Development of a Market Approach to Integrate Microsources in LV Distribution Networks

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Abstract **— This paper describes the research under development regarding the integration of several types of micro-source in LV distribution networks. This research is financed through an EU R&D project and tackles several scientific and technological related problems in the fields of micro-source electrical modelling, power system LV operational impact analysis, monitoring and control, power quality and network reliability, protection coordination and personnel safety, communications, economical and electrical market driven procedures and definition of new interconnection standards. In particular, in this paper we describe an approach to schedule micro-source generation and to validate that dispatch from a technical point of view using a lineraized optimization problem. The paper includes results from a case study developed in a LV test network used in the scope of the referred project.**

Index Terms **— microgeneration, microgrids, LV networks, technical adjustment studies.**

I. INTRODUCTION

In the scope of the MicroGrids Project - Large Scale Integration of Micro-Generation to Low Voltage Grids (http://microgrids.power.ece.ntua.gr) – under contract No. ENK5-CT-2002-00610 with the European Union, a MicroGrid comprises a number of components illustrated in Figure 1. These components include a low voltage network, a number of loads – some of them controllable and some others not controllable, a number of small scale generation devices – small turbines, fuel cells, PV panels, wind parks, … , storage devices – flywheels, capacitors and batteries, and a number of control devices. These control devices are associated to the micro-sources – MC controllers, with the controllable loads – LC controllers as well as the MicroGrid Central Controller – MGCC, located in the beginning of the LV feeder [1]. The MGCC acts as an interface both with the upstream Distribution Management System – DMS of the Distribution Grid Company and with the downstream load and micro-source controllers – LC and MC. It basically aims at ensuring the efficient operation of the MicroGrid both from the technical and economic points of view.

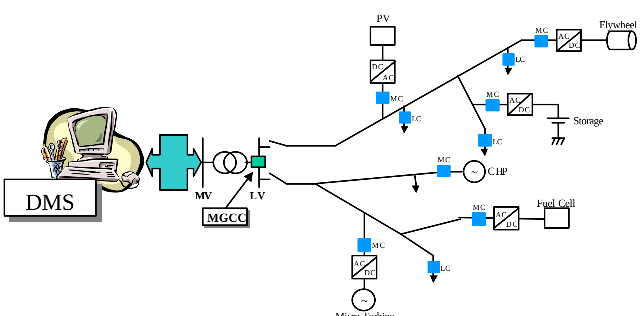

Figure 1 – Illustrative scheme of a MicroGrid.

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A MicroGrid doesn't just correspond to a set of micro-sources connected to a LV network. If it was like this, there wouldn't be so much difference between LV networks having micro-sources connected with them and today MV networks with distributed generation.

Differently, the MicroGrids project aims at defining and developing a new paradigm in which there is an association of micro-sources, controllable and non controllable loads, a LV network and control capabilities to operate as efficiently, economically and reliably as possible this network. This includes not only the Normal Interconnected Mode in which the MicroGrid is connected with the main MV upstream network but also the Emergency Islanded Operation Mode. Apart from other advantages from Microgrids, the possibility of operation in an islanded mode is one of the most important ones, given the possibility of increasing quality of service by reducing the number of interruptions and the global duration of interruption.

The activities of the MicroGrid Central Controller assume a different nature when passing from a Normal Interconnected Mode to the Emergency Islanded one. In fact, the Normal Interconnected Mode corresponds to a steady state operation in which:

- it is necessary to ensure the technical operation standards (as voltage levels, frequency deviations or branch limits);
- it is reasonable to consider economic issues, such as using as much power directly connected to the MicroGrid as possible provided that is justified in view of the electricity price in the upstream MV network.

In the advent of a fault in the MV grid leading to the Islanded Emergency Operation Mode, the control strategy should change from an active/reactive power control to a frequency/voltage control. In this case, the MicroGrid Central Controller has to balance the use of the resources in the MicroGrid, namely micro-sources, controllable loads, storage devices, to maintain frequency and voltage levels as stable as possible. In view of this, the Economic Scheduling functions to discuss will basically apply to the normal interconnected mode.

In the scope of the activities developed in the referred Project, this paper discusses how micro-sources can be integrated in the operation of a LV distribution network both in economic and technical terms. After being scheduled, the set of micro-generation values and loads must be validated by the MicroGrid Central Controller to ensure the adequate voltage levels and that there are no overloads. Apart from this introductory section, Section II discusses the advantages and the challenges imposed by the incorporation of micro-generation in LV networks, Section III details possible economic scheduling approaches, Section IV describes the technical evaluation studies, Section V presents a case study using a LV test network and Section VI draws the most relevant conclusions.

