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Cost Allocation Model for Distribution Networks Considering Flexibility from Distributed Energy Resources

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Abstract

The world is in continuous transformation, and the way of operation and structure of the energy distribution system as well. The continuous increase of distributed generation, electric vehicles and energy storage systems is changing the planning, operation and management of distribution networks.

Several factors contribute to the transformation of the distribution network, among them is the liberalization of the energy market. Consequently, more users have joined the energy market. Another factor is the proliferation of renewable energy sources, electric vehicles and energy storage systems, technologies that allow to reduce the dependence of fossil fuels and therefore reduce the GHG emissions.

The conventional operation of the power systems implies the unidirectional power flow, in which goes from producer to the user, and all the operation costs are assigned to the user. With the distribution generation (namely renewable energy resources, electric vehicles and storage energy systems), power can also be injected into medium and low voltages levels leading to a bidirectional power flow. The bidirectional power flow entails new challenges to solve, such as problems of line congestions, increase of voltage level, increase of losses in low voltage and more variables to be considered to determine the impact that each user has in the distribution network.

This work arises from the need to study the impact of these innovations in the network and help develop a methodology that allows to represent and allocate more accurately, fairly and economically the costs and impacts of all users of the distribution network. This work comprises three different stages. Firstly, an energy resource scheduling to meet the demand is performed. Secondly, two different power tracing methods (namely, Abdelkader and Bialek) are compared and used to determine the impact that each generator has on the loads and lines of the distribution network. Finally, a variation of the MW-mile method is used to determine and distribute the network usage, congestion and line losses.

The proposed methodology has been simulated, tested and validated on a 33-bus distribution network considering a wide range of distributed energy resources such as wind farms, small-hydro, photovoltaic, cogeneration, fuel cells, biomass, waste-to-energy, demand response programs, energy storage units and electric vehicles.

Regarding the network usage, congestion and line losses, it was considered that the loads would account for 50% of the costs and generators would responsible for the other 50%. The results of the proposed methodology were analyzed, and the proper conclusions were withdrawn.

Sumário

O mundo está em continua transformação e as metodologias de operação e a estrutura do sistema de distribuição de energia elétrica também. A crescente integração de produção distribuída, veículos elétricos e unidades de armazenamento de energia elétrica estão a mudar o planeamento, operação e a gestão das redes de distribuição.

Diversos fatores têm contribuído para a transformação da rede de distribuição, entre elas a liberalização do mercado de energia elétrica, o que tem conduzido a um aumento de utilizadores da rede. Outro fator prende-se com a proliferação do uso de energias provenientes de fontes renováveis, veículos elétricos e sistemas de armazenamento de energia elétrica, tecnologias que contribuem para uma redução da dependência de combustíveis fósseis e consequentemente redução das emissões de gases com efeito de estufa.

No antigo paradigma da distribuição de energia elétrica, o fluxo de energia elétrica era unidirecional, a energia era produzida de forma centralizada e era transmitida aos utilizadores através da rede de transporte/distribuição até aos utilizadores finais. Estes utilizadores finais arcavam com todos os custos de operação da rede de transporte. Com a crescente penetração de produção distribuída (integração de produção de energia proveniente de fontes de energia renováveis, veículos elétricos e unidades de armazenamento de energia elétrica), pode ser injetada energia em níveis de média e baixa tensão levando ao aparecimento de fluxos bidirecionais de energia. Os fluxos bidirecionais de energia trazem novos desafios à rede, como congestionamentos das linhas, aumento dos níveis de tensão, aumento das perdas resistivas em baixa tensão e também o aumento do número de variáveis a ter em conta de forma de forma a determinar o impacto que cada utilizador tem na rede de distribuição.

Este trabalho surge da necessidade de estudar o impacto destas transformações na rede de distribuição e ajudar a desenvolver uma metodologia de alocação de custos da mesma que represente de forma mais precisa, justa e económica o impacto que cada utilizador tem na utilização da de rede de distribuição de energia. Este trabalho é composto por três fases. Na primeira fase é realizado um despacho dos recursos energéticos do sistema de forma a que todas as cargas sejam alimentadas. Na segunda fase, dois métodos diferentes *de power flow tracing* são utilizados e comparados (nomeadamente, os métodos de Abdelkader e Bialek) para determinar o impacto que cada gerador tem em cada carga e em cada linha da rede de distribuição. Finalmente, é utilizada uma variação do método MW-mile para determinar e distribuir os custos de utilização da rede, custos de congestionamentos e custos das perdas.

A metodologia proposta foi simulada, testada e validada numa rede de distribuição de 33 barramentos que integra uma grande diversidade de recursos energéticos como parques eólicos, mini-hídricas, parques fotovoltaicos, cogeração, células de combustível, biomassa,

resíduos sólidos urbanos, programas de *demand response*, unidades de armazenamento de energia elétrica e veículos elétricos.

Em relação ao uso da rede, congestionamentos e perdas na linha, considerou-se que as cargas representariam 50% dos custos e os geradores seriam responsáveis pelos outros 50%. Os resultados da metodologia proposta foram analisados e as devidas conclusões foram retiradas.

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Abbreviations

Acronyms

AC	Alternating current;
CHP	Combined Heat and Power;
DC	Direct current;
DR	Demand response;
DER	Distributed Energy Resources;
DG	Distribution generation;
EBE	Equivalent Bilateral Exchanges;
ESS	Energy storage systems;
EV	Electric Vehicles;
GGDF	Generalized Generation Distribution Factor;
GLDF	Generalized Load Distribution Factor;
LMP	Locational marginal price;
NGDF	Nodal Generation distribution factor;
OPF	Optimal power flow;
PS	Power System;
PF	Power Flow;
PFT	Power Flow Tracing;
PSP	Proportional Sharing Principle;
RES	Renewable Energy Sources;
TGDF	Topological generation distribution factor;
TC	Transmission Costs
WtE	Waste to Energy;
V2G	Vehicle to grid;

Indices

dg	Distribution generation index;
Ij	Node index;
sp	External suppliers index;
st	Energy storage system index;
t	Time index;

Symbology

α	Is a very small, positive number, set to 10^{-8}.
α_N,	Set of negative elements in row *i*;
α_P,	Set of positive elements in row *i*;
$\alpha_i^{(u)}$	Set of nodes supplying straight node *i;*
η_c	Grid-to-storage/vehicle efficiency;
η_d	Storage/vehicle-to-grid efficiency;
A_{ij}	Contribution of a generator to the power flow in a line;
B	Imaginary part of admittance matrix;
B_{ij}	Imaginay part of admittance matrix (S);
$C_{(i)}^{Fix}$	Fixed cost line *i;*
$C_{DG(i,dg)}^{Fix}$	Total fixed cost caused by generator *dg* in line *i*;
$C_{DR(i,dr)}^{Fix}$	Total fixed cost caused by demand response *dr* in line *i*;
$C_{ESS(i,ess)}^{Fix}$	Total fixed cost caused by demand response *ess* in line *i*;
$C_{L(i,l)}^{Fix}$	Total fixed cost caused by load *l* in line *i*;
$C_{V2G(i,v2g)}^{Fix}$	Total fixed cost caused by V2G *v2g* in line *i;*
$C_{DG(i,dg)}^{Loss}$	Total loss cost by generator *dg* in line *i*;
$C_{DR(i,dr)}^{Loss}$	Total loss cost caused by demand response *dr* in line *i*;
$C_{ESS(i,ess)}^{Loss}$	Total loss cost caused by ESS *ess* in line *i*;
$C_{L(i,l)}^{Loss}$	Total loss cost caused by Load *l* in line *i*;
$C_{V2G(i,v2g)}^{Loss}$	Total loss cost caused by V2G *v2g* in line *i*;
$C_{Branch(i,j)}^{NetUse}$	Network use cost;
$C_{Branch(i,j)}^{NetUseA}$	Network use costs for condition A;
$C_{Branch(i,j)}^{NetUseB}$	Network use costs for condition B;
$C_{Branch(i,j)}^{NetUseC}$	Network use costs for condition C;
$C_{DG(i,dg)}^{NetUse}$	Total Network use cost by generator *dg* in line *i*;
$C_{DR(i,dr)}^{NetUse}$	Total network use cost cost caused by demand response *dr* in line *i*;
$C_{ESS(i,ess)}^{NetUse}$	Total Network use cost caused by ESS *ess* in line *i*;

$C_{L(i,l)}^{NetUse}$	Total Network use cost cause by load l in line *i*;
$C_{V2G(i,v2g)}^{NetUse}$	Total Network use cost caused by V2G v2g in line *i*;
CA_K	Cost related to the transit in the line k;
CB_K	Cost of the capacity not used for line k;
C_k	Cost of line *k* (u.m.);
c_{ji}	Total supplementary charge;
CT	Transmission total cost (k(u.m.));
$D_{i-j,k}^{L}$	Topological generation distribution factor in line *i-j;*
F_i	Flow in line i;
f_{ij}	Power extracted from bus *i* by line *j*;
$F_j.(P_j)$	Cost function of the jth generating units (u.m./h);
F_k	Flow in line k in the initial conditions (MW);
$F_k(u)$	Impact of transaction *u* in line *k* (MW);
G_{ii}	Real part of admittance matrix (G);
k	Circuit that conects the bus *i* with bus j
L	Branches Losses (KW);
L_k	Length of the line *k* (km);
N_B	Number of resources that contains imaginary part in admittance matrix(S);
N_L	Total number of lines connect to the node;
N_g	Is the total number of generators in the power system;
P	Vector of nodal through-flows;
$P_{Ch(ess,t)}^{i}$	Active Power charged by ESS;
$P_{Ch(v2g,t)}^{i}$	Active Power charged by V2G;
$P_{DR_{A(l,t)}}^{i}$	Active power reduction by load;
$P_{DR_{B(l,t)}}^{i}$	Active power curtailment by load;
$P_{DG(dg,t)}^{i}$	Active Power production by DG;
$P_{Dch(ess,,t)}^{i}$	Active Power discharged by ESS;
$P_{Dch(v2g,t)}^{i}$	Active Power discharged by V2G;
P_G	Vector of nodal generation;
$P_{GCP(dg,t)}^{i}$	Generation curtailment power;
P_{Gi}	Generation at node *I;*
$P_{Load(l,t)}^{i}$	Load consumption;
$P_{NSD(l,t)}^{i}$	Not supplied demand;
P_g	Power produced by the generator g*;*
P_{i-j}	Line flow from node *i* to node *j;*
P_j	Real output of the jth generating units in (MW);
$Q_{DG(dg,t)}^{i}$	Reactive Power production of a generator;

$Q^{i}_{Load(l,t)}$	Reactive Power consumed by the load;
$Q^{i}_{NSD(l,t)}$	Reactive Power non-supplied to the load;
$Q^{i}_{SP(sp,t)}$	Reactive Power introduced by the external supplier;
$R(u)$	Allocated cost to user *u;*
$RA(u)$	Base Capacity;
$RB(u)$	Additional capacity;
S	Apparent power flow in branch (KVA);
T	Total number of periods;
$Total\ Cost_{DG(dg)}$	Total cost caused by DG;
$Total\ Cost_{DR(dr)}$	Total cost caused by DR;
$Total\ Cost_{L(l)}$	Total cost caused by load;
$Total\ Cost_{ESS(ess)}$	Total cost caused by ESS;
$U^{-}_{i(t)}$	Voltage in polar form at bus i;
$V_{i\ (t)}$	Voltage at node i*;*
c_{ji}	Total supplementary charge
$y^{-}_{ij(t)}$	Series admittance of line that connects buses i j;
$y^{-}_{sh_j}$	Shunt admittance of line that connects two buses;
$R(u)$	Allocated cost to user *u;*
$RA(u)$	Base capacity;
$RB(u)$	Adicional capacity;

<u>Subscript</u>

A	Fixed component of cost function (m.u./h);
B	Linear component of cost function (m.u./kWh);
$BatMax$	Battery maximum capacity;
BatMin	Battery minimum capacity;
Ch	Storage or V2G charge process;
Dch	Storage or V2G discharge process;
DR_B	Active power curtailment of load;
DR_A	Active power reduction of load;
ESS	Energy storage system;
GCP	Generation curtailment power Load loads;
L	Load;
LTC	Loads total cost;
Max	Upper bound limit;

Min	Lower bound limit;
NSD	Non-supplied demand;
SP	External supplier;
V2G	Vehicle-to-grid;

Superscript

i	Bus;
Fix	Fixed costs (m.u.);
Loss	Losses costs (m.u.);
NetUse	Network use costs (m.u.);

Variables

C	Cost (m.u.);
P	Active Power (KW);
Q	Reactive Power (KVar);
TC	Total allocation cost (m.u.);
V	Voltage magnitude (V);
Θ	Voltage angle;

1 Introduction

1.1 Motivation

The Power System (PS) is undergoing a thorough overhaul. The liberalization of the electric market is one of the factors that has contributed to this reform. The Portuguese Power System, as an image of what has happened in other European countries, is no longer vertically integrated [1], a natural monopoly ceases to exist in the PS and Energias de Portugal no longer have the monopoly of the entire Portuguese electricity sector.

Hence, additional players have entered in system, leading to a competitive environment. According to the vertically integrated structure of the PS, energy was produced in large plants, and then transported and distributed to all consumers with PS planning activities carried out in a simpler way than nowadays [2].

Giving the Portuguese PS as an example of the new paradigm, it is possible to verify that energy production is now liberalized, considering several different producers operating under a competitive market environment. The transport of energy is done through the national transmission network (there is only one transport network operator, because it is not economically feasible to have several), which was commissioned by the Portuguese state to Rede Energética Nacional. The distribution of energy is also a non-liberalized activity, being commissioned to EDP Distribuição at the medium and high voltage level, while the activity at the low voltage level is done through agreements made between EDP Distribuição and the various municipalities. The production and commercialization of energy are liberalized activities, where several entities compete among each other in the energy market to provide energy to their customers. In contrast to the old paradigm, there are now several players in the PS [3].

In addition to this liberalization of the EPS, the increasing concern about the impact of man-made pollution on the sustainability of our planet, coupled with a strong dependence on imported fuels, has led to a greater focus on the use of Renewable Energy Sources (RES) and on Distributed Energy Resources (DER). It is expected that production from renewables will be an important part of the future generation mix, reaching between 60% and 65% of all electric energy produced by the year 2050 [4].

The transformations in the structure of the electric network are not limited to the liberalization of the EPS and changes of the means of production of electric energy. In the old paradigm, when the demand is greater than the production, blackouts may occur, causing serious problems in the society. The lack of information along the energy transport chain makes its management difficult.

The "convergence of information technology and communication technology with power system engineering" [5], led to the emergence of smart grids. "Smart grids are expected to address the major shortcomings of the existing grid" [5].

The smart grids are characterized by bringing to the network the capacity to use information in real time and bring a two-way flow of information between production, consumption and all intermediate points. Besides using artificial intelligence and cyber secure communications technologies where smart meters and price signals are used [6]. These new features allow a much faster reaction to problems that may appear on the grid.

Notwithstanding, the distribution network under the smart grid paradigms comprises several types of DER including RES, Electric Storage Systems (ESSs), Electric Vehicles (EVs), Demand Response programs (DR) among other resources. DER resources can be divided in two types. Dispatchable generators, which can be turn on and off at the request of power grid operators, according to market needs. For instance, Combined Heat and Power (CHP), small-hydro, Waste-to-Energy (WtE), Fuel Cell, Biomass. The other type of DER resources is the non-dispatchable generators that depend on climatic conditions and therefore are intermittent and variable on time. Some of these power sources are Photovoltaic panels and wind turbines.

The introduction of DER has brought with it some challenges. In the old paradigm, the power flow occurred vertically, the voltage levels are higher at the level of the large production centers and will be smaller as the various consumers are fed, according to hierarchized voltage levels.

With the new paradigm, all the energy produced by the DER and not consumed locally can raise some problems, such as the variation of the voltage levels in the buses, congestion in the branches, short circuits with higher power, decrease of the wavelength quality related to the number of harmonies and even the growth of flicker effect [7].

The smart grids paradigm allows a much more efficient and precise management of the network, as it allows the use of new tools and programs, such as DR [8]. DR programs promote the interaction and accountability of customers, as they are given incentives to reduce and / or curtail consumption, which are practices that can help in the network management. In this context, the ESSs and EVs with Vehicle-to–Grid (V2G) capability are very important, since they can mitigate the uncertain and intermittent behavior of RES. The introduction of these technologies brings more resilience to networks since they allow to store energy and inject it into the network when necessary, bringing greater flexibility to the network.

Still, the upstream connection of the network continues to play a very relevant role, since it is able to feed the loads when the RES diminishes or cannot produce, because they are non-dispatchable resources with intermittent and variable generation.

Despite the transformations that EPS is experiencing, there are still many flaws. Electric Power, to propagate from the production centers to the end-user, uses the transmission and distribution network. Such use has inherent costs, such as fixed(investments), network (operating and maintenance) and losses costs. With the introduction of DER, it is necessary to reformulate the methodologies used to allocate these costs. These methodologies should more accurately represent the impact that each user has on the system. Because different costs must be allocated to users in buses with high penetration of DER and to users in buses with little or no DER penetration. The present work intends to contribute to solve the problem of cost allocation of a network with high penetration of DER.

