New rules to employ distributed generators in voltage control: assessment and numerical validation using DOME

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Abstract—**In recent years, several countries have published new technical rules for the connection of distributed generators to medium and low voltage networks. A common requisite is that distributed generators should be able to module both active and reactive power. The paper duly reviews these rules and presents a variety of simulations referred to actual distribution networks using a new software tool: DOME.**

Index Terms—**Distributed generators, voltage control, reactive power control, PV generators.**

I. INTRODUCTION

Several factors lead to an increase in the exploitation of renewable energy resources (PV, wind and others) [1][2] and to a better utilization of fossil fuels resources through cogenerative power plants that are often implemented with small and medium size generators located near the loads:

- Governments have enacted policies like the European climate and energy packet known as the 20-20-20 targets;
- The liberalization of electricity markets augments the possibility for investments in the production of electrical energy also with small capitals and therefore small size generators;
- The constant increase in electrical energy consumption and in the costs for traditional fossil fuels.

This new paradigm for the generation and distribution of electrical energy is not based on big centralized power plants any more but it is characterized by a geographically distributed generation with small and medium sized generators. It brings new problems to the operation of distribution grids. A brief list of the technical issues arising when introducing distributed generation in distribution networks includes: thermal rating of equipment; system faults levels; stability; reverse power flow; steady state voltage rise; power quality; protection systems.

To make it possible the integration of distributed generators (DG) while keeping an adequate level of power quality and quality of service, actual distribution networks have necessarily to evolve towards the so-called Smart Grids (i.e. the electrical grid is integrated with information and communication technologies).

Several authors agree with the need to change in real time the set-point of the generators [3-5] and several different control strategies have been proposed in literature: based on multi-agent approach as in [6] or on sensitivity theory as in [7].

There is still a very poor harmonization among different countries about the rules of connection for the DGs:

- In Germany, a new grid code has been introduced for MV and HV networks (BDEW 2008), followed for new guidelines for LV grid (VDE-AR-N4105);
- In Spain, new rules for PV and Wind plants to increase their voltage support have been implemented (P.O. 12.3);
- In Italy, the new released A70 document for LV and MV grids, the new releases of CEI 0-16 (MV connected distributed generators) and CEI 0-21 (LV connected distributed generators) have deeply changed the connection rules for DGs.

At the European level there are some technical requirements under development: TS50549-1 and -2. Although these are not in a final state yet, they should be already quite developed. After having been rejected twice, a new decision on their adoption is expected for Spring 2013.

There are some common points in all rules cited above, at least in the goals they try to accomplish:

- Participation of DG in the voltage control through reactive power dispatch;
- Limitation of active power for frequency control;
- LVRT (Low Voltage Ride Through) functionalities;
- Remote control of the DGs.

This paper shows the application of new rules for connection of active users, with particular reference to the employment of distributed generators in a voltage control system. The effectiveness of new rules for distribution networks is analyzed and validated through numerical simulations solved using a new software tool: DOME.

II. VOLTAGE CONTROL LOGICS

Two control logics required for static generators by the new version of the CEI 0-16 [8] have been simulated:

A. *Power factor control*

Automatic adjustment of reactive power according to a characteristic curve cos φ = f (P), where P is the generator active power.

This control law provides the absorption of reactive power by distributed generators, only in order to limit the voltage rise caused by injection of active power by the same generator.

The control logic is as follows:

- For values of injected active power $P/P_n < 0.5$, the inverter works at cos φ = 1
- On exceeding the working point $P/P_n = 0.5$, the inverter checks if the voltage at its terminals is greater than a critical value of lock-in, provided by the DSO (for example equal to 1.05 V_n) and in this case is activated the reactive power regulation, placing the working point P-Q according to the following expression according to Fig.1:

$$\cos\varphi = -0.2\frac{P}{P_n} + 1.1$$

- The reactive power regulation is removed only when the active power P falls below 50% of P_n (active power lock-out), independently from the voltage measured at the terminals, or if the voltage falls below a certain value (tension lock-out) adjustable between 0.9 V_n and V_n.

