Provision of Some Ancillary Services by Microgrid Agents

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Abstract — **This paper describes part of the research developed by the Power Systems Unit of INESC Porto in the scope of the MoreMicrogrids EU financed project (under the Contract No: PL019864). In this project, and apart from other issues, it was investigated how microgrid agents could participate in a more effective way in electricity markets. In this paper we present models to enable the participation of microgrid agents in the provision of ancillary services, namely reactive power/voltage control, active loss balancing and demand interruption. This participation is accomplished after running the day-ahead market and it corresponds to the activation of a specific market to allocate these services. The implementation of this kind of models can contribute to create a new stream of money to microgrid agents so that they can integrate themselves in a more natural way in power systems, eventually eliminating subsidized tariffs that represent in several countries an increasing amount of the final end user tariffs. Finally, the paper includes a Case Study to illustrate the use of the developed approaches.**

Index Terms—**microgrids, ancillary services, reactive power, active loss balancing, demand interruption, adjustment market.**

I. Introduction

MICROGRIDS started to emerge in the beginning of this decade and they are currently seen as being able to change the paradigm of distribution system operation and planning [1, 2, 3, 4, 5]. A microgrid can be seen as an association of a low voltage distribution network together with microgeneration sources (as small turbines, fuel cells, PV panels and wind turbines), storage devices (as flywheels, capacitors and batteries), loads and a number of control devices. These control devices are associated both with the microsources, the loads and the storage devices as well as with the control of the whole network itself. In this case, this control device is termed as Microgrid Central Controller, MGCC, and it is located in the beginning of the feeders, adopting the structure detailed in [5]. The MGCC has a crucial role in the sense that it interfaces with the devices controlling the microsources, the loads and the storage devices and with the upper level network, namely with the DMS system of the Distribution Network Operator. As indicated in [5, 6], the development and widespread of microgrids has a number of advantages and still displays a number of challenges and difficulties. The advantages are related with the closer proximity between generation and demand (increasing the awareness of the demand to generation issues and contributing to reduce losses), improvement of reliability and security of supply (namely if microgrids operate not only on a connected mode with the upstream network and but also in an isolated mode if there is an upstream fault, [7, 8]), eventual postponement of investments in new transmission and large generation facilities, environmental advantages (due to the more reduced impact of small scale generation) and market issues. Regarding this last topic, advantages are related both with generation and demand. On one side, microsource controllers can communicate selling bids to the MGCC that conveys them to the Market Operator. Therefore, this design is able to enlarge the number of players and so to contribute to reduce the market power that large generation companies still have. Apart from this, microsources can also be remunerated for services provided as loss balancing and reactive power generation. Regarding the demand, loads can also provide services namely the possibility of being interrupted provided they receive an adequate remuneration. This will induce a larger participation of the demand thus contributing to reduce the asymmetry of current electricity market implementations.

In line with these concerns, this paper describes part of the research developed in INESC Porto in the scope of two EU financed projects (MicroGrids and MoreMicroGrids) regarding the provision of loss balancing, reactive power and load interruption ancillary services by microgrid agents. After receiving the economic dispatch from the Market Operator, the MGCC runs a number of studies to check the technical feasibility of these hourly schedules, namely considering branch flow and voltage limits. To do this, the MGCC activates a secondary market using adjustment bids sent by microgrid agents and it allocates generation to balance active losses, reactive power and eventually accepts load interruption bids, provided loads are paid for this service. This corresponds to a non-linear optimization problem that is solved using a Sequential Linear Programming, SLP, approach. Apart from this and recognizing that some limits (for instance, branch flow and voltage limits) can be exceeded during some limited time, the developed model is able to represent these limits by soft constraints using concepts of the Theory of Fuzzy Sets [9]. Finally, the developed approach will be illustrated using a Case Study based on a 55-node microgrid.

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II. Overview About Microgrids

The increase of the participation of small generation sources and loads in electricity markets and the provision of some ancillary services are mentioned as important advantages of microgrids in early publications on this subject. In fact, [4, 5] consider this participation as possible and desirable, although several problems were identified turning difficult this participation. Apart from other considerations, increasing the participation of DG, in general, and of small generation sources in microgrids, in particular, will allow treating these generation facilities in a more natural way, moving away from subsidizing schemes that, in several countries, already represent a large share of the final end user tariffs.

On the other hand, [4, 5] explicitly consider that small generation sources are not the unique entities to integrate in electricity markets. The demand traditionally displays a very passive behavior, meaning that due to the type of consumption, due to the lack of information or given the small scale of LV loads, it shows a very inelastic behavior. This is a major drawback in current electricity markets because they are extremely asymmetrical since the demand pays as much as required to be supplied. Associating control devices to loads in the scope of microgrids and remunerating the demand if it admits interruptions can contribute to induce demand changes turning electricity markets more symmetric and contributing to reduce the market power of large generation companies.

In this scope, [10] describes a market cycle to conceptualize the participation of microgrids in electricity markets. It includes the communication by the Market Operator of its buying, BP, and selling, SP, energy prices, followed by negotiation periods of 15 min. In each of these periods, the microgrid loads communicate their demands and their initial negotiation price, DP, and it is used an auction mechanism to maximize the benefit of all agents. This corresponds to a symmetric assignment problem that also considers the main grid as a buying/selling agent so that it is possible to buy power from it to supply the microgrid demand, and to inject power in the grid meaning that the microgrid generation or storage units can also sell to the upward voltage network.

In a different perspective, [11] describes an EMS using neural networks to dispatch in an autonomous way the microgrid sources minimizing the global energy cost. The authors want to substitute the target “badly behaved systems components” frequently assigned to distributed generation substituting it by the target “good citizens”, interpreted as “an aggregate of generation and load which behave as nearly conventional loads”. To accomplish this objective, the authors detail a number of functions of the microgrid EMS in preparing the dispatch of the microgrid sources in order to make the best use of their capacity to generate electricity and heat. As a final remark, the authors indicate that this approach can be extended to loads using them as distributed resources taking advantage of their possible interruption.

In [12, 13] microgrids are modeled using agent based approaches. As an example, [12] details the characteristics of intelligent agents in terms of autonomy, proactivity and ability to cooperate with other agents and including:

- the MGCC modeled by agents to get information from the generation sources, interfacing with the database, adopting control actions and scheduling load shifting and shedding;
- Micro-source controllers modeled by a generator agent used to send set points and receive information, a scheduler agent to apply the power schedule and a bid agent to send selling bids to the Market Operator;
- Load Controllers modeled by an agent to enable demand side management actions as load shifting and curtailment, a status agent to control the on/off status of the load and a switch agent to receive and execute the selected actions.

This agent platform was developed on a laboratory environment and the authors describe case studies using a single storage system and a multiple storage system.

The provision of ancillary services by microgrid agents is addressed in [14]. The authors consider this topic as relevant because apart from being remunerated for their participation in electricity markets, microgrid agents can also contribute to provide some ancillary services and be paid by this provision. This paper addresses the provision of primary reserve, but the developed models and techniques can be extended to the secondary and tertiary reserves. The authors describe an optimisation model aiming at maximizing the hourly revenue assuming there is a coordinated real-time control, given that the authors indicate that specific markets to contract ancillary services are not generalized in many countries. The objective function of this optimisation problem includes positive terms related with the revenues obtained from selling energy in the day-ahead market and the provision of primary reserve and a negative term representing the generation cost.

III. Allocation of Ancillary Services

A. General Approach

The models developed in this research are based on the microgrid architecture described in [5]. This design includes a Microgrid Central Controller, MGCC, that manages the network and interfaces both with the upstream DMS system and with the microsource and load local controllers. The MGCC has a wide range of functions as follows:

- it receives the buying and selling bids prepared by the load and generation controllers and it sends this information to the Market Operator to run the day ahead market;
- it receives the economic schedule sent by the Market Operator regarding set points for the microgrid sources and for the accepted demand values;
- using these values, the MGCC runs a technical study to validate the operation point of the microgrid. When acting like this, the MGCC works as a System Operator, in terms of checking branch and nodal voltage limits;
- when running this technical validation, the MGCC is also in charge of allocating voltage control/reactive power, of allocating the loss balancing service and eventually allocating demand interruption based on interruption bids sent by the load local controllers.

The allocation of these ancillary services is performed running a market based on adjustment bids sent both by microsources and loads. The basic concepts regarding this adjustment market were originally described in [15]. In this model, generation agents admit changing the active power scheduled by the Market Operator provided they are paid for it. Changes on the generation schedule can be due to the need to enforce operation constraints or to enable a reactive power output given that the P and Q values are coupled via the capability diagram of the generators. From a mathematical point of view, the changes due to operation limit constraint enforcements are represented by ΔPg_i^A variables that can assume both positive and negative values implying, in both cases, the payment of an adjustment price, Cg_i^A. Apart from this adjustment price, these bids can also include an indication regarding the maximum variation, vg_i^{tol}, it is admitted regarding the base power scheduled by the Market Operator.

The schedule of microsources can also change to contribute to balance active losses. These non-negative changes are modeled by ΔPg_i^L variables. As a result, if Pg_i^o represents the active power initially scheduled by the Market Operator, then the final active power allocated to generator *i* is given by (1).

$$Pg_i^{final} = Pg_i^o + \Delta Pg_i^A + \Delta Pg_i^L \tag{1}$$

The demand can also send adjustment bids to the MGCC. One of the advantages associated with the microgrids that were identified in early publications comes from turning generation closer to the demand, thus increasing the awareness of consumers to the use of energy. This increased awareness can contribute to enlarge the demand elasticity to price and to more easily accept load shifting from a period to another one or load curtailment. This increased participation of the demand in electricity markets is positive in itself because it contributes to turn these markets more symmetric. In this sense, loads can play an important role in alleviating some constraints provided that they accept being interrupted if they are adequately remunerated for this service. Using this concept, load adjustment bids include an adjustment price, Cd_j^A, together with the amount of load scheduled in the day-ahead market that one admits to curtail. This capability can be interpreted as an ancillary service provided to the MGCC turning the operation of the microgrid more flexible. Mathematically, this is modeled by non-positive ΔPd_j^A variables. As a result, once the mentioned adjustment market is run, the final scheduled loads are given by (2) assuming that Pd_j^o represents the demand *j* initially scheduled by the Market Operator.

$$Pd_j^{final} = Pd_j^o + \Delta Pd_j^A \tag{2}$$

B. Modeling Synchronous Generators

In several optimization problems, the feasible operation region of synchronous generators is modeled by independent active and reactive power limits that graphically correspond to the area delimited by a rectangle in the P, Q plan. In fact, this simple model in insufficient because the feasible operation area of synchronous generators is delimited by several curves leading to a diagram as the one in Figure 1. This means that active and reactive powers are coupled and so the simple rectangle P, Q model contains (P, Q) points that are outside the real capability diagram meaning that they are unfeasible.

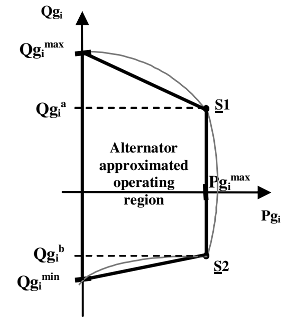

Fig. 1. Capability diagram of a synchronous generator.

