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Islanding Operation among Solar Hybrid System and Grid-tied PV System in Buildings

Piyadanai Pachanapan*,[1], Phisut Apichayakul*, Akaraphunt Vongkunghae*, and Sarintip Tantanee

ARTICLE INFO

Article history:
Received 15 September 2021
Received in revised form 15 November 2021
Accepted 29 November 2021

Keywords:
Grid-tied inverter
Hybrid inverter
Islanding operation
Power curtailment
Solar hybrid system

ABSTRACT

The solar hybrid system which consists of photovoltaic (PV) and battery storage can provide electricity supply to the buildings both on-grid and off-grid conditions. To improve the uninterrupted operation, it is possible to integrate the grid-tied PV system, without the battery, with the solar hybrid system to enhance the power generation during islanding condition. However, many hybrid on/off grid inverters do not allow the other energy sources to charge the battery in the off-grid mode. A particular power curtailment control is then required for the grid-tied inverter to prevent the excessive power. In this work, the power curtailment controller with the combination of smart meter and solar irradiance sensor is introduced. The set-point of grid-tied inverter is automatically adjusted following the changes of load consumption and PV power. The performance of islanding operation among solar hybrid and grid-tied PV systems is examined based on a time-sweep power flow calculation on DIgSILENT PowerFactory software. It is shown that instead of using solar hybrid system alone, coupling with the grid-tied PV system can help increasing the efficiency of battery usage. Hence, this can extend the continued electricity supply to the building during the loss of grid voltage.

1. INTRODUCTION

The renewable energy sources of the kW range such as solar photovoltaic (PV) system are particularly suitable for on-site generation in business and industrial buildings. The integration of PV system provides the benefit in terms of saving electricity cost and improving power quality, such as voltage profiles and power losses [1]. Moreover, a solar hybrid system which includes PV modules and battery storage can be used as the emergency generation, similar to an uninterruptible power supply (UPS). The solar hybrid system can provide continuing electricity supply during the loss of grid voltage for the specific load, such as lifts, air-conditions and lights. [2].

The PV system and battery energy storage system in a large-scale solar hybrid system (MW range) each have their own power converter unit and connect to the electricity system separately. On the other hand, PV arrays and battery storage in a small-scale solar hybrid system (kW range) can be integrated with the main grid via a solar hybrid on/off grid inverter such as the product of hybrid PV inverter in [3]. This type of inverter can operate in both on-grid and off-grid condition. It works as the grid following inverter during grid-connected operation, whilst it runs as the grid forming inverter to maintain satisfied voltage and frequency in the system during islanding operation. If the event of interruption occurs during the day, PV array and the battery are plausible to supply most loads in the building. On the other hand, only battery would be able to supply only essential loads at night, due to the lack of supply from the PV array.

The challenge of islanding operation is to maintain a constant power balance between the power generation and load consumption. The power mismatch will cause the system frequency and voltage to deviate from the nominal values. Moreover, most of solar hybrid on/off grid inverters in the market is unable to absorb power from the other energy sources when operating in off-grid mode [3]. If the building has a mix of solar hybrid on/off grid inverters and conventional grid-tied PV inverters, the grid tied PV inverter is usually disconnected when the islanding operation is detected. As a result, the solar hybrid on/off grid inverter is solely device capable of supplying the electricity to the specific loads. This solution can prevent the injection of excess power from PV generation, particularly at midday. However, this basic strategy has a drawback in terms of generation loss [4].

To avoid surplus injection during the off-grid operation, the grid-tied PV inverter is possible to stay connected to the isolated system if the power curtailment controller is activated. Typically, the grid-tied PV inverter is a grid-following type which the PV generation is the energy captured from the sun according

