VOLTAGE AND REACTIVE POWER CONTROL PROVIDED BY DG UNITS

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Summary – This paper describes the feasibility of using Distributed Generation (DG) for voltage and reactive power control. The control capabilities of different energy conversion technologies exploited by DG are analyzed and discussed. The benefits for the grid of using such capabilities are evaluated by comparing network performance in several operating scenarios of a real HV distribution network. The adequate control actions to be adopted are identified after solving an optimization problem where the objective is the minimization of the network active losses. The solution of such problem was obtained with an Evolutionary Particle Swarm Optimization algorithm (EPSO).

Keywords: Reactive power, Voltage control, Distributed generation, Optimization

1 INTRODUCTION

Distributed generation (DG), exploiting different kinds of primary energy sources, is achieving increased levels of penetration in High Voltage and Medium Voltage distribution networks. In general, these generation units are not subjected to a centralized dispatch, being allowed to inject in the network active power without any constrain. This does not apply, however, to reactive power production, which is usually restricted by operation rules defined by distribution system operators (DSO).

In Portugal, the present regulations define that, during peak load periods, a penalty should be paid if the reactive power production (capacitive) of DG units is lower than 40% of the produced active power. A penalty should also be paid if the producers supply capacitive reactive power to the network during off-peak load periods.

These rules were defined some years ago, when the level of penetration of DG in distribution networks was still reduced, as a first approach to exploit the benefits of DG. In fact, these generation units were supposed to produce capacitive reactive power near consumers and therefore contributing to decrease grid losses and branch loads. However, the significant growth of DG grid penetration, witnessed in the last years, together with a policy for improving industrial consumer's power factor, lead to occurrence of significant operational

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problems, namely regarding grid overvoltages and reactive power control.
The occurrence of different load levels and the unpredictability of some DG production, namely wind generation, require a new operation philosophy to exploit the reactive power production capability of these units with the objective of optimizing network operation – minimization of losses and fulfillment of technical restrictions for buses voltage and branch load flows. This implies that some DG units should adjust their reactive power production according to the interests of the network, supplying therefore an ancillary service of voltage and reactive power control. To implement such procedure it is necessary to control DG units from the distribution grid dispatching. Since this is not a common practice, some investments in communications and control may become necessary. However, it is expected that the estimated operational efficiency gains can compensate the costs of preparing the system for being capable to deal with this new paradigm.
In this paper the technical advantages and the feasibility of implementing this new operation philosophy are investigated by analyzing the impact of the proposed control procedures in distribution networks. A test system, derived from a real distribution network (fifteen 60 kV buses) with high level of DG integration (several wind parks and mini-hydros), was considered for this purpose. Comparative studies analyzing the present practices and new control procedures were performed in different operating scenarios. The performance evaluation parameters used to assess quality of the operation practices are the active losses, voltage profiles and level of branch congestion.
Identification of control action needs is achieved after solving an optimization problem, where the active losses are minimized subjected to a set of functional and technical constrains. The control variables considered are the reactive power production in DG units, transformers taps and capacitors banks installed in distribution substations. Active power production is not subject to any control.

2 DG TECHNOLOGY

There are different types of DG energy conversion systems. In terms of reactive power generation, these units can be considered as controllable and non-controllable. Non-controllable units are, nowadays, only conventional induction generators without capacitor banks or with only a single capacitor bank, which means not enough flexibility for reactive power control purposes. These generators are mainly used by old or small wind energy conversion systems as well as in some mini-hydros.
Synchronous generators, usually adopted in cogeneration plants and in some mini-hydros, do have reactive power control capabilities.
Modern wind generators are using mainly double fed induction machines and variable speed synchronous units connected to the grid through electronic interfaces [1]. These units provide large reactive power and terminal voltage control capabilities. A set point (in voltage or reactive power) can be defined for the control system of these units in order to control either voltage or reactive power output (capacitive or inductive), provided that its physical operating limits are not violated.

3 PROBLEM FORMULATION

The identification of new operating strategies to improve operation efficiency in distribution grids with high levels of DG integration can be achieved solving an optimization problem. The adopted formulation is an adaptation of the well known optimal reactive power dispatch problem [2][3].

