Feasibility of Continued Operation of Photovoltaic Systems with Energy Storage during Grid Outages

Invited Paper

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***Abstract*—Photovoltaic systems (PV) have been growing extensively due to various government incentives to improve the security of energy supplies and mitigate the climate change issue. Usually, customers own the PV systems that operate on their network to reduce the amount of fuel generated electricity used. The customers expect the PV systems to operate as reliable as possible in order to justify their financial investment. However, based on the current practice, any PV systems must be shut down immediately if the customers' networks are removed from the grid. Such a practice is established to minimize the damage or risk due to unregulated voltage and frequency on the islanded networks. However, this practice can cause any available clean energy to be wasted during the outage of the grid. Therefore, a wireless fuzzy-controlled energy storage system has been proposed to be used with the PV systems to provide an effective means of regulating the frequency and voltage throughout the outage of the grid. A number of case studies have been carried out to prove that the energy storage systems are an effective approach of regulating the voltage and frequency of the islanded networks. The customers can continue to gain the financial benefit from their existing PV systems and the utility company can improve the performance of their networks by reducing the number of power outages.**

***Index Terms*—Fuzzy control, energy storage, photovoltaic systems, islanded operation.**

I. Introduction

Governments have set up a number of incentives to promote the use of photovoltaic systems toward mitigating global warming and climate change issues [1]. Therefore, the amount of photovoltaic systems has been growing extensively in the past one decade [2]. Usually, customers own and install their photovoltaic systems on their distribution network. They expect the PV systems to operate as reliable as possible in order to justify their financial investments. However, based on the current practice, any PV systems must be shut down if the main grid is out of service [3]. This means that islanded operation of the PV systems is not allowed at present. This practice was established to avoid any equipment damage or risk due to the fact that the frequency and voltage of the islanded networks are not regulated within the required tolerances [4]. Based on the IEC 61727 standards, the PV systems must be disconnected from the customer network within a required duration of seconds if the voltage and frequency of the networks are detected to be out of the specified ranges [5]. However, shutting down their PV systems during grid outages can cause the customers to unnecessarily waste their available clean energy.

To improve the reliability of their PV systems, it has been proposed to use an energy storage system in conjunction with the PV systems on the customers' network. The energy storage system can serve as a voltage source to the PV system during grid outage, maintaining the voltage of the islanded network to be within the required tolerance [6]–[8]. The frequency of the islanded network will be stable if the energy storage system can maintain the balance between generation and demand on the islanded network [9]. There are a number of available control strategies; namely, concentrated control [10], master/slave controls [11], and distributed control [12] used to manipulate the operation of the energy storage system so that it can maintain the balance between the generation and demand. With these control strategies, communication lines are used in between the energy storage systems and the PV systems in order to maintain the balance between the generation and demand during islanded operation. The communication lines are expensive, particularly for a large distribution network [13]. Also, the lines can fail to function occasionally, leading to the malfunction of the energy storage system.

There are several wireless control strategies that can be used based on droop characteristics [14], virtual structure based approach [15], and constructed-and-compensated based method [16]. These control strategies focus on the stability of any renewable energy sources during islanded operation where the generation and demand is well balanced. It is worth noting that most of the frequency violations happen at the beginning of the grid outage because the power mismatch between the generation and load is at its maximum. Fig. 1 shows that the power mismatch between the generation and demand is highest

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when the customer network is about to be removed from the grid. This maximum power mismatch can create a high frequency excursion, which can trigger the PV system to trip off from the customer network at the start of the outage [17]. Once the PV is tripped off, the islanded network becomes deenergized for the remaining period of the outage.

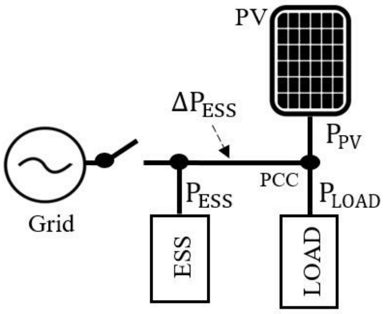

Figure 1. The power mismatch ΔP_{ESS} at its highest at the beginning of the islanded operation.

