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Three-phase inverter-connected DG-units and voltage unbalance

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ABSTRACT

The increasing presence of single-phase distributed generators and unbalanced loads in the electric power system may lead to unbalance of the three phase voltages, resulting in increased losses and heating. The distribution network operators (DNOs) are increasingly being challenged to maintain the required power quality. To reduce voltage unbalance DNOs are seeking to connect larger DG units to the three phases instead of a single-phase connection. The three-phase connection can be realised by three single-phase inverters or by a three-phase inverter. Each inverter topology can be implemented with different control strategies. The control can be equiped with active power filtering functions which can improve the power quality. In this paper, the effect of connecting DG units by means of a three-phase connection instead of a single-phase connection on voltage unbalance is studied. Besides two commonly used control strategies, two other control strategies that combine DG and active power filtering functions are implemented and their effect on voltage unbalance is studied. The last two control strategies lead to the reduction of voltage unbalance such that the voltage requirements are maintained.

1. Introduction

Ideally, the generated voltages in three-phase power systems are symmetrical. However, the resulting voltages at the point of common coupling (PCC) and at the point of connection (POC) can be unbalanced for several reasons. The nature of the unbalance includes unequal voltage magnitudes at the fundamental system frequency (under- and over-voltage), fundamental phase angle deviation and unequal levels of harmonic distortion between the phases [32].

Unbalance can result in adverse effects on equipment and on the distribution system. An unbalanced distribution system will be subjected to more losses and heating effects. Voltage unbalance can also have negative effects on equipment such as induction motors, power electronic converters and adjustable speed drives [17,16,32,22,29]. Avoiding these negative effects requires maintaining a balanced voltage at the POC.

The distribution network operators (DNOs) are increasingly being challenged to maintain the required power quality. DNOs are imposing to connect larger distributed generation (DG) units (viz >3.6 kVA in Belgium) to the three phases instead of one to reduce voltage unbalance.

Improving voltage unbalance can be achieved by installing three-phase systems especially designed to improve the power quality. An example of such a three-phase system is a Unified Power Quality Conditioner (UPQC) which is controlled to deliver a small amount of negative-sequence current into the grid to decrease the negative-sequence voltage component [33,13].

There are several possible topologies to connect DG units to a three-phase distribution network. The most common practice nowadays is to use three single-phase inverters which share a common dc-bus and the corresponding dc-bus voltage controller [8,5,7,27]. This will result in a system with power factor near to one as three single-phase current controllers are used which result in currents in phase with the grid voltage. Another possibility is a three-phase four-wire inverter [4,19,9]. Both topologies can be controlled by using different control strategies [23,24].

Presently, two control strategies are frequently used. For three-phase systems consisting of three single-phase inverters with a common dc-bus, a single-phase sinusoidal control strategy is used [8,5,7]. Each single-phase inverter injects a sinusoidal current in phase with the respective phase voltage. Another frequently used control strategy for three-phase inverters is the positive-sequence control strategy [4,34,19,3,2]. The inverter is controlled such that it injects a positive-sequence current. These two control strategies will not deteriorate the voltage unbalance but will neither improve it.

The voltage unbalance can be improved when the control strategies are altered such that they possess active power filtering functions [14,28]. Adding active power filtering functions to the control strategy of inverter-connected DG units can lead to an improved power quality [15]. Therefore in this paper, the two previous commonly used control strategies are equiped with active power filtering functions. The single-phase sinusoidal con-

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Table 1
Supply voltage requirements according to EN 50160.

Parameter	Characteristics
Power frequency	LV, MV: mean value of fundamental measured over 10 s. ±1% (49.5–50.5 Hz) for 99.5% of week −%/+ 4% (47–52 Hz) for 100% of week
Voltage magnitude variations	V_{nom} = 230 V, ±10% for 95% of week; mean 10 min rms values
Supply voltage dips	Majority: duration <1s, depth <60%. Locally limited dips caused by load switching on: 10–50%
Supply voltage unbalance	Negative-sequence voltage component <2% for 95% of the week, mean 10 min rms values

trol strategy can be improved by adding a signal to the reference current, this signal results in a resistive behaviour towards voltage disturbances independently of the input power [26,25]. An alternative three-phase control strategy is the three-phase damping control strategy which is presented in this paper. Besides injecting positive-sequence power, the three-phase damping control strategy behaves resistively towards the zero- and negative-sequence voltage component (independently of the input power) which will lead to an improved voltage unbalance.

Instead of installing three-phase systems especially designed to improve the power quality, the increasing presence of inverter-connected DG units can be used to decrease voltage unbalance by implementing the appropriate control strategy. In this paper, the influence of the different control strategies for DG-units on voltage unbalance is studied.

