MV NETWORK WITH DISPERSED GENERATION: VOLTAGE REGULATION BASED ON LOCAL CONTROLLERS

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ABSTRACT

The presence of Dispersed Generation (DG) in MV distribution network affects voltage profile along the feeders, in particular over-voltage at the DG Point of Common Coupling (PCC) may occur.

This paper is focused on possible improvements in terms of Hosting Capacity (HC) deriving from a novel voltage regulation approach, involving GD units in order to mitigate overvoltage violations. The proposed approach is based on a modulation of reactive power injected/absorbed by the DG power plants; in particular the proposed control law is based only on local measures. The analysis indicates that the proposed local voltage control may increase the HC of existing networks, moreover the proposed control strategy could minimize the reactive power flows on the distribution network limiting the consequent impact on active power losses.

INTRODUCTION

In the past distribution networks were designed to behave as a passive system, i.e. without Dispersed Generation (DG) connected. Power injections at medium and low voltage level introduce new issues in network management: the fast expanding of DG can affect quality of supply as well as voltage quality. In particular, to have a more effective voltage regulation, i.e. to avoid voltage quality violations, it is necessary to exploit DG units as voltage control resources.

Generally speaking, two possible regulation strategies can be adopted. In a *Local control strategy* each generator operates without coordination with other devices and communication infrastructures aren't required. However in an electrical network each regulation action affects the voltage of all buses of the system, for that reason voltage profile and reactive power flow could be not in an optimum working point [3]. Conversely, in a *Global control strategy* all regulation resources are coordinated and equipments are adjusted remotely in order to obtain an optimum voltage profile; this approach is quite similar to the scheme usually adopted for the transmission networks [3][4]; in literature several proposals has been envisaged [1][2]. This second approach assures a better working point for the distribution network but it requires an integration between power network, telecommunication infrastructure, state estimation procedure and optimal power flow; moreover the whole regulation cycle (to results effective) has to be executed in a limited time frame (tens of seconds) [6][7]; likely this control scheme will be realistic in a medium-long time period.

The local control system represents the first viable step toward a 'smart grid' management; it is feasible in a short term scenario limiting the need of capital investment in new network assets. In [8] the two methods (local, global) are compared and it is depicted how, within suitable assumptions, local voltage control gives similar results in terms of hosting capacity to those obtained by coordinated management.

In this paper the local approach is considered: after a brief description of the proposed control law, some results obtained with models based on real networks are summarized and a short discussion about possible improvements following this approach is given.

LOCAL VOLTAGE CONTROL STRATEGY

As for voltage quality standards, the steady-state voltage limits in the MV distribution system are ±10 % of the rated voltage (CEI EN 50160). In a passive network the voltage profile decreases monotonically along the feeder. However, with DG connected, the voltage profile is no longer monotonous and DG can either lead to serious over-voltages to other customers connected or contribute to sustain feeder's voltage profile. Furthermore the control function for the definition of the HV/MV transformer secondary busbar voltage set point may not work correctly (On Load Tap Changer – OLTC).

This work aims to verify the performance of a local voltage control strategy obtained by power factor regulation of DG units once voltage at PCC reaches defined thresholds. In particular DG may inject active power at not-unitary power factor, absorbing reactive power in order to mitigate the voltage profile [5]. DG impact on the voltage profile depends directly on the entity of active power P_{DG} and reactive power Q_{DG} injection:

$$\Delta V \approx R(P_L - P_{DG}) + X(Q_L - Q_{DG}) \quad (1)$$

where R and X indicate respectively the resistance and reactance of the line, P_L and Q_L are the load absorptions.

A first possible solution, named *control strategy A*, is depicted in Fig. 1. This method comprises two condition: a normal operating situation, where no control action is required, and a situation where first voltage thresholds (V_1 and V_2) are violated. In the latter case, the generator operates at a not-unitary power factor injecting/absorbing reactive power from the network according to the local voltage (compound curve).

