A Novel Market Based Distribution System Controller for Active Distribution Networks

F. Bignucolo, R. Caldon, A. Sacco
Department of Electrical Engineering, University of Padova, Italy
E-mail: fabio.bignucolo@die.unipd.it

***Abstract*- The high growth trend characterizing the Distributed Generation (DG) diffusion in traditional radial structure MV networks leads Distribution System Operators (DSOs) to face, and rapidly solve, some technical, management and commercial issues which may limit the diffusion of DG plants. In the next future DSOs will be called to adopt innovative network control architectures, communication channels and marketplaces in order to coordinate the operation and the management of their electrical systems.**

The paper presents a new scenario, based on a local price signal theory applied to the distribution network context. A pricing system, computed at each node both for active and reactive energy, may be an efficient way to solve power system management, operation and planning, meeting all the distribution network operational constraints.

***Index Terms*-- Active distribution networks, distributed generation (DG), optimal power flow (OPF), smart grids, spot pricing.**

I INTRODUCTION

The improving performances of small plants, the growth in Renewable Energy Sources (RES) use due to incentives introduced to meet the environmental targets, and the current electrical system liberalisation process are accelerating the diffusion of Distributed Generation (DG) units connected to Medium Voltage (MV) distribution networks. Instead that appears to be curbed by technical issues, such as the power flow redeployment, the possible feeder ampacity violations and the impact on voltage regulation and protection system.

At present DSOs define the connection main characteristics through a traditional “fit&forget” criterion; from now on, leaving behind this criterion, which may involve heavy limitations to the maximum number and size of the connectable DG plants, DSOs will be called to adopt innovative techniques, with a gradual shift from centralized to more decentralized strategies, suitable for coordinating operation, managing and planning the distribution network [1].

In a market based distribution system, it results necessary to operate the network in the optimal way, trying to achieve the maximum benefit from electrical energy usage at minimum cost, without the direct control of all the customers. Hence the optimal operating point calculation reveals a crucially important subject for the network management with regard to immediate impact on operational costs, accessibility and reliability of the whole system.

Price signals are an available mechanism to coordinate the operation of a power system in the emerging competitive environment [1]; in particular the spot pricing theory is here applied to the distribution network context considering its typical operational constraints. A spot price based energy marketplace could be a new and transparently computed control signal. On a medium term perspective, spot pricing may be an equity choice: each national regulatory commission may no longer determine the values of electrical energy rates, but only the formulas which will be used to compute spot prices at each node or network zone [2].

In this paper the implemented algorithm is presented, aiming to consider all the network constraints derived from the operation of MV systems with a high DG penetration level. Section II describes the optimization problem and how it can be solved applying a spot pricing technique. In section III the earliest spot pricing theory and its development to distribution system applications are illustrated. Section IV presents the proposed algorithm and section V provides some results obtained on a realistic case study grid.

II OPTIMIZATION

A. Spot pricing concept

Fundamental changes in the society views about the electrical energy are under way, being the electrical energy more and more treated as a commodity which can be bought, sold and traded taking into account its time- and space-varying values and costs. With these assumptions, spot pricing theory has been derived from [2], [3] and here applied to the distribution systems context.

Any responsive price regulation approach is based on the economical quantification of the product value as a function of the way in which it is made available. In particular, dealing with transmission and distribution systems regulation, the product at issue is the electrical energy exchanged with the grid by users. Electrical energy, in fact, increases or decreases its value in term of the location of the system bus where it is required or made available.

Hence, as shown in (1), spot price at *k*-th bus represents the marginal cost of providing a further electrical energy unit (MWh) to customers connected to *k*-th bus during hour *t*.

$$\rho_k(t) = \frac{\partial(\text{total cost})}{\partial d_k(t)} \tag{1}$$

Typically a spot pricing system based on marginal costs calculation has the property of cover both operating and capital costs.

B. Problem and methodology

From an analytical point of view the optimized usage of distributed energy resources, based on generators capability, generation costs and system operating constraints, is an economic dispatch problem, whose variables are the set-points of the DG plants connected to the grid and the consumer consumptions (in case of price dependent loads). These set-points may be given as generated active power and voltage at the connection bus (PV control) or as generated active and reactive power (PQ control).

This Optimal Power Flow (OPF) problem has to meet some constraints that essentially are represented by the power flow redeployment and the typical technical-operational constraints characterizing any distribution system. Its peculiarities are the non-linearity and the considerable dimensions of both the objective function and the constraints formulations.