This diagram was modeled using the following three curves:

- Curve 1, between (0, Qg_i^{max}) and (Pg_i^{max}, Qg_i^a), is the rotor field current limit;
- Curve 2, from $\underline{S}_1$ to $\underline{S}_2$, is the armature limit. It can be represented by a vertical line often associated with the maximum output power of the primary machine;
- Curve 3, the arc between ($0, Qg_i^{min}$) and (Pg_i^{max}, Qg_i^b), represents the stability limit.

Once these points are known, we can formulate constraints (3) to (5) to integrate in the optimization problem to run by the MGCC. The P and the Q values are not independent, meaning that the Market Operator can allocate a P value, in the first place, then the MGCC assigns a Q value required to ensure an adequate voltage profile, and this (P, Q) point can eventually be unfeasible. Including this model of the capability diagram in the optimization problem will ensure that these situations will not happen, thus improving the realism of the final results.

$$Qg_i \le Qg_i^{max} - \frac{Qg_i^{max} - Qg_i^a}{Pg_i^{max}}.Pg_i \tag{3}$$

$$Pg_i \le Pg_i^{max} \tag{4}$$

$$Qg_i \ge Qg_i^{min} + \frac{Qg_i^b - Qg_i^{min}}{Pg_i^{max}}.Pg_i \tag{5}$$

C. Model 1 - Crisp Optimization Model

The original adjustment market was described in [15]. This paper develops that original contribution in two ways:

- decoupling generator adjustments in ΔPg_i^L and in ΔPg_i^L variables so that we can compute the contribution of each generator to balance active losses;
- formulating the problem using Fuzzy Set Theory concepts so that it is possible to consider soft limit constraints.

The original optimization problem is non-linear due to the non-linear AC injected power expressions and to the branch apparent power flow limit constraints. To solve this problem we used a Sequential Linear Programming, SLP, algorithm in which we use the initial Market Operator schedule to obtain a complete operation point of the microgrid running an AC Power Flow. This operation point is then used to linearize the non-linear constraints. As a result of solving this linearized optimization problem, we obtain the active and reactive power and voltage magnitude deviations. Afterwards, the operation point is updated running a new AC Power Flow and finally we check the convergence of the iterative process. Using these ideas, in each iteration of the SLP algorithm it is solved the linear problem (6) to (19) admitting that the microgrid has Ng generators, Nd loads and Nb branches.

$$Min\ Z = \rho^{MO} . \sum_{i=1}^{Ng} \Delta Pg_i^L + \sum_{i=1}^{Ng} \left|\Delta Pg_i^A\right| . Cg_i^A + \sum_{j=1}^{Nd} \left|\Delta Pd_j^A\right| . Cd_j^A \qquad (6)$$

$$Subj. \quad \Delta V_i^{min} \le \Delta V_i \le \Delta V_i^{max} \qquad (7)$$

$$\Delta \theta_{ij}^{min} \le \Delta \theta_{ij} \le \Delta \theta_{ij}^{max} \qquad (8)$$

$$0 \le \Delta Pg_i^L \le \Delta Pg_i^{L\,max} \qquad (9)$$

$$-\frac{vg_i^{tol}}{100} \times Pg_i^o \le \Delta Pg_i^A \le \frac{vg_i^{tol}}{100} \times Pg_i^o \qquad (10)$$

$$0 \le \Delta Pg_i^A \le \frac{vg_i^{tol}}{100} \times Pg_i^{max} \qquad (11)$$

$$\Delta Pg_i^{min} \le \Delta Pg_i^A + \Delta Pg_i^L \le \Delta Pg_i^{max} \qquad (12)$$

$$-Pd_j^o \le \Delta Pd_j^A \le 0 \qquad (13)$$

$$Qg_i^o + \Delta Qg_i \ge Qg_i^{min} + \frac{Qg_i^b - Qg_i^{min}}{Pg_i^{max}} . (Pg_i^o + \Delta Pg_i^A + \Delta Pg_i^L) \qquad (14)$$

$$Qg_i^o + \Delta Qg_i \le Qg_i^{max} - \frac{Qg_i^{max} - Qg_i^a}{Pg_i^{max}} . (Pg_i^o + \Delta Pg_i^A + \Delta Pg_i^L) \qquad (15)$$

$$\sum_{k=1}^{Nb} \Delta P_k^{loss}(\Delta V, \Delta \theta) = \sum_{i=1}^{Ng} \Delta Pg_i^L \qquad (16)$$

$$\Delta P_i^{inj}(\Delta V, \Delta \theta) = (\Delta Pg_i^A + \Delta Pg_i^L) - \Delta Pd_i^A \qquad (17)$$

$$\Delta Q_i^{inj}(\Delta V, \Delta \theta) = \Delta Qg_i - \Delta Qd_i \qquad (18)$$

$$\Delta S_{ij}^{min} \le \Delta S_{ij}(\Delta V, \Delta \theta) \le \Delta S_{ij}^{max} \qquad (19)$$

The objective function (6) minimizes the cost of the active power generated to balance active losses plus the global adjustment cost required to turn the operation of the microgrid feasible, namely in terms of generator and demand variations regarding the values obtained in the initial Market Operator economic schedule. The first term models the cost of balancing active losses and it corresponds to the multiplication of the electricity market price, ρ^{MO}, by the sum of the ΔPg_i^L variables representing the contribution of each generator to balance active losses. The second and the third terms model generation and load adjustment costs and are obtained multiplying the generation/demand adjustment variables, ΔPg_i^A / ΔPd_j^A, by their adjustment costs, Cg_i^A / Cd_j^A.

