

FACULTY OF ENGINEERING OF UNIVERSITY OF PORTO
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Agent-based Technology Applied to Power Systems Reliability

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*A diferença entre Sucesso e Felicidade é que
Sucesso é conseguir o que se quer e Felicidade é gostar do que se conseguiu.*

(Dale Carnegie)

*The difference between Success and Happiness is that
Success is to achieve something that you wish and Happiness is to enjoy what you
have achieved.*

(Dale Carnegie)

*La différence entre le Succès et le Bonheur est que le Succès est la réalisation de
ce que vous voulez et le Bonheur est comme ce qui est réalisé.*

(Dale Carnegie)

Para os meus Pais

To my parents

À mes parents

Em memória de Maria Clara

In memory of Maria Clara

À la mémoire de Maria Clara

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RESUMO

Na perspectiva dos sistemas eléctricos de potência (SEP), nos últimos anos, é notório que o mundo tem passado por muitas transformações. Alertas constantes às mudanças climáticas associadas ao crescimento económico e a outros factores importantes têm submetido os SEP a mudanças dramáticas, afectando principalmente a forma como são projectados, planeados, operados e geridos. Muitas actividades estão direccionadas a campos tecnológicos de regulamentação e económicos que, necessariamente, afectam por inteiro o SEP. Investimentos em investigação e desenvolvimento têm sido uma solução para minimizar os riscos associados a mudanças tecnológicas e regulamentais, bem como têm atraído capital para a indústria dos SEP. Uma das primeiras áreas a ser afectada com tais alterações é a de análise de sistemas eléctricos, pois requer uma colecção de ferramentas de simulação que sejam capazes de representar todas essas mudanças tecnológicas, tais como a inclusão das produções renováveis (eólica, solar, etc.), e como a análise dos impactos de regulação, nomeadamente, o problema da escala de manutenção de grandes equipamentos num mercado aberto de energia.

Esta tese explora novos caminhos na área de análise de sistemas eléctricos através do uso da tecnologia de agentes. Primeiramente, o trabalho de pesquisa discute o desenvolvimento de uma plataforma baseada na tecnologia de Sistemas Multi-Agentes (SMA), com potencial para aplicações em gestão e simulação de processos na área dos SEP. Com o objectivo de explorar algumas das particularidades dos SMA, é proposta uma nova metodologia para avaliar a fiabilidade dos SEP, baseada na Simulação de Monte Carlo (SMC), explorando os benefícios da área de inteligência artificial distribuída e, principalmente, no uso desta capacidade distribuída de duas formas: construindo comportamentos autónomos para as aplicações e reduzindo esforço computacional. Através do uso dessa tecnologia, foi possível dividir o algoritmo da SMC em tarefas distintas e submetê-las à execução de agentes. Duas abordagens diferentes para resolver o problema de avaliação da fiabilidade de sistemas de geração baseadas na SMC cronológica ilustram o potencial dos SMA no problema de avaliação da fiabilidade dos SEP. Em segundo lugar, é discutido o problema de programas de manutenção para unidades produtoras. Decisões de programas de manutenção em mercados de electricidade são um dos mais importantes conflitos estratégicos entre os participantes do mercado. Por

exemplo, uma companhia produtora de electricidade é uma entidade com interesse próprio nos seus riscos e, ao mesmo tempo, responsável pelos riscos associados aos SEP. Por outro lado, para grandes equipamentos que suprem muitos consumidores, a tarefa de elaborar uma boa programação para a manutenção desses equipamentos, preservando a fiabilidade do sistema, é direccionada para o operador independente do sistema (OIS). Este relacionamento é, algumas vezes, conflituoso e pode ser visto como um obstáculo para as companhias produtoras na maximização dos seus lucros, bem como para o OIS em manter um nível de risco adequado para todo o sistema. Neste sentido, a atenção é focalizada sobre este relacionamento. Além do mais, ressalta a proposta de construir um ambiente dedicado com o objectivo de melhorar e clarificar as discussões sobre programas de manutenção para grandes equipamentos, usando a tecnologia de agentes. Adicionalmente, são incluídas discussões sobre programas de manutenção que envolvem equipamentos tradicionais para a produção (hidrológicos e térmicos) e SEP com alta penetração de produção renovável. Assim, também são apresentados resultados usando alguns SEP, como exemplos.

Na terceira parte deste trabalho de pesquisa, é feita uma listagem de algumas melhorias, na ferramenta de simulação proposta, como solução complementar para a avaliação da fiabilidade dos SEP. Novos caminhos são explorados de forma a tornar viáveis estudos de fiabilidade através de diferentes métodos e de acordo com a complexidade dos SEP avaliados. É apresentada uma aplicação do algoritmo de *Optimização de Enxames de Partículas Evolucionário* (Evolutionary Particle Swarm Optimization - EPSO) para avaliar a fiabilidade dos SEP como uma alternativa à abordagem tradicional da SMC. Neste sentido, um método baseado em populações, como o EPSO, aparece como competidor do método tradicional da SMC. O trabalho reportado, nesta terceira parte da pesquisa, demonstra que uma variação do EPSO pode focar a busca numa região do espaço de estados onde as contribuições para a formação dos índices de fiabilidade podem ser encontradas, ao invés de conduzir uma procura cega no espaço. Essencialmente, consiste numa alternativa de análise *encapsulada* na ferramenta de simulação proposta. A metodologia apresentada, nesta parte do trabalho, tem por objectivo introduzir não só componentes de software baseados em agentes combinados com metas heurísticas, mas também discutir o uso de alguns tópicos de inteligência artificial aplicados a sistemas de agentes inteligentes com o intuito de tornar viáveis avaliações de fiabilidade para SEP com grande dimensão.

ABSTRACT

From the power systems perspective, the world has experienced dramatic changes over the past few years. Global climate warnings associated with economic progress and other factors have led the power systems to undergo changes, mainly affecting the way they are designed, planned, operated and managed. A significant amount of activity is underway on the technological, policy and economic fronts, which necessarily affects the entire electric power sector. Investments in research and development (R&D) have been the solution to mitigate the technological and policy risks of these changes and have attracted market capital to the power system industry. One of the first areas affected by these changes is the power systems analysis area, which requires the ability of a set of simulation tools to represent the changes associated with the technological front, such as wind and solar power energy penetrations, and/or analysis of policy impacts (e.g. maintenance schedule of large equipment in the open market energy).

This thesis has explored new ways for power system analyses through the use of agent-based technology. First, the research work discusses the development of a Multi-Agent Systems (MAS) technology-based platform with potential applications in management and simulation processes in power systems. In order to explore some of the features of MAS, a new methodology is proposed to assess power systems reliability based on the Monte Carlo simulation (MCS), exploiting the benefits of the distributed artificial intelligence area and, mainly, the use of the distributed capacity in two ways: building autonomous behaviors for the applications and mitigating computational effort. Through the use of this technology, it was possible to divide the MCS algorithm into distinct tasks and submit them to the agent processing. Two different approaches to solve reliability problems in generating capacity based on chronological MCS illustrate the potential of MAS in power systems reliability assessment. Second, the maintenance schedule generating units are discussed. Maintenance decisions in electricity markets are one of the most important strategic conflicts among power players. For instance, a generation company is a self-interested entity that is responsible for its own risk-based level. On the other hand, for large equipment supplying many customers, it is the Transmission System Operator's task to schedule the most suitable period for maintenance, thus preserving system reliability. This relationship is sometimes conflicting and can be seen as an obstacle to the generation companies maximizes profits, as well as to the transmission system operator, since it is

mandatory to keep in an adequate risk level based on the overall system. In this sense, the attention is focused on this relationship. Moreover, it highlights the proposal of building a dedicated environment in order to improve and clarify the discussions about maintenance outage schedule for large equipments, using the agent-based technology. In addition, maintenance discussions involving conventional power plants (hydro and thermal) and systems with high penetration of renewable generation are included. Results from the use of several systems are also presented.

In the third part of this research work, some improvements on the proposed simulation tool are listed as complementary solutions to power system reliability assessment. Some ways to make reliability studies feasible using different methods that consider the complexity of the power system are explored. An application of Evolutionary Particle Swarm Optimization (EPSO) based methods to evaluate power system reliability is presented as an alternative to the Monte Carlo approach. In this sense, Population-based (PB) methods appear as competitors to the traditional MCS because they are computationally efficient in estimating a variety of reliability indices. The work reported in the third part of this research demonstrates that EPSO variants can focus the search in the region of the state space, where contributions for the formation of a reliability index may be found, instead of conducting a blind sampling of the space. Essentially, it consists of a search alternative encapsulated into a proposed simulation tool. The methodology presented in this part of the work intends to introduce, not only agent-based component software combined with a meta-heuristic based on Population-based methods, but also to discuss the use of some artificial intelligence topics in the intelligent agent systems in order to make feasible power system reliability assessments for large systems.

RESUME

Dans la perspective des systèmes électriques de puissance (SEP), il est notoire que le monde a subi d'innombrables transformations durant ces dernières années. Des alertes constantes aux dérèglements climatiques associées au développement économique et à d'autres facteurs importants, ont soumis les SEP à des changements dramatiques, en touchant principalement la façon dont les SEP sont projetés, planifiés, opérés et gérés. De nombreuses activités sont dirigées vers des domaines technologiques, de réglementation et économiques qui, nécessairement, affectent totalement le SEP. Des investissements en investigation et développement ont été une solution pour minimiser les dangers associés aux changements technologiques et réglementaires, tout comme ils ont attiré des capitaux pour l'industrie des SEP. Un des premiers domaines affecté par ces changements est celui de l'analyse de systèmes électriques, car il requière toute une gamme d'outils de simulation qui soit capable de représenter tous ces changements technologiques, tels que l'inclusion des productions renouvelables (éolique, solaire, etc.), tout comme l'analyse des impacts de régulation, nommément, le problème de l'échelle de manutention de grands équipements dans un marché ouvert de l'énergie.

Cette thèse exploite de nouvelles voies dans le domaine des systèmes électriques par l'utilisation de la technologie d'agents. Dans un premier temps, ce travail aborde le développement d'une plate-forme basée sur la technologie des Systèmes Multi-Agents (SMA), avec du potentiel pour des applications en gestion et simulation de procédés dans le domaine des SEP. Avec l'objectif d'exploiter certaines des particularités des SMA, une nouvelle méthodologie pour évaluer la fiabilité des SEP est proposée, basée sur la simulation de Monte Carlo (SMC), exploitant les bénéfices du domaine de intelligence artificielle distribuée et, principalement, dans l'usage de cette capacité distribuée de deux façons: en construisant des comportements autonomes pour les applications et en réduisant l'effort informatique. A l'aide de l'usage de cette technologie, il a été possible de diviser l'algorithme de la SMC en tâches distinctes et les soumettre à l'exécution d'agents. Deux abordages différents pour résoudre le problème d'évaluation de la fiabilité des systèmes de gestion basée sur la SMC chronologique illustrent le potentiel des SMA quant au problème de fiabilité des SEP. Deuxièmement, le problème des programmes de manutention pour des unités productrices est débattu. Des décisions de programmes de manutention dans les

marchés de l'électricité sont un des plus importants conflits stratégiques parmi les intervenants de ce marché. Par exemple, une compagnie productrice d'électricité est une entité avec des intérêts propres sur ses risques et, au même moment, responsable des risques associés aux SEP. En contre partie, pour de grands équipements qui pourvoient beaucoup de consommateurs, la tâche d'élaborer une bonne programmation pour la manutention de ces équipements, en préservant la fiabilité du système, est dirigée vers l'opérateur indépendant du système (OIS). Cette relation est, quelques fois, conflictuelle et peut être vue comme un obstacle pour les compagnies productrices dans le but de la maximisation de leurs profits, ainsi que pour l'OIS à fin de maintenir un niveau de risque adéquat dans tout le système. En ce sens, l'attention est focalisée sur cette relation. De plus, il est important de souligner que la proposition de créer un climat favorable avec l'objectif d'améliorer et clarifier les discussions sur les programmes de manutention pour de grands équipements, en utilisant la technologie d'agents. De plus, sont incluses des discussions sur des programmes de manutention qui incluent des équipements traditionnels pour la production (hydrologiques et thermiques) et le SEP avec une forte présence de production renouvelable. Ainsi, les résultats sont présentés en utilisant quelques SEP comme exemples.

Dans le troisième volet de ce travail de recherche, une liste de quelques améliorations est élaborée, dans l'outil de simulation proposée, comme solution complémentaire pour l'évaluation de fiabilité des SEP. De nouvelles voies sont exploitées de façon à rendre viables des études de fiabilité à travers différentes méthodes et conformément à la complexité des SEP évalués. Une application de l'algorithme de l'*Optimisation des Examens de Particules Evolutives* (Evolutionary Particle Swarm Optimization - EPSO) pour évaluer la fiabilité des SEP comme une alternative à l'approche traditionnelle de la SMC. En ce sens, une méthode basée sur des populations, comme l'EPSO, se présente comme la concurrente de la méthode traditionnelle de la SMC. Le travail présenté, dans ce troisième volet de la recherche, montre qu'une variation de l'EPSO peut focaliser la recherche dans une région de l'espace des états où la contribution pour la formation des indices de fiabilité peut être identifiée, plutôt que de mener une recherche aveugle dans l'espace. Il s'agit essentiellement d'une alternative d'analyse *intégrée* dans l'outil de simulation proposée. La méthodologie présentée dans ce volet du document, a comme finalité d'introduire, non seulement, des composants de software basés sur des agents combinés avec des objectifs heuristiques, mais aussi de discuter l'utilisation de quelques

topiques d'intelligence artificielle appliqués à des systèmes d'agents intelligents dans le but de rendre viables des évaluations de fiabilité pour des SEP de grande dimension.

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LIST OF ABBREVIATIONS AND SYMBOLS

ACL	Agent Communication Language
A	Availability
AI	Artificial Intelligence
AOP	Agent-Oriented Programming
BDI	Belief-Desire-Intention
β	Coefficient of Variation
CFP	Call for Proposal
CG	Conventional Generation
CPU	Central Processing Unit
DG	Distributed Generation
DISCO	Distribution Company
EPSO	Evolutionary Particle Swarm Optimization
FIPA	Foundation for Intelligent Physical Agent
FISO	Facilitator Independent System Operator
FOR	Forced Out Rate
GENCO	Generation Company
GUI	Graphic User Interface
HL	Hierarchical Levels
ISO	Independent System Operator
IA	Intelligent Agent
IC	Index Calculator
IT	Information Technology
KQML	Knowledge Query and Manipulation Language
LV	Low Voltage
λ	Failure Rate
MAS	Multi-Agent Systems
MCS	Monte Carlo Simulation
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
MV	Medium Voltage
μ	Repair Rate
NY	Number of Years

NS	Number of Samples
η	Computational Efficiency
OOM	Object-Oriented Modeling
PGS	Portuguese Generating System
PB	Population-Based
PDF	Probability Density Function
PRS	Procedural Reasoning System
REN	Redes Energéticas Nacionais (Portuguese TSO)
REE	Red Eléctrica de España (Spanish TSO)
R&D	Research and Development
RMI	Remote Method Invocation
SGS	Spain Generating Systems
SP	Sequence Producer
SE	State Evaluator
S_u	Speed-up
TRANSCO	Transmission Company
T	Time Period
U	Unavailability

Chapter 1

INTRODUCTION

1.1 INTRODUCTION TO GREEN POWER

Global warming and environmental concerns of increasing carbon emissions, among others, are becoming increasingly apparent. As a result, a few years ago, an important environmental defense movement started not only alerting to the risk of maintaining the *status quo* for carbon emissions, but also highlighting the need of making a transition to an emission free and sustainable energy system. The environmental defense movement envisions a decarbonization pathway through an efficient use of existing fossil fuel resources, tending to rely more on fuels with lower carbon content (i.e. natural gas), and ultimately a complete shift toward renewable energy resources [1]. As an immediate consequence, the mix of primary fuels used to generate electricity has changed a great deal over the last years on a worldwide basis. Coal has continued to be the most widely used fuel for electricity generation, albeit generations from nuclear and natural gas have constituted an important option for several countries. However, the most significant change is that the use of oil for electricity generation has been declining.

Renewable resources are environmentally benign, locally generated, and can play a significant role in fueling a thriving worldwide economy with sustainable energy sources that take both the social and economic well being of citizens into account [1]. A renewable energy source is defined as any energy resource naturally regenerated over a short time scale that is derived directly from the sun (such as solar thermal and photovoltaic resources), indirectly from the sun (such as wind, hydropower and photosynthetic energy stored in biomass), or from other natural movements and mechanisms of the environment (such as geothermal and ocean energy) [2]. Following these definitions, there is a wide variation in the expectations for the use of renewable energies among the countries. In the developing nations of Asia and Central and South America, it is expected that the hydroelectric power plants will dominate the increasing use of renewable energies over the next years. China, India, and Brazil have plans to expand the hydroelectric capacity in order to meet the growing electricity demand [3]. In contrast, hydroelectricity is not likely to expand strongly in other countries where have no the natural resources needed to construct power hydroelectric facilities. In the cases of several European countries, most of the growth in renewable electricity is likely to come from non-hydroelectric renewable energy sources, especially wind, solar and biomass energy. Regardless of the worldwide scenario, the increased use of electricity produced from renewable energy sources constitutes an important part of the package of measures

needed to comply with the Kyoto Protocol to the United Nations Framework Convention on Climate Change. Renewable energies may play a prominent role in tackling the twin challenge of energy security and global warming because they are not depletable and produce less greenhouse-gas emissions than fossil fuels. The promotion of this type of electricity has a high priority in many countries, particularly in the European Union.

In the last few years, there were several discussions among European governments and associations. In March 2007, Europe's Heads of State agreed to a binding target of 20% renewable energy by 2020 [4], [5]. This decision gives a strong signal for Europe's future energy policy, as well as for the expansion of the European renewable energy industry, which includes the development of new ways of operating and planning power systems.

1.2 RELIABILITY ASSESSMENT CONCERNING GREEN POWER

The European proposed level of commitment to renewable sources offers many benefits, including a more diversified fuel mix and reduced emissions. Nonetheless, just as with any new technology, certain challenges to reliably regarding the integration of green power into the system must be addressed. Meanwhile, there is a significant worldwide focus on wind power to provide the growing requirements for electric power, mainly due to the maturity of the technology and availability of suitable sites for development. One of the most important challenges around this type of technology is their forecasting properties, which must be improved to manage wind uncertainty [6]. Power system planners and operators are already familiar with a certain amount of variability and uncertainty, particularly because it is related to the system demand and, to a certain extent, to the conventional generation. Output from wind generation is, however, not as dispatchable as conventional sources. Undoubtedly, the number of random variables and system complexities increases exponentially when wind power is added to the system, due to the fluctuating capacity levels of these sources. Other green technologies, such as solar thermal and photovoltaic, biomass, and others, are increasingly explored. The aim is to allow countries to comply with the Kyoto Protocol to the United Nations Framework Convention on Climate Change. As a result, there are also several challenges that must be addressed in order to reliably integrate these technologies into the system.

A major paradigm has been discussed surrounding this green power movement in which the focus is the transmission system. Transmission lines are the critical link between

generation and customers. As demand grows and generation is built in areas remote from the demand, more capacity on the transmission system is needed to meet the demand. In this sense, when wind sites and/or solar thermal systems are installed, for instance, far from demand, it is necessary to pay attention to the flexibility of the transmission system, which must be expanded to enable management of both the uncertainty and variability of wind and/or solar resources. On the other hand, green sources as wind power, solar photovoltaic, biomass and others, can eventually be connected near to the demand. Therefore, the concept of distributed generation must be evaluated.

Distributed generation (DG) is a term used to describe the small scale production of power, typically located close to demand or connected to distribution systems. In certain cases, the plants may often be located “behind the meter” at different sites such as hospitals and industrial facilities. DG is also known as on-site generation, dispersed generation or embedded generation [7]. Typical system reliability benefits attributed to DG may include:

- Reduced energy losses and upstream congestion on transmission lines;
- Improved local reliability;
- Faster permitting than transmission line upgrades.

Several issues have remained, thus complicating the way in which distributed generation is “counted on” for reliability. First and foremost, different from the largest generating units, system operators do not typically have the same kind of visibility and control over these distributed assets – especially those connected to the distribution network as opposed to the transmission system. As it can be understood, green power added to distributed generation can be a complicated challenge to the system planners and operators.

New computational models and tools have to be developed in order to deal with these new variables, particularly those related with wind power, since they are the most popular source of green electricity. A high number of technical works have recently been published in this area and can be found in [8-15].

From the planning point of view, deterministic based approaches have very attractive characteristics, such as simple implementation, easy understanding, assessment and judgment by planners in relation to severe conditions like network outages and system peak load. Unfortunately, although the perception of many planning engineers, whose

past experience, in addition to some known critical situations, is enough to assess system risk conditions, it is not valid. Moreover, past experience with renewable sources like wind power is very limited. However, the principles of some deterministic standards (e.g. “N-1” criterion) must be recognized as attractive.

Conversely, methodologies based on probability concepts may be extremely useful in assessing the performance of power systems [16]. They have been successfully applied to many areas, including generation and transmission capacity planning, operating reserve assessment, distribution systems, and others. The proper measure of risk can only be achieved by recognizing the probabilistic nature of power system parameters.

A new framework, named system well-being analysis [17-19], has been built combining deterministic perception with probability concepts. This new framework reduces the gap between deterministic and probabilistic approaches by providing the ability to measure the degree of success of any operating system state. In a well-being analysis, success states are further split into healthy and marginal states, using the previously mentioned engineers' perception as criterion. In the last decade, well-being analysis has been applied to areas such as generating systems, operating reserve assessment, and composite generation and transmission systems. Chronological or sequential Monte Carlo simulation has been used for generating system well-being analysis, considering the loss of the largest available unit in the system as the deterministic criterion. This concept may be extremely useful for dimensioning the static and operating reserve capacities considering renewable resources [20-27].

1.3 AGENT-BASED TECHNOLOGY IN POWER SYSTEMS ANALYSIS

Due to the sheer size of the power system, hand-based calculations are nearly impossible and computers offer the only truly viable means for system analysis. The power industry is one of the largest users of computer technology and one of the first industries to embrace the potential of computer analysis when mainframes first became available [28]. System analysis is very important to predict and continually update the operating status of the network. This includes estimating the current power flows and bus voltages (Power Flow Analysis and State Estimation); determining the stability limits of the system (Continuation Power Flow, Numerical Integration for Transient Stability and Eigenvalue Analysis); minimizing costs (Optimal Power Flow, Unit Commitment), as well as

determining the risk-based level on the overall system (Reliability Assessment). Therefore, as power systems increasingly operate under stressed conditions, computer simulation has promoted a large role in control through the adequacy and security assessments.

Most real power system problems are much larger in size and scope, requiring some distributed capacities that enable a dynamic interaction among entities. In Artificial Intelligence (AI) and Computer Science, agent-based technology has offered these capacities through the use of the Agent-Oriented Programming and Multi-agent Systems. In fact, in the last years, both areas have merged concepts, promoting a sophisticated software design in which certain software is able to percept and react when embedded in a specific environment. Some researchers have clearly distinguished the agent definitions proposed by the Computer Science and AI areas [29-30]. The weak notion of an agent, proposed essentially by distributed computation and distributed artificial intelligence areas, has defined an agent as a software automation paradigm, where software agents cooperate with one another in a distributed environment in order to solve problems. Therefore, agents exhibit certain properties, such as autonomy, reactive and proactive actions, rationality and sociability. The strong notion of an agent, proposed by the AI area, has defined an agent as software with cognitive capacities. The idea is that it is possible to talk about computer programs as if they had a mental state. Therefore, agents exhibit capacities [31-32] such as belief, desire, intention, knowledge, obligations, and others. Hence, agent-based technology is considered to be like sophisticated computer programs that act autonomously on behalf of their users, across open and distributed environments, to solve a growing number of complex problems. Additionally, multi-agent system is a loosely coupled network of software agents that interact in order to solve problems that are beyond the individual capacities or knowledge of each problem solver.

For a long time, the commitment between power industry and the computation area has evolved in different ways. In the last decade, several heuristic tools were applied to a variety of power system problems in order to facilitate solving optimization issues that were previously difficult or impossible to solve. Recently, these new heuristic tools have been combined among themselves and with knowledge elements, as well as with more traditional approaches, such as the statistical analysis to solve extremely challenging problems [33]. Naturally, evolutionary computation, genetic algorithms, evolutionary programming and strategies, particle swarm optimization, ant colony algorithm, simulated

annealing, tabu search, hybrid systems of evolutionary computation and other modern heuristic approaches have been part of the intelligent techniques used in power industry. The natural challenge to the next years will be combining intelligent techniques or AI techniques with intelligent agents (IA) or agent-based technology, in order to promote a sophisticated software design in computer simulation and control to the power system industry.

1.4 SCOPE AND OBJECTIVES OF THE THESIS

Due to the seriousness of the problem, reliability studies involving a complete electric power system - including generation, transmission and distribution facilities - are not usually conducted. Therefore, generation systems, composite systems (generation plus transmission) and distribution systems studies are usually conducted independently. Moreover, some new challenges as energy market rules and green power paradigm are added to the power systems analysis, thus making reliability studies increase in size and scope. These studies are an important requirement in overall power system planning and operation.

Traditional software design, which usually uses mathematical programming environments, has been supporting reliability studies for a long time. In general, FORTRAN is the most widely used programming language to support reliability studies in a variety of power facilities and research academic environments around the world. This happens mainly due to the suitable performance when working with mathematical approaches, as well as their wide mathematical libraries. One of the most important objectives of this thesis is to explore new ways to build software to power systems analysis, which will be adequate to the size and scope of the power system problems. Specifically, this thesis will explore the distributed capacities of the agent software paradigm in power system reliability assessment. In general, the adequacy generation assessment was used to test agent and multi-agent features through the use of sequential Monte Carlo simulation. Hitherto, several mechanisms have been used in power system literature in order to improve computational performance for the reliability assessment of power systems. Bearing the last years in mind, it can be stated that researchers have used, for instance, heuristic tools to estimate reliability indices, artificial intelligence techniques or variance reduction techniques to improve Monte Carlo Simulation, Hybrid approaches,

and others. Therefore, this work intends to explore an agent-based architecture design, not only to mitigate computational effort and achieve a better performance, but also to promote a suitable reliability platform based on multi-agent systems, combining the agent-distributed capacities with other mechanisms to achieve computational robustness. In order to cover all characteristics of the agent-based platform, besides the sequential Monte Carlo simulation, other methods were tested in the generating adequacy assessment problem. Some important examples are the non-sequential Monte Carlo simulation, the convolution technique and population-based methods, aiming to make a reliability agent-based platform as flexible as possible.

With the purpose of searching other potentialities of the agent-based technology in conflicting solutions within the power industry, an application based on distributed capabilities usually applied in electronic business is proposed as a potential mechanism used by ISOs (Independent System Operator). The aim is to coordinate maintenance schedule generating units in the energy market. Due to the time-dependence of the maintenance problem, as well as its complexities, which generally involves several technical and economic interests, some natural distributed features of the agent-based technology, widely used in electronic commerce, are explored. These abilities are combined with a suitable reliability tool based on the sequential Monte Carlo simulation, which was prepared to capture the distributional aspects of several reliability indices, considering a power plant with a high participation of the renewable sources (green sources) in the total production. Some scenarios using the IEEE-RTS (IEEE Reliability Test System) and real configurations of the generation systems are used to illustrate the maintenance schedule discussions based on agent-based technology.

Essentially, the main objective of this research work is to merge agent-based programming paradigm with power systems problems in order to study the potentialities of this new software paradigm in the power systems area.

1.5 THESIS OUTLINE

This thesis is divided into seven chapters. All these chapters were written to be read independently of one another, with the exception of Chapter 6. Regardless of this fact, each chapter presents a brief state of the art and its scopes, as well as the main objective in its introduction. Chapters 2 and 3 form the basis of the understanding of the

applications that will be presented in Chapters 4, 5, and 6. Chapter 7 closes the work, emphasizing some remarks.

A brief history about agent-based technology and the basic concepts used in this work concerning agent-based and multi-agent systems are presented in Chapter 2. Concepts as agent architectures, agent environments and agent-oriented programming are discussed to support the understanding of agent applications used in the following chapters. A multi-agent paradigm is also presented in Chapter 2. Concepts involving cooperation, competition and coordination are explored through the use of the communication process. A short discussion on ontology and agent-related technology for infrastructure support is then emphasized.

In Chapter 3, the basis for the power system reliability assessment is presented. A brief discussion on the evolution of the functional zones and its implications is promoted in order to contextualize the power systems reliability studies. The objectives of the generating adequacy assessment, composite systems and distribution assessment are explored, but generating assessment is the one essentially emphasized. Some computational representations, such as state space and chronological, are presented, aiming to contribute to the reader's understanding on the mechanisms employed in the following chapters. Some methods, such as convolution, state enumeration, non-sequential and sequential Monte Carlo simulation, population-based, and pseudo sequential Monte Carlo simulation are revisited. Other important issue discussed is the load model, usually employed together with these methods. In order to highlight the power system reliability assessment considering new issues such as renewable sources, a case study involving two real systems is presented. Using several planning configurations of the Portuguese and Spanish generating systems, and a sequential tool written in FORTRAN language based on sequential Monte Carlo simulation, the problem of the CPU time to each reliability study is taken into consideration, allowing the reader to realize the requirement needs in this power systems analysis.

Chapter 4 presents the power agent platform proposed in this work. Basically, it is an overview of the power agent platform and its interaction levels. Some potentialities are then emphasized. A brief discussion involving some requirements of the power agent platform, which intends to incorporate artificial intelligence into intelligent agents, justifies the proposed computation architecture design. In sequence, the multi-agent system applied to chronological Monte Carlo simulation is introduced through the

revisited text of the Monte Carlo concepts. At this point, two architecture designs – synchronized and non synchronized approaches – are presented, followed by the several results and performance measures of both. A discussion about Java environment calculations and their use in power systems reliability assessment closes the chapter, pointing out some remarks to the next developments.

In order to explore other potentialities of the agent-based technology, Chapter 5 presents a tool based on agent technology in order to support decision-making in conflict solutions. Therefore, Chapter 5 explores the unit maintenance scheduling problem and its complexities, involving several entities of the energy market. First, the reader will briefly understand the history of this problem within the power system industry over the last decade, through the ongoing changes promoted during this time. Thus, the conventional maintenance scheduling problem becomes the strategic maintenance scheduling assets due to the market deregulation, and it increases in complexity when maintenance scheduling considers renewable sources. Still in Chapter 5, the multi-agent system in the electrical power industry is introduced through the use of condition monitoring and e-maintenance¹ concepts. These discussions intend to help the reader understand the proposed methodology, which is entirely based on current market rules. Essentially, the chapter explores the distributed potentialities of the multi-agent systems combined with a suitable reliability tool to coordinate maintenance schedule discussions. Several application examples, involving a test system and two real systems, close Chapter 5.

With the purpose of improving the power agent platform presented in Chapter 4, some improvements were listed and tested in Chapter 6. Essentially, some AI topics that have already been used in power system reliability analysis are presented in order to make the proposal more flexible. An application based on population methods are explored as an alternative to the Monte Carlo approach.

Chapter 7 closes the thesis presenting the main contributions of this research work and listing some possible future researches linked to these ideas.

¹ It is an e-jargon that considers the integration of the information and communication technologies within the maintenance strategy and/or plan.

Chapter 2

THE MULTI-AGENT SYSTEM PARADIGM

2.1 INTRODUCTION

The history of artificial intelligence (AI) research started before the development of the first digital computers, but today it is strongly linked to the computation area. For artificial intelligence to succeed, two factors are essential: intelligence and an artifact. The computer has been the artifact of choice [34]. In fact, the modern engineering discipline of AI started with the advent of the modern digital computer [35]. Nevertheless, some authors have claimed that IA (intelligent agents) is 99% computer science and 1% AI [36].

In the last six decades, hardware and software have been significantly improved in performance and availability inside of the modern computation area. Initially, the challenges of the programmers and computer developers were to minimize memory usage and to maximize processing speeds in their applications. These hardware objectives were won since the invention of the integrated circuit in 1958. Nowadays, almost every measure of the capabilities of digital electronic devices, such as memory capacity and processing speed, as well as the number and size of pixels in a digital camera, are linked to Moore's law [37] and do not constitute an obstacle in modern computation. Later, between the 1970s and 1980s, the object-oriented paradigm sought to maximize the modularity and re-usability of the code, and to minimize the post-deployment system maintenance. As a result of these developments, hundreds of programming languages are available today in order to help programmers build different solutions to a variety of areas. In the sequence of history, the increasing importance of the internet has led, however, to a new understanding of the nature of computation that places interaction at its centre. The agent-oriented paradigm has sought to maximize adaptability and robustness of systems in open environments [38]. Therefore, the challenge today is to design systems capable of being adapted to dynamic environments and also capable of configuring, managing, and maintaining themselves. The power of the agent paradigm is that it provides the means, at the appropriate level of abstraction, to conceive, design and manage such systems. In this chapter, a visit to some concepts on agent-based systems has been proposed, and the most attractive definitions have been presented. They are usually pointed out in the specialized literature around agent technology in order to support the concepts applied into proposed applications. The aim is to collaborate with a basic idea about agent-based technology and its wide applicability to all sorts of different problems.

2.2 INTELLIGENT AGENTS

Although does not exist a consensus in the agent definition, some AI authors bring out their basic functions in order to better define their abilities. Thus, an agent is just something that acts (agent comes from the Latin *agere*, to do). However, computer agents are expected to have other attributes that distinguish them from mere programs [34], such as operating under autonomous control, perceiving their environment, persisting over a prolonged time period, adapting to change, and being capable of taking on another's goals [34]. Hence, agents are expected to deal with a different set of objectives than do just simple programs. They are, most of the time, defined as systems or computer programs that are *situated* in some environment and are capable of sensing their *environment* through the use of sensors. Consequently, they need to have a repertoire of possible *actions* that they can perform through the use of effectors or actuators, aiming to modify their environment. Figure 2.1 shows the basic architecture to the agent system.

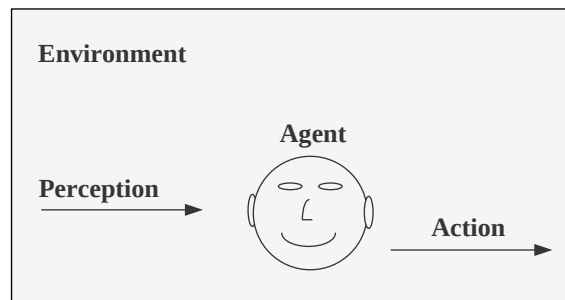


Fig. 2.1 – Agent Basic Architecture

The challenge here is to understand how to go from perception input to action output. In other words: how to decide what to do based on the information obtained via sensors [32]. A practical vision about agent systems leads to the organization of the all possible actual abilities with which an agent might be constructed. It is mandatory to construct agent systems using the most recent mechanisms available in the AI area, such as communication techniques, vision systems, search techniques, knowledge representation, reasoning systems, learning systems, as well as the infrastructure solutions offered by the computation area – Web Services technologies, Peer-to-Peer, Grid Computing technologies and others – in order to provide the special ability with which agents may decide what to do by manipulating plans.

Agents are sophisticated distributed systems that inevitably involve a huge set of other related areas and their implementation constitutes a complex task. In fact, agent technology currently represents the most important new paradigm of software development since object orientation [38].

2.2.1. AGENT ENVIRONMENTS

The environment that an agent occupies may be physical or a software environment. In the first case, it is possible to have the example of robots, which inhabit physical world, whereas in the latter, it is feasible to think about a software agent inhabiting a computer operating system or network [32]. An exact and explicit notion of environment may be a key aspect in developing some agent-based systems, even though it is not a mandatory issue. Some examples of the explicit environment can be listed as a real world, where robots can perform different jobs, or the internet, where software agents are situated in order to execute a variety of tasks: from a simple search as a Google agent, to a complicated participation in the auctions, as electronic auctions.

Several authors have revisited the environment classification proposed by Russell and Norvig [34] in order to support their developments. The main characteristics of some environments may be described as:

- Accessible or inaccessible: An accessible environment is an environment in which the agent can obtain complete, accurate, up-to-date information about the environment state;
- Deterministic or non-deterministic: A deterministic environment is an environment in which any action has a single guarantee effect – there is no uncertainty about the state, which will result from performing an action;
- Static or dynamic: A static environment is an environment that may be expected to remain unchanged due to actions performed by the agent. In contrast, it is considered a dynamic environment when there is another process operating on it, in which changes happen in ways beyond the agent's control;
- Discrete or continuous: An environment is discrete if it has a fixed, finite number of actions and perceptions.

An evident characteristic in agent-based systems is the interaction level between an agent and its environment. As presented in Figure 2.1, an agent needs to sense its environment in order to perform any action and consequently change the environment state, or directly achieve its goals. The quality of decisions that an agent can make clearly depends on the quality of the information available in its environment [34]. In other words, the quality of decisions that an agent can make is directly linked to the level of interaction between the agent and its environment, rather than the level of knowledge that an agent has about that environment. In the real world, environments are usually classified as inaccessible, non-deterministic, dynamic and continuous, thus constituting the most complex environments for the development of agent systems. Discussions about environments can be found in a variety of papers and books that support agent-based systems [30-32].

2.2.2. AGENT-ORIENTED PROGRAMMING

Object-oriented programming languages, such as Java, C#, Smalltalk, and others, are by far the largest class of formal languages, which, in fact, one can use to represent the world as objects. Data structures within programs can represent facts in this context [34]. Therefore, a natural progress on the programming paradigm could be cited as Agent-oriented Programming (AOP), which has been widely articulated in the last years [39]. Essentially, the idea is to program computer systems inspired by the *belief-desire-intention* (BDI) model [32], which are based on a model of human behavior developed by philosophers [40]. The motivation behind the proposal is that humans use such concepts as abstraction mechanisms to represent the properties of complex systems. These mentalist notions are the basis of the proposed AOP [39], which helps to develop agents directly.

2.2.3. AGENT ARCHITECTURES

The central idea of the AOP idealizes computer programs as if they had a mental state. Thus, when this metaphoric process is used, it is possible to talk about *belief - desire - intention* system as a familiar programming paradigm. The Procedural Reasoning System (PRS), presented in Figure 2.2, originally developed at the Stanford Research Institute by Michael Georgeff and Amy Lansky, was perhaps the first agent architecture to explicitly embody the *belief – desire – intention* paradigm, thus proving to be one of the most durable approaches to develop agents up to date [31].

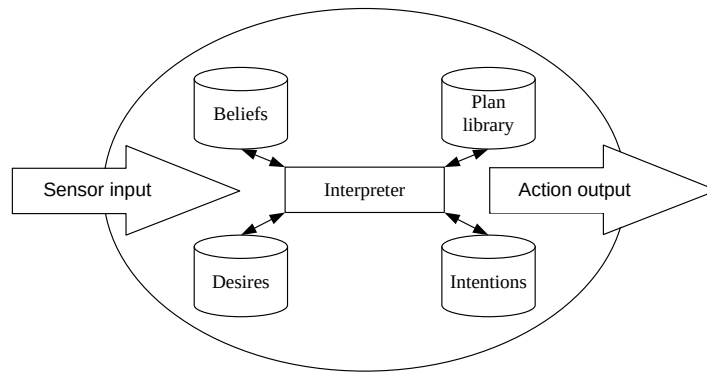


Fig. 2.2 – The Procedural Reasoning System (PRS)

In the PRS, an agent does not plan from first principles. Instead, it is equipped with a library of pre-compiled plans. These plans are manually constructed in advance by the agent programmer [31].