II. Advantages And Challenges of Microgrids

As referred before, MicroGrids are very promising given the advantages that can be achieved [2, 3, 4]. The careful discussion of these advantages, or at least of some of them, is important in itself since it can supply inputs to be considered when building an economic approach to frame the operation of these micro-sources. In other words, saying that several micro-source technologies are still too expensive may correspond to a narrow vision of the problem since we are not yet internalizing in the economic analysis several aspects from the use of micro-sources that have benefits. This also means that if these advantages are adequately considered, micro-sources connected to MicroGrids can be, if not competitive, at least not so uncompetitive regarding large traditional power stations connected to HV or EHV transmission networks.

The advantages of MicroGrids can be gathered in the following four sets of issues:

- Operation and investment issues - reduction of the physical and electrical distance between generation and loads. This can contribute to:
  - improve the reactive support of the whole system thus enhancing the voltage profile;
  - reduce losses in upstream higher voltage networks;
  - reduce or, at least, postpone investments in new transmission and large scale generation systems;
- Environmental issues – the environmental impact of microsources is expected to be smaller than large traditional thermal or hydro stations. Apart from that, the physical closeness of consumers regarding micro-sources can contribute to increase the awareness of consumers towards the use of energy;
- Power quality issues - increase of system reliability and, in general, of power quality due to the decentralization of supply, to the better match of supply and demand and to the reduction of the impact of transmission and large scale generation outages;
- Market issues – it is foreseen the development of market operation procedures of the micro-sources leading to the reduction of market power of generation companies and to the contribution of the micro-sources to the provision of some ancillary services.

Among these advantages, it should be noticed that Investment, Environmental and Power Quality aspects should be evaluated and internalized in the economic scheduling functions in a similar way to the approach used in several countries to remunerate the energy coming from distributed resources connected to MV networks [5]. If these aspects are considered, the current high costs of several technologies can be mitigated and so we are moving forward in turning micro-sources more competitive regarding traditional large power stations.

However, the development of MicroGrids still faces several challenges, difficulties and drawbacks, such as:

- High cost of distributed energy resources – this eventually requires some kind of subsidies to induce investments, at least during a transitory period. Although this can be justified as a kick off measure, in the long term it would certainly be seen as a distortion regarding market rules;
- Technical difficulties - these are related with the lack of experience and difficulty to control a significant number of micro-sources, thus requiring more research on dispatch real time models, dynamic models for several devices, simulation of real time operation and control, design of protection schemes. Specific communication infrastructures and communication protocols need to be developed to help managing, operating and controlling these MicroGrids [6];
- Absence of standards – since this is a new potential area, there are not yet available standards for several crucial issues as power quality data for several micro-source generation and safety and protection guidelines;
- Administrative and legal barriers – in general there is lack of legislation and regulations to frame the operation of micro-sources. In some countries, as in Portugal, there is already specific legislation namely establishing the tariffs to be paid to micro-generation. Although important, this can only be seen as a first step aiming at inducing investments. A new step has to be adopted in the future to go from a simple micro-source integration in LV networks – actually much similar to the integration of dispersed generation in MV networks – to the real possibility of establishing a MicroGrid, that is an association of a LV network, micro-sources and electrical loads able to operate in an interconnected or in an autonomous isolated mode. In this sense, several issues have to be co-ordinated with the MV distribution company such as dispatch, real time management and ancillary services provision, operation upon unplanned events and during black start and electrical equipment safety practices.

III. Possible Economic Scheduling Approaches

A. General Aspects

Economic scheduling aims at determining the amount of active/reactive power to allocate to each micro-source, as well as the amount of energy coming from the upstream MV network. In more elaborated approaches, it can also deal with the selection of levels of use of other resources as controllable loads or storage devices.

B. Hypothesis 1 - Legal Enforcement

The simplest economic scheduling strategy simply consists of legally imposing that all power coming from these micro-sources has to be accepted by distribution grid company. This energy is then remunerated according to some pre-specified tariffs designed to turn the investments attractive. However, it should be noticed that the legal enforcement to accept all energy – in other words, the existence of an inelastic market forced to accept all available resources – is part of the global mechanism to improve the economic attractiveness of these investments.