In the literature, several methods have been presented, aiming to achieve different objectives, for instance losses minimization, generation costs reduction or optimal network re-configuration allowing intentional or accidental islanding. Therefore an optimized management of the distribution system permits to develop new and interesting opportunities for DSOs and customers [4].

According to the problem dimensions, the optimization can be carried out with genetic algorithms based on evolutionary techniques or with iterative methods, introducing, if necessary, some simplifications as the linearization of non-linear constraints. To be more precise the optimization is obtained through a minimization of a suitable objective function, which can be formulated as the weighted linear combination of many components, each one considered with its own weight. These components may be quantities to minimize (for example active power losses) or differences to keep as close as possible to zero (for example the difference between the bus voltage and its rated value).

Unfortunately many of the proposed approaches are available only under some strict simplifying hypothesis. In particular it is assumed that all, or a part of, the DG units are owned or directly managed by the DSO or that all the power generated in excess can be stored and used when it is more convenient.

Referring to present distribution networks, previously introduced hypothesis seem to be really far from the concrete. In particular each producer can freely have at his disposal the chance to define his own generation profile, just remaining into the bounds stated by the contract stipulated at the act of connection to the grid but being totally independent from reference values stated by the DSO.

As regards the Italian context, any DG plant owner can chose if facing up to the electrical energy market, accepting to generate the exact amount established in the day ahead market, or planning his production on the basis of bilateral contract, or else, in case of renewable or high efficiency cogeneration plants, giving his energy up to GSE (Gestore dei Servizi Elettrici) in a dedicated reclaim or on-site exchange way depending on the plant size, submitting if necessary or desired his generation schedules, which however cannot be modified by GSE.

It outlines hence the need to have a tool able to lead to an appropriate optimization of the distribution system and, at the same time, to supply all customers with clear and unequivocal signals addressing them to have the best behaviour, not only for themselves but for the whole system. A distribution spot prices approach can surely be an effective method to supply each customer with proper indications, in particular a price signal diversified at each bus of the grid, considering the different influence of energy demand or generation at each bus has on the whole system, has been introduced.

III Spot Pricing Theory applied to Distribution Systems

A. The earliest theory formulation

The spot prices calculation method aims to maximize the Social Welfare, defined as the difference between total benefit $B[d(t)]$ achieved by consumers using the electrical energy demand $d(t)$ and operational costs $G_{FM}[\underline{g}(t)]$ met by the system to generate and distribute the total generation $g(t)$. The objective function to minimize is the Social Cost, which is the opposite of the Social Welfare.

$$\text{Social Cost}\,(SC) = G_{FM}\left[\underline{g}(t)\right] - B[\underline{d}(t)] \tag{2}$$

The SC definition must be enriched, as in (3), in order to take into account other cost terms, which are G_{QS} (quality of supply generation costs), N_M (network maintenance costs) and N_{QS} (quality of supply network costs).

$$SC = G_{FM}\left[\underline{g}(t)\right] + G_{QS}\left[\underline{g}(t)\right] + N_M\left[\underline{z}(t)\right] + N_{QS}\left[\underline{z}(t)\right] - B[\underline{d}(t)] \tag{3}$$

The minimization of SC must be subjected to technical and operational constraints which have to be satisfied in the optimized scenario: the power balance equations (both active and reactive), the accepted range of variation for bus voltages, the lines ampacity and the capability curves of each generator.

Spot pricing theory, as proposed in its original version, has been mainly applied to transmission systems, usually having recourse to some simplifications leading to identify an equivalent grid representing the system under investigation. In fact it is a common practice to aggregate grid portions, poorly representative and typically free from line congestions, in a unique equivalent bus, defining it as a zone. All the customers in that zone will see the same spot price. Unlike this earliest theory, thought on purpose to be used with EHV and HV transmission systems, the new version proposed in this paper considers the typical peculiarities of MV and LV distribution systems which make the original theory inapt to our purposes.

A first outstanding point is the economical quantification not only for the active energy but also for the reactive one; in the original theory, instead, only active energy spot price was introduced, counting on simplifications based on some hypothesis, likely for transmissions systems, which allow to adopt a simplified DC power flow method, requiring the solution of a linear equations system.

