INNOVATIVE VOLTAGE REGULATION METHOD FOR DISTRIBUTION NETWORKS WITH DISTRIBUTED GENERATION

Stefania CONTI
DIEES, University of Catania – Italy
sconti@diees.unict.it

Andrea Maria GRECO
DIEES, University of Catania – Italy
angreco@diees.unict.it

ABSTRACT

The presence of a significant distributed generation (DG) capacity in distribution networks would result in some conflicts with present system operation criteria, mainly because, unlike the meshed transmission system, the distribution system is usually designed as a "passive" radial system, which is conceived with neither generators operating in parallel nor power flow control. The present paper deals with voltage regulation issues in MV distribution networks connecting DG systems and proposes a new voltage control method that allows to avoid typical under/overvoltages occurring when distributed generators are operated in parallel to the network. The advantages of the innovative regulation procedure are due to a direct involvement of DG and to the possibility to be harmoniously integrated with the present Italian network control systems. The presented work is part of a research project conducted by the authors in collaboration with ENEL Distribuzione S.p.A. (which is the major Italian distribution operator).

INTRODUCTION

Under the influence of political, economical and technical factors, distribution networks tend to become "active" systems, i.e. based on a wide use of electronic and information technologies that allow to appropriately modify and control network operating criteria to account for the presence of distributed generation (DG) [1]. It is known that the integration of DG into distribution networks involves many technical problems, most of which are still to be solved in order to guarantee a reliable and economic service to customers [2]. The present work deals with voltage regulation issues in MV distribution networks connecting DG and proposes a new control method that allows to maintain voltage within the standard limits, established by norm EN50160, avoiding under/overvoltages potentially caused by DG connection [3],[4].

It is worth to highlight that, in Italy, during the last years, management of MV distribution networks has yet undergone substantial changes to improve service quality. In particular, a MV network Telecontrol System (MV-TS) has been established to extend remote control functions, typical of HV systems, to the MV protection devices. However, in order to increase DG penetration other work is still to be done. In this framework, the present paper proposes a control logic for voltage regulation that integrates itself into the present control systems (whose hardware and software are to be appropriately adapted) and involves DG in the innovative regulation procedure.

In practice, the idea is to employ the hardware platform currently used by *ENEL Distribuzione S.p.A.* and to add new functions to the regulation board (used to control the on-load tap changer - OLTC - of distribution transformers), such as automatic switching between "constant voltage" and "voltage drop compensation" control modes. The control procedure involves the connected DG systems by adjusting their reactive power while maximising the active power output. After the occurrence of critical operating conditions, typically characterised by under/overvoltages, it is possible to restore the normal state by means of a coordinated control of transformers tap position, transformer voltage regulation mode and generators reactive power output.

The presented work is part of a research project conducted by the authors in collaboration with *ENEL Distribuzione S.p.A.*

VOLTAGE REGULATION ISSUES IN MV DISTRIBUTION NETWORKS WITH DG

In traditional distribution networks voltage regulation typically relies on the action of the OLTC of the HV/MV primary substation (PS) transformer and on the off-load choice of an appropriate tap position for the MV/LV secondary substation transformers. In Italy, for example, two voltage control mode are possible with regard to the control actions performed on primary substation transformers:

- "line drop compensation" control mode, called *SP1 mode* (described in the following);
- "constant voltage" control mode, called *SP2 mode*, which keeps constant the voltage at the MV transformer busbars.

The control action, commonly based on *SP1 mode*, is performed by an Automatic Voltage Regulator (AVR), providing a line drop compensation (LDC) which dynamically modifies the reference voltage set point of the OLTC to maintain the voltage profile of each feeder within a voltage range imposed by power quality standards (Norm EN50160).

In particular, node voltage variations are to be kept within a range whose limits are given by $\pm s \cdot V_n$, where V_n is the system nominal voltage and s is, typically, 0.1 p.u.