1.2 Objectives

The continuous penetration of DER in the distribution system brings new challenges in the planning, operation and management of the distribution networks. One of the main challenges is to fairly allocate and distribute the costs of network investments and usage throughout all energy resources present in future distribution networks.

In this context, this dissertation offers a significant contribution in the definition of distribution network tariffs, based on cost allocation methodologies. In particular, the study and comparison of existing cost allocation methodologies makes possible the development of a tool to access the fairness of establishing flexible network tariffs for different players in the system. Within this scope, the specific objective defined for this dissertation are the following:

- Adaption of tracing algorithms to future characteristics of distribution systems.
- Implementation of a variant of MW-mile to allocate the costs of distribution resources
- Comparison of a Bialek and Abdelkader tracing algorithms.
- Evaluation of fixed, network usage and losses costs.

1.3 Structure

The present dissertation is divided into 5 chapters.

In Chapter 1, a brief introduction is made on the subject under study, as well as the motivation of study and its main objectives.

In Chapter 2, it corresponds to the State of Art where the concept of tariff is approached, besides a great variability of methodologies of allocation of costs of the transport networks.

In Chapter 3, the methodology used is presented in detail. The proposed methodology is composed of three distinct phases. In the first phase an Economic Dispatch is realized to realize which generators must come into operation to feed all loads. In the second phase, two Power Flow Tracing Algorithms were implemented, in order to understand the impact of each technology has on the flow of each line for each hour and, finally, in the 3 phases of this project, the costs of using the system are calculated and allocated. Three cost are calculated, namely fixed costs, congestion costs and costs of losses. Summing up these three costs we get the total costs of the system.

In Chapter 4, the results of the application of the chosen methodology are presented and discussed. The developed methodologies are tested and validated on a 33-bus distribution network considering 2040 scenario of high DER introduction.

Finally, chapter 5 presents the conclusions of the work developed and proposals for future works are addressed.

2. State of art

Since the end of the 90's and due to the deregulation of power systems, the design and development of methodologies to establish network tariffs has becoming popular, mainly to transmission networks. Several methods have been developed taking into account a fairer distribution of the costs related to network investments and usage at the transmission level [9]. More recently and within the smart grid concept (in which DER are fully integrated in distribution systems), the standard tariffs for cost allocating the distribution network usage are no longer fair to all network users.

This chapter explores the concept of tariffs applied to power system networks identifying the different characteristics used to set the network tariffs. In addition, a comprehensive review of the most distinct approaches existing in the literature is provided with special coverage of methodologies directed to distribution networks.

2.1 Concept and Definition of Network Tariff

A network tariff is a means of remuneration that aims to recover the costs of using the transmission/distribution lines in the most appropriate and fair way possible. The distribution network tariff is applied to all network users by the entities responsible for the operation of the network (system operators). The network tariff is designed to recover the capital and operating costs of the grid. In addition, the tariff should encourage an efficient use of the network and promote network investments[10]. A fair tariff should also promote equality of opportunity to all users. The structure must be as simple as possible, easy to understand, and easy to implement.

There are several different methodologies to determine the network tariff, performing the cost allocation to all energy resources. More precisely, the design of a network tariff can follow different approaches and assumptions, one more complex than another. Still, in most countries the loads get higher share for the transmission network costs than generators because it is assumed that the end-users should support most of the costs for using the network [11].

There are several different methodologies for cost allocation, the most known of which are discussed below [12].

1) **By peak consumption or generation**: this methodology divides the costs of network utilization by all its users, taking into account the maximum amount of load or generation, usually measured when the generation / load reaches its maximum in the system. For this method the location of users is irrelevant.

2) **By amount of usage**: with this methodology the allocation of costs is made through the amount of energy consumed and/or generated in Megawatt-hour in a year. Is not taken into account the location of the load or generators and it is also a simple application methodology.

3) **By a monetary impact basis**: Using this methodology, the costs are shared by the entities that receive a monetary gain and that are influenced by the variation of the energy prices and consequently changes in the cost of production. This method is used in wholesale markets where locational prices and market simulations are used to estimate the economic benefits of variation of energy prices;

4) **By flow-basis**: Power flow studies are used to plan economic dispatches and determine the marginal prices of the energy market. It also serves to determine the impact that users have on the system, based on the power they receive and / or send and also the location.

2.2 Cost Allocation Methodologies

In this section several methods of cost allocation are described. This includes the description of the most common methodologies used in many countries, as well as new methodologies that are emerging now in the scientific community. Most of these methodologies were designed for transmission networks but can also be applied to distribution networks.

In this context and for simplicity and comprehensibility, this dissertation splits the methods into five distinct groups, namely: (i)embedded methods; (ii) Incremental type methods; (iii) Marginal methods; (iv) hybrid methods (combining characteristics of the types of methods mentioned previously); and (v) finally methods based on Game Theory.

2.2.1 Embedded Methodologies

This group of cost allocation methodologies is characterized by the simplicity in the determination of the network costs. The total costs are allocated to network users based on a system usage measure previously defined, which depends on the "extent of use" of the system. A fixed cost per unit of energy is defined and it is considered that all users have the same impact on the transport and / or distribution system. The tariff calculation in these methods is based on the ration between a cost of a transaction and the sum of costs of all transactions.

For this reason, the methods within this category are used in markets with transaction-based contracts and not in spot markets[2]. These methods are simple and easy to apply. They also, do not consider the characteristics of network, neither the Power Flow in the branches or the cost of a new transaction that may lead to a reinforcing of the network. That cost of reinforcing the network is diluted by all users, sending erroneous economic signals to them [13].

2.2.1.1 Postage Stamp Methodology

In this method, the remuneration R_t of the assets and costs of operation and maintenance of the electricity network is calculated by summing the total costs of transmission TC, times the power generated or received by the customer P_t to be divided by the total demand of the system P_{peak}. The units in this division are a cost in $ to be applied to users. It is assumed that each transaction affects the electrical system in the same way, not taking into account the location of the loads and the generators [13].

$$RT = TC * \frac{P_t}{P_{peak}} \quad (1)$$

2.2.1.2 Contract Path Method

This method is like the Postage Stamp method. However, the contract path method allocates the distribution costs considering the cost of the continuous path that connects the injection points and energy consumption times the energy received or sent by the customer and divided by the total demand of the system. This method ignores the actual operation of the system, since the electric energy tends to flow through the "path" that offers less resistance. This method does not consider the real path of energy, instead it considers penalties for the contracted path[14].

2.2.1.3 Mean Participation Factors

This method calculates the fraction of each line in which each user has an impact, based on a previous power flow and calculating the proportionality between the power that enters or leaves the node and all the power that enters or leaves that node. This method does not represent the operation of the electrical network because it treats the electrical system as if it were a water pipeline system [5] once its operating mechanism is based on proportionality between injections and power.

2.2.2 Power Flow Based Methodologies

These methodologies are based on Power Flow studies and allocate transmission costs based on functions relative to the distance, path and magnitude of the electrical energy that runs through the system (being considered characteristics that were neglected in the methods used previously). Flow Based Methods can be divided into two groups. Those based on Alternative Current (AC) power flow and those based on DC power flow.

2.2.2.1 Methodologies based on DC Power Flow

Power flow methods based in the DC Power Flow are usually used in situations where there is a need to represent the system in a simple way, with no need of taking in account the cost of losses.

2.2.2.2 Classic MW-mile method

This method takes into account, for each transaction, the power flow of all the lines between the generation and the load, considering the grid structure for the calculation of the tariff. The tariff *P* is obtained by multiplying the impact of a transaction on each line *R(u)* (calculated throw DC power flow) by the length of the line , and also by a unit capacity cost of the line[15]. This method can only be applied in bilateral transactions since it is only in this type of transactions that the point of injection and reception of energy is known and considers the negatives flows advantageous[16]. This tariff has as advantages its simplicity and easy application.

$$P = \frac{CT}{\sum_k F_k \times L_k} \tag{2}$$

$$R(u) = \sum_k P_g \times F_{k(u)} \times L_k \tag{3}$$

- k – Circuit that conects the bus *i* with bus
- C_k- Cost of line *k* (um)
- F_k - Flow in line k in the initial conditions (MW)
- L_k - Length of the line *k* (km)
- CT =$\sum_k C_k$ - Total cost of transmission (k(u.m.))
- $F_k(u)$ - Impact of transaction *u* in line *k* (MW)
- P_g - Power produced by the generator *g*
- $R(u)$- Allocated cost to user *u*

2.2.2.2.1 **Variants of MW-mile method**

There are several variations of the MW mile method. These variations share in common the percentages of the capacity of the lines used along the energy flow path.
These variants of the MW-mile are Base, Module or Use, Zero Counterflow and Dominant Flows[16]. The variations of the method appeared to reduce the shortcomings of the original method.

2.2.2.2.1.1 Base

This method is similar to MW-mile Classic but has a large difference because this method considers in the denominator the total power flow that passes in the line ($\sum_s F_k(s)$) instead of its maximum capacity. With this method, the total system costs are allocated to all users who participate in the transactions according to their impact on the network. Under this method some fees may be negative and the users responsible for these transactions may receive benefits, this is only relevant if the line operates close to its maximum capacity(because negative flows contributes in the relieving of congested transmission lines[17]). Well, if this does not happen, this condition can lead to some users receiving a gain, but without bringing benefits to the network[16].

$$R(u) = \sum_{K} C_k \frac{F_k(u)}{\sum_s F_k(s)} \tag{4}$$

C_k- Cost of line k (um)
R_u- Allocated cost to user
F_k - Flow in line k in the initial conditions (MW)

2.2.2.2.1.2 Module or Use

This method allocates the total system costs for all transactions, considering the transactions in both directions. According to this methodology, in order to determine the contribution of each transaction, first a power flow study is carried out in which all transactions are considered, being this the case of reference, then a study of the power flow is considering a transaction, and n studies are made for n transactions. The difference between this method and the original is that it considers the absolute values of each line flow instead of it original value(with signal)[16].All transaction are taken in account and the cost are more distributed among all users responsible for the transactions , this methods also provides the recovery of the cost of using the System[18].

$$R(u) = \sum_{K} C_k \frac{|F_k(u)|}{\sum_s |F_k(s)|} \tag{5}$$

2.2.2.2.1.3 Zero Counterflow

In the mentioned method, only flows in the same direction as the actual flow in the component are charged[16]. In this case, transactions relating to contributions of counterflows are not charged because they contribute to improving the efficiency of the use of the distribution system. This method does not address the negative impacts, but also does not assign any benefit to the corresponding transaction. Under this method transactions are only charged due to the positive impacts on the lines.

As a main disadvantage of this method is the possibility of tariff discontinuity and volatility[19] In systems with few transactions, the power flows can change direction easily, therefore, transactions that correspond to negative power transits (considered beneficial to the system and therefore not charged), can change to positive, starting to pay a tariff[2].

The formula (6) determines the tariff for R(u):

$$R(u) = \begin{cases} \sum_k C_k \frac{F_k(u)}{\sum_s FD_k} & \text{for } F_k(u) > 0 \\ 0 & \text{for } F_k(u) \leq 0 \end{cases} \quad (6)$$

$$FD_k(u) = \begin{cases} F_k(u) & \text{for } F_k(u) > 0 \\ 0 & \text{for } F_k(u) \leq 0 \end{cases} \quad (7)$$

The expression (7) accounts the effect caused by the transaction *u* in line *k* if that transaction *u* increases the active power flow in a line.

2.2.2.2.1.4 Dominant Flow

In general, this method is assumed to be a combination of the "Module or Use" method, and the Zero Counterflow method whose main objective is to reduce or even eliminate the problems related to the other methods presented[16].

In the Dominant Flow method, the tariff is divided into 2 steps:

1) Base capacity: this part is linked to the effective use of the branches of the system and is calculated using "Module or use" method (RA);

2) Additional capacity: associated with capacity available in the branches, circuit reserve .The method used to calculate this parcel is the Zero Counter Flow(RB) [20].

$$\begin{cases} RA(u) = \sum_k CB_K \frac{|F_k(u)|}{\sum_s |F_k(s)|} \\ RB(u) = \begin{cases} \sum_k CA_k \frac{F_k(u)}{\sum_s FD_k(s)} & \text{for } F_k(u) > 0 \\ 0 & \text{for } F_k(u) \leq 0 \end{cases} \end{cases} \quad (8)$$

$$\begin{cases} CA_K = C_k \frac{FM_k - F_k(u)}{FM_k} \\ CB_K = C_k \frac{F_k(u)}{FM_k} \end{cases} \quad (9)$$

CA_K -is used to calculate the cost related to the transit in the line;
CB_K -is used to calculate the cost of the capacity not used;

2.2.2.2.2 **Bilateral Equivalent Exchange Method**

The Equivalent Bilateral Exchange (EBE) is a method that translates the resolution of an Optimal Power Flow (OPF) that respects the laws of Kirchhoff, not violating any line limit or generation limit. In this type of method, the original scheme is developed for a pool market (not based on transactions), with the final objective of obtaining the final rates of transmission for each node.

The method imposes a rule on the snap shot of established power flow. The rule is based on the assumption that every generator contributes to each load. Each charge is obtained by a fraction of each generator, whose fraction is evenly divided by all charges. Thus, how much power the generator supplies to the load is defined. In addition, The method provides fair price signals and proves to be useful in the pool system, where bilateral transactions are non-existent [21].

2.2.2.2.3 **Generalized Distribution Factors Method**

This type of method is obtained through the power transits in the lines. They are widely used as techniques of calculating the allocation of costs associated with the use of the transmission system.

This type of methods are widely used in security analysis and system contingency problems [18].

You can consider two types of distribution factors:

1) **GGDF - Generalized Generation Distribution Factor** → distribution factor relates the variation of production to the power flow of the lines;
2) **GLDF - Generalized Load Distribution Factor** → distribution factor relates the variation of Load consumption to the power flow of the lines.

As already mentioned, these two methods evaluate the impact of generators and loads on the Power Flow in each line.

To study the impact, we use sensitivity coefficients, which are based on the DC model [21]. These coefficients corelate the value of the power flow of a line with a variation in the Production (GGDF) or a variation in the Load (GLDF). The imposed variation is compensated by subtracting this variation from the reference bus [18]. These methods aim to assess the costs of incremental resource utilization [21].

2.2.2.2.4 **Rate System Path**

This method is based on the analysis of the power flow of the network and consequent study of the transmission capacity of each line, considering the normal conditions of exploitation and situations of occurrence of faults in the network. This method is commonly used to study the stability of an electrical system. When a new equipment is added to the system, its distribution capacity is improved, and all calculations are repeated in order to calculate the benefit of the improvement. This method is widely used for studies considering lines of great length, which limits of stability of transmission capacity between zones are establish. In situations where the network is heavily tangle, the use of this method is not recommended, since it is very difficult to define the different zones [2].

2.2.2.2.5 **General Agreement on Parallel Paths**

This method is not a typical method. Because it consists of a set of studies aimed at compensating the companies that have networks that suffer the impact of undesired power transits, such as loop flows. The impact of the Power Flow (PF) on each line is studied, and it is possible to construct a matrix of participation factors to determine the percentage of each transaction flowing through the networks of the various companies and consequently the cost of the reimbursement to be given to these companies[2].

2.2.2.3 Methodologies based on AC Power Flow

The AC power flow is characterized by approximating the natural behavior of the power system. It is a better approximation than the DC power flow, since takes into account the active and reactive power in the system. In this context, this section presents the main methodologies of the cost allocation problem based on the AC power flow.

2.2.2.3.1 **Zbus Methodology**

The Zbus method is a method that determines network costs based on the intrinsic characteristics of the distribution networks.

It presents a solution based on circuit theory, the network matrix Z^{bus} considering and considers the current injection in each bus.

The combination of these two elements (matrix Z^{bus} and current injections) determines a measure of sensitivity that which indicates the individual contribution of each current injection of the system to form the flow in a transmission line. The method can be divided into 3 main steps [22]:

1) Active power of each transmission line is associated with each nodal injection.

2) Cost of a line is allocated to all generators and loads.

3) Process repeats for all lines.

2.2.2.3.2 **Power tracing Methodologies**

Power flow tracing methodologies are characterized by the tracing of the flow in the network, based on the proportional sharing concept. The proportional sharing concept is “for every node in a network, the proportion of power flow on each outflow branch fed by each inflow branch is equal to the proportion of the inflow from this branch in the total inflows” [23] Methodologies based on this concept can recover the network usage costs in a fair and distributed way. There are several methods developed based on this concept. The main methods found in literature are: *(i)* Bialek tracing method; *(ii)* Kirschen tracing method; and *(iii)* Abdelkader tracing method.

2.2.2.3.2.1 Bialek Method

In this type of method, the generator contributions for the active, reactive power and power losses are determined for each line of an electrical system and is based on the example analyzed previously for the Proportional Sharing[24].

This method is commonly used to obtain the active power contribution by network users using the DC power flow but can also works using the AC power flow. In this way, it is possible to determine the active and reactive power contributions of each user. This method only works in lossless flows. Bialek proposes three different ways of considering the loss flows in order to consider the flows lossless.

In short, this methodology in a first phase allocates the cost of the use of the transmission of each generators and distributes the losses with the loads and in a second phase the cost of the use in the transmission of each load is allocated, at the same time that the losses are distributed by generator[25]. This methodology is used in this work, so a more detailed definition can be found at section 3.3.4.