B. *Reactive power control*

This control law requires an absorption or injection of reactive power in function of the terminals voltage value, in order to provide a network service: to limit voltage variations at node considered even if caused by other generators / loads of network.

To accomplish this, generators must be capable to absorb or inject reactive power automatically in a local control logic on the basis of a characteristic curve Q = f (V) shown in Fig. 2.

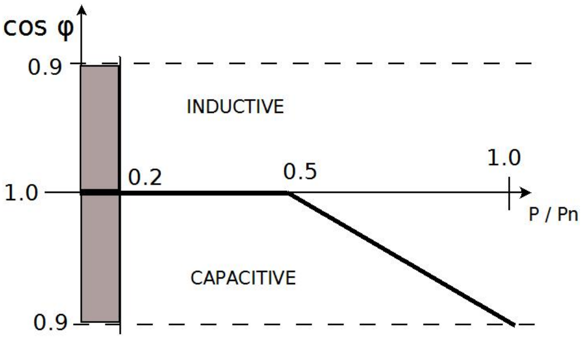

Fig. 1. Power factor control law.

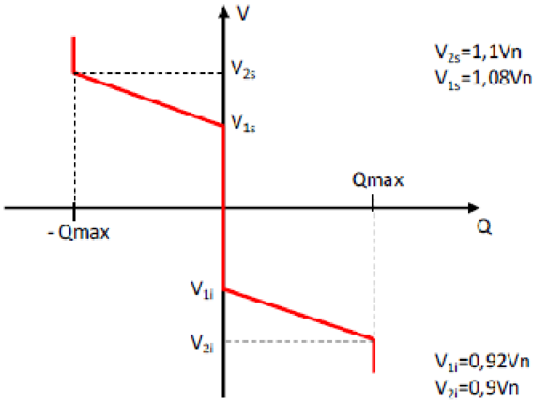

Fig. 2. Reactive power factor control

where V_{1i}, V_{1s}, V_{2i}, V_{2s} are defined by DSO within these limits:

- $V_{1i} < V_n < V_{1s}$;
- $V_{2s} < V_{max}$;
  with $V_{max} \leq$ 59.S1 (default value: $V_{max} = 1{,}1\ V_n$);
- $V_{2i} > V_{min}$;
  with $V_{min} \geq$ 27.S1 (default value: $V_{min} = 0{,}9$ Vn);
- $|Q_{min}|$ e $|Q_{max}| \geq 0{,}436$*Sn.

III. OUTLINES OF DOME SOFTWARE TOOL

DOME is a Python-based software [9] tool founded on two main principles: modularity and reusability of the code. Basically no part of the code, except for a tiny kernel, is really necessary. Rather, the code is based on a reduced number of milestones that have to be available, but how such milestones solve their duty is not relevant for the main kernel. The milestones are only four:

- Parsing the data file and initializing device models.
- Solving the power flow analysis.
- Solving other analyses, e.g., time domain simulation.
- Dumping data to adequate output files.

Each milestone is composed by several independent Python modules. The user can also provide his own custom modules. Figure 3 illustrates the concepts discussed so far. The only requirement that each module has to satisfy is a common "communication protocol" with DOME core functions. This modular structure is the key, along with the versatility of Python classes, for a quick and easy development of the code.

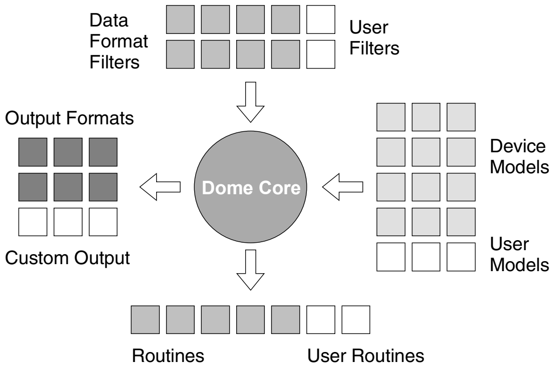

Fig. 3 Qualitative representation of the structure of Dome.