As an example to illustrate these tariff mechanisms, in March and July 2002 it was approved in Portugal new legislation to frame the micro-generation connected to LV networks. According to this legislation, micro-generation is an activity predominantly for self-consumption but being able to deliver the excess to other consumers or to the grid. Self-generation implies that that at least 50% of the energy is for own consumption. A micro-generator is an autonomous main generation equipment including motors, micro-turbines, or fuel cells, using synchronous or asynchronous generators, solar photovoltaic panels, and other autonomous generation equipments and the power to deliver to the grid in each reception point cannot exceed 150 kW. The remuneration tariff is defined by (1).

$$VRD_m = VRD(BTE)_m + C_t.EEC_m.\frac{IPC_{Dec}}{IPC_{ref}} \qquad (1)$$

In this expression:

- $VRD(BTE)_m$ (€) – amount corresponding to energy injected in month m, paid at the tariff for LV consumers with contracted power larger than 41,4 kW;
- EEC_m (kWh) - injected energy in month m;
- Ct (€/kWh) – coefficient dependent on the technology. It reflects the interest in developing or inducing the use of a particular technology and the amount required to turn the investment economically feasible.

C. Hypothesis 2

A second approach, named signal approach, corresponds to an iterative procedure including exchange of information between the Wholesale Market Operator - WMO, the MGCC and the LC and MC controllers. In this case, the WMO performs a centralized day-ahead dispatch according to selling and buying bids transmitted by the participants in the market. At this stage, micro-source availability is not considered. The dispatch information together is then conveyed to the System Operator, to check for technical feasibility. When that is guaranteed, it is possible to go down the grid till reaching the MV/LV substation at which the MicroGrid is connected in order to include tariffs for the use of networks or any other tariffs in force in order to determine the electricity price at that node. This price is then communicated to the MGCC and conveyed to the LC and MC controllers. According to their analysis, these agents can propose to substitute power initially allocated by the WMO to traditional power stations. If this occurs, the centralized day-ahead dispatch is adjusted in order to reduce generated and power from traditional stations.

D. Hypothesis 3

In the third approach, the MGCC acts as an aggregator of selling or buying bids communicated by the MC and LC. These aggregated selling and buying bids will then internalize the factors that correspond to the advantages of having micro-sources close to loads (reduction of losses, reduction of bottlenecks in upstream networks, reduction of investments in system expansion, reduction of gas emissions), and will be communicated to the WMO.

The power dispatched to the MGCC will then be disaggregated by the MGCC according to the merit order of the generation bids. In this case, the MGCC will also act as the MicroGrid System Operator – MSO, in order to check for the feasibility of the power allocation inside the MicroGrid. If any branch limits are violated, some changes will finally have to be made regarding the powers originally allocated to the micro-sources.

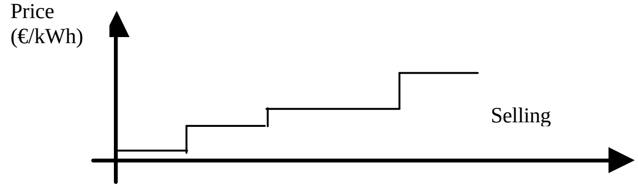

Figure 2 - Aggregated selling curve resulting from the offers communicated by the micro-source local controllers.

The WMO will then perform a centralized day-ahead market based on selling and buying bids received from all agents. The MGCC is therefore considered an agent of the market that will receive information about the market-clearing price and dispatched quantities.

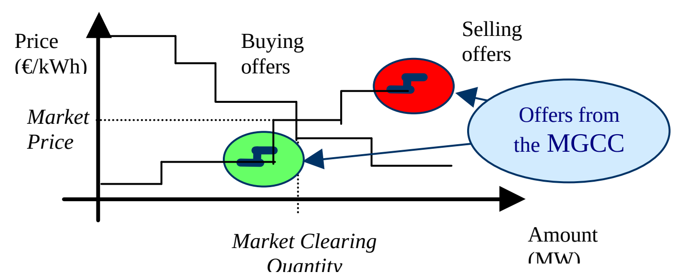

Figure 3 - Result of the market matching algorithm including the selling offers presented by the MGCC.

IV. Technical Evaluation and Adjustment Analysis

A. Adjustment Model

As referred previously, the generation and demand bids communicated by the micro-source controllers to the MGCC can lead to overloads or voltages out of a specified range. These situations are detected by an initial AC Power Flow. To eliminate these infeasibilities it will be solved a linearized optimization problem formulated by (2) to (22). This problem uses a number of sensitivity coefficients to express variations of branch flows and active and reactive injections regarding voltage and phases.