2.2.2.3.2.2 Kirschen method

The Kirschen's present method calculates the contribution of each generator in the flow transits of each line and the contribution of the generators in the power that reaches each bus. That is, it is a technique that aims to determine the impact that generation and consumption have on the network usage of the distribution network. This method is based on a graphical perspective of the network, also known as graph methods for power flow tracing, which comprises three different components:

Three key aspects are considered:

Domains – set of buses that get power from a generator;
Commons - set of buses fed by the same generation group
Links – lines which connect commons.

Like the previous method, this also serves to calculate the contributions of the generators to the commons, connections and loads and to obtain the line flows within each common.

The method can be applied to all resource types. However, there are two different algorithms (upstream and downstream looking algorithms) that are used to trace the power of generation and consumption resources. The upstream algorithm determines the share of generation resources, while the downstream algorithm determines the impact of the resource consumption on the system[26].

2.2.2.3.2.3 Abdelkader method

In 2007, S. Abdelkader presented a power flow tracing methodology using the proportional Sharing principle. This method starts with a Power Flow study, in order to be able to observe the signal and magnitudes of each energy flow that enters in each bus. Based on this information a matrix A is built where the different buses are classified. These buses can be classified as Source, Generation, Sink and Load. Then two algorithms can be used to determine the share that each user has on the grid. Downstream algorithm where the share of each generator in the different lines, loads and losses is calculated. And the Upstream algorithm used to calculate the share that each load has on the different lines, generators and losses. This method is used to trace active and reactive power flows [27][28]. This method is covered in detail in section 3.3.3..

2.2.3 Nodal marginal methods

The nodal marginal method is based on the AC power flow and determines the costs following the power that enters and leaves each node, being influenced by the nodal marginal prices. The method can be applied to all resource types. However, there are two different algorithms (upstream and downstream looking algorithms) that are used to trace the power of generation and consumption resources. The upstream algorithm determines the share of generation resources, while the downstream algorithm determines the impact of the loads on the system. Due to the potential of nodal marginal prices in terms of their transparency and quality of transmitted signals, it is necessary to develop methods that include operating costs and costs of expanding and strengthening networks. Thus, marginal prices can be considered to establish the variation of the cost function if a change of one unit of load occurs in that particular node. That is, the Locational Marginal Price (LMP) is defined as the increase in the cost (system, congestion and losses costs) for supporting the increment of one load unit (1 MW) in a single bus of the network. The LPM comprises different costs, such as: *(i)* system costs, which are related to energy production; *(ii)* network congestion, which is the cost for using other generation resources when the network branches have no capacity to provide the energy from the cheapest energy resources; and *(iii)* losses cost related to the power losses.

The LMP calculation is obtained from the optimal power flow problem, which minimizes the total production costs of the system, thus guaranteeing the lowest possible tariff to the consumer. In short, the nodal marginal methods can be divided into two different categories: the short run marginal cost; and long run marginal cost [26].

2.2.3.1 Short Run Marginal Cost (SRMC)

This cost is determined through the minimization problem of generation costs, satisfying the loading conditions. Thus, this cost can be obtained by calculating the cost of producing an extra unit of output [29]. The SRMC is a cost, which considers the variable costs originated by the transaction (operational cost), however does not consider the cost of reinforcement. In this type of price, capital investments are defined as a fixed cost, so the SRMC corresponds to the cost of producing one more unit of output or providing an addition of service with existing capacity. This costing method uses a transmission analysis model such as an AC or DC load flow that can calculate the price at individual buses [29].

2.2.3.2 Long Run Marginal Cost (LRMC)

Contrary to the short run marginal cost, the long run marginal cost can be determined through several ways. However, its resolution is much more complex. The optimization problem to determine this cost considers operating costs and investment costs related to the expansion and reinforcement of the network. In this type of cost, capital investments may have a variable value [27]. The LRMC is defined as the marginal cost of supplying an additional unit of energy when the installed capacity of the system can increase optimally in response to the marginal increase of the demand. So, both capital and operating costs are incorporated. The LRMC provides a tariff today based on the cost of future system operation [30].

As is easy to understand, the method to determine the LRMC is much more complex than the method to determine the SRMC. Thus, it is very difficult to find the correct calculation of the LRMC, reason why it must be based on assumptions about the future behavior of the power system. Still, the LRMC presents some advantages, namely:

- High stability and Low volatility - daily variations in marginal prices are oscillations around a long-term basis value;
- Optimum pricing and recovery of companies' compensation – the optimization problem considers the operating and investment costs. In this case, when the optimum is achieved, the associated costs can be recovered [5].

2.2.4 Hybrid methodologies

The hybrid methodologies combine different methods in order to overcome their limitations and provide more accurate solutions.

2.2.4.1 AMP-MILE method

The Amp-mile extent of use method that uses marginal changes in current, as opposed to power (MW-mile method), in a distribution asset with respect to both active and reactive power injections multiplied by those injections to determine the extent of use at any time . The fixed charges computed under Amp-mile have two parts. The first part is based on the extent of use of all circuits by loads at each bus at the system coincident peak (locational portion) for only the portion of the circuit capacity that is used. The second part of the charge covers costs associated with the unused portion of the circuit capacity and is recovered over all load at coincident peak. Thus, the mechanism has the property that when the circuit is at full capacity, all costs for that circuit are recovered through locational charges. When the circuit is relatively unloaded, the majority of costs will be recovered over all loads at peak [31].

2.2.5 Other methodologies

2.2.5.1 Games Theory

Game theory is a set of practices used to analyze and describe the behavior of agents in situations of strategic interaction where the agents can get rewards or punishments [32]. This work technique as a lot of interest for areas of economics and management.

A game consist of [33]:

- At least 2 players
- **Moves** - it is through the moves that players progress through the game. These moves can happen alternately between players (like in chess games) or simultaneously (like in a football game). The moves happen according to the decision of the players or because of a probabilistic event.
- **A strategy**- corresponds to a set of "moves", as an algorithm, that tells the player what to do over the game.
- **Payoff** - corresponds to the result obtained after a set of moves, at the end of the game the result will be positive, negative or zero. The payoff gives the motivation for the players moves.
-

Games Theory can be divided into two branches: Non-cooperative Games Theory and Cooperative Games theory.

- **Non-cooperative Games Theory**: this Game Theory is “based on the absence of coalitions”[34] among the various players of the game. Players make decisions in order to maximize their payoff, regardless of the interests and plays of the other players with no communication or cooperation between them[35].

- **Cooperative Games Theory** : is used for cost allocations in services used by several players[36]. The purpose of cooperative games is to maximize the benefit of all players, so that allocation of costs is done fairly. For this to be possible, players are expected to make decisions that benefit the "common good". Two examples of cooperative games are discussed in the following section.

2.2.5.1.1 Nucleolus

It can be defined as the set of all non-dominated imputations via any coalition, or the set of those for which there are no objections. In this case the solution or the solutions are chosen, eliminating during the negotiation the imputations for which any objection was presented. Formally the nucleus can be represented by the set of all imputations x such that:

$$\sum X_i \geq v(s) \forall S \in i \tag{10}$$

The mathematical expression above ensures that if any group of individuals S, which is part of the set of individuals composing the game, resolve to make a coalition, it will never obtain a value greater than the sum of the individual gains that it obtains in the imputation x. Any imputation belonging to the core is stable in the sense that there is no coalition that simultaneously has the stimulus and the power to change the outcome of the game. The nucleus may be presented differently. Let$(x, k) = V(k) - x(K)$ be the complaint of coalition members K in relation to the imputation x. Then, one can express it as the set of all imputations whose maximum claims against them are less than or equal to zero [37].

2.2.5.1.2 Shapley Value

In this technique a value is assigned to each unit that contributes to the grand coalition in a game with a function of particular characteristics. This application makes possible to know the probability of a particular player joining the coalition, determining the players payouts depending on the contribution that each player gave to the total payout. The solution to this problem is know as “Shapley Value” , and consist in allocating to each player a weighted average of all the marginal costs associated with its participation in all possible coalitions, considering all those possible coalition in a random manner [38].

2.3 Conclusion

Throughout this chapter has been referenced some methodologies of cost allocation of a transmission system.

Embedded methods are based on the application of an “extent of use” measure of the grid, considering that users have the same impact on the network. Although they are easy to implement, they are not very fair because they do not consider the characteristics of the grid.

The methods based on power flow determine the impact that different users have on the grid through power flow studies. These methods take into account the characteristics of the network, but they some flaws because they don’t take into account the cost attributed by new transactions and costs related to the expansion of the grid.

The methods based on marginal costs help to respond to the failures of previous methods because they use marginal costs to identify optimal decisions in the operation of the grid. These marginal costs reflect the cost of producing an extra unit of energy [2]. This methodology is fair, but it is difficult to apply because many variables need to be considered in order to calculate these marginal costs.

The methods based on the theory of cooperative games allow to study solutions in the various users make decisions in order to maximize the common good.

The hybrid costs result from the combination of one or more methods, thus aiming to reduce the defects of the individual use of these methods and thus obtain a more robust method. In Chapter 3 it is presented a hybrid method that was used in this work.

3 Cost allocation method

3.1 General overview

The proposed cost allocation model consists of three stages. In the first phase, an energy scheduling based on AC OPF is performed, determining which generators must be put into operation to supply the loads in the most economical way possible, considering several constraints, thus minimizing the operating costs of the system. In the second phase of the methodology, the power contributions of each generator and each load in each line are determined through Abdelkader's and Bialek's power flow tracing methods. Based on the impact that each generator / load has on the lines, it is possible to determine the costs of using the distribution network by these energy resources (third phase). Figure 3.1 depicts the overall flow of information and phases of the proposed model.

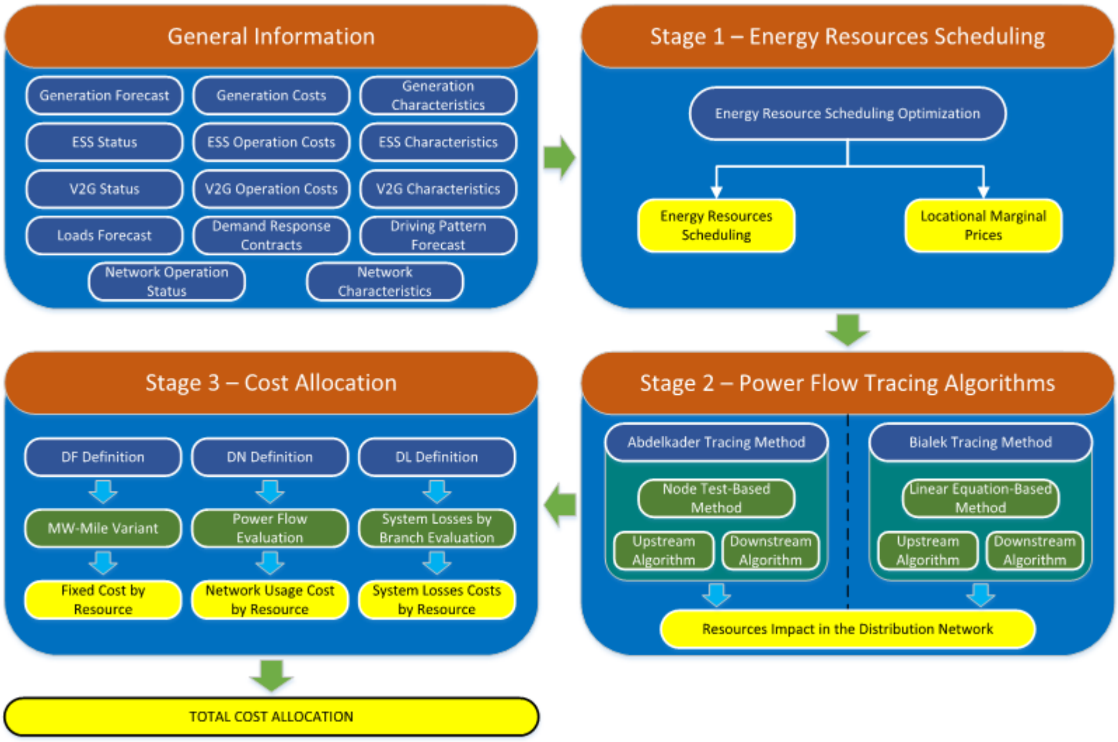

Figure 3-1-Diagram of the proposal model [39].

3.2 First stage - Energy scheduling problem

The transmission and distribution network are used to transport electricity from generation points to consumption points. The main objective of the EPS is to feed all loads as efficiently and economically as possible.

The economic dispatch is a tool that determines which generators and what power they must produce in such a way that all the loads are fed, in the most economical way possible, while respecting all constraints of the problem [40].

The problem of economic dispatch can be formulated mathematically by the following objective function.

$$Minimize\ F_{Cost} = \sum_{j=1}^{N_g} F_j.(P_j) \tag{3.1}$$

- $F_j.(P_j)$ represents the cost function of the jth generating units (in $/h);
- P_j represents the real output of the jth generating units in (MW);
- N_g is the total number of generators in the power system;

The above formula expresses the problem of economic dispatch in a very simplified way. The general information of the proposed problem takes in account the generation and load characteristics, ESS's, electrics vehicles which can charge and discharge (V2G) and the network characteristics. The active participation of consumers in direct load control demand response is also considered. The energy resources scheduling can be better illustrated below.

$$Minimize\ f = min \tag{3.2}$$

$$\sum_{t=1}^{T}[\sum_{dg=1}^{N_{DG}}(Y_{DG(dg,t)} *\ c_{A(dg,t)} +\ P_{DG(dg,t)} * c_{B(dg,t)} + P_{DG(dg,t)}^{2} * c_{C(dg,t)} + P_{CGP(dg,t)} * c_{GCP(dg,t)})$$
$$+ \sum_{v2g=1}^{N_{V2G}}\left(P_{Dch(v2g,t)} * C_{Dch(v2g,t)} + P_{Ch(v2g,t)} * C_{Ch(v2g,t)}\right)$$
$$+ \sum_{l=1}^{N_{L}}\left(P_{DR_{A(l,t)}} * C_{DR_{A(l,t)}} + P_{DR_{B(l,t)}} * C_{DR_{B(l,t)}} + P_{NSD(l,t)} * C_{NSD(l,t)}\right)$$
$$+ \sum_{ess=1}^{N_{V2G}}\left(P_{ESSDch(ess,t)} * C_{ESSDch(ess,t)} + P_{ESSCh(ess,t)} * C_{ESSCh(ess,t)}\right)$$
$$+ (\sum_{sp=1}^{N_{SP}} P_{SP(sp,t)} * C_{SP(sp,t)})]$$

- $Y_{DG(dg,t)} *\ C_{A(dg,t)}$, represents the fixed component of cost function of Distributed Generation (DG) (namely, CHP, Small-Hydric, Biomass, WtE, Wind, PV and Fuel cell)
- $P_{DG(dg,t)} * C_{B(dg,t)}$, represents the linear component of cost function of DG;
- $P_{DG(dg,t)}^{2} * C_{C(dg,t)}$, represents the quadratic component of cost function of DG;
- $P_{CGP(dg,t)} * C_{GCP(dg,t)}$, represents the cost of generation curtailment power;
- $P_{Dch(v2g,t)} * C_{Dch(v2g,t)} + P_{Ch(v2g,t)} * C_{Ch(v2g,t)}$, represents the cost of each V2G charging and discharging to the system;
- $P_{DR_{A(l,t)}} * C_{DR_{A(l,t)}}$, represents the cost of reduction the active power of load;
- $P_{DR_{B(l,t)}} * C_{DR_{B(l,t)}}$, represents the cost of curtailment the active power of load;
- $P_{Ch(v2g,t)} * C_{Ch(v2g,t)}$, represents the cost of not supplying;
- $P_{ESSDch(ess,t)} * C_{ESSDch(ess,t)} + P_{ESSCh(ess,t)} * C_{ESSCh(ess,t)}$, represents the cost of each ESS charging and discharging to the system;
- $P_{SP(sp,t)} * C_{SP(sp,t)}$, represents the cost of the external supplier for each time.

The AC OPF is modeled considering several constraints of the network being studied. These constrains may prioritize dispatch of energy from renewable sources. The capacity of lines, available generators, external suppliers active (3.3) and reactive (3.4) limits of power delivery are constrains considered. Distribution generation comprise active generation limits (3.5), generation curtailment in active (3.6) and reactive power (3.7). The active participation of consumers in direct load control is also considered through constraints (3.8) and (3.9).

$$0 \leq P_{SP(sp,t)} \leq P_{Max(sp,t)} \tag{3.3}$$

$$0 \leq Q_{SP(sp,t)} \leq Q_{Max(sp,t)} \tag{3.4}$$

$$P_{\min(dg,t)} \times Y_{DG(dg,t)} \leq P_{DG(dg,t)} \leq P_{Max(dg,t)} \times Y_{DG(dg,t)} \tag{3.5}$$

$$P_{DG(dg,t)} + P_{PGC(dg,t)} \leq P_{Max(dg,t)} + Y_{DG(dg,t)} \tag{3.6}$$

$$Q_{\min(dg,t)} \times Y_{DG(dg,t)} \leq Q_{DG(dg,t)} \leq Q_{Max(dg,t)} \times Y_{DG(dg,t)} \tag{3.7}$$

$$P_{\mathrm{DR\_A}(l,t)} \leq P_{DR_A;Max(l,t)} \tag{3.8}$$

$$P_{\mathrm{DR\_B}(l,t)} = P_{DR\_B;Max(l,t)} \times Y_{DR\_B(l,t)} \tag{3.9}$$

$$\forall \mathrm{t} \in \{1,\ldots,T\};\ \forall \mathrm{dg} \in \{1,\ldots,N_{dg}\}$$

Others very important constraints of the problem are related with V2G resources and ESS's units. V2G resources will have big impact in the future distribution systems, but they bring some new constraints which will increase the complexity of the problem.