To avoid any frequency violations at the start of the supply outage, an innovative wireless fuzzy-based controller was developed to control the energy storage system such that the power mismatch ΔP_{ESS} is always maintained within a small value, which will not trip off the PV systems when the customer network is disconnected from the grid. As a result, the customers can continue to utilize the available clean energy without any power interruption. The utility company can also improve the reliability of electricity supply for the customers. This paper presents the details of the wireless fuzzy controller in terms of its role in conducting the islanded operation of PV systems. A number of case studies have been carried out and are presented in this paper to show that the wireless fuzzy controller can conduct the islanded operation of the PV systems successfully. This paper will begin with the experimental set-up of the customer network with energy storage, controllable load, PV systems. Following that, details of the fuzzy controller are described before presenting the case studies and the conclusions.

II. Experimental Set-up of the Customer Networks with Energy Storage and PV Systems

Fig. 2 shows the layout of the customer network with the PV systems, loads, and energy storage system, which are set up at the university campus. The PV system is comprised of a 3.6 kW single-phase PV system together with a 3.0 kW controllable load emulator. The load is controlled using a series of solid-state relays via aNI-9403 digital module. The energy storage system consists of a 6 kW bi-directional inverter with four parallel strings of lead acid batteries. Each string is made up of four cells of 115 Ah valve-regulated lead acid batteries, which give a total terminal voltage of 48 V and capacity of 22 kWh. This means that the total capacity of the energy storage system is 88 kWh.

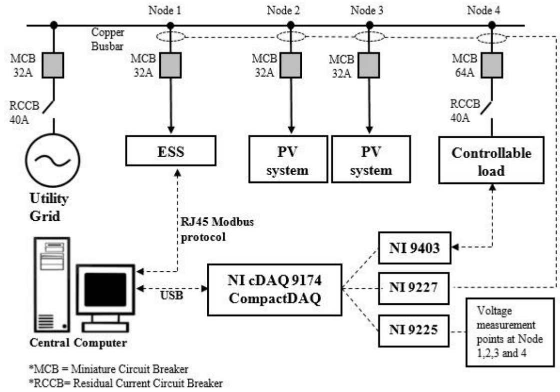

Figure 2. The layout of the experimental network with PV, load, and energy storage.

The bi-directional inverter is controlled using a central computer via Speedwire Modbus. The fuzzy controller was written in National Instrument (NI) Labview to translate the commands into Modbus protocol before sending it to the bi-directional inverter.

Current transformers (CT) rated at 40/5-A were used along with a NI current metering module, NI-9227, to measure the current of the PV, load, and energy storage system whereas the NI voltage input module, NI-9225, was used to measure the voltage at the PCC. LabVIEW software in the central computer was used to retrieve and analyze the measurement data from the modules of NI-9225, NI-9227 and NI-9403.

III. The Role of the Energy Storage System on the Customer Network with Photovoltaic Systems

Photovoltaic systems will trip off from the customer network at the start of the grid outage because the voltage and frequency of the network are detected to be outside a boundary known as the non-detection zone. The boundary for the frequency is from 49.5 Hz to 50.5 Hz whereas the voltage is from 216.2 V to 253.0 V. The changes in the frequency and voltage in the customer network during the grid outage are correlated to ΔP_{ESS} and ΔQ_{ESS}, which are also the mismatches of the real and reactive power along the point of common coupling, as shown in (1). Fig. 3 shows the single-line diagram with the definition of the parameters.

$$\begin{aligned} \Delta P_{\text{ESS}} &= P_{\text{LOAD}} - P_{\text{PV}} - P_{\text{ESS}} \\ \Delta Q_{\text{ESS}} &= Q_{\text{LOAD}} - Q_{\text{PV}} - Q_{\text{ESS}} \end{aligned} \tag{1}$$

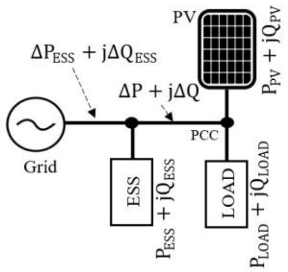

Figure 3. The definition of P_{ESS} and Q_{ESS} on the point of common coupling.