$$\min \sum_{i=1}^{nb}\left[c_{Pgi}\cdot\Delta P_{gi}^{mg} + c_{Qgi}\cdot\Delta Q_{gi}^{mg}\right] - \sum_{i=1}^{nb}\left[c_{Pci}\cdot\Delta P_{ci}^{mg} + c_{Qci}\cdot\Delta Q_{ci}^{mg}\right] \qquad (2)$$

$$\text{subj.}\quad P_{gi}^{min} \le P_{gi}^{0} + \Delta P_{gi} \le P_{gi}^{max} \qquad (3)$$

$$\Delta P_{gi} = \Delta P_{gi}^{mg} \qquad (4)$$

$$Q_{gi}^{min} \le Q_{gi}^{0} + \Delta Q_{gi} \le Q_{gi}^{max} \qquad (5)$$

$$\Delta Q_{gi} = \Delta Q_{gi}^{mg} \qquad (6)$$

$$-P_{ci}^{o} \le \Delta P_{ci} \le 0 \qquad (7)$$

$$\Delta P_{ci} = \Delta P_{ci}^{mg} \qquad (8)$$

$$-Q_{ci}^{o} \le \Delta Q_{ci} \le 0 \qquad (9)$$

$$\Delta Q_{ci} = \Delta Q_{ci}^{mg} \qquad (10)$$

$$P_{ij}^{min} \le P_{ij}^{0} + \Delta P_{ij} \le P_{ij}^{max} \qquad (11)$$

$$\Delta P_{ij} = SC_{Pij}^{\theta i}.\Delta\theta_i + SC_{Pij}^{\theta j}.\Delta\theta_j + SC_{Pij}^{Vi}.\Delta V_i + SC_{Pij}^{Vj}.\Delta V_j \qquad (12)$$

$$Q_{ij}^{min} \le Q_{ij}^{0} + \Delta Q_{ij} \le Q_{ij}^{max} \quad (13)$$

$$\Delta Q_{ij} = SC_{Qij}^{\theta i}.\Delta\theta_i + SC_{Qij}^{\theta j}.\Delta\theta_j + SC_{Qij}^{Vi}.\Delta V_i + SC_{Qij}^{Vj}.\Delta V_j \quad (14)$$

$$V_i^{min} \le V_i^{0} + \Delta V_i \le V_i^{max} \quad (15)$$

$$\theta_{ij}^{min} \le \left(\theta_i^0 + \Delta\theta_i\right) - \left(\theta_j^0 + \Delta\theta_j\right) \le \theta_{ij}^{max} \quad (16)$$

$$\Delta P_i = \Delta P_{gi} - \Delta P_{ci} \quad (17)$$

$$\Delta P_i = \sum_{i=1}^{nb} SC_{Pi}\left(\Delta\theta, \Delta V\right) \quad (18)$$

$$\Delta Q_i = \Delta Q_{gi} - \Delta Q_{ci} \quad (19)$$

$$\Delta Q_i = \sum_{i=1}^{nb} SC_{Qi}\left(\Delta\theta, \Delta V\right) \quad (20)$$

$$\sum \Delta P_{gi}^{mg} = \sum \Delta P_{ci}^{mg} \quad (21)$$

$$\Delta\theta_{ref} = 0 \quad (22)$$

The above problem admits that they are proposed adjustment prices to increase or decrease active and reactive generation (c_{Pgi} and c_{Qgi}) as well as adjustment prices to decrease active or reactive load (c_{Pci} and c_{Qci}), so that the objective function (2) is expressed by the difference between the following two terms:

- generation adjustments multiplied by generation adjustment cost;
- load adjustments multiplied by load adjustment costs. Constraints (7) and (9) impose that load adjustments are non positive, meaning that if necessary load can be shed. This is why the term representing load adjustment cost has a negative sign in (2).

The minimization problem includes constraints related with generation active and reactive limits ((3) to 6)), active and reactive load maximum adjustments ((7) to (10)), branch active and reactive flows ((11) to (14)), voltage ranges and difference between nodal phases ((15) and (16)), nodal active and reactive balances ((17) to (20)) and global balance of the active adjustments (21).

Regarding this formulation, it will now be detailed the meaning of the parameters and coefficients in use:

- nb – number of buses;
- mg – index used to denote generated or load powers obtained from decisions taken according to the Wholesale Market Price, once referred to the LV initial node of the MicroGrid using the Tariffs due for the Use of Networks;
- c_{Pgi} , c_{Qgi} , c_{Pci} , c_{Qci} - adjustment prices of the active and reactive power of generator or load i;
- P_{gi}^{min} , P_{gi}^{max} , Q_{gi}^{min} , Q_{gi}^{max} - maximum and minimum active and reactive powers of generator i;
- P_{ij}^{min} , P_{ij}^{max} , Q_{ij}^{min} , Q_{ij}^{max} - maximum and minimum active and reactive power flows of branch ij;
- $SC_{Pij}^{\theta i}$, $SC_{Pij}^{\theta j}$, SC_{Pij}^{Vi} , SC_{Pij}^{Vj} - sensitivity coefficients of the active flow in branch ij regarding the phases and voltages in the extremes buses, i and j;
- $SC_{Qij}^{\theta i}$, $SC_{Qij}^{\theta j}$, SC_{Qij}^{Vi} , SC_{Qij}^{Vj} - sensitivity coefficients of the reactive flow in branch ij regarding the phases and voltages in the extremes buses, i and j;
- SC_{Pi} and SC_{Qi} - sensitivity coefficients of the active and reactive injected powers in node i regarding the phases and voltages in all system buses;
- V_i^{min} and V_i^{max} - max and min voltages in bus i;
- θ_{ij}^{min} and θ_{ij}^{max} - max and min phase difference between nodes i and j.