So, it is imperative to optimize the state of charge stored in each V2G in each period (3.10). This optimization can be achieved considering the location of each vehicle, the minimum (3.11) and maximum (3.12) limits of the energy stored their battery's and the efficiency of the charge and discharge energy in the grid. Also, must be considered that each V2G can only be connected at one branch a time, they cannot charge and discharge energy at the same time (3.13). The constraints related to ESS's are very similar to the ones applied to V2G regardless the principle that their location is fix and they don't need energy to travel like V2G (3.16-3.22).

$$E_{Stored(v2g,t)} = E_{Stored(v2g,t-1)} - E_{Trip(v2g,t)} + \eta_{c(v2g)} \times P_{Ch(v2g,t)} - \frac{1}{\eta_{d(v2g)}} \times P_{Dch(v2g,t)} \tag{3.10}$$

$$\forall \mathrm{t} \in \{1,\ldots,T\};\ \forall \mathrm{v2g} \in \{1,\ldots,N_{V2G}\};\ \Delta t = 1;\ t = 1 \rightarrow E_{Stored(v2g,t-1)} = E_{Initial(v2g)}$$

$$E_{\mathrm{Stored}(v2g,t)} \geq E_{BatMin(v2g,t)} \tag{3.11}$$

$$E_{\mathrm{Stored}(v2g,t)} \leq E_{BatMax(v2g,t)} \tag{3.12}$$

$$P_{Ch(v2g,t)} \leq P_{Max(v2g,t)} \times Y_{Ch(dg,t)} \tag{3.13}$$

$$P_{Dch(v2g,t)} \leq P_{Max(v2g,t)} \times Y_{Dch(dg,t)} \tag{3.14}$$

$$Y_{Ch(v2g,t)} + Y_{Dch(v2g,t)} \leq 1;\ Y_{Ch(v2g,t)}\ and\ Y_{Dch(v2g,t)} \in \{0,1\} \tag{3.15}$$

$$E_{Stored(st,t)} = E_{Stored(st,t-1)} + \eta_{c(st)} \times P_{Ch(st,t)} - \frac{1}{\eta_{d(v2g)}} \times P_{Dch(st,t)} \quad (3.16)$$

$$\forall \text{t} \in \{1,\ldots,T\};\ \forall \text{st} \in \{1,\ldots,N_{st}\};\ \Delta t = 1; t = 1 \rightarrow E_{Stored(st,t-1)} = E_{Initial(st)}$$

$$E_{\text{Stored}(st,t)} \geq E_{BatMin(st,t)} \quad (3.17)$$

$$E_{\text{Stored}(st,t)} \leq E_{BatMax(st,t)} \quad (3.18)$$

$$P_{Ch(st,t)} \leq P_{Max(st,t)} \times Y_{Ch(dg,t)} \quad (3.19)$$

$$P_{Dch(st,t)} \leq P_{Max(st,t)} \times Y_{Dch(dg,t)} \quad (3.20)$$

$$Y_{Ch(st,t)} + Y_{Dch(st,t)} \leq 1;\ Y_{Ch(st,t)}\ \ and\ Y_{Dch(st,t)} \in \{0,1\} \quad (3.21)$$

To solve the problem of optimizing the power distribution problem, a powerful tool called AC OPF is used.

This tool provides information about the network under study in a steady state, allowing the system operator to make better decisions in the operation of the network [41]. Some of the information that can be collected through the OPF are the magnitude(3.24) and angles(3.25) of the voltages in the different buses which should be between a finite interval, taking in account the branch thermal limits(3.26) and (3.27) and the active and reactive power flow in the different lines and the losses caused by the power flow in the lines.

The AC OPF was divided into two, one to determine the active Power transit between generation and loads, and another to determine the reactive power flow in each line between generators and loads.

For the calculation of the active balance, all the resources available in the system were considered.

$$\sum_{dg=1}^{N_{DG}^{i}} \left(P_{DG(dg,t)}^{i} - P_{GCP(dg,t)}^{i}\right) + \sum_{sp=1}^{N_{SP}^{i}} P_{SP(sp,t)}^{i} + \sum_{v2g=1}^{N_{V2G}^{i}} \left(P_{Dch(v2g,t)}^{i} - P_{Ch(sp,t)}^{i}\right) + \sum_{ess=1}^{N_{ESS}^{i}} \left(P_{Dch(st,t)}^{i} - P_{Ch(st,t)}^{i}\right) - \sum_{l=1}^{N_{L}^{i}} \left(P_{Load(l,t)}^{i} - P_{NSD(l,t)}^{i} - P_{DR_{A(l,t)}}^{i} - P_{DR_{B(l,t)}}^{i}\right) = G_{ii} - V_{i(t)}^{2} + V_{i\,(t)} * \sum_{j \in L^{i}} V_{j(t)} * \left(G_{ij} * sin\theta_{ij(t)} - B_{ij} * cos\theta_{ij(t)}\right) - B_{ii} * V_{i(t)}^{2}$$

$$\forall \text{t} \in \{1,\ldots,T\};\ \forall \text{i} \in \{1,\ldots,N_{B}\};\ \theta_{ij(t)} = \theta_{i(t)} - \theta_{j(t)} \quad (3.22)$$

- $\left(P_{DG(dg,t)}^{i} - P_{GCP(dg,t)}^{i}\right)$, represents the Active Power production of a generator minus the generation curtailment power;
- $P_{SP(sp,t)}^{i}$, represents the active power fromy6 External Supplier;
- $(P_{Dch(v2g,t)}^{i} - P_{Ch(v2g,t)}^{i})$, represents the Active Power discharged -Active Power charged by a V2G;
- $((P_{Dch(ess,t)}^{i} - P_{Ch(st,t)}^{i})$, represents the Active Power discharged -Active Power
- $(P_{Load(l,t)}^{i} - P_{NSD(l,t)}^{i} - P_{DR_{A(l,t)}}^{i} - P_{DR_{B(l,t)}}^{i})$, represents the Load consumption minus the not supplied demand minus two Demand Response (A - Active power reduction, B - Active power curtailment);
- G_{ii} , represents the real part of admittance matrix (G);
- B_{ij}, represents the imaginary part of admittance matrix (G);
- $V_{i\,(t)}$, represents voltage at node i;

For the calculation of the reactive balance, only the resources that produce and consume reactive power were considered.

$$\sum_{dg=1}^{N_{DG}^{i}} \left(Q_{DG(dg,t)}^{i}\right) + \sum_{sp=1}^{N_{SP}^{i}} Q_{SP(sp,t)}^{i} - \sum_{l=1}^{N_{L}^{i}} (Q_{LOAD(l,t)}^{i} - Q_{NSD(l,t)}^{i})$$

$$= V_{i(t)} * \sum_{j \in L^{i}} V_{j(t)} * \left(G_{ij} * sin\theta_{ij(t)} - B_{ij} * cos\theta_{ij(t)}\right) - B_{ii} * V_{i(t)}^{2}$$

$$\forall \mathrm{t} \in \{1,\ldots,T\};\ \forall \mathrm{i} \in \{1,\ldots,N_B\};\ \theta_{ij(t)} = \theta_{i(t)} - \theta_{j(t)} \qquad (3.23)$$

- $Q_{DG(dg,t)}^{i}$, represents the Reactive Power production of a generator;
- $Q_{SP(sp,t)}^{i}$, represents the Reactive Power introduced by the external supplier;
- $Q_{Load(l,t)}^{i} - Q_{NSD(l,t)}^{i}$, represents the Reactive Power consumed by a load minus the Reactive Power non-supplied to the load.

$$V_{Min}^{i} \leq V_{i(t)} \leq V_{Max}^{i} \qquad (3.24)$$

$$\theta_{Min}^{i} \leq \theta_{i(t)} \leq \theta_{Max}^{i} \qquad (3.25)$$

$$|\ \bar{U_{i(t)}} \times [\bar{y_{ij(t)}} \times \left(\bar{U_{i(t)}} - \bar{U_{j(t)}}\right) + \bar{y_{sh_i}} \times \bar{U_{i(t)}}]^{*} \leq S_{Branch(i,j)}^{Max} \qquad (3.26)$$

$$|\ \bar{U_{j(t)}} \times [\bar{y_{ij(t)}} \times \left(\bar{U_{j(t)}} - \bar{U_{i(t)}}\right) + \bar{y_{sh_j}} \times \bar{U_{j(t)}}]^{*} \leq S_{Branch(i,j)}^{Max} \qquad (3.27)$$

$$\forall \mathrm{t} \in \{1,\ldots,T\};\ \forall \mathrm{i,j} \in \{1,\ldots,N_B\};\ i \neq j$$

- $V_{i(t)}$, voltage magnitude at bus i;
- $\theta_{i(t)}$, voltage angles at bus i;
- $U_{\bar{i}(t)}$, voltage in polar form at bus i;
- $y_{\bar{ij}(t)}$, series admittance of line that connects buses ij;
- $y_{\bar{sh}_j}$, shunt admittance of line that connects two buses;
- T , total number of periods;
- N_B, number of resources that contains imaginary part in admittance matrix(S);
-

3.3 Second stage - Power Flow Tracing

3.3.1 Power Flow tracing (overview)

This chapter will address the theme "Power flow tracing" and talk about two methods of proportional sharing (the Abdelkader and the Bialek method).

Power Flow Tracing (PFT) can be performed on a network where there is a power flow transit. If the traffic is positive, the tracing is done in order to determine the contribution of the generation power in the loads **(downstream**), and, if the traffic is negative, the power flow tracing is performed to determine the contribution of the loads in the generators (**upstream**). Power flow tracing is a tool with several possible uses, such as allocating costs to generators and loads by their system impact, load shedding determine the proportion of contribution of generators to C_{02} emissions.

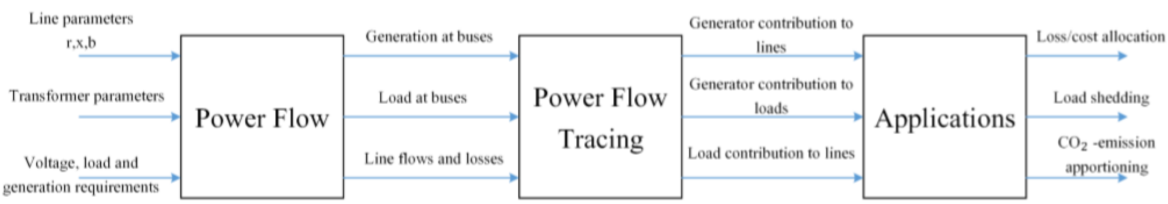

Figure 3-2 Inputs and Output's [42].

PFT is based on the Proportional Sharing Principle (PSP) that tries to answer the question about who contributes to the traffic of the branches. It's a complex question since the energy can move in any direction, always choosing the path with the least impedance.

According to this method, the power present in a node is proportional to the power that feeds the node and the power that leaves the node. The figure 3-2 that illustrates the operation of the PSP method [43].

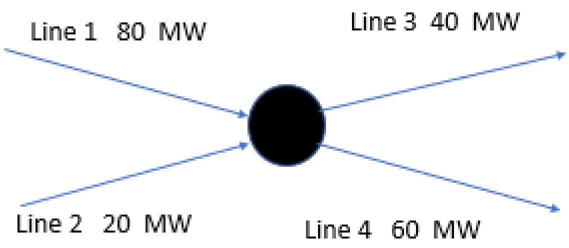

Figure 3-3-Proportional Sharing Principle [23].

- Line 1 injects $\frac{80}{100} \times 40 = 32\ MW$ in line 3 and $\frac{80}{100} \times 60 = 48\ MW$ in line 4.
- Line 2 injects $\frac{20}{100} \times 40 = 8\ MW$ in line 3 and $\frac{20}{100} \times 60 = 12\ MW$ in line 4.

According to this method, Kirchhoff current law is fulfilled, the sum of the power that leaves the node is equal to the sum of the powers that enters in the node.

3.3.2 Node Test-Based Method

In the 2007, S. Abdelkader presented a power flow tracing methodology using the PSP. This method uses nodal generation distribution factors (NDFG), which determines the share of a specific generator in all the lines flow [44]. This methodology uses as a starting point, an optimal power flow study. With this study, it is possible to build the line flow matrix. This matrix is used to classify the different nodes, and from there it is used to calculate the share that each generator has on the different lines, loads and losses (downstream algorithm). This methodology can also be used to calculate the share that each load has on the different lines, generators and losses (upstream algorithm). The method can be used to trace active and reactive power flows. Some of the advantages of this method are that no exhaustive search is required, there is no need of creating fictional nodes to handle losses and no inversion of matrix is needed [28] [27].

3.3.3 General Algorithm

The present algorithm was created by S.Abdelkader [28] and the following description was adapted from [27] and [28].

The algorithm starts with the **classification of all nodes** of the network. The nodes can be classified in four different categories. There are source nodes, generation nodes, load nodes and sink nodes. The classification of a bus depends on the direction of the line flows that affecting that bus, as presented in Figure 3-4.

In Table 3-1 is presented the node classification conditions.

A **source node** (a) is a node that supplies power to all rows that departing from that node to adjacent nodes. This node injects all his power into the lines connected to it. In other words, the flow of energy in all the lines departing from that node is positive.

A **sink node** (b) is a node that receives power from all the lines connected to it. The energy flow in all the lines are negative. The load at a sink node extracts all the power from the node.

The nodes classified as **generation** (c) and **load**(d) are connected to lines in transporting power to the node (inflows) and that carrying energy to the adjacent nodes (outflow). The **generation** nodes are those in which the net flow is positive, and the **load** nodes when the net flow is negative.

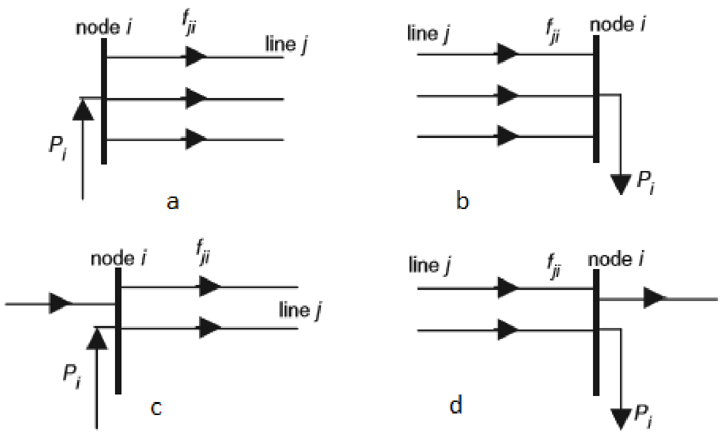

Figure 3-4-Types of system nodes [25].

Node Type	Condition
Source node	$f_{ii} \leq 0\; j = 1, N_L$
Sink node	$f_{ij} \geq 0\; j = 1, N_L$
Generation node	$\sum_{j=1}^{N_L} f_{ij} \quad \leq 0\; j = 1, N_L$
Load node	$\sum_{j=1}^{N_L} f_{ij} \quad \geq 0\; j = 1, N_L$

F=$[f_{ij}]\; I = 1, \quad j = 1, N_L$

Table 1-Node classification condition [28].

- f_{ij} , represents the power extracted from bus i by line j;
- N_L , represents the total number of lines connect to the node.

A line flow matrix F is constructed based on all the line flows affecting each bus $, f_{ij}$. Having the F matrix is now possible to build the A matrix. Each element in the A matrix represents the contribution of a generator to the power flow in a line (extraction factor) and it is calculated using formula 3.28.

$$A_{ij} = \frac{Power\ flow\ in\ line\ j\ caused\ by\ node\ i}{Total\ power\ flow\ in\ line\ j} \qquad 3.28$$

To trace the power flow from a generator to the respective lines and loads, it is needed to create a participation factor matrix. Each line of the matrix represents a different node. Based on each node classification, it is possible to determine the participation of that node in the different lines.

Source node: In the F matrix, the row of a source node contains only positive elements. The correspondent row in the A matrix is built by replacing all the elements different from 0 by 1.

Sink node: In a Sink node, no power is injected in the node, therefore all the elements in that row must be replaced by 0.