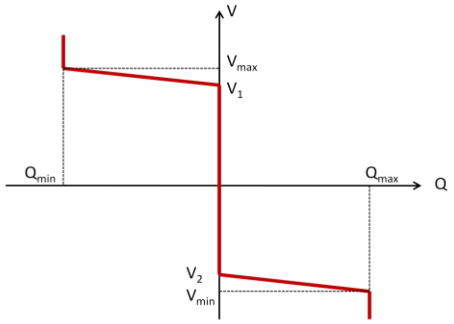

Fig. 1: *Local voltage control strategy A*

A second solution, usually mentioned in literature, consists in a voltage control without a compound characteristic. With this strategy, named here *control strategy B*, once the voltage reaches its threshold the generator starts injecting/absorbing reactive power at fixed power factor (Fig. 2 depicts one possible implementation of such a regulation, introducing an hysteresis between the activation threshold and the deactivation one in order to limit oscillation).

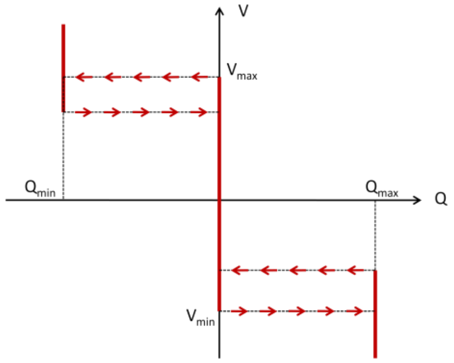

Fig. 2: *Local voltage control strategy B*

However both the proposed approaches limit the participation of generators to the voltage control only when the nodal voltage is out of a pre-defined range. In this way, the reactive power generated by the DG is null when the network voltage is within the admissible range, limiting current flows and avoiding power losses increase. Different local strategies (e.g. different voltage thresholds and different control performances) can impact on the voltage quality and network stability differently. In fact, a series of regulator actions occurring at the same time can trigger critical situations, therefore the performance of a widespread adoption of local control has to be deeply explored. A proper time constant (seconds/tens of seconds) of the local control strategy is required in order to separate DG local voltage control from other regulation resources and to avoid fluctuations. In any case, the analysis here proposed has to be intended as the first step toward the design of the complete voltage controller.

CASE STUDY

Selection and modelling of test networks

Two realistic distribution networks with radial structure (based on real network data) have been adopted in order to model the MV Italian distribution networks; in particular configurations where DG presence may lead to critical voltage conditions have been selected. The identified networks have the following main features:

1. Voltage at the MV Primary Substation (PS) busbar between 1.04 and 1.06 p.u. during peak, in order to avoid under-voltage conditions.
2. 15 kV rated voltage (voltage typical for Italian MV distribution network).
3. Standard characteristics in term of dimension, losses, HV/MV transformer loading factor.
4. Several feeders, in particular in the same network a feeder with high voltage profile and a feeder with low voltage profile are present.

In the present work, for each network, only the feeder with the highest voltage profile and the one with the lowest one (named main feeders) have been modelled in detail, whereas other feeders have been described as equivalent loads. It can be expected that the feeder with lower voltage profile has the ability to connect larger generators, while an higher voltage profile entails low margin to connectable capacity. The analysis were carried out simulating a minimum load condition, i.e. the condition in which the impact of DG injections is more critical. Finally, the tap changer of transformer installed in the PS operates at fixed value (the one relevant to the peak load condition).

Procedure developed

In this study the impact of the voltage control is quantified for a *multi-generator* configuration: it reflects a more realistic situation than the single-generator approach. A parametric study based on load flow simulations was carried out in order to include a representative variety of generation scenarios, exploiting the DIgSILENT PowerFactory package capability.

Tab. 1: *Generation scenarios*

Scenarios	% GD first bus	% GD middle bus	% GD last bus
Scenario 1	70	20	10
Scenario 2	50	30	20
Scenario 3	40	30	30
Scenario 4	30	30	40
Scenario 5	20	30	50
Scenario 6	10	20	70

Three generators for each feeder were considered; they

have been located at the first bus, the last bus and the bus in the middle (in term of electrical distance) of the main feeders.
The total active power injection (evaluated up to 10 MW) and the power distribution along the three generators are modulated; in this way several *multi-generator* scenarios could be explored (Tab. 1).

