Voltage Control Algorithm for Distribution Systems with Distributed Generation

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Abstract — **This paper proposes an automatic voltage control method for distribution networks using distributed generators connected to the grid in order to maintain voltage levels and to provide reactive power. This method consists in exchanging information within a two-layer hierarchical control structure. The first one is the local control, responsible for monitoring each generator operating conditions. The second one is the central control, responsible for providing the appropriate setpoints to each local control with an algorithm based on the sensitivity theory. This method is based on a sensitivity theory that chooses the generator which will cause the major impact on the network voltage profile when changing its reactive power injection. In order to test the proposed method, the authors implemented the IEEE 13-node test feeder in the Real Time Digital Simulator at Escola Politécnica da Universidade de São Paulo - Brazil.**

Index Terms-- **Automatic control, Distributed power generation, Sensitivity analysis, Smart grids, Voltage control.**

I. Introduction

The growth and the importance that distributed generation (DG) will represent in the electrical systems in the world is undoubted. Some reasons for this expansion are society pressure against the environmental impacts caused by large generation centers, the search for customers' energy independence and recently, incentives to renewable sources and small energy producers [1].

With this notable expansion, energy distributors have worried about it and DG consequences [1]. Some of them can be easily identified, such as the changes in the power flux direction, the increase in short-circuit levels and variations in energy quality.

In addition, recently, several discussions about smart grids are taking place. The concept of smart grids takes into account the evolution of the current distribution networks to grids with advanced communication, automation, capacity of auto recovery and everything else related to better energy supply [2]. With the DG growth and the search for intelligent grids, both will certainly be jointly used in a near future [3].

In this context, DG can play an important role in the improvement of operation and reliability of energy supply with ancillary services, which are those related to keeping the good operation of the system, and are not related to the active power injected in it [4]–[6].

A very important service that can be explored is the voltage regulation of the network which is directly connected with the losses in the feeder. It is well known that, if load and generation are near, lower losses and voltage drops are observed. This can be used for active and reactive currents, which means that DG can supply not only active, but reactive power as well. Note that in conventional medium voltage feeders, in which the resistances of cables are not suppressed, the injection of active power increases the voltage level in the system [7]. Thus, the generator should also absorb reactive power in order to prevent high voltages in the system.

Nowadays, voltage regulation in distribution feeders occurs by changing the tap of substation's transformers and capacitor banks [7], [8]. With generators installed along the grid, these devices can help maintain a uniform voltage level.

In addition, most of these conventional methods of voltage control present long response time. With the increase of embedded generation units and effective participation of customers in the grid operation, the electrical networks will need faster control methods in order to keep the reliability of operation and quality in energy supply.

In smart grids studies, automatic voltage regulation is a topic of much interest and presents a lot of challenges to its implementation, mainly because of investments in advanced communication, automation and control systems [2], [3], [5]. In the last few years, some works about this topic have been published [9]–[14].

The proposed control method used herein is based on a hierarchical structure of control for automatic voltage regulation. The algorithm is based on the reference [12] and is an application of the sensitivity theory. However, some improvements were adopted in both control structure and mathematic equations, in an attempt to approximate the scenario of smart grids.

In sum, the objective of the method is to indicate the generator that, when changing its reactive power injection, causes the highest impact on a node that presents a non-desirable voltage level.

With the growth of embedded generation, high flux of information, need for grid real time monitoring and keeping the service quality, the simple formulation of the proposed algorithm and the facility of computational implementation very well fits the context of smart grids.

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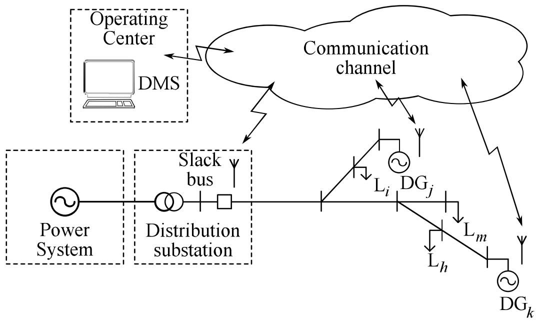

Figure 1. Proposed control system

II. PROPOSED CONTROL SYSTEM

The proposed control system follows a hierarchical structure based on two levels: the local level and the central one. The first is responsible for monitoring each generator operating conditions and for producing data to exchange with the central control level.