Generation node: in a generation node, the net injected power is positive. The corresponding elements in matrix A are calculated below:

$$A_{ij} = \begin{cases} \frac{P_{Gi}}{\sum_{m\in\alpha P} f_{im}}, & if\ f_{ij} > 0 \\ 0, & if\ f_{ij} = 0 \\ \frac{f_{ij}}{\sum_{m\in\alpha P} f_{im}}, & if\ f_{ij} < 0 \end{cases} \quad 2.29$$

Load node: in a load node, the net injected power is negative. In case of positive line flow the extraction factor, will be a very small number, which will be used to direct the power tracing process. The correspondent elements in matrix a calculated below:

$$A_{ij} = \begin{cases} \alpha, & if\ f_{ij} > 0 \\ 0, & if\ f_{ij} = 0 \\ \frac{f_{ij}}{\sum_{m\in\alpha_N} |f_{im|}} & if\ f_{ij} < 0 \end{cases} \quad 2.30$$

Where:

- P_{Gi}, is the generation node i;
- α_P, is the set of positive elements in row i;
- α_N, is the set of negative elements in row i;
- α, is a very small, positive number, set to 10^{-8}.

After building the A matrix, it is necessary to eliminate the negative elements, because negative elements represent the inflow in a node. A positive element represents a line carrying power from a node to another. Based in this two information's, it is possible to trace the path between a generator and a load.

Tracing procedure to eliminate negative elements in A matrix.

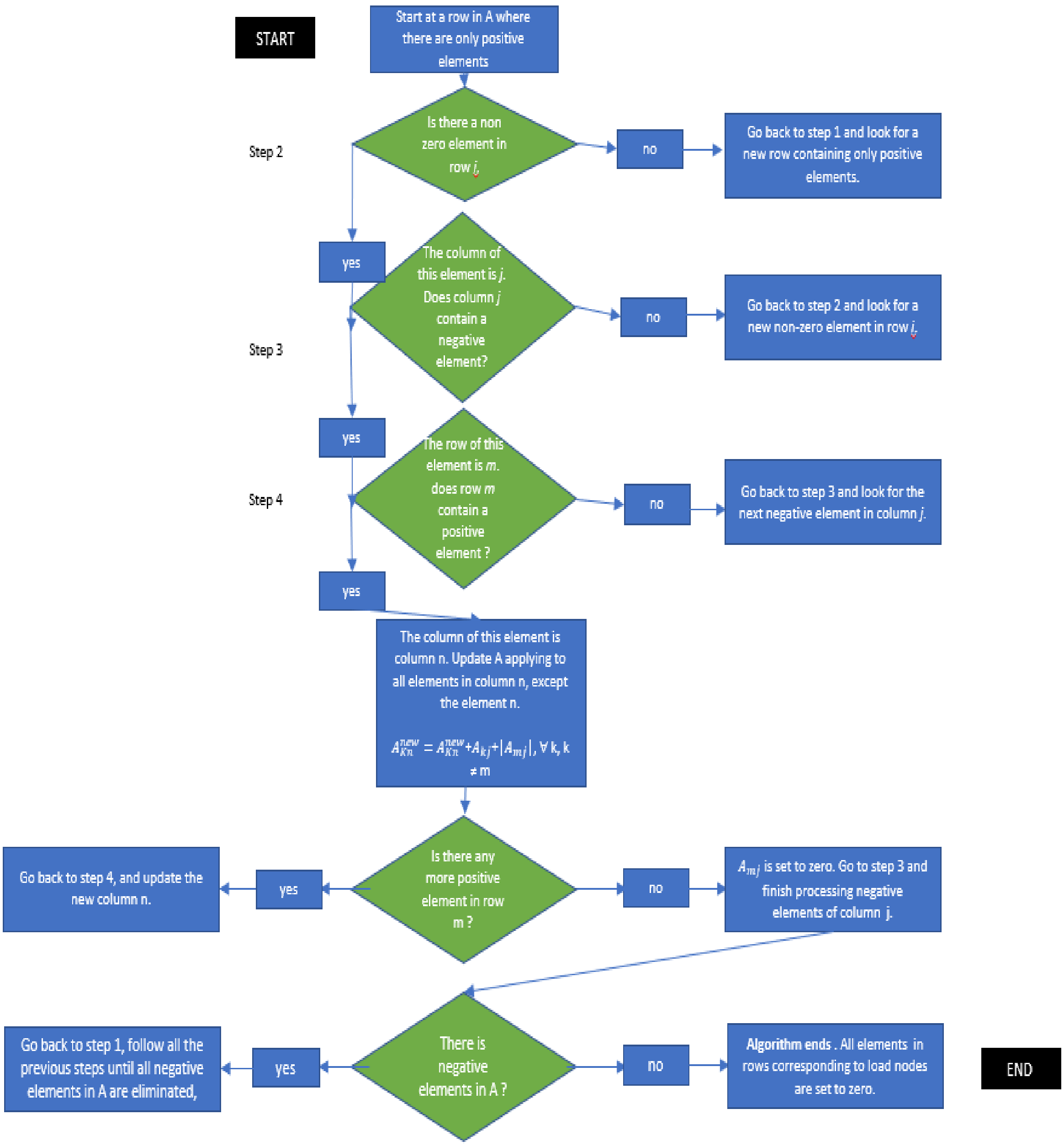

Figure 3-5-Elimination of A matrix negative elements algorithm [36].

The formulas used to determine the bus contribution in each branch(2.31) and load(2.32) are:

$$T = A\,diag\,(F_j) \qquad 2.31$$

The diag(F_j) is a diagonal matrix, where the diagonal elements are equal to the power at ending of line j.

The flow contribution of each bus in each load is determined by multiplying the A matrix by matrix F transposed.

$$P = A\,F^{t} \qquad 2.32$$

The algorithm can be summarized as follows:

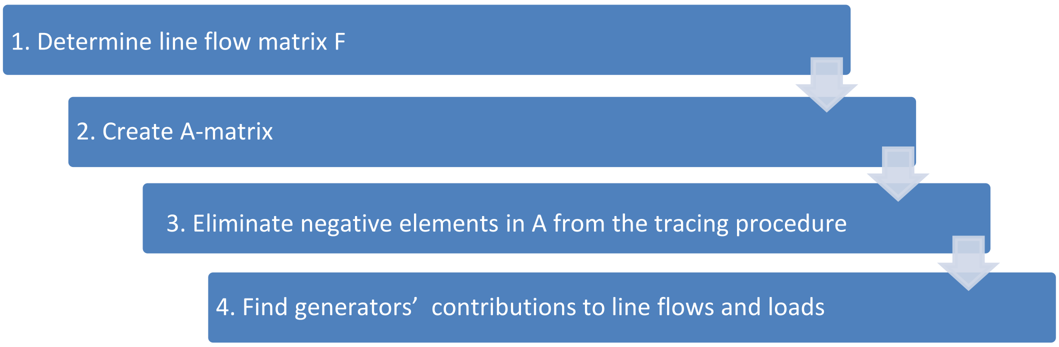

Figure 3-6- Abdelkader Power flow tracing

After the calculation of each resurce responsibility in the line flows it is also possible to calculate their contribution to the line losses. The line losses are porportional to the contribution of each generator in each branch, so they can be eassily obtained by multipliyng the resource responsabilitiy in % by the losses in that line.

Linear Equation-Based Method

In 1996, Bialek [45], proposed a new tracing method , based on PSP . This method revels the contribution of each generator has on a load and lines (downstream algorith), and the contribution that a load has on the lines and generators (Upstream algorithm).Bialek's method uses Topological Generation Distribution Factors (TGDF) to determine the contribution of each resource in each lines [46].This algorithm only works on lossless flows.Bialek proposes three different ways of considering it where an equivalent network is presented. To obtain a lossless flow, Bialek proposes to decrease generation (Net flows) used in the downstream algorithm and increase the loads (Gross flows) used in the upstream algorithm. Another approach is to change the values of the generation and loads (Average flows), where an equivalent network is created, and the losses of the line are divided by the beginning sending and the receiving end. The new equivalent network using average flows can be used in the downstream algorithm and the upstream algorithm. In this work, is presented how to calculate the contribution of the generation and loads using average flows.

3.3.4 Bialek tracing algorithm using average flows

In order to apply the Bialek's algorithm, it is necessary to convert the given network into a new equivalent network. The easiest way to do it, is assuming that the flow at beginning of the line is the same as the flow at the end of the line. This assumption can be done if the losses of the lines are divided by two. Half of the losses are subtracted to the power at the begginnig send of the line, and the other half of the losses are added to receiving end of the line. In the example a below(1) there is a simple example of how it is done [25].

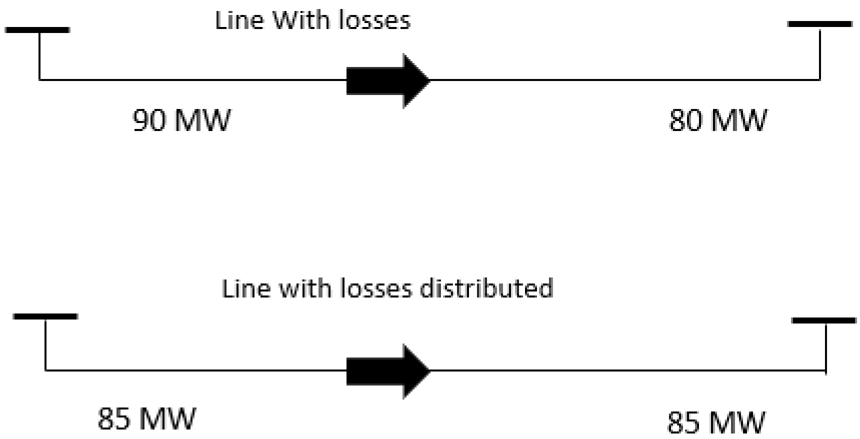

Figure 3-7-distribution of losses in a line.

Using the Upstream algorithm, it is possible to trace the contribution of each load in the different lines and generators in the system. Those contributions can be achieved by using the following process.

First is necessary to calculate the total flow at the nodes of the system. This can be done by adding the power generated at a node and the power flows that are connected to that node.

$$P_i = \sum_{j \in \alpha_i^{(u)}} |P_{i-j}| + P_{Gi} \quad for\ i = 1,2,\dots,n \tag{3.28}$$

- $\alpha_i^{(u)}$ correspond to the set of nodes supplying straight node *i*
- P_{i-j} correspond to the line flow from node *i* to node *j*
- P_{Gi} correspond to the generation at node *i*

Once there are no losses in the lines, $|\boldsymbol{P_{i-j}}|$=$|\boldsymbol{P_{j-i}}|$.

Considering $|P_{j-i}| = c_{ji}P_j$, is equivalent $c_{ji} = \frac{|P_{j-i}|}{P_j}$ so we have:

$$P_i = \sum_{j \in \alpha_i^{(u)}} c_{ji}P_j + P_{Gi} \tag{3.29}$$

Rearranging this equation:

$$P_{Gi} = P_i - \sum_{j \in \alpha_i^{(u)}} c_{ji}P_j \quad \text{or} \quad A_u P = P_G \tag{3.30}$$

- A_u, correspond to (n×n) upstream distribution matrix;
- P , correspond to the vector of nodal through-flows;
- P_G, correspond to the vector of nodal generation.

The A_u matrix elements are decided by

$$[A_u]_{ij} = \begin{cases} 1 & if\ i = j \\ -c_{ji} = -\frac{|P_{j-i}|}{P_j} & if\ j \in \alpha_i^{(u)} \\ 0 & otherwise \end{cases} \tag{3.31}$$

After the nodal average flows have been determined, the average line flows can be determined.

Now, the contribution of the *k*th generator to the *i*th nodal power is shown below.

$$P_i = \sum_{k=1}^{n} [A_u^{-1}]_{ik} P_{Gk} = \sum_{k=1}^{N} D_{i-j,k}^{L} \quad for\ i = 1,2, \dots, n \tag{3.32}$$

3.4 Third stage - Costs Allocations

After having the contribution of each generator and load in each line, it is possible to move to the last stage of the methodology. Now it is possible to calculate the fix, congestion and losses costs of each resource in the system.

To perform the calculation of the costs of the distribution network was used a variant of the MW-mile method. This method, in its traditional form, considers the length of the lines between the system nodes, the costs of using the lines per mile and the power flow that a user injects into the system to divide by the capacity of each line [47] .The variant of MW-mile method used multiplies the power provided by each user *by* the cost of the line, divided by the maximum capacity of the line.

In this work were calculated three different costs. Fixed cost, network costs and losses costs. The total cost of the system is equal to sum of each different cost per user [39].

3.4.1 Fixed cost

The system fixed cost is related to the maintenance, operation and plants for expansion and innovation of the electric network.

The fixed costs related to the DG are calculated by the following equation

$$C_{DG(i,dg)}^{Fix} = \frac{F_{(i,dg)} * C_{(i)}^{Fix}}{F_i} \tag{3.33}$$

The fixed costs of each line are calculated by multiplying the flow introduced into the lines by each generator$F_{(i,dg)}$ times the fixed cost of the line $C_{(i)}^{Fix}$ divided by the total power that is in that branch at that time.

The following equations are used to calculate the costs that the DR causes in the system.

$$C_{DR(i,dr)}^{Fix} = \frac{F_{(i,dr)} * C_{(i)}^{Fix}}{F_i} \tag{3.34}$$

All the parameters of the equation are the same as the equation described above. The only term that changes is the contribution of DR in the transit of line $F_{(i,dr)}$
The costs related with the loads are calculated below.

$$C_{L(i,l)}^{Fix} = \frac{F_{(i,l)} * C_{(i)}^{Fix}}{F_i} \tag{3.35}$$

All the parameters of the equation are the same as the equation described above. The only term that changes is the contribution of loads in the line flow *i*.

In the following formula is shown how to calculate the fixes costs related to the charges and discharges of storage. When a storage injects power in the grid it behaves as a generator, when it is charging it behaves as a load.

$$C_{Ess(i,st)}^{Fix} = \frac{F_{(i,essdch)} * C_{(i)}^{Fix}}{F_i} + \frac{F_{(i,essch)} * C_{(i)}^{Fix}}{F_i} \tag{3.36}$$

All the parameters of the equation 3.36 are the same as the equation described for 3.35. The only term that changes is the contribution of the charging and discharging power of a storage system in the line flow ***i***.

The formula below represent how V2G fixes costs are calculated. V2G works the same way storage batteries do. When the vehicle injects power in the grid he behaves as a generator, when it is is charging it behaves as a load.

$$C_{V2G(i,v2g)}^{Fix} = \frac{F_{(i,v2gdch)} * C_{(i)}^{Fix}}{F_i} + \frac{F_{(i,v2gch)} * C_{(i)}^{Fix}}{F_i} \tag{3.37}$$

All the parameters of the equation are the same as the equation described in 3.36. The only term that changes is the contribution of the charging and discharging power of a V2G in the line flow ***i***.

3.4.2 Network costs

The costs associated with network relate to the maximum capacity each line can support. These costs are intended to tax users who don't contribute to optimum use of line capacity. The costs of using the network were divided into three levels. In the first level, the cost is calculated by charging a fee in case the user contributes to a line flow ($Fix_{(i,user)}$) that has a line usage factor less than 85% of its maximum capacity, Cost A $C_{User(i,user)}^{A}$. The second level has an interval of 85% and 98% Cost B $C_{user(i,user)}^{B}$, and in the third level, the line usage factor is between 98% and 100% cost $C_{User(user,l)}^{C}$.

$$C_{Branch(i,j)}^{NetUse} = \begin{cases} C_{Branch(i,j)}^{NetUseA} = 5 * \left| LMP_{(j)} - LMP_{(i)} \right| \; if \; \frac{F_{(i,j)}}{F_{Max(i)}} (\%) \leq 85\% \\ C_{Branch(i,j)}^{NetUseB} = \left| LMP_{(j)} - LMP_{(i)} \right| \; if \; 85\% \frac{F_{(i,j)}}{F_{Max(i)}} (\%) \leq 98\% \\ C_{Branch(i,j)}^{NetUseC} = 10 \left| LMP_{(j)} - LMP_{(i)} \right| \; if \; 98\% \geq \frac{F_{(i,j)}}{F_{Max(i)}} (\%) < 100\% \end{cases} \tag{3.38}$$

To calculate the network cost is also used a modification of the MW-mile method, where the contribution of each resource is multiplied by the cost of each branch (3.38). This cost is applied to all resources connected to network(DG, ESS, DR,V2G and loads).

The network costs caused by distributed generation are calculated by the following equation

$$C_{DG(i,dg)}^{NetUse} = \frac{F_{(i,dg)} * C_{Branch(i)}^{NetUse}}{F_i} \tag{3.39}$$

The network costs of each line are calculated by multiplying the flow introduced into the lines by each generator times the fixed cost of the line $C_{Branch(i)}^{NetUse}$ divided by the total power that is in that branch at that time.

