Voltage Unbalance Mitigation in Low Voltage Distribution Networks with Photovoltaic Systems

Kein Huat Chua, Yun Seng Lim, Jianhui Wong, Philip Taylor, Ezra Morris, and Stella Morris

Abstract — This paper proposes a technique to mitigate the voltage unbalance issue caused by the high penetration of photovoltaic (PV) systems into the low voltage distribution networks (LVDN) using a single phase energy storage system (ESS). The ESS comprises a bi-directional power flow inverter and a battery bank. The system is capable of absorbing the excess power and delivering power to the network in order to keep the voltage unbalance factor (VUF) below the statutory limit of 1%. Investigations are carried out in the experimental small-scale energy zone (SSEZ). The experimental results demonstrate that the ESS is capable of mitigating the VUF of the network.

Index Terms — Energy storage system, low voltage distribution network, photovoltaic, voltage unbalance.

1. Introduction

In the year 2011, the Malaysian government has voiced proposals for a feed-in tariff (FIT) to allow electricity produced from renewable sources to be sold to utilities at a fixed-premium price. The feed-in tariff would be levied at 1% of consumers’ electricity tariff and be administered by the sustainable energy development authority under the Ministry of Energy, Green Technology and Water. Malaysia is located entirely at the equatorial region with an average daily solar radiation of 4500 kWh/m² and a sunshine duration of about 12 hours. Hence, solar energy will likely be the key focus, although the target suggests that over the next five years the emphasis is on putting in place the systems and infrastructure to support a future growth in renewable energy rather than racing ahead with building capacity[1]. Building integrated photovoltaic (BIPV) systems can lead to a sustainable and widespread application of photovoltaics (PVs) in low voltage distribution networks (LVDN). The Malaysia BIPV project was aimed to induce the growth of BIPV installations by approximately 400%, from 470 kW in 2006 to approximately 1,880 kW by 2010, with reduced cost of BIPV technology by about 20% by the year 2010, relative to the baseline in the year 2005. Currently, the BIPV project has achieved a 25% cost reduction[2].

However, the design of the existing LVDN does not take into account the expected technical issues caused by the possible growth of BIPV systems. A high level of PV integration into the network has the potential to cause several technical issues, namely 1) under- or over-voltage, 2) thermal limits of cables being exceeded, 3) increase in voltage unbalance, and 4) deterioration of network efficiency. Numerous studies were carried out to investigate the impacts of small-scale embedded generation (SSEG) or distributed generation (DG) on existing low-voltage 3-phase 4-wire distribution networks[3][5]. In Malaysia, the statutory limit of the voltage unbalance is 1%[6] which is much stringent as compared to 1.3% in the UK and 2% in EU[7]. With the anticipated growth of PV systems on the LVDN, the statutory limit of voltage unbalance is most likely to be exceeded.

BIPV systems are most likely to be single-phase and connected to the LVDN through the “fit and inform” policy by customers. Therefore, it may cause voltage unbalance in LVDN. The adverse effects of the voltage unbalance are the deterioration of performance and the short life span of three-phase induction machines as well as distribution transformers[8][9]. Studies show that the efficiency of the networks improves with the integration of distributed generation (DG)[10][13]. Currently there are various technologies used for mitigating the voltage unbalance caused by high penetration of DG[14][15]. However, the solutions proposed are mainly three phase compensation techniques. The approach used in this paper is a single phase energy storage system, where its main advantages are cost effectiveness and simplicity.

The objective of this paper is to investigate the voltage unbalance caused by PV systems in LVDN. Also, an effective strategy for mitigating the voltage unbalance of the LVDN is proposed.

2. Voltage Unbalance Factor

In a three phase balanced power system, the line to
neutral voltages are sinusoidal with equal magnitudes and phase angles. Unequal magnitudes or phase angles will result in an unbalanced supply. The voltage unbalance at the distribution networks may be caused by several factors as follows.

1) Uneven distribution of single phase load across the three-phase network.
2) Continuous changing of the instantaneous demand.
3) Unbalanced or unstable utility supply.

According to the European standards, voltage unbalance factor (VUF) is defined as the ratio of the negative sequence voltage ($V^-$) to the positive sequence voltage ($V^+$) represented as follows:[16],[17]:

$$VUF(\%) = \frac{V^-}{V^+}. \quad (1)$$

The negative and positive sequence of the system voltage can be computed as follow:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V^0 \\ V^+ \\ V^- \end{bmatrix} \quad (2)$$

where $V_a$, $V_b$, and $V_c$ are the three phase line voltages and $V^0$, $V^+$, and $V^-$ are the positive, negative and zero sequence voltage components, respectively.