The decision variables of this problem are:

- ΔP_{gi}^{mg} and ΔQ_{gi}^{mg} - active and reactive power adjustments of MicroGrid generators regarding the initial generation values;
- ΔP_{ci}^{mg} and ΔQ_{ci}^{mg} - active and reactive power adjustments of MicroGrid loads regarding the initial generation values;
- ΔP_{gi} , ΔQ_{gi} , ΔP_{ci} , ΔQ_{ci} , ΔP_{ij} , ΔQ_{ij} , ΔV , $\Delta\theta$ - active and reactive generation adjustments, active and reactive load adjustments, active and reactive branch flow adjustments, voltage and phase adjustments.

This problem is solved after running The AC Power Flow study referred in section IV.A. From this run, one gets the following initial values required to formulate the optimization problem:

- P_{gi}^{o} , Q_{gi}^{o} - active and reactive outputs of generator i;
- P_{ci}^{o} , Q_{ci}^{o} - active and reactive loads in bus i;
- P_{ij}^{o} , Q_{ij}^{o} - active and reactive flows of branch ij;
- V_i^{o} , θ_i^{o} - values for the voltage and phase in node i.

B. *Sensitivity Coefficients*

In the previous formulation, we linearized the branch active flow expressions and the injected active and reactive power expressions using the first order terms of the corresponding Taylor series. These first order Taylor series terms lead to sensitivity coefficients that express the dependency of the active and reactive branch flows or injected powers regarding voltages and phases deviations, that is, regarding ΔV and $\Delta\theta$.

As an example, if we consider the active power flow in branch ij, the corresponding variation is approximated by (23). Once the partial derivatives in (23) are computed, constraint (11) can be rewritten so that this type of constraints will be finally expressed by linear expressions in terms of voltage and phase deviations on the extreme buses of each branch. In constraint (18), the sensitivity coefficients $SC_{Pij}^{\theta i}$, $SC_{Pij}^{\theta j}$, SC_{Pij}^{Vi} and SC_{Pij}^{Vj} correspond to the values of the partial derivatives in expression (23).

$$\Delta P_{ij} \cong \frac{\partial P_{ij}}{\partial V_i}\Delta V_i + \frac{\partial P_{ij}}{\partial V_j}\Delta V_j + \frac{\partial P_{ij}}{\partial \theta_i}\Delta\theta_i + \frac{\partial P_{ij}}{\partial \theta_j}\Delta\theta_j \quad (23)$$

Since the fully non linear expression for the active power flow in branch ij is given by (24), it is possible to obtain the partial derivatives regarding the voltages and phases in the extreme buses of this branch ((25) to (28)). These derivatives are computed using the values V_i^o and θ_i^o obtained after running the initial AC Power Flow study.

$$P_{ij} = -g_{ij} V_i^2 + V_i V_j \cdot (g_{ij} \cos\theta_{ij} + b_{ij} \sin\theta_{ij}) \quad (24)$$

$$\frac{\partial P_{ij}}{\partial V_i} = -2 g_{ij} V_i + V_j \cdot (g_{ij} \cos\theta_{ij} + b_{ij} \sin\theta_{ij}) \quad (25)$$

$$\frac{\partial P_{ij}}{\partial V_j} = V_i \cdot (g_{ij} \cos\theta_{ij} + b_{ij} \sin\theta_{ij}) \quad (26)$$

$$\frac{\partial P_{ij}}{\partial \theta_i} = V_i V_j \cdot (-g_{ij} \sin\theta_{ij} + b_{ij} \cos\theta_{ij}) \quad (27)$$

$$\frac{\partial P_{ij}}{\partial \theta_j} = V_i V_j \cdot (g_{ij} \sin\theta_{ij} - b_{ij} \cos\theta_{ij}) = -\frac{\partial P_{ij}}{\partial \theta_i} \quad (28)$$

V. Case Study

A. LV Distribution Network

In order to illustrate the adjustment model described above we used The “Study-Case LV Network” defined in the scope of the MicroGrids project and presented in Figure 3.1. This network is supplied by a distribution transformer and by a number of micro-sources connected to nodes 6, 8, 10, 12 and 14. The complete data of this network can be provided by the authors on request. Using this LV network, we conducted some tests detailed in the next two sections to illustrate the use of the adjustment model with different levels of elastic loads.

