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Centralized voltage control for distribution networks with embedded PV systems

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ABSTRACT

This paper proposes a centralized control methodology for optimizing nodal voltages of distribution networks by acting on the reactive power produced by PV-inverters. Control actions are centrally evaluated in real-time by solving a constrained dynamic optimization problem aimed at minimizing the voltage deviation from a reference value. The solution of this problem is obtained by adopting an algorithm operating in the continuous time domain based on a fast artificial dynamic system involving the sensitivity theory. By this approach the controller is able to promptly respond to any change in the system operating point, allowing its adoption in the continuous time domain. However, it must be considered that the injection of the reactive power provided by PV-inverters entails greater conduction and switching losses, causing a reduction in the active power output, thus implying less incomings. As a consequence, these additional operating costs have been analyzed and evaluated in order to establish an economic compensation mechanism able to guarantee fair reimbursement to PV generators engaged in this regulation service. Computer simulations performed on an MV distribution system, demonstrate the effectiveness of the proposed control scheme under different operating conditions, confirming its ability to control the network in real-time.

1. Introduction

The intensive economic support programs adopted by the Italian Government [1] in recent years have resulted in a proliferation of Distributed Generators (DGs) and, more specifically, of Photovoltaic (PV) plants. The high degree of penetration of such sources requires a complete revision of existing practices of distribution systems operation. In fact, these generators, depending on their specific characteristics and location, significantly affect the voltage profile, network losses and fault levels [2–6]. All these factors can limit the full exploitation of such resources if adequate control actions and ancillary service providers are not available in the grid. Among possible providers, PV plants seem to be particularly attractive because of their power electronic converters even if, until now, this possibility has not been fully exploited due to the lack of adequate control methodologies. For this reason, some interconnection standards [7,8] imposing a unitary power factor at connection points have excluded these plants from the regulation service. More recently, thanks to scientific and technology improvements, this opportunity seems to be practicable. Therefore, new grid codes developed in many countries [9–17] require that new PV inverters must incorporate any reactive control signals coming from the network operator. However, the issue on how to control such devices in real time is still pending even if a lot of research is being carried out on this topic and, particularly, on the voltage regulation problem aimed at satisfying the standard EN 50160 [18]. Technical literature extensively reports methods based on Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Evolutionary PSO (EPSO), Discrete PSO (DPSO) and sensitivity theory [19–30]. In these works, control actions are centrally evaluated by solving a constrained optimization problem to minimize system losses. Control variables are the reactive powers supplied by PV-inverters, transformer taps and all other voltage control devices. Nodal voltages constitute the set of inequality constraints, thus disregarding the optimum condition on voltage levels. With these methodologies, the optimum condition is usually achieved by increasing the voltage profile, and then reducing current flows, until voltages at some nodes reach their limits. In this case, unpredicted events (sudden overloads, excursion of solar radiations or wind gusts), may bring voltages over the specified limits

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resulting in the nuisance of voltage relays tripping and cascade events. For this reason, it is advisable to directly focus on the optimization of the voltage profile, as we propose in this paper. In doing this, voltage deviations from a reference value are minimized by managing the reactive power provided by PV inverters by solving a constrained dynamic optimization problem. The methodology involves a fictitious dynamic system based on the Lyapunov function that guarantees the existence of a solution.

Additionally, it must be considered that the supplementary injection of reactive power increases inverter losses, thus minimizing PV incomes. In order to stimulate the provision of this important ancillary service, this loss of profits should require an economic compensation mechanism able to guarantee a fair reimbursement to PV generators engaged in this regulation service. With this aim a section of this paper is devoted to analyzing this economic impact.

Several computer simulations have been performed on a typical MV distribution network in order to test performance of the controller developed. The results obtained demonstrate that the controller is able to promptly respond to any change in the system operating point, confirming its ability to control the voltage profile in real-time. Moreover, as an additional output, the algorithm allows the *a-posteriori* costs corresponding to each control action to be evaluated on the basis of the feed in tariff plus the market clearing price for the energy not supplied due to additional inverter losses.