Currently, DOME provides about 50 parsers for input data, including most popular power system formats such as PSS/E and GE and SIMPOW formats; about 350 devices ranging from standard power flow models, synchronous machines, AVRs and other basic controllers to a variety of wind turbines, energy storage devices and distributed energy sources; 10 analysis tools including standard power flow analysis as well as three-phase unbalanced power flow, continuation power flow, OPF, time domain simulation, electromagnetic transients, eigenvalue analysis, short circuit analysis, equivalencing procedures and load admission control strategies for smart grids; and 10 output formats, including Latex, Excel, and 2D and 3D visualization tools.

Despite the vastness of the tools and models provided, DOME remains a light tool. Required modules are loaded at run-time. These are generally less than 1% of available modules. Hence, the project can grow indefinitely without affecting performance. Modularity has also the advantage of allowing parallel development of new modules: if a beta-version of a new function is broken, all users that are not using such function can continue using DOME smoothly. Moreover, no forking is necessary as different versions of the same module can coexist.

IV. CASE STUDY

In this paper, a modified version of the IEEE 37-bus distribution system [10] is used for testing the effects of the voltage control logics of DGs described in Section III. Fig. 4 shows the topology of the IEEE 37-bus network.

The same network has been already used to test voltage control strategies in [11-12].

The IEEE 37-bus network includes four types of cables whose data are based on [13]. The line styles used in Fig. 4 refer to the four cable technologies illustrated in Table I.

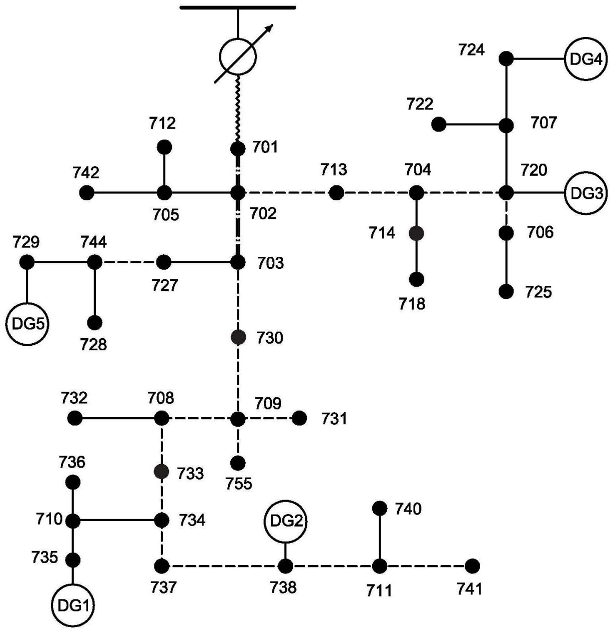

Fig. 4. IEEE 37-bus MV test system.

TABLE I
CABLE DATA FOR THE IEEE 37-BUS NETWORK

Line code	R [Ω/km]	L [mH/km]	Rate [A]
〰 (721)	0.065	0.567	698
⁞▬⁞ (722)	0.128	0.637	483
--- (723)	0.478	0.783	230
— (724)	0.957	0.853	200

The line lengths have been augmented from the original described in [10] in such a way the technical rules about voltage control are actively applied (i.e. at least a voltage of 1.05 V_n is reached). All line length changes are indicated in Table II.

TABLE II
CABLE LENGTHS

From bus	To bus	Original L [km]	Modified L [km]
701	702	0.293	1.0
702	705	0.122	0.122
702	713	0.110	1.0
702	703	0.402	1.0
703	727	0.073	0.073
703	730	0.183	1.0
704	714	0.024	0.024
704	720	0.244	0.244
705	742	0.098	0.098
705	712	0.073	0.073
706	725	0.085	0.085
707	724	0.232	1.0
707	722	0.037	0.037
708	733	0.098	0.098
708	732	0.098	0.098
709	731	0.183	0.183
709	708	0.098	0.098
710	735	0.061	1.0
710	736	0.390	0.390
711	741	0.122	0.122
711	740	0.061	0.061
713	704	0.158	1.0
714	718	0.158	0.158
720	707	0.280	1.0
720	706	0.183	0.183
727	744	0.085	0.085
730	709	0.061	1.0
733	734	0.171	0.171
734	737	0.195	0.195
734	710	0.158	0.159
737	738	0.122	1.0
738	711	0.122	0.122
744	728	0.061	0.061
744	729	0.085	2.0
799	701	0.564	3.0