This objective function is subjected to several constraints. Constraints (7) and (8) represent the minimum and maximum values of nodal voltages and phase differences. Constraints (9) limit the contribution of each generator to balance active losses, (10) and (11) define the range of generator adjustments to enforce technical or operational limits and (12) limits the sum of ΔPg_i^L and ΔPg_i^A. Then, (13) limits the possible adjustments on the demand and (14) and (15) represent the lower and upper curves of the capability diagram of Figure 1. Constraint (16) imposes that active losses computed using voltages and phases should match the value resulting from the addition of the ΔPg_i^L variables. In (16) the expression of the active loss in branch k, $\Delta P_k^{loss}(\Delta V, \Delta \theta)$, is linearized using the linear terms of the Taylor Series of the exact expression computed using the results of the most recent power flow study in the scope of the SLP algorithm. Constraints (17) and (18) correspond to the AC injected power equations using the linear terms of their Taylor Series. Finally, the branch ij apparent power flow constraints are modeled by (19) using the linear terms of the Taylor Series of the full AC expression.

D. *Modelization of Soft Constraints Using Fuzzy Sets*

As indicated in [9], constraints will often not display a rigid or crisp nature in the sense that the user can accept some degree of violation as a way to obtain better solutions. In this sense, we admitted that branch limits could be affected by some leeway as illustrated in Figure 2 representing the membership function of a branch flow limit. The membership value is 1 (meaning that it has the maximum acceptance degree) till x_1. Values from x_1 to x^{max} can still be accepted but they have a decreasing membership degree from 1 to 0. Mathematically, this is formulated by (20).

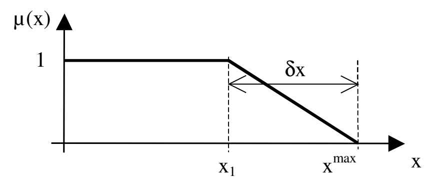

Fig. 2. Membership function of the fuzzy limit of a variable x.

$$\mu(x) = \begin{cases} 1, & if\ x \le x_1 \\ [0;1[, & if\ x_1 < x \le x^{max} \\ 0, & if\ x > x^{max} \end{cases} \qquad (20)$$

Figure 3 details the possible voltage values in node i. There is an interval of values from V_{i1} to V_{i2} having the maximum membership degree and voltages lower to V_{i1} or higher than V_{i2} can still be accepted but they have decreasing membership values from 1 to 0. Expression (21) represents this function.

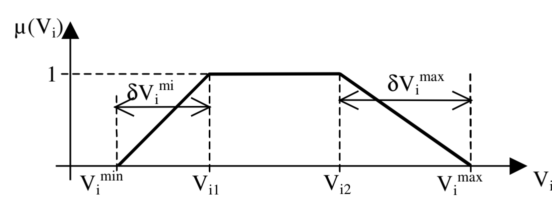

Fig. 3. Membership function of voltage limits.

$$\mu(V_i) = \begin{cases} 1, & if\ V_{i1} \le V_i \le V_{i2} \\ [0;1[, & if: V_i^{min} \le V_i < V_{i1}\ or\ V_{i2} < V_i \le V_i^{max} \\ 0, & if: V_i < V_i^{min}\ or\ V_i > V_i^{max} \end{cases} \qquad (21)$$

E. *Model 2 - Fuzzy Optimization Model*

In this case, one aims at maximizing the satisfaction degree μ of the solution of problem (22-38) associated with the membership degree of the constraints modeled using Fuzzy Sets. In this sense, the objective function of the problem described in Section C is now converted in the soft constraint (23). In (23) FO^{des} is the largest value that the original objective function can assume having the satisfaction degree of 1 and δ^{FO} is the admitted tolerance according to Figure 2.

$$Max\,Z = \mu \tag{22}$$

$$Subj.\quad FO + \mu.\delta^{FO} \le FO^{des} + \delta^{FO} \tag{23}$$

$$\Delta V_i - \mu.\delta^{V\,min} \ge \Delta V_i^{min} - \delta^{V\,min} \tag{24}$$

$$\Delta V_i + \mu.\delta^{V\,max} \ge \Delta V_i^{max} - \delta^{V\,max} \tag{25}$$

$$\Delta\theta_{ij}^{min} \le \Delta\theta_{ij} \le \Delta\theta_{ij}^{max} \tag{26}$$

$$\Delta Pg_i^{min} \le \Delta Pg_i^{A} + \Delta Pg_i^{L} \le \Delta Pg_i^{max} \tag{27}$$

$$-\frac{vg_i^{tol}}{100} \times Pg_i^{o} \le \Delta Pg_i^{A} \le \frac{vg_i^{tol}}{100} \times Pg_i^{o} \tag{28}$$

$$0 \le \Delta Pg_i^{A} \le \frac{vg_i^{tol}}{100} \times Pg_i^{max} \tag{29}$$

$$-Pd_j^{o} \le \Delta Pd_j^{A} \le 0 \tag{30}$$

$$Qg_i^{o} + \Delta Qg_i \ge Qg_i^{min} + \frac{Qg_i^{b} - Qg_i^{min}}{Pg_i^{max}}.(\,Pg_i^{o} + \Delta Pg_i^{A} + \Delta Pg_i^{L}\,) \tag{31}$$

$$Qg_i^{o} + \Delta Qg_i \le Qg_i^{max} - \frac{Qg_i^{max} - Qg_i^{a}}{Pg_i^{max}}.(\,Pg_i^{o} + \Delta Pg_i^{A} + \Delta Pg_i^{L}\,) \tag{32}$$