2. Voltage unbalance factor

There are three commonly used definitions of voltage unbalance, developed by NEMA (National Equipment Manufacturer's Association), IEEE and the power community, respectively [21,6]. In this paper, the percentage voltage unbalance factor (% VUF) is chosen as a measure to evaluate the voltage unbalance.

Based on the theory of symmetrical components, voltage unbalance can be divided into two parts corresponding to the negative-sequence and the zero-sequence component of the voltage. For instance, induction motors are very sensitive to the negative-sequence voltage component as the negative-sequence impedance is small. Even a small negative-sequence voltage component leads to large currents and thus increased losses. On the other hand, the zero-sequence component of the voltage can result in currents flowing in the neutral conductor which causes heating and zero-point shifting [12,28].

The voltage unbalance factor (% VUF) is given by the ratio of the magnitudes of the fundamental negative-sequence voltage component to the positive-sequence voltage component:

$$\%\mathrm{VUF} = \frac{V_2}{V_1}100. \tag{1}$$

The zero-sequence voltage unbalance factor (% VUF_0) is given by the ratio of the magnitudes of the zero-sequence voltage component to the positive-sequence voltage component:

$$\%\mathrm{VUF}_0 = \frac{V_0}{V_1}100. \tag{2}$$

The DNOs are obliged to maintain the voltage to certain requirements. The supply voltage requirements of public distribution systems in Belgium are based on the standard EN50160 [1]. An overview of the most important aspects of this standard is given in Table 1. The two most important parameters for this paper concern voltage magnitude variations and supply voltage unbalance.

3. Voltage-source inverter control strategies

The control of an inverter can be divided in two parts: the dc-bus voltage controller and the current controller. The dc-bus voltage controller maintains the balance between the ac- and dc-power and outputs the fundamental input conductance g_1 which is a measure for the power injected by the DG unit [20]. g_1 is positive when the inverter injects power and negative when the inverter absorbs power. In case of an unbalance between the ac- and dc-power, the dc-bus voltage will deviate from its reference value. The dc-bus voltage controller will react by changing the fundamental input conductance g_1 in order to restore the balance. This input conductance is used to derive the reference values for the different currents in the respective phases. The current controller makes sure that the inverter provides the reference current. The possible error between the reference current and the measured current is eliminated by a PI-controller which outputs the duty ratio for the switches.

As stated in the introduction, there are two possible topologies to connect the DG units to a three-phase distribution network. The first possibility is to use three single-phase inverters which share a common dc-bus and the corresponding dc-bus voltage controller. The second possibility is using a three-phase inverter. These two topologies can be combined with two current control strategies, which will be described further in this section. The control strategies differ in the way the reference values for the current are determined.

First, the two frequently used control strategies will be discussed, namely the single-phase sinusoidal control strategy and the (three-phase) positive-sequence control strategy. Then, the active power filter equiped control strategies will be handled: the single-phase control strategy behaving resistively towards voltage disturbances and the three-phase damping control strategy. The last two control strategies are not presently used but when implemented they could lead to an improved voltage unbalance as discussed further in this paper.

3.1. Single-phase sinusoidal control strategy

The reference values for the different currents in case of a sinusoidal current controller are:

$$i_x = g_1 \sin(\theta_x) \tag{3}$$

with $x = a, b$ or c and where g_1 is the fundamental input conductance. Small letters denote pu quantities. θ_x is the phase angle of phase voltage x. The current injected by the DG is in phase with the respective phase voltage (power factor equal to one). This can be achieved by using three single-phase inverters or by using a three-phase inverter and three single-phase phase-locked loop (PLL) systems. In both possibilities the phase angles of all three phase voltages are obtained such that a reference current can be obtained which is in phase with the respective phase voltage (cf (3)).

In order to achieve a better understanding on the influence of the sinusoidal control strategy on voltage unbalance, a symmetrical components model is deduced. Based on (3), the complex form of the injected currents can be written as:

$$\underline{i}_x = g_1 \exp(j\theta_x) \tag{4}$$

This equation can be converted to symmetrical components:

$$\begin{aligned}
\underline{i}_0 &= \frac{1}{3}g_1[\exp(j\theta_a) + \exp(j\theta_b) + \exp(j\theta_c)] \\
\underline{i}_1 &= \frac{1}{3}g_1\left[\exp(j\theta_a) + \exp\left(j\left(\theta_b + \frac{2\pi}{3}\right)\right) + \exp\left(j\left(\theta_c - \frac{2\pi}{3}\right)\right)\right] \\
\underline{i}_2 &= \frac{1}{3}g_1\left[\exp(j\theta_a) + \exp\left(j\left(\theta_b - \frac{2\pi}{3}\right)\right) + \exp\left(j\left(\theta_c + \frac{2\pi}{3}\right)\right)\right]
\end{aligned} \tag{5}$$