The central one is part of a Distributed Management System (DMS) and is responsible for receiving all the information from each local control to appropriately choose the generator that may change its reactive power injection in order to keep the grid voltage level under acceptable levels. If available, other information about equipment status installed along the grid may improve the control actions (e.g the state of reclosers and switches that may change the electrical topology of the grid).

The communication between both layers of control is illustrated in Fig. 1. Note that the reliable control operation is associated with an electric grid with high communication, control and automation devices. The two components of the control system will be explained in detail in the following section.

A. Local Control

The local level is installed with distributed generators. This layer is responsible for:

- Monitoring each generator operating conditions;
- Ensuring the change in reactive power of each generator; and
- Informing the central control the voltage values at the bus to which each generator is connected, the reactive power injected at each bus and amount of reactive power available.

The local control is much similar to the voltage regulators and governors of synchronous machines [7], and also to the strategies used to control electronic inverters that connect most renewable sources [15].

B. Central Control

The central control level is responsible for monitoring the whole electric grid, as part of the DMS. It processes the algorithm that chooses the generator that must change its reactive power in order to maintain the voltage levels of a certain distribution network under desirable conditions.

The mathematical algorithm is based on sensitivity theory presented in [12], and it considers only the absolute values of voltage at the nodes to which the DG is connected. The algorithm uses equation (1) to determine which generator must change its reactive power.

$$[\Delta V] = \underbrace{\left[S_p\right]\times[\Delta P]}_{\left[T_{sp}\right]} + \underbrace{\left[S_q\right]\times[\Delta Q]}_{\left[T_{sq}\right]} \tag{1}$$

Where:

$[\Delta V]$: array of bus voltage variations;

$\left[S_p\right]$: matrix of active sensitivity terms;

$[\Delta P]$: array of active power variations;

$\left[S_q\right]$: matrix of reactive sensitivity terms;

$[\Delta Q]$: array of reactive power variations

Expression (2) describes the sensitivity terms that comprise [Sp] and [Sq]. These terms relate the voltage variations at every node of the distribution network with variations in the active and reactive power supplied by generators.

$$\frac{\partial E_i}{\partial P_j} \text{ and } \frac{\partial E_i}{\partial Q_j} \tag{2}$$

Where

E_i : voltage magnitude at bus i;

P_j : injected active power at bus j;

Q_j : injected reactive power at bus j;

The sensitivity terms can be obtained using equations (3) and (4). For high voltage grids, these terms are well known, as in [16].

$$\frac{\partial E_i}{\partial P_j} = -\frac{1}{E_n}\cdot\left[\sum_{hk\in PT_{i,j}} R_{hk}\right] \tag{3}$$

$$\frac{\partial E_i}{\partial Q_j} = -\frac{1}{E_n}\cdot\left[\sum_{hk\in PT_{i,j}} X_{hk}\right] \tag{4}$$

Where:

$PT_{i,j}$: common path between bus i, j, and the slack bus;

E_n : rated phase-to-neutral voltage;

R_{hk} : total resistance of $PT_{i,j}$;

X_{hk} : total reactance of $PT_{i,j}$;

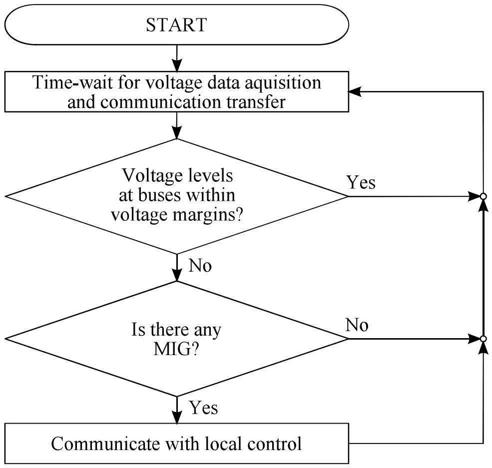

Figure 2. Central control flowchart.