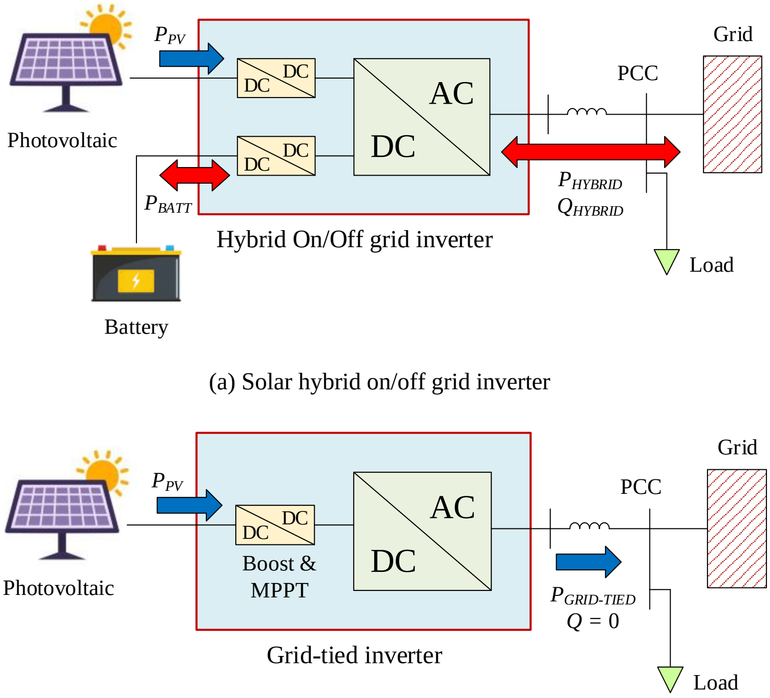
*Centre of Excellence on Energy Technology and Environment, Faculty of Engineering, Naresuan University, Phitsanulok, 65000, Thailand.

[1] Corresponding author:
Tel: + 66 55 964 322, Fax: + 66 55 964 005.
E-mail: piyadanip@nu.ac.th

to the maximum power extraction algorithm. Meanwhile, the PV power can be limited by decreasing the injected power from the PV array to below the maximum power point. The active power can be limited when a predetermined power production set-point is reached, or when either frequency or voltage exceeds the prescribed value [5], [6]. In addition, many modern grid-tied PV inverters already include power limiting function within their product, such as the product of smart grid-tied inverter in [7].

The power curtailment is employed into the grid-tied inverter for many applications such as zero energy exporting [8] which the PV system is only produces enough power for the local load and never injects power into the distribution network; over-voltage and thermal violation mitigations [9], [10]; solving grid congestion problems in power system planning [11]; improving power quality and providing frequency control in the microgrid systems with multi-energy sources [12], [13],[14]; improving a distributed power system control for multi-microgrid networks [15] and enhancing distribution system resiliency [16].

This paper introduces a particular power curtailment controller, which enables the grid-tied PV inverter to assist power generation during islanding operations rather than the solar hybrid on/off grid inverter alone. To prevent excessive PV feeding, the output power of grid-tied PV inverter is controlled by using information from the smart meter and solar irradiance sensor. The goal of this study is to demonstrate the performance of a purposed power limiting controller in supplying more power from a grid-tied PV inverter, which possibly reduce the use of discharging power from the battery. As a result, this strategy could help in the continuation of electricity supply following a loss from the main grid.



(a) Solar hybrid on/off grid inverter

(b) Grid-tied PV inverter

Fig. 1. The configurations of solar hybrid on/off grid inverter and grid-tied PV inverter.

2. GRID-TIED PV INVERTER AND SOLAR HYBRID ON-OFF GRID INVERTER

The configurations of grid-tied PV inverter and solar hybrid on/off grid inverter are shown in Figure 1. A PV panel - side DC/DC converter captures the maximum power from the solar irradiance according to the maximum power point tracking (MPPT) algorithm. In case of solar hybrid on/off grid inverter, it includes a battery – side DC/DC converter to control the charging/discharging of energy storage.

During the grid-connected operation, the grid-side DC/AC inverter is able to convert DC power from PV arrays/battery to AC power and then synchronizing with the distribution system via the grid interface control. Apart from injecting power to the network, the grid-side inverter of solar hybrid system can absorb the power from the main grid for charging the battery.