Loads have been expressed using static PQ constant models. DGs have been connected to selected buses as proposed in [14]. The rated capacity of the DGs is shown in Table III. All DGs are assumed to be solar photovoltaic

(PV) energy resources. This assumption is justified by the fact that the currently available standards that regulate the connection of DGs to distribution networks (see [8]) only consider static generators, i.e., generators that are connected to the grid through power-electronics-based static converters.

TABLE III
MV TEST NETWORK DGS DATA

DG unit	Bus	Rated Capacity [MW]
DG1	735	0.70
DG2	738	1.40
DG3	720	0.60
DG4	724	1.00
DG5	729	1.40

There are various models for inverter-based generators. The model adopted in this case study is a simplified d-q axis current control based on first order lag transfer functions as proposed in [15] and [16]. The qualitative control scheme of DGs is shown in Fig. 5.

The control scheme shown in Fig. 5 has been completed with the inclusion of the voltage control logics discussed in Section III. These logics are basically if-then loops that allow defining the value of Q_{ref} based in the current value of P_{ref}. We assume that P_{ref} is the available active power production resulting from the MPPT control of PV generators. We also assume that there are no restrictions on the active power output of DGs.

Active power profiles have been obtained from experimental data of some PV panels located on the roof of some buildings of the University of Trieste, Italy. Figures 6, 7 and 8 show a typical daily voltage profile of the point of connection of a PV device and refer to the voltage at bus 735 of the proposed case study. In particular, Fig. 6 shows the profile resulting by not applying any control, i.e., imposing a unity power factor, whereas Fig. 7 shows the effect of the reactive power control. Fig.8 shows the effects of the application of the power factor control law.

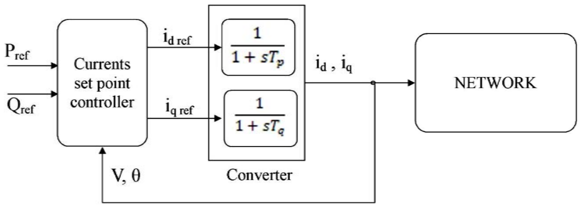

Fig. 5 Model used for PV energy resources.

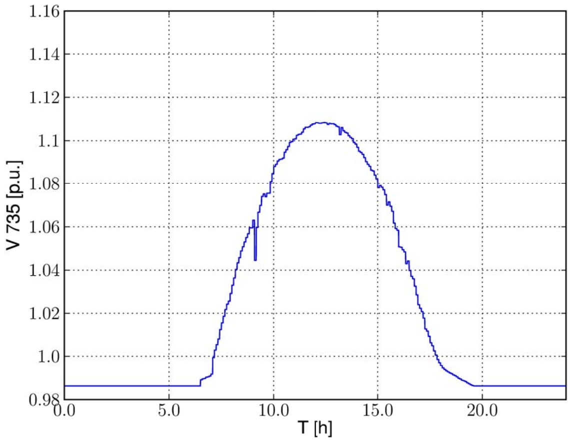

Fig. 6. Daily voltage profile at node 735 with unity power factor .

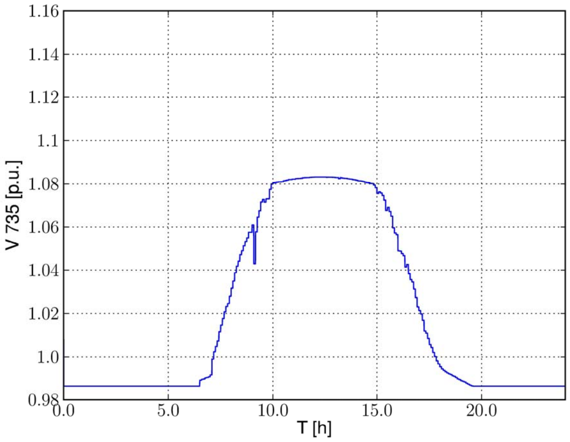

Fig. 7. Daily voltage profile at node 735 with reactive power control.