Although, the pre-conceptual architecture may help develop agent systems, architectures of agent applications depend essentially on the problem in which programmers can apply AOP. Architecture design is an important phase in which the use of several mechanisms is proposed for the development of the agent system's high-level design. Three fundamental aspects are often developed during this phase:

- Deciding on the agent types used in the application.
- Describing the interaction between agents, using interaction diagrams and interaction protocols.
- Designing the overall system structure (described by using a system overview diagram).

In summary, the architecture design defines what agents will be part of the system and how these agents will interact with each other in order to meet the required functionality of the system. The agent literature have cited several methodologies to help programmers design agent systems [39].

2.3 MULTI-AGENT SYSTEMS

So far, agents are defined as individual systems or computer programs, which are *situated* in some environment and are capable of sensing their *environment* through the use of sensors. In fact, the most popular title about agents presents them as a society or multi-agent systems that contain a number of agents that interact with one another through communication. In Figure 2.3, the typical structure of a multi-agent system, proposed by Jennings, is shown [41].

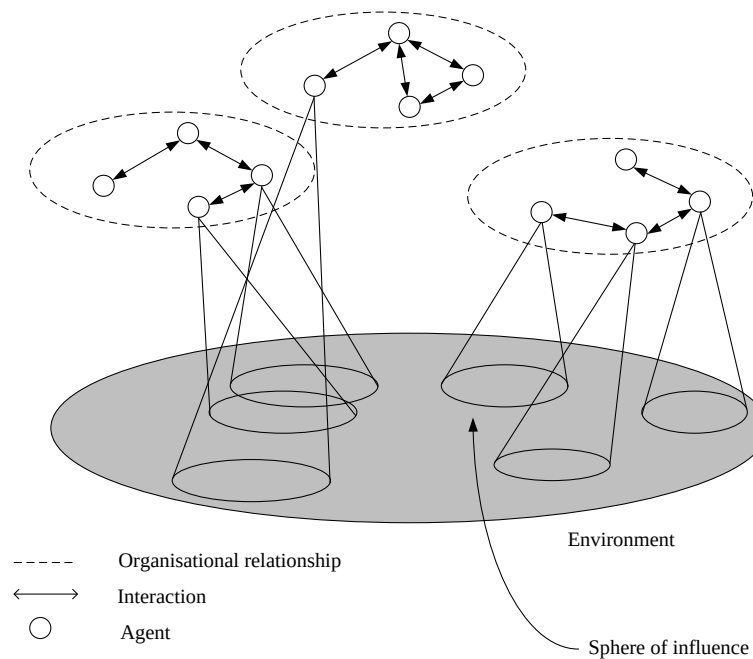


Fig. 2.3 – Typical Structure of a Multi-agent System

In the multi-agent system, the agents are able to act in an environment; different agents have different *spheres of influence*, in the sense that they will have control over – or at least be able to influence – different parts of the environment [32]. It may be that an agent may have the unique ability to control part of its environment, but generally, and even problematically, it is possible that the *sphere of influence* may overlap [32]. Nevertheless, in the multi-agent system, each agent may have some knowledge of the other agents in order to facilitate various organizational relationships to one another. The main idea is that an agent will act in its environment together with other agents in a coordinate mode, promoting cooperation or competition through the use of the communication process.

2.3.1. COOPERATION, COMPETITION AND COORDINATION BETWEEN AGENTS

Intuitively, it is possible to think that some multi-agent systems may be designed to act in different types of environments that might be classified as: cooperation environment and competition environment, based on coordination and communication processes.

In the cooperation environment, agents must be able to agree on their own goals. The challenge is to identify mechanisms that will allow agents to coordinate their actions or plans automatically, without the need for human supervision. In turn, cooperation refers to coordination with a common goal in mind [31]. On the other hand, not all multi-agent environments involve cooperative agents. In some cases, agents with conflicting utility functions are in competition with each other [31]. Usually, agents with competitive abilities are used to solve conflicts in a variety of areas. An agent in a competitive environment must recognize that there are other agents computing some of other agent's possible plans. At the same time, the agent should understand how the other agent's plans will interact with its plans, and decide on the best action according to these interactions. There is, however, no commitment to a joint plan in a competitive environment.

A considerable effort of the agent community has identified a huge range of different types of coordination, cooperation and competition mechanisms, ranging from emergent coordination, cooperation and competition protocols to distributed planning [38]. The key for the agents to reach an agreement is the communication established among them.

2.3.2. COMMUNICATION BETWEEN AGENTS

Agent communication is probably the most fundamental feature of the AOP, which, in fact, highlights the difference between agent programming paradigm and mere distributed computer programs. Agent communication is the study of how two or more software entities may communicate to each other [42]. One challenge is the difficulty of assessing meaning of utterances, since the precise meaning of a statement depends on:

- The context in which it is uttered;
- Its positions in a sequence of previous utterances;
- The nature of the statement (for instance, a request);

- The objects referred to in the statement (for instance, a real world object);
- The identity of the speaker and the intended listeners.

In order to cover great part of these challenges, FIPA (Foundation for Intelligent Physical Agents) [43] has proposed a specification to the communication between agents. Therefore, some authors follow these specifications so as to create a message structure that includes several fields containing suitable information that aims at characterizing a message. In summary, a message between agents can be viewed as follows [42]:

- The *sender* identity of the message;
- The list of *receivers*;
- The communicative act, usually called the *performative*, indicating what the sender intends to achieve by sending the message. (for instance: if the *performative* is the REQUEST, the sender wants the receiver to perform an action, if it is INFORM the sender wants the receiver to be aware of a fact, if it is a PROPOSE or a CFP, the sender wants to enter into a negotiation;
- The *content* containing the actual information to be exchanged by the message (for instance: the action to be performed in a REQUEST message;
- The content *language* indicating the syntax used to express the content;
- The *ontology* indicating the vocabulary of the symbols used in the content;
- Some additional fields used to control several concurrent conversations and to specify timeouts for receiving a reply.

Actually, agents need to be able to interact with users, with system resources, as well as with each other if they want to cooperate, collaborate, negotiate, and so on. In general, agents interact using a special communication language called *Knowledge Query and Manipulation Language* (KQML). KQML is an *outer* language for agent communication. It defines an *envelope* format for messages that an agent uses to explicitly state the intended illocutionary force of a message [44]. It defines the operations that agents may attempt on each other's knowledge bases and provides a basic architecture for agents to

share knowledge and information through special agents called facilitators. Besides the language that indicates the syntax used to express the content, other fundamental issue that supports agent communication is known as *ontology*.

2.3.3. ONTOLOGY

The broad range of issues in which the communication processes are involved, have proved to be important in such agent-based technology. In fact, if two agents are to communicate about some domain, besides agreeing with the used language or the syntax, they will need to agree on the terminology that they will use to describe the domain. This aspect of the communication process is usually denominated as *ontology*. In a more explicit way, ontology is a formal definition of a body of knowledge. The most typical type of ontology used in building agents involves a structural component. Essentially, it is a taxonomy of class and subclass relation coupled with the definitions of the relationships between these things [45-46].

As mentioned before, KQML uses ontologies (explicit specifications of the meaning, concepts, and relationships applicable to some specific domain) to ensure that two agents communicating in the same language can correctly interpret statements in that language [44]. Considerable research and development efforts will be needed to improve these computational mechanisms and strategies for such interactions.

2.3.4. AGENT-RELATED TECHNOLOGIES FOR INFRASTRUCTURE SUPPORT

Implementing agent-based systems is a hard task that involves a lot of correlated areas within the computation and artificial intelligence sciences. In order to reach and implement some fundamental aspects about agent-based systems, it is necessary to use some computational mechanisms that will allow the embodiment of autonomy, intelligence and mobility, among other characteristics, during the agent processing. Since the 1990s, several features have been introduced into the computation area, perhaps affected by the growth of the World Wide Web (www) and the rapid rise of e-Commerce, which enabled the construction of agent-based systems. Such related technologies have provided attractive solutions to the communication, coordination and security in distributed agent-based applications.

Recently, some studies have pointed out an important point of view. Albeit agent-based technology has been active for a decade, only after 1999, with the appearance of effective service-oriented technologies and pervasive computing technologies, it became possible to truly consider the possibility of building dynamic (ad-hoc) network systems without large investments in the establishment of the underlying infrastructure [38].

Although agent-related technologies for infrastructure support have merged distributed computation and artificial intelligence techniques, some pure computing solutions have been highlighted due to the real importance in the base of agent applications. Generally, middleware or platforms for agent interoperability, as well as standards, have been using solutions as Distributed Object Technologies, such as CORBA, RMI and “.NET”, in order to establish the base of the distributed applications. Other advanced computing technologies and infrastructure solutions, such as Peer-to-Peer, Service-Oriented Technologies, Pervasive Computing, Web Services and Grid computing technologies, have introduced new issues for the development of agent-based applications in industrial scales, and to distinguish agent solutions from other programming technologies, mainly due to the agent’s ability to incorporate autonomous and self-interested components.

2.4 JAVA-BASED INTELLIGENT AGENT ENVIRONMENT

An autonomous system is a system that can react intelligently and flexibly on changing operating conditions and demands from the surrounding process [44]. In some research areas, the word “intelligence” is strongly linked to the strict sense that uses reasoning systems, e.g. some heuristics searches or fuzzy inference, and/or learning systems, e.g. neural networks. Usually, an intelligent application must contain such required techniques. In fact, one way of defining AI is to consider it as the problem of building an intelligent agent. The discipline of intelligent agents has largely emerged from research in AI. However, it is important to distinguish between the broad intelligence that is the ultimate goal of the AI community, and the intelligence proposed in agent system. The only intelligent requirement that generally makes them intelligent agents is that they can make an acceptable decision concerning what action to perform next in their environment, in time for this decision to be useful [47]. In this thesis, the word “intelligence” is linked to the concept of intelligence used to construct intelligent agents, which implies that an

intelligent agent behavior must integrate some special characteristics, such as situated, autonomy, reactive, proactive, flexibility, robust and social [39]. It is of great importance to say that all agents will not necessarily need to be capable of learning. Hence, in this thesis agents have been built using Java language and its specific features, which support intelligent agent applications.

Java is an object-oriented language. It was originally designed for programming real-time embedded software for consumer electronics, particularly set-top boxes that interface between cable providers or broadcasters, and televisions or television-like appliances. However, the effort was redirected to the Internet when the market for set-top boxes did not develop quickly enough, while the Internet exploded in popularity [48-49]. For a software program to be situated, it must follow the concept of platform independence in order to exist in some environment. Java is designed to operate in heterogeneous environments. To enable a Java application to execute anywhere on the network, the compiler generates architecture-neutral byte code, as opposed to non-portable native code. For this code to be executed on a given computer, the Java runtime system must be presented. For a software program to be autonomous, it must be a separate process or thread. Java applications are separate processes and, as such, they can be long-running and autonomous. For a software program to be reactive, proactive, and social, it must be capable of communicating with other software. A Java application can communicate with other programs using sockets. As it can be seen, Java language provides some special features to support straightforward intelligent agent applications.

Based on these concepts, it is clear that there is much activity in this area around the world. Several middleware, platforms, frameworks and environments have appeared in order to help programmers develop multi-agent systems. In the Java world, there is a wide range of Java environments that intends to support agent-based systems, such as ABLE (Agent building and learning environment) [50], AgentBuilder [51], Aglets [52], FIPA-OS [53], Gossip [54], JADE [42], JATLite [55], Promeheus Methodology [39], Jason [32], and others.

Although all these suitable environments may help build agent systems, it is still a complex task. There have been several difficulties during the implementation phase partly due to the lack of maturity in both methodologies and implementation tools. Other difficulties can be

listed as lack of specialized debugging tools, and mainly lack of understanding on the nature of what is a new and distinct approach to the development of systems [38].

2.5 FINAL REMARKS

In this chapter, a brief description of agent-based technology was presented. Initially, AOP has been introduced through the characterization of the evolution of the computation area and its strong link with the Artificial Intelligence science. The central idea of the AOP was explored and the BDI model (*belief - desire - intention*) was presented aiming to show that it is possible to develop agent-based systems based on models introduced by philosophers. They are usually used to represent the human behavior, making some analogies possible, like software with a mental state for instance.

Some agent definitions have been explored in order to differentiate agent computer applications from mere computer programs. Hence, the fact that agents cope with a different set of objectives, as opposed to simple programs, was highlighted. For agent technologies, the objectives are to create systems situated in a dynamic and open environment, being able to adapt to these environments, and incorporate autonomous components.

The nature of environments was discussed in order to emphasize one of the most important issues on agent-based systems: the interaction between the agent and its environment. Considering that an agent needs to sense, process and react, it is necessary to specify some performance measures that generally involve the nature of environments, and the agent's actuators and sensors. Obviously, the architecture design is a crucial phase where several different mechanisms are proposed for the development of the high-level design of the agent system.

The importance of the communication process and the ontology were discussed as fundamental aspects used to make some multi-agent applications possible. Moreover, other advanced computing technologies and infrastructure solutions have been cited as new issues for the development of agent-based applications on an industrial scale.

The Java programming language was defined as the language used to develop agent-based systems in this thesis, mainly due to its ability to encapsulate other programs written in different languages, like FORTRAN. Therefore, it is possible to use several tools that have

already been developed in the power system area, and to avoid rewriting programs. In addition, the choice of this language was justified given the suitable features that support autonomy, intelligence, mobility and so on, in order to build agent-based systems.

As it can be seen, agent technologies may be distinguished from other programming technologies on the basis of their differing objectives. The application of these technologies depends on how many application domains require systems with these characteristics. The area of research is relatively new and requires time to mature concepts, models, computing technologies, and others.

Chapter 3

POWER SYSTEMS RELIABILITY ASSESSMENT

3.1 INTRODUCTION

The basic function of an electric power system is to meet customer electricity requirements with adequate quality and reliability, privileging an economical manner [56]. Therefore, the responsibility of the utility planners is to find a balance between costs and reliability. Generally, utilities around the world have performing this task with relative success.

During the last 20 years, several changes in the power industry have introduced complexities in the operation of the power systems. Investments in green power are growing in many countries in order to mitigate the oil energy dependence, as well as emissions of CO₂. However, these changes are directly affecting a wide range of deterministic and probabilistic techniques usually used by these utilities in order to plan and design the power systems. The number of uncertainties grows with these changes and makes some techniques inadequate if they do not consider green power criteria.

The intention with this chapter is to promote a brief review on the main reliability techniques usually used by most utilities, as well as to introduce some green power criteria and considerations for reliability studies. A case study involving two real power systems is presented to highlight the computational requirements in such representations.

3.2 FUNCTIONAL ZONES AND HIERARCHICAL LEVELS

An electric power system can be traditionally divided into three segments entitled functional zones, which contemplate generation, transmission and distribution systems [16]. These functional zones are commonly referred to hierarchical levels for reliability assessment. Although this division of the power system may seem somewhat simplistic, it is quite appropriated. It is so considered since most electric utilities are either divided into such zones for the purposes of organization, planning, operation and/or analysis, or they are solely responsible for one of these functions [56]. Bearing reliability studies in mind, these zones help conduct each adequacy evaluation individually following the hierarchical levels.

In the last 20 years, hierarchical level (HL) concepts have been revisited mainly due to the important changes in the power industry. Figure 3.1 shows the last evolutions proposed in the well known electrical functional zones.

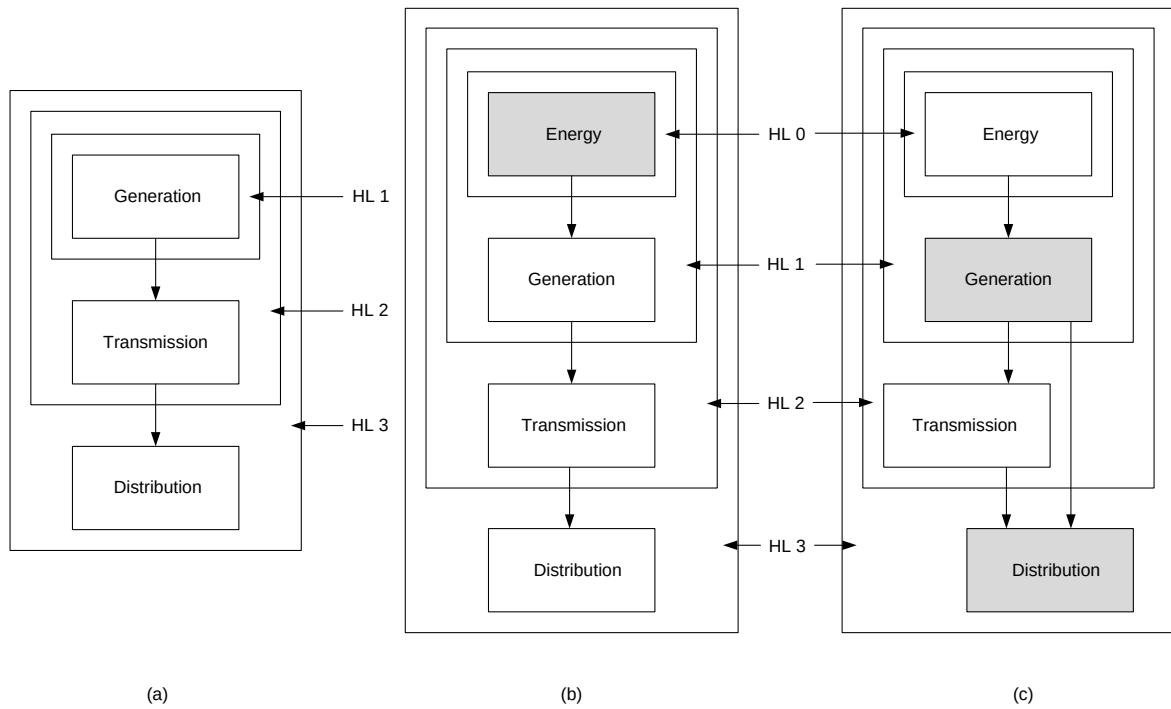


Fig. 3.1 – Power System Hierarchical Levels Evolution

In the functional zones presented in Figure 3.1(a), the traditional hierarchical levels were proposed under a centralized paradigm where the utilities were organized with the three segments (generation, transmission and distribution) aggregated in a company only. Adequacy evaluation at HL 1 is concerned with the adequacy of the generation in order to meet the total system load requirement, and to provide enough reserve to perform corrective and preventive maintenance. This area of activity is usually termed as generating capacity reliability evaluation. In HL 1 studies, the transmission system, its limitations, and the distribution system are ignored. Historically, the reserve capacity was set equal either to a percentage of the expected load or to one or more largest units, or even to a combination of both [7]. In most cases, these deterministic criteria were replaced by probabilistic methods, which contemplate a more complete view of the power systems. Generally, these reliability studies are performed assuming that the generating units, such as thermal and hydro, have enough primary resources, such as oil, coal, water, among others. Due to the restructuring and privatization process of the power sector, many countries in the world adopted a decentralized power industry where generation, transmission and distribution are managed separately. Hence, generation company strategies have incorporated primary resources as an important factor to be held under

consideration in the new power industry scenario. Figure 3.1(b) presents the first evolution in the traditionally functional zones of the power systems considering HL 0 – energetic resources [57].

The rapid growth of power networks and increasing interconnections among utilities led to the recognition of the critical role played by transmission networks as a way to determine the overall system reliability [58]. The second hierarchical level (HL 2) is frequently referred to composite or bulk power system, which contemplates the aggregated generation and transmission. The basic objective of assessing the reliability of power systems at this level consists of estimating the ability of the system to perform its function of transporting electricity over long distances, from the power generation system to substations that serve sub-transmission or distribution systems. The assessment of composite system reliability has traditionally been very complex [59-61] since it must consider the integrated reliability effects of generation and transmission. It generally involves complex mathematical tools and models in order to represent the stochastic behavior of power system components. Nowadays, in some countries, these reliability studies are performed taking the different responsibilities among companies into consideration, and it generally appears an entity named as the Independent System Operator (ISO) to coordinate this reliability assessment. In HL 2, the distribution networks are not considered.

At the HL 3, reliability evaluations are termed as overall power system adequacy assessment. In other words, HL 3 adequacy assessment involves the consideration of all the three functional zones [62]. It is usually impractical because of the huge dimension of generation, transmission and distribution systems. Instead of the complete aggregation, distribution reliability studies are separately performed, within the distribution system functional zone only. In general, it is acceptable because distribution networks often interface with the transmission system through one supply point, and this link (substation) with generation and transmission systems is assumed with unlimited capacity, and is 100% reliable. On the other hand, distribution systems account for up to 90% of all customer reliability problems [62] and, therefore, they dominate the overall reliability indices. Figure 3.1(c) presents the last evolution of the hierarchical levels in recent years, which considers the inclusion of local sources of generation in the distribution system. The inclusion of a large-scale generation directly in the distribution network is very promising for the electric

power industry since several advantages can easily be listed, especially the ones linked to green power solutions.

3.3 GENERATING ADEQUACY ASSESSMENT

In power system literature, there are several techniques available that allow an accurate assessment of the generating capacity. The basic consideration is to concentrate all generating units and loads in a single bus. The transmission lines constraints are totally ignored, and the performance of the generating system is measured by comparison between the available generating capacities and the load at different snapshot times. The problem consists, basically, of measuring the ability of the generation system to meet the total load requirement, considering the load variations, the failure of units, as well as the unavailability of energetic resources, which can directly affect the generating capacity. If one knows the stochastic parameters λ and μ (i.e. failure and repair rates, respectively) of each generating unit, it is possible to calculate the probabilities of generating units are running or not (up or down) during a simulation process. Bearing in mind that each generating unit (components) has two basic states, such as up or down, the following equations (3.1) and (3.2) can represent the availability (A) and unavailability (U) (or FOR – forced outage rate) of each generating unit [16]:

$$A = \frac{\mu}{\lambda + \mu} \quad (3.1)$$

$$U = 1 - A = \frac{\lambda}{\mu + \lambda} \quad (3.2)$$

The concept of availability and unavailability here are associated with the simple two-state model [16], which will be presented in the following sections of this chapter.

The load is often represented by a multi-state Markov model [61], [63-64]. Basically, three fundamental steps are presented in reliability assessment of generating systems:

- i. To build a capacity model, based on particularities of generating units;
- ii. To build a load model, based on all available data;
- iii. To build a risk model. This is generally a result of the two previous steps.

There are two important categories of reliability indices used to measure the risk in generating reliability studies [16], [65]:

- Traditional indices usually are:

LOLP – Loss of Load Probability;

LOLE – Loss of Load Expectation;

EPNS – Expected Power not Supply;

EENS – Expected Energy Not Supplied;

LOLF – Loss of Load Frequency;

LOLD – Loss of Load Duration;

LOLC – Loss of Load Cost.

- Well-being indices usually are:

Prob{H} – Healthy State Probability;

Prob{M} – Marginal State Probability;

Freq{H} – Healthy State Frequency;

Freq{M} – Marginal State Frequency;

Dur{H} – Healthy State Duration;

Dur{M} – Marginal State Duration.

The techniques used in generating adequacy assessment can be frequently divided into two basic categories: analytical and simulation. Generally, analytical approaches adopt the state space representation, but simulation can either adopt state space representation or chronological representation.

3.3.1. STATE SPACE REPRESENTATION

In state space representation the power systems are represented by system states and their transitions. Each system state can be seen as a particular condition of the system. In this particular condition, each component has its own state (up, down or any other) and it can transit following a pre-defined behavior. In other words, each system state k containing m components, including the load, can be seen as a vector $x^k = \{x_1, x_2, \dots, x_m\}$. The set of all possible system states is the state space X . If the failure probability of each component state x_i is known, it is possible to calculate the failure probability of the vector x^k , as well as the failure probability of each system state $P(x^k)$. If component failure and its transitions are independent, $P(x^k)$ can be calculated as follows:

$$P(x^k) = P(x_1) \times P(x_2) \times \dots \times P(x_m) \quad (3.3)$$

where $P(x_1), P(x_2), \dots, P(x_m)$ are the individual failure probability of each component, including the load transitions. Usually, the system states can be divided into *failure* and *success* states, and they are assessed through the use of appropriated test functions such as $F(x^k)$. Figure 3.2 shows the typical state space representation used in power systems problems.

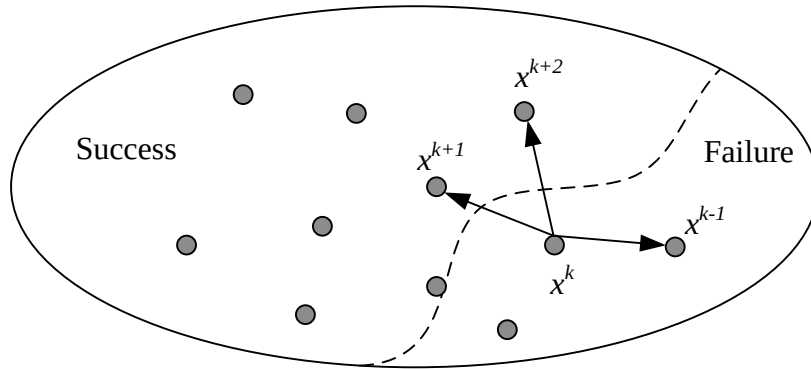


Fig. 3.2 – State Space Representation

Such test functions $F(x^k)$ are used in order to check whether the system state x^k is a *failure* or *success* state, depending if it is able to match the load. In Figure 3.2, the system state x^k is a failure state and $F(x^k)$ may represent the amount of load curtailment needs for the production match the load. Thus, if the $F(x^k) > 0$, it means that there is load curtailment, x^k

will be a failure state. Otherwise, if the $F(x^k) \leq 0$, it means that there is no load curtailment, x^k will be a success state. Therefore, the reliability indices are estimated through the use of appropriated test functions and they are calculated as a likelihood of these test functions, as follows:

$$E[F] = \sum_{x^k \in X} F(x)P(x) \quad (3.4)$$

Based on this state space representation, there are some methods generally used to estimate reliability indices.

3.3.1.1. CONVOLUTION

The convolution method is based on the fact that two or more independent distributions can be combined or convolved. The basic idea is to get capacity and load models, achieving the risk model through the use of a convolution operation. In order to better understand these concepts, a simple convolution example has been presented [66-67]:

The capacity model can be obtained through the combination of all generation units. Consider a small system consisting of only two generation units with capacities C_1 and C_2 . The probability of having C_1 out is $q_1 = 1 - p_1$ (where $p_1 = \text{FOR}_1$), and C_2 out is $q_2 = 1 - p_2$ (and $p_2 = \text{FOR}_2$). The possible combination of these units is shown in Table 3.1.

Table 3.1 – Capacity Outage Probability Table

Capacity on Outage	Probability
0	p_1p_2
C_1	q_1p_2
C_2	p_1q_2
C_1+C_2	q_1q_2

Each row in Table 3.1 represents a system state and this state can be considered as a random variable x^k from the system. The random vector x^k is the summation or combination of all component states x_1 and x_2 . Since x_1 and x_2 are statically independent

random variables, the probability density function (pdf) $f(x)$ is the convolution of the pdf 's $f_1(x)$ and $f_2(x)$, as follows:

$$f(x) = f_1(x) * f_2(x) \quad (3.5)$$

Thus, Table 1 can be described as $f(x)$. If the system has m units, the equation (3.5) can be generalized as:

$$f(x) = f_1(x) * f_2(x) * \dots * f_m(x) \quad (3.6)$$

Therefore, the capacity model is represented by an equivalent unit, which has several capacity states (c_g), the probability of these states (p_g) and their incremental frequencies² (f_g) [67]:

$$G = \{c_g, p_g, f_g\} \quad (3.7)$$

The load model can be represented through the same steps, taking into consideration each load level (c_L), the probability of this load level (p_L) and the incremental frequency (f_L) linked to this load level:

$$L = \{c_L, p_L, f_L\} \quad (3.8)$$

As previously mentioned, using capacity and load models, it is possible to achieve the reserve model through the use of the following equation:

$$R = G - L \quad (3.9)$$

Hence, R can be written as:

$$R = \{c_R, p_R, f_R\} \quad (3.10)$$

where, c_R , p_R and f_R are vectors that contain the capacities, probabilities and incremental frequencies linked to the reserve model. The reliability indices are calculated through the use of the reserve model.

² Incremental frequency denotes the transition rates from state k to states belonging x^{k+1} and x^{k-1} , respectively [67].

3.3.1.2. STATE ENUMERATION

The aim of the state enumeration methods is to assess all possible system states. On the other hand, the main difficulty of this method consists of knowing that the number of system states can greatly increase with the number of system components. For instance, considering a two-state Markov model in order to represent the thermal unit generation, a system with m units can reach 2^m system states. Therefore, depending on the number of the components, especially on the number of failure states, this method can be impracticable [57]. In order to mitigate this constraint and make a generalized application possible, the aim is to enumerate a subset $X' \subseteq X$ and perform the estimation of the indices considering some upper and lower bounds, as follow:

$$\tilde{E}[F]_{lower} = \sum_{x \in X} F(x)P(x) + F_{lower}[1 - P(X')] \quad (3.11)$$

$$\tilde{E}[F]_{upper} = \sum_{x \in X} F(x)P(x) + F_{upper}[1 - P(X')] \quad (3.12)$$

3.3.1.3. NON-SEQUENTIAL MONTE CARLO SIMULATION

Another alternative to estimate reliability indices using state space representation is the non-sequential Monte Carlo simulation. The idea is to sample randomly a sufficient amount of system states $x^k \in X$, through the use of their respective probability distribution. Furthermore, it is also important to promote the calculation of the appropriate test functions for each system state so as to estimate the reliability indices. Different from enumeration methods, which are strongly dependent on the system dimensions, the Monte Carlo does not depend directly on the number of states x^k in X . Another issue about this random sampling process of system states is that it does not carry any memory or time correlation.

The random process is repeated NS times and the reliability indices are estimated using the mean values of appropriate test functions, as follows:

$$\tilde{E}[F] = \frac{1}{NS} \sum_{k=1}^{NS} F(x^k) \quad (3.13)$$

Since $F(x^k)$ is a random variable, it can be understood that its mean value may also be a random variable with variance given by:

$$\tilde{V}[E(F)] = \frac{\tilde{V}(F)}{NS} \quad (3.14)$$

As it can be observed in equation (3.14), the reliability index accuracy depends on the variance of the test function and the number of system samples NS . This confirms the intuitive notion that the accuracy of the Monte Carlo experiment increases with larger sample sizes NS [58]. The uncertainty on the Monte Carlo estimate is often represented as a coefficient of variation β given by:

$$\beta = \frac{\sqrt{\tilde{V}(\tilde{E}(F))}}{\tilde{E}(F)} \times 100\% \quad (3.15)$$

The Monte Carlo approach can be implemented in the following steps [58]:

- i. do $NS = 0$;
- ii. Sample a vector $x^k \in X$ from their respective probability distribution $P(x^k)$; update NS ;
- iii. Calculate the function F to each sampled vector x^k ; i.e., calculate $\{F(x^k), k=1,...,NS\}$;
- iv. Estimate $\tilde{E}[F]$ as the average of the function values;
- v. Calculate β (coefficient of variation) using the equation (3.15): if the degree of accuracy or confidence is acceptable, stop the simulation, otherwise, go back to step ii.

A major constraint in the non-sequential Monte Carlo simulation is related to its difficulty in handling the chronological aspects of the system operation, which sometimes is a very useful feature to the simulation. This may be considered like that when aspects such as reservoir operation rules in hydroelectric systems, ramping rates in thermal units, wind time series in wind power, solar time series in photovoltaic and solar central receiver,

complex correlated load models, and others, need to be represented. On the other hand, in the last years some improvements have been incorporated in the non-sequential Monte Carlo simulation in order to include some chronological aspects, such as different load pattern per area or bus [63].

3.3.1.4. POPULATION-BASED METHODS

Recently, some methods such as genetic algorithm [68-69] and Evolutionary Particle Swarm Optimization have been experienced in reliability assessment of power systems. Such methods, classified as population-based (PB) methods, are essentially a variant of enumeration methods, which count different states in the state space. Generally, PB methods appear as a competitor to the Monte Carlo approach, being used to perform basic reliability indices in power systems evaluation.

In PB methods, the estimate $\tilde{F}$ of an index F is obtained by:

$$\tilde{F} = \sum_{x \in D} p_x \times F_x \quad (3.16)$$

where, D is the set of sampled failure system states, p_x is the probability of failure system state x , F_x is the value of the variable being assessed, in state x , and $D \subseteq X$ is a subset of all possible states X .

In PB methods, it is usual to accept that some truncation of the space of all failure states D_f is ensured ($D \subset D_f \subset X$). This is usually acceptable for a state x whose probability is very small (unless the value of F_x becomes unusually large). If the search process is adequately conducted, this will be assured in practice. Moreover, the truncation of the state space was an accepted fact in the past, when analytical models prevailed.

An important limitation of PB methods is the fact that they are not statistical methods. As a result, they do not allow the calculation of an interval of confidence to the result. Their stopping criterion is usually based on the stability of the index that is being calculated: after a number of iterations without meaningful progress, the process is considered to have reached a sufficiently narrow neighborhood of the real value and the search for more states stops. Nonetheless, if the search process is effective, this will typically happen long before any acceptable confidence interval may be calculated by a Monte Carlo simulation

(counting in terms of iterations or visited states): this is the practical value they offer. Certainly, this is a pragmatic approach taking advantage of the fact that, usually, power systems are very reliable and the subset of meaningfully contributing states to a reliability index is much smaller than the entire state space.

3.3.2. CHRONOLOGICAL REPRESENTATION

In the chronological representation, each subsequent system state is related to the previous set of sampled system states. As mentioned before, the chronological representation becomes a necessity when the operating system is history-dependent or time correlated, which is particularly fundamental to represent green power, such as wind and solar units and their respective time-dependent behaviors; at the same time, it can represent the impact on maintenance policies; ramping rates in thermal units, as well as complex correlated load models. Essentially in hydro electrical systems, when the reservoir has to be carefully controlled and, at any moment, the available power can depend on the past water inflows, on the past operation policies, and so on, the chronological representation becomes imperative [59]. Regarding the chronological representation, another attractive feature to bear in mind consists of making the development of the distributional aspects associated with system index mean values, as well as providing the most comprehensive range of reliability indices [70-71].

The problem of calculating reliability indices is equivalent to the evaluation of the following expression [72]:

$$E(F) = \frac{1}{T} \int_0^T F(t) dt \quad (3.17)$$

where: T is the period of simulation and $F(t)$ the test function to verify at any time t , if a related system state is adequate.

Two consecutive sampled system states differ from one state component only. This is understood since there is a great computational difference between state space representation by non-sequential Monte Carlo and chronological representation by sequential Monte Carlo, which makes the latter representation tremendously expensive from the computational point of view. Moreover, other crucial constraint to consider is the assumption of exponential distributions for all system state residence times.

3.3.2.1. SEQUENTIAL MONTE CARLO SIMULATION

The term sequential simulation means that the history of a system is simulated in fixed discrete time steps [73]. The sequential approach is based on sampling the probability distribution of the component state duration. It is used to simulate the stochastic process of the system operation through the use of its probabilities distributions, associated with mean-time-to-failure (MTTF) and mean-time-to-repair (MTTR) of each system component. Considering the two-state Markov Model, these are the operating and repair state duration distribution functions that are usually assumed to be exponential. Other distributions, such as Weibull, Normal, etc., can also be used to represent different behaviors. The problem of estimating reliability indices can be written as follows:

$$\tilde{E}[F] = \frac{1}{NY} \sum_{n=1}^{NY} F(y_n) \quad (3.18)$$

where: NY is the number of simulated years; y_n is the sequence of system states x^k , in the year n ; and $F(y_n)$ is the function to calculate yearly reliability indices over the sequence y_n . The sequential approach can be summarized in the following steps:

- i. Generate a yearly *synthetic* sequence of system states y_n by sequentially applying the failure/repair stochastic models of equipment and the chronological load model. Thus, the initial state of each component is sampled. Usually, in the first sample, it is assumed that all components are initially in the success or up state, even though other approaches may be used. The duration of each component residing in its present state is sampled from its probability distribution. Assuming an exponential probability distribution and using the inverse transform method [74], the duration of each component will follow:

$$T = -\frac{1}{\lambda} \ln(U) \quad (3.19)$$

where: T is the time residence of each equipment; λ is the failure rate of the component if the present state is the up state or λ is the repair rate of the component if the present state is the down state; and U is a uniformly distributed random number sampled in the interval between $[0,1]$;

- ii. Chronologically evaluate each system state x^k in the sequence y_n and accumulate the values;
- iii. In order to obtain yearly reliability indices, calculate the test function $F(y_n)$ over the accumulated values;
- iv. Estimate the expected mean values of the yearly indices as the average over the yearly results for each simulated sequence y_n ;
- v. The stop criterion is also based on the relative uncertainty of the estimates. Therefore, calculate β (coefficient of variation) using the equation (3.15);
- vi. Verify if the degree of accuracy or confidence interval is acceptable. If the answer is yes, stop the simulation; otherwise, go back to step i.;

In the sequential approach, the system evaluation is conducted for each different system state in order to achieve the reliability index function. For instance, considering the *LOLE* index: $F(y_n)$ = sum of the sampled duration of all failure states in y_n . In turn, if the $F(y_n)$ is the sum of energy not supplied associated with all failure states in y_n , $E[F]$ will represent the *EENS* index. Several other reliability indices can be easily achieved using the sequential approach.

3.3.2.2. PSEUDO-SEQUENTIAL MONTE CARLO SIMULATION

As presented before, the sequential Monte Carlo approach or chronological modeling requires more substantial computational effort than the non-sequential approach. Alternatively, pseudo-sequential Monte Carlo simulation [60] retains the computational efficiency of non-sequential Monte Carlo simulation and ability to model chronological aspects of the systems [61]. The pseudo-sequential approach can be summarized in the following steps [61]:

- i. Sample a system state $x^k \in X$, based on its distribution $P(x)$;
- ii. Evaluate the performance of the sampled system state x^k . If x^k is a success state, return to step i.; if x^k is a failure state, estimate the test function for LOLP and EENS indices, and go to the next step iii.;
- iii. Obtain the interruption sequence I associated with state x^k based on forward/backward simulation (see [61]). Estimate the test function for the LOLE and LOLC indices;

- iv. Evaluate the coefficient of variation β , using the equation (3.15); if convergence is not achieved, return to step i, otherwise calculate the LOLD index and stop.

The aim is to promote a hybrid method in which the non-sequential approach is used to select failure states, whereas the sequential approach is only applied to the sub-sequence of neighboring states that define the complete interruption. The procedure is more used in composite reliability, where the system state evaluation is more computationally expensive. More details on the pseudo-sequential approach can be found in [61].