The OLTC control is based on a local measurement of transformer secondary current, feeder sending-end current and MV bus-bar voltage. Further, the OLTC control modifies the MV bus-bar voltage V_i according to the following equation:

$$V_i = V_P + R \cdot I_T \tag{1}$$

where:

- V_i is the MV bus-bar voltage;
- V_P is the program voltage, chosen by the distribution operator;
- R is a compensation parameter;
- I_T is the transformer secondary current.

The evaluation of the regulation parameters (V_P, R) is based on forecast of the voltage profiles associated to maximum

and minimum feeders load conditions. This method relies on the fact that the voltage profile decreases along the feeder and that the feeder voltage drop is proportional to the load currents that flow along the feeders. In practice, the regulation parameters are chosen under the assumption that the feeder is "passive".
In fact, without grid-connected DG units, maximum and minimum voltage profiles are well predictable and power always flows from the PS to downstream feeders sections; further, maximum and minimum voltage values occurs, respectively, at the sending-end and the receiving-end of lines.
On the other hand, in presence of DG, which is, typically, neither centrally planned nor dispatched, the voltage profiles are no more predictable because they are strongly influenced by a number of aleatory factors such as power rating, operating conditions and position of the generators, load distribution, etc. [3], [4]. Moreover, the presence of DG determines a reduction in the equivalent load "seen" by the HV/MV transformer.
In conclusion, connection of DG invalidates the basic simplifying hypotheses used by traditional distribution planning.

THE PROPOSED VOLTAGE CONTROL AND ITS NUMERICAL SIMULATION

In order to overcome the above cited problems, a new control system for voltage regulation in distribution networks will be presented. As previously said in the introduction section, the main advantages of the proposed regulation procedure are due to the direct involvement of DG in the control method and the possibility to be harmoniously integrated with the present voltage control and the MV-TS, whose hardware and software are to be appropriately adapted.
Considering the amount of DG capacity presently allowed in Italian distribution networks, in order to quantify the effects that a greater DG penetration would cause on present voltage regulation systems, the authors performed the analysis of a real network that is operated in Sicily by *ENEL*. Numerical simulations carried out by means of the software *DIgSILENT Power Factory®* have been performed to integrate experimental data, to analyze critical network operating conditions and to show the operation of the proposed voltage control.

Control Algorithm

The proposed voltage regulation method is based on the monitoring and control actions reported in the flow chart of Fig. 1. The inputs for the algorithm are provided by the System Data Base (SDB), which contains information on the network structure, and by the MV-TS, which provides real time operating data. The outputs are the coordinated control actions to be performed on: transformers OLTC position, transformer voltage regulation mode and generators reactive power output.
"Network State" block represents the acquisition of the input data. As for real time operating data, the supplied information is:

- MV busbars voltage of the HV/MV transformer;
- secondary current of the HV/MV transformer;
- feeders sending-end currents;
- network components state (transformers, circuit breakers, switches, etc.);
- OLTC position.

Further, Peripheral Units (PUs), installed in appropriate customer/producer's and distributor's secondary substations (SSs), send the following information to the control system:

- local generators on/off state;
- value of net current supplied/drawn by the SSs;
- value of feeder current measured between consecutive SSs equipped with PUs.

As for distribution system structure data, the required information is:

- network physical structure;
- electrical network parameters (line impedance and current carrying capacity);
- feeder typology (cable or uninsulated conductors, overhead or underground lines);
- AVR parameters used by the regulation law;
- generators characteristics (characteristic parameters, loading capability diagram, etc.).

"State Variation" block includes evaluation procedures of change of network operating conditions related to:

- local generators on/off switching;
- feeder breakers opening/closing;
- manual or automatic operation of HV/MV transformer protections.