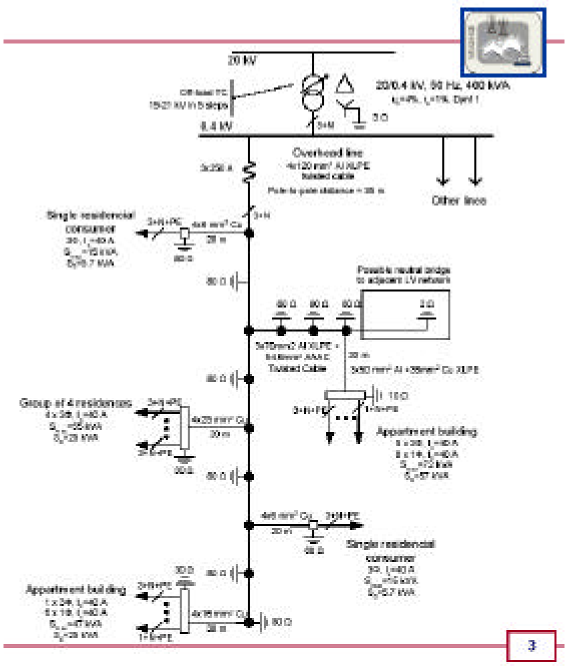

Figure 4 - Single line diagram of the LV network.

B. Case 1

In Table 1 we present the specified active and reactive nodal powers admitting they were the result of the clearing process based on the bids presented by micro-sources and loads. This means that micro-sources and loads presented their bids to the MGCC that aggregated them and conveyed them to the Wholesale Market Operator, WMO. The WMO cleared the market and returned information back to the MGCC in terms of accepted generation and load bids in the MicroGrid. These values are now used by the MGCC to run an initial power flow in order to check for the technical feasibility of this economic dispatch. In Table 1, we indicate powers for REF and PV buses and active and reactive powers for PV and PQ buses.

Tables 1 and 2 include the results obtained for the referred initial power flow. Table 1 includes voltage values, active and reactive generation in the REF bus and reactive generation in the PV buses. Table 2 presents the branch results, in terms of active and reactive flows and losses.

Table 1 – Specified values and results from the initial power flow study.

Bus		Voltage		Generation		Load	
Node	Type	Module (pu)	Phase (rad)	kW	kVAr	kW	kVAr
1	Ref	1,0369	0,0000	113,4	6,8	0	0
2	PQ	1,0363	-0,0105	0	0	0	0
3	PQ	1,0294	-0,0122	0	0	0	0
4	PQ	1,0231	-0,0109	0	0	15,0	3,6
5	PQ	1,0176	-0,0153	0	0	0	0
6	PV	1,0200	-0,0132	10,0	-7,9	0	0
7	PQ	1,0040	-0,0187	0	0	0	0
8	PV	1,0004	-0,0195	30,0	26,3	72,0	24,0
9	PQ	1,0100	-0,0181	0	0	0	0
10	PV	1,0066	-0,0186	18,3	17,9	50,0	16,0
11	PQ	1,0062	-0,0196	0	0	0	0
12	PV	1,0002	-0,0172	1,0	-1,9	15,0	4,0
13	PQ	1,0044	-0,0212	0	0	0	0
14	PV	1,0002	-0,0237	30,0	20,7	47,0	12,0

Table 2 – Branch results from the initial power flow study.

Branch		Emission		Reception		Losses	
Node i	Node j	kW	kVAr	kW	kVAr	kW	kVAr
1	2	113,4	6,8	-113,4	-5,6	0	1,1995
2	3	113,4	5,6	-112,6	-5,4	0,7452	0,2178
3	4	15,1	3,6	-15,0	-3,6	0,0969	0,0027
3	5	97,5	1,8	-96,4	-1,4	1,1154	0,3260
5	6	-9,9	7,9	10,0	-7,9	0,0404	0,0249
5	7	42,7	-2,1	-42,1	2,2	0.5765	0,1160
7	8	42,2	-2,2	-42,0	2,3	0,1531	0,0255
5	9	63,6	-4,4	-63,1	4,5	0,4882	0,1427
9	10	31,8	-1,9	-31,7	1,9	0,1081	0,0103
9	11	31,4	-2,7	-31,2	2,7	0,1206	0,0353
11	12	14,1	6,0	-14,0	-6,0	0,0986	0,0027
11	13	17,1	-8,7	-17,1	8,7	0,0452	0,0132
13	14	17,1	-8,7	-17,0	8,7	0,0942	0,0058

We now admitted that branch 3-5 active flow limit is 80 kW. This means that this operation point is unfeasible due to the congestion in this branch. To eliminate it, the MGCC uses adjustment prices presented by the micro-sources and elastic loads, indicated in Tables 3 and 4.

