by

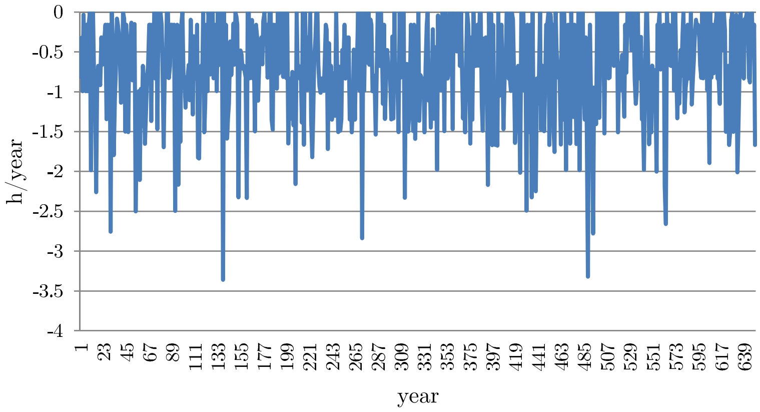


Fig. 6.34: Impact of outage management activities on the SAIDI of case O over each simulated year.

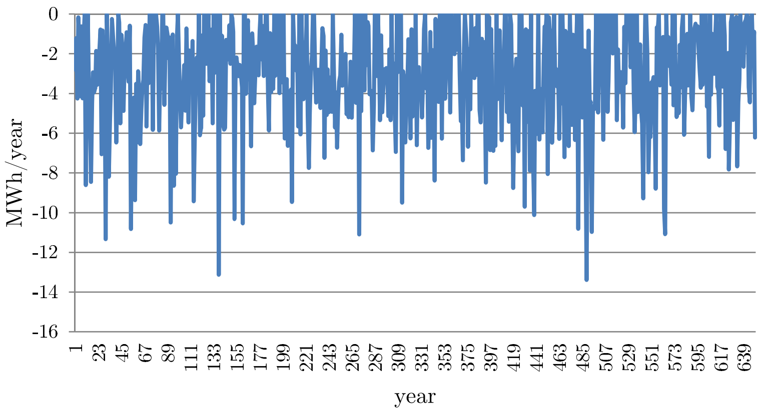


Fig. 6.35: Impact of outage management activities on the ENS of case O over each simulated year.

choosing a moderate/conservative assumption for the average time duration of the outage management strategies, great benefits can be achieved through their application. These benefits are also emphasized in the estimated probability distributions of the improvements on the SAIDI and ENS indices due to the outage management strategies, as shown in Fig. 6.36 and 6.37.

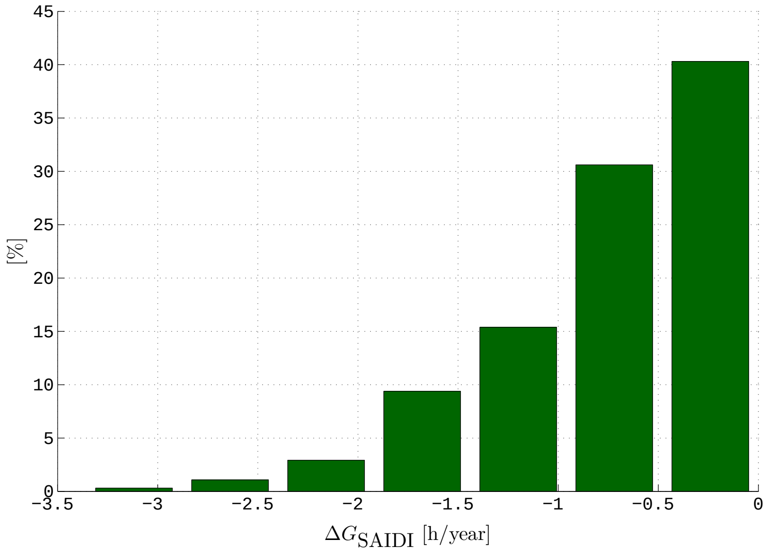


Fig. 6.36: Impact of outage management activities on the SAIDI of case O (4 bins).