3.1 CONTROL VARIABLES

Control variables of this problem are the reactive power production in DG units, transformer taps (discrete values) and capacitor banks (discrete values) installed in grid substations. In these studies the first set of variables has an increased interest, because the other variables are, at least in some degree, already controllable by the DSO. An example is the on load tap changing performed by transformers to keep bus voltages within a specified interval.

3.2 OBJECTIVE FUNCTION

The objective function adopted aims at the minimization of grid active losses, subjected to a set of functional and technical constrains. This objective is related to an economic benefit, which can be estimated by valuing the loss reduction through the use of an average price for energy at the distribution level.

3.3 CONSTRAINS

Two kinds of constrains are considered: technical and functional. Technical constrains represent operational limits of equipments and other physical limits imposed to system operation. The technical constrains include: a) Voltage limits in all buses (different according to voltage level); b) Power flow limits in lines and transformers; c) Transformers tap ratio limits and d) Capacitors steps limits.

Other kinds of constrains are considered as functional. In these studies, two functional constrains of commercial nature, derived from Portuguese regulation, are also included in the formulation. Such regulation states that the distribution company has to pay a penalty when:

- The reactive power supplied by the transmission grid to the distribution network during the peak load periods exceeds 40% of the total active power flow at the delivery nodes in the same period;
- There is reactive power supplied (capacitive) to the transmission grid during off-peak load periods.

3.4 MATHEMATICAL FORMULATION

Mathematically, the problem described before can then be formulated as a minimization one, where the objective function – OF (X) – describes the grid active power losses. Such formulation can be expressed as:

$$\min \quad OF(\underline{X}) = P_{LOSSES} \tag{1}$$

$$\text{subject to} \quad V_i^{\min} \leq V_i \leq V_i^{\max} \tag{2}$$

$$S_{ik}^{\min} \leq S_{ik} \leq S_{iK}^{\max} \tag{3}$$

$$t_i^{\min} \leq t_i \leq t_i^{\max} \tag{4}$$

$$Q_i^{\min} \leq Q_i \leq Q_i^{\max} \tag{5}$$

$$g(S_{ik}) \;\; S_{ik} \in \{\text{interconnection branches}\} \tag{6}$$

Where:

$\underline{X}$ - Set of control variables (solution of the problem);

V_i - Voltage at bus *i*;

$V_i^{\min}, V_i^{\max}$ - Minimum and maximum voltage at bus *i*;

S_{ik} - Power flow in branch *ik*;

$S_{ik}^{\min}, S_{iK}^{\max}$ - Minimum and maximum power flows in branch *ik*;

Q_i - Reactive power production of generator i;

$Q_i^{\min}, Q_i^{\max}$ - Minimum and maximum reactive power;

t_i - Transformer tap of or capacitor step position;

$t_i^{\min}, t_i^{\max}$ - Minimum and maximum tap;

$g(S_{ik})$ - Functional constrains.

The control variables (solution of the problem) are the reactive power production of each DG unit, the tap position of each transformer and the step of each capacitor bank. The optimization algorithm used to determine the solutions is discussed next.

3.5 OPTIMIZATION ALGORITHM

The solution of the optimization problem described before can be tackled using an optimization motor capable of dealing simultaneously with continuous and discrete variables. In this research a new optimization searching procedure - Evolutionary Particle Swarm Optimization, developed recently [3][5] and presenting excellent performances when dealing with this kind of problems, was used.

The idea behind the Evolutionary Particle Swarm Optimization (EPSO) algorithm is to include an explicit selection procedure that creates a self-adapting mechanism of the properties of the characteristic parameters used in the classical Particle Swarm Optimization (PSO) [4]. This methodology combines the benefits of both PSO and Evolutionary Strategies (ES) to create a more robust algorithm [3][5].