Table 3 – Generation adjustment prices.

Generation	Node	Adj. Pr. (€/kW.h)	Adj. Pr. (€/kVAr.h)	Max Adj. (kW)	Max Adj. (kVAr)
1	1	0,1	0,1	400	300
2	6	1,4	1,4	25	18,75
3	8	1,1	1,1	30	27
4	10	2,0	2,0	25	28,75
5	12	2,0	2,0	3	2,25
6	14	1,0	1,0	30	22,5

Table 4 – Load adjustment prices.

Load	Node	Adj. Pr. (€/kW.h)	Adj. Pr. (€/kVAr.h)
1	4	8,5	8,5
2	8	11,5	11,5
3	10	10,5	10,5
4	12	9,5	9,5
5	14	12,5	12,5
6	2	6,5	6,5

We used the model detailed in section 2, to conduct an adjustment exercise to obtain changes in micro-source outputs and in some elastic loads. Using these changed powers, a final power flow was run in order to check for the final feasibility of the dispatch. Tables 5 and 6 detail the specified powers and the results of this power flow exercise.

Table 5 – Specified values and results from the final power flow study.

Bus		Voltage		Generation		Load	
Node	Type	Module (pu)	Phase (rad)	kW	kVAr	kW	kVAr
1	Ref	1,0013	0	97,4	62,3	0	0
2	PQ	0,9951	-0,0097	0	0	0	0
3	PQ	0,9879	-0,0077	0	0	0	0
4	PQ	0,9814	-0,0063	0	0	15,0	3,6
5	PQ	0,9756	-0,0034	0	0	0	0
6	PV	0,9818	0,0031	25,0	-22,8	0	0
7	PQ	0,9553	-0,0010	0	0	0	0
8	PV	0,95	-0,0002	16,5	5,9	72,0	24,0
9	PQ	0,9690	-0,0032	0	0	0	0
10	PV	0,9682	-0,0010	25,0	-3,5	30,0	16,0
11	PQ	0,9637	-0,0054	0	0	0	0
12	P	0,9609	-0,0016	3,0	-5,3	9,0	3,3
13	PQ	0,9595	-0,0086	0	0	0	0
14	PV	0,95	-0,0128	11,4	24,9	47,0	12,0

Table 6 – Branch results from the final power flow study.

Branch		Emission		Reception		Losses	
Node i	Node j	kW	kVAr	kW	kVAr	kW	kVAr
1	2	97,4	62,3	-97,4	-60,9	0	1,3323
2	3	97,4	60,9	-96,5	-60,7	0,8277	0,2419
3	4	15,1	3,6	-15,0	-3,6	0,1053	0,0290
3	5	81,4	57,1	-80,2	-56,7	1,2592	0,3680
5	6	-24,7	22,8	25,0	-22,8	0,3073	0,0189
5	7	57,0	18,4	-55,8	-18,2	1,2297	0,2474
7	8	55,8	18,2	-55,5	-18,1	0,3266	0,0544
5	9	47,9	15,5	-47,5	-15,4	0,3304	0,0966
9	10	5,0	19,5	-5,0	-19,5	0,0472	0,0045
9	11	42,5	-4,1	-42,2	4,2	0,2411	0,0704
11	12	6,1	8,6	-6,0	-8,6	0,0506	0,0014
11	13	36,2	-12,8	-36,0	12,8	0,1971	0,0576
13	14	36,0	-12,8	-35,6	12,9	0,4104	0,0253

This second power flow indicates that the active flow in branch 3-5 is 81,4 kW, while the limit specified in the adjustment model was 80 kW. The difference is due to the linearized expressions used by the adjustment model while the final power flow uses the complete AC equations.

C. Case 2

In Case 2, we admitted that loads are less elastic than in Case 1. This is reflected in the adjustment prices that are now higher than the ones used previously (compare the values in Tables 4 and 7). We also considered that the active flow limit in branch 3-5 is 88,0 kW. The initial dispatch values are the same as in Case 1 so that the results of the initial power flow study are the ones already presented in Tables 1 and 2.

Table 7 – Modified adjustment prices for loads.

Load	Node	Adj. Pr. (€/kW.h)	Adj. Pr. (€/kVAr.h)
1	4	850	170
2	8	1150	230
3	10	1050	210
4	12	950	190
5	14	1250	250
6	2	650	130

Given the congestion in branch 3-5, we used the prices in Table 7 to run the adjustment model in order to eliminate the congestion in branch 3-5.

