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Can PV plants provide a reactive power ancillary service? A treat offered by an on-line controller

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ABSTRACT

This paper proposes an auto-adaptive controller that enables to suitably manage the reactive power supplied by the inverters of PV units whishing to provide the reactive power ancillary service on the base of standard needs or on a voluntary basis. The derived controller is based on an optimization procedure involving the sensitivity theory in conjunction with the Lyapunov function and provides control laws feeding the inverters of the PV units. The controller promptly minimizes system losses preserving the active power produced by the PV plants against the reactive one. In fact, when the PV modules do not get enough sunlight to generate active power, the proposed procedure forces the PV inverters to provide a reactive power equal to the rated power. On the contrary, in order to preserve the major economic benefits for the investor deriving from the produced active power during the sunlight hours, the method automatically reduces the injection of reactive power. The computer simulations, performed on a distribution system, demonstrate that the controller is capable to control the network in the real-time, mainly due to its ability to be auto-adaptive at any changes in the system operating conditions.

1. Introduction

Renewable and sustainable technologies play a key role in the greenhouse gas emission reduction policy across Europe [1]. In this sense, incentives and subsides provided by different countries promote the development of photovoltaic (PV) generation connected to distribution networks [2]. The Italian Government incentivizes the adoption of photovoltaic generation through intensive economic supporting programs [3], resulting in a proliferation of investments in this technology. This very interesting field of investment strongly impacts the energy infrastructure, requiring a new operation management paradigms for a complete restructuring of the infrastructure. In fact, actual systems are designed, constructed and operated in a way that these resources can create big problems, ranging from voltage rise, energy losses and system restoration in case of faults. All these factors can limit the fully exploitation of such resources if some remedial actions are not considered. A chance can be offered by photovoltaic plants, since they can be fruitfully adopted as reactive service providers within distribution grids. A constraint to the development of this ancillary service is imposed by specific technical rules [4] imposing a unitary power factor at connection points of these plants. However, the scientific community is trying to force this limitation developing several control techniques related to the reactive power management. In particular, many papers focus on the analysis of Distributed Generation (DG) impacts on distribution network losses, suggesting control strategies based on the optimal DG placement problem. As reported in [5], methods based on the gradient and the second order adopted in [6], reveal inefficiencies related to computational efforts and slow convergence. In order to overcome the inherent limitation of these methods, authors of [5] propose an optimization problem whose objective function consists of the exact loss formula, obtaining significant improvements in terms of computational efforts for radial and networked systems. Due to the size, complexity and specific characteristics of distribution networks, the method could not be directly applied to distribution systems, as pointed out by [7]. This paper proposes a simple method to contemporaneously minimize the cost of network investment and system losses, whilst meeting voltage constraints. In [8] the authors use a combination of optimal power flows and genetic algorithms deriving an alternative method with better robustness performances. Following the same aim, in [9] the authors propose a multi-objective optimization approach for finding the best compromise for both technical and economical aspects related, respectively, to the improvement of the distribution feeder voltage conditions and the profitability of both PV

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generation and potential loss reduction on the feeder. As observed by the same authors, in this approach the above objectives may conflict with each other. For this reason, authors give the chance to the user to define different scales of objective priorities. About pricing mechanisms, paper [10] suggests a method based on nodal pricing in order to maximize the profit, expressed in terms of cost of losses and voltage profile, of Distribution Companies incorporating DGs.

All these methods suffer the important limitation that they are not capable to consider an objective function related to investor's predilections on locations with more appeal in terms of simplification of authorization procedures or major returns on investments. In order to accomplish this investor's expectation, alternative control strategies are required to improve operation efficiency in distribution grids with high levels of DG integration. Starting from this need, the research activity performed in the last years has exploited the reactive power production capability of these units. This implies that adequate control strategies have to be adopted to manage the reactive power production providing an ancillary service of Volt/Var control. Paper [11] develops a new control algorithm that enables to suitably regulate the reactive power provided by DG units in a distribution feeder. The required control actions are assessed solving an optimization problem. In this problem, the objective function describes the network active power losses subjected to a set of functional and technical constraints. Assumed control variables are the reactive power produced by DG units, transformer taps and capacitors banks installed in distribution substations.

Paper [12] proposes an advanced control strategy decoupling the active and reactive power control chains provided by the PV units.

All these methods take great advances from the PV inverters since they provide good flexibility and versatility. Moreover, they are capable to economically supply reactive power for reducing network losses and congestions. In fact, as demonstrated in [13], the cost-benefit analysis shows the economic attractiveness deriving by the adoption of PV inverters.

In this paper a new method to control the reactive power provided by PV inverters in order to reduce network losses and to constraint voltage magnitudes within limits imposed by the power quality standards [14] is developed. This method is based on the Sensitivity theory involving the Lyapunov function, giving rise to a robust on-line controller.

