Electric Power Systems Research 136 (2016) 110–124

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Integrated voltage regulation in distribution grids with photovoltaic distribution generation assisted by telecommunication infrastructure

L. Leite [a,*], W. Boaventura [a], L. Errico [a], E. Cardoso [a], R. Dutra [b], B. Lopes [c]

[a] Graduate Program in Electrical Engineering—Federal University of Minas Gerais, Belo Horizonte, Brazil
[b] Department of Electrical Engineering—Federal University of Minas Gerais, Belo Horizonte, Brazil
[c] Compahia Energética de Minas Gerais, Belo Horizonte, Minas Gerais, Brazil

ARTICLE INFO

Article history:
Received 26 November 2015
Received in revised form 4 February 2016
Accepted 6 February 2016
Available online 26 February 2016

Keywords:
Photovoltaic distributed generation
Telecommunication network
Smart grids
Voltage regulation

ABSTRACT

Massive penetration of Distributed Generation Photovoltaic Systems – DGPV – connected to the power distribution grid through electronic inverters can contribute, in an aggregate scenario, to the performance of several power system control functions, notably in voltage regulation along a distribution feeder. In this context, the supervision and control of these generating units through a standardized, flexible and capillary communication infrastructure becomes a key factor in enabling large-scale integration. Present voltage regulation methods adopted in distribution grids using DGPV units are based on the local interaction of each source with the power grid, without exploiting the potential benefits of a wide integration among them. This paper proposes the use of an optimization method for voltage regulation, focused on reactive power injection control, based on a communication architecture model that coordinates the interaction among the inverters of DGPV units. This architecture enables each distributed source to perform in accordance with its operational characteristics and location, while dynamically coordinated by a DGMS (Distributed Generation Management System). The proposed communication infrastructure is based on the connectivity and interoperability requirements established by the international standard IEC 61850 and the IEEE 2030 reference model. A sensitivity analysis regarding the performance of voltage regulation and communication infrastructure, based on a co-simulation of PSCAD and MatLab, shows the effectiveness of the proposed optimization method. This work analyses the impact of communication network delay and unavailability in voltage regulation process.

1. Introduction

The penetration of distributed generation photovoltaic (DGPV) sources in electricity distribution systems is constantly increasing around the world. Reported international experiences present important contributions for the market expansion analysis, gains in production scale and cost savings for investors. According to data from the Solar Power Europe [1], the cumulative global installed capacity of photovoltaic power in 2014 reached 178 GW, from which 40 GW were installed this last year. Europe leads the global market with over 88 GW installed, roughly 50% of the world's capacity, followed by Asia Pacific (40 GW) and China (30 GW). Solar Power Europe studies indicate a PV generation growth of approximately 218 GW, in a moderate scenario, and 362 GW, in an incentive driven scenario, from 2015 to 2019.

Once photovoltaic sources have reached a significant penetration level, on both local and regional level, it is very important to mitigate the potential impacts caused by the inherent variability of these distributed generators. On the other hand, avoiding the disconnection of these sources during the occurrence of grid events can increase power supply availability, improving power quality. This is also favored by the ability of PV inverters to deal with both active and reactive power.

Specifically, considering the voltage regulation profile in distribution feeders, some control techniques using reactive power support from PV sources have been used. These include methods based on local voltage measurements, local power injection measurements or a combination of both [2–4]. Moreover, due to the high R/X values in LV networks, the effect of reactive power is limited. In this way, local active power curtailment methods are proposed [5,6]. A combination of central/local and active/reactive power control of PV inverters is discussed in [7]. A coordinated day-ahead voltage control strategy for an active distribution network with distributed generation is proposed in [8]. In [9], the authors propose a distributed control for voltage regulation based on

* Corresponding author. Tel.: +55 31 3409 3403; fax: +55 31 3409 4810.
E-mail address: lleite@cpdee.ufmg.br (L. Leite).

http://dx.doi.org/10.1016/j.epsr.2016.02.016
0378-7796/

coordination among local control agents via communication network. In the same way, a distributed control architecture that considers the allocation of controllers in each distribution grid node is proposed in [10]. However, these works consider a pre-existing communication infrastructure. The present work proposes an optimized voltage regulation strategy based on centralized control architecture assisted by an efficient and coordinated telecommunication infrastructure. It defines the connectivity and interoperability parameters to enable the voltage control in distribution grids benefiting from the optimized performance of multiple DGPV power sources.

Centralized control addressed in this paper contrasts with the decentralized control adopted by other methods. In the smart grid environment, these two control methods (centralized and decentralized) are possible and necessary.

In this approach, the architecture based on centralized control is therefore justified because the central management system manages the operation of multiple DGPV sources, remotely. If a failure occurs in the central control or in the communication path, the voltage regulation continues to be carried out locally, as in current methods, but without the benefits of integrated control.