The variables or parameters in an EPSO formulation are divided, according to the vocabulary used in the Evolution Strategies community, in object parameters (the X variables - control parameters of the problem) and strategic parameters (the weights w). The algorithm considers a set of solutions or alternatives that are called particles. A particle is a set of object and strategic parameters [X, w]. The X variables include all the control variables used in the voltage and reactive power control optimization problem, as described in the previous section. Strategic parameters (w) control the behavior of the optimization algorithm.

4 NUMERICAL RESULTS

The benefits of the proposed approach were assessed by comparing different operating conditions in a HV distribution system. For this purpose a comparison between the present practices and the ones that result from the solution of the optimization problem mentioned above was performed for a given set of operating conditions. The quality of the solutions was evaluated through active losses reduction, voltage profile improvement and level of branch flow congestion.

4.1 NETWORK CHARACTERIZATION

The system analyzed is the 60 kV distribution network presented in figure 1. It is a typical HV distribution system, including three connections to the transmission grid, with several HV to MV substations where loads, capacitors and DG producers are connected.

This system is very well suited for this analysis because it has a high level of DG integration, especially hydro generation and wind power, using several kinds of conversion technologies that are representative of the present state of the art. The generators connected to a bus represent a cluster of units connected to the same voltage level of a distribution substation. Table I presents the type of generators connected in each substation and its control capability, as discussed in section 2 (C - controllable and NC - non-controllable).

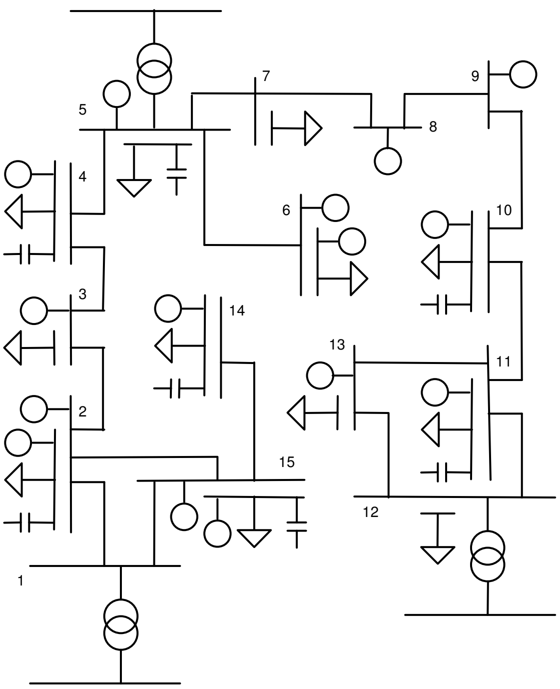

Fig. 1. Single-line diagram of the HV distribution system

TABLE I
DG TECHNOLOGY CHARACTERIZATION

HV Buses		MV Buses	
Substation	Type	Substation	Type
2	C	2	C
3	C+NC	4	C+NC
5	C	6	C+NC
6	NC	10	C
8	C	11	C
9	C	14	C+NC
13	C	15	C+NC
15	C	-	-

The capacitors included are also adjustable by discrete steps. Although HV to MV transformers are not shown in figure 1, they are also considered as well as their taps adjustment capacity.

This system was studied for two initial different scenarios of production and consumption: a) Peak load conditions and b) Off-peak scenario. For each one of these scenarios two situations have been analyzed: I) Initial scenario and II) Adjusted scenario where reactive power generation of DG units is used to control the system.

The peak load scenario is characterized by a DG production of approximately 140 MW, which represents about 60% of load. For this initial scenario, as already explained, to avoid penalty payments the reactive power production of the DG units should not be lower than 40% of the active power supplied to the grid. Care should also be taken to avoid reactive power consumption to be larger than 40% of the active power at each transmission interconnection bus.

An off-peak load scenario with 40% of peak load was also studied. The wind DG production level was assumed to be the same and the hydro generation was reduced to 30% of its maximum value, assuming that there is some capacity to modulate production from night to day periods. Due to the high level of DG integration and reduced load, there is almost a power balance in the distribution network. In this case, in order to avoid sending capacitive reactive power to the transmission grid, appropriate set points were defined for synchronous generators. For asynchronous machines it was assumed that they were absorbing reactive power from the grid with a 0.9 power factor value.