3.3.2.3. GENERATION PLANT REPRESENTATIONS

The selection of an appropriate model to represent the stochastic behavior of power system units is an essential requirement in the adequacy evaluation of generation systems. Essentially, two aspects must be represented to each technology: firstly, the up and down cycle (failure/repair) of each unit or set of units; and secondly, the power availability of each unit or set of units, considering their natural resources, such as water inflows, wind speed, solar irradiations, and others. The two-state Markov model [16] and the multi-state Markov model [75] will be used to represent the conventional generation technology with large units, such as thermal and hydropower plants, as well as the distributed generation (DG) technology with small units concentrated in farms or aggregations, such as wind power, solar central receiver or photovoltaic, small hydro generators, and others. These representations are depicted in Figure 3.3. More details about models can be found in [76].

Thermal power plant: based on the two-state Markov model, presented in Figure 3.3(a), the failure/repair cycles for all thermal power technologies, such as nuclear, coal, oil, gas, among others, are represented. The residence time to each state is assumed to be exponentially distributed, and can be calculated using equation (3.19). In thermal power plant representation, the available power is assumed to depend only on the unit unavailability. Clearly, any non-Markovian model could be used if the necessary parameters were available.

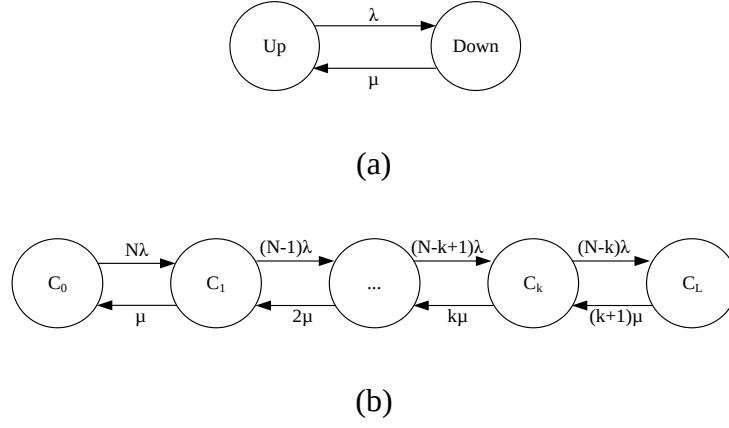


Fig. 3.3 – (a) Two States Markov Model, (b) Multi-state Markov Model

Hydropower plant: also based on two-state Markov model, presented in Figure 3.3(a), the failure/repair cycles for all hydro power units are represented. The residence time to each state is assumed to be exponentially distributed, and can be calculated using equation (3.19). In hydropower plant representation, the available power is assumed to depend on failure/repair cycle and on water storage of each reservoir. In other words, the level of each reservoir's water storage defines the power available for each unit.

Nevertheless, the levels of water storage of each reservoir vary due to several aspects, such as water coordination policies, yearly or monthly hydrologic conditions, daily hydro-thermal coordination, and others. The full impact of water inflows on the hydropower available for each unit should consider a complex model involving stochastic dynamic programming tools linked to historical hydrologic series [58]. In order to simplify the proposed model, the power available for each unit is assumed to be proportional to the level of water storage in its respective reservoir. Due to the small variation of daily water storage levels, a monthly water storage level variation is assumed, which can better represent the water storage behavior with relative accuracy. Thus, the hydro power units are combined in several reservoirs containing monthly historical series. These series are defined for each hydraulic basin based on historical data. The aim is to capture the historical inflows, reservoir volumes and type of operation. Therefore, the capacities of the hydro units will be defined for each month, according to the corresponding hydrological series.

Wind power: Usually, in a wind power site, there are several generating units grouped into an equivalent multi-state Markov model, as shown in Figure 3.3(b). Only two stochastic

parameters are necessary: unit failure and repair rates. Parameter N represents the number of generating units of the wind farm. If C is the unit capacity, the amount of power associated with the k_{th} state is given by $C_k = (N-k) \times C$, $k = 0, \dots, N$. The cumulative probability P_k (from 0 to k) associated with this state can be easily calculated. In order to reduce the number of these states during the chronological MCS, a simple truncation process sets the desired order of accuracy. Therefore, instead of $N+1$ states, a much smaller number up to the capacity C_L will limit this model; e.g. $1-P_L \leq \text{tolerance}$.

The productions of the wind generating units will be defined for each hour, according to the hourly wind series for each geographic region. The wind series try to capture the wind speed and power conversion characteristics. Historical yearly series per unit capacity fluctuations have to be provided per hour.

Small hydropower plants: Small-hydro units are modeled similarly to the hydro generating units from the hydrological point of view, but they are grouped into multi-state units of figure 3.3(b) to simplify the modeling processing. Due to the lack of specific data in relation to the hydrological basin, where they are located as well as the technical characteristics of each small hydro unit, an equivalent reservoir is used to model the capacity variations with time, so some small unit clusters are promoted. In order to better represent the up and down cycles and their hydrologic fluctuations, they are grouped according to their main characteristics, such as capacity in MW, year unavailability (FOR) and mean time to repair (MTTR), as well as their geographic position. Therefore, each small hydro group can be seen as a small hydropower plant, which has similar units with the same characteristics, but different numbers of units. Obviously, if specific data are available, they can be properly considered. The benefits in terms of accuracy and the cost in terms of computing effort, as well as the levels of model detail, must always be balanced.

Solar central receiver and photovoltaic: Solar energy can provide huge amounts of the energy share, especially in regions with high solar irradiations [77]. There are different ways to access solar energy: either power plants that use solar energy by concentrating direct irradiation, converting it into heat and finally in electricity (solar central receiver), or those that use flat plate collectors or photovoltaic panels. In both cases, the up and down cycles are represented by a multi-state Markov model, as depicted in Figure 3.3(b). In order to better represent the up and down cycles and their capacity fluctuations, they are

grouped according to their main characteristics, such as capacity in MW, year unavailability (FOR) and mean time to repair (MTTR), as well as their geographic position. Solar irradiations can be seen as the “fuel” for these devices. Hence, it is necessary to build yearly series that may be representative of the capacity fluctuations per hour, considering the geographic position [77].

Cogeneration: Cogenerating units are modeled similarly to the thermal units. However, like in the previous case, they are also clustered using multi-state units of Figure 3.3(b). Moreover, an *hourly utilization factor* is specified, which models the actual cogeneration power used by the system. This factor varies during the year following the tariff attractiveness and/or the industry production cycle.

3.4 LOAD MODEL

Generally, based on the forecast supply and demand curves, a utility can examine its current and future state of generation, transmission and distribution of energy. One of the difficulties in applying probabilistic methods to the power systems reliability assessment is the level of necessary details in some representations. For instance, specific load data is necessary to assess interruption costs involving several customer sectors [56].

Since load curves vary by season and by day of the week, reliability characteristics of a system may change throughout the days of the year. In some systems, summer electrical load is dominated by air conditioners, whereas winter electrical load is dominated by electric heating. In both cases, there are great differences in load shapes. In general, load characteristics are very important in reliability studies, so the detailed load curves must be modeled [78]. On the other hand, it is known that any load model is an approximation of the actual load. Its accuracy depends on the amount and quality of available data [63]. The most detailed load curves span all 365 days of the year and consist of 8760 hourly demand points.

In state space representation, some load models based on Markovian assumptions have been used [63]. Usually, these models make it possible to keep track of the chronological aspects of the load shape of power systems reliability assessment, thus contributing to the reduction of the computational effort. However, in chronological representations, the standard chronological load model is used containing 8760 levels, which correspond to

each hour of a year. The chronological MCS will sequentially follow these load steps during the simulation process [74].

In load forecast studies, a fundamental topic that must be taken into consideration is the fact that the actual peak load generally differs from the forecast value within a certain error. In other words, the load forecast may assume a predication error. As the forecast is normally predicted on past experience, a level of uncertainty must be considered in order to insert a noise in the chronological representation. Two uncertainty levels, representing short and long-term load forecasting deviations, can be simulated through the MCS process. Gaussian or any other type of distribution may be used [16]. In the short-term representation, an hourly uncertainty is inserted during the simulation process, whereas in the long-term representation a yearly uncertainty is inserted during the same process.

3.5 COMPOSITE SYSTEMS ADEQUACY ASSESSMENT

Composite generating and transmission system adequacy evaluation involves the simulation of the major problem of assessing the generation and transmission facilities' ability in service, so as to adequately supply the system load requirements at the major load points within acceptable limits [58]. The objective of HL 2 is to study the system conditions for each possible state assumed in the composite system, considering generating and transmission constraints. Such states may drive the system to voltage violations, line and/or generator overloads, and generator reactive power limit violations, load curtailment, and others. Generally, adequacy at HL 2 normally comprises the following basic steps [58]:

- i. Evaluate the performance of the power network without removing any component. This can be designated as the study of the performance of the base case system;
- ii. Make changes in the network configuration due to the “credible” outage(s) of various components;
- iii. Check the adequacy of the modified power system;
- iv. If necessary, take any corrective action, such as rescheduling the generating units, lining overloads alleviation, correcting bus voltages and loading curtailment at buses;

- v. Calculate the adequacy indices for the individual load buses and for the whole system.

Extensive work in the area of HL 2 adequacy evaluation has been promoted in the specialized literature [79-83]. There is a wide range of indices that can be calculated at each major load point and for the overall system. Different from generating evaluation, which considers all units in a single bus, the composite systems intend to identify weak points in the system through the individual load point adequacy indices. Therefore, there are three fundamental parameters in the calculation of system adequacy indices:

- Frequency of events;
- Duration of events;
- Severity of events.

The severity of an event depends not only on the importance of each failure component, but also on its location in the network. A comprehensive list of HL 2 adequacy indices can be found in the specialized literature [16].

Quantitative assessment of the adequacy of a composite system may be performed using the MCS approach. In fact, there are two main approaches frequently used in composite systems: the analytical enumeration and the MCS. The latter is more flexible, especially when large systems need to be evaluated. As mentioned before, the non-sequential MCS is a remarkable tool used to assess composite systems, perhaps due to the depleted moderate computational cost. Consequently, there is a large number of composite system reliability evaluation programs using the state space representation, mainly due to the simple characteristics used in these representations. However, the sequential MCS is the most suitable tool, when complex operating conditions and system considerations, such as chronological aspects, reservoir operating rules, bus load uncertainties, and others, need to be considered. The computational cost required in such analyses, especially in reliability studies of large power systems, depends on several system characteristics, including the network dimension and how rare the failure states are [73]. Hence, the chronological representation requires a more substantial computational effort than the other approaches, although it is infeasible for some applications [61]. In this sense, plenty of researches have been promoted in order to make the sequential simulation feasible.

In the last years, many works have been proposed to reduce the computational cost of composite reliability evaluation. It is fundamental to mention some of these approaches: distributed processing [84], artificial neural networks [85], variance reduction [86], pseudo-chronological simulations [61], and others. There are other related techniques to reduce CPU costs that may be found in the bibliography lists of the previous references. One of the targets of this thesis is exploring MAS technology in order to organize these methodologies aiming to sum all individual benefits previously achieved in a unique way. Therefore, composite reliability assessment based on sequential MCS methods can become feasible for large-scale power networks.

3.6 DISTRIBUTION SYSTEMS RELIABILITY ASSESSMENT

Since the distribution system must deliver electricity to each customer's service entrance, promoting distribution reliability studies is the key to understand the complete functional zones of the power systems. As mentioned before, in the context of reliability, generation, transmission and distribution are referred to as functional zones [62]. Usually, due to the complexity of the distribution systems, reliability studies are promoted regardless of the generation and transmission levels.

Historically, distribution systems reliability assessment can be divided into two basic segments: past system performance and predictive future performance [87]. The most common approach used in the utilities is the past system performance, where they keep tracking all accurate historical reliability data in order to measure the past network performance, as well as to plan future network improvements. On the other hand, predictive reliability evaluation is an attempt to estimate future performance of the distribution networks [7]. It follows the same structure of the transmission system indices, in which distribution system indices are divided into two basic groups: (i) individual customer load points, which is assessed through: failure rate λ (usually interpreted as a frequency), failure duration r , unavailability U , and energy not supplied ENS ; (ii) overall distribution system, where the most popular range of possible service performance indices are [62]:

- SAIFI – defined as the average number of interruptions per customer served per time unit;

- SAIDI – defined as the average interruption duration for customers served per time unit;
- CAIDI – defined as the interruption duration for customers interrupted per time unit;
- ASAI – defined as the ratio of the total number of customer hours that service was available during a year, to the total customer hours demanded;
- AENS – defined as the ratio of the total energy not supplied to the total number of customers served.

Generally, these distribution indices provide a comprehensive measure about frequency, duration and severity of each interruption on the load points or overall system. All these indices are defined in [62].

Recently, the reliability assessment of distribution systems has received considerable attention. In fact, there are a large number of publications dealing with the theoretical developments and applications [88], as well as other important indices related to service performance measures [89]. The usual method to evaluate the reliability indices is an analytical approach based on a failure mode assessment and on the use of equations for series and parallel networks [7]. A simulation approach is sometimes used for special purposes in order to determine, for instance, the probability distributions of the reliability indices [70]. Future performance using simulation approach is a valuable procedure that can be used to determine system reinforcements and to compare expansion alternatives. Moreover, in order to accurately assess these probability distribution functions, associated with any reliability index, the sequential MCS is the only consistent option [71]. Additionally, there has been a considerable revival of interest in connecting generation to the distribution network and this has come to be designated as dispersed or distributed generation [7]. Penetration of distributed generation across the world has reached a significant amount in medium voltage (MV) distribution level. Distributed power applications favor not only natural gas and wind technologies mainly due to the potential of low air emissions, but also a simple connection in the MV distribution or sub-transmission levels. Nevertheless, several emergent generation technologies, such as micro-turbines, photovoltaic, fuel-cells and gas internal combustion engines can also contribute to the mitigation of air emissions. Even though these technologies require a

more complicated system connection in the distribution systems [90], they are usually connected to the low voltage (LV) distribution level. This new scenario of network distribution operation highlights a new paradigm of network construction and operation known as Micro-grid [91]. As is the case for all recent areas, further research is required on Micro-grid, which include studies on control, power quality, protection coordination and personal safety, communications, economic and market-driven procedures, network reliability, and others.

Due to the dimension and the complexities mentioned before, distribution systems reliability studies using sequential MCS are generally avoided. Analytical approaches [87] or hybrid methodologies combining non-sequential MCS and cut-sets algorithm [16] are most suitable. Some works have tried to approach a reliability evaluation of the complete electric power system, including generation, transmission and distribution facilities [57], mainly promoting a separate evaluation of HL 2 impact on the distribution systems. Other ways such as distributed processing to assess reliability indices in distribution systems were applied with relative success [92]. In other words, quantitative reliability evaluation is an essential aspect of distribution system developments, and further research is required.

3.7 CASE STUDY ON OPERATING RESERVE ASSESSMENT

In order to show an application of the chronological representation by sequential MCS and its intensive programming models and accurate representations, which require a higher processing time, a case study involving two real systems is presented. The main target is to emphasize the computational cost involved in this application considering real systems including correlations between variables. The application was developed involving two research institutions (INESC Porto and Federal University of Itajubá) and two TSOs (REN – the Portuguese TSO and REE – the Spanish TSO). Another important aspect that needs to be highlighted is that this application was entirely developed in FORTRAN, which can be considered as an appropriate programming language for intensive numerical evaluations. In order to deal with some confidential information from both TSOs, the simulation results are partially shown and discussed.

3.7.1. INTRODUCTION

Even in a liberalized environment, managing the security of the supply associated to the generating system continues to be a major task of the System Operators. The increased use of renewable energy, particularly wind power and other intermittent sources, adds new challenges to the process, namely in countries like Portugal and Spain, where strong investments in wind power have been made and are foreseen for the next years. In order to tackle this issue, REN (the Portuguese TSO), REE (the Spanish TSO) and INESC Porto (an R&D institute) joined together to develop a project where the MCS is used to evaluate the risk associated with specific configurations of the generating system, until the horizon of 2025.

Probabilistic simulation was chosen because deterministic approaches to this problem, albeit simple to understand and easy to implement, are problematic in a sense that we cannot rely too much on expected values or estimated quantities, and so the probabilistic simulation is unable to completely deal with the complex relations between different uncertain variables. Besides, it does not provide a meaningful measure of risk, but only a rule associated to a threshold whose definition is not always clear.

The chronological representation is used in order to preserve the relations between load variation, wind power variation, hydro monthly conditions, cogeneration variation and other variables, such as generation maintenance and management, pumped storage operations, combined heat and power generation or small hydro generation. This strategy recognizes the statistical dependence between these variables and creates states that follow the complex joint distributions they exhibit. Merging these variations with the sampling of unit failures and repair times leads to loss of load statistics, from which risk indices of generation adequacy are calculated. LOLP (Loss of Load Probability), LOLE (Loss of Load Expectation) or EENS (Expected Energy Not Supplied) are classic examples of those indices. Extension of the concept to check secondary reserve availability in each state is also included, in the process known in the literature as “well-being analysis” [19], where each simulated state is further classified as “healthy” (enough reserve margin), “marginal” (partial reserve margin) or “at risk” (loss of load). Probabilities of these three conditions and the expected number of hours per year in each one are useful indices to complement the classic ones.

A crucial feature of the model is the possibility of synchronizing the simulations carried

out for Portugal and Spain, which allowed us to check the cases where one of the systems can support the other in “marginal” or “at risk” situations through interconnections.

Another new feature is the analysis of the operational reserve through an inner simulation process that estimates, in each simulated state, the unforeseen change in load (using a normal distribution of the forecast error) and in wind power (assuming forecasting by persistence). These unexpected changes are then compared with the total available operating reserve, defined by the actual secondary reserve plus the tertiary reserve units with lead time up to one hour. From this exercise, different statistics related to reserve needs and reserve adequacy are constructed, leading to indices that can be compared with benchmark values. These values are defined from a known condition (in this case the year 2005). This kind of information is essential in the validation of reserve requirements for the future, in order to maintain or decrease the risk level.

It is important to point out that the proposed simulation is a tool that enables us, not only to detect future risk conditions, but also to quantify the adequacy of different reserve requirements, solutions for reserve enhancement, and others, in order to perform techno-economic analysis and to support the decision of making process.

3.7.2. CONSIDERATIONS AND DEVELOPMENTS

All previous risk indices are based on the following power balance equation:

$$R_{STA} = G - L < 0 \quad (3.20)$$

where G represents the system available generation, L is the total system load and R_{STA} is the static reserve. The random variable G depends on the equipment availabilities and on the capacity *fluctuations* due to, for instance, hydrology and wind variations, etc. The random variable L depends on the short and long-term uncertainties and also on the hourly variations.

In order to assess the performance of the operating reserve, new variables have to be defined as shown in Figure 3.4. In this case study, the primary (or regulation) and secondary (or spinning) reserves are pre-defined values. Obviously, the spinning reserve amount can always be redefined, in case its associated performance is below a pre-established acceptable value. The tertiary reserve (non-spinning) is set up by those generators that can be synchronized within 1 hour. This reserve is the most relevant in the

present study and it constitutes the major concern for planners in this new environment characterized by a profusion of renewable sources.

The following power balance equation is set to assess the risk indices associated with the operating reserve:

$$R_{OPE} = R_S + R_T < \Delta L + \Delta P_w + \Delta G \quad (3.21)$$

where ΔL represents the short-term load deviation at hour “ t ”; ΔP_w represents the possible wind power capacity variation at hour “ t ”; and ΔG represents the generating capacity variation due to forced outages at hour “ t ”. From Figure 3.4, it is possible to observe an extra amount of capacity at the top of the tertiary reserve. This is due to the discrete effect of unit generating capacities.

Equation (3.21) describes the risk of changes in the load, wind power capacity, as well as generating outages not duly covered by the amount of spinning reserve, and also by the generators that can be synchronized within 1 hour. Therefore, the same traditional and well-being indices can be evaluated with this risk equation.

Although there are many reference values for LOLP or LOLE indices (i.e. static reserve), within the framework of generation planning, there are no reference values for the well-being indices, nor for the operating reserve proposed framework.

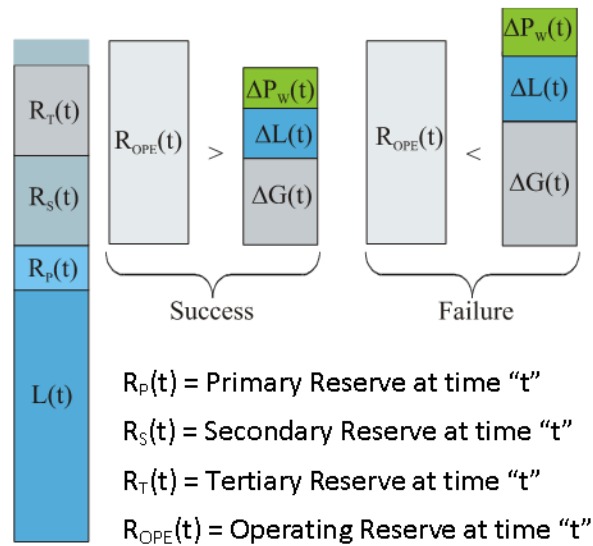


Fig. 3.4 – Operating Reserve Assessment

The implementation of the previous models is carried out through a FORTRAN (calculation mode). The convergence process is tracked by a coefficient of variation specified for the EENS index. Usually, when the convergence of EENS index is ensured, the others will converge as well. The probability distributions of all, conventional and well-being, static and operating reliability indices are also evaluated.

3.7.3. PORTUGUESE AND SPANISH SYSTEMS

The proposed algorithm has been tested under several conditions with different systems. Two cases using the Portuguese and Spanish Generating System (PGS and SGS, respectively) will be discussed next. The first case will show the results using the PGS and SGS configurations for the year 2005. The idea is to evaluate these configurations to establish certain reliability parameters or standards for the years to come. The second case will illustrate the results obtained with the proposed algorithm considering *potential* configurations for the year 2020. This is part of the expansion plan studies of the PGS and SGS.

For the year 2005, the PGS had 1035 units with a total installed capacity of 12.59 GW, distributed as follows: 4.38 GW (Hydro); 5.43 GW (Thermal); 0.98 GW (Wind); 0.34 GW (Mini-hydro); and 1.46 GW (Cogeneration). The annual peak load occurred in January and it was approximately 8.53 GW. Bearing these two values in mind, the static system reserve corresponds to 32% of the installed capacity. Also, the amount of renewable power in the system is 45% of the total capacity. In 2020, this amount will correspond to 60% of the total capacity, from this total 5.21 GW of wind power.

For the year 2005, the SGS had 8150 units with a total installed capacity of 70.2 GW, distributed as follows: 15.17 GW (Hydro); 37.1 GW (Thermal); 9.54 GW (Wind); 0.79 GW (Mini-hydro); and 7.6 GW (Cogeneration). The annual peak load occurred in January and it was approximately 43.14 GW. Bearing these two values in mind, the static system reserve corresponds to 38% of the installed capacity. Also, the amount of renewable power in the system is 36% of the total capacity. In 2020, this amount will correspond to 47% of the total capacity, from this total 28.16 GW of wind power.

Figure 3.5 shows the capacity evolution for the Portuguese (a) and Spanish (b) generating systems from 2005 to 2025.

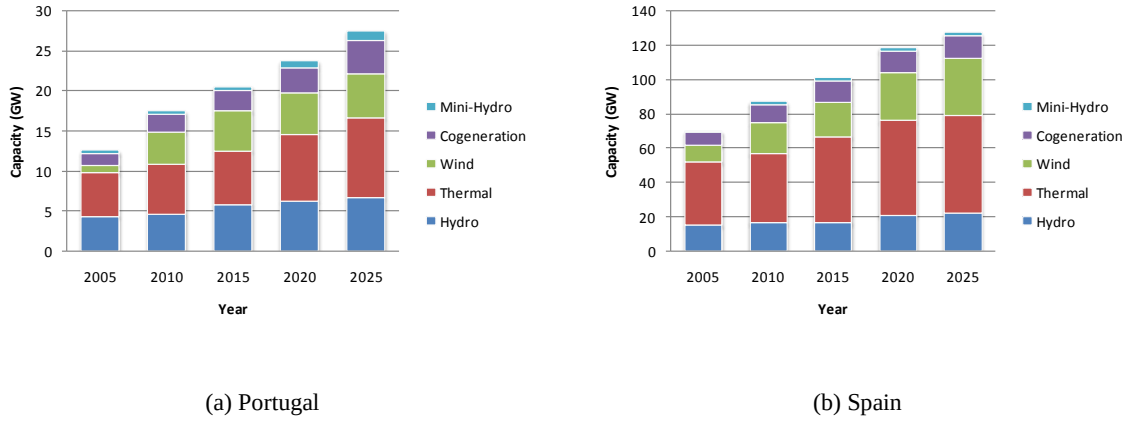


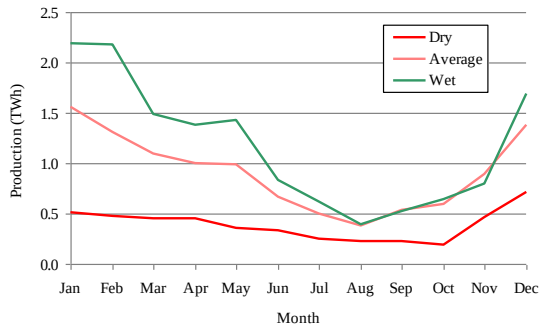
Fig. 3.5 – Generating System Capacity Evolution

In 2005, there were 35 hydropower plants in Portugal and 174 in Spain. In this study, 6 hydrological basins in Portugal and 6 in Spain were considered, referring to 16 years of monthly hydrological conditions (1990-2005). Figure 3.6 shows the hydro production variations (Dry, Average and Wet conditions) for Portugal (a) and Spain (b). The driest year was 2005 for Portugal and 1992 for Spain, and the wettest year was 1996 for Portugal and 2003 for Spain. These monthly variations must be duly captured by the proposed algorithm for sequential MCS reliability assessment.

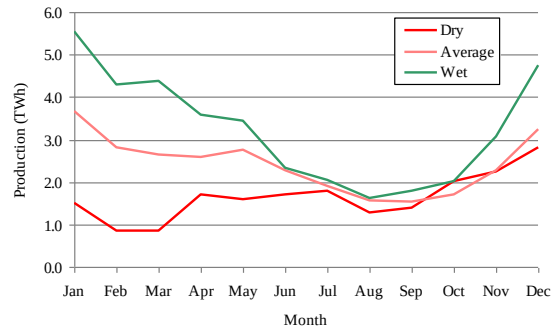
In 2005, there were 8 thermal power plants in Portugal and 74 in Spain (not including cogeneration). Some important maintenance procedures with nuclear power units were simulated for the Spanish system, as well as the starting operation of new wind power plants.

In 2005, about 655 wind-generating turbines (units) were in the PGS and 6365 in the SGS. Bearing the wind series in mind, Portugal was divided into 7 regions and Spain into 18 regions. Figure 3.7 shows typical wind power fluctuations along the day. In 2005, for the PGS, the highest capacity peak occurred on November 6th, and the lowest on July 20th. In 2005, for the SGS, the highest capacity peak occurred on August 8th, and the lowest on April 8th. The average p.u. value remains around “0.26” of the maximum installed capacity for both systems. In order to model the deviation ΔP_w in (3.21), a forecasting error by persistence was assumed.

Typical hourly load curves were used for both PGS and SGS. Two uncertainty levels with Gaussian deviations were used to represent the short-term, i.e. expression ΔL in (3.21), and long-term load forecasting.

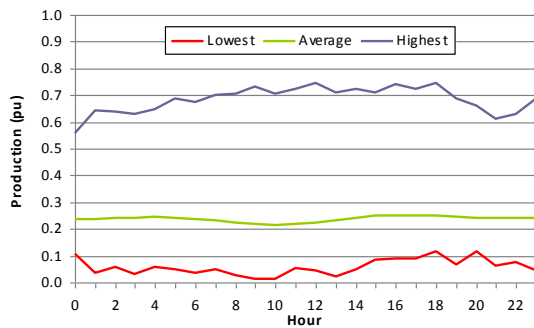


(a) Portugal

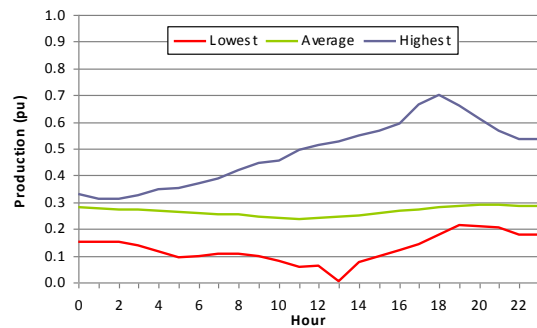


(b) Spain

Fig. 3.6 – Hydro Production, 1990-2005



(a) Portugal



(b) Spain

Fig. 3.7 – Wind Power Typical Fluctuations

These deviations were assumed to be within the range between 2% and 4%. In fact, sensitivity analyses were preliminarily carried out to validate these values. As the cogeneration production is an important component in the total generation plant, the cogeneration units consider the average behavior experienced in the last years due to the past used incentives. Thus, typical hourly factors were calculated in order to model the cogeneration production behavior. Several other data involving mini-hydro, solar power and maintenance policies, etc. also have to be processed.

3.7.4. APPLICATION RESULTS

The proposed sequential MCS algorithm is being tested with several planned configurations of the PGS and SGS. The aim is to determine the required amount of system generating reserve capacity, static and operating, to ensure an adequate power supply.

These steps should be taken bearing in mind not only the uncertainties from the equipment availabilities, but also the uncertainties caused by capacity variations in renewable power sources. This study is being carried out considering a horizon of 20 years (2005-2025). Different scenarios involving not only hydro and wind unfavorable conditions, but also cogeneration usage and maintenance strategies are being analyzed.

3.7.4.1. ANALYSIS FOR THE 2005 CONFIGURATION

The 2005 configuration was used in order to define reliability standards for the PGS and SGS. Although several operating conditions or cases were tested, only four of them will be discussed. For the Base case, all historical hydrological and wind series were simulated with the 2005 configuration for both systems. In the H^+ case, the wettest hydrological year was considered, and in the H^- case, the driest hydrological was simulated. The HWM case considers that the driest hydrological condition occurs simultaneously with all observed wind series, which causes their capacities to be reduced by 50%. Moreover, the usual amount of power on maintenance was increased by 20%. Certainly, this is a very severe scenario.

Tables 3.2 and 3.3 show the traditional reliability indices (static and operating reserves) for the PGS and SGS, respectively. As it can be seen from these tables, both PGS and SGC configurations (2005) are extremely robust. As expected, the worst condition occurs for “HWM”, thus leading to indices like: $LOLE_{STA} = 0.023$ hours/year and the $LOLE_{OPE} = 0.032$ hour/year for the PGS; $LOLE_{STA} = 2.596$ hours/year and the $LOLE_{OPE} = 2.832$ hour/year for the SGS. Under these “HWM” conditions, the previous performance can be considered to be perfectly acceptable.

Tables 3.4 and 3.5 show the well-being reliability indices (static and operating reserves) for the PGS and SGS, respectively. The following interpretation for the SGS can be provided, if everything goes wrong (i.e. HWM case) with the 2005 configuration. Bearing the static reserve in mind, the SGS will stay, in average per year, 8754 hours in healthy states, 3.814 hours in marginal states, and 2.596 hours in risk states. Bearing the operating reserve in mind, the SGS will stay, in average, 8741 hours in a healthy state, 16.20 hours in a marginal state and 2.832 hours in the at risk state.

Table 3.2 – Reliability Indices – Portugal/05

Case	LOLE (hours)	EENS (MWh/yr)	LOLF (occ./yr)	LOLD (hours)
<i>Static Reserve</i>				
Base	0.006	0.915	0.006	1.036
H ⁺	0.001	0.240	0.002	0.870
H ⁻	0.012	1.704	0.011	1.057
HWM	0.023	3.784	0.021	1.076
<i>Operating Reserve</i>				
Base	0.036	3.760	0.044	0.817
H ⁺	0.147	12.66	0.190	0.773
H ⁻	0.017	2.542	0.016	1.092
HWM	0.032	3.304	0.031	1.026

Table 3.3 – Reliability Indices – Spain/05

Case	LOLE (hours)	EENS (MWh/yr)	LOLF (occ./yr)	LOLD (hours)
<i>Static Reserve</i>				
Base	0.040	23.76	0.033	1.238
H ⁺	0.000	0.000	0.000	0.000
H ⁻	0.496	365.4	0.371	1.336
HWM	2.596	2280	1.704	1.524
<i>Operating Reserve</i>				
Base	0.154	63.11	0.259	0.594
H ⁺	0.021	5.564	0.050	0.417
H ⁻	0.757	476.5	0.809	0.935
HWM	2.832	2150	2.446	1.158

Table 3.4 – Well-being Indices – Portugal/05

Case	E _H (hours)	F _H (occ./yr)	E _M (hours)	F _M (occ./yr)
<i>Static Reserve</i>				
Base	8760	0.096	0.092	0.093
H ⁺	8760	0.024	0.024	0.023
H ⁻	8760	0.147	0.137	0.141
HWM	8760	0.343	0.323	0.332
<i>Operating Reserve</i>				
Base	8758	1.516	1.321	1.506
H ⁺	8755	6.409	5.447	6.318
H ⁻	8760	0.210	0.202	0.200
HWM	8759	0.499	0.480	0.481

Table 3.5 – Well-being Indices – Spain/05

Case	E _H (hours)	F _H (occ./yr)	E _M (hours)	F _M (occ./yr)
<i>Static Reserve</i>				
Base	8760	0.147	0.153	0.144
H ⁺	8760	0.000	0.001	0.000
H ⁻	8758	1.068	1.107	0.994
HWM	8754	3.568	3.814	3.455
<i>Operating Reserve</i>				
Base	8756	6.914	4.188	6.909
H ⁺	8758	1.914	1.169	1.917
H ⁻	8751	12.12	7.508	12.19
HWM	8741	24.68	16.20	24.60

These are indeed very low values for that particular stressing scenario. It has to be pointed out that the “HWM” scenario caused more impact on the Spanish system than on the Portuguese system, since the SGS depended much more on wind sources in 2005: 13.6% of the installed capacity in Spain, against 7.8% in Portugal.

It is also interesting to observe that, for the PGS, the average number of hours in a marginal state under the H⁺ (the wettest scenario) condition is curiously high for the operating reserve, i.e. 5.447 hours/year. Actually, as an H⁺ condition occurs, hydraulic units are intensively used and, consequently, there are less generating units to participate as tertiary reserves. However, the PGS will remain, in average per year, only 0.147 hours, which the worst condition for the PGS. Once more, these are very low risk values.

In conclusion, the PGS and SGS had a substantial robust configuration for the year 2005. Moreover, the proposed simulation algorithm properly captured the performance of both static and operating reserves.

3.7.4.2. ANALYSIS FOR FUTURE CONFIGURATIONS

Initially, some sensitivity analyses were carried out with the 2005 configurations, by increasing the peak load of both systems in order to measure the capacity slackness in these configurations. Figure 3.8 shows the results for the LOLE index associated with the static reserve for the PGS (a) and for the SGS (b). As it can be observed, both systems will experience some difficulties in surviving more than 10% of load growth from the 2005 configurations. Similar sensitivity tests were carried with the $LOLE_{OPE}$ indices, and a similar conclusion can be stated. Obviously, REN and REE have positively acted on this matter and, as a consequence, a series of new configurations have been proposed, tested, and the results have been adequately discussed.

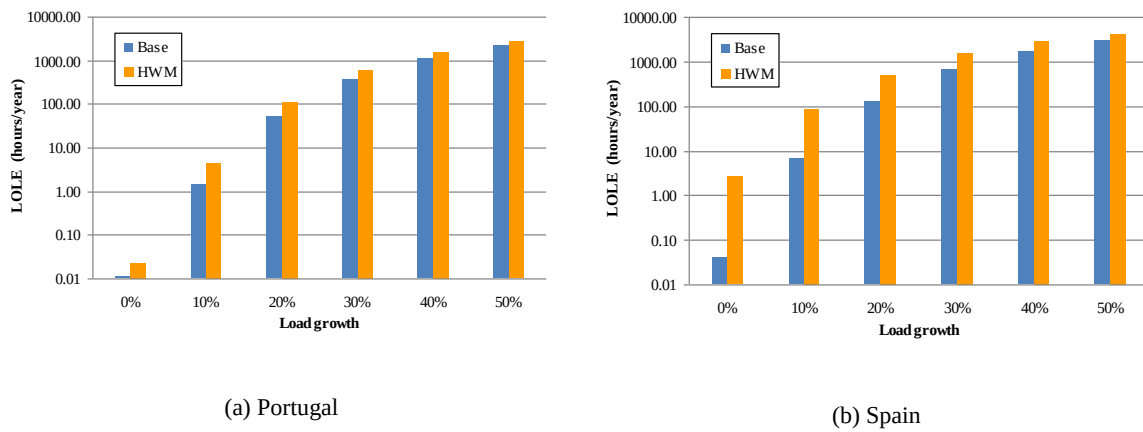


Fig. 3.8 – Sensitivity Analyses – $LOLE_{STA}$ (hours/year)

Figure 3.9 shows the perspectives of demand evolution for the Portuguese and Spanish systems (up to 2025), and how REN and REE are planning to increase their installed capacity. Clearly, these are possible scenarios to be dealt with by planners. For the PGS in 2020, for instance, the forecasted peak load is about 15.1 GW, and there will be a total of 23.8 GW of installed capacity. From this total, 26.6% will come from hydro power, 21.9% from wind power and 3.6% from mini-hydro sources. For the SGS in 2020, for instance, the forecasted peak load is about 68.5 GW, and there will be a total of 119 GW of installed capacity. From this total, 17.8% will come from hydro power, 23.7% from wind power and 1.8% from mini-hydro sources. In both systems, other renewable power sources (e.g. solar and biomass) were considered.

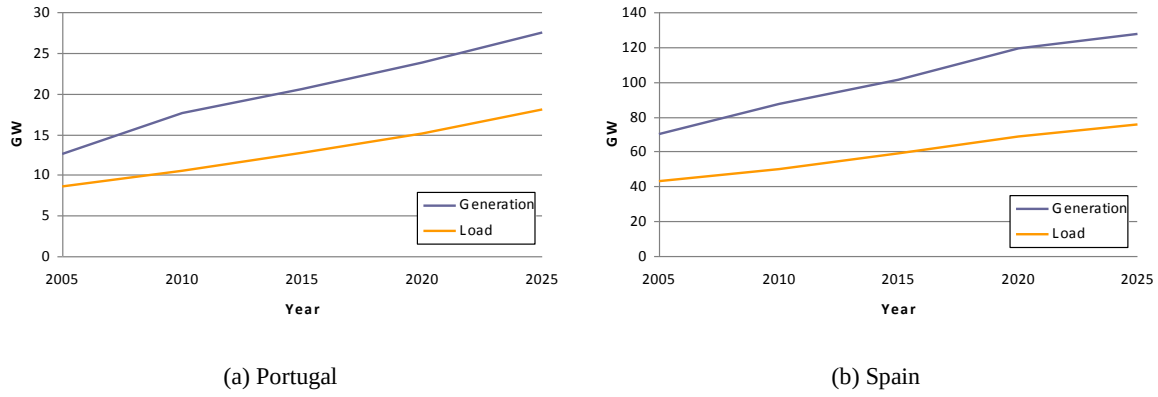


Fig. 3.9 – Installed Capacity vs. Peak Load (2005-2025)

In order to assess the risks associated with both static and operating reserves, the chronological MCS based algorithm has been run for both the PGS and SGS. The results have been used to assist planning engineers in finding the best balance between reliability and costs. As previously stated, the simulation results that involve a complete future assessment, including several scenarios may be consulted in [93].

3.7.4.3. CPU TIME CONSUMING ANALYSIS

The parameter β was set to 5% in all tests for EENS index, and a maximum of 3000 years were simulated. All simulations were carried out in a PC with 2.8 GHz. The CPU time for each case is shown in Table 3.6.

Table 3.6 – CPU Time from Portugal and Spain in 2005

Case	CPU Time Portugal (min)	CPU Time Spain (min)
Base	31	473
H ⁺	29	554
H ⁻	30	233
HWM	32	153
Average	30	353

On average, the PGS required 30 minutes for each simulation and the SGS required 353 minutes for each simulation. This high CPU time indicates that both systems are very reliable. As it can be observed in Table 3.6, some SGS cases as Base and H^+ have performed the simulation in a large CPU time (473 and 554 minutes or approximately 7 and 9 hours). On the other hand, in the same SGS, cases as H^- and HWM require a different amount of CPU time (233 and 153 minutes or approximately 4 and 3 hours). This happens mainly due to three conditions: (i) the size of the SGS; (ii) the rarity of failure events in the SGS; (iii) the sequential MCS is an expensive computational approach to assess reliability indices. Still in Table 3.6, the PGS system requires less computation time (30 minutes), mainly because it is a very small system, when compared to the SGS, and the rarity of failure events also differs from SGS. It is important to highlight that generating assessment generally requires less computational costs than the composite system assessment, which proves that this type of simulation entails high computational costs.

3.8 FINAL REMARKS

This chapter presented a brief review of the reliability techniques usually used in the power industry in order to assess power systems. Due to the last investments in green power around the world, renewable energy technologies will take a greater share of the electricity generation mix in order to minimize the dependence on oil and the emission of CO_2 . While contributions from renewable energy sources for electricity production are small, with the exception of hydro, their market penetration is growing at a much faster rate than any other conventional source.

Nonetheless, there are consequences to these changes, since more renewable power sources cause an increase in the number of random variables and operation complexities in the system. This is explained by the fluctuating production levels of these sources.

A case study involving two European countries shows that the determination of the required amount of system capacity (both static and operating reserves) to ensure an adequate supply becomes a very important aspect of generating capacity expansion analyses. The dimensioning of operating reserve, spinning and non-spinning, plays prominent role in systems with high penetration levels of renewable sources, mainly wind power levels, due to its natural volatility.

Besides the technical conclusions involving reserve needs for the planned years, one of the most complicated obstacles was promoting the balance between costs and security (reliability) linked to the operational reserve problem, considering systems with high participation of intermittent power. The lack of reliability standards that can adequately represent this balance was checked through a simple standard comparison between countries, considering the LOLE index, which can vary from 0.1 days/years, such as in the United States of America, to 60 hours/years, as in Brazil. In the last years, a mechanism known as “performance based regulation” [94] has been introduced to encourage power utilities to become more economically efficient, and, at the same time, to discourage utilities from sacrificing service quality, which sometimes can lead to an aggressive operation security policy. This discussion is an essential issue to the modern power system operation, and it needs to be taken into consideration for the years to come.

A fundamental characteristic concerning all new variables taken with the green power paradigm is the change needs in the techniques used by utilities. It is mandatory to incorporate these new variables in power system assessment. On the other hand, the computational requirement increases when more detailed representations are needed. Exploring new computational paradigms can represent an alternative to improve power computational tools.

Discussions on innovative representations or computational models, operation strategies and mainly assessment tools are the new insights of power systems reliability assessment considering renewable power sources for the years to come.

Chapter 4

MULTI-AGENT SYSTEMS APPLIED TO RELIABILITY ASSESSMENT OF POWER SYSTEMS

4.1 INTRODUCTION

In artificial intelligence (AI) research, agent-based systems technology is a new paradigm for conceptualizing, designing, and implementing software systems. Intelligent agents are sophisticated computer programs that act autonomously on behalf of their users, across open and distributed environments, to solve a growing number of complex problems. Increasingly, however, applications have required multiple intelligent agents (IA) that can work together. A multi-agent system (MAS) is a loosely coupled network of software agents that interact to solve problems that are beyond the individual capacities or knowledge of each problem solver.

Several technical works using MAS technology have been published in the literature [95-101], showing potential applications to solve problems related with electric power systems. Recently, two important contributions have organized the concepts, approaches, technical challenges, technologies, standards, and tools to build MAS applied to power engineering [95-96]. Many aspects were discussed regarding the benefits of this technology, besides providing guidance and information on the state-of-the-art of MAS research for the power industry. Some favored issues in power agent applications have been indicated: modeling, simulation and distributed control. In particular, the modeling of the electricity market as a complex adaptive system [97] and the optimization of decisions in retail markets [98] have been discussed. In the last few years, some other applications were carried out to solve power engineering problems [95-96], such as systems integration with database, systems and equipment monitoring, interpretation and analysis of outage date, system restoration [96], support to decision in micro-grids operation [100], and environment simulation [101]. These approaches have shown the great potential of MAS, exploring the concepts of communication and autonomous behaviors offered by this technology. In order to explore some other features of the MAS technology, an application to power systems reliability assessment is being proposed in this chapter. It uses the benefits from the distributed artificial intelligence area in two ways: building autonomous behaviors and reducing computational effort on power systems reliability evaluations.

Many works have explored the use of the distributed or parallel environment in power system evaluations [84], [102-103], some of them including reliability assessment [84]. Different from these works, which generally aim at mitigating computational effort and at making some expensive simulations feasible, this thesis intends to build a software

environment that agents are capable of sensing it through the use of basic intelligence offered by the agent-based technology. This environment facilitates the agents to recognize others specific agents, within the platform, as well as to promote communication among them through the use of *performative* structures. In order to introduce computational intelligence in power system reliability assessment, MAS using Java technology is being proposed, where the agent base is supported by distributed computing technology [44], [49].

This chapter discusses the development of a MAS technology-based platform to assess generating capacity reliability indices, based on sequential or chronological Monte Carlo Simulation (MCS) processes. Although the focus will be on the application of MAS to this particular reliability problem, other simulation-based applications can also benefit from this platform. The MAS construction was designed under the concept of reliability assessment by the sequential MCS. JADE Library (Java Agent Development Framework) [42], standardized by FIPA (Foundation for Intelligent Physical Agents) [43], is used and, sometimes, only Java language is called to construct agents. In the next sections, one will present an overview of the power agent platform, the application of MAS in power systems reliability assessment based on two different approaches, and the results of the reliability evaluations of two different electric systems: the IEEE-RTS, with 32 unit generators, and a modified configuration of the Brazilian South/Southeastern System (BSS), with 242 unit generators. In this chapter, these two new systems will be used in order to preserve the data, discussions and analyses on the Portuguese and Spanish systems. However, some comparisons will be provided in order to demonstrate the potential of MAS technology.

4.2 OVERVIEW OF THE POWER AGENT PLATFORM

The proposed power agent platform can be described through layers, as shown in Figure 4.1. In the first level, at the bottom (in red), there is the class diagram that represents the electric power system. Representations such as generators, transmission lines, distribution network, buses, etc. have a relationship among them, based on the Oriented Object Modeling (OOM). In the second level, at the right side (in green), there is the class diagram named *class service* that represents the tools linked to each evaluation algorithm, such as reliability assessment by a sequential MCS. In the third level, at the top (in blue), there is the class diagram with the MAS technology, where agents are built and provided

with some abilities to use the first and the second levels, previously described. Figure 4.1 also shows a *Generator Agent* using the *Monte Carlo Class* and the *Generator Class*, which has taken an action after a perception on its specific environment. Obviously, this simple representation intends to show the philosophy of the simulation platform using one of the main characteristic of agents: autonomy.

In a simpler sense, an agent can be classified as software or hardware elements located in a specific environment, which is able to note changes and react to these changes [31]. Following the same idea, power engineers can compare this concept with an old and simple well-known agent: an over-current relay, which will take an action after perceiving an over-current, switching the electric circuit off. Characteristics such as *Reactivity*, *Pro-Activity* and *Social Ability* are described in several references on AI and MAS [31], and here they are applied to this proposed simulation platform. Essentially, the MAS technology is the combination of these inherent characteristics and others, which makes it different from other conventional tools in the power systems analysis. One of the most important characteristics of this technology is the application of Java to build agents and its ability to distribute applications and run concurrency programming. This feature enables the building of power models using intelligent behaviors in a very distinctive way.

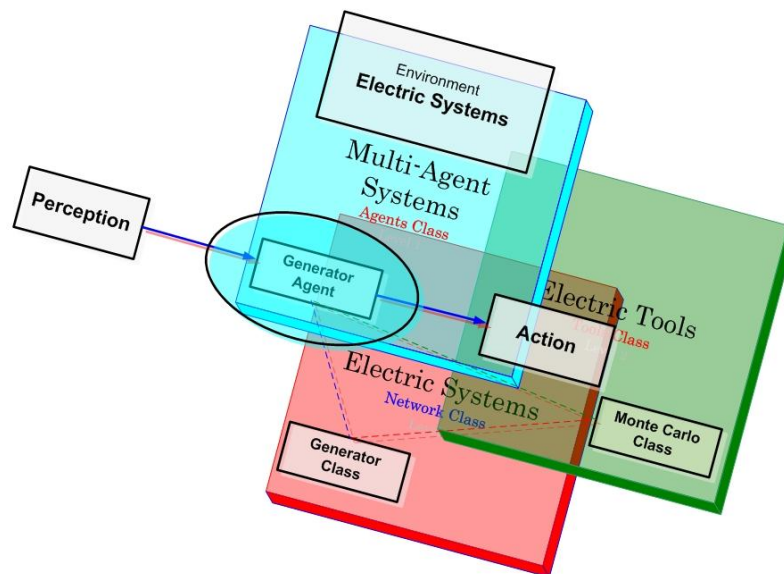


Fig. 4.1 – Representation of the Platform Layers

4.3 RELIABILITY ASSESSMENT USING MAS

The reliability assessment of real large power systems by sequential MCS is known for being a very expensive computational evaluation. Moreover, to analyze the sampled states, heavy computational tools such as optimal power flows are intensively used [84-85]. The solution time for analytical techniques is relatively short, but usually requires a simplification of the systems [87]. However, sequential MCS makes it possible to use a wide range of detailed models, including non-Markovian representations for generation and transmission equipment, correlated chronological load models, and others. In order to reduce this expensive computational cost, different techniques have been proposed: distributed processing [84], artificial neural networks [85], variance reduction [72], [86], pseudo-chronological simulations [61]. There are other related techniques to reduce CPU costs that can be found in the bibliography lists of the previous references.

4.3.1. USING IA TO SUPPORT AI IN POWER SYSTEM RELIABILITY ASSESSMENT

The Monte Carlo technique is a statistical-based method that can be naturally divided into three inherent stages in order to assess reliability indices: state selection, state evaluation and index calculation. Many works have explored AI topics as search techniques, knowledge representation, reasoning and learning systems, as well as some mathematical approaches aiming to incorporate intelligence on these stages [69], [85], [104]. Generally, these approaches appear as competitors to the non-sequential Monte Carlo simulation, in order to achieve a more efficient simulation process. Figure 4.2 shows an overview of these representations. This thesis intends to construct an agent-based application in order to support the natural transition from AI to IA in power system reliability assessment. The main idea is to construct a basic intelligent distributed environment that can be able to support sequential Monte Carlo representation using IA features.

Instead of applying AI techniques in order to improve a single stage of non-sequential MCS, this thesis intends to build an IA architecture that supports sequential MCS, as well as AI techniques in more than one stage of the simulation process. Consequently, it will be possible to measure the gains of an agent-based distributed structure in reliability assessment before applying AI topics, using an intelligent agent architecture design.

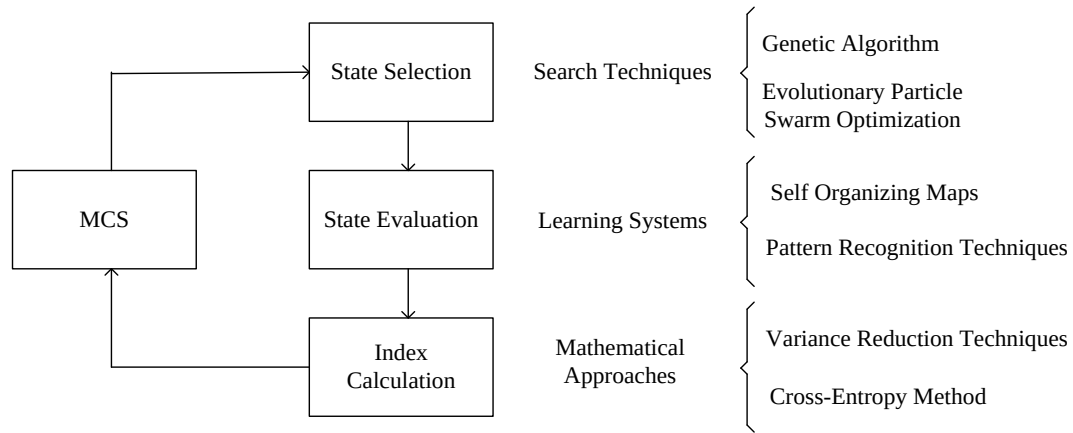


Fig. 4.2 – MCS Stages and Most Recent Approaches

Different from a simple distributed approach, which uses signals to control computers inside a network [84], this thesis uses agent communication language (KQML: Knowledge Query and Manipulation Language) [42] in order to establish communication among agents. KQML is essentially a knowledge-level message language that defines a number of performatives and makes an agent's intentions explicit [31]. Firstly, the aim is to combine KQML with autonomous behaviors of each stage of the sequential Monte Carlo representation in order to define an IA architecture design. In addition, this IA architecture will be prepared in order to support different AI techniques.

4.3.2. SEQUENTIAL MONTE CARLO SIMULATION

In order to propose a new way to address reliability assessment using MAS technology, some basic concepts used by the sequential MCS are revisited. This is a very flexible simulation type, as it allows non-exponential residence times to be represented, which is useful when dealing with chronological processes. The operation history of system states, for a simulation period T , is based on stochastic models of the components and on the load model. The initial state is usually sampled from a non-sequential Monte Carlo simulation algorithm. After evaluating each state, performance indices are estimated using test-functions $G(t)$

$$E[G] = \frac{1}{T} \int_0^T G(t) dt. \quad (4.1)$$

Each performance index can be estimated using a suitable test-function. The failure probability, for instance, corresponds to the expected value of an indicator function, where $G(t)=1$ if the system associated with time t is a failure state; otherwise $G(t)=0$. Another way of estimating the expected value of $G(t)$ is shown as follows

$$\tilde{E}[G] = \frac{1}{NY} \sum_{k=1}^{NY} G(y_k) \quad (4.2)$$

where NY is the number of simulated years and y_k is a sequence of system states in year k . For instance, the energy not supplied will be the summation of unsupplied energy associated with each interruption of a simulated year. The uncertainty around the estimated indices is given by the variance of the estimator

$$V(\tilde{E}[G]) = \frac{V(G)}{NY} \quad (4.3)$$

where $V(G)$ is the variance of the test-function. The convergence of the simulation process is tested using the coefficient of variation β [61], [72], [86].

$$\beta = \sqrt{V(\tilde{E}[G])} / \tilde{E}[G] \quad (4.4)$$

In this chapter, the problem in power system reliability assessment to be used as an example of the application of MAS technology is the generating capacity evaluation [16], although any similar reliability application (e.g. composite generation and transmission) could be exploited.

4.3.3. MAS APPLIED TO CHRONOLOGICAL MCS

It is important to observe that the concept of agent was designed for flexibility, not for speed. This means that communication speed must not be required within the algorithm, and all efforts should be concentrated on the relevant local tasks for all agents, as to reduce network calling or sending of messages. Therefore, it will be possible to increase processing speed through flexibility. In order to describe the inherent tasks carried out for the agents to evaluate (4.1) to (4.4), bearing a generating capacity reliability assessment in mind, the following algorithm is used:

- i) Sample a sequence of generation states based on the failure and repair rates of the generating system units, until year k is completed;
- ii) Select the chronological load levels for that period (load uncertainties can be included if necessary);
- iii) Identify the set of ordered points in time, which can be linked to system state transitions, to define sequence y_k ;
- iv) Evaluate the generating system condition, if success or failure, for the state sequence y_k ;
- v) Identify for sequence y_k the contributions for all reliability indices, expressed by the general function G ;
- vi) Estimate $\tilde{E}[G]$ in (4.2) for all generating capacity reliability indices;
- vii) Update the overall indices and estimate their β coefficients as in (4.4). If the estimate accuracies are acceptable, than stop; otherwise, return to step (i).

Therefore, it is possible to divide and organize tasks for agents as follows:

- Sequence producer (SP) agent: task number (i) to (iii);
- State evaluator (SE) agent: task number (iv) and (v);
- Index calculator (IC) agent: task number (vi) and (vii).

Although the tasks could be divided differently, it is important to observe that this proposal provides more flexibility to run autonomous agents. All agents have their own time to work on the platform and to carry out their tasks independently from each other. However, all agents search a common sense, such as a target to achieve results in less time. The Java technology makes it possible to distribute and keep the control of the applications with flexibility and relative speed thus improving the simulation process.

Two approaches will be designed to implement the proposed MAS based reliability methodology. The first is named non-synchronized approach, which uses JADE library, and the other one is called synchronized approach, and simply uses Java technology.

4.3.4. NON-SYNCHRONIZED APPROACH

There are different ways to apply the concept of agents to the reliability evaluation. Obviously, the idea is to concentrate computationally expensive tasks on agents that can be replicated and work on a parallel sense, that is, making agents work together in different

parts of the evaluation. Monte Carlo techniques allow this kind of approach because of their inherent characteristic to produce independent blocks of information. These blocks, as it will be discussed later in this chapter, are composed of yearly sequences of system states. These sequences can be separately generated, and, in this case, the initial states of the generating units (i.e. if up or down) are sampled according to the corresponding unavailabilities. This sampling process removes possible biases in the simulation. The other option is to chronologically connect all yearly sequences y_k within those previously mentioned blocks. This is the procedure adopted in this chapter. Thus, an agent produces as many blocks of system states as necessary in order to assess the reliability indices; these blocks are sent to other agents to carry out the evaluation of the associated state sequences, and then resent to another agent to estimate the indices and check the convergence. Figure 4.3 depicts this first approach.

It can be observed that the SP agent works in the third level of the platform producing sequence of states for the system. This agent uses the other two levels: MCS tools (second level) and the power systems representation (first level). The SP agent behaves differently bearing in mind the following two major tasks: first, to generate the state sequences, and second to communicate with the SE agents. In the second task, the SP agent keeps the communication and the control of the simulation, receiving information from other agents to manage the messages sent.

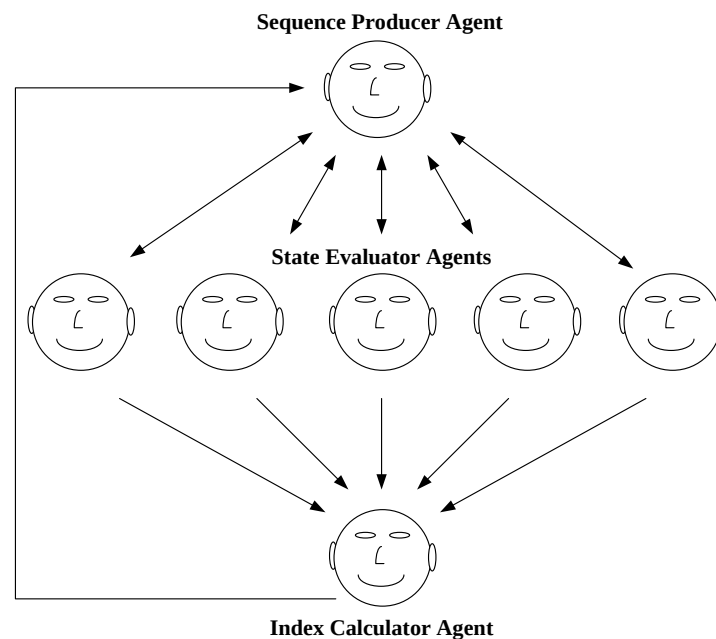


Fig. 4.3 – Agent Communication in the First Approach

Note that there is a clear concurrent process for all tasks in which the message exchanges must be minimized in order to maximize the efficiency and speed-up of the simulation process. One of the most important tasks of the SP agent is to distribute work (i.e. blocks of information through dynamic sequence matrices) to the SE agents. This important behavior ensures the complete control of the process, that is, when the SP agent sends a message to the SE agent, it receives two replies: one to confirm whether the message was sent correctly or not, and another one when the SE agent ends its task and states that it is free again to receive other dynamic sequence matrices for evaluation. Therefore, it is possible to control the availability of agents.

This approach was called non-synchronized because there are agents that end their tasks and remain idle, waiting to receive more work, thus wasting CPU time. Obviously, this means that the simulation process loses efficiency although the implementation of this non-synchronized approach is very simple. In the next sub-section, a more sophisticated approach to minimize waiting times will be presented.

In order to illustrate the importance of creating more agents for the SE, a straightforward test is carried out, where only one agent is used for each level. Table 4.1 presents the CPU time, in seconds, spent by each agent to assess generating capacity reliability indices for the IEEE-RTS [105] and BSS systems. The detail characteristics of these systems are provided in Section 4.4. As it can be observed, considering the IEEE-RTS, the CPU time spent by the SE agent is about 10 and 268 times greater, respectively, than the CPU time spent by the SP and IC agents. Considering the BSS system, these values become 23 and 877, respectively. For the RTS, 2500 years were used as the stopping criterion, which ensures a coefficient of variation (β), set for the Expected energy not-supplied (EENS) index, of approximately 5%.

Table 4.1 – Measure Average Timing Consuming Tasks (50-year sequence)

Tool	Identification	Tasks	CPU Time (s)	
			RTS	SSB
Power Agent Platform	SP Agent	1 to 3	0.3050	0.8355
	SE Agent	4 to 5	2.9424	19.1360
	IC Agent	6 to 7	0.0110	0.0218

For the BSS, the MCS stops at $\beta=5\%$ for the EENS index (i.e. 1340 years). These cases were performed in a 2.66 GHz Intel Core 2 Duo.

The convergence characteristics are not so much related with the system size, but mainly with the probability of system failure. The previous example has proved this well-known characteristic in power system reliability evaluation and, therefore, it justifies the use of more agents to act as SE to improve the simulation process efficiency. However, if necessary, one can increase the number of SP and IC agents as well.

There are other variables that should also be considered when defining the main characteristics (including the number of agents per level) of any MAS application. In this particular reliability application involving sequential MCS, the size of the dynamic matrices (i.e. hashtables [49]) being exchanged among agent levels is quite relevant. Moreover, the hardware processing capacity associated with the agents must also be taken into account. Finally, when the SP agent receives the stop signal from the IC agent, it propagates this signal for all agents and so the work is completed.

As previously mentioned, the SP agent behaves differently, as illustrated in Figure 4.4. There are three possible statuses for this agent at the beginning of its behavior. First of all, it looks for SE agents registered in the platform and verifies their availability to perform a task. If it does not find any SE agent available, the SP agent immediately enters in sleep mode, until it receives a new message from an SE agent.

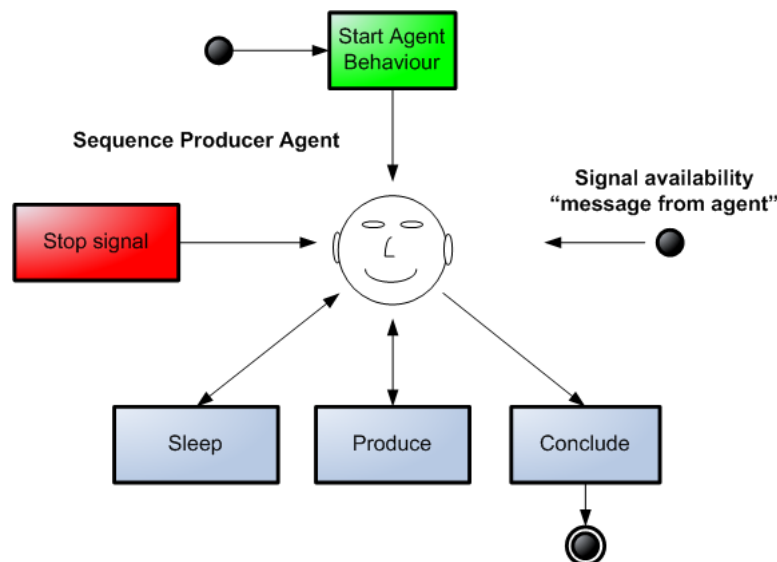


Fig. 4.4 – SP Agent Behavior: Non-synchronized Approach

Once the SP agent perceives an availability signal, it starts generating yearly sequences of states until completing a dynamic sequence matrix to be promptly sent to the available SE agent. From time to time, this process is repeated until a stop signal is sent by the IC agent. The agent behavior is built on the thread process, which is offered within the Java technology. Threads in Java are processes that run in parallel within the Java Virtual Machine [49].

4.3.5. SYNCHRONIZED APPROACH

In this sub-section, another approach to deal with the division of tasks among agents is presented. The major idea is to minimize the waiting time between generations of yearly state sequences, through better synchronized actions among agents. This will be accomplished by avoiding the use of messages for all communication processes and allowing the agents to manage their own remote calls. Figure 4.5 shows this new communication approach and includes the concept of buffer in the process: a device (computer area) that temporarily stores data that is being transferred between two machines that process data at different rates.

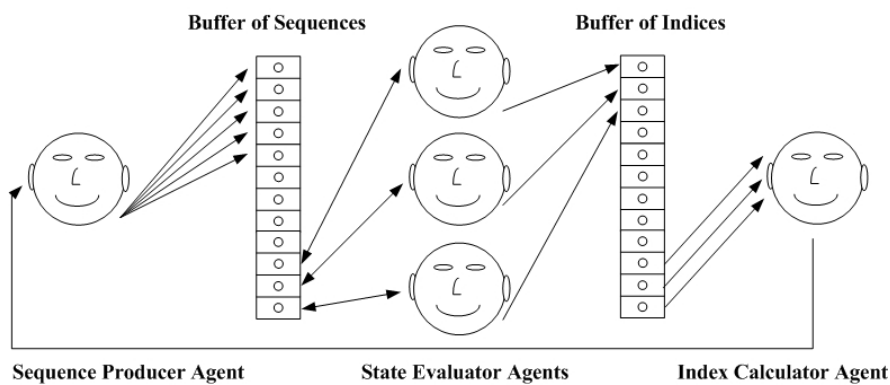


Fig. 4.5 – Agent Communication in the Second Approach

The buffer of sequences enables synchronized tasks between all agents, since the SP agent can produce its dynamic sequence matrix independently, and place it in the buffer of sequences, so any SE agent can get its tasks from this buffer. Therefore, more autonomy is being given to the agents. From Table 4.1, it is possible to observe that the SP agent is very fast and, most of the time, it ends its tasks before all SE agents. However, the use of buffers to store state sequences and index updates may lead to some known problems, such as:

- Memory heap space (buffer);
- Size of dynamic matrices (remote calls);
- Serialized network communication.

These problems can be solved using some computational procedures available in Java Technology [49]. Basically, the agents must have the ability of automatically switch to the sleep mode, every time the buffer of sequences is full. The agents should remain in this mode during a certain period of time until the buffer has been partially emptied. This ability enables the optimization of the number of SE agents that are necessary to carry out the tasks, thus reducing the waiting time. Whenever an SP agent switches to sleep mode, a new group of SE agents must come to assist with the evaluation tasks. This behavior is especially designed to provide more speed-up and efficiency to the sequential MCS process using intelligent agents.

The same principles applied to the buffer of sequences are also used for the buffer of indices. In this case, this task is simpler since only one IC agent is being shown but, as previously commented, more agents of this type can be employed. The most important task is to verify whether the estimate accuracies are acceptable or not, and send a single message to the SP agent to stop the simulation. For that, a conventional communication process (single message) is used.

It is not always possible to improve the computational efficiency simply by increasing the number of SE agents. As discussed for the non-synchronized approach, the synchronized scheme also depends on the definition of some parameters to reach its best performance. The adequate dimensioning of the buffers for sequences and indices, the close monitoring of the sleep mode time, the careful choice of agents with different processing capacity, etc. will determine the computational efficiency, together with the quality of Java programming techniques used to solve the application.

It should be observed that the number of SP and IC agents can eventually be increased to improve the overall performance. The main concern is to maximize the usage of agents with a minimum number of these agents in order to reduce the CPU time to acceptable levels.

Similarly to the non-synchronized approach, the SP agent behaves in a more complex way, as illustrated in Figure 4.6. There are also three possible statuses for this agent at the

beginning of its behavior. Here, however, the inclusion of the buffer concept allows the agent to work without looking for other agents, thus eliminating the use of messages. The SP agent can, therefore, work regardless of the SE agent availabilities.

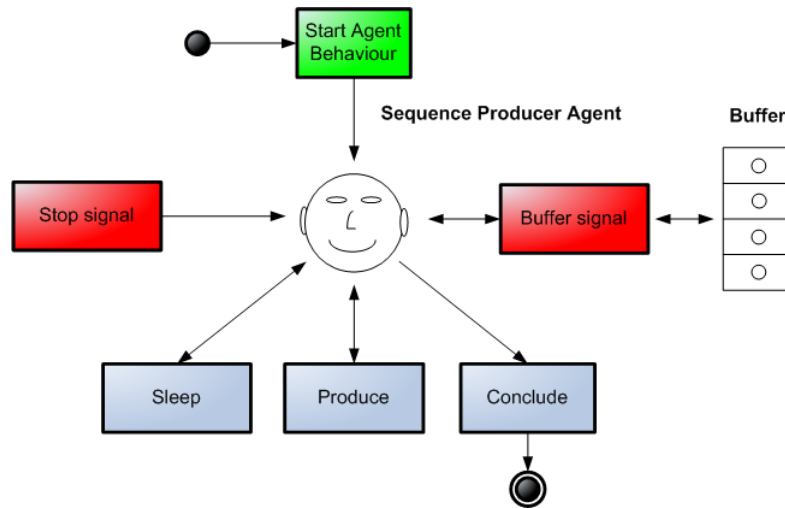


Fig. 4.6 – SP Agent Behavior: Synchronized Approach

The SP agent begins to produce the yearly sequences of states and sends them to the buffer through a dynamic sequence matrix. If the buffer has space, the SP agent keeps its status of generating sequences, until the buffer is full, and then it signals to switch the SP agent status to the sleep mode. Although this action can indicate that time is being wasted, it can also be used to wake other SE agent up. The single message used here is the stop signal, which is sent by the IC agent to conclude the simulation process.

The SP agent behavior can be called synchronized because it has more autonomy and minimizes *waiting times* for all tasks among agents. Observe that the SE agents do not need to wait for their task; they only access the buffer through a remote call and get the dynamic sequence matrices to evaluate. Finally, before switching to the conclude status, the SP agent propagates the stop signal to all agents. Undoubtedly, the synchronized approach is computationally more efficient than the non-synchronized approach, although the associated programming is indeed more complex.

4.4 RESULTS

The evaluation of the proposed MAS technology-based platform to assess generating capacity reliability indices will be verified as follows: first, the proposed sequential MCS process is applied to the IEEE-RTS [105] and the obtained results are compared with two other programming FORTRAN standards – an analytical program [67] and a chronological MCS program [75]. The basic idea is to ensure that the Java language can be used for scientific applications. This comparison is followed by two other sub-sections where the results obtained with the non-synchronized and synchronized approaches are shown and discussed.

4.4.1. JAVA ENVIRONMENT CALCULATIONS

The analytical program used is written in FORTRAN language and is based on very fast convolution techniques. It uses a generalized frequency and duration methodology, whose accuracy can be controlled by a *capacity rounding increment* (CRI), in MW, and also by a *truncation probability* (TProb) [67]. The other used program is also written in FORTRAN and has several modeling features to cope with hydrological inflows, wind power generation, etc. It is capable of evaluating all sorts of reliability indices, including those from the well-being analysis [75]. Obviously, the full potential of these two FORTRAN algorithms will not be completely exploited with the simple IEEE-RTS: 32 generating units, 3405 MW of installed capacity with a load model covering 8736 hours. However, this system is a benchmark whose results can be easily replicated.

Three indices are chosen to carry out the comparisons: LOLE = Loss of Load Expectation, EENS = Expected Energy Not Supplied, and LOLF = Loss of Load Frequency. For the analytical program, the following parameters are used: CRI = 1 MW and TProb = 10^{-16} . Considering the sequential MCS, 2500 simulated years are used in the simulation process. Table 4.2 shows the results achieved with the three tools: the analytical [67], the sequential MCS [75], both using the conventional FORTRAN language, and the sequential MCS using the Java platform. Taking the analytical results as reference, the accuracies of both sequential simulations are within the coefficient of variation related with 2500 simulated years, i.e. $\beta \cong 5\%$.

Table 4.2 – Comparison Results with Three Different Tools (IEEE-RTS)

Indices	Analytical [30]	Sequential MCS [31]	Proposed MCS-MAS
LOLE (hr/yr)	9.3942	9.4984	9.3690
EENS (MWh/yr)	1176.3	1162.3	1158.4
LOLF (occ./yr)	2.0197	2.0732	2.0388

Analytical generating capacity reliability assessment algorithms are very efficient tools from the computational point of view. However, they are based on Markovian models, which drastically reduce their ability to deal with several real applications [75]. Conversely, sequential or chronological MCS algorithms are very flexible tools, from the modeling point of view, but also very time consuming techniques. Therefore, the comparison between analytical and sequential MCS is inadequate in terms of computational effort. However, the comparison between the two sequential MCS, i.e. the one from [75] written in FORTRAN and the one proposed here written in Java language and run under a MAS platform (25-year sequence), can be done.

In this first test, to provide a better idea regarding the programming language, only one agent is used for each task. The proposed Java-based algorithm spent 241 seconds, while the FORTRAN-based algorithm spent 124 seconds. All cases were performed in a 2.4 GHz Pentium IV processor. It must be pointed out that the latter is a much more sophisticated program with several available features, when compared to the Java-based program. Moreover, FORTRAN has more efficient libraries available for scientific developments than Java. However, the performance of the proposed Java-based algorithm is very good, bearing in mind that the potential language for flexible communication was not yet explored in this example, since only one SE agent was used.

In order to assess the full potential of the proposed MAS-based algorithm, the IEEE-RTS and the BSS systems are tested considering both the non-synchronized and the synchronized approaches. The configuration used for the BSS contains 413 buses, 685 circuits and 242 generating units. The installed capacity and annual peak load are equal to 46 GW and 41 GW, respectively. This was the configuration used in planning studies during the 1990s. A typical annual curve, with 8736 levels, is used to represent the behavior of the hourly load in all system buses .

4.4.2. NON-SYNCHRONIZED APPROACH

Firstly, 15 personal computing machines, all connected in a local area network, with different processing capacities, were chosen to participate in this test. One machine was selected to act as the SP agent, up to 8 machines were chosen to work as SE agents, and one machine was also selected to perform as the IC agent. The generation of yearly sequences varied in sizes of 25, 50, 75 and 100 years. Figure 4.7 shows sensitivity tests for the IEEE-RTS, considering these parameter variations, i.e. the number of SP agents and the sequence sizes.

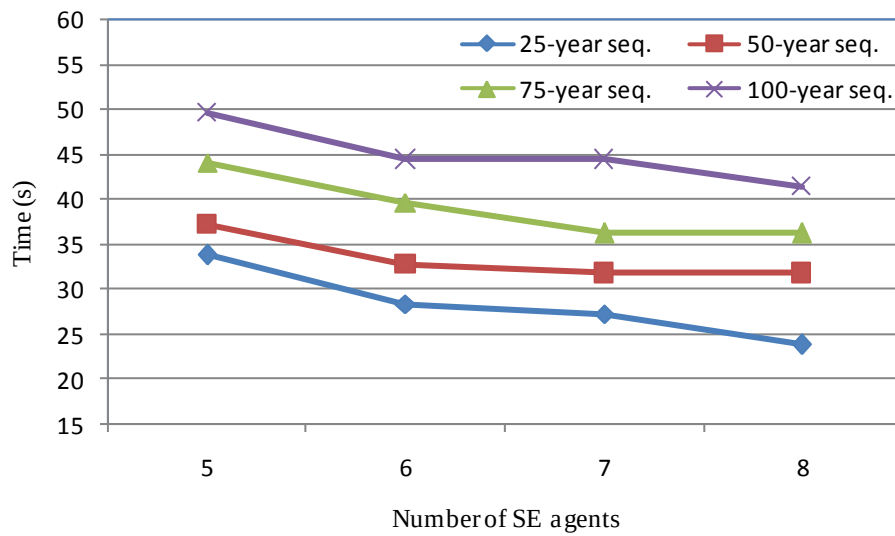


Fig. 4.7 – Non-synchronized Approach: Sensitivity Tests (IEEE-RTS)

As it can be observed, the overall CPU times range between 23 and 50 seconds, depending on the number of SE agents and on the size of the sequences sent by the SP agent. Moreover, in all cases the CPU times saturate in a narrower range between 23 and 42 seconds. It can be concluded that it is not worth increasing the number of SE agents beyond a certain number. In a Java environment, the relationship between producers (i.e. SP agent) and consumers (i.e. SE agents) is extremely important in order to reach the best computational benefits [49]. Clearly, two explanations can be given for the observed saturation. First, the SP agent is running with full capacity, generating state sequences without ever entering the sleep mode. This condition can only be improved if more SP agents are provided to the proposed MAS-based framework. The second reason is that the relationship between producer and consumer is not sufficiently organized, for instance, due

to the excessive number of message exchanges, which can be minimized by the use of the proposed synchronized approach to be shown in the next sub-section.

Considering 8 SE agents and a 25-year sequence, it can be observed in Table 4.3 that the total CPU times to assess the reliability indices are 23.8 seconds and 79.7 seconds for the IEEE-RTS and BSS systems, respectively. These values can be compared with those obtained with one SE agent only, also shown in Table 4.3. From these results, it is possible to evaluate the speed-up (S_U) and the computational efficiency (η), expressing the use of computing resources, as compared to an ideal case of optimal performance [106]. For these systems:

IEEE-RTS $\Rightarrow S_U \cong 10.1$ and $\eta \cong 71.2\%$, BSS $\Rightarrow S_U \cong 9.86$ and $\eta \cong 72.7\%$.