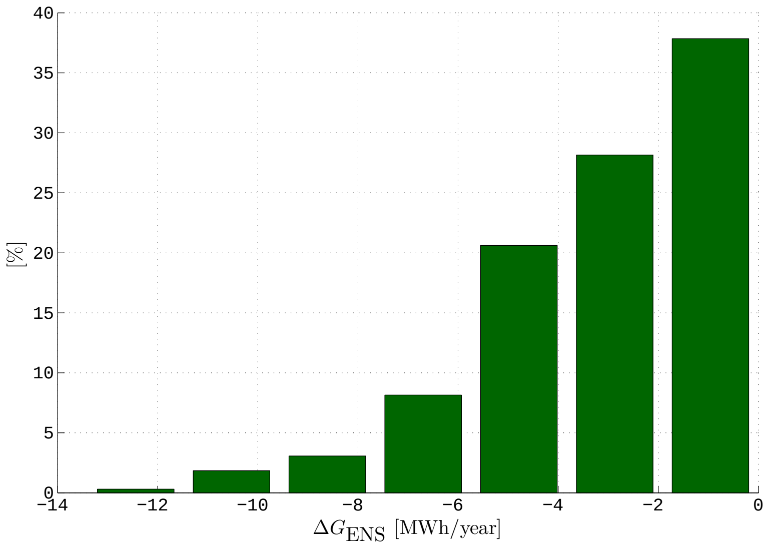
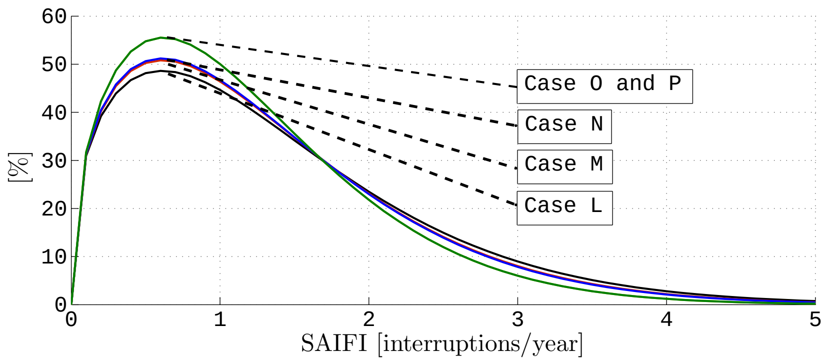


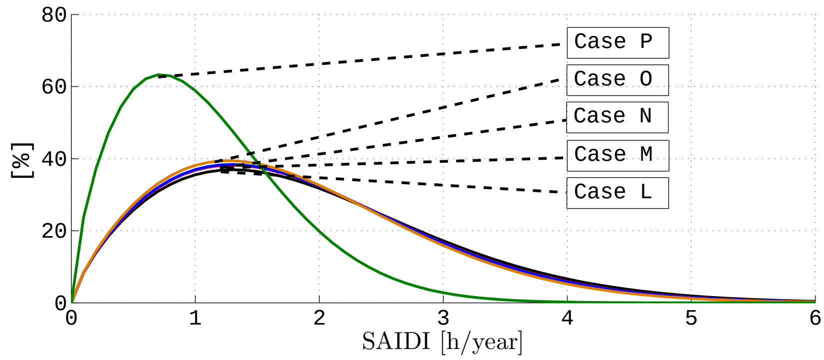
Fig. 6.37: Impact of outage management activities on the ENS of case O (4 bins).

On the other hand, benefits in the systemic number of interruption occurrences were not found. As a matter of fact, one might observe that cases O and P share the same SAIFI values. This outcome was anticipated since the probability of a second component outage during an outage management already in place is quite low for the CAX1-105 feeder. Therefore, similarly to the RBTS-BUS2-F1 feeder, these particular cases were not verified within the entire set of years of operation.

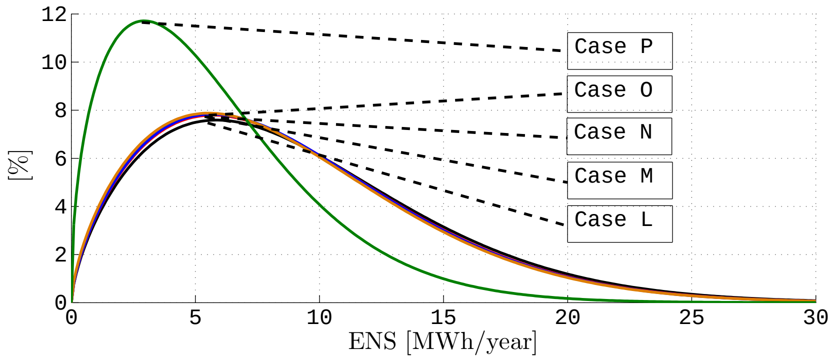
Finally, for the sake of comparing the results achieved in cases L–P, Fig. 6.38 exhibits the estimated Weibull probability density functions of the performance indices achieved in all these cases. In this