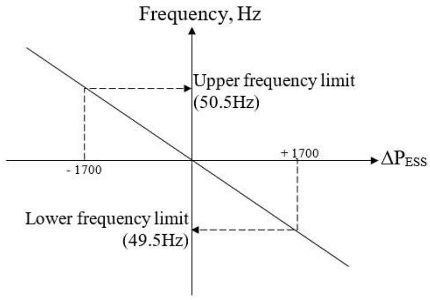

Figure 4. The correlation between ΔP_{ESS} and the frequency deviation at the start of the grid outage.

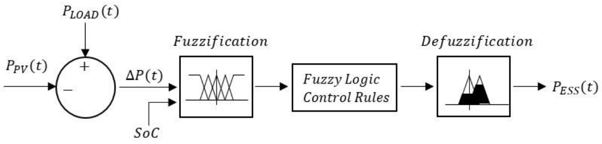

Figure 5. A flow diagram of the fuzzy controller.

The power mismatches ΔP_{ESS} and ΔQ_{ESS} must be as small as possible in order to minimize any frequency and voltage fluctuations, which would otherwise trip off the PV system at the beginning of the grid outage. However, it is noticeable that the reactive power mismatch ΔQ_{ESS} is usually very small because the load does not require much reactive power Q_{LOAD} and the PV system injects very little reactive power Q_{PV}. Therefore, the main role of the energy storage system is to reduce the real power mismatch ΔP_{ESS} to a small value in order to avoid any significant frequency changes at the beginning of the grid outage. Through experimental studies, it is found out that ΔP_{ESS} must be less than ±1.7 kW at all times in order to ensure the frequency is within the range of 50.5 Hz and 49.5 Hz, as shown in Fig. 4.

IV. The Fuzzy Controller for the Energy Storage System

To avoid any frequency violation at the start of the grid outage, a fuzzy controller was developed to control the operation of the energy storage system on the customer network. This controller is able to make sure the real power mismatch ΔP_{ESS} is less than ±1.7 kW at all times as long as the state of charge of the batteries is within the healthy range of 100% and 60%. The fuzzy controller uses two parameters as its inputs: i) The SOC and ii) the power mismatch (ΔP) between the load (P_{LOAD}) and PV system (P_{PV}). Fig. 5 shows the flow diagram of the fuzzy controller. The controller captures the two inputs of SOC and ΔP to undergo fuzzification and defuzzification in order to generate the output of P_{ESS}, which will be the input to the energy storage system to make the power mismatch less than ±1.7 kW.

The pre-defined fuzzy membership of ΔP is enclosed by six trapeziums; namely, extremely very negative (EVN), very negative (VN), negative (N), positive (P), very positive (VP) and extremely very positive (EVP), as shown in Fig. 6. The fuzzy membership function for SOC is shown in Fig. 7. There are three curves for the SOC; namely, low, medium, and high. During fuzzification, the input of ΔP to the fuzzy membership generates two power mismatch conditions with their respective linguistic values. The input of SOC to the membership produces two conditions of SOCs with their respective fuzzy values. In total, there are four linguistic outputs generated from the fuzzification.