Table 4.3 – Comparison of CPU Time (25-year sequence)

Approach	No. of SE Agents	IEEE-RTS Time (s)	BSS Time (s)
Sequential	1	241	786.4
Non-synchronized	8	23.8	79.7
Synchronized	8	17.2	58.1

4.4.3. SYNCHRONIZED APPROACH

The MAS technology was initially based on the distributed computation concept and uses TCP/IP protocol, which does not allow fast remote call or fast interchange message. There are other communication techniques that enable fast communication, or improve efficient remote call between computers, e.g. Java RMI (Remote Method Invocation) [107]. Java RMI enables the programmer to create distributed Java technology-based to Java technology-based applications, in which the methods of remote Java objects can be invoked from other Java virtual machines, possibly on different hosts. RMI uses object serialization to marshal and *unmarshal* parameters and does not truncate types, supporting true object-oriented polymorphism. Therefore, the proposed synchronized approach was designed using this technology.

Considering the same 15 machines used with the non-synchronized approach, Figure 4.8 shows the same sensitivity performance tests using the synchronized approach. As it can be observed, the overall CPU times range between 15 and 50 seconds, depending on the number of SE agents and on the size of the sequences sent by the SP agent. Moreover, in all cases, the CPU times start saturating in a narrower range between 15 and 32 seconds. Clearly, it can be noted that the saturation point is shifted to 8 SE agents, as compared to the non-synchronized case. This proves the benefits of the buffers and the use of a more appropriate Java environment.

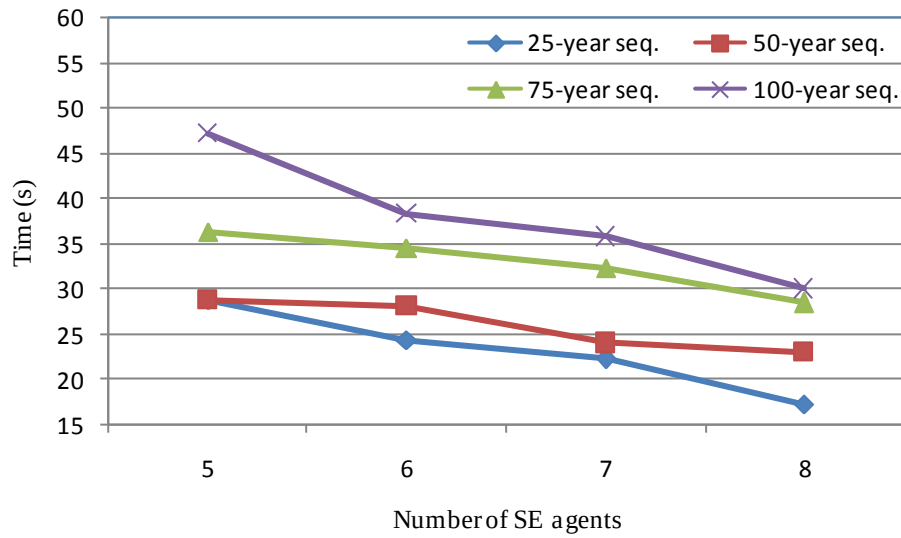


Fig. 4.8 – Synchronized Approach: Sensitivity Tests (IEEE-RTS)

Considering 8 SE agents and a 25-year sequence, it can be observed in Table 4.3 that the total CPU times to assess the reliability indices are 17.2 seconds and 58.1 seconds for the IEEE-RTS and BSS systems, respectively. For these conditions, the speed-up and efficiency performance indices are as follows: IEEE-RTS $\Rightarrow S_U \cong 14.0$ and $\eta \cong 98.8\%$, BSS $\Rightarrow S_U \cong 13.5$ and $\eta \cong 99.7\%$. Therefore, the speed-up and efficiency depend on the sequence size, on the number of agents per level and on the computational power of the involved processors.

4.5 FINAL REMARKS

Power systems analysis is known as a research subject strongly linked to computation and mathematical areas, but extremely rigid to change concepts and tools, particularly those

related with programming paradigms. Bearing this aspect in mind, this chapter presented a new way to address one typical power system problem, the generating capacity reliability assessment, using MAS technology. It was proved that is possible to use this technology to achieve very good results based on two structures: non-synchronized and synchronized. Although the first one is very simple to handle, the latter usually achieves higher computing performance. However, there are several aspects related with the MAS environment that should be taken into account: organization of tasks, number of agents per task, size of the local network, information exchange, among others. The results were achieved using regular computers, that is, personal computers used every day and linked to conventional networks, commonly used in power system utilities.

The computational requirements showed in Chapter 3 revealed a huge amount of simulation time to assess reliability indices. On the other hand, the gains achieved in this Chapter 4 can represent an alternative to improve power computational tools when more detailed representations are needed. A simpler extrapolation could be made in cases such as the Spanish and Portuguese systems presented in Chapter 3, where the computational time may decrease approximately from 554 minutes to 39.6 minutes and 29 minutes to 2.1 minutes, respectively (see Table 3.6 in Chapter 3), through the use of proposed MAS-based Platform.

The MAS technology is very attractive since it merges artificial intelligence and distributed computation areas in a simple way. This technology is ready to be applied to complex power system evaluations, and can achieve good results due to its main characteristic: communication flexibility. Java environment offers several features, including the possibility to encapsulate programs/codes written in other languages (e.g. FORTRAN or C). Thus, there should be no concern among power system researchers and engineers that well tested programs will have to be rewritten. Moreover, other methods to improve computational efficiency, such as variance reduction techniques usually used in problems involving MCS, can be easily established in this new framework.

The extension of the proposed methodology to other power reliability problems or applications involving population-based heuristics is almost straightforward and will be explored in the next chapters. This thesis opens the way to build models where more intelligence is added to the agents, so that they may autonomously organize themselves to manage the computational efficiency and speed-up better.

Chapter 5

INTELLIGENT AGENT-BASED

ENVIRONMENT TO COORDINATE

MAINTENANCE SCHEDULE DISCUSSIONS

5.1 INTRODUCTION

Modern software and technological systems that are able to manage themselves have been part of the vision for computer science and engineering applications for a long time. Nowadays, multi-agent systems have offered strong models to represent complex and dynamic real-world environments in order to help users and/or to improve life quality [38].

Many works have introduced multi-agent systems (MAS) in the electrical power industry [95-96], [108-109], mainly due to a suitable ability in which programs and humans can interact naturally, promoting hybrid systems. In the last ten years, paradigm changes in the electrical power industry have led to changing responsibilities of the power players. Complexities in the information management, as well as conflicting decisions involving different interests, were introduced to the deregulated power systems environment, so as to do some specific analyses, whereas the examination of alternative security-economy decisions became a complex and stressful activity performed by the transmission systems operator (TSO). Agent-based systems not only span a range of specific techniques and algorithms for dealing with dynamic interactions in open environments, but they are also adequate for some complex human discussions in order to achieve their major goals. This technology is ready and has shown an important penetration in the power systems industry [98-100] to support many kinds of conflicts.

Maintenance decisions in electricity markets are one of the most important strategic conflicts among power players. For instance, a generation company (Gencos players) is a self-interested entity responsible for its own risk-based maintenance outage scheduling [110]. On the other hand, for large equipment supplying many customers, it is the TSO's task to schedule the most suitable period for maintenance, and thus preserve the system reliability [111]. This relationship is sometimes conflicting and can be seen as an obstacle to Genco ability to maximize profit, as well as to the TSO capacity to keep the suitable risk-based level on the overall system. In some countries, independent entities designated as Independent System Operator (ISO) coordinate the activities that involve generation, transmission and distribution companies. In this chapter, the attention is focused on this relationship. Moreover, it highlights the proposal of building a dedicated environment in order to improve and clarify the discussions on maintenance outage schedule for large equipments, using the agent-based technology. An important change in this relationship is to take the TSO maintenance outage schedule decision or the ISO tasks, using distributed

features offered by agent-based technology, which promote them as a facilitator transmission system operator (FTSO) or facilitator independent system operator (FISO). This process ought to be transparent, that is, a process in which no individual company (player) can be treated unfairly. Today, when the ISO receives the outage requests for maintenance from the players, a decision is centralized and it should review all submissions of planned outages based on security criteria, and be able to make decisions on whether to permit, deny, or adjust planned outage schedules in order to preserve the system security [111-112]. Generally, the criteria for this decision include: the effect of maintenance outage on the system and customer reliability; the cost incurred and the revenue lost due to the outage; some economic reasons; and the risk of postponing maintenance until the designated time [111]. This is a combinatorial problem that involves several constraints and many players with their own interests. The ISO is not directly responsible for minimizing potential players' financial risks, but sometimes its decisions can affect any player indirectly.

In order to propose a way to improve this relationship, this chapter has proposed the establishment of an environment based on MAS, where the players can interact with each other under the supervision of FISO, and can achieve the most appropriate maintenance schedule. In this distributed computational environment, FISO makes a suitable reliability tool available, as well as enough data for any player to assess the power system reliability during discussions, taking some week risk-based standards into account and providing guidance to players so that they can achieve the most appropriate maintenance schedule.

Although this thesis has used a generation company to show the advantages of this computational environment, this approach can be easily extended to all market participants, such as transmission companies (Trancos), distribution companies (Discos), and other important entities.

The next sections will consider several relevant topics, such as the review about the unit maintenance scheduling problem along the years; multi-agent systems applied to the power industry; a brief description of the developed computational system and its requirements will also be included, as well as some results involving IEEE-RTS system in order to show the proposed methodology; and finally some results involving a fictional configuration of the Portuguese and Spanish Systems, under several uncertainties with high penetration of renewable power plants. The discussion and results involving those systems do not

constitute a real situation with realistic players, and therefore it must be seen as a comprehensive example that places green power as a relevant rule.

5.2 UNIT MAINTENANCE SCHEDULING PROBLEM

In the past, the practices of electrical utilities meant to centralize plans and coordinate maintenance scheduling mainly for large equipments. For generators, maintenance was carried out during low-load seasons and the duration of scheduling outage was influenced by crucial considerations, such as the risk-based level to the system and production costs.

Nowadays, in a deregulated scenario, unit maintenance scheduling has not been planned to centralize, even though it needs to be coordinated through the centralized operation. As mentioned before, the ISO receives a request for maintenance and it ought to be able to make a decision. Nevertheless, generator owners always want to keep the units running when the market prices are high, and to perform maintenance only when the market prices are low. Furthermore, they may wish to maximize sales energy and ancillary services, offering their products (energy and others) in a neighboring control area in which periods of high load, and consequently high prices, differ from those in their own geographical location [113]. Under these circumstances, the generator owners may tend to adopt an aggressive maintenance policy, leading the unit generator until the maximum performance. This decision might increase the number of requests for emergency maintenance, and make it difficult to plan and coordinate a specific schedule for generator outages by ISO. However, it may also lead generator owners to invest in maintenance policies in accordance with the adequate unit generator risk-based level in order to preserve their assets. Although this chapter does not explore maintenance policies, it is imperative to mention some strategies used by the generator owners who use agent-based applications in this area. Some relevant works have explored policies that essentially place maximum asset performance as a major goal for electric power system managers [114], and conducting the maintenance decisions through the use of some heuristics procedures [115]. A complete review about maintenance policies can be found in [116].

5.2.1. CONVENTIONAL MAINTENANCE SCHEDULING OF GENERATION UNITS

The general purpose of conventional generating units maintenance scheduling is to determine the time and sequence of generating unit outages that represent the best assignment of these equipment to maintenance periods in a given time horizon, in such way that the reliability of the system is maximized [111]. Regardless of the scenario, deregulated or not, the main objective of generating units maintenance scheduling remains the same, and perhaps this problem has been one of the most complex ones in power systems due to the astronomical number of possible schedules, as well as to the complexity of the constraints and objectives involved [117]. During the last years, different approaches have been used to solve this combinatorial problem. They have shown that, in general, the most attractive and promising optimization approach applied to this problem was integer programming, even though the heuristic procedures could achieve good results with accomplished CPU time. One major research [111], [117] has been proposed in order to ensure reliability. The ISO could consider several heuristic procedures, as well as some reliability indices such as LOLP (Loss of Load Probability) or EENS (Expected Energy Not Supplied) to assess each schedule. This work also sought to provide an answer to the question of how a certain chronological sequence of schedule could cause an impact on the system reliability, considering economic implications. In this sense, it is interesting to search the best assignment of units. This requires a visit plenty of unit combinations and an assessment on the reliability impact of the system on each of the unit combinations. The great contribution of this work was to build a suitable composite reliability tool considering several heuristic procedures in order to maximize reliability and revenue, covering the lack of researches in this area.

For the last years, the maintenance schedule problem has been incorporating new concepts following the changes in the power industry, such as the deregulated market environment and high penetration by renewable sources.

5.2.2. STRATEGIC MAINTENANCE SCHEDULING OF GENERATION UNITS

In some competitive market environments, the maintenance scheduling of generating units can be considered as one of the most prominent strategies used by Gencos to maximize their market profit [118]. They generally intend to minimize potential financial risks when

planning outages to maintenance and this information might be an important input for market players [110]. A few years ago, strategic maintenance decisions by any Gencos in Australia and Canada [118] showed the real importance of scheduling of generating units in a competition environment. Generator owners have alleged the needs of carrying out the maintenance of major units during high demand periods which led to sustained high spot price events in these markets [119]. These strategic maintenance decisions have been used to manipulate market energy prices through capacity withdrawal and to prove their importance in deregulated environments. This is bound to happen since in some competitive markets around the world, the corresponding rules provide independence to Gencos plans outages, and the coordination of outage generally involves multiple interactions between generator owners (market participant), ISO, and other relevant entities [120-121].

With the coordination processes, it is possible to understand how ISO adjusts certain maintenance scheduling of generation units and how each Genco responds to the adjusted schedule change. The conventional maintenance schedule problem became a strategic dilemma, and there is no efficient procedure either to compute the solution, or to allow the transparent discussions for the most appropriate maintenance schedules.

5.2.3. MAINTENANCE SCHEDULE WITH RENEWABLE GENERATION

Presently, the power system is undergoing a considerable change due to the appearance of new concepts concerning green electricity production. Besides the ordinary uncertainties around the strategic maintenance schedule problem (such as load forecasting, fuel prices and maintenance costs, maintenance crew availability, market forces and its competition, and others), the ISO needs to manage a power generation plant with high participation of renewable sources in the total production, such as wind power, solar thermal and photovoltaic, biomass, some cogeneration, and other renewable sources in the nearest future, such as geothermal and ocean energies. These green sources bring with them an amount of others uncertainties, such as wind and solar power volatility production with intermittent behavior, seasonable cogeneration and others. These uncertainties make it difficult to coordinate an entire maintenance schedule requirement in the new power system environment.

The previous concerns put ISOs under a huge pressure to come up with appropriate maintenance schedule solutions bearing these new technologies in mind. As can be seen, the number of random variables and system complexities increases greatly when renewable energy sources are added to the system, mainly due to the fluctuating capacity levels of these sources [122]. At the present time, there are few works in the literature that have paid much attention to the maintenance schedule problem considering renewable sources.

5.3 MULTI-AGENT SYSTEMS IN THE ELECTRICAL POWER INDUSTRY

There are several distinct research areas applying agent-based features to solve a variety of problems. The entrance door to MAS in the electrical power industry is strongly linked to information technology (IT), which has been widely used in the power industry over the last fifteen years [109]. The concept of *autonomous system* found a direct application over the IT and Condition Monitoring infrastructure used by the power industry to monitor and control substations, transformers, circuit breakers, and others. Major researches applying agent-based and condition monitoring techniques have explored agent concepts, such as self-organization, interaction, cooperation, communication, and others [123-125]. Another important issue that has contributed to the introduction of distributed intelligent concepts in the power industry was the growing use of internet web services and their agilities in power applications [108]. Recently, two important contributions have organized the concepts, approaches, technical challenges, technologies, standards, and tools for building MAS applied to power engineering [95-96]. Many aspects were discussed regarding the benefits of this technology, and guidance and information on the state-of-the-art of MAS research for the power industry were also provided. Some favored issues in power agent applications have been indicated: modeling, simulation and distributed control. In addition, some recent concepts have been used to fulfill online diagnostics and equipment predictive maintenance based on the e-maintenance concept [126-127].

5.3.1 AGENT-BASED, CONDITION MONITORING AND E-MAINTENANCE

The basic goal of all maintenance policies is to prevent or forestall future random failures of the system by removing equipments from service at an appropriate time, providing unexpected zero-downtime [112], [116]. Based on this concept, the generator owners have been done investments in preventive or predictive maintenance policies using condition

monitoring techniques, agent-based and web service technology to keep the maximum control over the equipment [127-128]. Preventive maintenance deeply depends on the information obtained from condition monitoring. Currently, many developments offer various condition monitoring techniques which affect the existing maintenance policies directly (or indirectly). Data acquisition systems, signal processing techniques, experts systems, e-maintenance and web applications make the condition monitoring much more attractive, and accurate as well [125]. In order to integrate all the mentioned issues within the condition monitoring techniques, agent-based technology offers an interaction level that includes coordination abilities. Coordination is defined in many ways, but in its simplest form it refers to the capacity of ensuring that the actions of independent agents (actors) are in some way coherent in an environment. Maintenance policies can be seen as coordination actions that enable better decisions on maintenance schemes.

5.3.2. AGENT-BASED TECHNOLOGY IN CONFLICT SOLUTIONS

Generally, researchers use agent-based technology to represent real world situations through the use of a computational simulation process, where agents can interact with each other to find a common sense that is sometimes understood as a solution in such representation. Typically, in these environments agents have conflicting goals. In such circumstances, agents will negotiate with each other in order to resolve conflicts.

As mentioned before, the power industry has plenty of situations in accordance with these characteristics. In a traditional approach, power engineers seek to solve such situations using mathematical programming, which sometimes can capture a partial characteristic of the problem without considering all constraints, perhaps due to the lack of complete models, or due to the complex nature of such problems. In order to address some specific situations in the power industry, researchers were encouraged to use multi-agent negotiation systems in the same sense as that of the mathematical programming, considering its distinct advantage, which has to do with the fact that it works in a distributed decision-making environment in accordance with the actual situation of power industry [109], [129-130]. In general, several negotiation techniques may also provide a low level of agent reasoning to solve simpler conflicts. Reasoning is a critical faculty of agents that account for the reason why implementing multi-agent systems is a complex task [31].

5.4 PROPOSED METHODOLOGY

Regardless of which are the market participant (power players) obligations, each one has its individual goals. Some researchers have approached the individual strategy to Genco in order to maximize profits [110], [118-119]. In a real market, the relationship among players can be seen as a competitive relationship, where the market forces drive prices of energy and services throughout the competitive behavior of their players. In order to clarify this relationship in a real market and show the proposal of this research work, a general view on market rules for system reliability has been presented [120], [131]. The summary of the market rules regarding the planned outage schedules during ordinary operational procedures is as follows:

- i. Each market participant shall inform the ISO of its long-term plans for outages. The participant will establish its outage planning process in a way that will make it possible to comply with its reporting and scheduling obligations. A planned outage submitted by a market participant shall represent its intent to take the relevant equipment out of service during the scheduled period;
- ii. ISO shall coordinate maintenance outages with the market participants. It is the responsible for approving, denying, or adjusting all requests related to planned outage submitted by the market participants;
- iii. No market participant shall remove equipment or facilities from the service except in accordance with ISO, unless such removal from service is necessary for safety reasons;
- iv. When the scheduling of planned outages submitted by different market participant conflicts such that the planned outages cannot both or all be approved by the ISO, it shall inform the affected market participants and request that they should resolve the conflict. Should the conflict remain unresolved, the ISO shall determine which of the planned outages can be approved;
- v. Each market participant shall notify the ISO in advance of a forced outage and provide a brief description of the nature and causes of the forced outage;
- vi. ISO shall maintain a database of all submissions to the outage planning and scheduling process.

There are other important issues within the market rules that must be taken under consideration since they may complicate this relationship. It is fundamental to refer the extension or re-scheduling requests, the replacement of energy to support planned outages, as well as other factors. But essentially, these six steps represent the ordinary relations between ISO and players. In order to improve this relationship and treat each interest separately, a recent research work proposes a coordinating mechanism based on incentives/disincentives between producers and ISO, which allows both to pursue their goals [121].

Nevertheless, the process is still obscure, and no player knows exactly the involved criteria and uncertainties that were considered for the established system reliability target. An important issue in markets is to clarify rules and constraints for all participants. Following this concept, this thesis proposes an open environment based on agent technology where ISO and players can discuss planned outages, knowing the risk-based level established for the system reliability and the impact of each respective player plan on the customer reliability. This knowledge will be used to find the best assignment to maintenance schedule, allowing players to pursue maximum profits without manipulating capacity withdrawal. It is important to highlight that the proposal does not intend to change currently used market rules, but to improve and clarify the use of these rules.

5.4.1. INTELLIGENT AGENT-BASED ENVIRONMENT TO COORDINATE MAINTENANCE SCHEDULE DISCUSSIONS

First, it has been proposed that the previously mentioned market rules should be rewritten, without changing the meanings or interpretations. The main goal of this proposal is to take the maintenance schedule decision of the ISO task and divide the impact of the players' plan on the system reliability among all participants, without mitigating competitive player behavior. Obviously, the ISO remains ahead of the decisions, but it is promoted to the FISO, whereby it assumes other behavior. The proposal follows the same conceptual algorithm (structure) presented before to the market rules:

- i. A MAS environment can represent the appropriate place to discuss maintenance outage scheduling between the FISO agent and the market participant agents;
- ii. FISO shall promote a long-term weekly loadability analysis (one year), considering all available market participants, in order to determine if the portion of the

- withdrawal capacity is safe to the system reliability, compiling some basic standards indices per week, month and year;
- iii. FISO shall inform all market participants of the respective withdrawal capacity per week and make the suitable tool available to assess system reliability for all market participants;
 - iv. Each market participant shall promote its own reliability study, seeking to measure the impact of its own planned outage on system and customer reliability, verifying whether its intents are practicable or not according to the previously determined safety capacity withdrawal, and its profit target;
 - v. Each market participant shall inform the FISO of its long-term plans for outages (one year). The market participant will establish its outage planning process in a way that will enable it to comply with its reporting and scheduling obligations. A planned outage submitted by a market participant shall represent the intent of the market participant to take the relevant equipment out of service at the scheduled time;
 - vi. FISO shall coordinate maintenance outages with market participants. FISO is responsible for identifying conflicts among maintenance outage intents and it shall inform the affected market participants. Moreover, FISO shall request that they solve the conflict using the open environment and the available reliability tool to find a suitable solution;
 - vii. Each market participant can adopt its own agent strategy to negotiate a place in the conflicting maintenance outage scheduling;
 - viii. Should the conflict remain unresolved, the FISO shall determine which of the planned outages can be approved, using its own criteria;
 - ix. FISO is the responsible for approving, denying or suggesting adjustments for all requests related to planned outage submitted by the market participants inside the appropriate environment;
 - x. Each market participant shall notify FISO in advance regarding forced outages and provide a brief description of the nature and causes of the forced outage;
 - xi. FISO shall maintain a database of all submissions to the outage planning and scheduling process;

As it is possible to observe, the market rules were naturally introduced in a conceptual MAS environment, creating an appropriate model to improve and clarify a maintenance discussion and the actions of all participants. In the following point, a brief description of the computational environment will be presented, as well as a MAS built to discuss maintenance schedule.

5.4.2. MULTI-AGENT COMPUTATIONAL ENVIRONMENT

Despite all the number of languages, frameworks, developed environments and platforms that have appeared in the literature, implementing multi-agent systems is still a complex task [38]. In the Java world, there is a variety of environments to help developers build agents based on features offered by Java language [50-55]. In this chapter, the IBM ABLE environment was used [44], [50] to build intelligent agents. ABLE (*Agent Building and Learning environment*) offers a set of reusable Java Bean components, called *AbleBean*, along with several flexible interconnection methods to combine those components and thus create software agents [49-50]. Furthermore, ABLE have used Knowledge Query and Manipulation Language (KQML) to promote communications among agents inside the platform. KQML provides the bases for the most widely used agent communication language (ACL), and over the last years it has been extended, modified, and standardized by FIPA [43]. Agents use KQML in order to send performatives to indicate the action that another agent should take on its behalf. Another important meaning of the KQML is that it uses ontologies to ensure that two agents communicating in the same language can correctly interpret statements in that language. The main reason for the choice of ABLE is based on the fact that it works with Java Bean technology, which allows developers to reap the benefits of rapid application development in Java by assembling predefined software components.

Following the same concept used in electronic markets, the proposal application is an intelligent agent maintenance discussion place in which market participant agents cooperate and compete to process maintenance schedule priorities for their owners. The FISO agent is developed to act as a manager for the maintenance discussion place, where it provides a suitable tool and reliability standards (information) to the market participants, leading the negotiations among them. Market participants use forward-chaining inference

cycle in their negotiation strategies. All of these developed agents follow the ABLE specifications and are derived from the ABLE classes [50].

FISO may open the maintenance discussion place for two distinct negotiations:

- a. Long-term planning negotiations;
 - b. Short-term planning negotiations (Emergency).
- a. In the long-term planning negotiations, the market participants negotiate appropriate scheduling outages, pursuing their own goals, which include obligations to the system and customer reliability. In this kind of negotiation, FISO makes some information available to all market participants (as the conceptual algorithm presented before), and each one of them promotes its own maintenance schedule outage plan, returning their wishes to the FISO. FISO makes the results of the individual plan combination available and presents a report identifying conflict points and the respective market participants involved. At this moment, FISO opens the maintenance discussion place, where each market participant can interact with its opponents under the supervision of the FISO.

Most of the time, the best decision for maintenance schedule outage indicates a combination plan with the smallest number of equipment on maintenance [111]. Usually, this decision is strongly linked to acceptable costs that are a function of production costs, interruption costs, maintenance costs and revenue lost by the utilities [117]. The costs incurred for maintenance procedures are an extremely important characteristic of this complex problem, and must be incorporated as a criterion to the ISO strategy. In order to improve the system reliability and promote an optimized maintenance schedule, FISO assumes its own strategy and informs all market participants of the priorities established during the individual plan combination assessment. Such strategy can be described as follows:

“Among all possibilities of presented maintenance requests, FISO will give priority to the one with the maximum number of components and/or capacity on maintenance that incurred in minimum impact of the system and costumer security (reliability), as well as with acceptable costs”.

In fact, to minimizing reliability and its related costs from maintenance procedures is a hard task to any coordination mechanism. The system security or reliability are also a function of the system load level, and therefore, there will be some periods (weeks) in which certain equipment removals are acceptable, considering the technical point of view, but unacceptable for economic implications. On the other hand, some economic issues may be suitable for the ISO and players, but the equipment removals lead to the violation of the technical risk criterion. The balance between the system security criterion and cost implications was explored in some works [111], [117], [121], where each maintenance request is assessed considering both implications: (i) acceptable costs; (ii) and maximum number of equipment/elements on outage. In order to promote an appropriate coordinating mechanism that allows a balance between security and costs, this chapter follows the same concepts proposed in [111] and [117]. However, the discussions on prices and costs incurred due to maintenance procedures are not the purpose of Chapter 5.

In this sense, FISO books a range of positions for all market participants and defines who needs to advertise their desire to negotiate or change priorities, and who the owner of each schedule priority is. The idea of FISO is to promote a fair range of priorities, establishing advantages for the market participant who shows the best assignment to the large equipments, in accordance with the above mentioned FISO maintenance strategy and their market obligations. When two or more market participants are drawn, FISO may use a specific strategy to define priorities.

- b. In short-term planning negotiation, the market participants have the chance to modify priorities in accordance with their needs, buying or selling maintenance priorities; promoting a new scheme of planned outage during the current year; and preserving the FISO strategy. Sometimes, when FISO receives an emergency maintenance request, the request must be classified into four categories: immediate emergency, next day emergency, next weekend emergency or some other time. FISO may decide to open the maintenance discussion place, for short-term planning, in order to accommodate some emergency requests, or due to the large number of forced outages, which will make the long-term plan impracticable.

Regardless of the negotiation type, when FISO opens the maintenance discussion place, all market participant agents must register with FISO before they can interact with any other market participant agent in the market discussion place.

There are several graphic users interface (GUI) available to support agent discussions in Java. Following ABLE specifications, the application proposal has been using ABLE Market Place Frame [50] to display messages from FISO and market participant agents. Figure 5.1 shows the main GUI used in maintenance discussion place, where a suitable reliability tool was incorporated in order to make it possible for users to perform reliability studies.

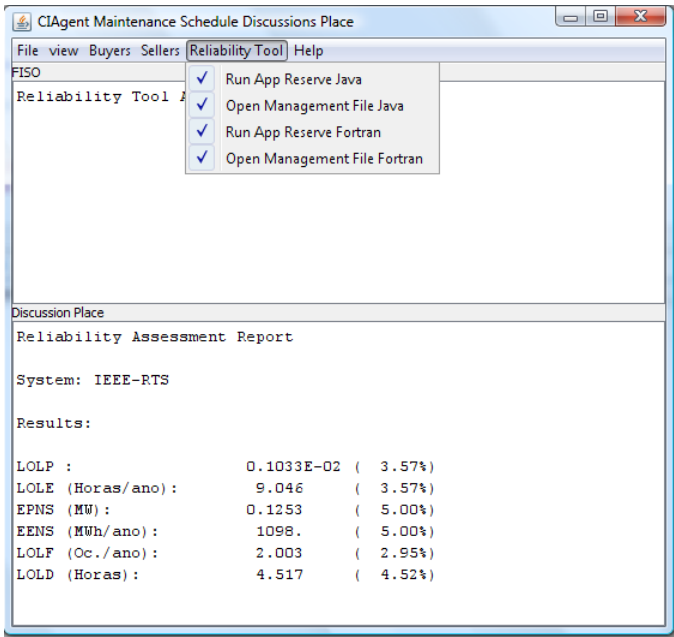


Fig. 5.1 – GUI for the Maintenance Discussion Place

An important aspect related to the GUI choice lies in the use of the Singleton design pattern [50], which ensures that only a single instance of maintenance discussion place and consequently FISO, takes place at one time, and prevents frauds on this application.

5.4.3. FISO – FACILITATOR INDEPENDENT SYSTEM OPERATOR

Generally, in real electronic markets, agents act autonomously on behalf of their users, assuming a direct approach where each agent interacts directly with its opponent. The use of a facilitator agent (FISO), which acts as an intermediary between all market participant agents, has been proposed in this application. Such decision ensures that all market entities

with system reliability and costumer obligations will participate in the maintenance schedule decisions, and will take it off the ISO's tasks. After being informed of the range of priorities by FISO, each market participant can interact with its opponent using the maintenance discussion place area, available in the maintenance discussion frame presented in Figure 5.1. This area is totally dedicated to monitoring agent discussions, without intervention by FISO. FISO appears only when the conflict ends, and the market participant agents present a solution or when the market participant agents present some difficulties.

When the maintenance discussion place opens, FISO uses a hashtable to register all conflicts and their involved market participant agents, in order to control FISO activities. FISO has implemented Java Runnable interface that uses the threads process, which is the mechanism used to give *autonomy* to the FISO agent. After that, FISO waits for the market participant agents to register their intention of negotiating, and so the negotiations begin. At each 10 seconds, it wakes up and verifies the arguments for each conflict. When all market participant agents achieve an agreement, they inform FISO using messages and change conflict arguments within the hashtable. At this moment, FISO is able to declare and publish the achieved maintenance schedule solution.

5.4.4. MARKET PARTICIPANT AGENT

In this section, a brief description of market participant agents will be provided, anticipating some of the possible interactions within maintenance discussion place. Some definitions, such as types of performatives and negotiation details will be better defined in the following sections. Based on the Rule Class offered by ABLE, which implements reasoning algorithms [50], our market participant agent is able to act as a *negotiator* of priorities, and its behavior will depend on the position established by the FISO during the combination assessment of individual plans. In this chapter three different negotiation strategies have been explored for each kind of market participant agent. ABLE marketplace offers a basic, better and best negotiation strategy in the marketplace and it has been used to illustrate our proposal. Otherwise, each market participant agent can simply assume a satisfaction position in the first maintenance schedule proposed by FISO, and does not show any negotiating intention. There are plenty of arbitrary decisions that can represent the behaviors of the market participant agent. The design chosen for this

application tries to simplify those behaviors in order to easily show the potentialities of this technology in solving conflicts.

One of the most important data members (attribute) of the market participant agent is its wish list, which contains the intentions of their owners. These intentions are stored in a vector and are part of the necessary data to compose a working memory during the inference process or negotiations.

When the FISO opens the maintenance discussion place, it waits for *negotiators* to show the intention of negotiating their priorities. Basically, the *negotiator* wishes will be registered in a hashtable and other market participant agent will be recommended to negotiate. Next, both opponents will be presented and start the negotiation protocol using the maintenance discussion area. The *negotiator*, who has the advantage, waits for an offer sent by its opponent. This offer will contain performatives that will indicate the intention of this *negotiator*. In this chapter, the performatives that contain the buy or sell intention priorities have been explored. A set of dedicated performatives and a special ontology might be developed for maintenance discussions in order to improve this environment. At this moment, the market participant agent will verify the wish list and make a decision: if the offer contains an intention to buy, the market participant agent will assess the offered price and other schedule options to cover its own needs, and replay whether the offer will be accepted or not. As mentioned before, the three different negotiation strategies that were explored will be discussed in more detail in the next section. This first approach represents the basic strategy negotiation, where the market participant agent only checks its wish list and tries to achieve the goal intended by its owners. During the process, the market participant agent can assess the reliability tool available in maintenance discussion place, so as to assess other maintenance schedule options and keep the FISO strategy.

5.5 RELIABILITY TOOL DESCRIPTION

Due to its chronological nature, the maintenance schedule problem requires models and tools that are capable of keeping track of all time correlations during the system reliability assessment. In hydrothermal systems, it is necessary to consider the dynamics of the reservoir system and the uncertainty of water inflows. Additional difficulties arise when it is necessary to consider renewable sources with high participation in the total production.

In these cases, the number of random variables and system complexities increase greatly, whereby ISOs experiment a huge pressure to settle on time sequences for large equipment outages, bearing in mind the effects of these new technologies in the overall system reliability. Hence, finding out the best unit maintenance schedule is now even more complex than in the past.

Currently, the sequential MCS for reliability power system assessment is the best realistic option available to study time-dependent aspects [71]. Details on the MC method and the implementation of this tool can be found in Chapters 3 and 4, where all these models for thermal, hydro, wind, mini-hydro and cogeneration units are described. With the purpose of assessing the impact of each maintenance request on the overall system reliability, the market participant and FISO agents have used this tool together, sharing responsibilities about the system and costumer reliability. In this chapter, two computational approaches were used to demonstrate the potentialities of MAS technology developed in Java. The first one uses a power agent platform developed in Chapter 4, where the tool is coded entirely in Java language in order to facilitate the integration into maintenance discussion place environment. This integration intends to explore the previously achieved efficiency simulation in order to promote fast answers to the maintenance discussion place users. The latter employs a powerful tool developed entirely in FORTRAN language, which is encapsulated into the maintenance discussion place through the use of flexible features offered by Java technology. Both are prepared to display annual, monthly and weekly reliability indices and to follow the same concept developed in [111], [117] in order to assess the reliability impact of each sequence choice for maintenance during a year. This approach tries to model, as close as possible, the real conditions used in maintenance process without affecting the simulation results. However, the sampling process for simulating the failure events is considered to be independent from the proposed maintenance scheduling. Hence, the up/down cycles simulated by Monte Carlo sampling process and the up/down cycles promoted by maintenance scheduling can sometimes come into conflict. Some assumptions related to the up/down cycles may be illustrated in Figure 5.2 [111]:

- In cases (a) and (c), a forced outage takes the equipment out of operation just before its maintenance outages;
- Cases (b) and (d) represent a failure event during the maintenance process.

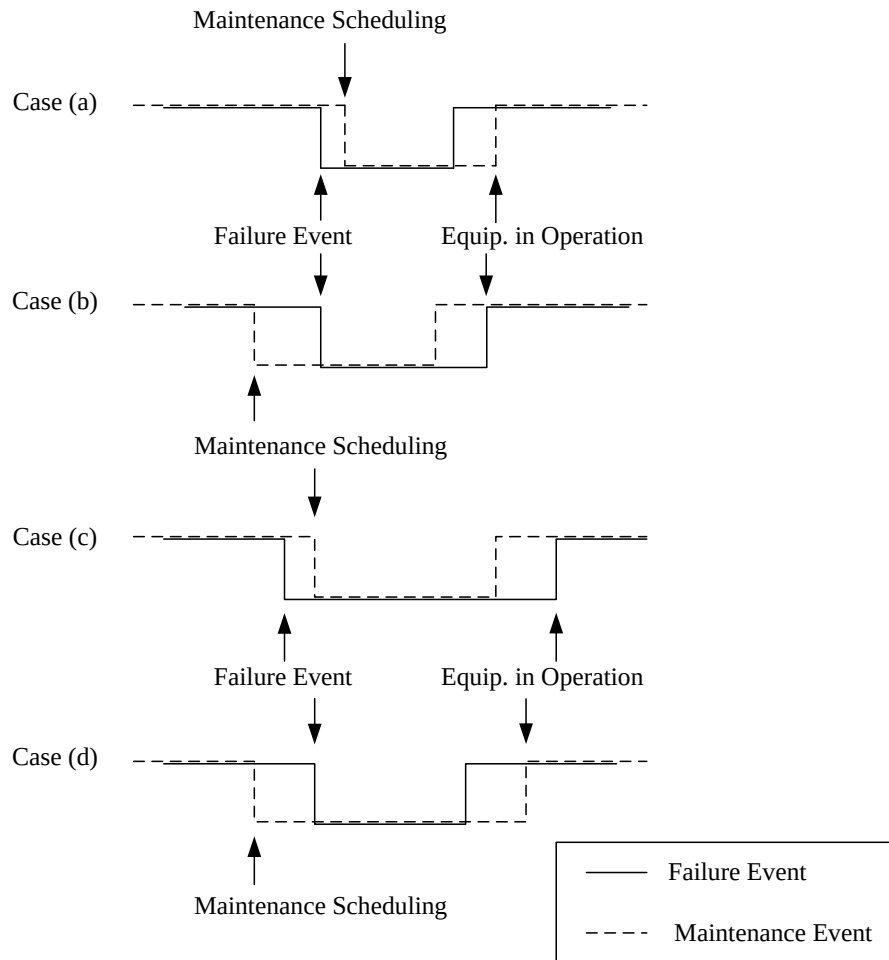


Fig. 5.2 – Up/Down Cycles for Equipment Repair and Maintenance

In all cases, the equipment will be back in operation after finishing the maintenance or repair procedures, depending on which of them it spends more time.

5.6 APPLICATION EXAMPLES

Three different systems will be used in order to illustrate the use of the intelligent agent-based environment for maintenance schedule discussions. Firstly, the proposed MAS-based methodology will be applied to coordinate maintenance schedule for IEEE-RTS [105]. The basic idea is to use the simple configuration of the IEEE-RTS in order to show the maintenance impact, as well as its consequences when the generation companies interests differ from each other. Thus, it is possible to solve a simple conflict using the proposed algorithm. The IEEE-RTS consists of: 32 generating units performing 3405 MW of installed capacity; 24 bus locations connected by 33 lines and 5 transformers involving two areas with distinct voltage levels (138 kV and 230 kV); a load model covering 8736

hours and a 2850 MW annual peak load that occurs during the winter. The maintenance schedule proposed to the IEEE-RTS [132] will be assessed and a conflict involving two generation companies located in the two distinct areas will be proposed. The aim is to show the potentialities of the intelligent agent-based environment in the benchmark system, whose results can be easily replicated. Afterwards, recent configuration of the Portuguese and Spanish systems, which includes renewable sources, will be discussed. The idea is to promote discussions about maintenance schedules when the systems have an important portion of intermittent production, as well as to identify the impact of maintenance schedule, not only in the static reserve, but also considering operating reserve assessment.