In the event of loss of grid voltage, the typical grid-tied PV inverter is forced to disconnect via the anti-islanding protection. While the solar hybrid on/off grid inverter remains connected and then switched the operation from grid-following mode to grid-forming mode to provide the references for system voltage and frequency during islanding operation. Based on decentralized control [17], [18], the droop control methods are applied to control active and reactive power of solar hybrid on/off grid inverter. The frequency-droop and voltage-droop characteristics can be written as;

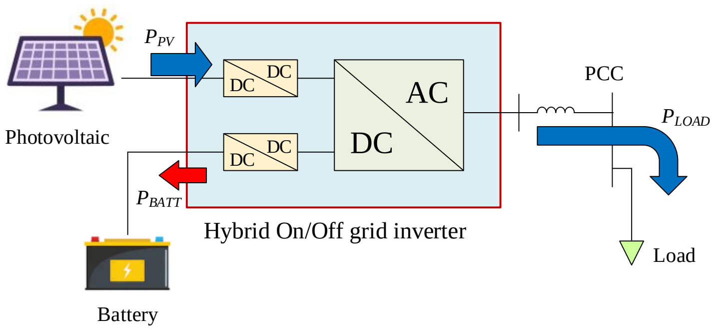
$$P = -\frac{(f - f_0)}{K_P} \text{ and } Q = -\frac{(V - V_0)}{K_Q} \tag{1}$$

where P and Q are the active and reactive powers produced by the inverter, K_P and K_Q are the droop gains, f_0 and V_0 are the reference frequency and voltage.

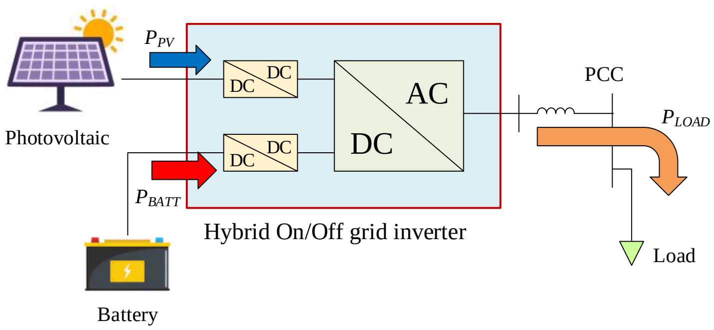
When the solar hybrid on/off grid inverter is working in the off-grid mode, the PV array will provide power to the load first and then charge the battery. In addition, if there is exceeding PV power after supporting the load, it will charge the battery first, as shown in Figure 2 (a). However, the battery cannot be charged by other energy sources such as diesel generator, until the PV power is unavailable. On the other hand, the battery will discharge power to the load if the PV power is insufficient (see Figure 2 (b)).

In a case that the battery power is running out and the PV power is not enough to supply load, the load will be disconnected. The electricity supply is then interrupted, and the outage event may happen. Only PV power can provide the battery charging, as presented in Figure 2 (c). When it reaches the acceptable level of battery, the load is therefore reconnected, and the solar hybrid system will resume supplying power to the load.

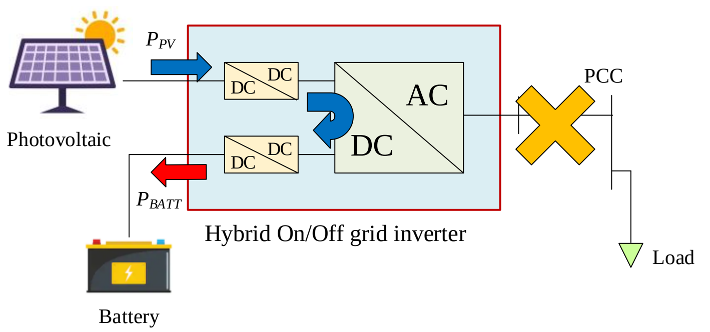
The grid-tied inverter is possible to resynchronize with the isolated system, after the solar hybrid on/off grid inverter can supply load properly. However, it needs to ensure that the supporting power from the other inverter will not lead the excess injection to the system which cause the abrupt changes in system voltage and frequency. Therefore, the active power curtailment control is necessary for allowing the grid-tied inverter to be included in the islanding operation.



(a) PV supplies power to load and then charging the battery.



(b) Both PV and battery supply power to load



(c) PV provides the battery charging after the battery ran out

Fig. 2. The operation of solar hybrid on/off grid inverter in off-grid mode.