"Data Acquisition for Network Analysis" block represents the acquisition of the current values measured by the sensing devices installed at the producers'. Information on feeders state variation is also supplied. The gathered data are used to perform a *dynamic load flow* on the network or on limited portions of it. This allows to calculate feeders voltage profiles in order to verify whether allowed voltage limits are exceeded or not.
The presence of a critical profile is evaluated in the "Critical State" block.
We consider as "critical" a feeder in which one or more node voltages are approaching the limit values (V_{inf} or V_{sup}). In practice, the control actions start when voltage reaches, respectively, the lower limit $V_{\inf} + \Delta V$ or the higher one $V_{\sup} - \Delta V$, where ΔV defines the tolerance band. Voltage variation speed is also accounted for.
The following steps represent control actions related to the specific critical states, which can be present in more feeders at the same time.
As previously said, the control actions can be summarised in the change of transformers OLTC position, of transformer voltage regulation mode and, when necessary, even of generators reactive power output. These actions can be appropriately combined together.
"Generators Reactive Power Variation" block has the following functions:

- acquisition of information made available by "Network State" block on present network configuration;
- voltage sensitivity analysis of network nodes with respect to reactive power injection [5];
- sending the changed reactive power reference values to the concerned generators.

Network monitoring actions during normal operating conditions are performed by the "Operating Conditions Check" block, which looks after those feeders where critical states are likely to occur.

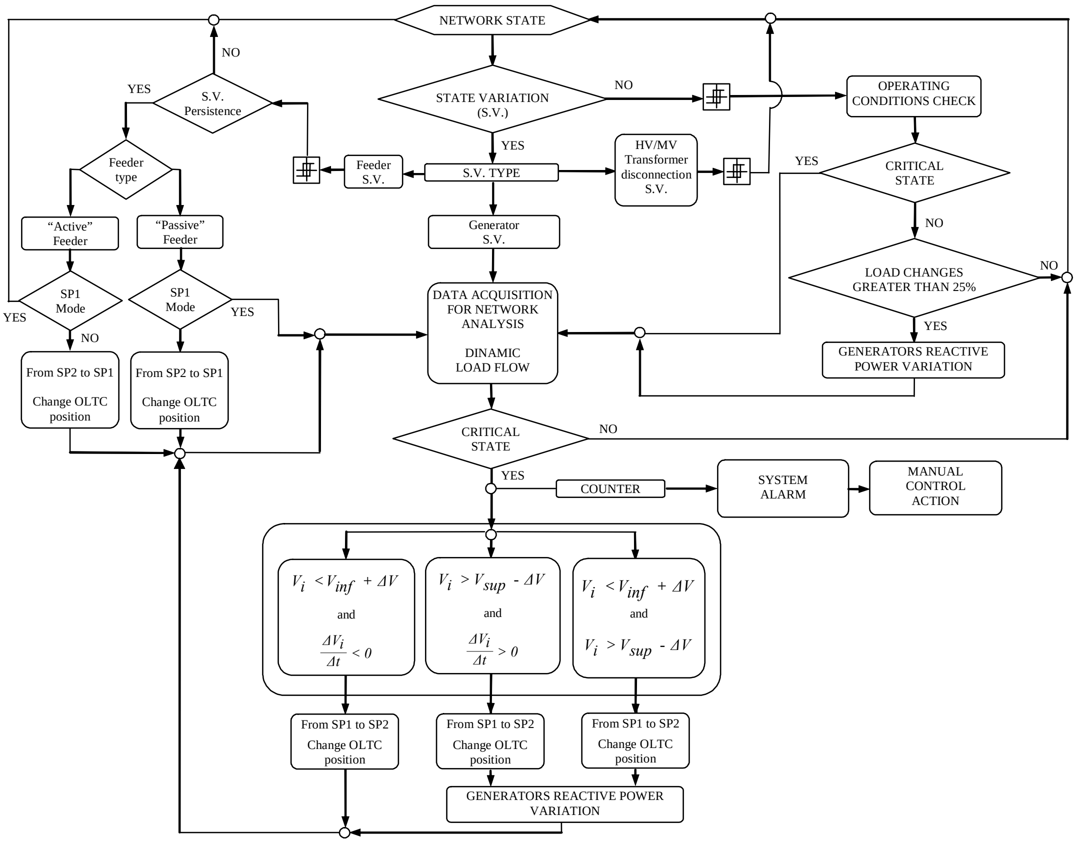

Fig. 1. Flow chart of the voltage control algorithm.

Seldom, the algorithm could require an excessively high number of cycles (counted up by "Counter" block) to find the control solution that avoids the occurrence of critical states in networks. To account for this possibility, "Manual Control Action" block represents the human operator intervention to solve the problem.