Results

The two main feeders of the first network, namely Test Network N1, are shown in Fig. 3. In passive condition Feeder 2 has the higher voltage profile and Feeder 4 presents the lower one. In the figure the locations of the three DG units of the feeder (representing the generic DG distribution along the feeder itself) are depicted with red circles (feeder 4, middle of the scheme) and green circles (feeder 2, upper branch).

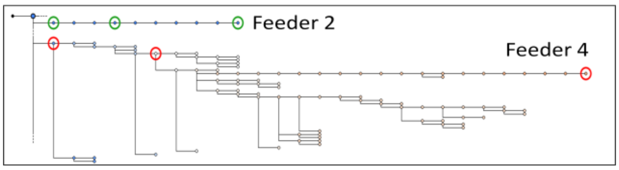

Fig. 3: *Network Test* N1 *– Main feeders and DG unit locations.*

The Hosting Capacity for voltage constraint (±10% Vn) has been calculated considering each DG plant individually (nodal HC); results are reported in Tab. 2.

Tab. 2: *Nodal Hosting Capacity – Test Network* N1.

	Feeder 2 Hosting Capacity [MW]	Feeder 4 Hosting Capacity [MW]
First bus	10	10
Middle bus	10	4.52
Last bus	10	2.11

The lower nodal HC is observed for 2.11 MW connected to the bus of the feeder 4: it means that, contrary to what was expected, in this network the feeder with the greater voltage drop has a lower hosting capacity. Therefore voltage drop is not a significant parameter for indentifying critical feeders, where overvoltage may occur during DG injections.
The *multi-generator* analysis has been carried out for the Feeder 4, where for each scenario (reported in Tab. 1) the nodal HC was evaluated.

Tab. 3: *Hosting Capacity – Test Network N1, feeder 4*

Scenarios	cos ϕ=1 P_{HC} [MW]	cos ϕ=0.95 P_{HC} [MW]	cos ϕ=0.9 P_{HC} [MW]
# 1	8.44	11	12.7
# 2	5.49	8.02	10.1
# 3	4.43	6.96	10.1
# 4	3.8	6.12	10.6
# 5	3.17	5.7	Under-voltage
# 6	2.53	5.28	Under-voltage

Tab. 3 summarizes the results: it can be seen (as expected) that when the power injection is spread along the feeder the HC is greater than the case where the total power is injected in a single bus; the analysis performed give a first idea on the HC sensitivity with respect to the DG distribution along the feeder.

The over-voltage always occurs in the last bus of the feeder, for this reason only the power factor of DG unit installed in last bus is changed to 0.95 and 0.9 (Tab. 3, third and fourth columns). In these cases the voltage profile decreases and the level of GD capacity that can be accommodated (HC) raises. Considering scenario 5 and scenario 6, the power supply at cosφ=0.9 can cause under-voltage violations.
In Fig. 4 the voltage profile of scenario 2 (P_{DG}=10.1 MW and cosφ=0.9) is shown. The profile increases monotonically along the feeder 4: the voltage constraint is met at the end of the feeder. In addition, the current flow increases substantially because of DG operation at non unitary power factor and thermal constraints are violated.

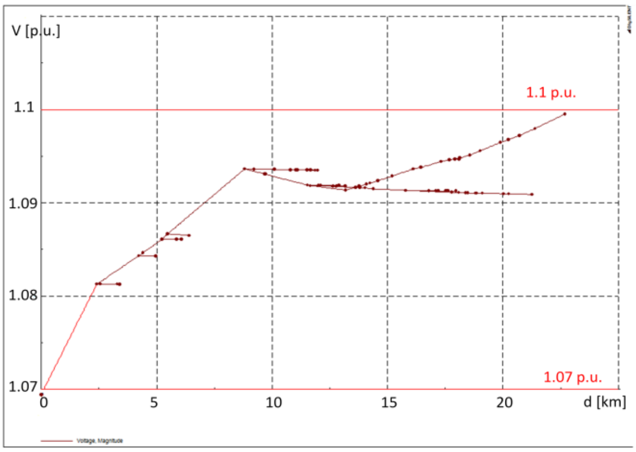

Fig. 4: *Voltage profile along the feeder 4 – scenario2.*

A new Hosting Capacity considering both voltage constraints and thermal constraints was calculated (Tab. 4). When thermal constraint is reached, table cells are dashed (results in red).