$$\sum_{k=1}^{Nb} \Delta P_k^{loss}(\,\Delta V, \Delta\theta\,) = \sum_{i=1}^{Ng} \Delta Pg_i^{L} \tag{33}$$

$$\Delta P_i^{inj}(\,\Delta V, \Delta\theta\,) = (\,\Delta Pg_i^{A} + \Delta Pg_i^{L}\,) - \Delta Pd_i^{A} \tag{34}$$

$$\Delta Q_i^{inj}(\,\Delta V, \Delta\theta\,) = \Delta Qg_i - \Delta Qd_i \tag{35}$$

$$\Delta S_{ij}(\,\Delta V, \Delta\theta\,) \ge \Delta S_{ij}^{min} \tag{36}$$

$$\Delta S_{ij}(\,\Delta V, \Delta\theta\,) + \mu.\delta_{ij}^{Sij} \le \Delta S_{ij}^{max} + \delta_{ij}^{Sij} \tag{37}$$

$$0 \le \mu \le 1 \tag{38}$$

Regarding this formulation, constraints (26) to (36) are common to the model described in Section C. As mentioned above, constraint (23) results from converting the objective function (6) in a soft constraint and constraints (24) and (25) model the soft minimum and maximum voltage limits. Constraints (37) represent the soft version of the maximum limit of the apparent power flow in branch *ij* using the model detailed in Section D. Finally, (38) specifies the range of the membership degree μ.

F. Solution Algorithm

As indicated above, the original adjustment market is modeled by a non-linear optimization problem given the non-linear expression of the active and reactive injected powers, of the branch losses and of the branch flow limits. In Sections C and E we described linearized versions of this problem to be solved in each iteration of the SLP algorithm as follows:

- in the first place, the Market Operator conveys the results of the day ahead market to the MGCC;
- the MGCC acting as the Microgrid System Operator, uses this active power economic schedule to run a technical validation study checking branch flow and voltage limits. This study takes the form of an adjustment market that uses adjustment bids both from sources and loads;
- this adjustment market is modeled by a non linear optimization problem that is solved using SLP. In this scope, using the Market Operator initial schedule, the MGCC runs an AC Power Flow to obtain an operation point of the system. Then, it linearizes the non-linear constraints (14) to (19) regarding Model 1 and (33) to (37 for Model 2 and it solves the resulting linear problem. In this case, we used MatLab and in particular the Linprog function to solve these linear problems. As a result, we obtain voltage magnitude, phase, generation and load deviations that are used to update the operation point. This point is refreshed running a new AC Power Flow and starting a new iteration. This iterative algorithm ends when the absolute value of all these deviations are smaller than specified tolerances. At that point, we obtain the final operation point, the contribution of each generator to balance active losses and eventually the demand interruption bids that were used by the MGCC.

IV. Case Study

A. Data

The described models were tested using the 55 node MV/LV network detailed in [16]. Figure 4 presents the scheme of the network that is connected to an upstream HV network in node 55 and that has generation sources connected to nodes 13, 43, 46, 47, 49, 49, 50, 51, 52 and 53.

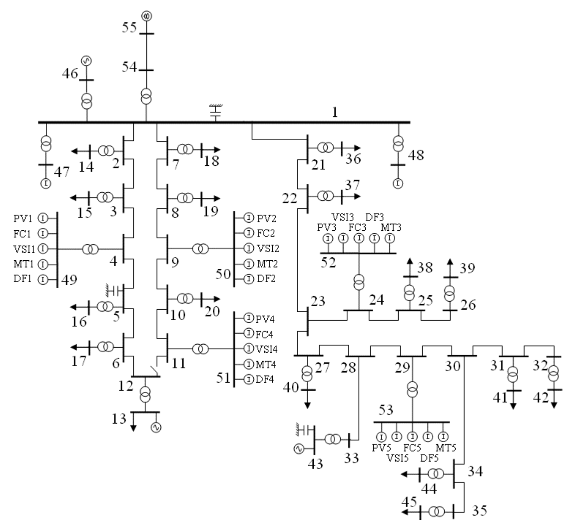

Fig. 4. Scheme of the 55 node MV/LV network.

This network has capacitor banks connected to nodes 1 (2.0 Mvar), 5 (0.5 Mvar) and 43 (0.5 Mvar). Table I details the generator selling bids, Table II includes the data to model the capability diagram of the generators and their adjustment bids, Table III has the load buying and adjustment bids and finally Table IV has the branch and transformer data. Branch 11- 12 includes a breaker that, when closed, creates a loop including the two feeders on the left side of the network. In the simulations we used 0.97 pu and 1.03 pu for voltage limits.

B. Initial Market Operator Economic Schedule

Using the generator selling bids in Table I and the load buying bids in Table III, it was run an uniform price auction leading to the market price, ρ^{MO}, of 40.8 €/MWh and to the economic schedule detailed in Table V.