3. POWER CURTIALMENT CONTROLLER

A particular power curtailment controller is introduced to prevent the exceeded power of grid-tied PV inverter during islanding operation. It is the real-time control which requires the combining information of load consumption and PV output of solar hybrid on/off grid inverter. In addition, the load consumption is measured by high resolution power meter and the PV output of solar hybrid on/off grid inverter is estimated via the solar irradiance measured by the pyranometer. The real-time data is accordingly sent to the power curtailment controller via communication system, for determining the suitable PV output of grid-tied inverter, as demonstrated in Figure 3.

From Figure 3, the PV power of solar hybrid on/off grid inverter ($P_{PV,hybrid}$) is calculated by using the measured solar irradiance. It is adapted from the PVWatts manual [19] which the impact on cell temperature is neglected. The predicted PV output, $P_{PV}^{predict}$, at time, *t*, can be written as;

$$P_{PV}^{predict}(t) = \eta \cdot \frac{I_{tr}(t)}{1000} \cdot P_{dc0} \tag{2}$$

where I_{tr} is solar irradiance (W/m^2). P_{dc0} is the nameplate DC rating of PV array. η is the DC-to-AC derate factor. If the size of PV array of solar hybrid system and grid-tied PV system is known, the PV outputs of those systems can be predicted by using (2) and then written in terms of $P_{PV,hybrid}^{predict}$ and $P_{PV,grid-tied}^{predict}$ respectively.

After the grid-tied inverter can re-synchronize with the islanded electricity system, The PV power will supply to the system only when the load consumption, P_{LOAD}, is higher than $P_{PV,hybrid}^{predict}$. Therefore, the grid-tied inverter's PV power set-point, $P_{PV,grid\text{-}tied}$ is considered as;

$$\Delta P(t) = P_{LOAD}(t) - P_{PV,hybrid}^{predict}(t) \tag{3}$$

If $P_{LOAD}(t) > P_{PV,hybrid}^{predict}(t)$, then

$$P_{PV,grid-tied}(t) = \begin{cases} \Delta P & \text{if } \Delta P < P_{PV,grid-tied}^{predict} \\ P_{PV,grid-tied}^{predict} & \text{else} \end{cases} \tag{4}$$

Otherwise,

$$P_{PV,grid-tied}(t) = 0 \tag{5}$$

In the real operation, a small amount of power from the battery may be required to secure the power balancing mechanism due to the error from the prediction and some power losses, such as line loss, which are not included in (2) to (5).

The performance of proposed power curtailment algorithm is examined based on computer simulation in DIgSILENT *PowerFactory* environment. The test system is a building made up of solar hybrid on/off grid inverter and grid-tied PV inverter. The measured data in Thailand is used to generate the daily load profile and solar irradiance profile. To demonstrate PV power curtailment potential, an islanding condition is established by disconnecting the building from the main grid during periods when aggregated PV generation exceeds load usage. The PV power outputs of the solar hybrid on/off grid inverter and the grid-tied PV inverter, as well as the battery condition, are investigated in two scenarios: 1) the grid-tied PV inverter is not included in the islanding operation, and 2) the grid-tied PV inverter with power curtailment is included in the islanding operation.