The equation 3.40 is used to calculate the costs DR causes in the network.

$$C_{DR(i,dr)}^{NetUse} = \frac{F_{(i,dr)} * C_{(i)}^{NetUse}}{F_i} \tag{3.40}$$

All the parameters of the equation are the same as the equation described for 3.40. The only term that changes is the contribution of Demand Response in the flow of line $F_{(i,dr)}$

The costs related with the loads are calculated below.

$$C_{L(i,load)}^{NetUse} = \frac{F_{(i,l)} * C_{(i)}^{NetUse}}{F_i} \tag{3.41}$$

The formula used to calculate the cost of the loads is the same used in 3.40. The only term that changes is the contribution of Loads in the line flow *i*

In the folowing formula it is be presented how to calculate the network costs related to the charges and discharges of storage. When a storage injects power in the grid it behaves as a generator, when it is charging, it behaves as a load.

$$C_{Ess(i,st)}^{NetUse} = \frac{F_{(i,essdch)} * C_{(i)}^{NetUse}}{F_i} + \frac{F_{(i,essch)} * C_{(i)}^{NetUse}}{F_i} \tag{3.42}$$

All the parameters of the equation 3.42 are the same as the equation described in 3.41. The only term that changes is the contribution of the charging and discharging power of a storage system in the line flow *i*

The formula below represent how vehicles to grid (V2G) network are calculated. V2G work the same way storage do. When the vehicle injects power in the grid he behaves as a generator, when it is is charging it behaves as a load.

$$C_{V2G(i,v2g)}^{NetUse} = \frac{F_{(i,v2gdch)} * C_{(i,)}^{NetUse}}{F_i} + \frac{F_{(i,,v2gch)} * C_{(i,)}^{NetUse}}{F_i} \quad (3.43)$$

All the parameters of the equation are the same as the equation described in equation (3.42). The only term that changes is the contribution of the charging and discharging power of a V2G in the line flow ***i***.

3.4.3 Loss costs

The costs associated with losses are calculated based on the impact each resource has on the line losses. The cost of each line is determined using the higher LMP of the two nodes that connects a line. These LMP values were calculated in phase 1. The loss cost are calculated by multiplying the impact of each resource by the line loss *times the* cost of the line, and after divide all by the total loss of that line.

The loss costs related to the DG are calculated by the following equation

$$C_{DG(i,st)}^{Loss} = \frac{F_{L(i,dg)} * C_{(i)}^{NetUse}}{F_i} \quad (3.44)$$

The fixed costs of each line are calculated by multiplying the flow introduced into the losses flow by each generator ***times*** the line cost of the line $C_{(i)}^{loss}$ and divided by the total losses in that branch at that time L_i.

The following equation is used to allocate the costs of DR impact in the system.

$$C_{DR(i,dr)}^{Loss} = \frac{F_{L(i,dr)} * C_{(i)}^{NetUse}}{F_i} \quad (3.45)$$

All the parameters of the equation 3.45 are the same as the equation described in 3.44. The only term that changes is the contribution of DR in the line losses flow $F_{L(i,dr)}$.The costs related with the loads losses are calculated below.

$$C_{L(i,l)}^{Loss} = \frac{F_{L(i,l)} * C_{(i)}^{loss}}{L_i} \quad (3.46)$$

All the parameters of the equation 3.45 are the same as the equation described in 3.46. The only term that changes is the contribution of loads in the line losses *i*.

In the folowing formula 3.47 it is presented how to calculate the fixes costes related to the charges and discharges of storage.

$$C_{ESS(i,l)}^{loss} = \frac{F_{L(i,essdch)} * C_{(i)}^{loss}}{L_i} + \frac{F_{L(i,essch)} * C_{(i)}^{loss}}{L_i} \quad (3.47)$$

All the parameters of the equation 3.47 are the same as the equation described in 3.46. In order to calculate the costs of each batery the costs of the batery charging ared added to the costs of the batery discharging .

The formula 3.48 represent how V2G fixes costs are calculated. V2G work the same way storage do. When the vehicle injects power in the grid he behavess as a generator, when it is is charging it behavesas a load.

$$C_{V2G(i,v2g)}^{loss} = \frac{F_{L(i,v2gch)} * C_{(i)}^{loss}}{L_i} + \frac{F_{L(i,v2gch)} * C_{(i)}^{loss}}{L_i} \quad (3.48)$$

All the parameters of the equation are the same as the equation described for storage 3.47. The only term that changes is the contribution of the charging and discharging power of a V2G in the line losses *i*.

3.4.4 Total costs

Total cost allocated to each resource result from the sum of all cost costs calculated from section 3.4.1 to 3.4.3. So, each resource should pay fixed, network cost and losses costs. The total cost formula for each resource is from 3.49 to 3.53.

For DG (3.49), DR (3.50) and loads (3.51) the calculation of the total cost is very similar.

$$Total\ Cost_{DG(dg)} = C^{Fix}_{DG(i,dg)} + C^{NetUse}_{DG(i,dg)} + C^{Loss}_{DG(i,dg)} \tag{3.49}$$

$$Total\ Cost_{DR(dr)} = C^{Fix}_{DR(i,dr)} + C^{NetUse}_{DR(i,dr)} + C^{Loss}_{DR(i,dr)} \tag{3.50}$$

$$Total\ Cost_{L(l)} = C^{Fix}_{L(i,l)} + C^{NetUse}_{L(i,l)} + C^{Loss}_{L(i,l)} \tag{3.51}$$

For ESS's (3.52) and V2G (3.53) the total cost takes into account the fact that these resources use the network for two different purposes. To inject energy in the grid and to receive energy from the grid.

$$Total\ Cost_{ESS(ess)} = C^{Fix}_{ESS(i,ess)} + C^{NetUse}_{ESS(i,ess)} + C^{Loss}_{ESS(i,ess)} \tag{3.52}$$

$$Total\ Cost_{V2G(v2g)} = C^{Fix}_{V2G(i,v2g)} + C^{NetUse}_{V2G(i,v2g)} + C^{Loss}_{V2G(i,v2g)} \tag{3.53}$$

3.5 Conclusion

This chapter addresses the methodology used to charge all the users of the distribution network and thus allocate all the costs inherent to its use.

The first part of the methodology was scheduled which generators should be in operation for each hour to feed the demand as efficiently and economically as possible.

The second part of the methodology is studied the contribution that each user of the distribution network has in the energy flow that flows through each one of the lines for each hour. Two different methods were used to perform this study. The Bialek method, which uses TGDF and so is considered that the lines are lossless, and the Abdelkader method which uses NGDF, losses are taken into account. In the two methods, two approaches were taken: one for the flow of energy from the generators to the loads (downstream algorithm) and another approach in which the flow from the loads to the generators (upstream algorithm) is studied.

After studying the contributions of each generator and each load in all the lines of the system it is possible to distribute the share of using the distribution network operating costs of the distribution network by all its users. Three costs were addressed, fixed costs, costs related to network usage and losses costs.

4 Case Study

4.1 Outline

In this chapter, it is discussed the results of the application of the methodology. The distribution network in study has radial configuration and consists of 33 buses (Figure 4-1). One of the busbars connects this distribution network to the upstream network (in which the power flowing to the distribution network is represented by an external supplier), in all other buses it is possible to find loads and generators. In this network there is a great variety of distributed production, coming from renewable and non-renewable energy sources. The technologies used to produce renewable energy are PV, wind farms and small-hydro. The production of energy from non-renewable sources comes from fuel cells, cogeneration, biomass and WtE.

Production Type	Quantity	Aggregator	Total capacity (MW)
Photovoltaic	32	1,3,6,8,10,12,14,18,20,21,23,25,27,29,31,33,35, 37,39,41,43,45,46,48,51,52,54,56,58,60,63,65	0.558
Wind farms	5	15,30,42,49,61	0.525
WTE	1	24	0.1
Cogeneration	15	2,7,13,16,26,28,36,40,44,47,50,53,57,59,64	1.240
Fuel cell	8	4,9,11,17,32,55,62,66	0.235
Biomass	3	19,22,34	0.350
Mini hydric	2	5,38	0.070
Total	66		2.690

Table 2- Types of technologies, quantity, aggregator and total capacity.

In this study is possible to find ESS's and electric vehicles, which can charge and discharge energy in the grid in the most convenient time giving flexibility to grid. ESSs and EVs with V2G ability can be used to charge at off-pick hours (when energy is cheaper) and discharge at peak hours (when energy is more expensive) obtaining a positive trade-off.

Technology	Quantity	Bus	Maximum Capacity (MWh)
ESS	10	3, 4, 5, 6,10, 14, 19, 23,28,32	1200
V2G	50	Varies by hour	7828

Table 3 Technologies with storage capacity.

These resources are distributed over the network by the 33 buses, only the bus 0 has no DG, since it is a connection bus to an external supplier (connection to the upstream network). In this network there are DR programs, responsible for the flexibility of the loads, being possible to reduce and /or curtail them.

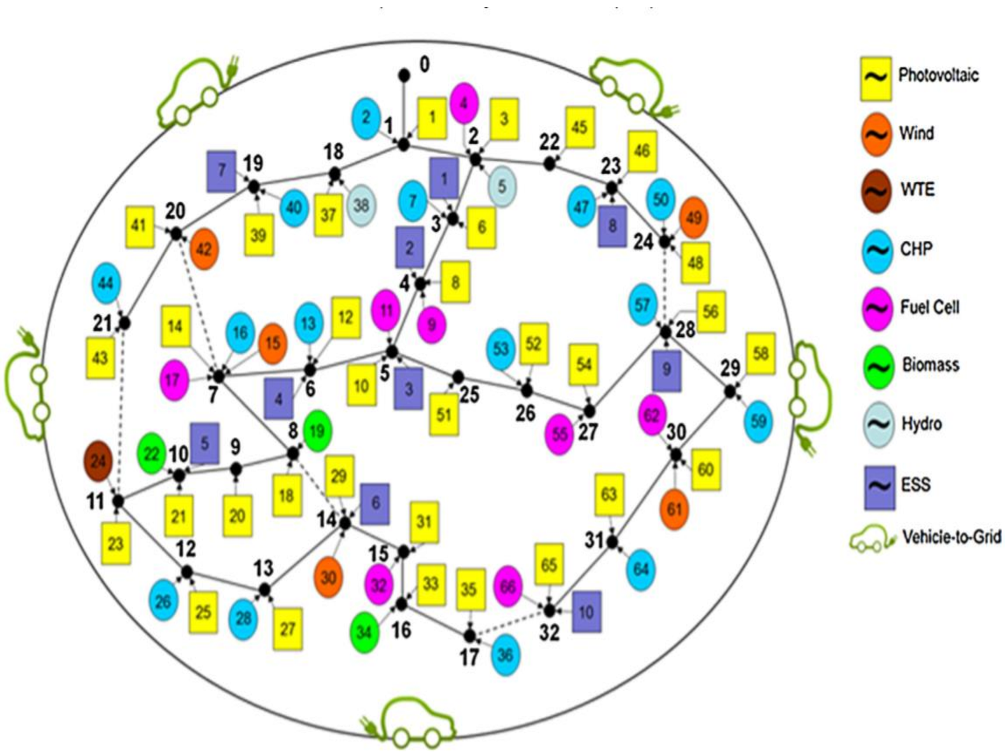

Figure 4-1-Study network.

The line parameters of the networks considered were resistance, reactance, susceptance and their maximum capacity.

The parameters of the generators considered were maximum and minimum capacity of production and variation of production prices.

In relation to EVs and ESS, their state-of-charge, maximum capacity was taken into account, besides charging and discharging prices.

The characteristics of the DR are the capacity and the maximum, minimum and average price of the of reducing and curtail the load.

It is also possible to find a table with the load diagrams, which serves to realize which units of production must be put into operation in order to feed the loads in the most economical way possible.

4.2 Results

The methodology used in this study is composed of three phases which has been designed to determine and allocate the network usage costs to all users (generators and loads). Three different costs were calculated, fixed costs, namely the fixed, congestion and losses costs. The impact that each resource has on the network was calculated through two methods, the Bialek's and Abdelkader's tracing methods. The results of the two studies are presented in this section. According to these two methodologies, the costs of using the network are divided by two entities in the same way. 50% of the costs are attributed to the producers by the injection of energy in the network, and 50% to the consumers, by the energy consumption in the network.

In addition, a robustness test of the Abdelkader algorithm was also performed.

4.2.1 First step - Energy resources schedule result

The first step in the methodology is to run an economic dispatch and calculate the LMP’s for each bus and schedule the production resources over a day to feed as efficiently and economically as possible all.

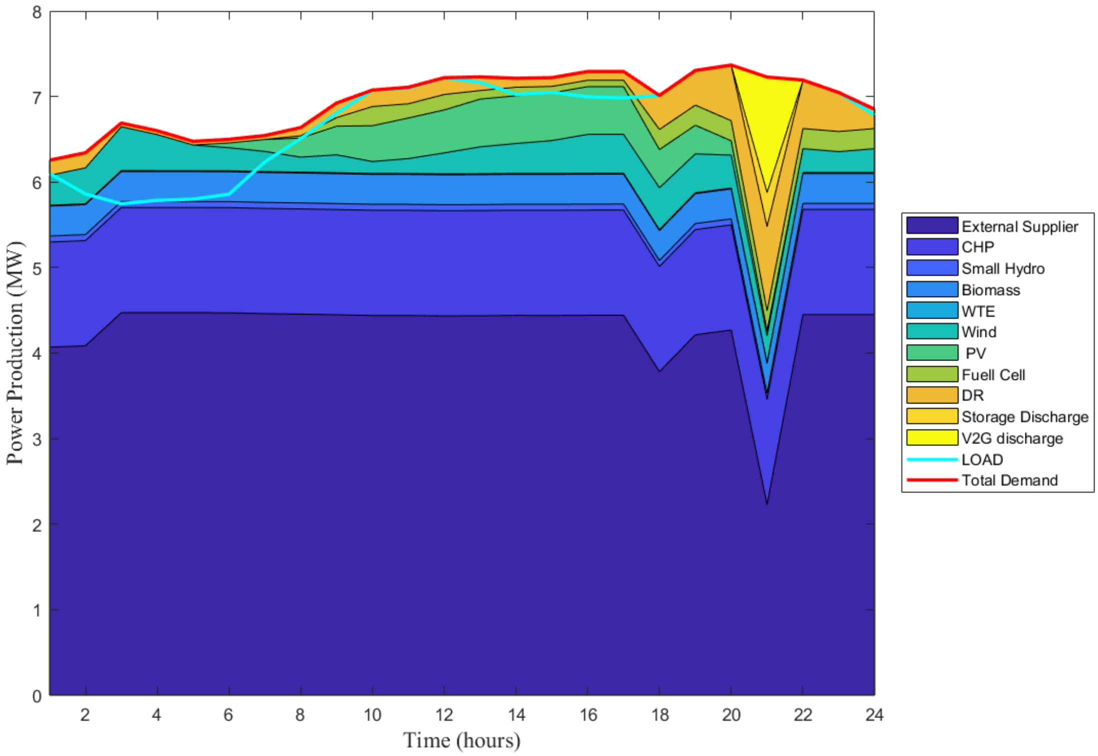

Figure 4-2-Energy resources schedule in the distribution system.

Figure 4-2 depicts the day-ahead resources scheduling for a 24-hour period.In this figure it is possible to see that there is a peak of consumption between the 20 and the 22 hours (rush hour), and that the consumption is smaller during the dawn (hours of emptiness). It is noteworthy that most of the energy supplying the loads comes from the external supplier, accounting for 61% of all the energy produced. The DG has a large impact (about 35%), and the remaining 4% is assured by ESSs, EVs with V2G ability and DR programs

The ESSs and EVs are scheduled to discharge are programmed to discharge energy in the network between the 20 and the 22 hours, because the use of these resources is expensive, being possible to maximize the profitability of these resources if these are used when the price of the energy is greater.

At hour 21 the contribution of external supplier resource is 30.83%, CHP is 17.018 %, small-hydro is 9.69%, biomass id 4.84 %, RSU is 2.70%, wind farms are 4.36%, PV is 1.84%, fuel cell is 3.25% DR is 13.6269%, ESS's discharging is 5.53% and finally V2g Discharging is responsible for 18.67% of total generation.

Another set of relevant information can be drawn from the analysis of Figure 4-3 in which the LMPs of all the busses are observed for hour 21 (time chosen for the study, since it is the hour with greater demand and therefore is the hour in ESSs, EVs and DR programs are activated).

It is also possible to visualize several steps in the function of the LMP that denounce the radial structure of the network. We can see a step from bus 1 to 17, another from bus 22 to bus 24, another run from bus 26 to bus 32. In this last step, the rung could start on bus 25, but as this bus has a large energy production by feeding the adjacent buses provoking a counterflow, it is possible to observe an inversion in the concavity of the LMP's function.

In Figure4-4 is possible to observe the line congestion and the bus voltage for hour 21, there are no line congestioned and all the nodes are between the normal voltages values.

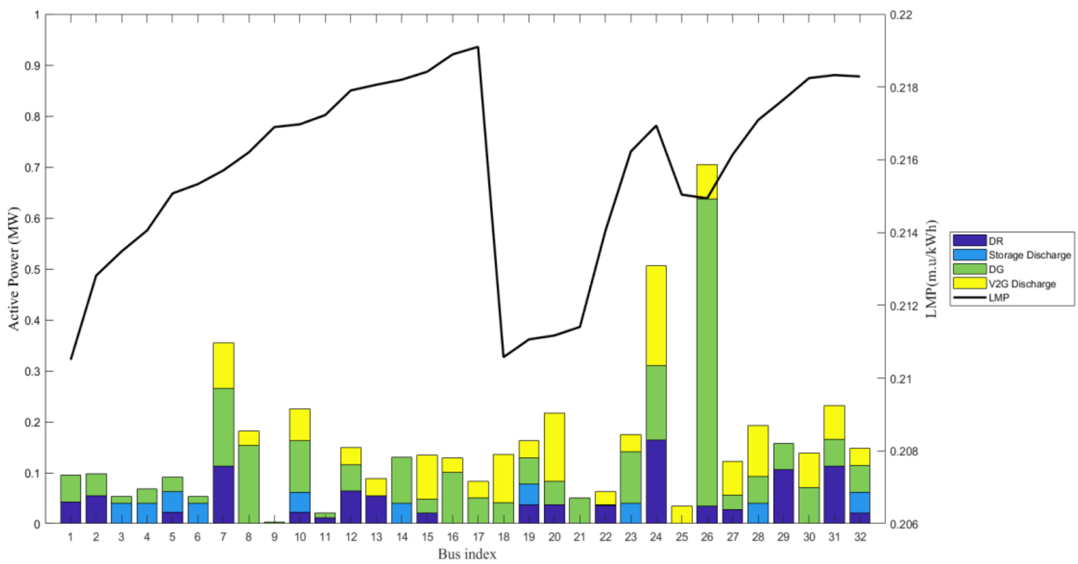

Figure 4-3- Distributed energy resources dispatch and LMP by bus for hour 21.