In 2008, Portuguese and Spanish Generating Systems (PGS and SGS, respectively) consisted of 2238 and 11456 units respectively, performing a total of 13694 units in the Electricity Iberian Market (MIBEL). PGS and SGS had a total installed capacity of 15.2 and 90.2 GW, as well as an annual peak load of approximately 9.6 and 47.5 GW, which occurred in January. Both systems (PGS and SGS) were distributed as shown in Table 5.1.

Table 5.1 – PGS and SGS Installed Capacity in 2008

Installed Capacity (GW)	Portugal	Spain
	2008	2008
Thermal	5.8	50.8
Hydro	4.8	18.1
Wind	2.7	16
Solar	-	1.5
Others Renewable	1.7	1.1
Pumped Stations	0.2	2.7
Total	15.2	90.2

Representations such as hydrological conditions, wind and solar power production are considered through the use of monthly hydrological series, hourly wind series, as well as solar production series. In order to illustrate the intelligent agent-based environment for maintenance schedule discussions, some important units will be chosen to represent generation companies. Some conflicts between these fictional generation companies will be discussed.

5.6.1. AGENT-BASED GENERALIZED ARCHITECTURE

Multi-agent systems provide a complex and interesting environment for evaluating intelligent agent behavior. While computer-aided design applications take advantage of multi-agent systems, the domain knowledge that requires the understanding of those applications is quite specialized [50]. As mentioned before, the proposed environment is based on the electronic market place and its agents are derived from the ABLE classes. The intelligent agent-based environment for maintenance discussions consists of an open and distributed application that can be used by any market participant in order to negotiate the maintenance priorities of their generating units. Figure 5.3 presents the proposed general architecture in which the Internet network provides a suitable environment to the maintenance discussions. In this generalized application, each Genco, Transco and Disco can assess a single object aiming to interact with ISO and other market participants in the system.

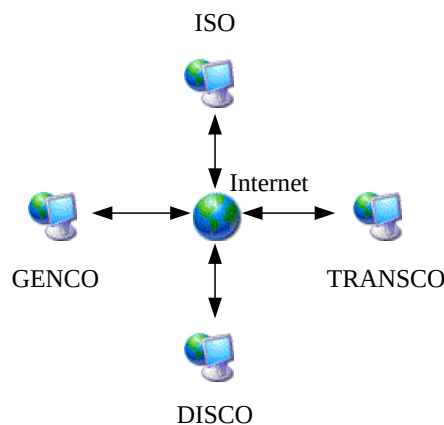


Fig. 5.3 – Generalized Architecture for Intelligent Agent-based Environment for Maintenance Discussions

The maintenance schedule discussion is divided into two instants: first, the market participants will use the reliability tool to establish a suitable planned outage according to the ISO strategies; second, they will discuss priorities using agent-based autonomous systems in order to negotiate some possible conflicts in the established planned outage. This type of interaction can be considered asynchronous, since the reliability assessment cannot be performed on line for the evaluation of changes on requests. In the second step, the communication process between agents takes place through the use of KQML message, which consists of an interchanging process where performatives are sent and received by each agent. All messages contain: a performative; the name of the sender; a content string; the name of the receiver; a string specifying what the message is in reply to or a string to use when replying; specification for the language and ontology [50]. KQML messages encode information at three different architecture levels: content, message, and communication. Different from a pure distributed system, the agent communication process holds a complete range of meanings in each message. For instance, an agent would like to know if other agents wish to negotiate. Therefore, the single KQML message should contain:

Performative: (ask-one : receiver *market participant B* : ontology *NYSE-TICKS)*
: sender *market participant A* : reply – *with information yes*
: content (*generic.method()*) : language *java*

ABLE system architecture offers some types of performatives such as *advertise*, *unadvertised*, *tell*, *ask*, *deny*, *recommended-one*, *make-offer*, *accept-offer*, and *reject-offer*. In this chapter, the agents will try to negotiate maintenance priorities, buying and selling their maintenance scheduling, based on the costs incurred in each change requested, in the free market negotiation. Obviously, in a real condition they can make these negotiations more specialized.

5.6.2. IEEE-RTS EXAMPLE

Since 1979, IEEE-RTS [105] have been revisited in order to make this test system more useful in assessing different reliability modeling and evaluation methodologies. In 1986, the second version of the IEEE-RST [132] suggested several new data, including a package

with maintenance schedule. Figure 5.4 shows the topology for IEEE-RTS assuming two different GENCOs (A and B) located in buses 1 and 22.

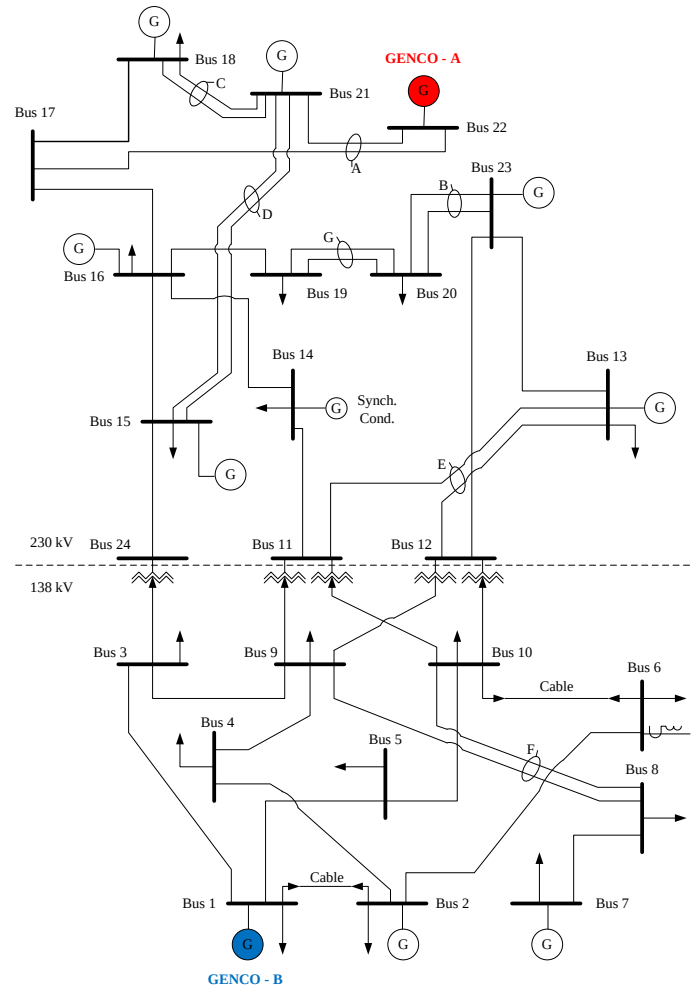


Fig. 5.4 – IEEE-RTS Network Topology

GENCO A has connected a power plant containing six generating units at bus 22; each unit has 50 MW, performing a total installed capacity of 300 MW. GENCO B has connected a power plant containing four generating units at the bus 1: two 20 MW units and two 76 MW units, performing a total installed capacity of 192 MW. The purpose of this section is to create a simple conflict between two market participants, using the IEEE-RTS available data to show the potentialities of the agent-based environment. Table 5.2 shows the scheduled outages, expressed in weeks for each unit, recommended to the overall IEEE-RTS generating units.

Table 5.2 – IEEE-RTS Maintenance Schedules

Generating Unit Size (MW)	Number of Units	Maintenance Schedule (Weeks/year)
12	5	2
20	4	2
50	6	2
76	4	3
100	3	3
155	4	4
197	3	4
350	1	5
400	2	6

As previously stated, there are two main aspects regarding scheduled outage: promoting the schedule and to measure its effect on the reliability system. Increasing reliability indices are expected when maintenance scheduling is considered. However, an appropriate evaluation can help identify the suitable weeks to carry out maintenance.

Once maintenance discussions in the intelligent agent-based environment are opened, it is necessary to follow all the steps suggested in the proposed methodology presented in Section 5.4.1, and to provide enough information to the market participants as well. The first steps of the proposed methodology require some individual actions of the ISO and market participants, taking advantage of the internet environment to achieve a suitable maintenance schedule in accordance with the ISO strategies. The fundamental aim is to solve the conflicts between market participants through the use of electronic market environment, where any market participant can negotiate its maintenance schedule priorities. Figure 5.1, previously showed in the Section 5.4.2, presents the main panel used in the application, where a reliability tool is available for the ISO and market participants. Therefore, at the beginning of the process, each market participant needs to perform

individual reliability studies in order to prepare its maintenance requests. Firstly, it is assumed that all system equipment, generating units, are in service. The intention is to measure the maximum reliability of the system in order to provide a reference for all reliability indices used. With the objective of ensuring reliability, all market participants can consider some reliability indices such as LOLP (Loss of Load Probability), LOLE (Loss of Load Expectation), EPNS (Expected Power Not Supplied), EENS (Expected Energy Not Supplied), LOLF (Loss of Load Frequency), LOLD (Loss of Load Duration), and even including some costs [133]. It is important to highlight that the convergence of the simulation process is based on an annual index (e.g. EENS), which uses the coefficient of variation β presented in Chapters 3 and 4. Nonetheless, the simulation process emphasizes some week indices due to the time dependence of the maintenance procedures. Hence, the uncertainty around the annual estimated index is set, for instance, to 1% so as to ensure week index convergence.

After several interactions among FISO and all market participants, it is assumed that Table 5.3 is a result of all maintenance schedule requests by Gencos in the overall system, in accordance with ISO strategies and based on the results presented in Table 5.4.

Table 5.3 – IEEE-RTS Approved Maintenance Schedule

Units (bus)	Weeks	Units (bus)	Weeks	Units (bus)	Weeks	Units (bus)	Weeks
76(1)	3 - 5	20(2)	12, 13	100(7)	27 - 29	400(21)	35 - 40
155(15)	6 - 9	197(13)	15 - 18	50(22)	27, 28	155(23)	36 - 39
197(13)	8 - 11	76(1)	15 - 17	76(2)	30 - 32	50(22)	38, 39
20(1)	9, 10	50(22)	16, 17	350(23)	31 - 35	12(15)	38, 39
12(15)	9, 10	100(7)	20 - 22	50(22)	31, 32	197(13)	40 - 43
400(18)	10 - 15	50(22)	21, 22	20(2)	33, 34	100(7)	41 - 43
155(16)	11 - 14	155(23)	26 - 29	12(15)	33, 34	50(22)	41, 42
20(1)	12 - 13	12(15)	26, 27	76(2)	34 - 36	12(15)	41, 42

In Table 5.4 is shown the annual reference system reliability values without maintenance for the IEEE-RTS and the annual impact of maintenance requests presented in Table 5.3. All week indices and their respective coefficient of variation are presented in Appendix A.

Table 5.4 – IEEE-RTS Annual System Reliability Indices

Indices	Without Maintenance	$\beta(\%)$	With Maintenance	$\beta(\%)$
LOLP	0.1077E-02	0.69	0.2026E-02	0.69
LOLE (h/yr)	9.405	0.69	17.75	0.69
EPNS (MW)	0.1343	1.00	0.2358	1.00
EENS (MWh/yr)	1173	1.00	2065	1.00
LOLF (Occ./yr)	2.019	0.55	4.224	0.56
LOLD (h)	4.659	0.87	4.203	0.86

The effect of the proposed scheduled maintenance is quite intuitive. These annual results show that the risk is approximately doubled when this maintenance schedule is included. The reference LOLE index is 9.405 hour/year (without maintenance) and increases to 17.75 hour/year considering the proposed maintenance schedule. In general, all annual indices increase when maintenance schedule is included. The doubled LOLF index (from 2.019 to 4.224 occ./yr) indicates that the number of events increase in different time positions during the year. As a result, the increased number of events (failures and scheduled outages), cause the LOLD index to decrease (from 4.659 hour to 4.203 hour), mainly for the reduced time-to-repair of each generating unit on maintenance. Figure 5.5 shows the reference reliability indices per week and the impact of maintenance requests presented in Table 5.3.

Intuitively, the ISO and maintenance planners were led to choose the weeks for maintenance with less reliability impact in accordance with the ISO strategy. The weeks as 1, 2, 19, 23 – 25, and 44 – 52 were considered ineligible for maintenance by ISO.

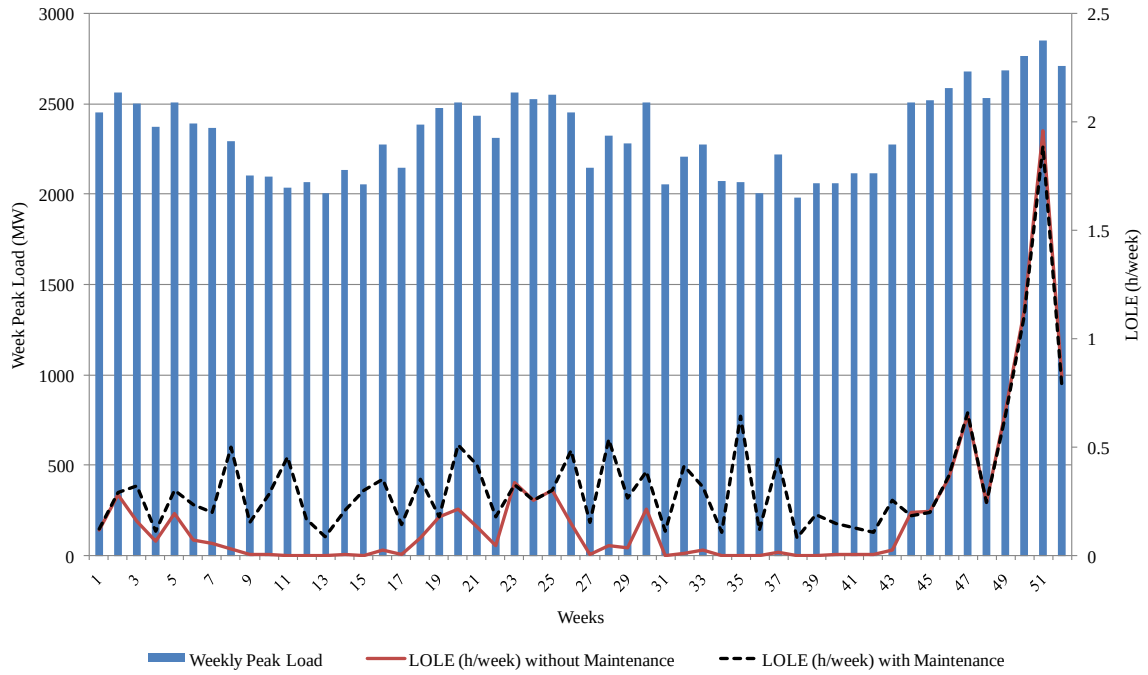


Fig. 5.5 – IEEE-RTS Reliability Indices Impact per Week

Regardless of the fact that the annual risk-based level has doubled, Figure 5.5 shows that the risk-based week has not increased too much throughout the year. A simple analysis may consider that the reference annual LOLE = 9.405 hour/year might be distributed by 52 weeks. Thus, the LOLE reference per week might be established, on average, as 0.181 hour/week, without considering maintenance. Including maintenance, the weekly LOLE index might be established, on average, as 0.341 hour/week. Therefore, the ISO will promote a balance among weeks in order to keep track of the annual reference. This will take place, albeit some of them will work above the weekly reference value. On the other hand, the ineligible weeks remain with the same risk-based level, which ensures the fact that the risk increases when distributed along the acceptable weeks. In week 35, the highest LOLE is achieved (0.646 hour/week) as a result of the proposed maintenance schedule. Another important point focuses on the fact that the highest risk-based level is concentrated in the ineligible weeks 44 – 52 (1.963 hour/week). As it can be seen, this weekly risk view provides guidance to the maintenance schedule discussions that enable a transparent process in which no individual company can be treated unfairly. In order to establish some acceptable risk references to the players, the ISO may allow a simple criterion based on IEEE-RTS evaluation with and without maintenance:

- i. without maintenance: 10 hours/year $\Rightarrow$ 1 hour/month $\Rightarrow$ 0.25 hours/week
- ii. with maintenance: 20 hours/year $\Rightarrow$ 2 hours/month $\Rightarrow$ 0.50 hours/week

The idea is to keep the balance between annual, monthly, and weekly indices, where these reference values could be seen as acceptable risk-based levels. For instance, in (i) the ISO might allow up to 2 hours/month, two times during low-load seasons. Otherwise, in (ii) the ISO may allow up to 1 hour/month ten times during eligible months. Obviously, the criterion must be used as a reference to the discussions, allowing better solutions for maintenance scheduling. As a result of these discussions, the ISO can approve these planned outages, presented in Table 5.3, as a maintenance schedule planned for the next year.

In order to create a simple conflict between two market participants, it is assumed that the GENCO A needs to perform maintenance in the two 50 MW generating units as soon as the year begins. Its scheduled maintenance was previously planned for weeks 16, 17 and 21, 22, respectively. GENCO A will perform a reliability assessment, in order to evaluate the effects that these changes on the consolidated maintenance scheduling. Thus, it will seek to know whether the other market participant is able to negotiate or not, as well as if the ISO will allow this negotiation. The first weeks available for maintenance are from 3 to 5, which are occupied by GENCO B in order to perform maintenance in the 76 MW generating unit. As mentioned before, maintenance schedules for generating units are described with the specification of *hour*, *day* and *month* so as to cover the 52 weeks of the year. This flexibility makes it possible for maintenance procedures to start and end at any time. In this context, the first change proposed by GENCO A involves two 50 MW generating units. Each generating unit needs 2 weeks to perform maintenance. Table 5.5 shows the approved maintenance schedule (AMS) to the generating units involved, as well as the first proposed change (FPG) and second proposed change (SPC). The FPG by GENCO A consists of forestalling the approved scheduled maintenance for both generating units without moving GENCO B. Thus, if ISO allows the changes, GENCO A avoids conflict with GENCO B. Table 5.6 shows the reliability impact of this first proposed change.

Table 5.5 – IEEE-RTS Weekly Requests

Generating Unit (Bus)	Starting			Ending		
	Hour	Day	Month	Hour	Day	Month
Approved Maintenance Schedule (AMS)						
50(22)	00:00	16	April	23:59	29	April
50(22)	00:00	21	May	23:59	03	June
76(1)	00:00	15	January	23:59	04	February
First Change Proposed (FPC)						
50(22)	00:00	15	January	23:59	28	January
50(22)	00:00	22	January	23:59	04	February
76(1)	00:00	15	January	23:59	04	February
Second Change Proposed (SPC)						
50(22)	00:00	15	January	23:59	28	January
50(22)	00:00	22	January	23:59	04	February
76(1)	00:00	16	April	23:59	06	May

The annual reliability impact of the FPC moves the LOLE index from 17.75 to 17.88 hour/year. The involved weeks are shown in the Table 5.6. In the Northern hemisphere, some ISOs avoid planning outages during January and February due to the high load level registered in the winter. In the AMS, only one 76 MW generating unit is assumed in the first three eligible weeks of the year. The reliability impact over the involved weeks on the AMS and FPC scenarios can be seen in Table 5.6. It can be observed that weeks 3, 4 and 5 have an adequate LOLE index relating to the week reference in the AMS scenario. It is also possible to observe that weeks 3 and 5 have high values for LOLE in the FPC scenario, when compared with all other scenarios, and therefore, they can be considered inadequate due to high-load season. Obviously, the other weeks involved in the FPC scenario, such as weeks 16, 17 and 21, 22 are alleviated and, in these cases, the LOLE index decreases. The other scenario (SPC) consists of forestalling the AMS for both generating units, postponing the GENCO B generating unit (76 MW).

Table 5.6 – IEEE-RTS Weekly Impacts

Week	LOLE (h/week) without Maint.	β (%)	LOLE (h/week) AMS	β (%)	LOLE (h/week) FPC	β (%)	LOLE (h/week) SPC	β (%)
3	0.161	4.2	0.321	4.4	0.481	3.8	0.262	4.8
4	0.066	6.4	0.113	7.1	0.258	5	0.139	6.5
5	0.196	4.2	0.301	4.7	0.457	3.8	0.245	5.2
16	0.026	9.4	0.355	4.6	0.249	5.5	0.438	4.1
17	0.007	19.7	0.146	6.6	0.096	7.7	0.180	6.1
18	0.085	5.9	0.352	4.3	0.346	4.3	0.664	3.2
21	0.136	4.9	0.418	4.2	0.291	5	0.292	5.0
22	0.047	7.4	0.178	6	0.114	7.3	0.116	7.2

Different from FPC, which requires two weeks for the 50 MW generating units, SPC requires three weeks to perform maintenance in the 76 MW generating unit . Thus, when this generating unit (76 MW) is deferred for weeks 16, 17 and 18, the annual reliability impact moves the LOLE index from 17.75 to 17.92 hour/year. The mentioned weeks are reserved for other three different generating units (197, 76 and 50 respectively) in order to perform maintenance. Comparing both proposed scenarios, the summation of the individual week contribution to the LOLE index is 2.292 hour/year for the FPC and 2.336 hour/year for the SPC. On the other hand, weeks 3, 4 and 5 have an adequate LOLE index concerning the week reference in the SCP scenario, exactly in the winter months. Although the SCP scenario seems worse than FCP in terms of risk (LOLE), it is assumed that the ISO approved SCP as a solution, based on the weekly load levels. Nevertheless, GENCO A needs to negotiate with GENCO B in order to buy and change the settled schedule. Obviously, several different scenarios and solutions might be proposed for this problem, but this thesis intends to be a simple evidence of the negotiation potential of autonomous agents.

5.6.3. IEEE-RTS AGENT-BASED NEGOTIATION

After defining the positions in the maintenance discussion environment, GENCO A and GENCO B may start the negotiation process, using their individual strategies incorporated in the agents. ABLE offers seven types of agents, six of which are prepared to buy and sell in the electronic markets, whereas the seventh is a matchmaker. For the purpose of this chapter, Buyer agents will represent GENCO A, which needs to buy the priority belonging to GENCO B, while Seller agents will represent GENCO B, which has the priority of weeks 3, 4 and 5. It is believed that, if GENCO A takes the priority over GENCO B, it must pay the costs involved in these changes, as well as the possible profits or revenues lost by GENCO B. The Matchmaker will represent ISO, which is promoted by the facilitator. FISO uses *tell* performative to let GENCO A know about GENCO B, which is interested in negotiating its priority. The Buyer agent uses *ask*, *make-offer* and *tell* performatives to communicate with the Seller agent during a negotiation, whereas the Seller agent uses not only *make-offer*, *deny*, *reject-offer*, and *accept-offer* performatives to negotiate with the Buyer agent, but also *advertise* and *unadvertised* performatives to let the FISO know what will be negotiated. All agents make their decisions on the basis of the content of the performative field, deciding then how to respond the messages. Figure 5.6 shows the communication architecture used in the basic strategy of the application.

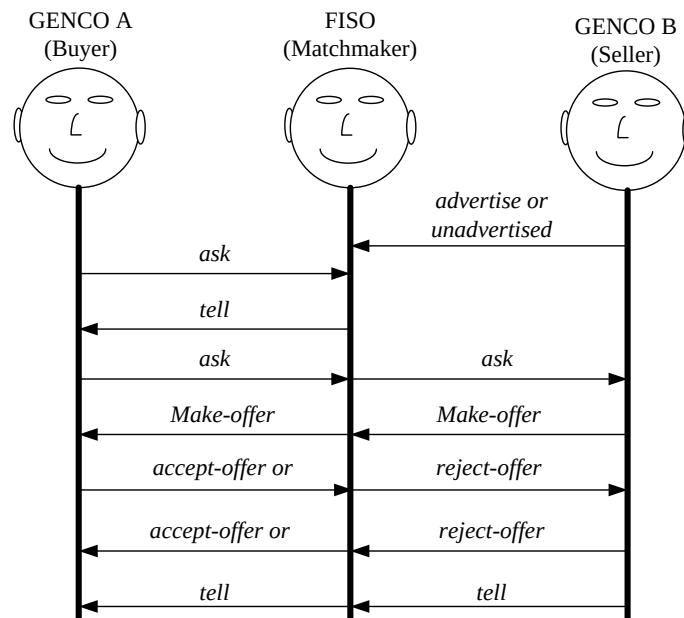
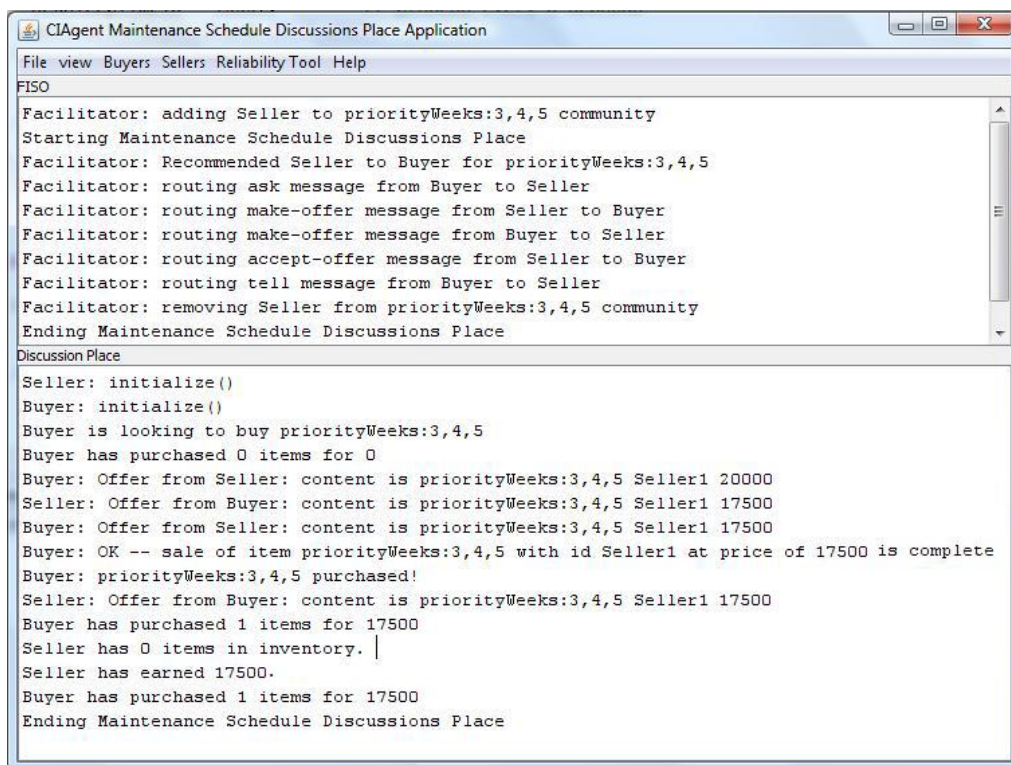


Fig. 5.6 – Agent-based Communication Process

In real electronic markets, agents may interact directly with each other, albeit that situation does not take place in this particular example. In this case, all communication uses the facilitator as a go-between in the process. However, in much larger maintenance environment discussions, where there is the possibility of hundreds agents discussing, the architecture might be modified, perhaps with a direct approach. Therefore, the first step in the maintenance discussion environment is to register all participants. Figure 5.7 shows the dialogue between all participants. At the top of the panel, the controlled area is identified by FISO and the area controlled by market participants is at the bottom. After FISO registers the agents, the seller (GENCO B) agent *advertises* their wares. The basic strategy is to advertise the priority weeks with an initial price different from its strike price (usually higher), and afterwards start FISO maintenance discussion place. At the bottom, GENCOs will initialize their seller and buyer agents. In the next steps, agents will start the negotiation, using appropriate performatives to reach an agreement. At this point, it is necessary to establish some prices for each scheduled outages, based on the costs incurred with maintenance schedule changes. In fact, the discussions on prices and costs will not be part of the scope of this thesis. However, some fictional prices will be used on each negotiation in order to highlight the potentialities of the maintenance discussion place.



```

CIAgent Maintenance Schedule Discussions Place Application
File view Buyers Sellers Reliability Tool Help
FISO
Facilitator: adding Seller to priorityWeeks:3,4,5 community
Starting Maintenance Schedule Discussions Place
Facilitator: Recommended Seller to Buyer for priorityWeeks:3,4,5
Facilitator: routing ask message from Buyer to Seller
Facilitator: routing make-offer message from Seller to Buyer
Facilitator: routing make-offer message from Buyer to Seller
Facilitator: routing accept-offer message from Seller to Buyer
Facilitator: routing tell message from Buyer to Seller
Facilitator: removing Seller from priorityWeeks:3,4,5 community
Ending Maintenance Schedule Discussions Place
Discussion Place
Seller: initialize()
Buyer: initialize()
Buyer is looking to buy priorityWeeks:3,4,5
Buyer has purchased 0 items for 0
Buyer: Offer from Seller: content is priorityWeeks:3,4,5 Seller1 20000
Seller: Offer from Buyer: content is priorityWeeks:3,4,5 Seller1 17500
Buyer: Offer from Seller: content is priorityWeeks:3,4,5 Seller1 17500
Buyer: OK -- sale of item priorityWeeks:3,4,5 with id Seller1 at price of 17500 is complete
Buyer: priorityWeeks:3,4,5 purchased!
Seller: Offer from Buyer: content is priorityWeeks:3,4,5 Seller1 17500
Buyer has purchased 1 items for 17500
Seller has 0 items in inventory. |
Seller has earned 17500.
Buyer has purchased 1 items for 17500
Ending Maintenance Schedule Discussions Place

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Fig. 5.7 – Basic Strategy Agent-based Tracking Messages

Aiming to illustrate the negotiation process, the GENCO B *make-offer* to GENCO A sets its priority at \$20000. GENCO A receives the proposal and sends a counter offer with a different price: \$17500. GENCO B checks the offer: if the offer is equal or higher than its strike price, it will be accepted and a *tell* message will be sent to GENCO A; otherwise, the negotiation will be denied (*deny* message). The process will be completed when the agents achieve an agreement. Programming details about buyer and seller agents may be consulted in [50]. Moreover, ABLE offers different strategies to other agents, so that they can buy and sell in the electronic markets, which are used here for the maintenance discussion environment. In the next section, better and best agent strategies will be explored. Platforms like ABLE provide general introspection facilities for the state of agents and for messages. However, they enforce a concrete agent architecture that may not be appropriate for all applications [38]. In the maintenance discussion place, it would be necessary to develop a dedicated set of performatives and ontology, as well as agent strategies in order to facilitate the integration with the maintenance schedule problem.

5.6.4. PGS AND SGS EXAMPLES

Renewable energy technologies, such as wind and solar power, have been largely introduced in the Iberian systems, performing a higher share of the electricity generation mix. In 2008, renewable energies represented approximately 20% of the installed capacity in the overall system. In this context, maintenance schedule coordination may represent a fundamental factor for the Iberian electricity market, since it is known for being a hard problem that involves not only the ISO interest, but also all market participants' interests. Besides the static reserve presented before, primary, secondary and tertiary reserves need to be taken under consideration in all planned outages, mainly to monitor the generating units, which will be considered in the daily, weekly or monthly unit commitment. In this chapter, the primary (or regulation) and secondary (or spinning) reserves are pre-defined values. Obviously, the spinning reserve amount can always be redefined, in case its associated performance is below a pre-established acceptable value. The tertiary reserve (non-spinning) is composed by those generators that can be synchronized within 1 hour. This reserve is the most relevant for this study and it constitutes the major concern for maintenance planners in this environment with profusion of renewable sources. The concepts of operating reserve and all the new variables involved in this tool can be revisited in [122] [94].

Following the same evaluation proposed in the previous Section 5.6.2, PGS and SGS make assessments in order to establish the standard reliability indices for both systems. Different from the IEEE-RTS, the PGS and SGS Base cases will consider a usual amount of power on maintenance, as well as all hydrological, wind and solar conditions previously modeled for the 2008 configuration [122]. Table 5.7 indicates these usual amounts of capacity withdrawal to maintenance, per month, for both systems.

Table 5.7 – PGS and SGS Maintenance Amount in 2008

	PGS (MW)	SGS (MW)		PGS (MW)	SGS (MW)
January	108.80	25.69	July	609.37	2157.94
February	217.61	370.23	August	1138.90	2981.67
March	457.00	1344.57	September	1024.62	2716.98
April	727.18	3217.97	October	730.83	3802.00
May	950.26	3824.89	November	108.80	1322.67
June	1098.98	2836.17	December	54.40	324.17

The studies were developed not only for the Base scenarios, where all the hydro, wind and solar series were equally probable, but also for more stressing scenarios corresponding, for instance, to conditions in which reduced wind power and increased maintenance are combined. The HWM case was chosen to represent a very severe scenario in which the driest hydrological condition occurred simultaneously with all the observed wind series, having their capacities reduced by 50%, as well as the usual amount of power on maintenance was increased by 20%. Obviously, several other scenarios could be considered in order to assess reliability indices and maintenance impacts. Table 5.8 shows the annual reliability indices for both proposed cases, where the LOLE index will be presented as static reserve LOLE (LOLE_{STC}) and operational reserve LOLE (LOLE_{OPE}).

Table 5.8 – PGS and SGS Annual Indices (2008)

Cases	PGS		SGS	
	LOLE _{STC} (h/yr)	LOLE _{OPE} (h/yr)	LOLE _{STC} (h/yr)	LOLE _{OPE} (h/yr)
Base	3.290	3.982	0.000	0.233×10^{-3}
HWM	13.750	16.020	0.000	0.250×10^{-3}

The preliminary annual results indicated that the 2008 configurations for the PGS and SGS presented different behaviors in both cases. As it can be observed in this table, the PGS Base case with the 2008 configuration is relatively acceptable. The variations caused by intermittent production and load uncertainty are covered by generating units used in the operational reserve, thus bringing LOLE_{OPE} relatively close to LOLE_{STC}. As it could be expected, the worst condition occurs for the HWM case, resulting in indices like: LOLE_{STC} = 13.750 hours/year and LOLE_{OPE} = 16.020 hour/year. Under these HWM conditions, the performance can be considered unacceptable for this severe case. Still observing the same table, it is possible to conclude that the SGS Base case with the 2008 configuration is totally acceptable. All the variations caused by intermittent production and load uncertainty are covered by generating units used in the operational reserve, thus making LOLE_{OPE} and LOLE_{STC} ≈ 0 hours/year. As it could be expected, the worst condition occurred for HWM, resulting in indices with the same impact (LOLE_{STC} and LOLE_{OPE} ≈ 0 hours/year). Under these circumstances, the performance can be considered totally acceptable since SGS presents an extremely robust system to the 2008 configuration. Therefore, the SGS can perfectly perform the usual maintenance procedures, taking off a significant amount of generation capacity per month, without affecting the overall system reliability.

As far as the PGS 2008 configuration is concerned, it is necessary to promote some additional analyses, since it seems to be acceptable to consider the Base case performance, but not the HWM case. In order to measure the impact of the usual maintenance procedures on the PGS Base case, an alternative case was performed. This particular case did not take the usual maintenance procedures under consideration. The results indicated that the planned maintenance schedule needed to be revised, since it is responsible for approximately 80% of the failures caused on PGS, in the proposed Base case. In the

alternative case, annual indices such as $LOLE_{STC} = 0.656$ hour/year and $LOLE_{OPE} = 0.869$ hour/year were performed using the same 2008 configuration, with only one difference: the usual maintenance procedures are removed. Figure 5.8 shows a monthly analysis of the static and operational reserve for the PGS, where the LOLE index highlights the maintenance impact on the overall system performance, especially when maintenance procedures are combined with the high load level of March.

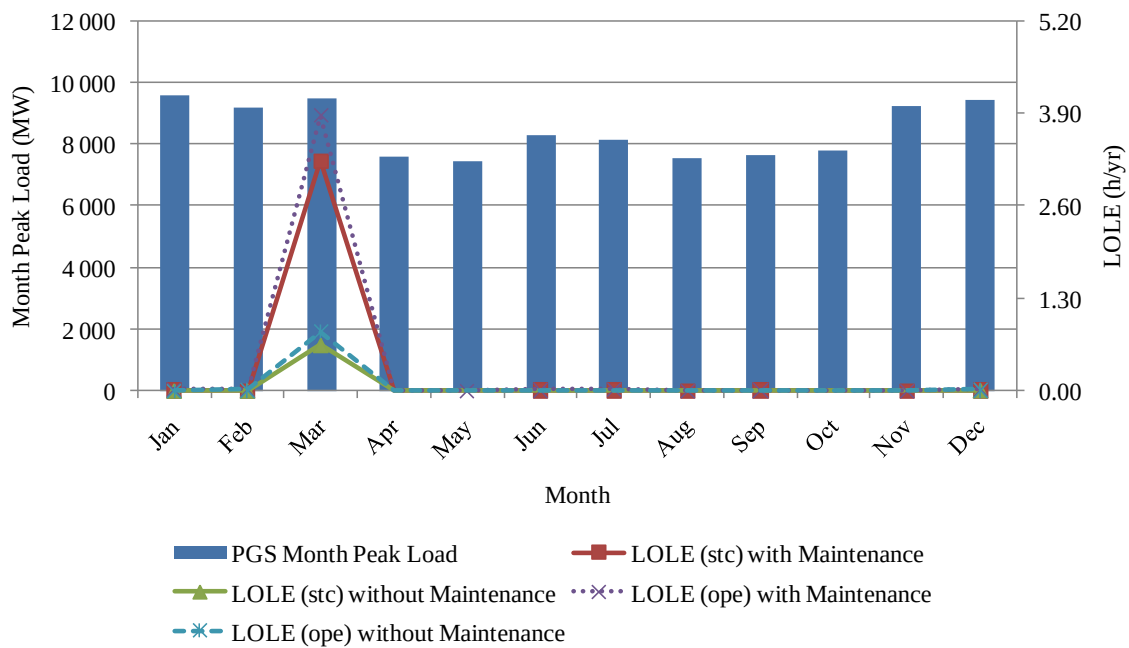


Fig. 5.8 – PGS Reliability Indices Impact per Month

As pointed out before, the same week evaluation proposed in the previous section (Section 5.6.2) was carried out in order to assess the weekly reliability impact, especially in March. These analyses indicated that some weeks of March were the most problematic for PGS, mainly due to the amount of the capacity withdrawal on maintenance in this period. Obviously, this situation was built on a fictional conflict, where two generating units were chosen to explore the maintenance discussion place. Thus, two possible scenarios were explored in order to study the system reliability problems. In the first place, the maintenance schedule was preserved (MSP) and a week analysis was promoted aiming to assess the week impact of the planned outage. In addition, another schedule was proposed (ASP) in order to decrease the reliability impact on PGS.

From this point, it is implicit that this reliability discussion was caused by two fictional Gencos that were requesting the same weeks to the ISO to perform maintenance in March. GENCO C has connected a power plant in the PGS containing two 82.5 MW generating units performing a 165 MW total installed capacity. GENCO D has connected a power plant in the PGS containing one generating unit performing a 292 MW total installed capacity. As it is indicated in Table 5.7, the capacity withdrawal on maintenance proposed to month of March is approximately 457 MW. The weeks involved in their requests were weeks 9, 10, 11, 12 and 13. It is fundamental to bear in mind that week number 9 is composed by the last three days of February and week number 13 is composed by the first days of April. A load analysis has indicated that March's peak load took place in the beginning of the month. Hence, the requests involving week number 9 need to be accurately assessed. Table 5.9 shows the impact of reliability on PGS maintenance planned for the involved weeks. As expected, week number 9, in the MSP scenario, is the most problematic due to the combination between high load level and a significant amount of capacity withdrawal. Other than that, the other weeks present no failures, with the exception of week number 10.

Table 5.9 – PGS Week Reliability Impact

Weeks	LOLE _{STC} (h/week) MSP	LOLE _{OPE} (h/week) MSP	LOLE _{STC} (h/week) ASP	LOLE _{OPE} (h/week) ASP
9	3.066	3.641	1.115	1.364
10	0.224	0.341	0.122	0.169
11	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.000
15	0.000	0.000	0.000	0.000

The ASP consists of postponing the outage requested by GENCO D, proposing to start its maintenance procedures during week number 11 in order to mitigate the risk-based level in

the overall PGS. Other possible solution would be to postpone the scheduled outage requested by GENCO C. The reliability results of the ASP proposal are shown in Table 5.9, including the reliability impact on weeks 14 and 15, which were involved when GENCO D maintenance request was postponed. The results indicate that it is possible to carry out this improved planned outage, decreasing the annual reliability impact on PGS, and thus moving the $LOLE_{STC}$ index from 3.290 to 1.284 hours/year. For the purpose of this chapter, it is assumed that the conflicts between GENCO C and GENCO D were concentrated in these weeks in March. Nevertheless, several other conflicts could be explored in this context. Information on capacity maintenance amounts and their reliability impacts, as well as on PGS and SGS can be consulted in [94].

5.6.5. PGS AND SGS – AGENT-BASED NEGOTIATION

After defining the conflict between GENCO C and GENCO B in the maintenance discussion environment and before starting the negotiation process, it is extremely important to highlight some differences between *Basic*, *Better* and *Best* agent strategies. In the *Basic* strategy used before, the buyer agent only checks whether the seller's offer price is lower than the strike-price, which is the desired maximum price. If so, the buyer agent accepts the offer by echoing the message back to the seller agent, assuming that the seller will accept the offer that had just been made. If the other price is higher than what the buyer is willing to pay, the buyer agent must make a counter-offer, which will be analyzed by the seller. This simple process was improved in order to promote a more aggressive negotiation strategy and to warrant no further discussion [50]. The *Better* strategy uses *hard-coded logic*, whereas the *Best* strategy uses *Boolean* and *if/then* rules in order to determine their prices and actions during the negotiations. The sophistication of the processing logic is based on the *negotiate* method implemented by ABLE where, in each negotiation process, the agents are able to ask: (what else?) in order to enforce a new price on the negotiation. Moreover, in the *Basic* strategy, the buyer agent simply takes a fixed value of the seller's offer and makes a counter-offer, hoping that the seller will accept. Now, using the same forward-chaining inference cycle and the same performatives mentioned before, the *Better* and *Best* strategies consist of making use of additional information. During the inference process, this information will allow agents to consider new variables so that they may decide what they must do. These new variables, such as *offer delta*, *spread* and *first offer*, represent a very attractive property, in which users who

want to trust on agents to make actual purchases, may implement their market actions. All these variables, agent improvements and implementation details may be consulted in [50]. Although ABLE offers different strategies to their agents, the idea is to show that market participants can adopt their own strategies as a competition factor on maintenance schedule discussions.

So far, ABLE agent strategies were highlighted in order to demonstrate the difference between negotiation levels. This thesis intends to use the *Best* strategy to illustrate the negotiation process established between GENCO C and GENCO D. It is assumed that, as opposed to the first example, this conflict between Gencos took place at the beginning of the maintenance discussions, since there was no priority defined to the market participants. Therefore, the advantage of the negotiation will be defined by the ISO strategy presented in the Section 5.4.2. Following the ISO strategy, GENCO C has priority over GENCO D because it has two generating units and a lower impact on system and costumer reliability. For the purpose of this chapter, Buyer agents will represent GENCO D, assuming that the maintenance of its generating unit cannot be postponed. As a result, it is necessary to buy the priority that belongs to GENCO C. The Seller agent will represent GENCO C, which has priority in weeks 9 and 10. Figure 5.9 illustrates the steps used by each Genco until an agreement is achieved. Following the same communication process used before, the first step in the maintenance discussion environment is to register all participants. In Figure 5.9, the dialogue between all participants is shown. At the top of the panel, there is the area controlled by FISO, thus making it possible to keep track of the messages exchanged by market participants, whereas at the bottom there is the area controlled by market participants. In order to simply show the main dialogue between agents, some sentences were omitted in the FISO controlled area at the top of the panel. After all agents are registered with the FISO, the seller (GENCO C) agent *advertises* its wares. In the *Best* strategy, the priority weeks will be advertised with an initial price that is different from its strike price (usually higher) and, therefore, FISO will start the maintenance discussion place. Once again, it is necessary to establish some prices for each scheduled outages, based on the costs incurred with maintenance schedule changes. As stated before, the discussions on prices and costs will not be part of the scope of this thesis. However, some fictional prices will be used on each negotiation in order to highlight the potentialities of the maintenance discussion place.