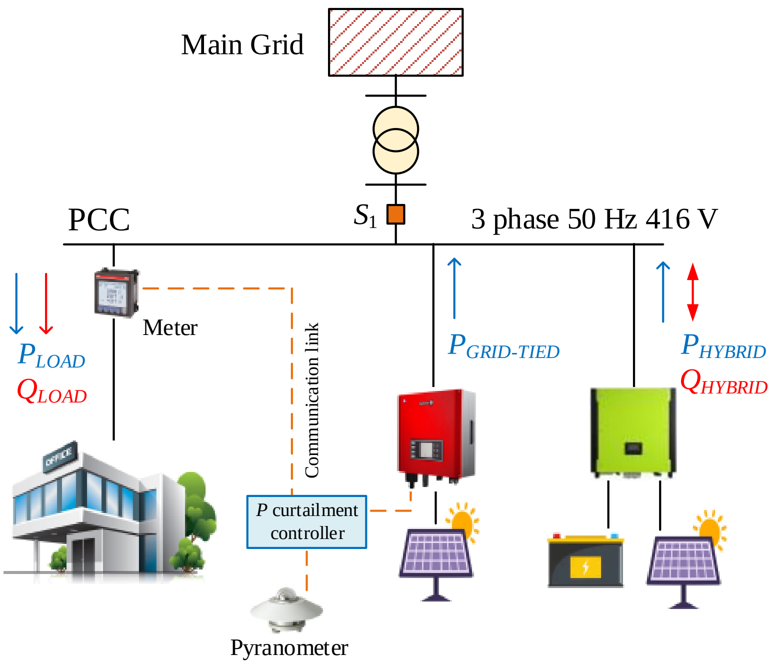


Fig. 3. The proposed active power curtailment controller.

4. TEST SYSTEM

Based on Figure 3, the experimental building which connects to a three-phase 416 V, 50 Hz distribution network, has been tested in this study. In addition, the 5 kW/5 kWh solar hybrid system and 5 kW grid-tied PV system are installed in this system. The size of inverter in both systems is 5 kVA and the battery is a gel type. The characteristic of daily load demand is shown in Figure 4. While the 24 hour - solar irradiance and power generation of 5 kW PV system, calculated by using (2), are demonstrated in Figure 5.

During the grid-connecting operation, solar hybrid on/off grid inverter and grid-tied PV inverter have been operating at the maximum power point to supply PV powers into the system as much as possible which are at a constant power factor of 1.0. In this test, the reverse power flow occurred by the PV generation exceeds the load demand is permitted. In on-grid mode, the battery is fully charge at 80% of state of charge (*SoC*) all the time. Additionally, the battery can be charged either by PV power of the solar hybrid on/off inverter or absorbing power from the grid.

The main grid is separated by disconnecting the switch S_1. Assuming the loss of grid supply occurs between 9.00 a.m. and 17.00 p.m., on the same day (11 hours of islanding condition). During the islanding operation, the solar hybrid on/off grid inverter is operated in grid-forming mode to provide the system frequency and voltage regulations. To maintain power balancing mechanism, the solar hybrid system needs to deal with the changes of active and reactive powers consumed by the load. The main power generation is from the PV array, while the battery will supply power only when the PV generation of hybrid system is inadequate.

In off-grid mode, the battery cannot be charged from the other energy sources if the solar hybrid on/off grid inverter is supplying electricity into the islanded system. The solar hybrid system can support electricity supply until the battery *SoC* is lower than 20 %. Hence, the solar hybrid on/off grid inverter is pulled out from the system. During this time, no electricity is supplied to the load. The solar hybrid on/off grid inverter resumes supplying the electricity, after the battery is charging by PV power of solar hybrid system until the *SoC* is 80%.

After the main grid is reconnected by closing the switch S_1, solar hybrid on/off grid inverter and grid-tied PV inverter return to grid-following mode and therefore feeding PV power at the maximum power point. If the battery level is lower than 80%, the battery will be charged suddenly. In order to charge the gel-type battery with a reasonable time, it is recommended that the charging power should be 15 to 25 % of the battery capacity [20].

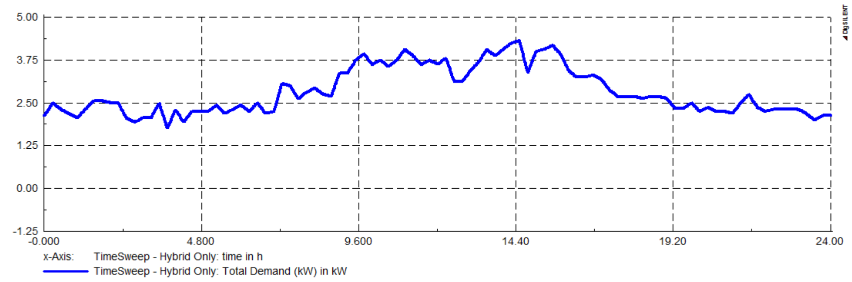
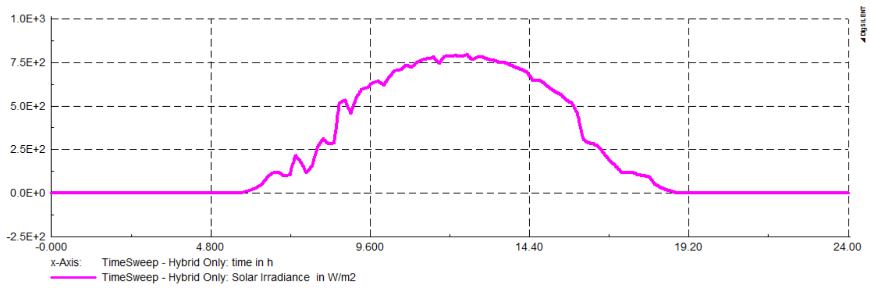
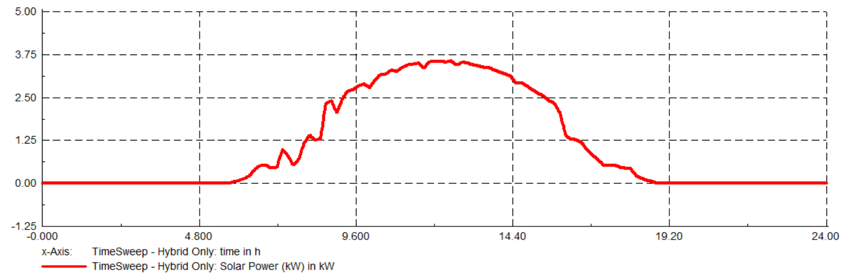


Fig. 4. Daily load profile.



(a) Solar irradiance (W/m^2).



(b) Predicted PV power (5 kW capacity).

Fig. 5. Daily solar irradiance and predicted power generated by 5 kW PV system.

5. SIMULATION RESULTS AND DISCUSSION

The performance of islanding operation is investigated in two scenarios, with and without the supporting from the grid-tied PV system, by using the 24-hour time-sweep load flow calculation on DIgSILENT *PowerFactory* software. The simulations are on 1-minute time step. The results from computer simulation are discussed as followings.

5.1 *Case 1: The Grid-Tied PV System is Not Included in Islanding Operation*

In this case, only solar hybrid on/off grid inverter supports electricity supply during in the event of loss of grid voltage. The simulation results are in Figure 6 to Figure 9. Voltage at the PCC and supplied load are shown in Figure 6. PV powers of solar hybrid on/off grid inverter and grid-tied PV inverter are presented in Figure 7. The battery charging/discharging and the level of *SoC* are illustrated in Figure 8. The flow of active and reactive powers through the solar hybrid on/off grid inverter is demonstrated in Figure 9.

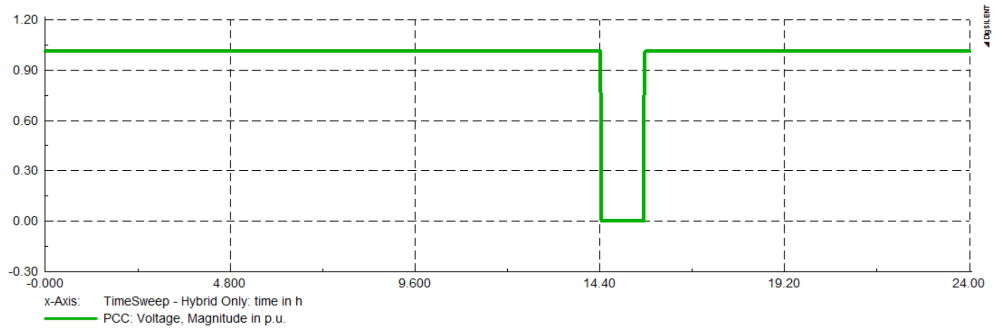
After the islanding is detected, at 9.00 a.m., the grid-tied PV system is disconnected while both PV and battery in the solar hybrid system can smoothly supply electricity power to the load. It can be seen that the solar hybrid system can support active and reactive powers, without any interruptions, only for 5 hours 24 minutes. In addition, at 14.30 p.m., the battery level is lower than 20 % and then the solar hybrid system is disconnected causing the load is unsupplied.

The loss of electricity supply occurs around 1 hour for charging battery by PV power until the *SoC* reaches 80 %. Since 15.30 p.m., the solar hybrid system can resume supplying electricity to the load. After the main grid is reconnected at 17.00 p.m., the grid-tied PV system is able to re-supply power to the grid. Due to the *SoC* is lower than 80 %, the battery is then charging with the rate of 1 kW charging power (20% of battery capacity). It can be seen that the active power is flowing back through the solar hybrid on/off grid inverter, during the on-grid charging process.

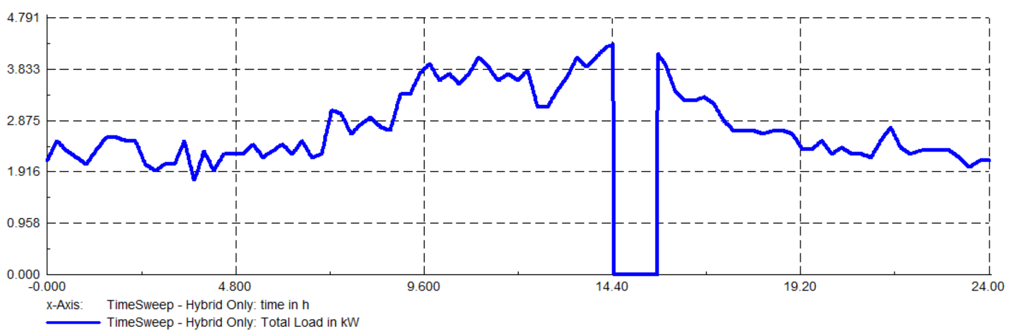
5.2 *Case 2: The Grid-Tied PV System with Power Curtailment Control is Included in Islanding Operation*

The supporting from the grid-tied PV system with additional power limit control during islanding operation is demonstrated in Figure 10 to Figure 13. The power curtailment controller, as explained in Section 3, can adjust the output of grid-tied PV system to maintain the balance between power generation and load consumption, effectively. With the support from grid-tied PV system, the battery will provide a lower power supply when comparing to the case 1. It also showed that the battery increased the discharging power significantly after 16.00 p.m., since the PV generation is dramatically dropped in the late afternoon due to low solar irradiance.

Furthermore, it is found that the integration of grid-tied PV inverter with solar hybrid on/off grid inverter for islanding operation can enhance the uninterrupted operation in the building. In this test, with the small amount of power supplied by battery, the islanding operation can provide continuing electricity supply without interruption. Additionally, the battery *SoC* was slightly reduced since the energy stored in the battery was used only about 25% of its capacity, during the loss of grid voltage.

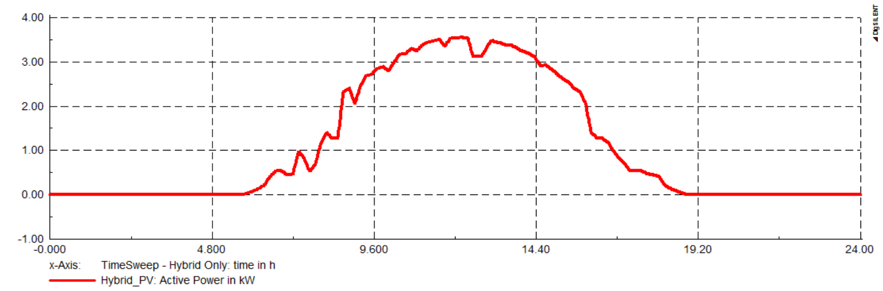


(a) Voltage at PCC.

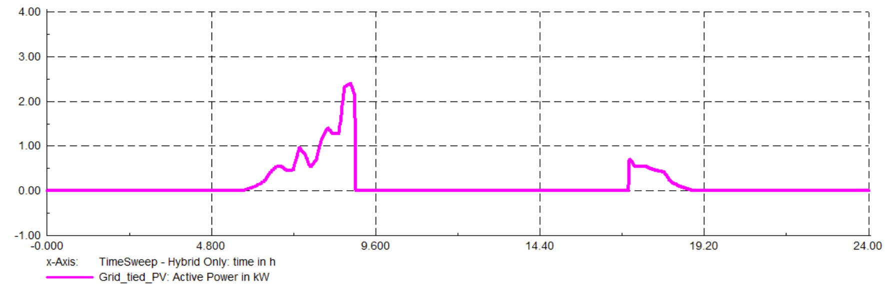


(b) Supplied load.