Table 8 – Specified values and results from the final power flow study.

Bus		Voltage		Generation		Load	
Node	Type	Module (pu)	Phase (rad)	kW	kVAr	kW	kVAr
1	Ref	0,9994	0,0000	107,7	86,4	0	0
2	PQ	0,9908	-0,0109	0	0	0	0
3	PQ	0,9825	-0,0075	0	0	0	0
4	PQ	0,9760	-0,0061	0	0	15,0	3,6
5	PQ	0,9680	-0,0005	0	0	0	0
6	PV	0,9735	0,0173	25,0	-63,3	0	0
7	PQ	0,9537	0,0088	0	0	0	0
8	PV	0,9500	0,0114	37,1	-9,1	72,0	24,0
9	PQ	0,9588	-0,0057	0	0	0	0
10	PV	0,9530	-0,0051	0	6,0	50,0	16,0
11	PQ	0,9564	-0,0104	0	0	0	0
12	PV	0,9522	-0,0257	5,0	36,2	15,0	4,0
13	PQ	0,9542	-0,0103	0	0	0	0
14	PV	0,9500	-0,0091	31,8	6,7	47,0	12,0

As it can be seen in Table 8, active and reactive loads are equal to the ones in Table 1, indicating that load adjustment bids were not used, as load is now more inelastic. Similarly to Case 1, the final active flow in branch 3-5 is different from the specified limit. This difference is once again due to the use of the full AC equations in the final power flow, compared with the linearized expressions used in the adjustment model.

Table 9 – Branch results from the final power flow study.

Branch		Emission		Reception		Losses	
Node i	Node j	kW	kVAr	kW	kVAr	kW	kVAr
1	2	107,7	86,4	-107,7	-84,5	0,0	1,9
2	3	107,7	84,5	-106,5	-84,1	1,2	0,3
3	4	15,1	3,6	-15,0	-3,6	0,1	0,0
3	5	91,4	80,5	-89,5	-80,0	1,9	0,6
5	6	-23,7	63,4	25,0	-63,3	1,3	0,1
5	7	36,0	33,3	-35,2	-33,2	0,8	0,2
7	8	35,2	33,2	-34,9	-33,1	0,2	0,0
5	9	77,2	-16,8	-76,4	17,0	0,8	0,2
9	10	50,3	10,0	-50,0	-10,0	0,3	0,0
9	11	26,1	-27,0	-25,9	27,1	0,2	0,1
11	12	10,5	-32,4	-10,0	32,4	0,5	0,0
11	13	15,3	5,3	-15,3	-5,3	0,0	0,0
13	14	15,3	5,3	-15,2	-5,3	0,1	0,0

VI. CONCLUSIONS

MicroGrids represent a new paradigm regarding the organization of power systems, possibly leading to more important changes than the ones we have been facing given they will occur closely to end consumers. This will certainly have the potential to increase the awareness of LV consumers to the energy problem as well as contributing to increase the continuity indices of power supply in LV.

As detailed in the paper, the development and generalization of MicroGrids still faces a large number of legal, administrative, market, safety and standardization challenges and difficulties that are being analysed and tackled in the MicroGrids EU financed project. This ultimately means that the MicroGrids project is an opportunity to investigate these topics and to demonstrate results that may be generalized in the next 10 to 20 years.

In particular, this paper presents a contribution to this discussion as it aims at developing a model to schedule micro-sources and to validate this dispatch from a technical point of view using adjustment prices. These operations are foreseen to be developed in an automatic way by the MicroGrid Central Controller and by Load and Generator Controllers in order to turn all these technical aspects as transparent as possible to resource owners. As referred, this model should be interpreted as a contribution to a discussion and research phase currently being developed in several countries.

VII. References

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VIII. Biographies

João Tomé Saraiva was born in Porto, Portugal in 1962. In 1987, 1993 and 2002 he got his MSc, PhD, and Agregado degrees in Electrical and Computer Engineering from the Faculdade de Engenharia da Universidade do Porto, FEUP, where he is currently Professor. In 1985 he joined INESC Porto – a private research institute – where he was head researcher or collaborated in several projects related with the development of DMS systems, quality in power systems, and tariffs due for the use of transmission and distribution networks. Several of these projects were developed under consultancy contracts with the Portuguese Electricity Regulatory Agency.

André Ribeiro Sá was born in Espinho, Portugal in 1977. He concluded his degree and MSc in Electrical and Computer Engineering from the Faculdade de Engenharia da Universidade do Porto, FEUP, Portugal, in 2000 and 2003. Currently he is with Fábrica Têxtil Riopele SA, a textile manufacturer, where he works in the energy management department and cogeneration station.