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Decentralized voltage control of distributed generation using a distribution system structural MIMO model

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ABSTRACT

The voltage control problem in Low Voltage (LV) distribution systems is becoming increasingly important due to the presence of Distributed Generation (DG). Recently, DG units have been proposed to contribute to voltage control according to a Volt/Var law which does not realize regulation. Moreover, since the existing LV systems are operated in a decentralized way without communication links, the simultaneous response of the controllers of the DG units may result into operational conflicts and instability. To overcome these problems, the present paper illustrates a design methodology for decentralized voltage controllers that act on DG reactive power injections. The controllers are suitable for the LV systems since they ensure voltage regulation and stability by using only local measurements and without information exchanges. The design is based on a proposed structural MIMO model of the distribution system. Robust stability is also analyzed: changes in the operating conditions of the distribution system are modeled as unstructured additive uncertainties affecting the MIMO model. A case study gives evidence of the applicability of the proposed design; the performance of the controllers in terms of both stability and regulation of the nodal voltages of three DG units connected to a LV distribution feeder is tested by numerical simulations; finally, a comparison with a Volt/Var technique is performed.

1. Introduction

The increasing number of Distributed Generation (DG) units in Low Voltage (LV) distribution systems impacts on some key issues related to the management and control of the networks and, in particular, on voltage regulation (Chen et al., 2012; Ferreira, Carvalho, Ferreira, & Ilic, 2013; Tonkoski, Turcotte, & El-Fouly, 2012). Existing distribution networks were designed to deliver unidirectional power flows from the Medium Voltage (MV) network, through the secondary substation and the feeders, to the consumers; consequently, the voltage profile was characterized by decreasing voltage along the feeders. The introduction of DG gives rise to bi-directional power flows that can cause current overflows in critical lines and overvoltages along the feeders. Consequently, maintaining the nodal voltages within the required limits is a challenge for the LV distribution system and their operators.

Traditionally, voltage regulation in LV distribution networks relies on an appropriate choice for the off-load tap position of the MV/LV transformers in the secondary substations. To remove the negative impact of the DG on the nodal voltages, initially an "on/off control action" has been adopted that shuts down the DG units when the voltage at the Point of Common Coupling (PCC) overcomes some fixed thresholds (Conti, Greco, Messina, & Raiti, 2006; Ferreira et al., 2013). In the traditional approach, the connection of DG to the distributions system is considered a problem rather than a chance.

In future LV distribution smart grids, new voltage regulation strategies are being developed involving not only DG units but also smart secondary substations (Kabiri, Holmes, & McGrath, 2014) and other Distributed Energy Resources (DERs) (e.g. management of smart loads and storage) (Geibel et al., 2012; Juamperez, Yang, & Kjaer, 2014). Various solutions have been proposed in the literature adopting centralized or distributed/coordinated approaches with communication infrastructures (Bolognani & Zampieri, 2012; García, Mastromauro, & Liserre, 2014; Kulmala, Repo, & Järventausta, 2014; Ranamuka, Agalgaonkar, & Muttaqu, 2014; Vovos, Kiprakis, Wallace, & Harrison, 2007; Yazdanian & Mehrizi-Sani, 2014). These solutions offer the advantages of coordinating the local actions of the DERs through data collected by smart meters (Madureira & Lopes, 2009; Mokhtari, Ghosh, Nourbakhsh, & Ledwich, 2013; Senjyu, Miyazato, Yona, Urasaki, & Funabashi, 2008; Yu, Czarkowski, & de Leòn, 2012). On the other hand, depending on the number of DERs to be connected, both centralized and distributed/coordinated control techniques represent expensive solutions and require huge investments on the existing distribution systems.

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A viable alternative is represented by the decentralized approach, which does not require any communication among the various devices and, consequently, is the lowest-cost solution to start involving DG units in voltage control of the existing LV distribution networks. Recently, some innovative solutions adopting a decentralized approach are being experimented.

A first technique is based on the partial curtailment of the DG active power injection in the case of over/under voltages at the PCC (Conti et al., 2006; Chalise et al., 2013; Demirok et al., 2010). Unfortunately, this technique impacts on the active powers and is not economically favorable for the DG owners, who cannot maximize their revenues. Moreover, DG units connected to LV distribution systems typically use renewable energy sources and, consequently, their active powers are not dispatchable. Finally, this technique is becoming less attractive also from the system operator point of view, due to the increasing relevance of DG using renewable sources in the generation mix at the national power system level.

An alternative solution is to act on the reactive powers which can be injected by some DG units. Indeed, reactive powers have a weaker impact on nodal voltages than active powers in LV distribution systems; on the other hand, the great advantage is that no direct cost is related to reactive powers. In this view, decentralized "Volt/Var control" is adopted in some distribution networks around the world (Esslinger & Witzmann, 2013; Jahangiri & Aliprantis, 2013; Juamperez et al., 2014). Such a control determines the DG reactive power to be injected as a function of the voltage at the DG terminals, according to a piecewise linear relationship $Q(V)$ including a large dead-zone. As alternative, a "power factor control" can be adopted (Juamperez et al., 2014), in which the power factor to be imposed is a function of the DG active power injection, $\cos\phi(P)$. It is worth underlining that all these solution do not achieve a voltage set-point regulation but realize the pre-assigned $Q(V)$ and $\cos\phi(P)$ characteristics.