3. Experimental Small-Scale Energy Zone

The experimental small-scale energy zone (SSEZ) has been designed for investigating the effect of high DG penetrations on distribution networks. It consists of a load emulator, a wind turbine generator emulator, a PV generation emulator, an energy storage unit (ESU), and a low voltage network emulator, as shown in Fig. 1. The electrical layout of the SSEZ is illustrated in Fig. 2. The SSEZ has a tapered, radial topology and its impedances are primarily resistive. In this paper, the wind turbine generator emulator is deactivated from the network because the main focus of this paper is the impacts of PV systems on the network. The load emulator is formed by a number of resistors such that the demand of the load can be adjusted from 250 W to 2500 W per phase.

### Table 1: Design considerations for the energy storage device

<table>
<thead>
<tr>
<th>Energy storage technology</th>
<th>Advantages</th>
<th>Disadvantages</th>
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<tbody>
<tr>
<td>Lead-acid batteries</td>
<td>Low initial cost</td>
<td>Short lifetime (3 to 7 years)</td>
</tr>
<tr>
<td>NiMH batteries</td>
<td>Reliable, long lifetime</td>
<td>10 times as expensive as lead-acid batteries</td>
</tr>
<tr>
<td>Hydrogen fuel cell (PEMFC)</td>
<td>High power density</td>
<td>Expensive, short lifetime</td>
</tr>
<tr>
<td>Lithium ion (Li-Ion)</td>
<td>High specific energy, power, long lifetime</td>
<td>Expensive</td>
</tr>
</tbody>
</table>

4. Energy Storage System

Energy storage technologies benefit the electrical networks to improve the power quality, stability and reliability of power supply. The design considerations for the battery are cost, rating, energy capacity, and lifetimes. A summary of a review of the various technologies is shown in Table 1.

Lead-acid battery is chosen in this experiment because of its low initial cost. The capacity of each lead-acid battery is 110 Ah which is commercially available. There are four batteries connected in series with a total capacity of 440 Ah. The energy storage system (ESS) consists of a SMA Sunny Island 4500™ bi-directional power inverter and a battery bank consisting of 4 batteries. The bi-directional power inverter is set, by default, to operate within the range from 70% to 30% of the full capacity of the batteries. In other words, the available energy of the ESS is 176 Ah. The ESS can supply its maximum current of 18.75 A continuously for about 9 hours. Such capacity is sufficient to deal with the technical issues caused by PV systems as it provides power for about 8 hours per day. If the batteries are discharged down to 30% of the full state-of-charge, the inverter will terminate the discharging process. The Sunny Island 4500™ bi-directional power inverter features the ability to be connected in parallel with the utility grid in single phase and also facilitates islanded operation of an LVDN. In the experimental SSEZ, the frequency of the system is fixed using the network connection emulator. The power output of the ESS is varied by changing the nominal frequency parameter of the Sunny Island 4500™. Similarly, reactive power output from the Sunny Island 4500™ can be controlled by varying the value of the nominal voltage. Fig. 3 illustrates the energy storage system.
5. **Strategy for Voltage Unbalance Mitigation**

In an ideal balanced distribution network, the neutral current is always zero. In the real network, the voltage is inherently unbalanced due to the loading variations in each phase. The neutral current of the network is no longer zero when there is a voltage unbalance in the network. Hence, the current flow in the neutral line is used as an indicator for VUF. A graphical interface panel for the SSEZ developed in Labview is shown in Fig. 4. The loading condition is varied through the press buttons in the diagram. A PV system is integrated into the network and controlled manually to inject specific power to the network via a DC drive. During the experiments, the neutral current is monitored and the energy storage system is adjusted to either deliver or absorb power from the network such that the neutral current is kept in its minimal value. As a result, the VUF of the network is kept at its minimal value, too.

6. **Experimental Results**

The initial investigation is to identify the most imbalance loading conditions for the SSEZ. Several sets of loading conditions are included in each of the phases. In the balanced load condition, the VUF is found to be 0.1921%. Among all the unbalanced loading conditions considered, the VUF is the highest when one of the phases is fully loaded and the other two phases have no load. Fig. 5 shows the VUF for the unbalanced loading condition with an increase in load at phase A. The VUF increases linearly with an increment of load at phase A. The VUF is found to be 2.08% when the load achieves 2500 W. This loading condition has caused the VUF to exceed the statutory limit of 1% which is significant enough for the network operator to take an action to mitigate the unbalance.

