On the Reliability Improvement of Distribution Systems Using PV Grid-Connected Systems

Prakasit Sritakaew¹, Anawach Sangswang², and Krissanapong Kirtikara³, Non-members

ABSTRACT

The purpose of this paper is to examine issues related to the distribution system reliability improvement using photovoltaic (PV) grid-connected systems. The output characteristics of a PV system are experimentally measured. The measured data are used to investigate the effects of PV system installation to improve the distribution system’s reliability. The system constraints such as, recovered real power, and loading reduction of the tie line/switch after the installation of PV grid-connected systems are concentrated. Simulation results show that with the action of a tie switch, system losses and loading level of the tie switch can be reduced with proper installation location.

Keywords: Reliability, distribution system, PV inverter

1. INTRODUCTION

Recently, PV systems have widely received much attention due to many important advantages such as infinite availability of the prime energy source and no polluted emission. The amount of PV generation is growing rapidly both in size and complexity [6]. As a result, the price of PV systems is continually decreasing. It has been reported that 77.48% of the 1809 MWp installed worldwide is grid-connected [7]. This is due to the inherent benefits of using PV systems as the distributed generation (DG) to the electric utilities. The major advantage of PV generator is from its close location to the customers which significantly reduces transmission and distribution costs [9]. They can also be used to level the system load curve, improve the voltage profile and reduce line losses as well as transformer’s loading. Utilities economically benefit from deferment of the investment for transformer and transmission lines upgrades and maintenance cost reduction [10]. To achieve the mentioned benefits, the PV generators must be of appropriate penetration level and at suitable locations [5]. In practice, utilities cannot dictate these factors since the PV generators are not utility owned. In addition, its so-called infinite source is a variable energy source. The injected output power to the distribution system varies greatly on the weather conditions of a specific day. There is no guarantee that the mentioned benefits can be fully realized. The operation of the PV grid-connected systems and their responses to disturbances and/or conditions of the distribution system has increasingly raised concerns, especially in high penetration of PV systems [5]. Regardless of the uncertain characteristics of the generated output power, the PV systems can be used to improve system reliability for radial distribution networks. However, it should be noted that the traditional reliability indices [14] are among the most controversial topics. Most of the indices depend on service interruptions, but the term interruption is not uniformly defined. Extensive research on a reliability evaluation of interconnected power system has been conducted in the past years. In [9], hierarchical Markov modeling has been proposed to assess the distribution system reliability. A switch placement, with DG in consideration, has shown to improve the system reliability in terms of load servicing in the presence of fault [12]. Reliability modeling techniques for DG on distribution systems and the methods to analyze them are developed using predictive reliability assessment tools [13]. In [15], network restoration sequence and constraints have been used to evaluate the system reliability. Optimal utilization of PV and wind energy sources has shown to increase capacity of isolated power systems [16].

When a fault occurs in a distribution feeder, there are customers who unavoidably experience power outage. However, all grid-connected inverters must detect the islanding and stop energizing [11]. With a network reconfiguration through an operation of a tie switch/line, portions of the network outage can receive power transferred from other branches or feeders. By allowing the PV generators to support the recovered portions of the system, the amount of cus-

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tomers with power outage can be reduced along with the tie line loading and losses. Therefore, the system reliability may be improved. Note that, in this work, conventional reliability indices are not appropriate since, in an event of fault, alternate supply routes are available through tie lines/switches. The interruptions may not be recorded in such an event.

In this paper, issues related to improving reliability of the distribution system using PV grid-connected systems in the event of faults are concentrated. The output characteristics of a PV system are experimentally measured. The measured data are used in computer simulation to investigate issues related to distribution system reliability improvement.

Fig. 1: Measurement setup

Our attention is concentrated on the system constraints such as, recovered real power, and loading reduction of the tie line/switch after the PV grid-connected system installations. This paper is organized as follows. Section 2 provides experimental measurement of PV grid-connected system. In section 3, issues related to reliability improvement using PV generators are discussed. Numerical results on a test system are given in section 4. Section 5 concludes the work.