```
File view Buyers Sellers ReliabilityTool Help
FISO
Facilitator: adding BestSeller to priorityWeeks:9,10 community
Starting Maintenance Schedule Discussions Place
Facilitator: Recommended BestSeller to BestBuyer for priorityWeeks:9,10
Facilitator: routing ask message from BestBuyer to BestSeller
Facilitator: routing make-offer message from BestSeller to BestBuyer
Facilitator: routing make-offer message from BestBuyer to BestSeller
Facilitator: routing accept-offer message from BestSeller to BestBuyer
Facilitator: routing tell message from BestBuyer to BestSeller
Facilitator: removing BestSeller from priorityWeeks:9,10 community
Ending Maintenance Schedule Discussions Place
Discussion Place
BestSeller: initialize()
BestBuyer: initialize()
BestBuyer is looking to buy priorityWeeks:9,10
BestBuyer has purchased 0 items for 0
BestBuyer: Offer from BestSeller: content is priorityWeeks:9,10 BestSeller1 20000
BestSeller: Offer from BestBuyer: content is priorityWeeks:9,10 BestSeller1 12500
BestBuyer: Offer from BestSeller: content is priorityWeeks:9,10 BestSeller1 17500
BestSeller: Offer from BestBuyer: content is priorityWeeks:9,10 BestSeller1 12500
BestBuyer: Offer from BestSeller: content is priorityWeeks:9,10 BestSeller1 16500
BestSeller: Offer from BestBuyer: content is priorityWeeks:9,10 BestSeller1 11500
BestBuyer: Offer from BestSeller: content is priorityWeeks:9,10 BestSeller1 11500
BestBuyer: OK -- sale of item priorityWeeks:9,10 with id BestSeller1 at price of 11500 is complete
BestBuyer: priorityWeeks:9,10 purchased!
BestBuyer has purchased 1 items for 11500
BestSeller: Offer from BestBuyer: content is priorityWeeks:9,10 BestSeller1 11500
BestSeller has 0 items in inventory.
BestSeller has earned 11500.
BestBuyer has purchased 1 items for 11500
BestSeller has 0 items in inventory.
BestSeller has earned 11500.
Ending Maintenance Schedule Discussions Place
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Fig. 5.9 – Best Strategy for Agent-based Message Tracking

Aiming to promote a comparison between both negotiations presented, the prices used in the two examples shown in Figures 5.7 and 5.9 will be the same, regardless of the number of weeks involved in each negotiation. The main difference between negotiations is understood when the results achieved in both cases are compared. In Figure 5.7, when the negotiation was supported by *Basic* strategy, the week's priority was obtained at \$17500, whereas in Figure 5.9, when the negotiation was supported by *Best* strategy, the priority was obtained at \$11500. Nevertheless, several other strategies and examples might be explored in order to show the potentialities of agent-based technology in conflicting solutions. As mentioned previously, in the maintenance discussion place, it would be necessary to develop a dedicated set of performatives and ontology, as well as agent strategies in order to enable a better integration with the maintenance schedule problem.

5.7 FINAL REMARKS

In this chapter, the maintenance schedule problem on the current power system environment was intensively discussed. As stated before, throughout the last years, the issue that particularly copes with the maintenance schedule generating units and broadly deals with the maintenance schedule in general, for special components or equipments supplying many customers, has been suffering modifications due to the last changes in power industry. In this context, this problem was firstly classified as a *conventional* problem, since the general purpose was to determine the time and sequence of equipment outages that represented the best assignment of that component to maintenance periods in a given time horizon, in such way that the reliability of the system would be maximized. Secondly, the maintenance schedule was classified as a *strategic* dilemma since in some competitive market environments, the maintenance scheduling of generating units can be considered as one of the most prominent strategies used by Gencos to maximize their market profit. Thirdly, it was classified as a *problematic operation task* for the ISOs due to the ordinary uncertainties around strategic maintenance schedule problems, such as load forecasting, fuel prices and maintenance costs, maintenance crew availability, market forces and its competition, and others, which were added to the concepts concerning green electricity production. It was highlighted that this problem involves a complicated relationship between ISOs or TSOs, Gencos, Transcos, Discos, and any other important entities linked to the power industry.

In order to improve this relationship, a methodology based on multi-agent technology was proposed. Essentially, a distributed tool entitled *intelligent agent-based environment to coordinate maintenance schedule discussions*, as well as a simple methodology based on real market rules, were developed. However, a suitable reliability tool developed in Chapter 4, based on sequential MCS, was incorporated into this computational environment, aiming to help their users (market participants) pursue ISO strategies and their own interests as well. The main idea was to replace an optimization tool, which usually requires a complex mathematical formulation, by a simple distributed environment, where agents can negotiate scheduled outages seeking an optimal maintenance schedule. However, as previously stated, the environment can be classified as asynchronous since the reliability assessment cannot be performed on-line in order to evaluate changes on requests.

Therefore, reliability discussions and negotiations involving market participants represented by intelligent agents were performed, though the use of several examples. They have revealed that it is feasible to work with a suitable environment, in which programs and humans can naturally interact, promoting hybrid systems where humans may define their goals first and agents can pursue those goals afterwards, taking advantage of the distributed environment offered by the Internet. Furthermore, this proposal has shown that agent-based technology is ready to be used. In fact, it consists of a very attractive technology since it merges artificial intelligence and distributed computation areas.

It is fundamental to heavily stress the idea that in the proposed maintenance discussion place, it will be necessary to develop a dedicated set of performatives and ontology, as well as agent strategies, in order to enable a better integration with the maintenance schedule problem. This thesis opens the way for new agent-based solutions in specific and traditional conflicts in the power system area.

Chapter 6

IMPROVEMENTS IN POWER AGENT PLATFORM

6.1 INTRODUCTION

Due to the strongest link between power system industry and computation science, computational centralized solutions, which cover a large number of power system applications, have been preferred by power engineers for a very long time. However, from the beginning of the Internet advent and the development of the network communication in 1980 [48], the computation paradigm based on the unique computer for centralized sequential solutions had to share space with distributed solutions. Thus, distributed systems are generally adopted when the problem to be solved is a composition of sub-problems, and/or is much larger in size and scope [134]. The use of distributed solutions in power system problems can be divided into two moments: first, when the resources of the distributed solutions are based on multi-processor architecture with poor infrastructure for the communication process [135-138], and second, when a more specialized infrastructure for communication and interaction between autonomous computer arises and makes it possible to coordinate tasks better [84], [92], [102], [139]. A few years ago, advances in communication, such as the Common Information Model (CIM), made it possible to specify classes and attributes for each component of the power network. This makes it an ideal template for both the internal storage and external transfer of the data in the next generation of power system analysis tools [140].

Historically, reliability assessment of power systems has been addressed through the use of several different techniques, such as distributed processing [84], artificial neural networks [85], variance reduction [72], [86], pseudo-chronological simulations [61], and other related techniques, which usually aim at achieving a better performance, typically in a centralized solution. The performance of the application, either being centralized or distributed, must be measured through the accuracy of the results, and the number of visited states needs to achieve these accuracy results. Therefore, the way these states can be evaluated is directly reflected on the efficiency and CPU time spent to assess reliability indices. Undoubtedly, the task of estimating reliability indices in power systems has proved to be complex.

Chapter 4 has introduced a flexible tool in order to assess the reliability of the power system based on multi-agent technology. Instead of applying distributed processing individually, AI techniques, and/or some variance reduction as a single solution to maximize performance, Chapter 4 proposes the creation of an IA architecture that would

support more than one of those techniques. As a result, the power agent platform proposed to the combination of the distributed processing gains, which can provide an excellent level of efficiency and CPU time to the reliability problem with other techniques, by incorporating intelligence. This happens since there is the purpose of approaching other ways to maximize performance, such as the number of visited states, and to evaluate these states. In this sense, different from a simple distributed processing approach, which uses signals to control computers inside a network [84], this architecture explores agent communication language (KQML: Knowledge Query and Manipulation Language) [44] in order to establish communication among agents.

Currently, sequential Monte Carlo simulation (MCS) for reliability power system assessment is the only realistic option available to study the distributional aspects associated with system index mean values [71]. On the other hand, from the computational point of view, it is the most expensive technique to estimate reliability indices in power systems. For this reason, this technique has been the one used to develop the power agent platform. Nevertheless, in agent-based technology, one of the most important challenges is to identify multiple ways to make agents capable of achieving their goals. Flexibility is a difficult characteristic of the agent systems because it requires a great deal of combined techniques to solve a type of problem. Chapter 6 intends to discuss some other difficult characteristics of the agent-based technology in order to improve the multi-agent architecture proposed in Chapter 4. Specifically, this chapter intends to identify different mechanisms that may improve the performance of the power agent platform. Therefore, the chapter starts with a list of some possible improvements for the power agent platform, as well as with a discussion of a simple classification for the agents and a natural transition from AI to IA proposed before. The *Belief-Desire-Intention* (BDI) architecture is presented and a short discussion about the agents' features is proposed. Finally, the chapter is closed with a discussion on an efficient search mechanism that aims at improving performance by using the previously proposed incorporated transition from AI to IA.

6.2 IMPROVEMENTS IN THE PROPOSED MULTI-AGENT ARCHITECTURE

The task of estimating reliability indices can often be divided into three inherent stages: state selection, state evaluation and index calculation. The strategy used in the state selection stage from statistical methods, such as Monte Carlo, is based on *brute-force*,

uninformed, or even *blind* search. This happens regardless of the representation: state space with non-sequential Monte Carlo, or chronological with sequential Monte Carlo simulation. The state selection task will define the commitment with the other stages. In other words, depending on the state selection technique used in the first stage, the third stage (index calculation) will change its strategy in order to estimate the reliability indices. For instance, if the SP agent follows the probability distribution defined for each equipment (e.g. FOR in generating units) aiming to sample a state for the system, the IC agent can estimate the indices without using any correction. In order to improve the multi-agent architecture proposed in Chapter 4, it is necessary to revisit some concepts and choices made to implement the power agent platform.

6.2.1. REACTIVE AGENTS TO ESTIMATE RELIABILITY INDICES

The architecture proposed in Chapter 4 is based on a statistical method (sequential MCS), which not only defines how the State Producer agent (SP) will select the states produced to be evaluated by the State Evaluate agent (SE), but also how the Indices Calculator agent (IC) will estimate the indices through the use of the updates also promoted by the SE agent evaluations. Figure 6.1 shows the basic architecture proposed. This multi-agent architecture was specified based on the collaborative behavior of each agent, where the group agrees to achieve the goal of estimating reliability indices. In artificial intelligence science, there are three main classes of agents: deliberative, reactive and hybrid agents [29]. Through this categorization, it is possible to classify the agents proposed in Chapter 4 as a reactive group of agents that follow the simple characteristics of reacting in real time, based on simple rules. They behave as automaton that are plunked down in an environment, which requires a simple knowledge.

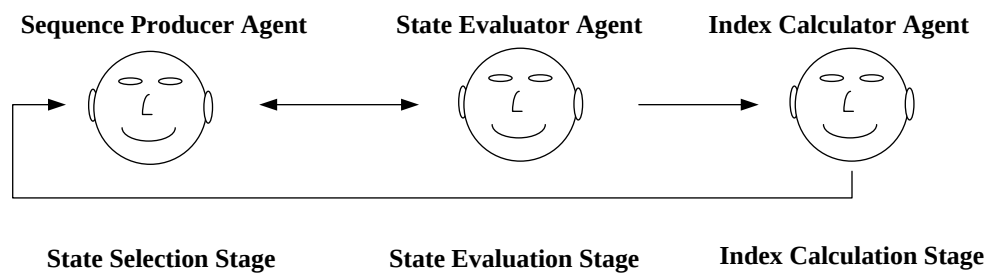


Fig. 6.1 – Agent Architecture Proposed for SMCS

The main advantage of this architecture resides in the second stage of the task of estimating reliability indices. The SE agent may be replicated in order to evaluate states. In Chapter 4, it was proved that the high computational cost to estimate reliability indices resides in this second stage. Therefore, an important aim with this chapter is to add some abilities in this reactive group of agents, promoting more flexibility in the power agent platform.

6.2.2. INCORPORATING FLEXIBILITY IN THE POWER AGENT PLATFORM

So far, it has proposed the approach of estimating reliability indices through the use of sequential MCS, mainly due to its suitable characteristic of representing time-dependence conditions, which are usually present in generating technologies (green sources), such as wind and solar power. In Chapter 3, several other approaches that might be used to estimate reliability indices were revisited, but they do not generally carry any memory or time correlation. With the purpose of making the power agent platform flexible, this chapter will discuss an improvement on this agent platform by incorporating new ways for the SP, SE and IC agents to pursue their goals of estimating reliability indices. Obviously, the incorporated methodologies may hold differences in capabilities and/or applicability, and so this will represent an option that those agents can follow.

One of the most prominent changes will be reflected in the relationship between SP, SE and IC. Depending on the method applied to estimate reliability indices, they will change their individual strategies in each mentioned stage. Therefore, in the next sections the state space representation will be discussed as an alternative to estimate reliability indices, and two flexible approaches will be tested: the non-sequential MCS and population-based methods.

6.2.3. TRANSITION FROM AI TO IA IN POWER SYSTEMS RELIABILITY ASSESSMENT

A natural movement towards AI techniques took place in the last years in several research areas. In power systems, many research works have used AI topics like search techniques, knowledge representation, reasoning and learning systems, as well as heuristic tools in order to address power systems problems. Perhaps, this natural movement needs to be coordinated through the proposal of a new generation of power system tools, where several different techniques can be combined in order to maximize the each one's benefits and

advantages. As mentioned before, a variety of works have used intelligent techniques on power systems reliability assessment. Generally, the main target is to make complex representations feasible when combined with cheaper computational costs. In this sense, this section intends to explore the paradox between AI and IA over the multi-agent architecture proposed in Chapter 4, aiming to improve this proposed multi-agent architecture. Figure 6.2 shows these proposed improvements.

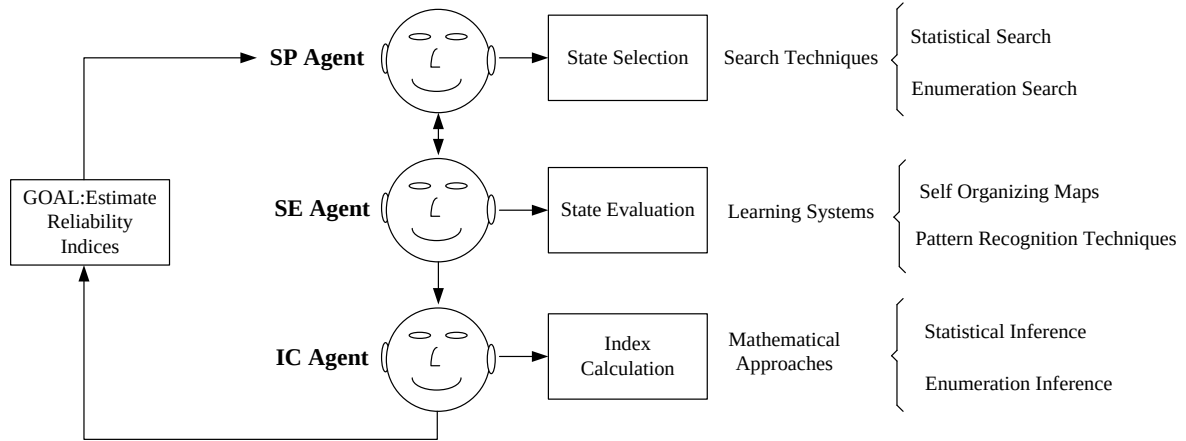


Fig. 6.2 – Improvement in Agent Architecture Proposed in Chapter 4

Essentially, this new architecture tries to take advantage of incorporating some efficient techniques in the stages of the estimation of reliability indices task. The proposal only tries to organize this natural movement, which already exists in the power system research area, making it possible to combine those techniques. Hitherto, the reactive agents built to assess reliability indices through the sequential MCS have been enough. However, in order to promote the proposed improvements, it will be necessary to migrate from the reactive actions to deliberative actions, leading its simple reactive characteristics towards deliberative or hybrid agent architecture. In the next section the BDI architecture will be explored to support the proposed improvements.

6.3 THE BDI ARCHITECTURE

The BDI model makes it possible to understand what is the conceptual agent and essentially what each agent must do. The aim is to programme computer systems inspired by the BDI model [32], which are based on a model of human behavior that was developed by philosophers [40]. It offers a familiar and non-technical way to talk about complex

systems. The central idea of the BDI model is that one can talk about computer programs as if they had a *mental state* [32]. Thus, it is important to understand the distinction between *beliefs*, *desires* and *intentions* inside this context.

- *Beliefs* are the information that the agent has about the world. This information is usually contained in the database upload before the program runs, but could be out of data, via sensor, with inaccurate content. The information on power system components, such as generators, transmission lines, buses and others are an important link between agents and their world. Mathematical representations, such as hydro and wind series, represent the interaction between power system components and their operational conditions. In fact, each agent believes in the state of each power system environment component in order to meet the goal of estimating reliability indices;
- *Desires* are all the possible states of affairs that the agent might like to accomplish. Having a desire, however, does not imply that an agent will act upon it. It will be a potential influencer of the agent's actions. Note that it is perfectly reasonable for a rational agent to have desires that are mutually incompatible with one another. Usually, the programmers think about desires as being options for an agent [32];
- *Intentions* are the states of affairs towards which the agent has decided to work. Intentions may be goals that are delegated to the agent, or may result from considering certain options. Options (desires) that are selected by an agent become intentions [32].

Although the BDI model may be used to highlight the narrow relationship between human and agent behaviors, it is extremely important to understand that agents are not magic [39]. They are simply an approach to structure and develop software that offers certain benefits.

6.3.1. INTENTIONS, DELIBERATIONS AND MEANS-ENDS REASONING

There is a significant difference among intentions, deliberations and means-ends reasoning for the agent's behavior. This takes place since the deliberation process causes an agent to adopt intentions, whereas the means-ends reasoning is the process of deciding how it is possible to achieve an end using the available means [31-32]. Perhaps, these titles are

better known as planning in AI. Planning is an area of the most current interest within AI because it combines the areas as *search* and *logic* [34]. One of the main ideas proposed in this discussion is to identify levels of planning to the SP, SE and IC agents, so that they can promote the transition from a reactive to hybrid architecture. As a simple example, it is possible to suppose that each agent (SP, SE and IC) inhabits a unique CPU, and the configurations defined to the simulation process follow the architectures presented in Figure 6.3.

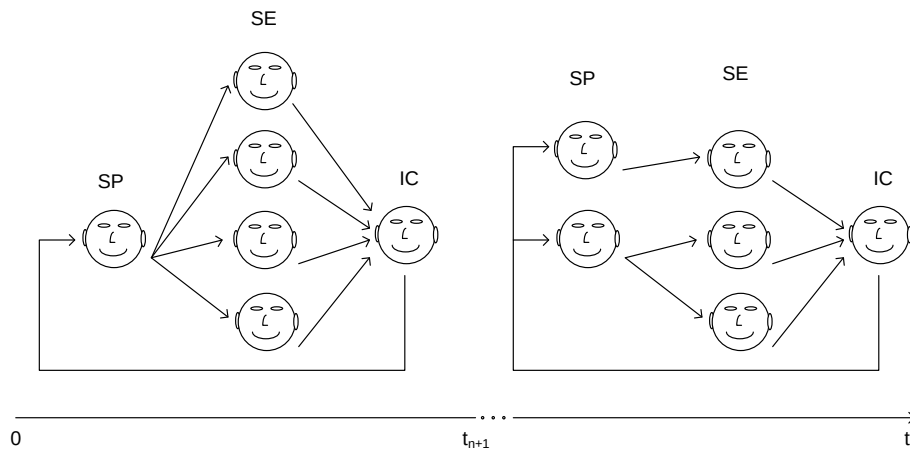


Fig. 6.3 – Multi-agent Dynamic Configuration

Besides that, it is believed that the simulation process starts identifying the configuration imposed by the user. Until the transition t_{n+1} , the SP, SE, and IC agents could execute their individual tasks using the configuration imposed by the user. During this time (in real time), they could seek to understand how the performance of the simulation is, maybe through the use of some performance measures such as the sleeping time spent by each SE agent. If necessary, they could plan another configuration to execute the task of estimating reliability indices including, for instance, another SP agent, as presented in Figure 6.3. The intention is to find a better balance to the simulation process. This example intends to show not only that the agents could have the intention (a goal) of using the resources in the best way, but also to demonstrate that they could deliberate or adopt this intention by choosing a better configuration for the simulation. With the purpose of achieving their intentions (goals), they will plan their actions during the simulation process, trying to find commitments between ends and means. Therefore, several improvements could be identified applying the BDI model in the power agent platform.

6.4 INCORPORATING AI IN IA

The power system environment could be categorized as hardest, because it ranges a set of hard properties such as *partially observable*, *stochastic*, *sequential*, *dynamic*, *continuous*, and in this case, *multi-agent* [34]. These environment characteristics may lead an agent to deal with unexpected facts, thus the agent needs to use its perception to dynamically discover what is happening while its plan is being executed and, if necessary, to modify or replace the plan. In a simpler sense, intelligent agents are supposed to maximize their performance measures in order to achieve their goals.

As mentioned before, the stages of the task of estimate reliability indices to power systems may incorporate some AI topics. The classic approach to the search problems is defined as the state space that forms a graph in which the nodes are states and the arcs between the nodes are actions [34]. Bearing this analogy in mind, the state selection process in reliability assessment of power systems could be addressed as a search problem, in which the SP agent could effectively seek states (nodes). The state evaluation process could be addressed as a learning problem (actions), in which the SE agent could learn things about each evaluated state. However, the strategies applied individually in these stages will have a strong impact on the commitment between agents.

6.4.1. STATE SELECTION PROCESS

Due to the statistical-based concept, the state selection process used by the Monte Carlo method is driven by a probability density function that throughout a blind selection leads to the expected values or results. This is accomplished with the use of the brute force technique. For many power system problems, however, the search space can grow very large. This situation happens often due to the fact that the power systems are very reliable and the subset of meaningfully contributing states for the reliability index is much smaller than the entire state space. In fact, the state selection process in the Monte Carlo method intends to build the power system images from several states in order to learn something about each state. This statistics gathering purpose needs to be preserved in order to experience a balance between good and bad situations promoting a number of meaningful observations to achieve the estimates. Depending on the state space, this search process may require more or less computational effort to select states. In other words, depending

on the rarity of the failure states, the Monte Carlo process may require more or less computational effort.

Another alternative to the state selection process could be a hybrid between a *random-restart search* (where each search process runs independently of the others) and a *local beam search* (where useful information is passed among each parallel search threads).

Recently, an alternative to MCS started to emerge: *population-based* methods (PB). PB methods are basically enumeration algorithms as shown in Chapter 3. If all states that contribute to a certain index could be identified and their probabilities known, the index would be accurately calculated. PB methods try, therefore, to discover the majority of states, if not the totality, so that a good approximation of the index may be calculated. The methods are called *population-based* because they rely on meta-heuristics that have a population of solutions (individuals, particles) as their core. In this class, one counts evolutionary algorithms (EA) – evolutionary programming or genetic algorithms (GA) – and particle swarm optimization algorithms (PSO). They were all developed to be optimization tools. Nevertheless, there is a problem since it is necessary to discover a set of states that have maximum contribution on the index, making it possible to calculate it. Thus, some mechanism to generate diversity must be devised, otherwise all solutions would tend to converge to a maximizing state and space exploration would be hampered. This chapter intends to use PB methods, specifically EPSO, in order to improve the state selection stage used by the SP agent. By incorporating the search strategies studied in [141] as possible strategies that the SP agent can assume, it is possible to accomplish the important aim of effectively producing states.

6.4.1.1. EPSO ALGORITHM AS AN EFFICIENT SEARCH MECHANISM

EPSO is a hybrid in the concepts of EA and PSO, first proposed in [142] and with an improved version in [143-144]. It is an Evolutionary Algorithm with an adaptive recombination operator inspired in the “movement rule” of PSO (Particle Swarm Optimization). The movement rule of PSO generates a new individual as a weighted combination of parents, which are: a given individual, in the population, not only the best ancestor of this individual, but also the best ancestor of the present generation. This may be seen as a form of intermediary recombination. In this type of recombination in evolutionary algorithms, a new individual is formed from a weighted mix of ancestors, and

this weighted mix may vary in each space dimension. The mutation operator is only applied to the weights.

The recombination rule for EPSO is the following: given a particle X_i , a new particle X_i^{new} results from

$$X_i^{(k+1)} = X_i^{(k)} + V_i^{(k+1)} \quad (6.1)$$

$$V_i^{(k+1)} = w_{i1}^* V_i^{(k)} + w_{i2}^* (b_i - X_i) + w_{i3}^* P(b_g^* - X_i), \quad (6.2)$$

where the symbol “*” indicates that these parameters will undergo evolution under a mutation process, and

- b_i best point found by the line of ancestors of individual i up to the current generation;
- b_g best overall point found by the swarm of particles in its past life up to the current generation;
- $b_g^* = b_g + w_{i4}^* N(0, 1) \Rightarrow$ particle in the neighborhood of b_g ;
- $X_i^{(k)}$ location of particle i in generation k ;
- $V_i^{(k)} = X_i^{(k)} - X_i^{(k-1)} \Rightarrow$ “velocity” of X_i in generation k ;
- w_{i1} weight of the *inertia* term (a new particle is created in the same direction as its previous couple of ancestors);
- w_{i2} weight of the *memory* term (the new particle is attracted to the best position occupied by its ancestors);
- w_{i3} weight of the *cooperation* or *information exchange* term (the new particle is attracted to the overall best-so-far found by the swarm);
- w_{i4} weight affecting dispersion around the best-so-far;
- P is a diagonal matrix with each element, in the main diagonal, being a binary variable equal to 1 with a given communication probability p , and 0 with probability $(1-p)$; in basic models, $p = 1$. However, in advanced models, p must be chosen from experiments, and values of $0.7 < p < 0.8$ have been shown to be optimal in many problems [143], although highly complex problems seem to require a very low non-zero value, such as $p < 0.2$.

Weights w_{ik} are mutated at each iteration according to $w_{ik}^* = w_{ik}^* [\log N(0,1)]^\tau$, $k=1,3$ and $w_{i4}^* = w_{i4} + \sigma N(0,1)$, where $\log N(0,1)$ is a random variable, which follows a Lognormal distribution from a Gaussian with zero mean and unit variance, and τ and σ are externally fixed learning parameters that control the amplitude of mutations.

6.4.1.2. SEARCH FOR MEANINGFUL STATES

The proposal of PB methods as a competitor to MC may be traced back to 2001 [68], when a modified GA was used to perform basic reliability indices evaluation of generating systems. An important work [141] reports a set of experiments to study and compare the effect in PB methods (especially in EPSO) of some factors that may influence performance: (a) the type of objective function that induces the algorithm search, and (b) the search mechanism.

To benefit from an enumeration process, a *case C* will be defined as a set of states resulting from permutations³ of equal rating generators (capacity) and FOR (forced outage rate) leading to the same occurrence probability of their combined states and the same load curtailment value [69]. To use this concept, the set of generators must be divided into G subsets, each with equal generators.

The probability of *case C_k* is given by $n_k \times p_k$, where p_k is the probability of any state belonging to C_k and n_k is the number of repetitions given by

$$n_k = \binom{N_{1k}}{M_{1k}} \times \binom{N_{2k}}{M_{2k}} \times \dots \times \binom{N_{Gk}}{M_{Gk}} \quad (6.3)$$

where, for each *case k*, N_{jk} is the number of equal generators of type j , $j = 1, \dots, G$, and M_{jk} is the number of generators of type j in the down state.

A *case C_k* is therefore described by a vector $[M_{1k}, \dots, M_{Gk}]$. The estimation of the EPNS will be done with p_k being the probability of any of the states in *case k*.

³ Permutation: The number of permutations of n different items is the number of different ways these items can be arranged [75].

$$EPNS = \sum_k n_k p_k L_k \quad (6.4)$$

Thus, a particle or individual represents a *case* and not a system state. As mentioned before, it is defined as a vector of integers where each element is the number of equal components of a given type in the down state [141]. This vector results from rounding the real values in a particle since each dimension is allowed to range in an interval of real numbers from 0 to the maximum number of equal components in the up state. This representation significantly reduces the dimension of a particle, especially in the case of power systems with a large number of components described by the same Markov models. Simple rounding is acceptable because the aim is not to optimize but to cover a set. The idea is to conduct a biased search in the state space, identifying states that have positive L_i . Examining Eq. (6.4), it is possible to conclude that those states that contribute more relevantly to form the index EPNS will come from larger values of L , n and p . If one disregards n , the search will take place in the space of states. If one considers the product $n \times p$, the search will take place in the space of cases.

6.4.2. STATE EVALUATION PROCESS

Most of the time consuming in estimating reliability indices is in the second stage (state evaluation) cited before, which consists of a characterization of the each sampled state promoted in the first stage (state selection). One of the main advantages of methods such as Monte Carlo and/or Population-based is unquestionably the ability to model complex systems in more detail and accuracy than it is likely in analytical methods. Consequently, the primary disadvantage of these methods is the lengthy computation time over the second stage, mainly due to the required model. In Table 4.1 of Chapter 4, a simple time consuming measure of these stages for the adequacy generating assessment using sequential MCS is presented. Albeit this example has not shown the real size of the problem, it intends to highlight the differences, in CPU time, between stages (tasks). Another example of more detailed models in the second stage of estimate reliability indices could be cited using the well-being framework [17-19], which was introduced in the last decade. The aim of the well-being analysis is to reduce the gap between deterministic and probabilistic approaches in reliability studies, by providing the ability to measure the degree of success of any operating system state [19]. In other words, an intermediate state

between *success* and *failure* states was introduced, which is usually called *marginal* state by promoting a more detailed model to assess reliability indices. Well-being analysis has been applied in areas such as composite generation and transmission systems, but essentially it requires detailed models, such as a contingency list, which is usually the deterministic criterion. Sequential MCS has been used for generating systems [27] and operating reserve assessment [122] combined with well-being analysis. The deterministic criterion to have under consideration is the loss of the largest available unit in the system. On the other hand, for composite studies to real large systems, the chronological simulation can be considered a restriction due to the time consuming. An alternative to the use of non-sequential Monte Carlo with memory has been proposed for these cases [63].

Recently, two new approaches have been proposed to mitigate the problem described before. Both have combined MCS with intelligent tools as neural networks [145], [85]. The first approach has proposed the use of neural networks (ANNs) based on self-organizing map (SOM), combined with MCS to evaluate composite reliability. This approach has presented limitations to estimate some reliability indices. The latter has used a neural network based on Group Method Data Handling (GMDH) combined with non sequential MCS. A polynomial network was used to classify the operating states during the Monte Carlo sampling. The main idea of this second approach is to provide a centralized simulation process with an intelligent memory, based on polynomial parameters, so as to speed up the evaluation of the operating sampled states. Therefore, a complete range of reliability indices, from the traditional indices (LOLE, LOLF, etc) up to well-being indices (Prob{H}, Freq{M}, etc) can be estimated through the use of this memory. A complete description of these procedures may be found in the cited literature [85], [146].

The aim of this section is to provide some basic knowledge about these procedures in order to incorporate these intelligent topics in the list of possible improvements to the power agent platform, especially focusing on the proposed SE agent. As it has been cited before, there is a natural movement towards intelligent topics in the reliability assessment of power systems.

6.4.3. INDEX CALCULATION PROCESS

One of the main sub-tasks of the problem of reliability assessment is concentrated in the third stage, in which the indices are in fact estimated and the control of the simulation is

performed. In fact, the task of calculating indices is crucial to define the commitment between all proposed agents. As mentioned before, if the state selection stage is driven by a statistic search based on the Monte Carlo method, the internal decision of the estimate indices in the third stage must follow the same choice for the simulation to succeed. In Chapter 4, the tasks of the IC agent were well defined through the use of the sequential Monte Carlo algorithm. In this Chapter 6, the improvement proposed through the use of the EPSO algorithm has promoted changes in the initially proposed commitment. Therefore, the tasks of the IC agent need to be revisited. Firstly, a small discussion about the stop criteria is presented.

Different from statistic-based methods, PB methods do not follow any statistic law, and therefore, they do not allow the direct calculation of a confidence interval for any result. Obviously, it constitutes a disadvantage of these methods, which needs to be further researched. Usually, there are three criteria to stop the simulation process based on PB methods (in this case EPSO algorithm):

- i. To stop after a certain number of swarm generations;
- ii. To stop after adding of a certain number of system failure states to memory;
- iii. To stop when a certain index has achieved the stability in a pre-defined interval.

Under such circumstances, some problems must be highlighted: (i) if a small number of generations are used, this will lead to inaccurate results, as an insufficient number of states will have been visited; (ii) depending on the system size and other stochastic characteristics, the memory scheme needs to be replaced to support a great number of system failures. The stop criterion used in this work is option (iii), based on the stability of the EPNS index. In other words, after a number of iterations without meaningful progress, the process is considered to have reached the neighborhood of the real value and then is stopped.

Another discussion about the sub-tasks carried out in the third stage is the effectiveness of index assessment, which continues to follow the same principle used before. The reliability indices such as LOLE, LOLF, EENS and others, are calculated using the same discrete convolution of hourly load values used in the Monte Carlo approach. Eventually, in order to make a more efficient assessment, from the computational point of view, a

chronological load model based on 8736 values (i.e. hours) transformed into a ten equivalent state Markovian model is used [63].

6.5 APPLICATION RESULTS AND DISCUSSIONS

Albeit the listed improvements could be implemented and tested, in this Chapter 6 the results and discussions will be made over the new proposed method for state selection based on the PB method. Firstly, tests were carried out with the IEEE-RTS-79 [105] generating system. Its choice is justified by two reasons: (a) it is the same system used in several publications, therefore allowing a comparison of results; (b) the exact results using the full load model with 8736 hours is known [67], which makes it possible to assess the accuracy of the achieved reliability indices, for the results with an analytical model (ANA), for the IEEE-RTS-79 based on discrete convolution model. Four reliability indices are shown: LOLE, LOLF, LOLD, and EENS. Table 6.1 shows that from a total of 32 units, there are 9 distinct cases of equal generators.