B. Theory improvement

In order to turn spot pricing theory into a powerful tool applicable to distribution grids it is necessary to add to the optimization problem some further variables, which are reactive power flows and nodal voltages, calculable through AC power flow. Thus only by a widening of the original theoretical structure reactive power and new operational constraints can be annexed to the problem formulation.

Bearing on MV distribution systems, but generally also lowering rated voltage value, the equivalent characteristics of typically installed lines show definitely higher R/X ratios. As a consequence, active and reactive power flows cannot be decoupled. Therefore, opposed to HV and EHV systems, it is not possible to verify lines congestions only analyzing active power transit and to control voltages uniquely acting on reactive power exchanges between customers. Hence both active and reactive power contribute towards the determination of the distribution network operating conditions; the general problem formulation can be shortly written as in (4).

$$\begin{cases} \min(SC) \\ \text{s.t.} \quad V_{min,i} \le V_i \le V_{MAX,i} & \forall i \\ \quad I_h \le I_{MAX,h} & \forall h \\ \quad g_P(t) = d_P(t) + L_P[\underline{z}(t)] \\ \quad g_Q(t) = d_Q(t) + L_Q[\underline{z}(t)] \\ \quad \text{capability curves of generators} \end{cases} \tag{4}$$

Accordingly this method wants to define the spot prices set able to lead consumers and producers to optimize their own energy exchanges and at the same time to verify the operational constraints affecting the whole distribution system and the single customer too.

IV Architecture of the Optimization Algorithm

An algorithm finalized to apply the spot pricing management and regulation technique to the MV distribution systems context has been developed and implemented. In detail, the research work allows a theory generalization achieving at the same time a well accurate solution in a satisfactory calculation time.

In order to obtain a partial simplification of the treatment in terms of results analysis, but without loss of generality in solving the problem, the proposed version of the algorithm considers a very rigid pattern for energy demand, so active and reactive power required by consumers are assumed as fixed.

The optimization is solved for a fixed temporal instant, assuming that it will be computed with a certain cadence; in this way the reliance on time of each evaluation can be dropped. In the case study exposed in the paper, a 60 minutes interval has been applied, just to obtain the algebraic equivalence between power, in (MW), and energy, in (MWh), values.

A. Objective function

The objective function to be minimized is the SC as expressed in (2) accepting, for simplicity, that all other cost terms are equal to zero. Operational generation cost G_{FM}, for both active and reactive power, is linearly formulated as the sum of a variable component, in (€/MWh), multiplied by generated power, and a fixed component, in (€/h). Consumers benefit, instead, is computed only for active power, as the product between a variable price entry, in (€/MWh), and the active power required in the considered time.

B. Optimization variables

The simplest way to solve the problem would be to consider as optimization variables only active and reactive power injected at generation buses, including the connection bus with the upstream network (which is the slack node). This approach, even if formally correct, would be poorly efficient when implemented: it involves a great number of external calls backs of the power flow calculation function to check the non-linear constraints and the criterion used by the solver to modify the variables at each iteration, looking for the optimal point, may be critical because there would be no direct correspondence between the optimization problem variables and the power flow calculation ones (bus voltages in magnitude and angle).

In order to solve these problems, the treatment has been expanded by including in the variables vector voltages angles and magnitudes (at each network bus), generated active and reactive power (at each generation bus) and the transformation ratio of each transformer, as shown in (5).

$$\underline{x} = \begin{bmatrix} \vartheta_i \\ V_i \\ g_{P,j} \\ g_{Q,j} \\ m_t \end{bmatrix} \quad \text{con} \quad \begin{array}{l} i = 1,\dots,n \\ j = 1,\dots,n_{GEN} \\ t = 1,\dots,n_{TRANSF} \end{array} \tag{5}$$

Voltages angles and magnitudes introduction into the optimization problem variables allows the internal solution of power flow calculations. In addition, non-linear constraints can be considered directly into the solver by introducing the network equations in their expressions. Except for the angles, which are expressed in radians, all the others variables are computed in per units.

C. Operational constraints

All the vector $\underline{x}$ components are upper and lower bounded by technical network constraints (voltages angles and magnitudes, transformation ratio) and customers constraints (maximum and minimum generated active and reactive power depending on DG capability curves). In this way the optimization problem is subjected to the following constraints:

$$\begin{array}{ll} \vartheta_{min,i} \le \vartheta_i \le \vartheta_{MAX,i} & \forall i \\ V_{min,i} \le V_i \le V_{MAX,i} & \forall i \\ g_{P,min,j} \le g_{P,j} \le g_{P,MAX,j} & \forall j \\ g_{Q,min,j} \le g_{Q,j} \le g_{Q,MAX,j} & \forall j \\ m_t(tap_{min}) \le m_t \le m_t(tap_{MAX}) & \forall t \\ P_i(\vartheta,V) = g_{P,i} - d_{P,i} & \forall i \\ Q_i(\vartheta,V) = g_{Q,i} - d_{Q,i} & \forall i \\ I_{s,h}(\vartheta,V) \le I_{MAX,h} & \forall h \\ I_{e,h}(\vartheta,V) \le I_{MAX,h} & \forall h \\ g_{P,GD} \le g_{P,GD,crit} & \\ g_{Q,GD} \le g_{Q,GD,crit} & \end{array} \tag{6}$$

At each k-th iteration it is possible to extract from $\underline{x}^k$ the transformer ratio and update the nodal admittance matrix; power balance equations are expressed for active and reactive power at each network bus, avoiding the computation of the total power balance which would have required to calculate the total losses too.

The lines ampacity constraints are checked by comparing the rms current value with the maximum admissible current. The last two constraints are related to the total DG generated power control, so that a certain reserve can be considered.

D. *Computation structure of the algorithm*

The algorithm starts from an initial network configuration $\underline{g}^0$ in which all generators set-points are supposed to be known. This first layout can be defined by producers choices or as the result of an economical dispatch, if producers offer their energy in the marketplace or in a local energy market.

The solver needs the OLTC position could be described as a linear function; after the first minimization, giving generally m_t value corresponding to a not feasible tap changer position, it is necessary to carry out other two minimizations rounding the tap position to the first upper and lower whole numbers.

The procedure, if obtainable with relation to the constraints severity, ends in case all the constraints are fulfilled and at the same time the objective function value (or the optimization variables) does not vary more than a prefixed value between two consecutive iterations. The algorithm supplies as output the optimal variables vector $\underline{x}^{opt}$, the objective function value SC^{opt} and Λ^{opt}, which is a structure grouping all the resulting values of Lagrange and Kuhn-Tucker multipliers, which will be useful to calculate spot prices.

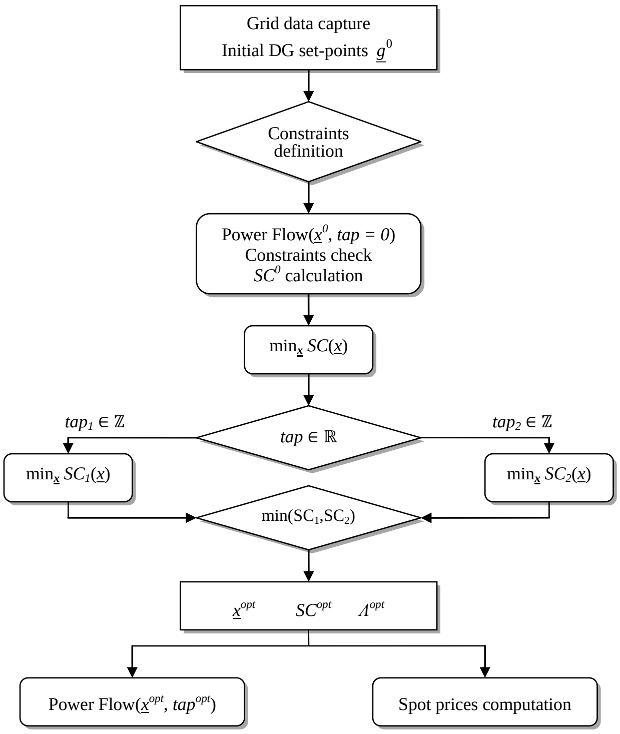

Fig. 1. Optimization algorithm flow chart

E. *Spot prices calculation*

Equation (7) is the generic expression of spot price at k-th bus for active energy.

$$\rho_{P,k} = \mu_{P,e} + \eta_{P,L,k} + \eta_{P,I_{MAX},k} + \eta_{P,V_{min},k} + \eta_{P,V_{MAX},k} \quad \left(\frac{€}{\mathrm{MWh}}\right) \tag{7}$$

The first term, $\mu_{P,e}$, is the Lagrange multiplier related to the whole active power balance equation; $\eta_{P,L,k}$ is the component considering active power losses, caused by energy demand or injection at k-th bus. Imposing the energy balance at each bus resulting multipliers already contain the component attributable to losses, as show in (8).

$$\mu_{P,e,k} = \mu_{P,e} + \eta_{P,L,k} = \mu_{P,e} + \mu_{P,e} \cdot \frac{\partial L_p(\underline{x})}{\partial d_{P,k}} \tag{8}$$

The reactive energy spot price can be similarly defined as represented in (9).

$$\rho_{Q,k} = \mu_{Q,e,k} + \eta_{Q,I_{MAX},k} + \eta_{Q,V_{min},k} + \eta_{Q,V_{MAX},k} \quad \left(\frac{€}{\mathrm{Mvarh}}\right) \tag{9}$$

According to the base principle of outlay and remuneration equity, inspiring the whole spot pricing theory, an analogous formulation of nodal spot price would be obtain considering the energy generation at k-th bus, instead of the demand.

V RESULTS

A. *Case study*

The developed and implemented algorithm has been applied to a reference distribution system (shown in Fig. 2) which can highlight some of the possible criticalities which may be verified in case of an high DG penetration.

Feeder D1 mainly consists of high section cable lines, instead D2 includes overhead lines and, anyway, lines with small section conductors. Total load connected to the first feeder demands 7.6 MW and 3.9 Mvar, whereas that of the second feeder 5.4 MW and 3.1 Mvar. DG plants technical characteristics are shortly listed in Table I; working limits, usually given by a capability curve, are here identified as lower and upper bounds of both active (30÷100% S_n) and reactive (–20÷20% S_n) generated power.

In a spot pricing control context, based on a free market mechanism with private customers not directly controlled by the DSO, each generator cost function and each consumer

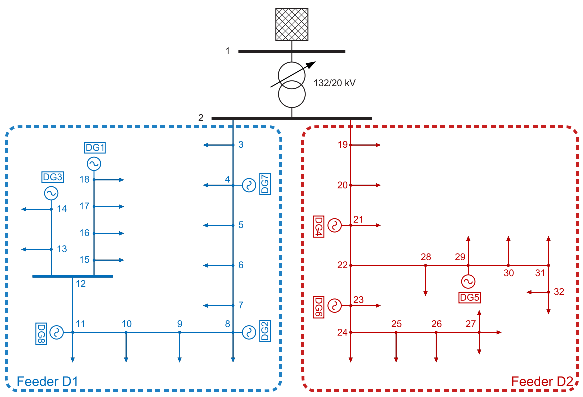

Fig. 2. Test grid scheme

TABLE I
DG PLANTS SIZES AND INITIAL SET-POINTS

Feeder	Name	Bus	S_n (MVA)	g_P^0 (MW)	g_Q^0 (Mvar)	$\cos\varphi^0$
D1	DG7	4	7.5	6.75	0	1
	DG2	8	3.5	3.15	2.36	0.8
	DG8	11	7.5	6.75	0	1
	DG3	14	3.5	3.15	2.36	0.8
	DG1	18	7.5	6.75	5.06	0.8
Total feeder D1			29.5	26.55	9.79	
D2	DG4	21	3.5	3.15	0	1
	DG6	23	7.5	6.75	0	1
	DG5	29	3.5	3.15	0	1
Total feeder D2			14.5	13.05	0	
Total grid			44.0	39.60	9.79	

specific benefit are unknown while their offer values are carried in the marketplace.

In the case study DG units connected to the grid consist of two biogas engines (DG1 and DG6) which bid at 79 €/MWh three MV wind turbines (DG4, DG11 and DG21) at 81 €/MWh and three small hydro plants (DG8, DG14 and DG29) at 86 €/MWh. Prices of reactive energy are assumed to be the 80% of those of active energy. The price for active energy acquired by HV grid has been supposed to be 120 €/MWh, equal to the mean marketplace price for peak hours in 2007 increased by an amount covering the transmission costs. The active energy sold to the HV grid, instead, is assessed at 100 €/MWh.

B. Grid optimization, with the highest DG penetration level

The following results are obtained considering the maximum line current equal to lines ampacity and the voltage regulation allowed in the range ±5% around the rated value. The maximum contemporary DG output is fixed in the 95% of the whole power deliverable by DG plants.

The dashed line in Fig. 3 and Fig. 4 show voltage profiles in the initial condition, while continuous profiles refer to the optimized condition.