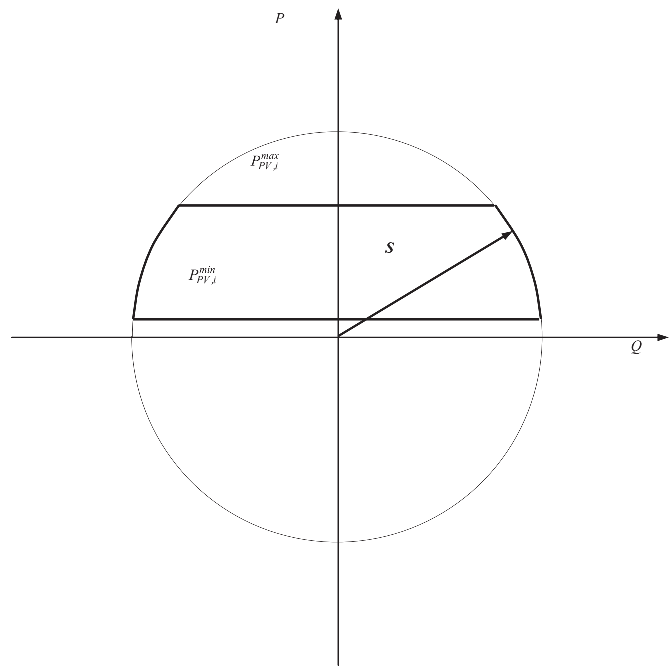

Fig. 1. Loading capability chart of the i-th photovoltaic generator.

2. Reactive power control method

From a mathematical point of view, the voltage control problem can be stated as an optimization problem aimed at minimizing the voltage deviation from a reference value.

The basic elements of the optimization procedure are defined as follows.

2.1. The objective function

Denoting the vector of nodal voltage magnitude measurements with $\boldsymbol{V}(\boldsymbol{Q}_{PV})$ and the vector of nodal reference voltage magnitudes at all buses with $\boldsymbol{V}_{ref}$, the vector of the control error can be defined as follows:

$$\boldsymbol{e}_V = \boldsymbol{V}(\boldsymbol{Q}_{PV}) - \boldsymbol{V}_{ref} \tag{1}$$

where $\boldsymbol{Q}_{PV}$ represents the vector of control variables, i.e. reactive powers injected by photovoltaic plants. The aim is to regulate $\boldsymbol{Q}_{PV}$ until $\boldsymbol{e}_V$ is either zero or minimal. For this purpose, the following performance index, V, is assumed:

$$V(\boldsymbol{e}_V) = \frac{1}{2}\boldsymbol{e}_V^T \boldsymbol{W} \boldsymbol{e}_V \tag{2}$$

where $\boldsymbol{W}$ is a symmetric positive definite matrix whose coefficients weight individual components of the performance index. Note that we have defined this function according to the methodology developed in Ref. [29] to be a Lyapunov function that guarantees the existence of a mathematical solution.

The optimization of the performance index (2) requires the following equality and inequality constraints to be satisfied.

2.2. Equality constraints

$$\boldsymbol{f}(\boldsymbol{x}, \boldsymbol{u}, \boldsymbol{Q}_{PV}) = 0 \tag{3}$$

Eqn. (3) represents the power flow equations, where the state vector $\boldsymbol{x}$ is the nodal voltage vector expressed in terms of magnitude and phase $\boldsymbol{x} = [\boldsymbol{V} \quad \vartheta]^T$, and $\boldsymbol{u} = [\boldsymbol{P}_{PV} \quad \boldsymbol{P}_L \quad \boldsymbol{Q}_L]^T$ is a vector whose elements are the active powers injected by all PV generators and active and reactive powers measured at all load buses.

2.3. Inequality constraints

To avoid impacting economic benefits deriving from the active power production of photovoltaic plants, the reactive power output must be controlled within the photovoltaic generator's capabilities.

There are mainly two factors influencing the capability of the generic *i-th* PV generator. The first one is the minimum $(P_{PV,i}^{\min})$ and maximum $(P_{PV,i}^{\max})$ injectable active power. $P_{PV,i}^{\min}$ represents the minimum value of production below which the inverter shuts down. $P_{PV,i}^{\max}$ is the nominal power of the DC generator corrected by the efficiency of the overall Balance Of System (BOS), typically equal to 75%.

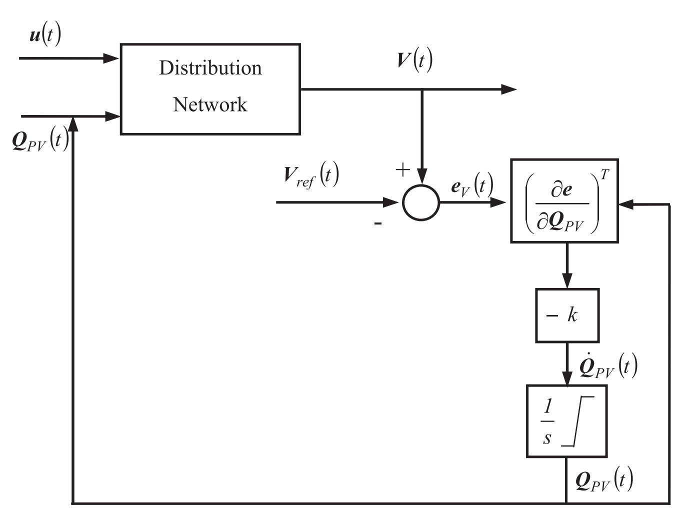

Fig. 2. Basic scheme of the proposed methodology.