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Distributed voltage control strategy for LV networks with inverter-interfaced generators

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ABSTRACT

Low voltage distribution networks are characterized by an ever growing diffusion of single and three phase distributed generators whose unregulated operation may deplete the power quality levels, in particular as regard voltage profiles and unbalances. This issue is at present under discussion by several national and international standardization bodies and the general trend is to require, for the new connections of generators to medium and low voltage grids, their participation to the reactive power network management. In this paper a novel strategy proposes to control the network voltage unbalance suitably for coordinating single and three-phase inverter interfaced embedded generators, concurrently with a local volt/var regulation action as foreseen by the new grid connection requirements. Simulations conducted on case study network representing a typical Italian 4-wire LV distribution system under different load/generation conditions, demonstrate that the coordinated action of single-phase and three-phase inverters may considerably reduce the degree of unbalance thus improving the network power quality levels.

1. Introduction

In modern electricity distribution networks the vertically integrated grid paradigm is rapidly changing due to an ever growing amount of power generated at lower voltage levels. The presence of renewable intermittent generation resources (e.g., photovoltaic) and new storage-capable loads (e.g., plug-in hybrid electric vehicles), commonly referred to as Distributed Energy Resources (DERs) is often cause of undesired voltage and current unbalances and higher network losses. It is thus recognized that additional network regulation actions are desirable, if not necessary, in order to operate LV active networks at acceptable power quality levels.

In this view, discussions are taking place within several national and international standard bodies, regarding the participation to active and reactive power control of these distributed resources [1,2]. Recently issued standards, for instance, specify the operational criteria that distributed generators connected to the distribution network are required to adopt in order to maintain the power quality levels or even to provide some ancillary services to the grid. For the scope, the standards define a number of different control strategies for modulating the generator power factor in order to exchange reactive power with the grid on the basis of either local measurements or remote signals [3,4].

Various control strategies have recently been proposed for modulating the reactive power exchanged by active users with the network, with the aim of mitigating the effects of their unregulated operation, basically exploiting the flexibility which may be provided by the inverter interfacing a DER to the grid [5–11]. The main underlying feature of these contributions is the possibility to provide ancillary services to the grid without imposing any curtailment, or additional active power production, to the DERs.

In this paper starting from, and going beyond, the recent grid connection rules defined in the Italian grid code for connection of LV generators [3], the possibility of a more effective participation of inverter-interfaced DGs for reactive power control is investigated. The idea is to efficiently exploit all the reactive power exchangeable by the inverter with the grid independently on the active power, thanks to the ability of inverters, suitably controlled, to work on four quadrants [7]. This feature could be available not only for generators, but for any user utilizing an inverter as interface with the network (such as, for instance, electric vehicles recharge systems).

Voltage magnitude deviation from rated level is only one aspect of the power quality issues that may occur. In fact, because of the single-phase nature of many of the LV network users, sometimes the voltage unbalance may reach unacceptable levels, causing the circulation of negative and zero-sequence currents. In addition, the local voltage regulation recently introduced by the standards for the distributed generators, if not correctly coordinated, may further increase the unbalance conditions.

With the aim of improving the power quality in LV networks, a control procedure for the voltage unbalance correction is proposed,

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consisting in a current control for the operation of three-phase inverters, even considering the option of redistributing the active power produced through the three phases, without altering the overall active power generation.

It is then shown that the same principle may be suitably adapted for a distributed network regulation strategy, giving the possibility to involve both single and three phase inverter-interfaced generators. For the scope, the correction currents are easily converted into conservative control variables, active and reactive power, in order to forward requests of contribution to the distributed inverters.

Three-phase asymmetrical power flow studies on a low voltage case study network have been carried out. Considering the generators interfaced to the grid through single-phase and three-phase inverters, control strategies for the concurrent regulation of voltage levels and unbalance compensation are applied. Analysis are conducted under several load and generation conditions through 24 h simulation on a case study LV network with unbalanced single-phase loads and photovoltaic DGs interfaced by single and three-phase inverters. Potential benefits and limitations of the proposed control scheme are analyzed and discussed.

2. Connection rules for low voltage active users

In the recent years, several new standards have been released, stating the new concept that LV active users have to provide some sort of ancillary services to the grid during their normal operation, basically by modulating their reactive power exchanged with the grid.

The German standard VDE 4105 [4] states that DGs connected to LV grids should apply a power factor (P.F.) adjustment in order to contribute to the network voltage regulation. This regulation is provided by an active-power based characteristic setting the dependency of the P.F. from the active power generated up to the lock-out value of 20% Pn.