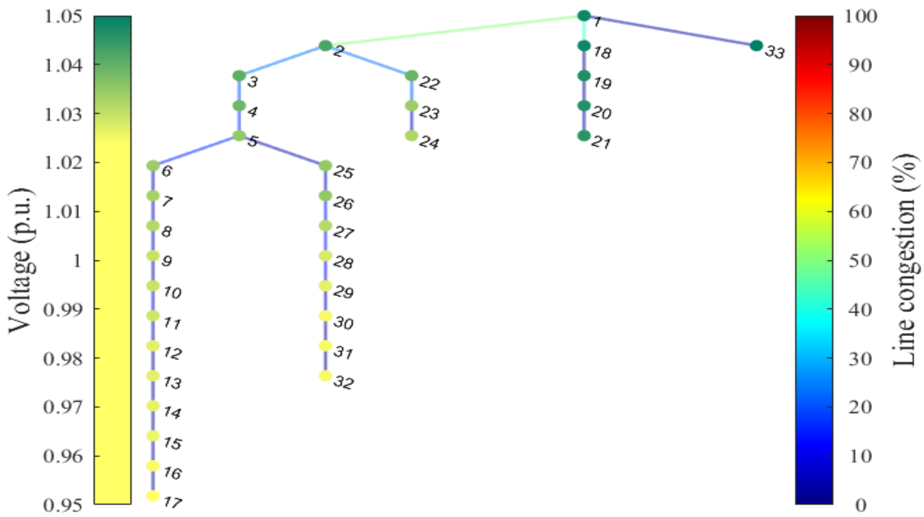

Figure 4-4-Network voltage and line congestion for hour 21.

4.2.2 Second step - Tracing algorithms results

In the second phase of the project will be addressed the impact that each user has on the System in each one of the lines. To calculate this impact, two methodologies were used. The Bialek methodology and the Abdelkader methodology. The results of the application of those two methodologies will be explained. In the figure below, it is possible to observe the impact of each technology in each line, for the 2 methodologies. To improve the understanding of results, the image is divided into 4 parts, each corresponding to a branch of the network. And a color diagram is used, in which the color gradient varies between red, yellow and white, depending on the impact a technology has on the line.

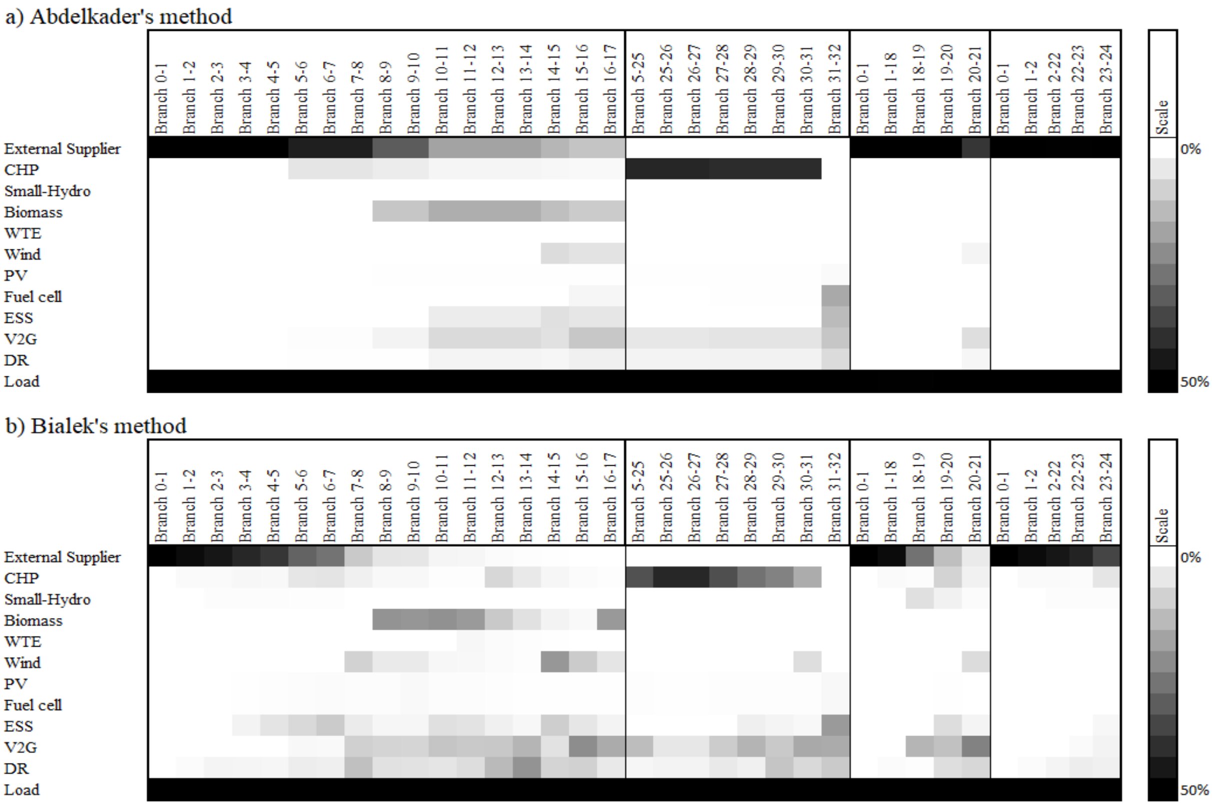

Figure 4-5 Total DER impact in each branch in hour 21 considering Abdelkader´s and Bialek's approaches.

As expected, the beginning of each branch of the network has a greater contribution from the external supplier that is diminished along the branch as the loads are being fed.

Comparing the results, it can be verified that according to the Bialek method there is a more diversified distribution of the impact of the several resources by the different lines than the Abdelkader method. This happens because in the Abdelkader method, before proceeding to the tracing process, need to classify the buses, so a balance is made between the power generated and consumed in the bus. If the generation is greater than the load, it is considered a generation node, if the bus only generates power is classified as Source. If the load on the bus is greater than the generation, the bus is classified as load, and if a bus only receives energy is classified as sink bus. If a bus is classified as generation, it is only possible to trace the difference between the production and the generation in that bus. If a bus is classified as load, only the difference between the load and the generation is considered in tracing algorithm. In practice, this means that, for example, in bus 2 there is a production of 0.03MW (from CHP) and a load of 0.1481 MW, so, this bus consumes 0.1181 MW and is classified as load bus. Therefore, the tracing of energy from this CHP is not considered. So, it is considered that the energy produced feeds the load on this bus and the energy cannot be traced.

For Bialek's methodology, both the generation and the loads of all buses are considered in the tracing algorithm, therefore we see the contribution of all technologies for all lines.

With this analysis, it is possible to observe a great difference between those two schemes. The Bialek method considers that each load can be fed by any generator, while the method of Abdelkader do not trace the flows provided by all generators, only by the generators which are from Generation or Source Buses. In this network, energy is produced in 29 buses, but because of the limitation of the Abdelkader algorithm, the downstream trancing algorithm only considers 9 buses.

4.2.3 Third step - Cost allocation results

In this step of the methodology the costs are allocated to each resource in order to distribute the costs of using the distribution network.

The table 4-3 presents the fixed, network usage and loss costs for the two methodologies, for each type of technology that is using the network at time 21. The combination of the three types of costs results in the total costs also presented.

The cost of every technology is different because they input different amounts of energy. It can be observed that costs related to losses are very small compared to fixed costs, and that the costs related to congestion are negligible in both methods.

Comparing the results of the two methods, it is possible to notice that external supplier account for a greater share of the costs in the Abedelkader method than in the Bialek method. The cause of this difference is because Abdelkader algorithm classify the buses subtracting the power produced by the power consumed. If the tradeoff is zero or less than zero, the bus is classified as load and the tracing of the technologies that feed that bus is not taken in account. In consequence, the contribution of small-hydro and WtE plants are not considered according to the method of Abdelkader.

Resources	Bialek approach				Abdelkader Approach			
	Fixed Costs (m.u/h)	Power Flow Costs (m.u/h)	Loss costs (m.u/h)	Total Costs (m.u./h)	Fixed Costs (m.u/h)	Power Flow Costs (m.u/h)	Loss costs (m.u/h)	Total Costs (m.u./h)
External Supplier	163.3163	0.0290	2.2339	165.5792	279.8738	0.0330	3.8406	283.7474
CHP	86.5959	0.0030	1.1984	87.7973	103.0345	0.0027	1.4295	104.4668
Small-Hydro	4.7858	0.0002	0.0651	4.8511	0.0000	0.0000	0.0000	0.0000
Biomass	37.7979	0.0008	0.5266	38.3254	37.4032	0.0008	0.5217	37.9257
WtE	1.1207	0.0000	0.0156	1.1364	0.0000	0.0000	0.0000	0.0000
Wind	21.3406	0.0004	0.2968	21.6379	6.3948	0.0001	0.0892	6.4841
PV	4.0633	0.0001	0.0563	4.1198	1.5212	0.0000	0.0212	1.5424
Fuel Cell	18.1435	0.0004	0.2525	18.3964	6.7526	0.0000	0.0944	6.8470
DR	52.6811	0.0017	0.7310	53.4138	14.0247	0.0003	0.1951	14.2201
ESS Disch	30.0074	0.0006	0.4161	30.4241	14.0985	0.0002	0.1970	14.2957
V2g Disch	80.1475	0.0016	1.1097	81.2589	36.8967	0.0008	0.5134	37.4108
Load	500.0000	0.0380	6.9021	506.9401	500.0000	0.0378	6.9021	506.9399
Total	1000.0000	0.0760	13.8042	1013.8802	1000.0000	0.0758	13.8042	1013.8800

Table 4-3- Distribution Costs to DER and Load

For both methods, the external supplier and the loads are the main users of the network, thus being responsible for allocating most of the costs.

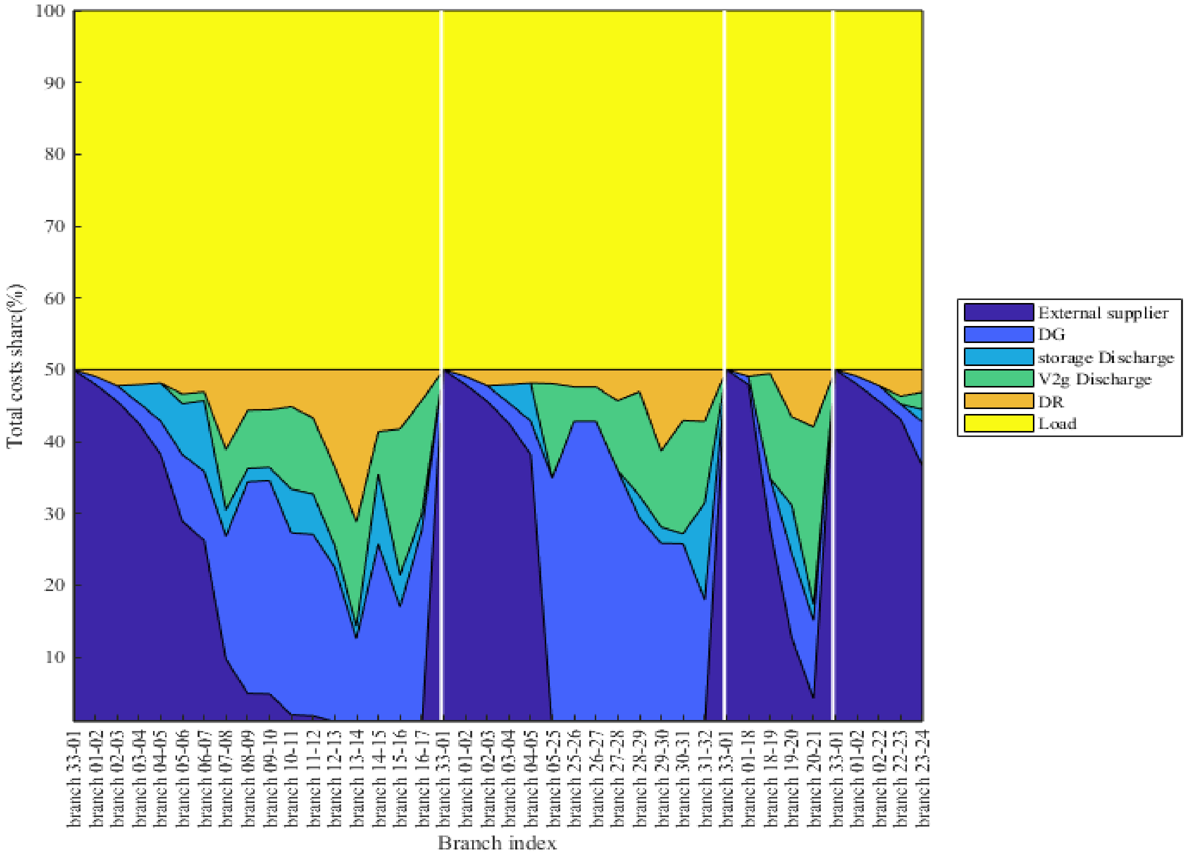

Figure 4-6 - Total Cost Share Bialek method.

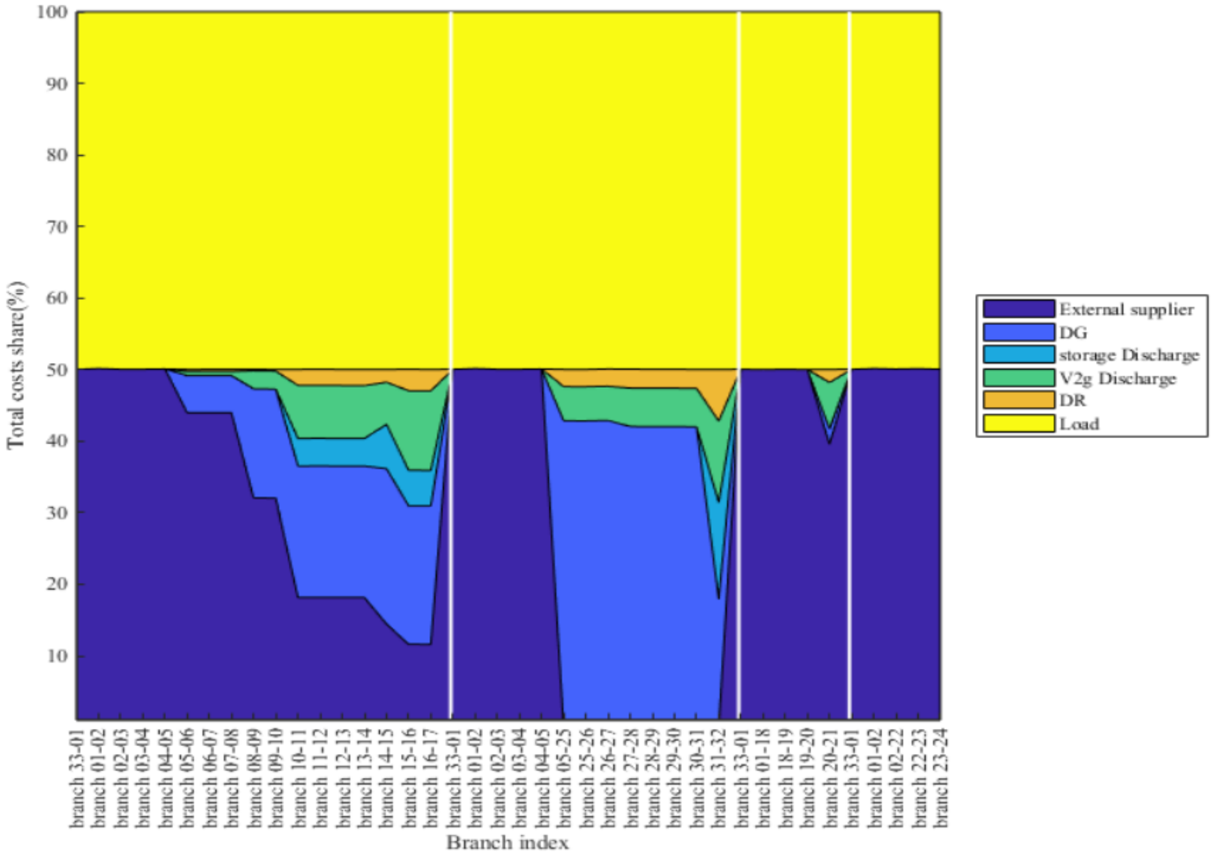

Figure 4-7- Total Cost Share Abdelkader method.