Indeed, there are still many open issues that must be tackled in the decentralized approaches. The presence of multiple DG units may introduce technical problems in network operation, including interaction among controllers and/or voltage instability (Jahangiri & Aliprantis, 2013; Kashem & Ledwich, 2005) and the investigation on these problems is not completed yet. To achieve a stable decentralized voltage control in the presence of multiple DG units, a model that correctly accounts for the interactions among the DG units is necessary but also this issue is still open (Farina, Guagliardi, Mariani, Sandroni, & Scattolini, 2015). Finally, the control design must account for the changes of the operating conditions of both the DG and the distribution system, by either adopting adaptive mechanisms (Di Fazio, Fusco, & Russo, 2013; Farina et al., 2015; Li, Li, Xu, Rizy, & Kueck, 2010) or ensuring robustness of the fixed controllers.

To pursue a low-cost decentralized approach, the present paper proposes a design methodology for voltage control of DG. The idea is to realize a secure *plug and play* connection of the DG units to the distribution system without any need of communication links or adaptive techniques but, at the same time, to improve the nodal voltages at the PCCs by acting on the DG reactive power injections. A local controller measures and regulates the voltage at the node to which each DG unit is connected. Its design is based on a structural MIMO model of the distribution system, and ensures a satisfactorily regulation while avoiding operation conflicts among DG units and system instability. The results of numerical simulations are presented to validate the proposed approach also in comparison with a "Volt/Var control" law.

2. System modelling

The aim is to derive a structural MIMO model of the LV distribution system suitable for decentralized voltage control design

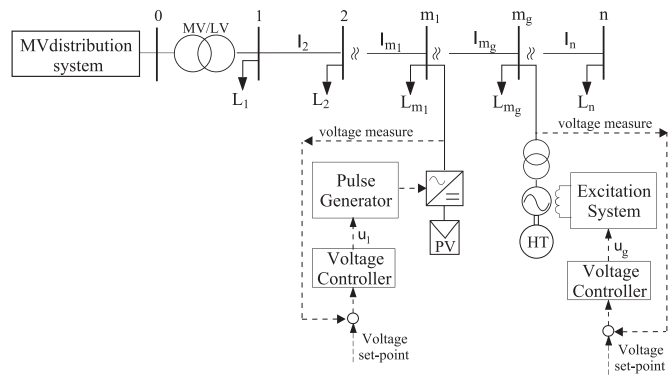

Fig. 1. Distribution feeder with DG units and local voltage control loops.

of DG units. Firstly, the DG models are derived. Then, the network model is developed based on the linearization of the classical DistFlow equations and on the enforcement of the border conditions for each feeder. Eventually, the network model is combined with the model of the DG units, yielding an accurate MIMO model that accounts for the interaction among the DG units along a feeder.

Let a LV distribution system be considered with a radial feeder composed of n nodes; the feeder is supplied by a secondary substation and other feeders supplied by the same MV/LV transformer are included in L_1 as equivalent active and reactive powers. Along the feeder, g DG units are connected to different nodes: the i-th DG unit is connected to the m_i–th node and the ordered set of indexes $\{m_1, \ldots, m_g\}$ denotes the nodes to which the DGs are connected, as shown in the one-line diagram in Fig. 1. Various types of DG units can be connected: for example in this figure a PhotoVoltaic (PV) generator and a HydroTurbine (HT) unit are considered. The local voltage control loops are also drawn in dashed lines.

2.1. DG modelling

The DG units that behave as reactive power sources contributing to voltage control in the distribution system fall into the following two cases:

1. static generators with power electronic interface to the distribution network;
2. synchronous generators directly connected to the distribution network.

In the following, for each case, the input command that can be used to control the output injected reactive power is identified and the related input–output transfer function is obtained.

In the first case, the interface inverter is typically equipped with a reactive power control loop: on the basis of a reactive power set-point, the inverter pulses are generated so as to inject the desired reactive power. Then, the DG reactive power closed-loop response can be characterized by a simple time constant T_{DG} of few milliseconds. Consequently, the transfer function referred to the i-th DG is

$$Q_{DG,i}(s) = \frac{1}{1 + sT_{DG,i}} U_i(s) \tag{1}$$

where $Q_{DG,i}$ is the injected reactive power, $T_{DG,i}$ is the time constant and U_i is the input command, that is the reactive power set-point to the inverter.

Concerning the second case of DG with a synchronous generator directly connected to the network, it is typically equipped with a static excitation system: on the basis of an input command to the static converter, the excitation current/voltage is controlled