Both terms of (1) can be expressed as in (5) and (6).

$$\left[T_{sp}\right]=\begin{bmatrix} \frac{\partial E_1}{\partial P_1}\cdot\Delta P_1 & \frac{\partial E_1}{\partial P_2}\cdot\Delta P_2 & \cdots & \frac{\partial E_1}{\partial P_j}\cdot\Delta P_j \\ \frac{\partial E_2}{\partial P_2}\cdot\Delta P_1 & \frac{\partial E_2}{\partial P_2}\cdot\Delta P_2 & \cdots & \frac{\partial E_2}{\partial P_j}\cdot\Delta P_j \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial E_i}{\partial P_1}\cdot\Delta P_1 & \frac{\partial E_i}{\partial P_2}\cdot\Delta P_2 & \cdots & \frac{\partial E_i}{\partial P_j}\cdot\Delta P_j \end{bmatrix} \tag{5}$$

$$\left[T_{sq}\right]=\begin{bmatrix} \frac{\partial E_1}{\partial Q_1}\cdot\Delta Q_1 & \frac{\partial E_1}{\partial Q_2}\cdot\Delta Q_2 & \cdots & \frac{\partial E_1}{\partial Q_j}\cdot\Delta Q_j \\ \frac{\partial E_2}{\partial Q_2}\cdot\Delta Q_1 & \frac{\partial E_2}{\partial Q_2}\cdot\Delta Q_2 & \cdots & \frac{\partial E_2}{\partial Q_j}\cdot\Delta Q_j \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial E_i}{\partial Q_1}\cdot\Delta Q_1 & \frac{\partial E_i}{\partial Q_2}\cdot\Delta Q_2 & \cdots & \frac{\partial E_i}{\partial Q_j}\cdot\Delta Q_j \end{bmatrix} \tag{6}$$

Equations (1), (5) and (6) allow finding the generator j that produces the major voltage variation at bus i. This generator is called Major Influence Generator (MIG). In this context, the central control is responsible for finding the MIG and for communicating with its local control, in order to change its reactive power dispatch. Fig. 2 illustrates this procedure.

C. Proposed Modification and Integration to the Grid

According to equation (1), the voltage variation at bus i due to a variation in the active and reactive power supplied by generator j is described in equation (7). Considering that it is more interesting to vary only the reactive power, the first term of equation (7) is null.

$$\Delta V_i=\frac{\partial E_i}{\partial P_j}\cdot\Delta P_j+\frac{\partial E_i}{\partial Q_j}\cdot\Delta Q_j \tag{7}$$

In reference [12], when the central control requires the MIG to vary its reactive power dispatch, it sends the MIG

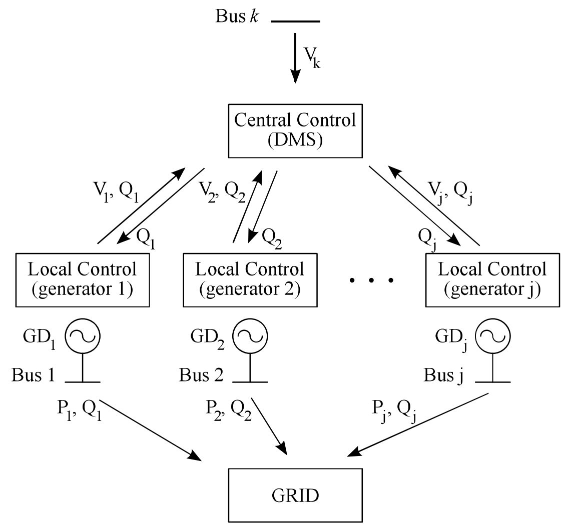

Figure 3. Integration between controls and the grid.

local control, via communication channels, new setpoints responsible for maintaining the reactive power at its rated value, providing the maximum reactive power dispatch. In this present work, the authors propose to use an iterative central control method that starts setting the local control setpoints of the MIG to maintain only part of the rated values. At each step, the algorithm recalculates the sensitivity terms in order to determine if it is possible to use other generators to improve the voltage profile of the distribution, instead of relying only one generator.