In Figure 4-6 and Figure 4-7 it is possible to study how the total cost were distributed by the different technologies for the two methodologies used, namely Bialek and Abdelkader Analyzing the two methods, one can see that the external supplier has a greater contribution at the beginning of each branch of the network, which is being replaced by the DER as long as moving away from the upstream connection to the inner branches of the network.

In the Abdelkader's method, the network usage costs are not allocated to CHP and WtE resources, since it is considered that these technologies, although they are providing power, are considered to feed the loads of these same buses in which they are allocated. The V2G discharging is responsible for 18.67% of the energy available for the hour 21, but is allocated only 3.69% of the total costs of network usage, while the external supplier is responsible for 30.83% of the supply and is charged with 27.99% of total costs. For the two methods all the fixed cost were successfully recovered

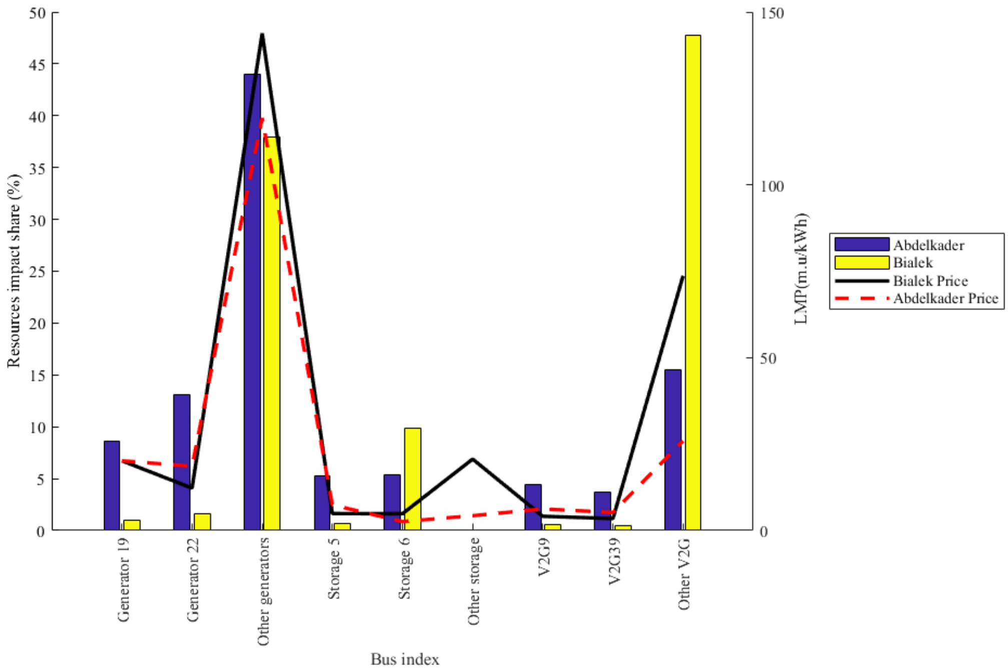

Figure 4-8- Contribution of generation resources for line 19 in period 21.

Figure 4-8 represents the contribution of generation resources for branch 19. This line was chosen because a great variability of DER contributes to the line flow, namely ESS's and V2G. It is possible to notice a greater impact of V2G technologies in the line flow using Bialek methodology than using Abdelkader methodology.

4.3.4Abdelkader robustness test

A robustness test was performed on the Abdelkader method. As described in section 4.2.2, this method has a limitation. In order to proceed to the first phase of the method, it is always necessary to calculate the balance between the production and the consumption in the buses in order to classify the node type.

The aim of test was to understand if the method was capable to classify with success the buses when the production or the load of a bus is moved to an adjacent node. This test was performed for the upstream and downstream version of the algorithm. And it consisted in removing the Load from bus 11 and adding it to the bus 12 for the upstream algorithm and for the downstream version adding the generation of the bus 11 to the bus 12.

As shown in Figure 4-9 , the algorithm successfully responded to the test because when the load of the bus 11 passed to the bus 12, the algorithm started to consider the bus as generation, leaving this bus to contribute to the contribution of the Loads in the lines, while the bus 12 be the sum of the two loads and it is possible to verify that it has more impact on the lines.

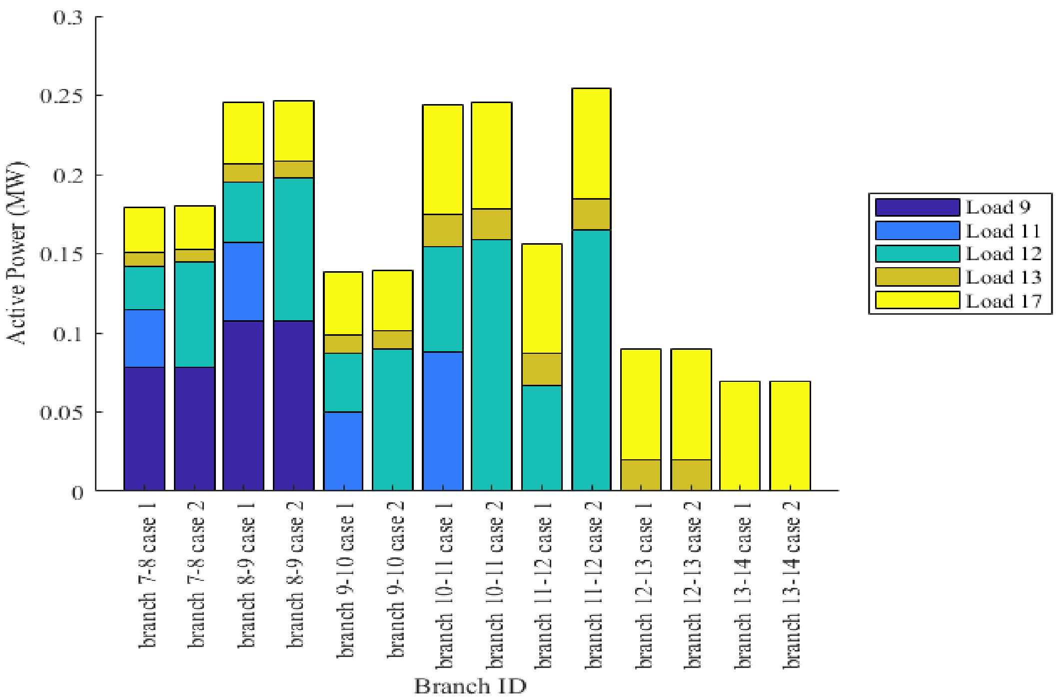

Figure 4-9- Upstream Algorithm.

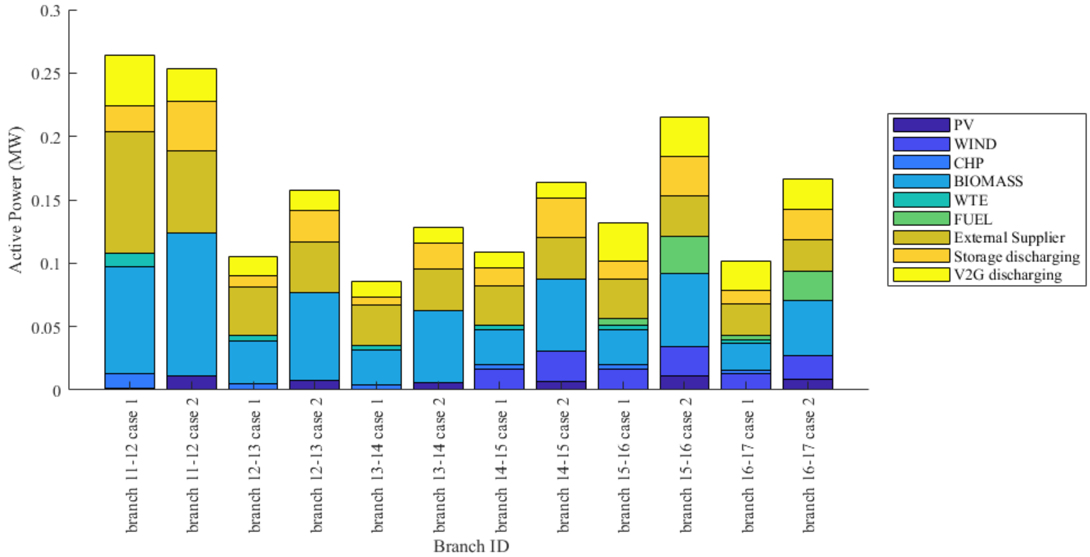

Figure 4-10-Downstream Algorithm.

For the Downstream algorithm (Figure 4-10), the change of generation from bus 11 to bus 12, caused the algorithm of Abdelkader, to classify the bus as Load, passing that bus to have no impact on the distribution lines and observe a greater impact of bus 12 generation technologies on all lines as expected.

It can be concluded that the algorithm works in the expected manner despite variations in production and Loads of buses.

4.4 Conclusion

After completing the observations on the case study, the main conclusions related to the charging model proposed above are addressed.

For this case study, the impact of several DER has been studied for a cost allocation problem allowing to recover the costs of using the distribution system.

The results portrayed come from the application of a hybrid methodology developed and implemented in MATLAB.

The first phase consists of an energy resources scheduling carried out to obtain the dispatch of the different producers, determining the power flow and LMPs.

In the second phase, the Abdelkader's and Bialek's methods were used to calculate the impact of the resources obtained in the previous phase in the lines power flow.

In the last phase, based on the impact of the various resources on the lines, a variation of the MW-Mile method was used to calculate three types of costs allocated to each resource.

Comparing the two methods used to calculate the impact of each technology on the different lines, it is concluded that the Abdelkader method blames the external supplier more than Bialek's method. This is because in the Abdelkader method considers that the generation of a bus feeds the load on this bus, and only the difference between the load and the generation in that bus is considered for the calculation of the contributions, whereas in the Bialek method the impact of all generators is considered.

It was observed that the use of DG brings advantages to the system, since during the hour of greatest demand, hour 21, no occupation was observed above 98% of the lines. It can be concluded that the use of these resources leads to a lower line overhead and, consequently, lower congestion costs.

It is also possible to observe that the costs related to losses are very low, because the introduction of DG reduces the distance between production and consumption, leading to a reduction of losses and consequent reduction of costs.

With the use of both methods, it was possible to recover all the costs of using the distribution system.

5 Conclusion

5.1 Main conclusions

The electric power system is undergoing a radical change in its constitution, increasing the use of DG combined with an increasing use of V2G and ESS's is transforming the structure, operation and the way costs are allocated.

The methodologies used for the old PS paradigm (centralized production) no longer represent an effective and fair way of allocating the distribution network using costs.

This study starts with a research on the most used methodologies in the cost allocation problem, concluding that the best way to distribute these is through the mixture of several methods. This ground-based study serves as the basis for the proposed methodology.

This work consisted in applying a hybrid methodology of cost allocation to a distribution network considering a large-scale integration of DER.

The studied methodology comprises three distinct phases.

The first phase corresponds to an optimization problem, where an economic dispatch was run in order to schedule the production resources in order to feed all loads, know the power flow for all the lines, and calculate the marginal prices for each node.

In the second phase, the contribution of each generator and each load for the power flow of the lines was calculated. To calculate this contribution, two different methodologies were used: the Abdelkader's and Bialek's tracing methods. These methods were initially used in transmission networks and were successfully adapted to the present distribution network. The two methodologies, despite being based on the same principle (proportional sharing principle), presented quite different results and a consequent distribution of costs as well. The most striking difference is that the Abdelkader method implies a greater weight to the external supplier than the Bialek method and ends up not accounting for the weight of some of the production technologies like WtE and small-hydro. Abdelkader method have the advantage of penalizing big producers, stimulating the usage of DER. Bialek method considers all the generators contributes to the network power flow, so it seems to be a fairer and better method than Abdelkader's. Despite the different results, all costs of using the system have been recovered. These tracing methods are commonly used for transmission networks but have successfully responded to use in distribution networks.

The third phase of the methodology refers to cost allocation of three types of costs, namely fixed costs related to the maintenance and investments in the network, network costs related to line congestion and loss costs related to network resistive losses. To calculate this tariff, a variation of MW-mile method was used, and LMP's were used in order to calculate the costs of each line.

Once DG, DR programs, ESS's and V2G are increasing, it is convenient to see how these resources can contribute to a greater system flexibility. Until very recently, all the energy produced would have to be consumed at the moment due to the lack of storage units. With these technologies it is possible to use these units in the way that is most convenient to the system. It is possible to store energy when the demand is lower, and to inject in the network, when to a greater demand and consequent higher price. DER helps to reduce line congestion, reduce losses and satisfy loads more reliably.

These conclusions are important because they can help to provide more information about the EPS management to the several entities that study the cost allocation problem.

5.2 Future Works

This work corresponded to a brief approach on the topic of cost allocation in the distribution network. However, this theme is of extreme importance for a more or less distant future, since there is a continuous growth of DER, ESS's and V2G.

In the next approach to this topic the following topics should be explored. Consider the use of different weights for different technologies in the calculation of costs in order to stimulate the use of RES, use of V2G and ESS's and penalize the traditional technologies responsible for pollution.

Test the methodology in a bigger distribution network.

Also, would be interesting to consider more variations of the MW-mile method, considering for example the distances, from the point of production to the points of consumption.

Another interesting experiment would be to compare the Bialek's and Abdelkader's methods with Kirchen's methodology and also, implement more trancing methodologies.

It would be also interesting to try to do some modification in Abdelkader tracing method in order to trace the energy from all the production units, since this method ends up penalizing the external supplier rather than the Bialek method and for failing to account all the technologies that are producing energy.

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7 Attachments

Attachments

Table 5-Branch characteristics

Branch	From Bus	To Bus	R (Ohm)	$\mathbf{X_L(Ohm)}$	$\boldsymbol{B_c}\mathbf{(Siemens)}$	*Thermal Limit (MVA)*
1	0	1	0.1332	0.0471	0	4.50
2	1	2	0.7122	0.2517	0	4.50
3	1	18	0.2699	0.0954	0	4.50
4	2	3	0.3890	0.1048	0	3.29
5	2	22	0.6039	0.2134	0	4.50
6	3	4	0.1911	0.0515	0	3.29
7	4	5	0.7262	0.1957	0	3.29
8	5	6	1.0514	0.2833	0	3.29
9	5	25	1.0656	0.2872	0	3.29
10	6	7	0.2007	0.0541	0	3.29
11	7	8	0.3822	0.1030	0	3.29
12	8	9	1.4984	0.4038	0	3.29
13	9	10	0.5528	0.1488	0	3.29
14	10	11	0.6033	0.1626	0	3.29
15	11	12	0.7618	0.2053	0	2.29
16	12	13	1.3157	0.3546	0	3.29
17	13	14	0.7472	0.2014	0	3.29
18	14	15	0.3280	0.0884	0	3.29
19	15	16	3.0084	0.8107	0	3.29
20	16	17	0.8190	0.2207	0	3.29
21	18	19	1.0241	0.3620	0	4.50
22	19	20	0.6518	0.2304	0	4.50
23	20	21	1.2973	0.4585	0	4.50
24	22	23	1.2944	0.4575	0	4.50
25	23	24	0.1497	0.0529	0	4.50
26	25	26	0.2901	0.0782	0	3.29
27	26	27	1.0810	0.2913	0	329

28	27	28	0.8209	0.2212	0	3.29
29	28	29	0.5180	0.1396	0	3.29
30	29	30	0.9946	0.2680	0	3.29
31	30	31	0.3169	0.0854	0	3.29
32	31	32	0.3481	0.0938	0	3.29

Table 6- Characteristics of the offers of the Distributed Production and External Suppliers resources.

	Quantity	Total Installed Power (kW)	Energy Price (m.u./kWh)		
			Minimum	Average	Maximum
Photovoltaic	32	528	0.0800	0.1394	0.2540
Eolic	5	490	0.0500	0.0652	0.0800
Mini hydric	2	70	0.0320	0.0432	0.0490
Biomassa	3	350	0.0600	0.2653	0.6500
WTE	1	10	0.0300	0.0484	0.0560
Cogeneration	15	1,240	0.0001	0.0179	0.0650
C Fuel cell	8	235	0.0950	0.1021	0.1100
Total DG	66	2,923	-	-	-
External Supplier	1	15,000	0.0150	0.0493	0.2100
Total	67	17,923	-	-	-

Table 7- Demand Response offer for energy services.

DR	Reduce (kW)			CUT (kW)		
	Minimum	Average	Maximum	Minimum	Average	Maximum
	7.1	22.2	250.2	7.1	18.1	147.5
	Reduce (m.u./kWh)			CUT (m.u./kWh)		
	Minimum	Average	Maximum	Minimum	Average	Maximum
	0.0550	0.1284	0.8000	0.0450	0.2184	1.2000

Table 8-Features of Storage Units

Storage Units	Initial state (kWh)	Battery capacity (kWh)	Discharge capacity (kWh)	Maximum Capacity (kW)	Charging Price (m.u./kWh)	Discharging Price (m.u./kWh)
Minimum	30	800	40	100	0.4000	0.0450
Average	56	800	40	120	0.4750	0.5053
Maximum	80	800	40	150	0.5500	0.6000