4.2 RESULTS OF PEAK THE LOAD SCENARIO

In the peak load scenario the active losses reduction was approximately 16% regarding the situation were the present local reactive power generation rules were followed.

As it can be seen in figure 2, the initial scenario presents high voltage values in substation 6. This is due to the reactive power injected by the wind parks connected to those buses and that exceeds greatly the consumption in that grid area. In the new adjusted scenario a violation persists because voltage at substation 12 increased, but the general voltage profile is more acceptable. After the implementation of the identified control measures, a generalized increase of voltage in HV buses occurs, since this reduces the current for the same power. However, this increase is controlled and the voltage at MV buses, shown in figure 3, is kept within its limits through the HV/MV transformers taps.

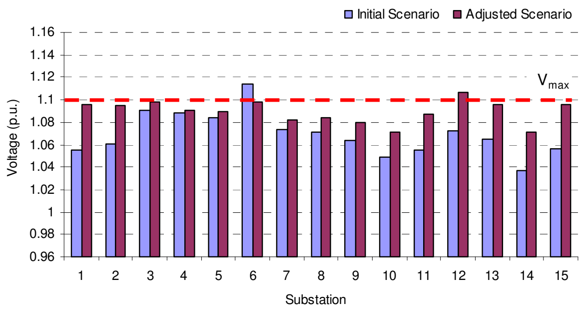

Fig. 2. Voltage at HV buses

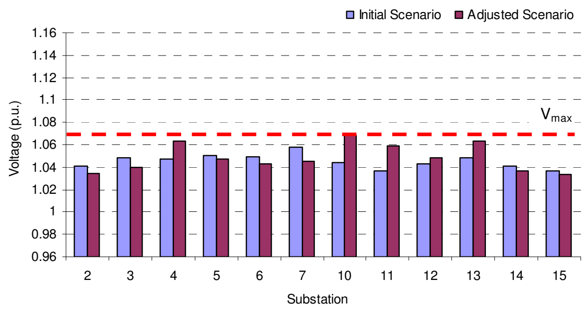

Fig. 3. Voltage at MV buses

The participation of DG in voltage control leads, in general, to a reduction of branch congestion levels, as shown in figure 4. Of course, an increase of power flow is also observed in some branches, but the magnitude of the variation has no significance and always happens in branches lightly loaded. This is indirectly reflected in the losses reduction.

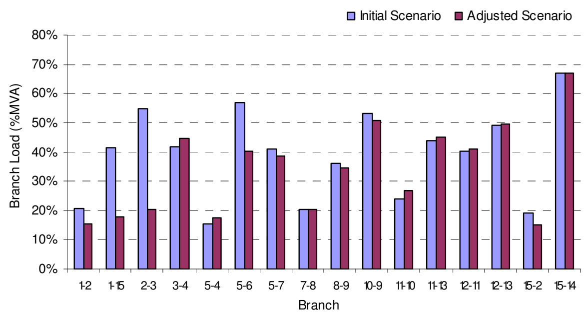

Fig. 4. Line congestion

The control actions that lead to these results can be identified in figures 5 and 6. Analyzing figure 5 it is possible to observe a generalized reduction of reactive power production in distributed generators. The reduction is more significant in buses without local load or with small loads. On the other hand, DG units near significant loads are required to increase its reactive power production. These adjustments in reactive power production, trying to generate it near the consumption and eliminating unnecessary production in distant places, result in a better compensation of load power factor.

The adjustments in reactive power production are performed together with an adequate selection of capacitors steps. Therefore it is possible to identify in figure 6 a similar pattern to the one observed in figure 5 and conclude that capacitors steps were activated to improve the global power factor seen from the HV network. This leads also to a reduction of reactive power flows in the network, contributing in this way to reduce the active power losses and to relief congestion levels of system branches. Transformers taps also operate to maintain the voltage of the MV buses within its limits.

