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A Voltage Rise Mitigation Strategy under Voltage Unbalance for a Grid-Connected Photovoltaic System

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Abstract

This paper analyzes the effect of unbalanced voltage on voltage rise for a grid-connected photovoltaic (PV) system, and proposes a voltage rise mitigation strategy which injects negative-sequence currents to compensate the unbalanced voltage aiming especially to reduce the voltage rise. The paper also discusses how the averaged powers related to the injected negative-sequence currents are measured by the power meter. Simulation result confirms the superior performance of the proposed strategy over the classical method which suppresses the voltage rise by adjusting the power factor.

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Keywords: grid-connected photovoltaic inverter; unbalanced voltage; voltage rise; negative-sequence current injection.

1. Introduction

The occurrence of voltage rise due to the injection of power from a PV system into the power system network is a major problem for high penetration of PV generation. It is also observed that the voltages at the point of common coupling (PCC) are usually unbalanced due to the unbalanced loads in the system. To keep the system in healthy condition, the limits around 5% for voltage rise and 2% for voltage unbalance are required. One popular method to solve the voltage rise problem is by injection of reactive power in positive sequence. However, this is uneconomic because the PV owner may be charged for the injected reactive power. Also, some works have been done on unbalanced voltage compensation by using strategies such as injection of active or reactive power [1-2]. But, their

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objective is rather to improve the power quality than to solve the voltage rise problem. In general, the voltage rise and voltage unbalance are treated as two unrelated issues.

However, in this paper, it is revealed that voltage unbalance usually contributes significantly to the maximum line-to-line voltage which is the criterion for voltage rise or overvoltage. Therefore, the voltage rise over the limit is in fact caused by two factors; the reverse power flow and the voltage unbalance. With this understanding, it is proposed in this paper that cancellation of voltage unbalance by negative-sequence current injection should be done first to reduce the maximum line-to-line voltage. And if this measure helps to bring the voltage back within the limit, then no further action is needed. Otherwise, additional (positive-sequence) reactive power injection or active power curtailment may be necessary. The advantages of the proposed voltage rise mitigation strategy are three folds. Firstly, the voltage rise is reduced. Secondly, the power quality is improved because the PCC voltage becomes balanced. Thirdly, since the active and reactive powers introduced by the negative-sequence currents are very small, it is more economic compared with the method of reactive power injection. In summary, the aims of this paper are (i) to analyze quantitatively the relationship between the voltage unbalance and the voltage rise, (ii) to discuss the effects of negative-sequence current injection on the power metering, and (iii) to confirm how the proposed strategy which prioritizes the voltage unbalance compensation can solve the voltage rise problem.

2. Relationship between unbalanced voltage and voltage rise

This section analyzes the effect of voltage unbalance based on symmetrical component in order to quantify the relationship between the magnitude of the negative-sequence voltage and the maximum line-to-line voltage defining the voltage rise. Under unbalanced voltage condition, the line-to-line voltages represented by $\mathbf{V}_{ab}$, $\mathbf{V}_{bc}$ and $\mathbf{V}_{ca}$ may be represented in terms of symmetrical components as shown in Eq. 1 where $\mathbf{V}^0$, $\mathbf{V}^+$ and $\mathbf{V}^-$ are the voltage phasors of zero, positive and negative sequences, respectively and $a = e^{j2\pi/3}$. For a three-phase three-wire system $\mathbf{V}^0=0$, and it can be derived that the magnitudes of the line-to-line voltages V_{ab}, V_{bc} and V_{ca} are given by Eq. 2. The magnitudes of the three voltages therefore depend on the phase angle α between $\mathbf{V}^+$ and $\mathbf{V}^-$.

$$\begin{bmatrix}\mathbf{V}_{ab}\\ \mathbf{V}_{bc}\\ \mathbf{V}_{ca}\end{bmatrix} = \begin{bmatrix}1 & 1 & 1\\ 1 & a^2 & a\\ 1 & a & a^2\end{bmatrix}\begin{bmatrix}\mathbf{V}^0\\ \mathbf{V}^+\\ \mathbf{V}^-\end{bmatrix} \quad (1)$$

$$\left.\begin{aligned} V_{ab} &= \left|\mathbf{V}^+ + \mathbf{V}^-\right| \\ V_{bc} &= \left|\mathbf{V}^+ + a^2\mathbf{V}^-\right| \\ V_{ca} &= \left|\mathbf{V}^+ + a\mathbf{V}^-\right| \end{aligned}\right\} \quad (2)$$

$$V_{\max(LL)} \geq V^+ + \cos\alpha \cdot V^- \quad (3)$$

$$V_{\max(LL)} \cong V^+ + \cos\alpha \cdot V^- \quad (4)$$

Fig. 1(a)-(c) illustrate examples when $0 \leq \alpha \leq 60°$ during which the maximum line-to-line voltage is V_{ab}. By symmetry, the same can be said for $-60° \leq \alpha < 0$. We can then show that the maximum line-to-line voltage $V_{max(LL)}$ satisfies Eq. 3. Normally, the ratio between negative-sequence and positive-sequence voltages is very small, so Eq. 3 can be approximated by Eq. 4.

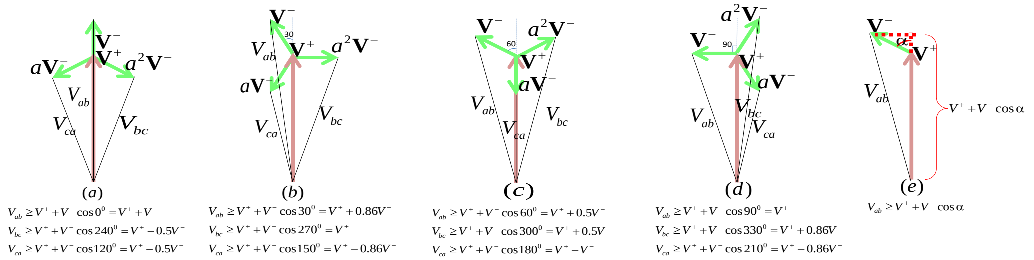

Fig. 1. Phasor diagram showing magnitudes of line-to-line voltages under voltage unbalance for various α.

When the phase angle α rotates further than 60^o, the maximum line-to-line voltage will change from V_{ab} to be V_{bc} or V_{ca} instead. However, similar relations (Eqs. 3-4) are still valid. From this investigation, it can be concluded that under any unbalanced condition, the maximum line-to-line voltage ($V_{max(LL)}$) is given by:

$$V_{\max(LL)} \cong V^+ + \cos\alpha \cdot V^- \quad \Rightarrow \quad V_{\max(LL)} \geq V^+ + kV^- \quad for\ 0 \leq \alpha \leq 60^0\ \&\ k = 0.5 \quad (5)$$

According to Eq. 5, it can be said that the voltage rise is caused by both positive and negative-sequence voltages. The maximum line-to-line voltage is always increased by the negative-sequence voltage by at least a factor of 0.5. As by the standard, the unbalanced voltage could reach 2% in the system, and this means that it will cause at least 1% of voltage rise which could not be neglected. Therefore, compensation of voltage unbalance by suppression