TABLE I - GENERATOR SELLING BIDS

bus i	Pg_i^{max} MW	Pg_i^{bid} MW	Cg_i^{bid} €/MW.h	bus i	Pg_i^{max} MW	Pg_i^{bid} MW	Cg_i^{bid} €/MW.h
13	0.40	0.40	16.0	50	0.25	0.25	24.0
43	1.50	1.50	16.0	51	0.25	0.25	28.0
46	0.70	0.70	16.0	52	0.25	0.25	32.0
47	0.10	0.10	60.0	53	0.25	0.25	16.0
48	0.80	0.80	24.0	55	7.00	7.00	40.8
49	0.25	0.25	32.0	-	-	-	-

TABLE II – DATA FOR THE CAPABILITY DIAGRAM AND ADJUSTMENT BIDS

bus i	Pg_i^{max} MW	Qg_i^{max} Mvar	Qg_i^{a} Mvar	Qg_i^{b} Mvar	Qg_i^{min} Mvar	vg_i^{tol} %	Cg_i^{A} €/MW.h
13	0.40	0.50	0.50	-0.50	-0.50	100	160.0
43	1.50	1.00	1.00	-0.50	-0.50	100	160.0
46	0.70	0.50	0.50	-0.50	-0.50	100	120.0
47	0.10	0.01	0.01	-0.01	-0.01	100	144.0
48	0.80	0.30	0.30	-0.30	-0.30	100	80.0
49	0.25	0.10	0.10	-0.10	-0.10	100	80.0
50	0.25	0.10	0.10	-0.10	-0.10	100	80.0
51	0.25	0.10	0.10	-0.10	-0.10	100	80.0
52	0.25	0.10	0.10	-0.10	-0.10	100	80.0
53	0.25	0.10	0.10	-0.10	-0.10	100	80.0
55	7.00	2.50	2.50	-2.50	-2.50	20	80.0

TABLE III – LOAD BUYING AND ADJUSTMENT BIDS

bus i	Pd_i^{bid} MW	Qd_j Mvar	Cd_j^{bid} €/MW.h	Cd_j^{A} €/MW.h	bus i	Pd_i^{bid} MW	Qd_j Mvar	Cd_j^{bid} €/MW.h	Cd_j^{A} €/MW.h
13	0.900	0.436	48.0	304.0	37	0.135	0.065	43.2	304.0
14	0.838	0.275	41.6	312.0	38	0.135	0.065	41.6	344.0
15	0.838	0.275	44.0	336.0	39	0.086	0.042	48.0	368.0
16	0.419	0.138	42.4	320.0	40	0.216	0.105	44.0	432.0
17	0.419	0.138	43.2	352.0	41	0.135	0.065	48.0	408.0
18	0.838	0.275	48.0	368.0	42	0.086	0.042	44.8	312.0
19	0.838	0.275	64.0	352.0	44	0.135	0.065	48.0	320.0
20	0.419	0.138	56.0	328.0	45	0.086	0.042	56.0	336.0
36	0.216	0.105	48.0	312.0	-	-	-	-	-

TABLE IV – TRANSFORMER AND BRANCH DATA.

branch	R_{ij} Ω	X_{ij} Ω	Y_{ij}^{sh} S	S_{ij}^{max} MVA	branch	R_{ij} Ω	X_{ij} Ω	Y_{ij}^{sh} S	S_{ij}^{max} MVA
1-2	0.0204	0.01508	2.76E-05	3.50	21-22	0.29236	0.1576	2.90E-06	2.00
1-7	0.0204	0.01508	2.76E-05	3.50	21-36	0	12.5	0	0.40
1-21	0.29236	0.1576	2.90E-06	2.00	22-23	0.29236	0.1576	2.90E-06	2.00
1-46	0	2.5	0	2.00	22-37	0	20	0	0.25
1-47	0	2.5	0	4.00	23-24	0.29236	0.1576	2.90E-06	2.00
1-48	0	1	0	10.00	23-27	0.29236	0.1576	2.90E-06	2.00
1-54	0	0.5	0	7.00	24-25	0.29236	0.1576	2.90E-06	2.00
2-3	0.0204	0.01508	2.76E-05	3.00	24-52	0	12.5	0	0.40
2-14	0	3.968254	0	1.26	25-26	0.29236	0.1576	2.90E-06	2.00
3-4	0.0204	0.01508	2.76E-05	2.00	25-38	0	20	0	0.25
3-15	0	3.968254	0	1.26	26-39	0	31.25	0	0.16
4-5	0.0204	0.01508	2.76E-05	2.00	27-28	0.29236	0.1576	2.90E-06	2.00
4-49	0	12.5	0	0.40	27-40	0	12.5	0	0.40
5-6	0.0204	0.01508	2.76E-05	2.00	28-29	0.29236	0.1576	2.90E-06	2.00
5-16	0	7.936508	0	0.63	28-33	0.29236	0.1576	2.90E-06	2.00
6-12	0.0204	0.01508	2.76E-05	2.00	29-30	0.29236	0.1576	2.90E-06	2.00
6-17	0	7.936508	0	0.63	29-53	0	12.5	0	0.40
7-8	0.0204	0.01508	2.76E-05	3.00	30-31	0.29236	0.1576	2.90E-06	2.00
7-18	0	3.968254	0	1.26	30-34	0.29236	0.1576	2.90E-06	2.00

TABLE IV – TRANSFORMER AND BRANCH DATA (CONTINUED)

branch	R_{ij} Ω	X_{ij} Ω	Y_{ij}^{sh} S	S_{ij}^{max} MVA	branch	R_{ij} Ω	X_{ij} Ω	Y_{ij}^{sh} S	S_{ij}^{max} MVA
8-9	0.0204	0.01508	2.76E-05	2.00	31-32	0.29236	0.1576	2.90E-06	2.00
8-19	0	3.968254	0	1.26	31-41	0	20	0	0.25
9-10	0.0204	0.01508	2.76E-05	2.00	32-42	0	31.25	0	0.16
9-50	0	12.5	0	0.40	33-43	0	2.5	0	2.00
10-11	0.0204	0.01508	2.76E-05	2.00	34-35	0.29236	0.1576	2.90E-06	2.00
10-20	0	7.936508	0	0.63	34-44	0	20	0	0.25
11-12	0.0204	0.01508	2.76E-05	2.00	35-45	0	31.25	0	0.16
11-51	0	12.5	0	0.40	54-55	0.0017	0.0058	0.00095	7.00
12-13	0	2.5	0	2.00	-	-	-	-	-