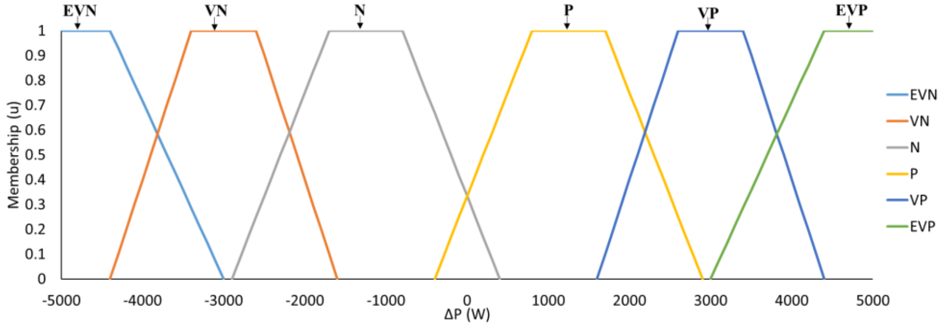

Figure 6. The membership function for ΔP.

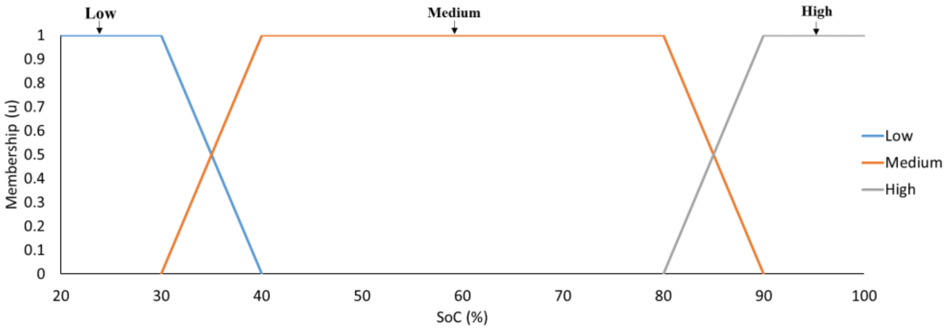

Figure 7. The membership function for the SOC.

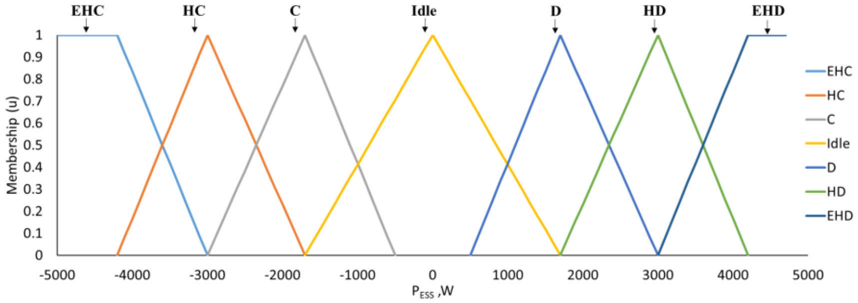

Figure 8. The fuzzy logic output membership function for P_{ESS} as an instruction to the bi-directional inverter.

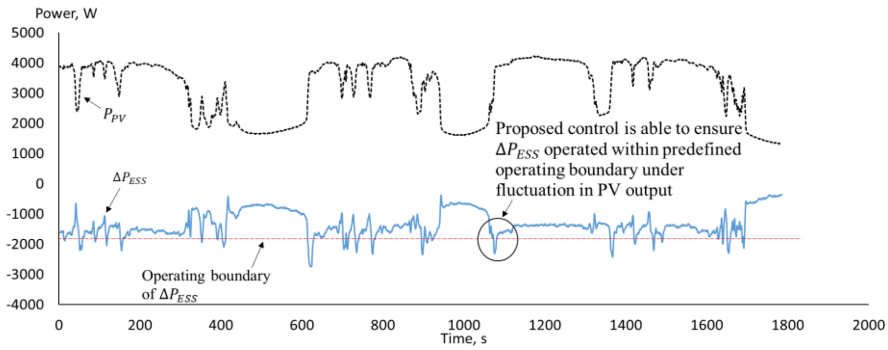

Figure 9. The power mismatch ΔP_{ESS} of less than 1.7 kW under various PV outputs.