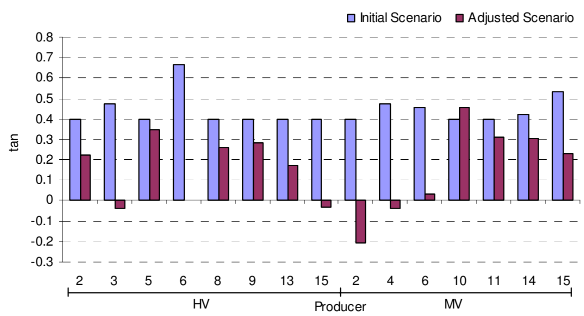

Fig. 5. tan ϕ at DG units

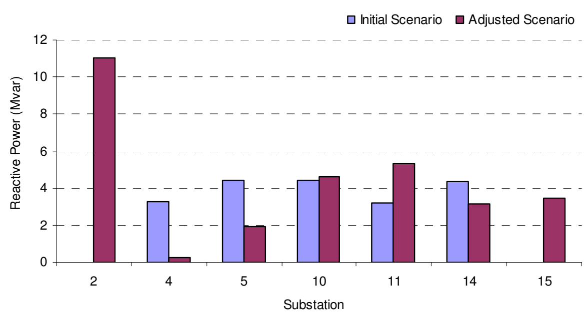

Fig. 6. Reactive power production of capacitors

The functional commercial constrains were not activated in this scenario, since the reactive power absorbed from grid is small or even negative. From these results it is possible to conclude that, in a peak load scenario, the participation of distributed generation in voltage regulation may contribute to improve the efficiency of the network. To assess if the benefits hold for different scenarios, one of extreme low load conditions was also analyzed.

4.3 RESULTS OF THE OFF-PEAK LOAD SCENARIO

The results presented for the peak load scenario have shown that imposing a fixed relation between active and reactive power is not an efficient solution. Allowing DG reactive power generation adjustment according to the network needs can provide significant gains in system efficiency and quality of service.

In fact, for this system it also happens that for the off-peak load scenario a reduction in active losses of 12% was obtained. Figures 7 and 8 also show that voltages are now lower than in the peak scenario and do not increase significantly in the adjusted scenario.

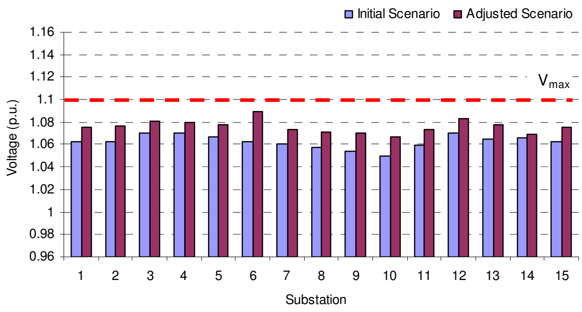

Fig. 7. Voltage at HV buses

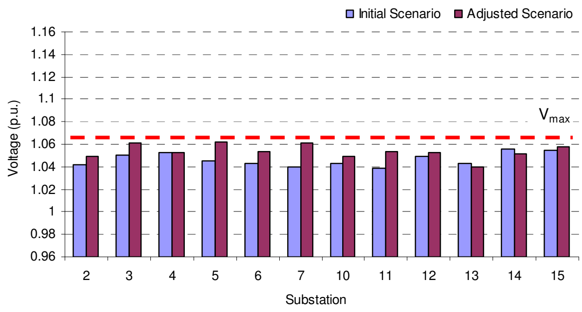

Fig. 8. Voltage at MV buses

This happens because the limiting constrain is, for this scenario, associated to the tan ϕ at the interconnection substations between the transmission grid and the distribution network. This is shown in figure 11, where active and reactive power flows from the transmission grid to the distribution network (positive flows), and the corresponding tan ϕ are presented. Only a small amount of reactive power is absorbed in substation 1 and no reactive power is imported from the transmission grid through the other substations. In this figure it is also possible to observe that active power is absorbed in substation 12 and supplied to the transmission grid in substations 1 and 5. For this scenario the congestion relief is not significant.

Transformers taps are adjusted to decrease voltage in MV buses and maintain them within its limits. However, a large number of transformers keep their original tap position, due to small variations of voltage at HV buses.