Test results on a distribution system have been performed to confirm the effectiveness of the developed methodology and, in addition, to demonstrate that it can be usefully applied for real-time applications.

2. Reactive power control method

The aim of this section is to develop a methodology able to minimize active power losses occurring on the system through the reactive power provided by each generation unit connected to the distribution network.

We suppose that the distribution system is fed by m transformer substations and n photovoltaic plants, as shown in Fig. 1.

With the aim to minimize system losses, we define a performance index, $\mathcal{V}$, as follows:

$$\mathcal{V}(\mathbf{Q}_{\mathrm{PV}}) = \frac{1}{2}\mathbf{P}_{\mathrm{TR}}^{\mathrm{T}}(\mathbf{Q}_{\mathrm{PV}})\mathbf{P}_{\mathrm{TR}}(\mathbf{Q}_{\mathrm{PV}}) \quad (1)$$

where components of the vector of control variables are represented by reactive powers injected by photovoltaic plants, $\mathbf{Q}_{\mathrm{PV}}$,

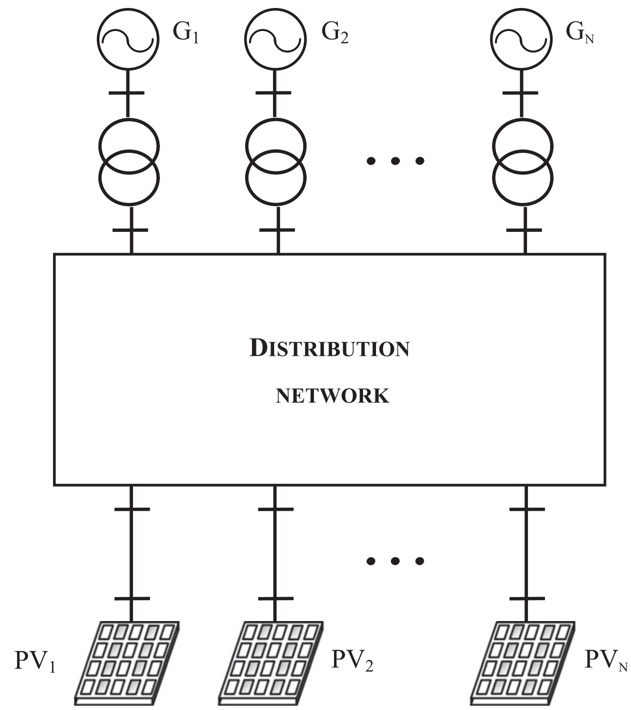

Fig. 1. Distribution Network scheme including PV systems.

whereas $\boldsymbol{P}_{\mathrm{TR}}$ represents the total active power injected by substation transformers.

For a fixed level of active power generated by photovoltaic plants, the minimization of the total active power injected by transformer substations induces an indirect reduction of system losses. Thus, assuming as cost function the performance index defined by (1), the overall optimization problem can be formulated as follows:

$$\min_{Q_{\mathrm{PV}}} \mathcal{V}(\mathbf{Q}_{\mathrm{PV}}) \quad (2)$$

subject to the following equality and inequality constraints:

$$f(\mathcal{V}, \vartheta, \mathbf{Q}_{\mathrm{PV}}) = 0 \quad (3)$$

$$\begin{gathered} -\sqrt{\mathbf{S}_{\max}^2 - \mathbf{P}_{\mathrm{PV}}^2} \le \mathbf{Q}_{\mathrm{PV}} \le \sqrt{\mathbf{S}_{\min}^2 - \mathbf{P}_{\mathrm{PV}}^2} \\ \mathbf{V}^{\min} \le \mathbf{V} \le \mathbf{V}^{\max} \end{gathered} \quad (4)$$

Eq. (3) represents the set of Load-Flow equations and inequalities expressed by (4) represent constraints on control variables and on operating limits of the network.

At every system change, the problem (2) needs to be restarted deriving a new subsequent optimal operating point. The basic idea of this paper is to develop an on-line optimization procedure able to renew the operating point in the continuous time domain. In this sense, the solution of the problem stated through (2) can be evaluated as the "equilibrium point" of a dynamic system whose state variables, $\mathbf{Q}_{\mathrm{PV}}$, change in the continuous time domain.

The resulting optimization problem can be solved finding the equilibrium point (if any) of the time domain behavior of the performance index (1). It must be noted that the defined function to be minimized is an always positive definite Lyapunov function. If the time derivative of $\mathcal{V}$, $\dot{\mathcal{V}}$, can be made negative definite, we can assure the existence of a stable equilibrium point. Thus, determining $\dot{\mathcal{V}}$, we obtain: