Distribution Network Voltage Unbalance Control under High Penetration of Single-Phase Photovoltaic Microgeneration

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Abstract. Electricity distribution networks are now faced with increasing penetration level of small-scale decentralized renewable energy generation. Meanwhile, distribution network operators are concerned with adverse impacts such as voltage rise and three-phase voltage unbalance that would result. This paper focuses on single-phase solar photovoltaic (PV) integration voltage unbalance issues and proposes a local voltage control strategy for a low voltage (LV) distribution network. The proposed control method is based on real-time management of the active and reactive powers. Simulation results show that the proposed algorithm maintains the quality and reliability of the three-phase voltage in the network and hence provides a potential solution to the challenges facing future distribution networks.

Keywords: Distributed generation (DG), voltage unbalance, distribution network, Photovoltaics.

1 Introduction

Recent years have witnessed a continuing upward trend in renewable energy infrastructure investments throughout the world. Several countries have adopted various support schemes to promote the renewable energy generation (feed-in tariffs, green certificates, capital subsidies and grants, tax exemptions etc.).These incentive measures have stimulated a widespread deployment of wide range of distributed electricity generation from renewables. Among these, local generation from roof mounted solar PV systems have been very popular.

Distributed energy generation (DG) has several technical advantages including balancing of power flow and steady-state conditions, grid support on power delivery, reduction in transmission line investment, easy installation and start-up and economic benefits from both the consumers and energy providers point of view.

However, the influx of DG connection to the LV distribution grid poses new challenges to network operators. The main technical issues are linked to the limitations of the grid DG hosting capacity in one hand, and the regulatory issues that require energy distributors to accept the connection of small-scale energy producers on the without violating the technical standards of the network (equipment ratings, power quality, etc.) on the other hand. These issues are currently largely debated to identify appropriate

regulations and methodologies on how to plan and operate the existing distribution networks [1, 2].
In the past, research and study have been focusing on the connection of DG on the medium voltage network without neutral line and balanced operation was assumed [3]-[4]. Now, residential customers can directly inject single phase DG power into the 3 phase 4 wire LV distribution network. The network voltage unbalance factor and power losses in the LV network with DG were studied [5-6]. The load models used in this paper are taken from [7].
This paper analyses the impacts of high penetration of single-phase solar PV systems on a three-phase distribution network under unbalanced conditions, taking into account the NEMA and IEEE indexes and proposes a method to regulate the voltage unbalance factor [8, 9]. The approach is based on the local control of reactive power production. Furthermore, all the DGs are controlled independently [10].
The paper is organized as follows: Section 2 overviews the voltage characteristics in LV networks under balanced and unbalanced conditions. Section 3 presents the proposed method to regulate the voltage unbalance factor. The results of the simulation studies are discussed in Section 4. Section 5 presents the conclusions of this simulation study.

2 Voltage Characteristics in LV Networks

A three phase system is said to be balanced or symmetrical if the voltages and phase currents have the same amplitude and are out phase by 120° with respect to each other. If at least one of these conditions is not met, the system called unbalanced or asymmetrical [11].

In most practical cases (without DG), the load asymmetry is the main cause of unbalance. However, in most low voltage network, the loads are usually single-phase, and are distributed on the phases of the three-phase system [12] therefore, it is difficult to maintain a balance between phases.

2.1 Voltage Unbalance

When seeking to evaluate the quality of a three-phase voltage system, it is important to ensure that the unbalance rate is below regulatory limit of the voltage unbalance factor.

The commonly used definitions to specify the level of voltage unbalance are given by IEEE and NEMA Standards [13]. Another definition of voltage unbalance is the ratio of the negative sequence voltage component to the positive sequence voltage component

$$\text{VUR}\ (\%) = \frac{V_2}{V_1} \times 100 \tag{1}$$

Where V_1 and V_2 are the rms of the inverse and direct system voltage respectively. Therefore, the determination of VUR is based on the properties of symmetrical components applied to the three-phase system. Note that when the system is balanced (no negative component), the unbalance rate is zero.

2.2 Symmetrical Components

The three-phase system can be decomposed into a direct component, a negative sequence and a zero sequence system, denoted by subscripts 1, 2 and 0 respectively as shown in Fig. 1.

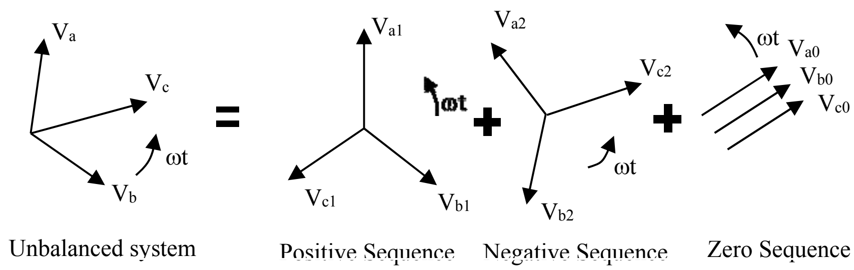

Fig. 1. Symmetrical components of unbalanced three phases.

The matrix representation of the three voltage components is written as:

$$V_{abc} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} V_{a1} \\ V_{b1} \\ V_{c1} \end{bmatrix} + \begin{bmatrix} V_{a2} \\ V_{b2} \\ V_{c2} \end{bmatrix} + \begin{bmatrix} V_{a0} \\ V_{b0} \\ V_{c0} \end{bmatrix} \quad (2)$$

The sequence components differ only by their phase angles, which are symmetrical and shifted by 120°. Define the operator φ phasor vector forward by that angle: $\varphi = e^{j120°}$ and $\varphi^2 = e^{j240°}$.

The zero sequence components are in phase and are denoted by:

$$V_0 \equiv V_{a0} = V_{b0} = V_{c0} \quad (3)$$

and the other phase sequences as:

$$V_1 \equiv V_{a1} = \varphi V_{b1} = \varphi^2 V_{c1}$$
$$V_2 \equiv V_{a2} = \varphi^2 V_{b2} = \varphi V_{c2} \quad (4)$$

Thus,

$$V_{abc} = \begin{bmatrix} V_0 \\ V_0 \\ V_0 \end{bmatrix} + \begin{bmatrix} V_1 \\ \varphi^2 V_1 \\ \varphi V_1 \end{bmatrix} + \begin{bmatrix} V_2 \\ \varphi V_2 \\ \varphi^2 V_2 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \varphi^2 & \varphi \\ 1 & \varphi & \varphi^2 \end{bmatrix} \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} \quad (5)$$

The vector for three phase voltages is determined by the matrix equation:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \varphi^2 & \varphi \\ 1 & \varphi & \varphi^2 \end{bmatrix} \cdot \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} \quad (6)$$

The symmetrical components for the voltages V_{abc} are determined by the inverse transform:

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \varphi & \varphi^2 \\ 1 & \varphi^2 & \varphi \end{bmatrix} . \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (7)$$

With these transformations the energy is invariant and therefore the powers calculated from the original values or transformed values will be the same.

3 Local Voltage Support Strategy

The voltage setting, before being considered as a centralized function coordinated by the DG, can also be studied from the local perspective.

The author in [14] proposed a voltage support scheme based on a local control strategy applied for each DG. The controller operates in two different modes: (1) Normal operation mode (called P/Q) provides power control (2) Perturbed operation mode (called P/V) provides voltage and active power control. Mode 1 applies when the voltage is below an intermediate pre-determined threshold value whereas mode 2 is used when the voltage increases above the permissible limit [15].

The supervisory controller is capable of adjusting the desired voltage level according to the operating voltage and power ratings of each DG. At each node, the desired voltage limits V_{min} and V_{max} are adapted to the voltage level and the amount of reactive power generated or absorbed. Using this adjustable limit of the desired voltage will allow all DGs to participate to the regulation of the overall voltage in the distribution network.

As the voltage gets closer to 1 p.u., the voltage window [V_{min}, V_{max}] becomes narrower. On the other hand, as the amount of reactive power injected or absorbed increases, the voltage window [V_{min}, V_{max}] becomes larger while respecting the order $V_{min,admissible} \leq V_{min,desired} \leq V_{max,desired} \leq V_{max,admissible}$.

Fig. 2 shows the structure of the supervisory controller adopted here.

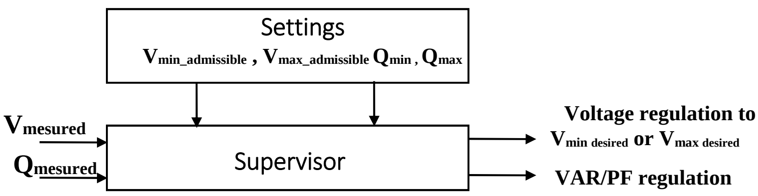

Fig. 2. Structure of the control scheme.

The operation principle of the self-adaptive control is shown in the Fig. 3(a). This controller does not take the voltage unbalance rate into account and the aim of this paper is to propose another approach which takes into account this constraint using VUR (%) as the control objective. This is illustrated in Fig. 3(b). The adaptive local setting is developed in Matlab whereas the unbalanced three phase load flow is performed under the distribution system simulator OpenDSS. The two programs are interfaced via a COM (Component Object Model) [16].

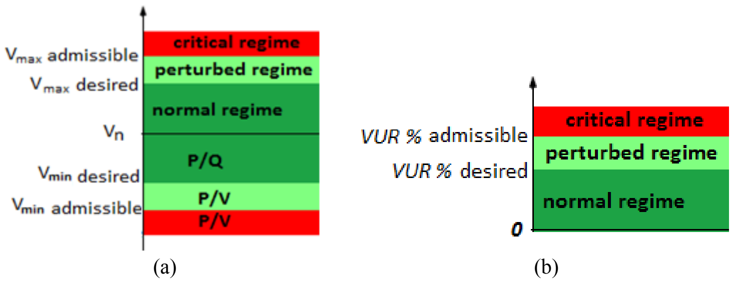

Fig. 3. Adaptive setting: (a) voltage thresholds (b) unbalance rate thresholds.

The implementation of the proposed method is described by the flowchart of Fig. 4.

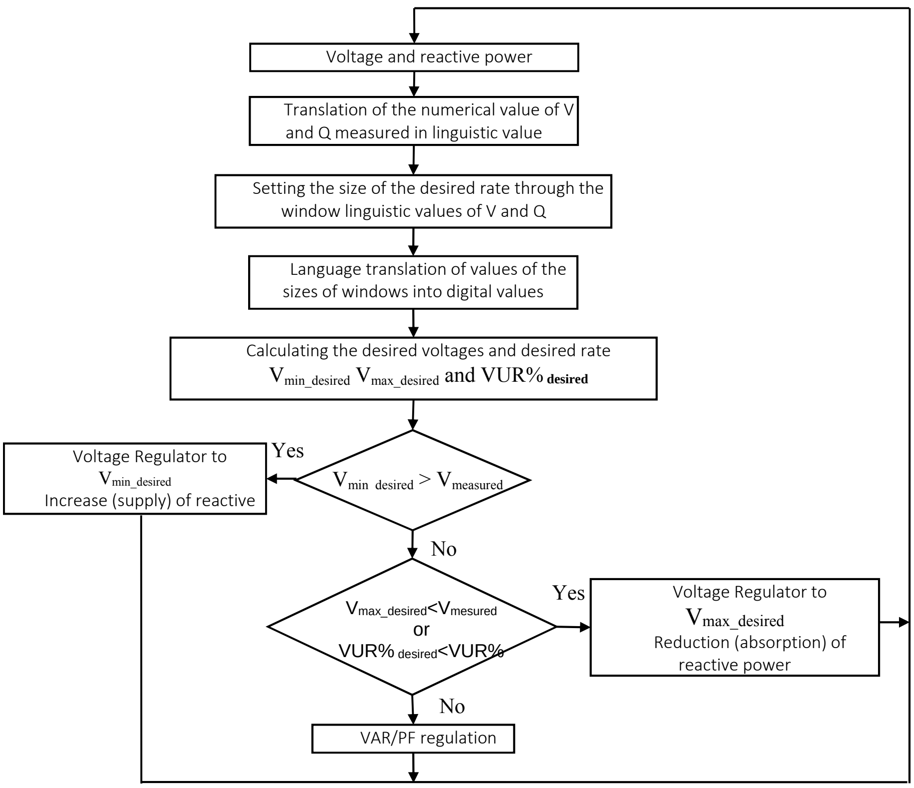

Fig. 4. Flowchart describing the implementation of the control method.

4 Test System

The proposed adaptive local setting is tested on a real LV network provided by SDO Algeria. The neutral phase OLT network is fed by a transformer of 160 kVA, 30/0.4

kV. It consists of 126 nodes,16 three-phase loads and 51 single-phase loads. The configuration of the network is shown in Fig. 5 [17].

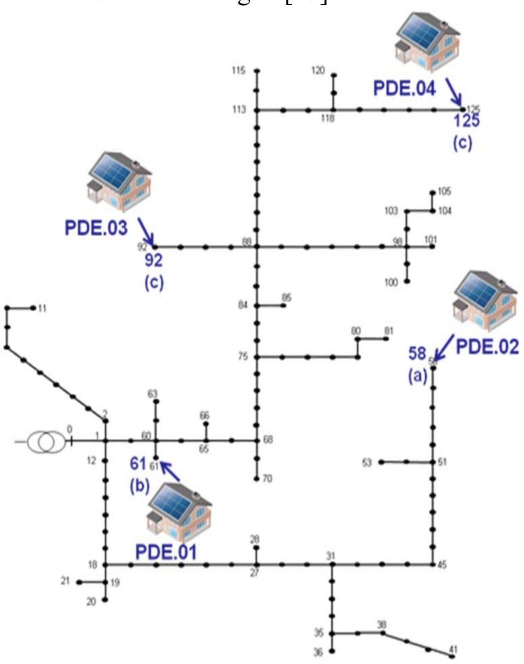

Fig. 5. LV network topology.

The load installed on the LV distribution network is shown in Fig. 6. The data was recorded in a rural area on 17thJune 2013.

There are four DG of 2 kW single-phase PV Type connected to the LV network. It is assumed that PV systems operate in voltage regulation mode. The voltage is set at 1.02 times their nominal values [18].

Fig. 7 shows the decentralized production value for each hour of a day of one PDE. PV power generation used in the simulations are given in [19].
The connection points of the four DGs on the LV network are summarized in Table 1.

Table 1. Connection points of the PDF over the network.

DG n°	Connecting point	
	at Bus	at phase
01	61	-b-
02	58	-a-
03	92	-c-
04	125	-c-

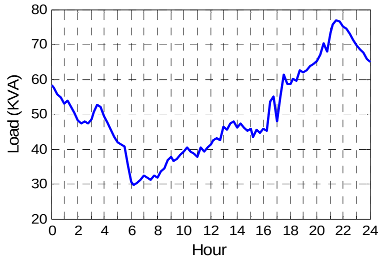

Fig. 6. Load curves.

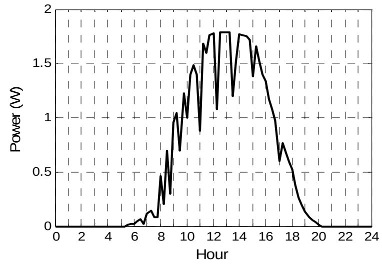

Fig. 7. Power profile generated by a DG.

5 Simulation Results

In this section, two simulation scenarios are presented to illustrate the performance of the proposed voltage control strategy.

5.1 Without regulation

The results of Fig. 8 show the voltage waveforms and unbalance rate at nodes 61, 58, 92 and 125.

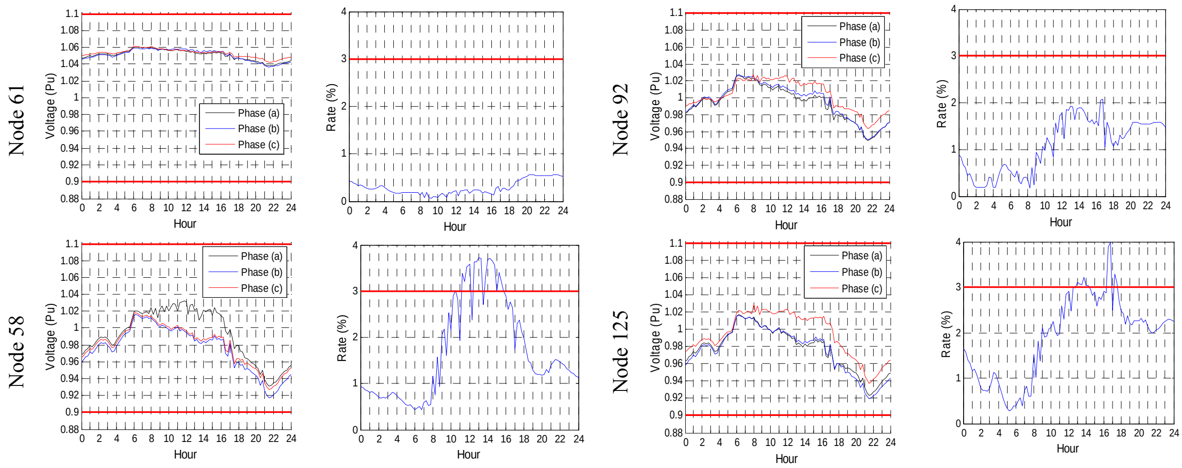

Fig. 8. Voltage and unbalance rate at the DG nodes (without voltage control).

The voltages of the three phases at node 61 are almost the same, because it is closer to the source (transformer station). That is why the voltage unbalance rate is lower. There is an increase in the difference between the voltages of phase (a) (DG connection phase) and the other phases in the period between 7 am and 5 pm. At this time, the PDE has sufficient power to maintain the voltage close to 1.02 p.u which causes an increase in the unbalance rate during this time period and an overshoot above the admissible limit of 3% (Fig. 8, nodes 58 and 125).

Similar remarks apply to the voltage response and unbalance rate at nodes 92 and 125 as for node 58. There is no unbalance rate limit at node 92 because the difference between the value of the voltage of the DG connection phase and the voltages of the other phases is lower due to a lower voltage drop across the phases when the DG is not connected.

5.2 With regulation

Fig. 9 show the voltage waveforms and unbalance rate at the nodes at which the four DGs are connected.

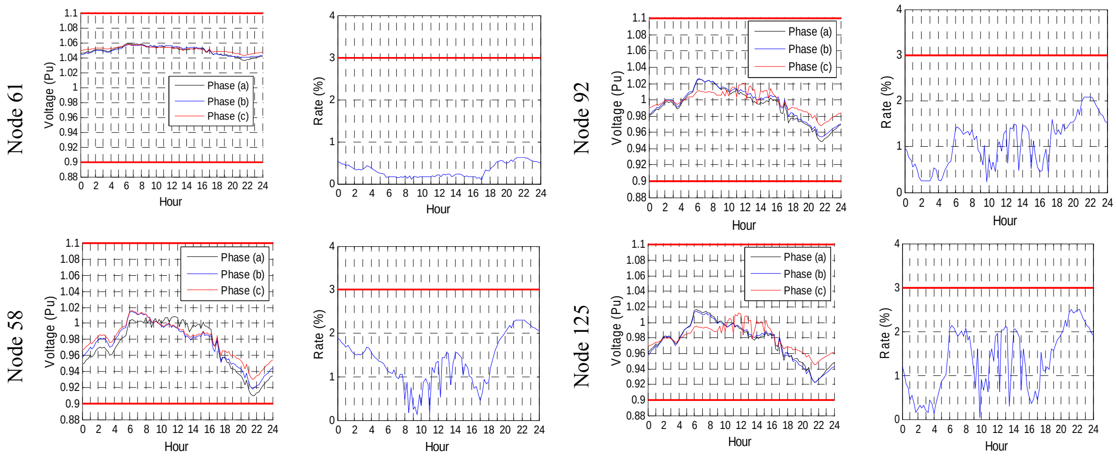

Fig. 9. Voltage and unbalance rate at the DG nodes (with voltage control).

These results show that with the proposed control strategy, the voltages at those nodes which exhibited severe unbalance in the previous simulations are maintained within the reasonable tolerance.

6 Conclusion

The paper proposed a control approach for the regulation of voltage unbalance in a distribution network with interconnected single-phase PV distributed generation. The simulations presented demonstrate the ability of supervisory controller to efficiency regulate the voltage and reactive power flows in the system under unbalanced conditions. In the case of the local setting, the participation of each DG is not optimised but depends on the constraints obtained at the connection point. In addition, the largest unbalance rates are obtained at the nodes connected to DGs and therefore are considered as local problems that are local problems and if the DGs are able to maintain the voltage at their connection point, the voltage unbalance will be eliminated from the whole network.

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