Table 6.1 – IEEE RTS-79: Generating System Data

Unit type	Unit size (MW)	FOR	Number of units
1	12	0.02	5
2	20	0.10	4
3	50	0.01	6
4	76	0.02	4
5	100	0.04	3
6	155	0.04	4
7	197	0.05	3
8	350	0.08	1
9	400	0.12	2

This allowed the chromosome coding for the EPSO algorithms to have a dimension of 9. All runs were done using a swarm of 40 particles, with a learning parameter of $\tau = 0.3$, and a communication probability of $p = 0.6$. The maximum number of iterations was 375,

meaning that 30000 fitness function evaluations were carried out and, so, 30000 states were visited. Secondly, on the IEEE RTS-96 [147] with 96 generating units, a peak load of 8550 MW and a chronological load model based on 8736 hour values transformed into a ten equivalent state Markovian model will be used. These comparisons between EPSO and MCS will be measured not only in terms of efficiency, considering a percentage of the significant visited cases against the total number of cases visited by the particles during the search, but also in terms of efficacy, evaluating the proximity of the achieved value with the exact result. Obviously, both methods are based on state space representation.

6.5.1. ACCURACY COMPARISON: ANALYTICAL, MONTE CARLO AND EPSO

Table 6.2 shows the accuracy comparison between non-sequential Monte Carlo simulation and EPSO algorithm to the IEEE-RTS-79, regarding an analytical tool [66] based on discrete convolution. As previously stated, the exact results using the full load model with 8736 hours are known [66]. Therefore, it is possible to assess the accuracy of the achieved reliability indices. In this case, the indices calculated by EPSO algorithm present an error below 1%, when compared with the analytical tool. This fact ensures that the EPSO has visited a sufficient number of meaningful states in order to present an accurate result. On the other hand, the coefficient of convergence β to the non-sequential MCS was set to 5%, which ensures an adequate result close to the result achieved with the analytical tool.

Table 6.2 – IEEE RTS-79: Accuracy Comparison

Adequacy Reliability Indices	Analytical (A)	MCS (B)	EPSO (C)	Error (%) (B $\times$ A)	Error (%) (C $\times$ A)
LOLE (hour/year)	9.394179	9.325843	9.352507	0.73	0.44
LOLF (occ./year)	2.019717	2.079906	2.010145	2.98	0.47
LOLD (hour/occ.)	4.651236	4.483780	4.679343	3.60	0.60
EENS (MWh/year)	1176.3	1200.6	1169.1	2.06	0.61

The purpose of this section is to measure the accuracy of the EPSO method, when compared with traditional methods commonly used by utilities. Obviously, if one sets up different coefficients of variation β to the MCS, different results, close to the analytical

approach, will be achieved, reducing the error between MCS and analytical tool. The main conclusion of these results is that the EPSO can perform simulation achieving accurate reliability indices.

6.5.2. EFFICIENCY COMPARISON: EPSO AND MONTE CARLO

In this section, the performance of the EPSO technique with a non-sequential MCS is compared. For this, some experiments are presented with:

- 1) the IEEE-RTS-79 (1) with 32 generating units, considering only a constant (peak) load value of 2850 MW;
- 2) the IEEE-RTS-96 (2) with 96 generating units, considering only a constant (peak) load value of 8550 MW;
- 3) the same test is repeated for the IEEE-RTS-96 (3) with 96 generating units, but now the constant (peak) load value has changed from 8550 MW to 9000 MW;
- 4) the IEEE-RTS-96 (4) with 96 generating units, an 8550 MW peak load and a chronological load model based on 8736 h values transformed into a ten equivalent state Markovian model;
- 5) the IEEE-RTS-96 (5) with 96 generating units, a 9000 MW peak load and a chronological load model based on 8736 h values transformed into a ten equivalent state Markovian model.

As mentioned before, the IEEE-RTS-79 has a 2850 MW peak load and a total 3405 MW installed capacity. This first experiment considered a load factor = 1 for this system. In other words, the load is the same during the whole operation year. The security margin of the system is 550 MW and the largest unit is 400 MW (see Table 6.1). If the system loses its largest unit, certainly it will experience a stressing operation close to the risk. In order to highlight these comments, a well-being analysis and EPNS index are presented for this system in Table 6.3. In general, this type of analysis consists of identifying the following indices: E_H , E_M , and E_R : number of hours in which the system ingresses in healthy, marginal and at risk states; and F_H , F_M , and F_R : number of occurrences in which the system ingresses in healthy, marginal and at risk states (see Chapter 3). In the IEEE-RTS-79 case (1), it is possible to see that the system has experienced 3197 hour/year in the marginal

state, and it has entered the marginal state with a frequency of 68.24 occ./yr, which can characterize a stressing operation.

Table 6.3 – IEEE-RTS Well-being and EPNS Index

Case	E_H (h)	F_H (occ./yr)	E_M (h)	F_M (occ./yr)	E_R (h)	F_R (occ./yr)	EPNS (MW)
IEEE-RTS-79 (1)	4822	49.58	3197	68.24	717	19.440	14.422
IEEE-RTS-96 (2)	8108	25.85	508	32.55	120	6.7084	2.7588
IEEE-RTS-96 (3)	6134	62.02	1844	92.23	758	30.204	21.640
IEEE-RTS-96 (4)	8735	0.37	0.86	0.42	0.14	0.0515	0.0027
IEEE-RTS-96 (5)	8729	2.03	6	2.37	1	0.3615	0.0280

Figure 6.1 presents the convergence characteristics of MCS and EPSO for a run on the IEEE-RTS-79 (1). The unilateral convergence is well illustrated.

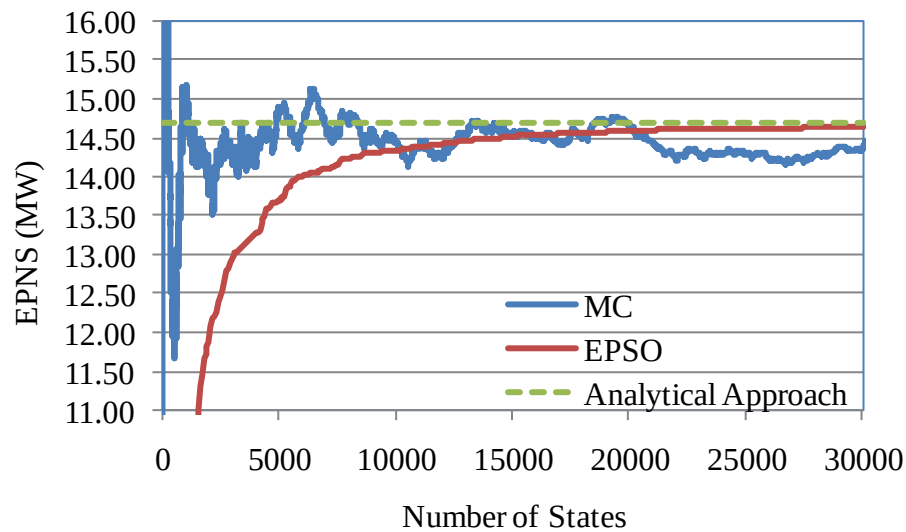


Fig. 6.4 – IEEE-RTS-79 (1): Evolution of Estimated EPNS for Both MC and EPSO

While Monte Carlo process needs to experience some EPNS values with a dashed curve oscillating around the real value (analytical result) towards the convergence criterion, the EPSO algorithm only tries to achieve the result adding values on a unique side, or making a line “asymptotically” converging to the exact result.

Considering this scenario, Table 6.4 compares the performance between MCS and EPSO for the estimation of EPNS and for different coefficients of variation β , applied to the MCS sampling.

Table 6.4 – IEEE-RTS-79: Comparison of Results from Analytical, MC and EPSO

1	ANA	EPNS (MW)	14.69575			
2	MCS	No. of States	31019	21587	7551	1865
3		β (%)	2.50	3.00	5.00	10.00
4		EPNS (MW)	14.42295	14.31442	14.54172	14.04935
5		$[\text{EPNS} \times (1 - 1.96\beta)]$	[13.71622	[13.47273	[13.11663	[11.29568
6		$\text{EPNS} \times (1 + 1.96\beta)]$	15.12967]	15.15610]	15.96681]	16.80302]
7	EPSO	EPNS (MW)	14.66185	14.62527	14.23322	11.84474
8		No. of States	30040	21500	7500	1800

Rows 4 and 5 show the limits for the confidence interval at 95% confidence level in each case. Two points should be noted: (i) the first one is that the value calculated by the EPSO method is, in all cases, inside the confidence interval obtained for the MCS; (ii) the second one is that the value obtained by the EPSO method, in 7500 analyzed states, is already inside the confidence interval, only reached by MCS after more than 31000 states sampled. Combining these analyses, it is possible to conclude that, in this scenario, the failure events are not rare, because the system is too stressed, which means that there are failure states that are contributing significantly to the reliability indices. In this case, EPSO seems to show some advantages over MCS.

The second experiment consists on the IEEE RTS-96 (2) with 96 generating units, considering only a constant (peak) 8550 MW load value. In this case, the IEEE-RTS-96 (2) has a total 10215 MW installed capacity. This experiment also considers a load factor equal 1 to the system. The security margin of this system is 1665 MW and the largest unit is still 400 MW. The same well-being analysis was performed for the IEEE-RTS-96 (2) considering a constant peak load. Table 6.3 shows that the IEEE-RTS-96 (2) remains 8108 hour/year in the healthy states and 508 hour/year in the marginal states, achieving these marginal states 32.55 times (occurrence) per year. Different from the first case, i.e. IEEE-

RTS-79 (1), if the system loses its largest unit, the security margin will be enough to keep the system far from the risk states (security margin: 1265 MW). On the other hand, the number of hours in which this system persists in risk⁴ states is still too high (120 hours). In fact, failure events are not rare because the system continues experiencing a stressing operation. However, in this case, i.e. IEEE-RTS-96 (2), the failure states are not contributing significantly to the reliability indices. A simple analysis involving EPNS, E_R and F_R indices (2.7588 MW, 120 hours and 6.7084 occ./yr, respectively) revealed a low severity of the failure events followed by a relatively low frequency, and consequently a high duration of these events. In Figure 6.5, the convergence characteristics of MCS and EPSO for a run on the IEEE-RTS-96 (2) are presented. Again, the unilateral convergence of the EPSO is well illustrated.

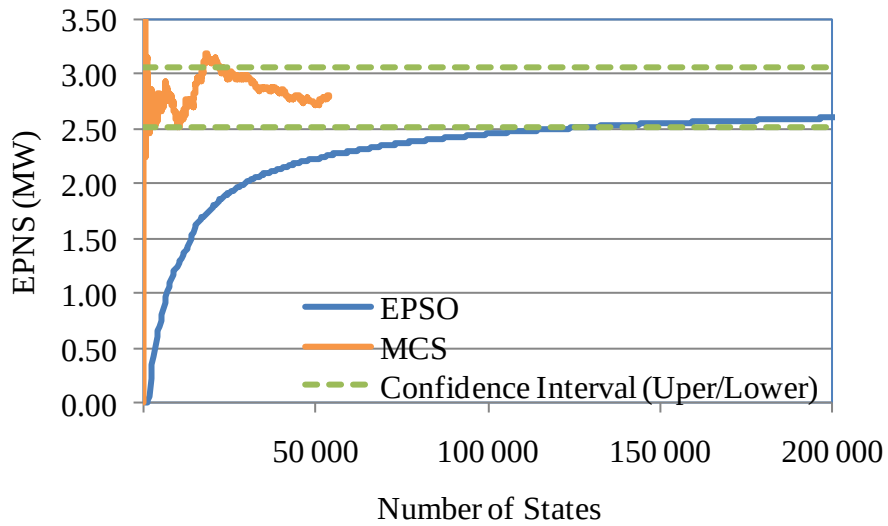


Fig. 6.5 – IEEE-RTS-96 (2): Evolution of Estimated EPNS for Both MC and EPSO

On the other hand, as opposed to the first experiment, the MCS required circa 32000 visits to system states to achieve the convergence criteria, whereas the EPSO required circa 130000 visits to system states to achieve only the lower bound of the confidence interval proposed by MCS. Combining these analyses, it is possible to conclude that, in this scenario, i.e. IEEE-RTS 96 (2), where the EPSO was tuned to the swarm of 40 particles with a learning parameter of $\tau = 0.3$, and a communication probability of $p = 0.6$, MCS seems to show some advantages over EPSO. Other EPSO tuning has revealed a small

⁴ E_R and F_R are equivalent to the LOLE and LOLF indices, respectively.

variation around the number of visited states, without contributing to the reliability assessment.

The third experiment consists on the IEEE-RTS-96 (3) with 96 generating units. Nonetheless, instead of a constant (peak) 8550 MW load value, the use of a constant (peak) 9000 MW load value is proposed. The idea is to stress the system throughout the increasing of its constant peak load, reducing the security margin from 1665 MW to 1215 MW, and maintaining the same system characteristics, such as the 400 MW largest unit. Figure 6.6 presents the convergence characteristics of MCS and EPSO for a run on the IEEE-RTS-96 (3).

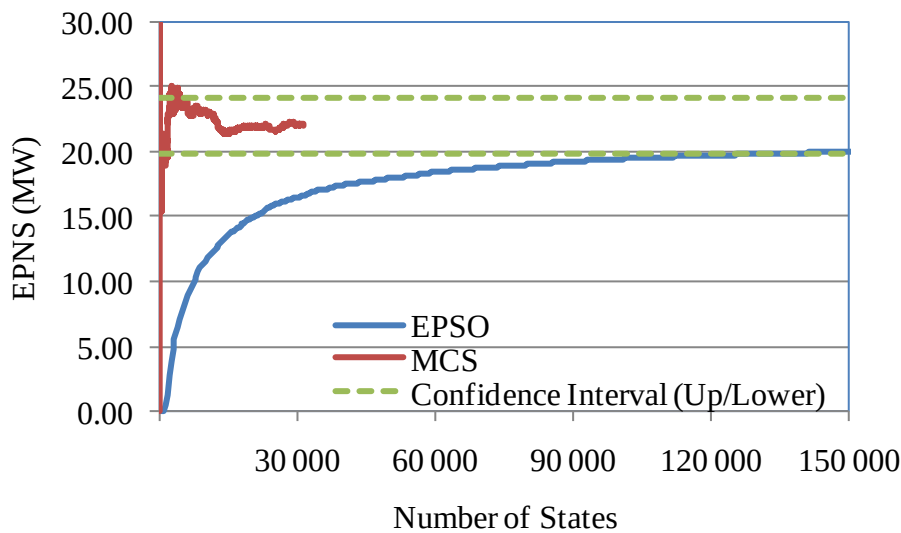


Fig. 6.6 – IEEE-RTS-96 (3): Evolution of Estimated EPNS for Both MC and EPSO

This experiment also considers a load factor equal 1 for the system. The same well-being analysis was performed for the IEEE-RTS-96 (3) considering a constant peak load. Different from the previous case, Table 6.3 shows that the system reduced from 8108 to 6134 hour/year in the healthy states and increased from 508 to 1844 hour/year in the marginal states, achieving these marginal states 92.23 times (occurrences) per year. If the system loses its largest unit, the security margin will continue being enough to keep the system far from the risk states (security margin: 815 MW). In this case, the number of hours in which this system persists in risk states increased (758 hours), when compared with the previous case, i.e. IEEE-RTS-96 (2). The failure events are not rare, and now the system is experiencing an evident stressing operation. The same simple analysis, carried

out before, involving EPNS, E_R and F_R indices (21.640 MW, 758 hours and 30.204 occ./yr, respectively) revealed that the severity also increased for the failure events, followed by a high frequency, and consequently a high duration of these events. Once again, to the same EPSO tuning (swarm of 40 particles, learning parameter of $\tau = 0.3$, communication probability of $p = 0.6$), MCS seems to show some advantages over EPSO. Although in the third case the EPNS index has revealed that the severity of each failure event (or load curtailment) has increased, regarding the first and second cases, the contribution of the index formation, caused by each failure event, to the first case was greater than to the second and third cases. A sensitivity analysis through the assessment of the unit size impact over the security margin may show the importance of the unit capacity size on index formation. As stated previously, other EPSO tuning was tried, increasing the number of visited failure states, without contributing, however, to the formation of reliability indices.

The fourth experiment consists on the IEEE RTS-96 (4) with 96 generating units, an 8550 MW peak load and a chronological load model based on 8736 values transformed into a ten equivalent state Markovian model. The idea is to dramatically reduce the system stress as shown in Table 6.3 and to perform a simulation, considering the original load factor for this system (0.61). In this case, the system has experienced less than 1 hour/year in the marginal state (see Table 6.3). Table 6.5 shows the results obtained for the IEEE-RTS 96 (4). The target coefficient of variation was $\beta = 5\%$ to the EENS index.

Table 6.5 – IEEE-RTS-96 (4): Comparison of Results from Analytical, MC and EPSO

Indices	Analytical	MCS	EPSO
LOLP	1.58694×10^{-5}	1.61081×10^{-5}	1.51430×10^{-5}
LOLE (h/yr)	0.138635	0.140721	0.132293
EPNS (MW)	0.002777	0.002743	0.002590
EENS (MWh/yr)	24.26002	23.97020	22.62624
LOLF (occ./yr)	0.052875	0.051543	0.050420
No. of States	-	45 567 000	400 200

The MCS required circa 45 million visits to system states in order to converge and produce all results, while the EPSO has required only circa 400 thousand visits to enter the confidence interval defined by the same β . The analytical results are included to make it possible to gauge the quality of the obtained results.

In this case, the failure events can be considered very rare and the system is not stressed. Currently, the state selection process conducted for the fitness function can perform an efficient search when the system failures are very rare. In this case, while MCS applied brute force to explore the state space, EPSO tries to visit only the meaningful states in the space. In these conditions, EPSO seems to show some advantages over MCS.

In order to ensure the last conclusions, a fifth experiment is proposed, which consists on the IEEE RTS-96 (5) with 96 generating units, a 9000 MW peak load and a chronological load model based on 8736 hour values transformed into a ten equivalent state Markovian model. The aim is not only to increase the system stress a little bit, bearing in mind the last experiment shown in Table 6.3, but also to perform a simulation, taking into account the original load factor for this system (0.61). In this case, the system has experienced less than 6 hour/year in the marginal state (see Table 6.3). Table 6.6 shows how sensitive the results obtained for the IEEE-RTS-96 are (5) as far as the system stress is concerned.

Table 6.6 – IEEE-RTS-96 (5): Comparison of Results from Analytical, MC and EPSO

Indices	Analytical	MCS	EPSO
LOLP	1.349061×10^{-4}	1.294588×10^{-4}	1.30×10^{-4}
LOLE (h/yr)	1.178540	1.130952	1.135040
EPNS (MW)	0.027322	0.028017	0.025795
EENS (MWh/yr)	238.6861	244.7595	225.3534
LOLF (occ./yr)	0.410037	0.361592	0.395097
No. of States	-	5 870 600	400 200

In fact, several factors may have an influence on the performance (i.e. accuracy, number of visited states and CPU time) of all the three methods (i.e. Analytical, PB and MCS). Among these factors, the following can be listed: system size, rarity of the failure event, number of different units, unit capacity sizes and load shape (load factor). Some of these

factors are interconnected and also related with other factors. For instance, event rarity is related to failure/repair rates and to other previously listed factors. Moreover, time dependent sources like wind generation, can also be dealt with PB methods (and, obviously, with the MCS), as it was shown in other relatively successful works [104]. Clearly, each method will have its best perform under very specific conditions. Undoubtedly, the proposed PB method, the EPSO algorithm, has demonstrated to be a serious challenger for the other two traditional methods.

6.6 FINAL REMARKS

This chapter has listed some improvements, which may be incorporated into the power agent platform proposed. Firstly, it started discussing the architecture proposed in Chapter 4 through the classification of those agents. A simple discussion about BDI architecture and an example involving balance between agent tasks was proposed. The main target of this chapter was to discuss some hard inherited characteristics of the agent technology, such as flexibility, aiming to find a better way for the agents to pursue their goal of estimating reliability indices. Therefore, in order to estimate reliability indices, other approaches, such as the non-sequential MCS and PB methods based on EPSO algorithm, were tested as flexible options for the agents. Population-based (PB) methods have proved to be a promising alternative approach to the MCS in non-chronological power system reliability assessment. From a theoretical point of view, PB methods can only be efficient when the cardinal of the set of states contributes to an index that is not too large (one must remember that this is an additive method). A weaker condition is that, although the cardinal of the set of states contributing to an index is larger, a subset of states with significant contributions to the index is not too large (this makes it possible for a much larger subset of states to co-exist, only contributing in extremely small amounts to the index under calculation).

When competing with MCS, it can also be assumed that PB methods gain advantage when the set of states contributing to the index is small, comparatively to the whole set of possible states. A reason for this to happen may be found in the fact that, in these cases, the MCS usually takes more iterations to converge, while the coverage of the set of contributing states is done more efficiently by PB methods.

PB methods are not statistic-based approaches and, therefore, no confidence interval has been calculated. However, they can be tuned with the MCS and with fast analytical convolution (FAC) methods as well to ensure the correct stopping criterion. Moreover, PB methods may be considered as excellent competitors to FAC-based methods, and also to MC-based methods equipped with variance reduction techniques. Finally, this work makes it possible to open another research frontier to tackle power system reliability assessment.

Chapter 7

SUMMARY AND CONCLUSIONS

7.1 INTRODUCTION

The development of power systems always poses new challenges in a world that is ever changing, where levels of reliable electrification need to be increased to cover the human being's natural dependence on electricity. Along the past 60 years, engineers have witnessed electric power systems becoming larger and more complex, mainly due to the unprecedented growth in the demand for electricity, coupled with population growth and the higher standards demanded by society. On the other hand, the ordinary citizen has no idea of the expensive, large, and complex system that enables him/her just to turn on the light, for instance, in the kitchen of his home. These complexities range from technical challenges, where green power must be taken into consideration for the following years, up to regulatory subjects involving several types of professionals in a variety of areas.

On the technology front, the penetration of new materials and system paradigms for efficient electric power systems, including green power, distributed generation, smart grids, micro-grids, and others, will depend on a set of efficient computation and analysis tools. These tools must be able to provide the flexible models to the engineers, promoting changes in the way that power systems are designed, planned, operated, and managed. Today, the monitoring, control, protection and automation of these systems in real time are becoming a reality. Undoubtedly, agent-based technology has already constituted this reality, providing flexible and autonomous software systems to solve a growing number of complex problems.

This thesis has introduced agent-based technology into two distinct areas of power systems: simulation and modeling and conflict solutions, in order to encourage engineers in the development of a new generation of tools with singular characteristics in computation and analysis. Firstly, a methodology based on the sequential Monte Carlo simulation to operational reserve assessment was presented through the use of real systems. The methodology focused on systems in which a great share of the production is based on green power. Sequential Monte Carlo simulation was chosen due to its suitable characteristic in capturing and representing time-dependent detailed models, such as wind and solar fluctuations, cogeneration policies, as well as hydro inflows. The power of this method was explored through the calculation of several traditional and preventive

reliability indices, such as LOLE, EENS and well-being analysis, including the distributional aspects associated with all system index mean values. On the other hand, the computational cost associated with these detailed models in a centralized software solution was emphasized throughout CPU time measures, as well as through the use of different configurations for those systems. The purpose was to highlight the existing connection between performance simulation and system characteristics. It was proved that different system characteristics, such as failure rates, repair times, unit capacity size and system size, reserve levels, load factor and others, will lead to different CPU costs.

One of the basic objectives of the research work described in this thesis was to develop comprehensive and efficient software architecture design to perform power system reliability studies. Therefore, this thesis extends some of the existing techniques to the reliability assessment of power systems usually applied to centralized software solutions. With the purpose of exploring agent-based technology, an agent reactive architecture based on the sequential Monte Carlo simulation was firstly proposed to assess reliability indices. Taking the distributed capacities of the multi-agent systems into consideration, two approaches named synchronized and non-synchronized approaches, were tested to estimate reliability indices. Both have presented advantages in speed up and efficiency with particularities in the commitment between the proposed agents. Essentially, the task of estimating reliability indices was successful when applied under an agent-based concept, mitigating the CPU time emphasized before. In the first part of the work, the power agent platform has proved to be an efficient and flexible tool to estimate reliability indices based on the sequential Monte Carlo simulation. It specifically opens the way to introduce some artificial intelligent topics in each reactive agent proposed. The main initial target of the platform was to prepare the way for a potential deliberative architecture, in which agents may present some deliberative behavior.

There is an increasing interest in economic optimization approaches for the coordination of power system critical activities. With a decentralized structure, where a set of assets belong to different companies, tools to solve conflict solutions in power systems, in which a unique interest is considered, must be avoided. This thesis has also proposed the use of agent-based technology to discuss the maintenance schedule of generating units. Due to the particular characteristic of the maintenance problem, a suitable environment where users and computer programs can interact to discuss maintenance schedule priorities was

implemented and tested so as to provide guidance to a fair planned outage. The potential of the communication between agents has shown that it is possible to build a dedicated set of performatives and a singular ontology to the maintenance schedule problem, promoting a suitable environment where ISOs, Gencos, Transcos, Discos, and other important entities of the power industry could participate in scheduled outages. Again, the maintenance discussions were supported by the sequential Monte Carlo approach, mainly due to the mandatory time dependence on the characteristic imposed by the maintenance schedule problem. Combining both potential tools and the sequential Monte Carlo simulation with a dedicated agent-based environment, an efficient, open and fair way to discuss risk-based level was suggested to the overall system due to planned outages in a power market using a distributed tool.

Reliability evaluation of a complete electric power system including generation, transmission and distribution facilities is normally not conducted due to the huge dimension of the problem. Instead, reliability studies of generation facilities, of composite generation and transmission systems, as well as of distribution system segments are conducted independently. For this reason, in the last years researchers have been presented with several ways to minimize computational effort in this type of studies. This thesis has dedicated a detailed analysis of the recent contributions to mitigate CPU time in reliability assessment, aiming to create a suitable power agent platform in which reliability studies could be performed in power systems with distinct characteristics. Therefore, this thesis has intended to create an agent-based simulation environment where the task of estimating reliability indices could be evaluated through the use of different agents. Individually, the agents are able to carry out their tasks using different ways and, collectively, the agent works to achieve the best possible performance. A natural transition towards computational intelligence techniques in reliability studies was highlighted. A new agent architecture, where reliability studies are performed, was proposed in order to make power system reliability assessment feasible for large real practical systems.

7.2 THESIS CONTRIBUTIONS

The design of the power system software has always been very conservative within the power system area, perhaps due to the narrow commitment between mathematical representations and precise models. Usually, this commitment requires computational tools with special characteristics, such as speed and efficiency, to deal with heavy mathematical problems. Therefore, the use of programming languages such as FORTRAN, C, among others, has been part of the choices made by engineers in software development. Changes in the software design for the power system problems were proposed in this thesis in order to make some large and complex power system studies feasible. Thus, the main contributions of this thesis could be summarized as:

- Using modern and sophisticated software design techniques to address the traditional power system reliability assessment;
- Introducing agent-based technology in power systems simulation and analysis;
- Proposing a multi-agent architecture design in which it is possible to combine several related techniques, such as Monte Carlo, Population-Based methods, Neural networks and distributed processing, in order to address power system reliability assessment;
- Suggesting a suitable environment to make maintenance schedule discussions feasible in the power system with an open energy market;
- Encouraging power system engineers to develop software systems using non-traditional programming languages such as Java, in order to solve power system problems;
- Combining the flexibility of Java language, aiming to create flexible models, with the speed and efficiency characteristics of FORTRAN language in order to achieve a better performance, through the use of encapsulation techniques.

7.3 FUTURE RESEARCH

The research conducted in this thesis lays its foundations on agent-based software tools to make the reliability assessment of power systems feasible. The intention was to start the power agent platform, aiming to show that it is possible to build software system equipped with a broad spectrum of technologies and tools, such as heuristic tools, distributed processing, intelligent search techniques, learning systems, and others. This thesis is concluded with a discussion on several possible improvements on the power agent platform, which can be listed as future researches on agent-based technology.

- In order to incorporate EPSO algorithm as an option to the state selection process, it is necessary to identify a better stop criterion for this type of method, in which would be possible to define a confidence interval for the calculated index;
- Identifying ways to promote a better balance between tasks, signaling performance measures to guide the agent decisions;
- In order to achieve a deliberative architecture for the power agent platform, some concepts about the BDI model could be explored. The agent could make feasible automatic deliberations, such as the best method to use in a certain specific power system;
- Exploring the understanding of power systems factors that influence the simulation performance;
- Exploring other important multi-agent characteristics, such as *robustness*, *social*, *pro-activeness*;
- It is necessary to implement a complete set of reliability tools in the power agent platform, including composite generation and transmission system, as well as distribution systems;
- Integrating machine learning algorithms within the agent actions in order to allow the agent, not only to learn the characteristics of its environment and make faster decisions, but also to allow the agent to exhibit a more autonomous behavior.

- Exploring other power system problems on the simulation environment provided by the power agent platform;
- Developing a set of specific performatives and ontology for conflict solution in the power system industry;
- Improving the agent-based environment to coordinate maintenance schedule discussions;
- Exploring some optimization techniques as support to the strategies for the agent negotiations within the maintenance schedule problem;
- Exploring negotiation strategies that support more than two players in order to promote different levels of interactions.

7.4 SUMMARY OF PAPERS

In the context of this thesis, the candidate has been involved with a research team, in which several works about operating reserve assessment based on the sequential Monte Carlo approach were developed. As a result of the research project, four papers have been sent to the specialized conferences in the power system area. Besides this thesis document, other four papers were sent to the journals and specialized periodicals on power system research, making a total of 8 publications, as follows:

Journals Papers:

1. Mauro A. da Rosa, Armando M. Leite da Silva, and Vladimiro Miranda - Multi-Agent Systems Applied to Reliability Assessment of Power Systems, *International Journal of Electric Power & Energy Systems*. Submitted in 2008.
2. V. Miranda, L. Carvalho, M. Rosa, A.M. Leite da Silva, C. Singh - Improving Power System Reliability Calculation Efficiency with EPSO Variants, *IEEE Transactions on Power Systems*. Accepted in 2009.
3. M. Matos, J.P.Lopes, M. Rosa, R. Ferreira, A.M. Leite da Silva, W. Sales, L. Resende, L. Manso, P. Cabral, M. Ferreira, N. Martins, C. Artaiz, F. Soto, R. López –

“Probabilistic Evaluation of Reserve Requirements of Generating Systems with Renewable Power Sources: The Portuguese and Spanish Cases”, *International Journal of Electric Power & Energy Systems*. On line available since 2009.05.05: <http://dx.doi.org/10.1016/j.ijepes.2009.03.031>.

4. Mauro A. da Rosa, Armando M. Leite da Silva, Vladimiro Miranda, Manuel Matos and Gerald Sheblé – Multi-Agent Environment to Coordinate Maintenance Schedules Discussions, *IET: The Institution of Engineering and Technology*. To be Submitted in 2009.

Conference Papers:

1. M. Matos, J.P.Lopes, M. Rosa, R. Ferreira, A.M. Leite da Silva, W. Sales, L. Resende, L. Manso, P. Cabral, M. Ferreira, N. Martins, C. Artaiz, F. Soto, R. López – “Probabilistic Evaluation of Reserve Requirements of Generating Systems with Renewable Power Sources: The Portuguese and Spanish Cases” PSCC 2008.
2. J.P Lopes, M. Matos, P. Cabral, M.P. Sampaio Ferreira, C. Artaiz, F. Soto, M. Rosa, R. Ferreira, A.M. Leite da Silva – “Dealing with intermittent generation in the long-term evaluation of system adequacy and operational reserve requirements in the Iberian Peninsula” CIGRE 2008.
3. C. Artaiz, M.I. Docavo, P. Cabral, N. Martins, M.N. Tavares, M. Matos, M. Rosa, R. Ferreira, A.M. Leite da Silva - “Evaluación de los niveles adecuados de Reserva de Operación en los Sistemas Eléctricos Ibéricos a medio y largo plazo” ERIAC 2009.
4. Mauro A. da Rosa, Armando M. Leite da Silva, Vladimiro Miranda, Manuel Matos and Gerald Sheblé - *Intelligent Agent-based Environment to Coordinate Maintenance Schedules Discussions*, ISAP: Intelligent Systems Applied to Power Systems . Submitted in 2009.

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APPENDIX A

Table A – Weekly System Reliability Indices for IEEE-RTS-86

Week	LOLP	β	LOLE	β	EENS	β	EPNS	β	LOLF	β	LOLD	β
(id)		(%)	(h/week)	(%)	(MWh/week)	(%)	MW	(%)	(oc./week)	(%)	(h)	(%)
1	0.0009	25.5	0.152	25.5	18.43	34.4	0.11	34.4	0.031	21.0	4.859	31.7
2	0.0018	17.5	0.305	17.5	28.93	24.5	0.17	24.5	0.076	13.1	4.002	21.1
3	0.0011	24.3	0.184	24.3	24.55	34.4	0.15	34.4	0.037	17.5	4.953	28.9
4	0.0002	39.4	0.041	39.4	3.92	62.5	0.02	62.5	0.011	30.4	3.888	46.3
5	0.0007	22.5	0.115	22.5	10.53	33.9	0.06	33.9	0.035	18.8	3.262	27.7
6	0.0005	25.5	0.083	25.5	7.79	31.4	0.05	31.4	0.022	21.5	3.856	31.2
7	0.0004	39.3	0.062	39.3	8.40	67.5	0.05	67.5	0.013	26.9	4.622	45.3
8	0.0001	58.3	0.019	58.3	0.97	65.6	0.01	65.6	0.006	53.4	2.982	69.4
9	0.0001	67.7	0.011	67.7	0.89	76.8	0.01	76.8	0.004	58.6	3.088	75.7
10	0	62.3	0.003	62.3	0.04	92.6	0.00	92.6	0.002	61.2	1.500	37.0
11	0	100.0	0.000	100.0	0.01	100.0	0.00	100.0	0.000	100.0	1.000	100.0
12	0.0001	59.2	0.014	59.2	1.43	65.4	0.01	65.4	0.005	54.7	3.020	68.8
13	0	100.0	0.000	100.0	0.00	100.0	0.00	100.0	0.000	100.0	0.000	0.0
14	0	72.1	0.005	72.1	0.13	72.4	0.00	72.4	0.002	70.7	2.500	67.8
15	0	79.1	0.004	79.1	0.51	97.5	0.00	97.5	0.002	66.3	1.780	73.3
16	0.0002	46.3	0.041	46.3	4.25	67.5	0.03	67.5	0.011	34.1	3.611	54.0
17	0	63.2	0.003	63.2	0.27	83.1	0.00	83.1	0.002	61.2	1.875	50.0
18	0.0005	38.3	0.086	38.3	14.57	65.6	0.09	65.6	0.016	24.5	5.529	43.8
19	0.0008	23.8	0.136	23.8	15.37	30.8	0.09	30.8	0.028	19.5	4.947	29.3
20	0.0011	20.1	0.180	20.1	12.01	23.7	0.07	23.7	0.045	17.3	4.047	25.4
21	0.0006	24.3	0.102	24.3	11.45	44.4	0.07	44.4	0.025	19.4	4.028	29.3
22	0.0004	34.8	0.064	34.8	5.37	39.0	0.03	39.0	0.012	30.7	5.344	43.6
23	0.0016	17.1	0.272	17.1	32.31	25.4	0.19	25.4	0.060	14.1	4.551	21.3
24	0.0015	19.7	0.257	19.7	29.37	26.9	0.17	26.9	0.056	16.3	4.586	24.7
25	0.0017	15.2	0.292	15.2	29.68	21.3	0.18	21.3	0.063	13.4	4.645	19.4
26	0.0007	28.2	0.110	28.2	8.94	36.6	0.05	36.6	0.026	21.5	4.215	33.9
27	0	93.7	0.004	93.7	0.22	96.2	0.00	96.2	0.001	70.7	3.958	85.7
28	0.0001	52.7	0.013	52.7	0.74	53.4	0.00	53.4	0.003	47.1	4.578	60.0
29	0.0002	48.0	0.034	48.0	2.22	53.9	0.01	53.9	0.008	45.9	4.303	60.3
30	0.0017	19.7	0.279	19.7	35.17	27.3	0.21	27.3	0.055	14.9	5.104	23.9
31	0	86.5	0.006	86.5	0.23	94.1	0.00	94.1	0.003	76.9	1.781	85.4
32	0.0001	62.9	0.017	62.9	1.70	69.5	0.01	69.5	0.005	64.8	3.792	75.0
33	0.0002	38.1	0.032	38.1	2.16	48.9	0.01	48.9	0.013	33.9	2.394	46.3
34	0	91.4	0.001	91.4	0.01	94.1	0.00	94.1	0.001	70.7	0.550	100.0
35	0	100.0	0.001	100.0	0.02	100.0	0.00	100.0	0.000	100.0	3.000	115.5
36	0	100.0	0.004	100.0	0.12	100.0	0.00	100.0	0.001	100.0	3.000	73.7
37	0.0002	45.2	0.035	45.2	3.36	52.9	0.02	52.9	0.011	39.5	3.182	55.3
38	0	100.0	0.002	100.0	0.04	100.0	0.00	100.0	0.001	100.0	2.000	122.5
39	0	100.0	0.001	100.0	0.13	100.0	0.00	100.0	0.000	100.0	3.000	115.5
40	0	79.0	0.002	79.0	0.06	96.2	0.00	96.2	0.001	70.7	2.000	25.1
41	0	84.5	0.008	84.5	0.50	94.7	0.00	94.7	0.002	79.0	4.329	87.0
42	0	100.0	0.000	100.0	0.00	100.0	0.00	100.0	0.000	100.0	0.000	0.0
43	0.0004	49.9	0.060	49.9	7.79	64.5	0.05	64.5	0.015	36.9	3.972	59.1
44	0.001	19.4	0.160	19.4	14.10	25.2	0.08	25.2	0.039	16.4	4.153	24.1
45	0.0018	19.9	0.304	19.9	40.18	26.2	0.24	26.2	0.069	15.1	4.417	24.2
46	0.0022	16.2	0.362	16.2	45.35	23.9	0.27	23.9	0.080	12.6	4.508	19.8
47	0.0034	11.8	0.575	11.8	64.58	19.9	0.38	19.9	0.152	9.5	3.774	14.6
48	0.0018	17.4	0.301	17.4	37.87	25.8	0.23	25.8	0.070	13.2	4.286	21.1
49	0.0038	11.6	0.642	11.6	75.90	16.5	0.45	16.5	0.150	9.9	4.291	14.7
50	0.0062	10.4	1.046	10.4	139.45	14.6	0.83	14.6	0.209	8.5	5.009	13.0
51	0.0107	8.2	1.789	8.2	251.07	10.5	1.49	10.5	0.337	6.8	5.305	10.3
52	0.0049	10.7	0.827	10.7	104.60	15.6	0.62	15.6	0.187	8.8	4.418	13.4