TABLE V – ECONOMIC SCHEDULE OF THE MARKET OPERATOR

bus i	Pg_i MW	Pd_i MW	bus i	Pg_i MW	Pd_i MW
13	0.40	0.900	42	-	0.086
14	-	0.838	43	1.50	-
15	-	0.838	44	-	0.135
16	-	0.419	45	-	0.086
17	-	0.419	46	0.70	-
18	-	0.838	47	0	-
19	-	0.838	48	0.80	-
20	-	0.419	49	0.25	-
36	-	0.216	50	0.25	-
37	-	0.135	51	0.25	-
38	-	0.135	52	0.25	-
39	-	0.086	53	0.25	-
40	-	0.216	55	2.089	-
41	-	0.135	-	-	-

C. Case 1 – Closed Breaker and Model 1

In the first place, we admitted that the breaker in branch 11 – 12 is closed creating a loop in the left part of the network. Using Model 1 detailed in Section III.C, we obtained the final dispatch detailed in Table VI. There are no violated branch flow or voltage magnitude limit constraints and so the values of the variables ΔPg_i^A are zero. The values of the ΔPd_j variables are also zero indicating that there was no load curtailment. The final results in Table VI show that branch losses take the value of 0.027 MW and are fully balanced in node 47. The final value of the objective function is 1.102 €/h and it is only associated with the first term in (6), since the second and the third terms of this expression are zero. This value results from multiplying branch losses by the market price, ρ^{MO} .

D. Case 2 – Open Breaker, Model 2 and 30% Load Increase

Now, we used the Fuzzy Model, Model 2, admitting that all loads were increased by 30% and using the following for the tolerances specified for the branch flow and for the voltage magnitude limit constraints and also to build constraint (23) to convert the objective function (6) of the original crisp model into a fuzzy constraint:

- δ_{ij}^{Sij} = 10 %;
- $\delta^{V\,min}$ =0.02 pu;
- δ^{Vmax} =0.02 pu;
- FO^{des} = 104.0 €/h;
- δ^{FO} = 56.0 €/h.

TABLE VI – FINAL DISPATCH FOR CASE 1

bus i	ΔPg_i^L MW	ΔPg_i^A MW	Pg_i MW	Qg_i Mvar	ΔPd_i^A MW	Pd_i MW	Qd_i Mvar
13	0	0	0.4	0.5	0	0.9	0.436
14	-	-	-	-	0	0.838	0.275
15	-	-	-	-	0	0.838	0.275
16	-	-	-	-	0	0.419	0.138
17	-	-	-	-	0	0.419	0.138
18	-	-	-	-	0	0.838	0.275
19	-	-	-	-	0	0.838	0.275
20	-	-	-	-	0	0.419	0.138
36	-	-	-	-	0	0.216	0.105
37	-	-	-	-	0	0.135	0.065
38	-	-	-	-	0	0.135	0.065
39	-	-	-	-	0	0.086	0.042
40	-	-	-	-	0	0.216	0.105
41	-	-	-	-	0	0.135	0.065
42	-	-	-	-	0	0.086	0.042
43	0	0	1.5	0.253	-	-	-
44	-	-	-	-	0	0.135	0.065
45	-	-	-	-	0	0.086	0.042
46	0	0	0.7	0.338	-	-	-
47	0.027	0	0.027	-0.007	-	-	-
48	0	0	0.8	-0.239	-	-	-
49	0	0	0.25	0.1	-	-	-
50	0	0	0.25	0.1	-	-	-
51	0	0	0.25	0.1	-	-	-
52	0	0	0.25	0.096	-	-	-
53	0	0	0.25	0.072	-	-	-
55	0	0	2.089	1.018	-	-	-

TABLE VII – FINAL DISPATCH FOR CASE 2

bus i	ΔPg_i^L MW	ΔPg_i^A MW	Pg_i MW	Qg_i Mvar	ΔPd_i^A MW	Pd_i MW	Qd_i Mvar
13	0	0	0.4	0.5	-0.290	0.88	0.426
14	-	-	-	-	0	1.089	0.358
15	-	-	-	-	0	1.089	0.358
16	-	-	-	-	0	0.545	0.179
17	-	-	-	-	0	0.545	0.179
18	-	-	-	-	0	1.089	0.358
19	-	-	-	-	0	1.089	0.358
20	-	-	-	-	0	0.545	0.179
36	-	-	-	-	0	0.281	0.136
37	-	-	-	-	0	0.176	0.085
38	-	-	-	-	0	0.176	0.085
39	-	-	-	-	0	0.112	0.054
40	-	-	-	-	0	0.281	0.136
41	-	-	-	-	0	0.176	0.085
42	-	-	-	-	0	0.112	0.054
43	0	0	1.5	-0.468	-	-	-
44	-	-	-	-	0	0.176	0.085
45	-	-	-	-	0	0.112	0.054
46	0	0	0.7	0.115	-	-	-
47	0.037	0	0.037	0.01	-	-	-
48	0	0	0.8	0.275	-	-	-
49	0	0	0.25	0.038	-	-	-
50	0	0	0.25	0.033	-	-	-
51	0	0	0.25	0.033	-	-	-
52	0	-0.040	0.21	0.048	-	-	-
53	0	-0.250	0	0.045	-	-	-
55	0	0	4.113	0.464	-	-	-

Taking the case of branch 1 – 2 as an example and using a membership function as the one illustrated in Figure 2, if the apparent power flow in branch 1 - 2 is not larger than 3.5 MVA the corresponding membership function is 1.0, meaning that the crisp limit is not exceeded. However, it is admitted a tolerance of 10% on this crisp limit, meaning that the apparent power flow in this branch can go till 3.85 MVA but the corresponding membership degree decreases from 1.0 to 0.0 when going from 3.5 to 3.85 MVA. Having this in mind, Table VII presents the results obtained for this Case for the final generation and load dispatch. The capacitors connected to nodes 1 and 5 generate 2.0 and 0.5 Mvar.