2. PV SYSTEM MEASUREMENT

2.1 Experimental Details

In order to characterize the output of the PV grid-connected system, a measurement setup is prepared as shown in Fig. 1. The test system is located in Ratchaburi province, Thailand. There are 3 types of PV arrays, monocrystalline, cadmium telluride and tandem-junction thin film which are capable of producing 7,200 Wp, 7,280 Wp and 7,224 Wp, respectively. Each PV array is connected to a separate inverter. The total output power of the 3 PV arrays is of 21.4 kWp. The inverter is a 220 V 50/60 Hz grid-connected type with maximum power point tracking (MPPT) control. A pyranometer is used to measure the solar radiation flux density (W/m²). A Campbell21X data logger collects both the solar radiation flux density and PV temperature. We use an automated data recording to measure voltage, current, active power, reactive power and power factor at the point of common coupling (PCC). The dc voltage and current are collected using an Agilent 34970A data acquisition unit.

2.2 Measurement Results

Every measurement in Fig. 1 is sampling every 5 minutes from 6.00AM to 6.00PM. The inverter’s real power, reactive power and power factor of the tandem-junction thin film is shown in Fig. 2. The system power factor is stable at 0.98 since the generated reactive power is relatively small compared with the active power. The PV systems can effectively decrease the load active power demand.

Fig. 2: Output of the PV grid-connected system

However, the output power fluctuation is the results of the meteorological condition that cannot be controlled. Note that these fluctuated powers are injected into the distribution system. It definitely results in issues of power quality and possible instability of the distribution systems which are not covered in this paper, but will be focused in a separate paper.

3. SYSTEM MODELING

As mentioned before, this work attempts to address the issues on system reliability. It is assumed that when a fault occurs, a network tie line/switch must be closed to support portions of the system. Then the PV grid-connected system is reconnected to the distribution system. To investigate the power distribution behavior, software with appropriate models and specific data of the system under study must be employed.

3.1 PV grid-connected system

In power flow studies, a distributed generator is usually modeled as a slack bus in the case of only one generator in the system. If there is more than one generator, the one with the largest adjustable real power output is modeled as a slack bus and the remaining generators are modeled as PV buses. For a PV grid-connected system, the PV modules inject power to the utility’s grid through an inverter with capability of detecting islanding operation. However,
a PV generator cannot operate in an isolated area as other types of distributed generators because of the landing requirement. From the last section, a PV grid-connected system has shown to effectively inject active power to the feeder. Therefore, the PV systems are modeled using PQ models.

### 3.2 Line and switch models

Transmission lines are the predominant branch connections existing in distribution networks. A standard-model admittance matrix for distribution lines and switches has been chosen for this work. The admittance matrix model is given as 

$$
Y_{\text{line}} = \begin{bmatrix}
Z_k^{-1} & \frac{1}{2}Y_k & -Z_k^{-1} \\
-Z_k^{-1} & Z_k^{-1} + \frac{1}{2}Y & -Z_k^{-1} \\
-Z_k^{-1} & -Z_k^{-1} & Z_k^{-1} + \frac{1}{2}Y
\end{bmatrix}
$$

(1)

where $Z_k$ and $Y_k$ are the series impedance and charging admittance, respectively.

### 3.3 Load Models

For any given amount of real and reactive load at each load bus, three static types of representation are used; constant impedance, constant current and constant power loads. For some buses the loads are represented as a linear combination of the three-load types.

### 4. ISSUES ON RELIABILITY IMPROVEMENT

Once a fault occurs and sustained, the relay senses it and sends a signal to trip circuit breakers. After the fault is isolated, the part of the feeder not affected by the fault is supplied through a tie line/switch. The positions of protection devices and fault locations are strongly dependent. In some cases, a tie switch/line cannot transfer enough power to support the isolated area. With a PV generator installed, the demand of the isolated area can be supplied. The number and duration of outages to the customers are reduced. Hence additional reliability is improved. In this operation, the coordination of PV generators with feeder protection devices and tie line/switch is necessary. The sequence of events after the fault is as follows:

- Fault is detected and isolated by one or more protection devices.
- PV system reconnects if not within the faulted zone.
- After the fault is isolated, recloser synchronizes its reclosing operation with the PV system.

In this work, we concentrate our effort on the effects of PV installation location under system constraints, namely voltages and the loading level of the tie switch/line.
\( V_{\text{min}}^k < |V_p^k| < V_{\text{max}}^k \)
\[
S_{\text{min}}^{3-\phi} \leq S_{ik}^{3-\phi} \leq S_{\text{min}}^{3-\phi}
\] (2)

where \( V_k \) is the voltage at bus \( k \) and \( S_k^{3-\phi} \) is the complex power flow from bus \( i \) to bus \( k \). The following 4 cases of PV installation locations are considered:

Case 1: PV is installed near the fault location
Case 2: PV is installed at the maximum load bus in the isolated area under consideration.
Case 3: PV is installed at the end of the line in the isolated area under consideration.
Case 4: PV is installed on the bus adjacent to a tie switch/line.