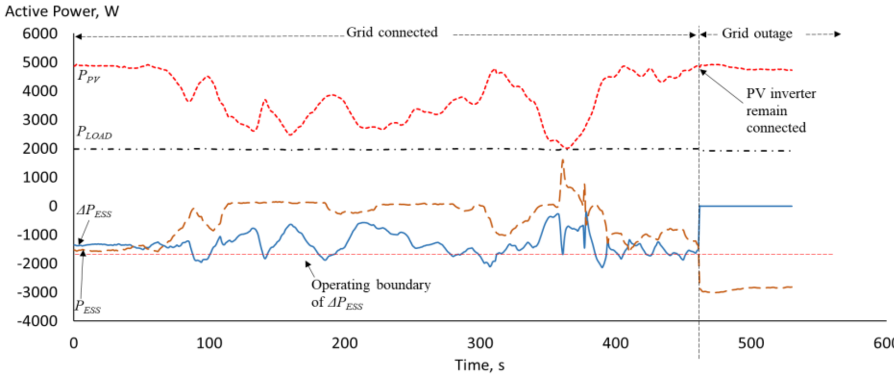

Figure 10. The PV being connected to the customer network after a grid outage.

TABLE I: MAPPING TABLE FOR GENERATING THE INSTRUCTIONS.

SOC	ΔP					
	EVN	VN	N	P	VP	EVP
Low	EHC	HC	C	Idle	D	HD
Medium	HC	C	Idle	Idle	D	HD
High	HC	C	Idle	D	HD	EHD

In the defuzzification process, the four linguistic outputs are mapped against each other to determine the conditions of the instructions (Table I). There are seven different types of instructions to be produced, which can be categorized as extremely high charge (EHC), high charge (HC), charge (C), idle, discharge (D), high discharge (HD), and extremely high discharge (EHD), as shown in Fig. 8. The conditions and values of the instructions are used to define the area enclosed in the fuzzy membership for the output as shown in the through the center of area (CoA) defuzzification method and the value of the output P_{ESS} is determined.

V. CASE STUDIES

A number of case studies have been carried to study the performance of the control strategy in response to a grid outage under the variation of the PV output.

Case Study 1: Power mismatch ΔP_{ESS} under the variation of the PV output

The objective of this case study 1 was to study the ΔP_{ESS} value under the variation of the PV power output before the grid outage. The results are shown in Fig. 9. It is shown that the ΔP_{ESS} value is always less than 1.7 kW under the frequent changes in the PV power output. It is proved that the fuzzy controller is able to keep the required power mismatch throughout the grid-connected operation.

Case Study 2: Continuous operation of the PV System after a grid outage

This case study was used to investigate whether the PV system will remain connected with the customer network after the grid outage. The results are shown in Fig. 10. It is shown that the grid outage occurs at 460 s and the PV system is still connected to the network after the outage. This has proven that the PV system can continue to operate after the grid outage.

VI. Conclusions

Customers always intend to utilize their renewable energy even during grid outages. An energy storage system can be used to maintain the continuous operation of PV systems after a grid outage because the energy storage system can act as a voltage reference for the PV system during the outage. Also the energy storage system can manipulate the power mismatch ΔP_{ESS} on the customer networks such that the power mismatch is always small, which will not cause any frequency violation at the point of grid outage. A fuzzy controller has been developed to maintain the small power mismatch ΔP_{ESS} at all times. This fuzzy controller has been implemented into the energy storage system in the experimental distribution network. A number of case studies have been carried out. The results show that the PV systems can continue to operate even after a grid outage. This fuzzy control approach can improve the utilization of green energy during a grid outage and the utility company can improve the reliability of electricity supply to its customers.

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