The paper is organized as follows: Section 2 presents the basic concepts of voltage regulation in distribution grids with DGPV. Section 3 analyses and compares the main voltage control strategies through the reactive power support from PV sources. Section 4 characterizes the communication infrastructure for distributed generation environment in terms of communication interface characteristics, interoperability and data modelling. In Section 5, a comprehensive voltage regulating architecture, considering the optimized contribution of each DGPV unit according to its generation capacity and location, assisted by telecommunication infrastructure, is proposed and validated. Section 6 presents a voltage sensitivity analysis, based on time-domain transient calculation from a co-simulation of distribution (PSCAD) and communication networks (PSCAD-Matlab interface) using four different scenarios. The details regarding the use of PSCAD and Matlab platforms are also presented. Section 7 discusses the impact of communication network performance and technology aspects. Section 8 presents a general discussion on the main benefits of the proposed voltage regulation strategy. Finally, conclusions and proposal for future work are provided.

2. Voltage regulation in distribution grids with DGPV

The connection of PV arrays in the distribution grid can affect the normal power flow condition and modify the voltage profile along the feeder. Fig. 1 shows a representation of a two-node system by its Thevenin equivalent with the presence of a photovoltaic generator connected to the load bus.

Analysing the diagram shown in Fig. 1, it is possible to predict the electrical grid behaviour with DGPV under different operating conditions. First, assume that the photovoltaic system is not generating power, $P_G = 0$, and that the load is inductive. In this case, the power grid will supply the load, and the current will flow in the forward direction, i.e., from S node to L node. The current intensity will depend on the P_L and Q_L demanded by the load. As the power demanded by the load increases, the voltage drop in the line also increases. Now, with the photovoltaic system generating power, the current in the line becomes dependent on the difference between the power generated by the DGPV unit and the power consumed by the load. The difference in the node voltages V_S and V_L is then regulated by the power flow, P and Q, as in the following equation:

$$\Delta\bar{V} = \bar{V}_L - \bar{V}_S \approx \frac{RP + XQ}{\bar{V}_L} \quad (1)$$

where R, X, P and Q denote, respectively, the line resistance, line reactance and the active and reactive power flow.

Considering that the angle variation between the L and S nodes is very small and that node L is a reference node, i.e., the voltage amplitude is $V_L = 1$, then the voltage variation is summarized in the following equation:

$$\Delta V = \bar{V}_L - \bar{V}_S \approx RP + XQ \quad (2)$$

where $P = (+P_G - P_L)$ and $Q = (\pm Q_G - Q_L)$.

The DGPV exports active power $(+P_G)$ and can export or import reactive power $(\pm Q_G)$, while the load consumes active power $(-P_L)$ and reactive power $(-Q_L)$. According to [11], for an n-nodes distribution system, when connecting a DGPV unit in the jth node, the voltage variation $\Delta\bar{V}_{ji}$ at the photovoltaic connection point can be written as the following equation:

$$\Delta\bar{V}_{ji} \approx \frac{R_{ij}\left(P_{Gj} - P_{Lj}\right) + X_{ij}\left(\pm Q_{Gj} - Q_{Lj}\right)}{\bar{V}_j} \quad (3)$$

Considering the case where the power injected by the photovoltaic source is maximum and the load is null (minimum local load condition), (3) can be rewritten as the following equation:

$$\Delta\bar{V}_{ji} \approx R_{ij}\left(P_{Gj}\right) + X_{ij}\left(\pm Q_{Gj}\right), \quad \left|\bar{V}_j\right| = 1 \quad (4)$$

In this way, considering (4), the voltage variation between two nodes (ji) will reduce or increase depending on the injection or absorption of reactive power by DGPV.

To enable a significant penetration of photovoltaic sources and to minimize the problems related to voltage variation without the need of large investments to expand the distribution grid capacity, it is an interesting option to adopt grid codes that consider the capacity and flexibility of PV inverters in the ancillary services, mainly reactive power injection/absorption, to ensure grid voltage compliance.

In this context, the following section discusses several voltage regulation strategies through reactive power compensation techniques using DGPV systems connected to the distribution grid.

3. Strategies for voltage regulation in grids with DGPV

The interconnection of distributed generation (large, medium or small) in a distribution system must comply with the requirements established by electric power utilities and regulatory agencies. In fact, there are different types of documents such as national standards, grid codes, rules and regulations enforced by utilities, which may confuse or override the understanding of their applications.

In the European Union, there are a number of initiatives carried out by various organizations to achieve a unified and standardized grid code [12]. Germany, because of its advanced stage of manufacture, installation and operation of grid-connected photovoltaic generation, is the country with a more comprehensive and updated grid code, serving as a reference for various studies around the world.

According to the German grid code [13], under normal operating conditions, DGPV sources must offer some ancillary services to grid support, particularly in relation to voltage stability through reactive

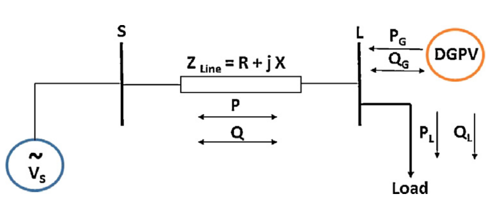

Fig. 1. Two-node equivalent distribution system with DGPV source.