Regarding the results in Table VII, there is now load curtailment because the ΔPd_j variable associated with node 13 is negative so that the final load in this node is 0.88 MW. Regarding the generation, there are also changes when compared with the initial scheduled values namely because the ΔPg_i^A variables associated with nodes 52 and 53 are negative and the global generation reduction is 0.290 MW. This generation reduction matches the load reduction already identified in node 13. Apart from the changes in the outputs of generators in nodes 52 and 53, there is also an increase of the generation in node 47 by 0.037 because branch active losses are fully balanced in this node. If the crisp model was used assuming the conditions of this Case, the load reduction would take the value of 0.342 MW. This means that using the Fuzzy Model allows reducing load curtailment from 0.342 MW to 0.290 MW, that is, by about 15%, admitting the 30% load increase. This is due to the model flexible operation of the network given the soft limit constraints that were used.

The final satisfaction degree, μ, obtained with the Fuzzy Model is 0.840 and this value is not larger and closer to 1.0 because of the branch 1-2 limit constraint. The apparent flow in this branch is 3.56 MVA (3.502 MW and 0.615 Mvar) and the resulting degree read in the corresponding membership function is 0.840. This indicates that the tolerance of 10% admitted for the apparent flow limit in this branch is not fully used. In fact, Table IV indicates that the flow limit of branch 1-2 is 3.5 MVA so that the maximum soft limit is 3.85 MVA. This mentioned tolerance is not further used because there are other constraints also using their tolerances. This is the case of the voltage magnitudes in nodes 1, 33 and 46 to 55 in which voltages magnitudes are larger than the crisp limit of 1.03 pu, meaning that the tolerance of 0.02 pu is also being used. Finally, the FO value, corresponding to the objective function of the original crisp model (6) takes the value of 112.96 €/h. This value is much larger than the one obtained in Case 1 namely because the load increase by 30% determines the use of adjustment generation and load bids. This means that there are now non-zero values for all the three terms in (6) while in Case 1 all ΔPg_i^A and ΔPd_j were zero.

E. *Voltage Profiles for Cases 1 and 2*

Finally, Figure 5 displays the voltage profiles obtained for:

- Case 1 using the crisp model, Model 1, detailed in Section C;
- Case 2 using the fuzzy model, Model 2, detailed in Section D;
- and also for comparison purposes the voltage profile for Case 2 if the crisp model, Model 1, was used.

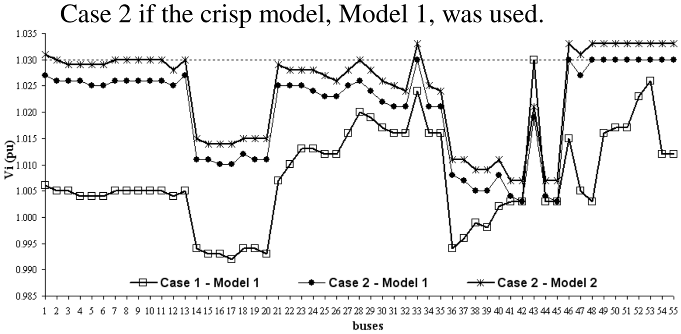

Fig. 5. Voltage profiles obtained for Cases 1 and 2, using Models 1 and 2.

These results reveal that the use of Model 2 in Case 2 allows some voltage magnitudes to exceed the crisp limit of 1.03 pu thus turning the operation of the network more flexible. In fact when using Model 1 in Case 2 it is possible to check that the voltage limit of 1.03 pu is not exceeded.

V. Conclusions

In this paper we presented two models to use by Microgrids Central Controller within the market cycle conceived to allow and induce the participation of microgrid agents in electricity markets. One of the models has crisp nature while the second one uses fuzzy concepts, namely to model soft voltage and branch flow constraints. This increases the operation flexibility leading to the reduction of load curtailment.

The developed models can be used to allocate reactive power, active power to balance active losses and load curtailment among Microgrid agents thus contributing to create conditions to remunerate these services and to create a new flow of money to these agents. This will induce their participation in electricity markets so that they can be paid not only for the electricity itself but also according to the provision of these ancillary services. This feature can ultimately contribute to integrate these sources in a more natural way in power systems, eventually eliminating large feed-in tariffs that represent in several countries an increasing share of the final end user tariffs.

These models can also contribute to create conditions to increase load elasticity thus reducing a major drawback of current electricity market implementations. As symmetry increases, competition will certainly increase and market power will be more limited. As a whole, microgrids can lead in the near future to a change of paradigm regarding the nature and the operation of distribution networks.

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VII. 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 namely in consultancy contracts with the Portuguese Electricity Regulatory Agency.

Mário Helder Rodrigues Gomes was born in Mozambique in 1972. He received his licentiate, MSc and PhD degrees from Faculdade de Engenharia da Universidade do Porto (FEUP) in 1997, 2000 and in 2007 in Electrical and Computer Engineering. In 1997 he joined the Polytechnic Institute of Tomar (IPT), Portugal, where he is currently Assistant Professor.