Tab. 4: *Hosting Capacity – Voltage and thermal constraints, Test network* N1*, feeder 4.*

Scenarios	Cos ϕ=1 P_{HC} [MW]	cos ϕ=0.95 P_{HC} [MW]	cos ϕ=0.9 P_{HC} [MW]
# 1	**8.08**	**8.08**	**8.04**
# 2	5.49	8.02	**8.02**
# 3	4.43	6.96	**7.98**
# 4	3.8	6.12	**7.92**
# 5	3.17	5.7	**7.82**
# 6	2.53	5.28	**7.57**

The results show that for power factor up to 0.95 the HC is limited by the upper-voltage constraint, whereas thermal limits become active at cosφ=0.9 in all operation conditions of scenario 1 (first row of Tab. 4).
Considering *control strategy B*, on network Test N1 it follows that the best choice is to operate at cosφ=0.95; the network can reach 8 MW of total capacity. On the other hand a voltage regulation at cosφ=0.9 doesn't

introduce further benefits because of thermal limits of network branches.
The structure of the second network analyzed (Test Network N2) is shown in Fig. 5. In passive conditions Feeder 8 has the higher voltage profile while Feeder 6 has the lower one.

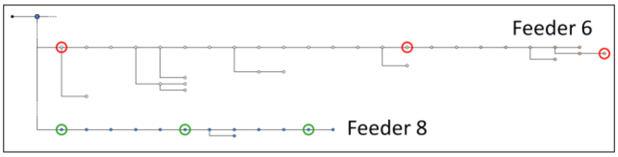

Fig. 5: *Test Network* N2 *– Main feeders and DG unit locations.*

The minimum nodal HC is 1.86 MW connected at the end of the Feeder 8, i.e. the line with the smaller voltage drop. This network depicts a behaviour quite different with respect to the previous Test Network N1. The same generation scenarios of Tab. 1 were replicated for the Feeder 8 of the Test Network N2, as summarized in Tab. 5.

Tab. 5: *Hosting Capacity – Voltage and thermal constraints, Test network* N2*, feeder 8*

Scenarios	cos ϕ=1 P_{HC} [MW]	cos ϕ=0.95 P_{HC} [MW]	cos ϕ=0.9 P_{HC} [MW]
# 1	7.3	7.3	7.28
# 2	4.84	6.51	7.28
# 3	4.1	5.39	6.88
# 4	3.16	4.65	6.14
# 5	2.79	4.28	5.58
# 6	2.23	3.72	5.39

Unlike the previous case N1, control strategy B with cosφ=0.9 is reasonable for improving the voltage quality of the system. Except Scenario 1 (dashed cells in Tab. 5), thermal constraints aren't violated, and in the scenario 6 it is possible to connect up to 5.39 MW from distributed power plants (compared to 1.86 MW of nodal HC).

CONCLUSION

The local voltage control strategy obtained by adjusting the reactive power output has been studied and discussed in different generation scenarios. The results show that, unlike usually expected, feeders with small voltage drop in passive condition do not always have high capacity of DG penetration. For this reason it is necessary to define new criteria to identify test network with critical features, for example based on lower nodal Hosting Capacity.
In case of over-voltage the reactive power absorption by generators allows to significantly increase DG penetration itself. In some circumstances low power factor doesn't introduce benefits in term of HC because of thermal constraints. For this reason it is necessary to use a voltage control scheme that guarantees to operate at variable power factor and to absorb reactive power according to the network response (control strategy A, Fig. 1). The improvement expected in network operation is mainly the enhancement of voltage regulation (i.e. fulfillment of limits related to supply voltage variations, within the range set by EN 50160), paying with higher losses due to the generators operating at not-unitary power factor.
A future evolution of the proposed regulation scheme will be devoted to the design of the voltage control law depicted in Fig. 1; in a further step a global voltage control that coordinates all the available resources with respect to the new 'smart grid' paradigm could be investigated.

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