Even if the voltage profiles are controllable only acting on OLTC regulation, Fig. 5 demonstrates that the initial grid configuration is affected by important line congestions.

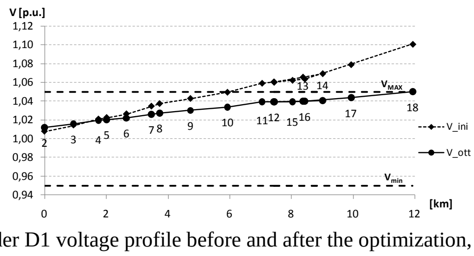

Fig. 3. Feeder D1 voltage profile before and after the optimization, with DG.

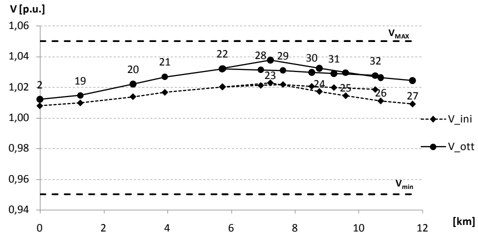

Fig. 4. Feeder D2 voltage profile before and after the optimization, with DG.

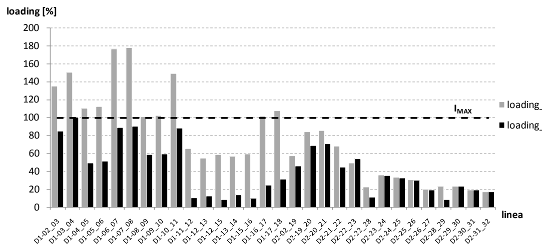

Fig. 5. Lines loading before and after the optimization

In this case, the developed algorithm allows to reduce *SC* from 558.13 €/h to 471.44 €/h, obtaining a sensible curtailment of active losses from 1266.94 kW to 459.98 kW.

Fig. 6. shows as energy prices drop at the terminal buses of D1, where the largest amount of DG is connected, in order to induce consumers to increase their demand or, in a dual way, producers to reduce their output.

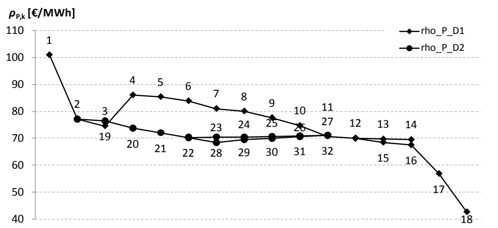

Fig. 6. Active energy spot prices, DG connected to both the feeders

VI CONCLUSIONS

Achieved results permit to demonstrate the technical and economical relevance of this enhanced spot pricing approach, in particular its ability to quantify the cost terms attributable to losses and constraints satisfaction for each network bus.

Moreover the definition of this pricing system, space- and time-varying, could reveal an efficient tool to lead consumers and producers to adopt the most virtuous behaviour aiding to obtain an economical advantage in behalf of the whole distribution system. After a thorough analysis of cost dynamics in the entire MV distribution network, active and passive customers can, at first, identify connection points more economically attractive and then modulate their load or generation schedules to maximize their own economical management. Interesting perspective can be obtained by electrical energy demand participation to the market dynamics [5], easily implementable in the exposed approach.

REFERENCES

[1] J. B. Cardell, “Distributed Resource Participation in Local Balancing Energy Markets”, *Proceedings of the 2007 IEEE Lusanne Power Tech*, 1-5 July 2007.

[2] F. C. Schweppe, M. C. Caramanis, R. D. Tabors and R. E. Bohn, *Spot pricing of electricity*, Boston, Dordrecht, London, Kluwer Academic Publishers, 1988.

[3] M.C. Caramanis, R.E. Bohn, F.C. Schweppe, “Optimal spot pricing: practice and theory”, *IEEE Transactions on Power Apparatus*, vol. PAS-101, n. 9, pp. 100-102, September 1982.

[4] E. Riva Sanseverino, G. Pecoraro, A. Borghetti, M. Bosetti, M. Paolone, “Optimal Operating Point Calculation for Medium Voltage Distribution Systems”, *Proceedings of the 2007 IEEE Lusanne Power Tech*, 1-5 July 2007.

[5] G. Strbac, “Demand side management: benefits and challenges”, *Energy Policy*, vol. 36, n. 12, 2008.