This procedure uses an adjustable factor k that controls the amount of reactive power required to maintain the voltage levels of the distribution network under acceptable levels. Therefore, it is possible to rewrite equation (7) as in

$$\Delta V_i=\frac{\partial E_i}{\partial Q_j}\cdot k\cdot\left(Q_{rated,j}-Q_j\right) \tag{8}$$

Where:

$Q_{rated,j}$: maximum reactive power of generator j;

Q_j : actual reactive power of generator j;

k : adjustable factor.

The integration of both local and central control is depicted in Fig. 3.

III. SIMULATION TESTS AND RESULTS

This section describes the distribution network and the simulation tests used to evaluate the control methods described in section III.

As briefly mentioned in the abstract, the simulations were performed using the Real Time Digital Simulator (RTDS) from University of São Paulo, Brazil. Therefore, it was possible to test the behavior of the method in real time, with regards to operating conditions that were deliberately changed.

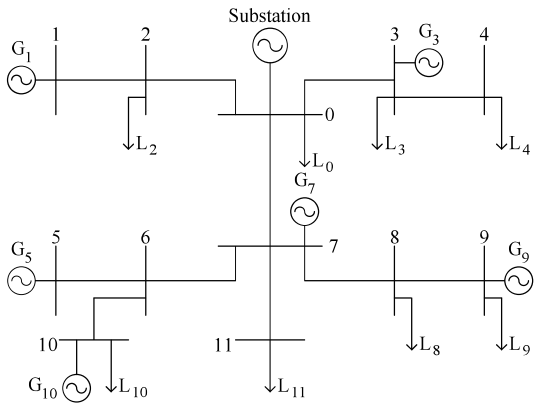

Figure 4. Network implemented in the RTDS.

The RTDS is a simulator designed specifically to simulate electrical power systems, and the related protective and control devices and algorithms using electrical and control blocks. It allows researchers to test the dynamic behavior of these systems, and also to include physical equipment in hardware-in-loop simulations.

A. Distribution Network Modeling

The distribution network used in the simulations is based on the system described in [17], and it is depicted in Fig. 4. It consists of a thirteen-bus distribution network, with a voltage level of 13.8 [kV] and different loads connected to the buses, which were modeled as constant power. The authors decided to convert this distribution network to an equivalent balanced one in order to simplify the real time implementation; however, it is possible to adapt the proposed control system to control any kind of electrical network.

Table III presents the positive sequence impedance of all the network branches, Table I presents the power consumption of each load, and Table II presents the active power produced by each generator.

The generation units connected to the buses were modeled using voltage controlled sources with internal reactances that represent the coupling reactances of transformers and the power electronic interface. The dynamic behavior of these sources emulate the dynamic behavior of synchronous generators and their local control was modeled using control blocks of the RTDS. The input of each block is the reactive power setpoint, sent from the central control via an emulated communication channel. Its outputs are line-to-line voltages and angles of each generator. Fig. 5 illustrates the local control function.

The Central Control was modeled as a new component. The inputs of this block are all bus voltages of the electrical system and the permissible reactive power of each generator. The output is the setpoint of reactive power for the MIG.

B. Tests

The distribution network implemented in the RTDS underwent several different tests and the authors observed its behavior and the performance of the proposed control system.

TABLE I. POWER COMSUMPTION PER LOAD.

Load	P(MW)	Q(MVAr)
L_0	4.09	2.17
L_2	6.93	0.99
L_3	0.34	0.21
L_4	0.93	0.44
L_8	7.70	1.71
L_9	0.50	0.38
L_{10}	3.52	1.90
L_{11}	6.26	3.19