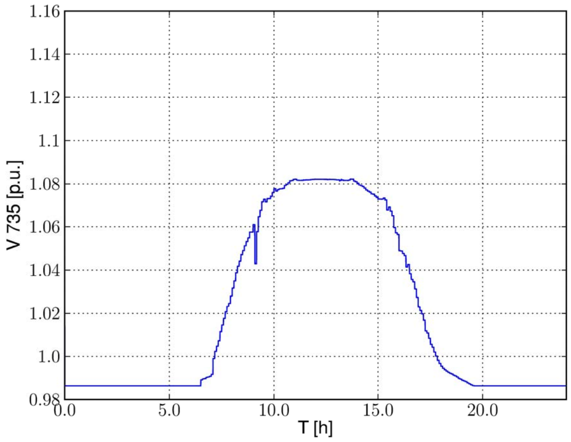

Fig. 8. Daily voltage profile at node 735 with power factor control.

In Fig. 9, three different voltage profiles for the network are shown. The red line is obtained with the produced maximum active power injection in the five DGs operating at power factor one. The cyan dot-dashed line is obtained applying the reactive power control, while the green dashed line is with the power factor

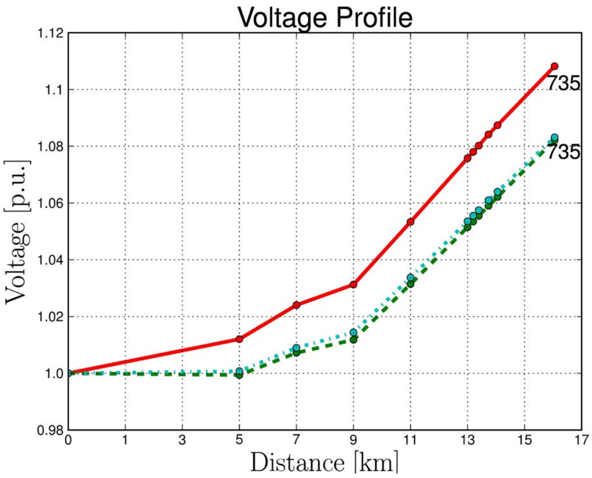

Fig. 9. Voltage profile for the test network IEEE 37-bus: the red line is the network without any voltage control, the cyan dash-dotted line is with reactive power control while the green dashed line is with power factor control. Only the radial branch to node 735 (DG1) is shown.

control.

For all three cases the load has been kept at the constant value reported in [10] and the active power considered is at the maximal irradiation time during the day. As it can be observed, node exceeds the value of 1.1 V_n. This voltage level is beyond the standard contractual limits agreed for load buses. Moreover, DGs should automatically disconnect from the grid if the voltage exceeds 1.1 V_n (i.e. loosing active power production).
Both the control strategies avoid the overvoltage keeping the voltage in the limits.

V. CONCLUSION

This paper discusses the effect of two voltage control logics for distributed generators. The logics discussed in the paper are based on recent CEI standards that, at the time of writing this paper, are still incomplete. As expected, to impose control actions over the voltage or the reactive power produced by distributed generators allow reducing the typical voltage raise experimented by radial networks that were not planned to include active power generation. With this regards, the voltage control and the reactive power control discussed in this paper show very similar effects on the bus voltage profile.

All simulations are solved using an experimental software tool for power flow analysis, namely DOME. This tool allows implementing novel control schemes as simple scripts that can be loaded at run time. The advantage of this approach is that several control schemes can be quickly tested and implemented. This flexibility is a crucial feature because the technical requirements of the voltage control that should be provided by distributed generators is currently an open field for proposals and standardization.

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