Network numerical implementation and simulation

In the following we will describe the network used to illustrate the preliminary study summarised in the second section and to show the operation of the proposed voltage control system. As said before, numerical simulations have been carried out by means of the software *DIgSILENT Power Factory®*.

The considered network is a 20 kV radial distribution system managed by *ENEL.* The system is shown in Fig. 2, where the following elements are represented: the HV side of the network, a AVR HV/MV transformer (whose OLTC has a minimum step equal to 1.5 % of the nominal secondary voltage) and four lines characterized by the presence of feeders with different load concentration levels (*high* concentration in feeder *A*, *medium* in feeder *B*, *low* in feeder C). Feeder *D* represents an equivalent load tapped at the MV busbars. Feeder *B* connects a synchronous generator (*DG1*) and feeder *C* connects three synchronous generators (*DG2*, *DG3* and *DG4*).

Data of interest referred to the MV distribution network and DG are reported in Table 1, 2, 3 and 4.

Table 1. HV/MV transformer characteristics.

Transformer rating	25 MVA
Primary/Secondary Voltage	150/20.8 kV
OLTC steps	12×1.5%

Table 2. Network geometrical characteristics.

Feeder	Total Length (km)	Cable Lines (km)	Uninsulated Overhead Lines (km)	Feeder section variation (mm^2)
A	17.23	7.63	9.60	3x(1x50) ÷ 3x(1x120)
B	4.30	4.30	---	3x(1x95) ÷ 3x(1x185)
C	20.37	---	20.37	3x(1x35) ÷ 3x(1x150)

Table 3. Overall apparent power of SSs supplied by each feeder.

Location	Apparent Power (kVA)	Maximum load factor (MLF)	Minimum load factor (mLF)
Feeder *A*	6,285	0.55	0.15
Feeder *B*	3,360	0.7	0.12
Feeder *C*	6,310	0.4	0.1
Feeder *D*	700	0.6	0.2

Table 4. Characteristics of the synchronous generators.

	Apparent power (MVA)	Power Factor	Neutral grounding
DG1	4.9	0.90	isolated
DG2	4.9	0.90	isolated
DG3	4.9	0.90	isolated
DG4	4.9	0.90	isolated

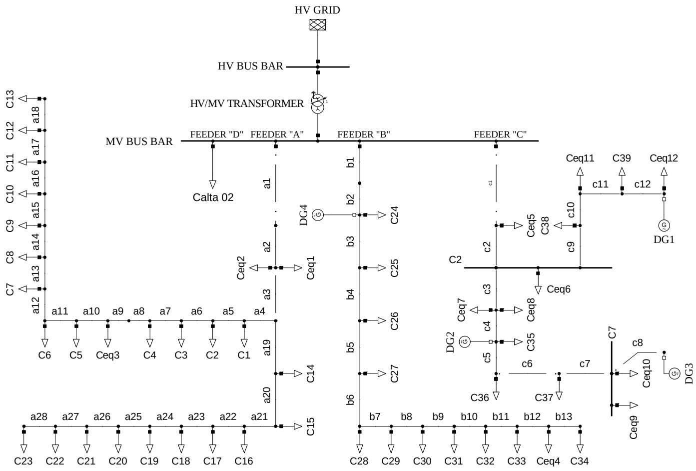

Fig. 2. MV distribution network model.

The case in which critical states occur on feeders ***A*** (*undervoltage*) and ***C*** (*overvoltage*) with traditional LDC regulation method has been observed. Simulations showed that the operation of the proposed voltage regulation procedure maintains the feeders voltage profiles within the allowed voltage range. For the sake of concision, it is not possible to show the operation of the proposed voltage control system by means of the graphical outputs of the simulations performed. However, significant data will be concisely illustrated in the Table 5.

Table 5. Data on operation of the proposed voltage control.