TABLE II. ACTIVE POWER PRODUCTION PER GENERATOR

Generator	P(MW)
P_1	5.0
P_3	2.4
P_5	6.0
P_7	3.5
P_9	4.0
P_{10}	4.0

TABLE III. POSITIVE SEQUENCE IMPEDANCE

Branch	R(Ω)	X(Ω)
1-2	0.0075	0.0096
0-2	0.0740	0.0974
0-3	0.1151	0.1474
3-4	0.0212	0.0272
0-7	1.5440	0.8560
6-10	0.2316	0.1284
5-6	0.4825	0.2675
6-7	0.1969	0.1091
7-8	0.8106	0.4494
8-9	1.1194	0.6206
7-11	0.6755	0.3745

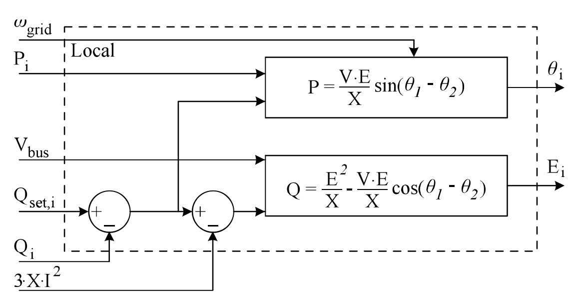

Figure 5. Local control.

The results presented herein are a small part of all the tests and contain details of two cases: generation unit disconnection and load disconnection.

In general, when the central control detects buses with undesirable voltage levels, it chooses the generator capable of correcting this situation, changing its reactive power injection.

[12] proposes a control approach that implies modifying the reactive power setpoint of the MIG to the total amount needed. The authors propose a different control approach that implies making graduate changes in the reactive power setpoint up to the total amount needed, in order to reduce the

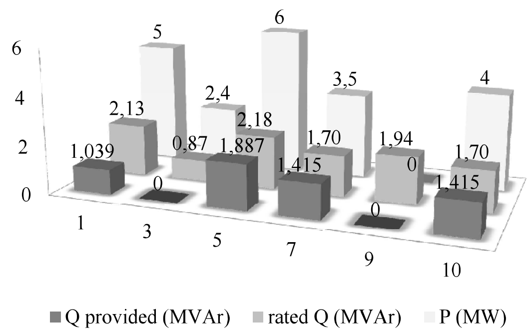

Figure 6. DG9 disconnection – k = 0.2

impact on the grid dynamics due to an abrupt change in its operating conditions.

The authors adopted two different premises for the tests: all the generation units operate under unitary power factor and only one generator acts as MIG. It is worth emphasizing that the stop criteria of the control algorithm is the voltage level at all buses. Adequate values are 0.93 [pu] to 1.05 [pu], in accordance with Brazilian regulatory policies.

C. Generation Unit Disconnection

The test considers the disconnection of generation unit G9 and the control system was observed to perform as desired. When this generator disconnects, some buses present undervoltage (under 0.93 [p.u]).

The proposed control system chooses the generator that may provide the required reactive power, while operating at maximum with no regard to the apparent power. The system provides growing setpoints to the chosen generator using a percentage of what is available, defined by factor k. Considering factor k = 0.2 as an example, the setup of the reactive power of the generator is presented in Fig. 6.

This figure illustrates the amount of active and reactive power available at all generators (rated Q and P), and the reactive power injected after the control action (Q provided). As observed, most generators benefitted from reactive power injection to correct the voltage levels of buses 8, 9 and 11. Table IV presents the voltage profile of these buses after the disconnection of generator G9.

Fig. 7 compares the voltage profiles due to the contingency (disconnection of generation unit G9) to the voltage profiles after the reactive power injection (k = 1 and k = 0.2). The control is sufficient to prevent undesired voltage profiles in both situations.

As mentioned before, this procedure minimizes network abrupt variations. Furthermore, the influence of each generator on providing the reactive power needed is divided, i.e., more generators may act. In any case, the control system operates satisfactorily.

D. Load Disconnection

This test considers the disconnection of load 11. This situation produces a positive variation of the voltage profile downstream bus 7. In this situation, there is an overvoltage at bus 5 (over 1.05 [p.u]). Hence, the control system may act in order to reduce these voltages imposing new setpoints that will make the generators absorb reactive power. The next sections present three different operations of the control system: k = 1, k = 0.5 and k = 0.2.