(a)



(b)



(c)

Fig. 6.38: Estimated Weibull probability density function of the performance indices of the CAX1-105 feeder.

illustration, one can observe that case P stands as the most attractive case in terms of the performance indices. However, if the purpose of exploiting the architecture lies "only" on reducing the frequency of customer interruptions, case O is the most attractive case since it provides the same SAIFI results of case P without incurring on the outage management strategies. Clearly, several other/additional capabilities might be envisioned and evaluated (e.g. adverse condition alerting, dealing with device problems) aiming at improving even more the service provided by the utility through this feeder. However, the large set of cases elaborated herein already highlights, to an actual feeder, the applicability of the block-oriented agent-based architecture in the support of the power distribution system operation. Moreover, the methodological vision devised in chapter 3 is general, allowing the design of agent-based solutions to power distribution systems from the abstraction of goals to the coding of agent plans. Furthermore, the environment model described in chapters 4 and 5 permits verifying the impact of the designed agent-based solutions on the power distribution system operation in terms of performance indices. Consequently, the whole framework developed in this research provides the design, simulation and analysis tools to justify altering the power distribution system infrastructures towards a more modern and intelligent grid, as promoted through the block-oriented agent-based architecture.

6.4 Summary and Discussions

This chapter presented a series of simulations and result analyzes regarding the research contributions of this thesis. Firstly, the main stochastic and deterministic models utilized in the combined discrete-continuous simulation approach were validated using a consolidated test feeder. Then, this same simulation model was utilized within a computational environment to simulate the operation of an actual feeder from the South of Brazil. Over this computational environment, the block-oriented agent-based architecture was applied to support the operation of the actual feeder. Hence, in the application, the feeder was divided in blocks according to its natural segmentation through sectionalize switches. Moreover, the feeder was enhanced with protective/control devices, a DG unit, an EV charging station and controllable/interruptible customer loads. Following the particularities of the enhanced feeder, several sorts of agent capabilities were established to support the operation of the feeder under the developed framework. Notably, most of the capabilities were directed towards an area of the feeder where the worst service indices were verified (rural area). Such directive is aligned to the justifications of applying a block-oriented philosophy of management and control, as discussed in section 3.1. Therefore, as examples of outcomes, the frequency and duration of inadequate voltage conditions was diminished in the referred area by managing load reductions. Furthermore, the frequency and duration of service interruptions was also diminished in the referred area through strategies to support block islanded operation procedures. As consequence, using the definitions provided in section 4.2, one can conclude that the service adequacy and security of the feeder were improved, thereby showing the applicability and validity of our research developments.

An overview about the simulation and result analyzes may unveil that several original abstract goals of the architecture (see section 3.2) were indeed addressed through the agent capabilities. One example lies on the goal of providing an adequate voltage waveform, which was tackled through diminishing the frequency and duration of inadequate voltage conditions and through reducing the frequency and duration of customer interruptions. Additionally, customer interruptions were reduced through islanded operation procedures, which in turn took advantage of the integration of DG units, distributed energy storage devices, and controllable loads. Moreover, other targets such as diminishing restoration times and promoting the participation of DERs in the system operation were clearly achieved as well. This revels that the general methodological view employed in the system design, involving from the abstraction of goals to the coding of agent plans, is applicable and verifiable in light of the power distribution engineering.

At last, one must emphasize that all these results could not be obtained without a clear design of the block-oriented agent-based architecture, a simulation model which unifies the representation of the long-term failure/repair cycle of system elements with aspects of steady-state and dynamic behavior analyzes, and a computational environment model which integrates the agent-based architecture with the simulation model mechanisms. Using these design, simulation and analysis tools, a utility engineer can pragmatically evaluate and justify the application of a given set of agent capabilities to a power distribution system, looking forward to a smart grid built under the well-defined notions of intelligence of the agent paradigm.

Chapter 7

Conclusions and Final Remarks

This chapter finalizes the thesis by enunciating its conclusions, outlining its main contributions and providing a series of research topics to be explored in the future.

7.1 Conclusions and Discussions

This research was conducted in a context which promotes the integration of renewable and distributed energy resources, decentralized management and control solutions, modernization of the power system infrastructures, and provision of high levels of reliability. These concepts are covered in the under maturing smart/modern grid paradigm, which brought plenty of ideas and challenges to the power industry. Over this paradigm, three main research questions were established and their associated answers were obtained during the development of the research. Therefore, we conclude this thesis by providing these answers, as discussed below.