<table>
<tr><th colspan="3"></th><th colspan="2">Without proposed control</th><th colspan="2">With proposed control</th></tr>
<tr><td rowspan="4">Feeder A</td><td colspan="2">Feeder loading condition</td><td colspan="2">(MLF * 6,310) MVA</td><td colspan="2">(MLF * 6,310) MVA</td></tr>
<tr><td colspan="2">Loads PF</td><td colspan="2">0.9</td><td colspan="2">0.9</td></tr>
<tr><td colspan="2">MV busbars voltage</td><td colspan="2">1.000 p.u.</td><td colspan="2">1.005 p.u.</td></tr>
<tr><td colspan="2">Feeder Voltage Profile</td><td colspan="2">Voltage range: 20,000 ÷19,020 V (near to undervoltage)</td><td colspan="2">20,197 ÷19,212 V</td></tr>
<tr><td rowspan="8">Feeder C</td><td colspan="2">Feeder loading condition</td><td colspan="2">(MLF * 6,285) MVA</td><td colspan="2">(MLF * 6,285) MVA</td></tr>
<tr><td colspan="2">Loads PF</td><td colspan="2">0.9</td><td colspan="2">0.9</td></tr>
<tr><td rowspan="4">DG power</td><td></td><td>P (MW)</td><td>Q (MVAR)</td><td>P (MW)</td><td>Q (MVAR)</td></tr>
<tr><td>DG1</td><td>2.00</td><td>0.97</td><td>2.00</td><td>0.406</td></tr>
<tr><td>DG2</td><td>1.50</td><td>0.73</td><td>1.50</td><td>0.305</td></tr>
<tr><td>DG3</td><td>2.00</td><td>0.97</td><td>2.00</td><td>0.406</td></tr>
<tr><td colspan="2">MV busbars voltage</td><td colspan="2">1.000 p.u.</td><td colspan="2">1.005 p.u</td></tr>
<tr><td colspan="2">Feeder Voltage Profile</td><td colspan="2">Voltage range: 20,000÷21,180 V (overvoltage)</td><td colspan="2">20,197÷21,021 V</td></tr>
</table>

CONCLUSIONS

The paper presented an innovative voltage control method for MV distribution networks that allows to maintain feeder voltage profiles within the standard limits, established by norm EN50160, avoiding under/overvoltages potentially caused by DG connection.

The new voltage control system integrates itself with the present distribution network control systems, i.e. voltage regulation and MV telecontrol systems, and involves DG in the proposed procedure.

The characteristics of the proposed control logic minimize the implementation costs, since the data required by the voltage control algorithm can be obtained by using the present monitoring and communication system employed by the MV-TS, which, almost always, has enough acquisition points in the power network. Extension of this system, if necessary, could also be possible in a relatively easy way by adding some devices that have been tested and used by the distribution operator yet. In fact, for example, the current measures can be performed by means of devices, called RGDAT (Italian acronym for *directional fault and lack of voltage detectors*), which are presently installed in *ENEL* distribution networks.

ACKNOWLEDGMENTS

The authors would like to thank C.S. Tosto and S. Giamboi (*ENEL Distribuzione S.p.A.*, Italy) for their valuable contribution to the development of the research project.

REFERENCES

[1] European Technology Platform “Smart Grids”, http://ec.europa.eu/research/energy/index_en.htm.

[2] N. Jenkins, R. Allan, P. Crossley, D. Kirschen, G. Strbac, *Embedded Generation*, The Institution of Electrical Engineers, London, 2000.

[3] S. Conti, S. Raiti, G. Tina, 2003, “Small-Scale Embedded Generation Effect on Voltage Profile: an Analytical Method”, *IEE Proc. on Generation, Transmission and Distribution*, Vol. 150, No. 1, pp. 78-86.

[4] S. Conti, S. Raiti, G. Tina, U. Vagliasindi, 2003, “Integration of multiple PV units in urban power distribution systems”, *Solar Energy*, Vol. 75, pp. 87-94.

[5] S. Conti, A. M. Greco, S. Raiti, 2006, “A Simplified Approach to Voltage Sensitivity Analysis in Radial LV and MV Distribution Networks”, *WSEAS Transactions on Power Systems*, Issue 11, Vol. 1, pp. 1837-1843.