- Unitary k – as proposed in [12]: only generator G5 receives new setpoints from the control system. After receiving them, the voltage at bus 5 reduces as presented at Table V.
- k = 0.5: only generator G5 receives new setpoints from the control system and absorbs only 50% of the reactive power it is capable of. This single action corrected the overvoltage at bus 5.

Fig. 8 presents the result of the control action. The control

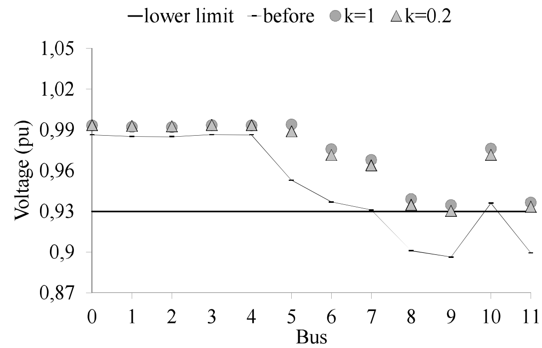

Figure 7. Comparative voltage profiles

TABLE IV. VOLTAGE LEVEL UNDER THE LOWER LIMITS

Bus	Voltage (p.u.)
8	0.9010
9	0.8963
11	0.8994

TABLE V. VOLTAGE AT BUS 5 BEFORE AND AFTER THE CONTROL ACTION

Bus	Before control (p.u.)	After control (p.u.)
5	1.0570	1.0390

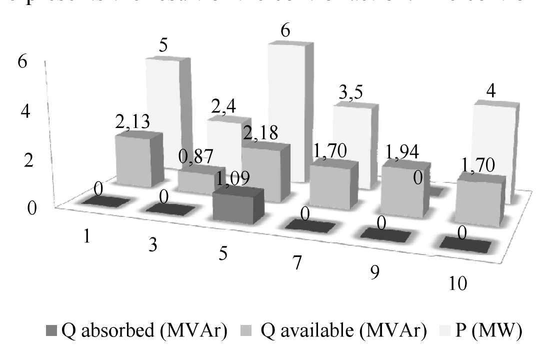

Figure 8. Load disconnection – k = 0.5.

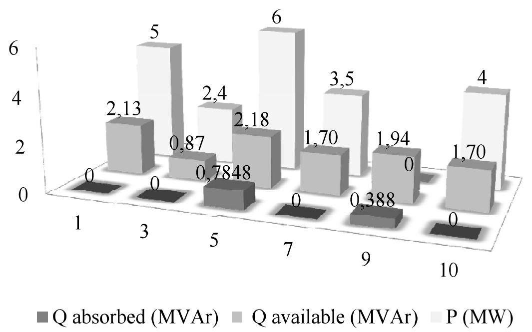

Figure 9. Load disconnection – k = 0.2.

system was verified to provide new setpoints to generator G5 and it was responsible for correcting the voltage levels.

This figure illustrates the amount of active and reactive power available at all generators (rated Q and P), and the reactive power injected after the control action (Q provided).

- k = 0.2: Fig. 9 presents the result of the control action. The control system was observed to provide new setpoints to generators G5 and G9, which were responsible for correcting the voltage levels.

This figure illustrates the amount of active and reactive power available at all generators (rated Q and P), and the reactive power injected after the control action (Q provided).

The control system can be concluded to be effective. Comparing to the unitary k approach, the proposed approach may be more advantageous considering aspects already discussed.

IV. CONCLUSIONS

This paper presented a control system for distribution systems with distributed generation and is based on reference [12]. The control system is based on a hierarchical control (local control and central control) and it was fully implemented in the RTDS. Both controls communicate with each other under this scenario and they proved to be effective in their objectives.

As presented in section IV, the proposed control system differs from the one presented in [12] as it considers making graduate changes in the reactive power setpoints (from the actual ones up to the total amount needed), in order to reduce the impact on the grid dynamics, and to add more generators in cooperative mode.

Considering the results presented herein, the control system was fully capable of correcting the voltage profiles during contingencies, such as generator(s) or load(s) disconnections. It acts independently of the operators' decisions, addressing smart grids conceptions.

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