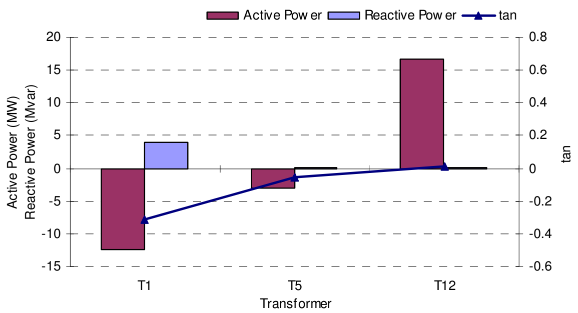

Fig. 9. tan ϕ at the connections to transmission grid

It can also be observed that in this case the action of some of the DG units is the opposite of the one performed for peak load scenario. Since there are now a great number of asynchronous machines absorbing reactive power, some compensation is needed.

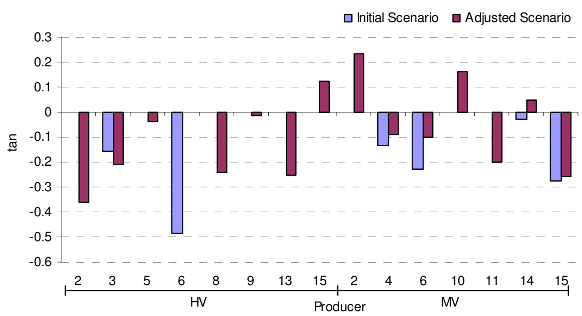

Fig. 10. tan ϕ at DG units

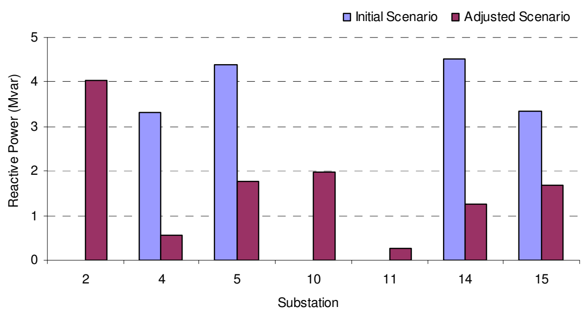

Fig. 11. Reactive power production of capacitors

These studies have shown that the participation of DG in voltage and reactive power control can contribute to improve significantly the operation efficiency of distribution networks. Namely by reducing losses, improving voltage profiles and relieving branch flows. These benefits are more significant for high load levels but also occur for lower load scenarios. Figure 12 summarizes the results in terms of active losses.

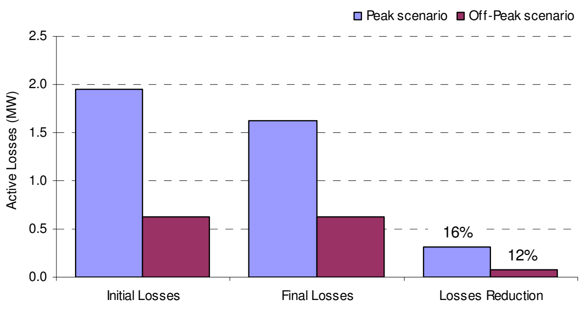

Fig. 12. Active losses balance

5 CONCLUSIONS

In this paper the effectiveness of the use of DG units to improve system operating conditions through the control of its voltage and reactive power generation was presented and discussed. A real HV distribution system with a large DG penetration level was used to assess the technical benefits that result from the use of this control strategy regarding the present operation rules followed in Portugal. The implementation of this approach requires, however, some additional measures:

- Identification of technical requirements and costs associated to the implementation of a simple and costless communications infra-structure capable of producing a dialog between the DSO dispatch centers and the DG units;
- Development of new DMS tools capable of defining the required control measures in an on-line environment;
- Introduction of changes in the legislation to allow additional remuneration for the ancillary services of voltage and reactive power control provided by DG units.

From the obtained results, one can conclude by the existence of clear benefits in the use of DG to help improving system operating conditions, namely losses and voltage profiles.

6 ACKNOWLEDGMENT

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