5. NUMERICAL RESULTS

The test system is a 266 bus radial distribution system of the Provincial Electricity Authority (PEA) of Thailand shown in Fig. 3. The amount of system load is 53.27 MW and 33.27 MVar. Detailed information about the number of components is given as follows:

\% of line with breaker 36
\% of loads 69
\% of unbalanced loads 11

The basic information of the system for all four cases to be presented is found in Table 1.

<table>
<thead>
<tr>
<th>Faults branch</th>
<th>105-106</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base system</td>
<td>22KV/100 MVA</td>
</tr>
<tr>
<td>The total load in the area isolated by fault</td>
<td>13.63520 MW</td>
</tr>
<tr>
<td>The total load in the area isolated by fault</td>
<td>10.8321 MVar</td>
</tr>
<tr>
<td>PV location case1</td>
<td>Bus 107</td>
</tr>
<tr>
<td>PV location case2</td>
<td>Bus 125</td>
</tr>
<tr>
<td>PV location case3</td>
<td>Bus 163</td>
</tr>
<tr>
<td>PV location case4</td>
<td>Bus 137</td>
</tr>
</tbody>
</table>

First, the effects of PV systems on the distribution system are demonstrated through minimum system voltages and real power losses. Under normal operation, there would be voltage drop on the distribution feeder between the transformer and customer’s service entrance which may result in extremely low voltage at the service entrance and real power loss. Since the grid-connected inverter is designed to inject real power produced from the PV system not to regulate it, therefore it can be seen, at the distribution feeder, as a negative load that reverses the power flow direction and decrease the local power demand. The measured data of a single day from section 2 is used in computer simulation. The situation where the PV installations are scattered along the load buses is studied first.

As expected, the system voltage has been improved and the losses are reduced at higher PV penetration.
level, as evident in Figs. 4 and 5, respectively. The effects are clearly seen around noon time. Fig 6 shows bus voltages with the total capacity of PV installed at 10% of total load. The installations are at buses 107, 125, 163 and 137 corresponding to case 1, 2, 3 and 4, respectively. At this level of penetration, the effect of installation location on bus voltages is not significant. The voltage rises at buses 137 and 143 are due to the action of the tie line which reconfigures the network such that bus 137 and 141 are the most upstream buses in the recovered area of interest. In Fig. 7, the penetration level is increased to 50% of local load.

This, in general, raises the bus voltages throughout the recovered area. Notice in case 3 where the PV system is installed at the end of the feeder (bus 163). It has shown to raise the bus voltages in the neighbourhood. This implies that special care must be taken in this case so that the voltage is not too high beyond the utility’s regulations. In addition, when there is a light load connected at the end of feeder, the voltage may be increased beyond the specified constraints.

The system losses for each case with different PV penetration level are shown in Fig. 8. Higher penetration level results in lower system losses.

However, the installation location has little effect to the system loss, especially when the penetration level is relatively low. Note that the original system is a well compensated system; if it was a lossy system the real power loss reduction would have been appreciable.

Next, let us consider the power flow on the tie switch. As mentioned before that the PV generator can be used to reduce the load demand of the feeder. The higher PV penetration yields lower demand, thus lower power flow on the tie switch, as shown in Fig. 9. It should be noted that the tie switch in our test system has the rating of 600A. At PV penetration of 10%, 25% and 50%, the power flow being transferred occupies 56.4%, 45.86%, and 28.43% of the tie switch capacity, respectively. When the loading level of the tie switch is reduced, it yields more load can be recovered during the event of fault. This means that for a high prefault load level, the PV systems can relieve the loading level of the tie switch which implies that more customers will receive power. As a result, the distribution system reliability is improved. The simulation results agree with the past work in similar DG situations where reliability can be improved in terms of recovered real power as well as lower customer service interruptions.

6. CONCLUSIONS

In this paper, the output characteristics of the PV grid-connected system have been investigated. The measured results are used to examine the issues related to reliability improvement for a radial distribution system.

It has been shown that with the action of a tie switch, the system losses and loading level of the tie switch can be reduced with appropriate installation location. In other words, the available transfer capability to the isolated area is increased which results in improved system reliability.

7. ACKNOWLEDGEMENT

The authors would like to thank the Thailand Research Fund for financial support under grant MGR4880133.

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