The recent Italian standard CEI 0-2 states similar operating conditions for DGs connected to LV networks, putting in evidence the importance active users to contribute to the grid management, requiring the adoption of different control schemes depending on the generator rated power and network conditions [3]. Two capability areas are specified for reactive power regulation: the first sets a dependency of the reactive power from the active power produced and is required for any inverter connected to the LV grid, whereas the second capability area, applicable for inverters with rated power above 6 kW, unties the regulation from the actual production. To be noted that the latter represents an important innovation since it states that inverters with rated power above 6 kW may be required to exchange reactive power even with low production, essentially providing an ancillary service to the grid.

The Italian normative also indicates the control strategies for performing the above mentioned “distributed” regulation actions, pictorially represented by the two characteristics reported in Fig. 1. DGs with small rated power ($3 \leq Pn \leq 6$ kW) are required to adopt the control shown in Fig. 1a (unitary P.F. when the generated active power is lower than 50% Pn and linearly decreasing with P.F., to a minimum of 0.9 lagging when $P = Pn$).

For installations with rated power higher than 6 kW, the reactive power to be exchanged with the network is evaluated according to a characteristic of the type shown in Fig. 1b. The distributors have the possibility to require an ancillary service setting the minimum and maximum voltages (lock-in and lock-out voltages) which, along with the maximum exchangeable reactive power, constitute the regulating characteristic of the inverter.

Although the new standards introduced several innovations to the inverter controls for grid services, the fact that modern inverters, when equipped with the appropriate control, offer the possibility to exchange reactive power with the grid also when the downstream generator is at low or null production level, expands the capacity of reactive power exchangeable with the grid even to the full rated inverter size [5,6].

3. Proposed voltage regulation strategy

In this section a novel control scheme is described for enabling inverter-interfaced DGs to participate in the network voltage unbalance compensation while concurrently performing the local voltage regulation through the reactive power modulation as foreseen by the standards and described in Section 2.

3.1. Problem definition for local control

In 4-wires LV distribution networks, where most of the users (loads and DGs) are single-phase connected, different loadings on the three-phases may cause high current unbalances, with significant negative and zero sequence current components which would adversely affect the operation of the network. The uncoordinated local voltage regulation action performed by distributed generators in accordance with the new grid connection rules, which may give rise to high reactive power flows, are likely to further worsen the voltage unbalance conditions throughout the network. In order to mitigate such unbalances, a number of strategies suitable for three-phase inverters can be found in the literature [6,7]. An alternative control method of three-phase inverter-connected DGs for compensating the negative and zero sequence current components has been proposed by the authors [8] and is briefly recalled below.

Four wires three-phase inverters can be used as shunt active power filters to reduce the zero- and negative-sequence current components generated by unbalanced loads [9]. In addition, besides being a source of controllable reactive power, they have also the ability of unevenly modulate the amount of active power injected on each leg (Pk, $k = a,b,c$), thus generating a non-symmetrical current triplet which can balance the branch currents while satisfying the constraint of maintaining a constant overall generated active power:

$$\sum_{k=a}^{c} P_k = \sum_{k=a}^{c} Re[E_k \times \hat{I}_{3ph_k}] = \bar{P}_{3-ph} \tag{1}$$

where E_k and I_{3ph_k} are the kth phase voltage and current, respectively, originally injected by the inverter, giving rise the total three-phase active power $\bar{P}_{3-ph}$,as schematically depicted in Fig. 2.

In order to calculate the correction currents to be injected by the inverter for balancing a branch current triplet, the well-known Fortescue transformation (2) allows estimating the sequence components of the current flowing in the interested branch,

$$\begin{bmatrix} Im_0 \\ Im_+ \\ Im_- \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \times \begin{bmatrix} Im_a \\ Im_b \\ Im_c \end{bmatrix} \tag{2}$$

where $Im_{0,+,-}$ indicate the sequence current components, whereas $Im_{a,b,c}$ are the actually measured branch currents.

The correction phase current triplet $dIB_{a,b,c}$ to be injected in order to balance the line currents, i.e., to maintain solely the positive sequence component, is straightforwardly calculated as

$$\begin{bmatrix} dI_{Ba} \\ dI_{Bb} \\ dI_{Bc} \end{bmatrix} = \left(\frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \right)^{-1} \times \begin{bmatrix} -Im_0 \\ 0 \\ -Im_- \end{bmatrix} \tag{3}$$