1. *Is it possible to develop local control strategies to improve the self-healing of power distribution systems by exploiting DER capabilities?*

   The research described herein presented a series of local control strategies where the self-healing of the power distribution systems is improved exactly through the exploitation of DER capabilities. The obvious example lies on the developed islanded operation strategies, which were designed to allow customers to be supplied after outages in the utility grid through the electric energy produced by DG units. Also, these islanded operation strategies were further improved by the management of controllable loads, the support to load shedding procedures, and the application of EV droop control schemes to be utilized at EV charging stations located in parking areas. Moreover, the promotion of the participation of DERs in the system operation was one of the goals established in devising this work. As consequence, DER capabilities were intensively exploited towards the improvement of the service adequacy and security, covering from strategies to mitigate inadequate voltage conditions to applications to provide outage management functions.

2. *How to coordinate these strategies in order to create a control architecture designed to support the power distribution system operation and to provide an adequate and secure service?*

This research achieved the coordination of local control strategies through the design of a block-oriented agent-based architecture capable of supporting the power distribution system operations under emergency situations. For this accomplishment, a block-oriented philosophy of management and control was devised using the agent paradigm to ascribe autonomy to entities responsible to support the operation of particular zones/blocks of the power distribution networks. Also, this autonomy was characterized by an explicit representation of goal-directed behaviors where the provision of service adequacy and security was targeted. Furthermore, the proposed design achieved smartness under the well-defined notions of intelligence of the agent paradigm. As consequence, local strategies were designed under the scope of agent-based systems and coordinated through agent interactions attaining altogether high levels of flexibility, extensibility, and robustness. These features are of major relevance to the gradual implementation of decentralized solutions in the system operation, allowing the smooth transition from actual to future power distribution systems in a way that enhancements in infrastructure are established according to a long-term vision.

3. *How to evaluate the impact of the designed architecture in the performance of the power distribution systems?*

   In order to answer this research question, this work culminated with the development of a simulation model which envelopes the representation of the long-term stochastic failure/repair cycle of system components with the representation of aspects of system steady-state and dynamic behavior analysis. From this simulation model, one can accurately verify the uprising/downsitting of standardized power distribution system performance indices due to tailored-made operational/control strategies. Hence, the simulation model mechanisms were included in a computational environment from where agents can perceive and act upon in runtime. This complex scheme permitted an effective evaluation of the impact of the block-oriented agent-based architecture in the performance of the power distribution systems.

After a pragmatical overview of all the work performed in this research, one can also conclude that the agent paradigm provides a suitable approach to structuring solutions to smart/modern grid environments. Moreover, the mix of power engineering and computational science disciplines can be highlighted as a determinant factor to allow consistent developments in our research area. Regarding this matter, power engineering academia should be aware that the description of software engineering design issues are of major relevance to guarantee their proposed agent systems can be actually extended in different contexts and applications. Finally, the usage of well established and documented agent design methodologies is appreciated to promote proper discussions about the virtues and drawbacks of each development.

7.2 Main Contributions

Looking forward to answer the research questions and after identifying the current research gaps in the state of the art, the following research contributions were provided in this thesis.

1. **Design of a block-oriented agent-based architecture to support power distribution system operations.**

This research introduced the design of a block-oriented agent-based architecture to support the power distribution system operations under emergency conditions, considering the integration of DERs. As previously discussed, the architecture is aligned with concepts of smart/modern grids, but providing smartness under the well-defined notions of intelligence behind the agent paradigm. In this architecture, a block-oriented philosophy of management and control is proposed and justified under the scope of the power distribution delivery. In addition, the architecture provides agent capabilities to information sharing, islanded operation and outage management in a way never conceived in the state of the art. Furthermore, as contribution to power engineering, it is employed a methodological vision where the conceptual framework is thoroughly described from the abstraction of goals to the coding of agent plans. Also, the design provides an explicit representation of goal-directed behaviors interrelated with agent planning, allowing a high-level representation of the agent's reasoning through JASON's syntax. All these features aids conjugating in a common framework agent solutions built to different activities and under different contexts. Moreover, the architecture was devised using concepts of the agent design methodology Prometheus as well as cognitive mapping, then permitting further variations, extensions, particularizations and discussions in the future. Finally, at the best of the author's knowledge, this work marks the first application of JASON and Prometheus to power engineering. From our experiences, JASON and Prometheus should both be exploited in the future under a large variety of power engineering problems yet to be tackled by our community.

2. **Design of a simulation model for the power distribution system operation to evaluate the long-term impact of operational/control solutions.**

   As contribution, this research promoted the concept of an integrated adequacy and security evaluation of power distribution systems with large scale integration of actively managed DERs, involving DG units, distributed energy storage devices (e.g. EV batteries) and controllable loads. Hence, the fundamental concepts behind service adequacy and security were revisited and alternative definitions to these concepts were proposed with focus on the power distribution delivery. Under these definitions, a combined discrete-continuous simulation model capable of providing integrated adequacy and security evaluations is thoroughly described. This simulation model unifies the representation of the long-term failure/repair cycle of system components with aspects of steady-state and dynamic behavior analysis, in a way absent in the state of the art. Furthermore, it includes additional contributions such as the design of a GMDH-based strategy to support load shedding activities, the mathematical disclosure of adverse weather event samplings using a non-homogeneous Poisson process model, the mathematical disclosure of test-functions for the variation of performance indices due to operational/control strategies, and the impact of DG islanding and islanded operation procedures, EV droop control, and load shedding strategies on the power distribution system performance indices.

3. **Development of an environment model able to integrate the agent architecture with the simulation model.**

   During the thesis' discussions, we emphasize that the key to promote the acceptance of agent-based solutions in the power distribution engineering lies on the development of an environment model from where the long-term impact of these solutions can be evaluated according to standardized performance indices. As a matter of fact, using such environment model, a utility engineer would be able to justify the deployment of agent-based solutions through the uprising/downsitting of performance indices. Therefore, this research provides the development of this environment model, where simulation mechanisms are embedded in artifacts to interact with the block-oriented agent-based architecture. For this accomplishment, an object-oriented modeling of our combined discrete-continuous simulation approach was introduced. Thus, an artifact scheme of a general-purpose power distribution system element was devised, allowing the representation of system components in the A&A meta model employed by CArtAgO. Moreover, an artifact-based scheme was developed to integrate the system state transitions of the simulation model with the solutions provided by the agent interactions. Therefore, using this scheme, the applicability of the block-oriented agent-based architecture was verified through its impact on the power distribution system performance indices. In fact, simulation experiments indicated that the active management of DERs provided by the architecture may allow significant improvements on the power distribution system performance indices. Furthermore, at the best of the author's knowledge, this research marked the first application of CArtAgO to power engineering modeling and simulation. This experience demonstrated that the A&A meta model employed by CArtAgO is practical and effective to building power engineering environments, providing a common infrastructure to agent platforms developed over a large variety of purposes.

7.3 Future Works

This thesis opens the way towards a series of research topics to be explored in the next years. In the followings, future research topics are described and discussed.

1. The research developments were devised using interactions between the agent programming employed by JASON and the environment programming employed by CArtAgO. This structure divides explicitly the *agent dimension* and the *environment dimension* in a combination referred to as JaCa in the literature. Recently, a novel dimension has emerged in the multi-agent programming's research community named *organizational dimension*. In this dimension, employed for instance by $\mathcal{M}$oise [307], organizational models are established with focus on their functioning (global plans, allocation of tasks, coordination of plan executions, time consumption, resource usage), structuring (roles, relation among roles, groups of roles) and norms (binding roles to missions). Therefore, future works will verify the application of $\mathcal{M}$oise in the block-oriented agent-based architecture, where the organization dimension will be exploited alongside JASON and CArtAgO in a framework referred to as JaCaMo [300].

2. The simulation model represents the component outages through their failure/repair cycle, as usually approached in reliability assessments. Hence, aiming at improving the adherence to the actual operation, future works will represent explicitly the failure modes and causes, link these modes and causes with the sampling of short-circuit events (if applicable) and repair times, consider the

separation between temporary and permanent faults, and provide a more accurate modeling of the protection activities by narrowing the timeframe representation. Moreover, besides technical matters, the simulation model will be extended to include the evaluation of customer interruption and duration cost indices.

3. The simulation model developed in this research neglects reasoning cycle time durations and communications delays. Hence, in order to consider the reasoning cycle time durations, a more accurate modeling of the hardware where the agents will be embedded might be required in the future. Moreover, the co-simulation of power engineering matters alongside communication matters may demand great efforts on modeling and simulation of communication media and technology.

4. Finally, in order to pragmatically verify novel possibilities for the architecture, its practical implementation would be appreciated. Therefore, future works might envision the development of hardware prototypes where the agents will be embedded and, posteriorly, the devising of field tests and applications. These processes might involve several challenges from choosing a utility interested in the framework to establishing compatibilities with current standards.

All these research topics will demand an even further mix of disciplines covering interactions with areas such as protection, automation and control, power electronics, communication, information technology, and software engineering.

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Appendix A

Publications

This appendix introduces the list of the papers published during the development of this Ph.D. thesis.

1. D. Issicaba, J. A. Peças Lopes, and M. A. Rosa, Adequacy and security evaluation of distribution systems with distributed generation, *IEEE Transactions on Power Systems*, 27(3):1681–1689, Aug. 2012.

2. A. M. Leite da Silva, L. C. Nascimento, M. A. Rosa, D. Issicaba, and J. A. Peças Lopes, Distributed energy resources impact on distribution system reliability under load transfer restrictions, *IEEE Transactions on Smart Grid*, 3(4):2048–2055, Dec. 2012.

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Appendix B

Device Function Numbers

Following the ANSI definitions, this appendix lists the IEEE standardized device function numbers alongside a brief functional description [308] in Table B.1.

Table B.1: Device function numbers

Function	Description
1	Master Element
2	Time Delay Starting or Closing Relay
3	Checking or Interlocking Relay
4	Master Contactor
5	Stopping Device
6	Starting Circuit Breaker
7	Rate of Change Relay
8	Control Power Disconnecting Device
9	Reversing Device
10	Unit Sequence Switch
11	Multi-function Device
12	Overspeed Device
13	Synchronous-speed Device
14	Underspeed Device
15	Speed or Frequency, Matching Device
16	Data Communications Device
17	Shunting or Discharge Switch
18	Accelerating or Decelerating Device
19	Starting to Running Transition Contactor
20	Electrically Operated Valve
21	Distance Relay
22	Equalizer Circuit Breaker
23	Temperature Control Device
24	Volts Per Hertz Relay
25	Synchronizing or Synchronism-Check Device
26	Apparatus Thermal Device
27	Undervoltage Relay
28	Flame detector
29	Isolating Contactor or Switch
30	Annunciator Relay

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Table B.1: Device function numbers

Function	Description
31	Separate Excitation Device
32	Directional Power Relay
33	Position Switch
34	Master Sequence Device
35	Brush-Operating or Slip-Ring Short-Circuiting Device
36	Polarity or Polarizing Voltage Devices
37	Undercurrent or Underpower Relay
38	Bearing Protective Device
39	Mechanical Condition Monitor
40	Field (over/under excitation) Relay
41	Field Circuit Breaker
42	Running Circuit Breaker
43	Manual Transfer or Selector Device
44	Unit Sequence Starting Relay
45	Abnormal Atmospheric Condition Monitor
46	Reverse-phase or Phase-Balance Current Relay
47	Phase-Sequence or Phase-Balance Voltage Relay
48	Incomplete Sequence Relay
49	Machine or Transformer, Thermal Relay
50	Instantaneous Overcurrent Relay
51	AC Inverse Time Overcurrent Relay
52	AC Circuit Breaker
53	Exciter or DC Generator Relay
54	Turning Gear Engaging Device
55	Power Factor Relay
56	Field Application Relay
57	Short-Circuiting or Grounding Device
58	Rectification Failure Relay
59	Overvoltage Relay
60	Voltage or Current Balance Relay
61	Density Switch or Sensor
62	Time-Delay Stopping or Opening Relay
63	Pressure Switch
64	Ground Detector Relay
65	Governor
66	Notching or Jogging Device
67	AC Directional Overcurrent Relay
68	Blocking or "Out-of-Step" Relay
69	Permissive Control Device
70	Rheostat
71	Liquid Level Switch
72	DC Circuit Breaker
73	Load-Resistor Contactor
74	Alarm Relay
75	Position Changing Mechanism
76	DC Overcurrent Relay
77	Telemetering Device
78	Phase-Angle Measuring Relay
79	AC Reclosing Relay
80	Flow Switch

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Table B.1: Device function numbers

Function	Description
81	Frequency Relay
82	DC Reclosing Relay
83	Automatic Selective Control or Transfer Relay
84	Operating Mechanism
85	Communications,Carrier or Pilot-Wire Relay
86	Lockout Relay
87	Differential Protective Relay
88	Auxiliary Motor or Motor Generator
89	Line Switch
90	Regulating Device
91	Voltage Directional Relay
92	Voltage and Power Directional Relay
93	Field Changing Contactor
94	Tripping or Trip-Free Relay
95–99	For other specific applications