In the following, Case A, Case B, and Case C show the impacts of PV system on the network VUF for balanced and unbalanced loading conditions. Case D, Case E, and Case F show the corrective actions taken by an energy storage system in mitigating the VUF.

6.1 **Case A: Balanced Network with PV System at Phase A**

In this case, the load in each phase was distributed equally. The PV system was placed at phase A with an increment of 250 W per step up to 1000 W. The investigation began with zero load, [0, 0, 0] W, followed by [500, 500, 500] W, and up to [2500, 2500, 2500] W. It was found that the differences of VUF between the balanced loading conditions were not significant because they were balance. Hence, VUF corresponding to [2500, 2500, 2500] W is illustrated in Fig. 6. It can be seen that the VUF increases almost in a linear manner with the increment of PV power. The VUF reach its statutory limit of 1% when the PV system delivers 850 W to the network. The PV system has caused the balanced network to be unbalanced.

![Graph showing VUF for balanced load and PV system at phase A.](image_url)
6.2 Case B: Unbalanced Network with Load and PV System at Phase A

In this case, a load is located at phase A while there are no loads at phase B and phase C. From Fig. 7, it can be seen that the VUF decreases for all loading conditions except for the loading condition of [500, 0, 0] W. The VUF under this loading condition is U-shaped. The minimum point occurs when the PV power is 500 W. This is due to the fact that the PV power has offset the load at phase A. Hence, the three phase loading profile of the network becomes more balanced. As the power of PV continues to increase, there is an excess power in phase A. Hence, the network becomes unbalanced. In fact, with this load condition, the placement of PV system at the same phase as load can help to mitigate the VUF as long as the power generated by the PV system does not exceed the load value.

6.3 Case C: Unbalanced Network with Load at Phase A and PV System at Phase B

In this case, a load is located at phase A while there are no loads at phase B and phase C. PV system is located at phase B. From Fig. 8, it can be found that the VUF increases with an increment of PV power. The load of [2500, 0, 0] W gives the highest VUF. It is also noted that the VUF in this case is higher than that in Case A and Case B. In other words, the placement of PV system in this condition can incur more voltage unbalance to the network.

6.4 Case D: Unbalanced Network with Load, PV System, and ESS at Phase A

This case is similar to Case B except that an additional ESS is installed at phase A. The ESS plays a role to correct the voltage unbalance in the network. In order to prove the effectiveness of ESS, a load of [2500, 0, 0] W is placed at phase A which generates the highest VUF in the network. Fig. 9 illustrates the results of the network before the connection of ESS and after the connection of ESS. The label “before correction” means the ESS is not connected to the network while “after correction” means the ESS is connected to the network. It can be noticed that before the connection of ESS, the VUF decreases with an increment of PV power. It is also found that the VUF has been successfully reduced by the ESS. The VUF is maintained in the range of 0.6% to 0.8%.

6.5 Case E: Unbalanced Network with Load and ESS at Phase A and PV System at Phase B

In this case, the load and ESS are located at phase A while the PV system is installed at phase B. Fig. 10 illustrates the results of the network before the connection of ESS and after the connection of ESS. It can be seen that the ESS is capable of mitigating the VUF in the network. The VUF is maintained in the range of 1.1% to 1.4%.
6.6 Case F: Unbalanced Network with Load at Phase A, PV System and ESS at Phase B

In this case, the load is located at phase A while the PV system and ESS are installed at phase B. Fig. 11 illustrates the results of the network before the connection of ESS and after the connection of ESS. The VUF is maintained in the range of 0.9% to 1.4%.

7. Conclusions

Energy storage system is proposed to be a solution for mitigating the voltage unbalance of the networks with high penetration of PV systems. The experimental results show that the VUF can be effectively reduced by the ESS. The ESS acts as an energy conditioning device to absorb excess power from the network that is integrated with PV systems and to deliver power to the network when the demand of the network is imbalanced and causes the voltage unbalance. The effectiveness of ESS in mitigating VUF depends on its location in the three phase network. The best location is when the PV system and ESS are placed on the phase with high demand, namely Case A. The VUF is successfully suppressed below 1%.

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References


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