Fig. 6. Voltage at PCC and supplied load in Case 1.

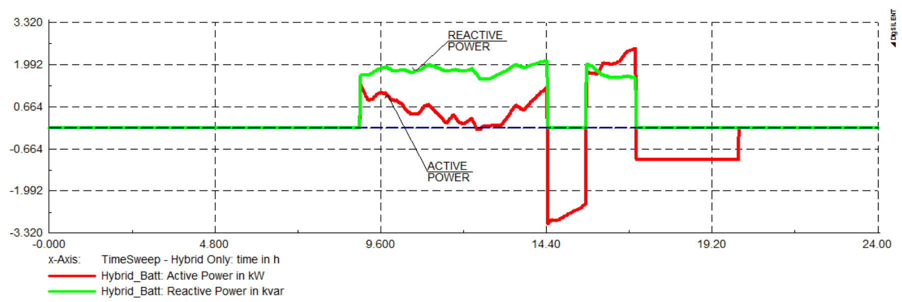


(a) PV power of solar hybrid on/off grid inverter.

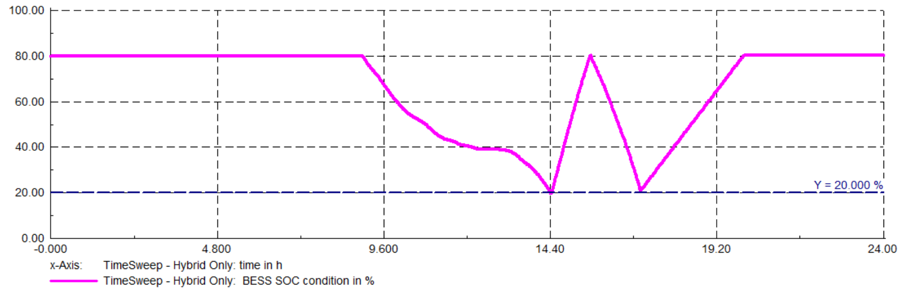


(b) PV power of grid-tied PV inverter.

Fig. 7. PV powers supplied by solar hybrid on/off grid inverter and grid-tied PV inverter in Case 1.



(a) Active and reactive powers of battery.



(b) Battery %*SoC*.

Fig. 8. Battery power and the level on *SoC* in Case 1

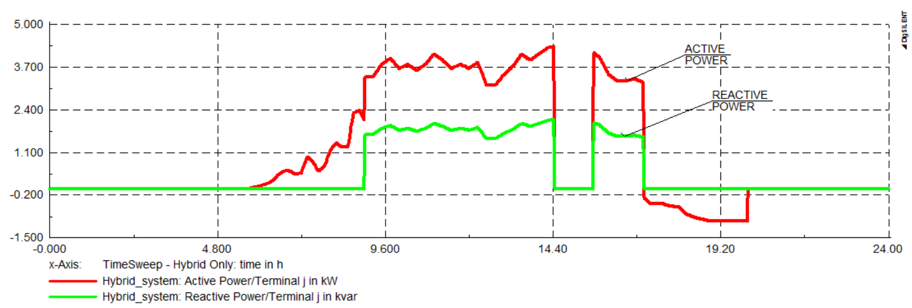
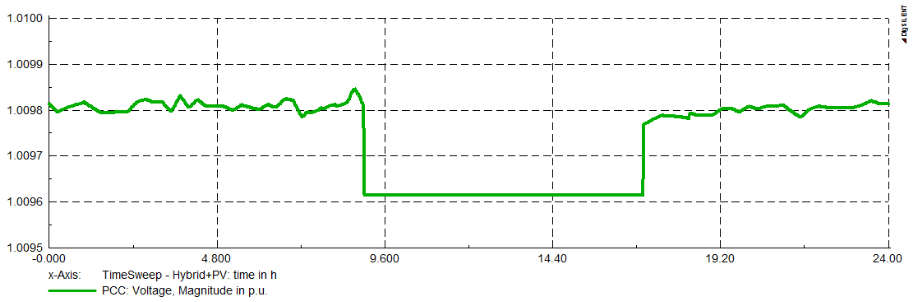


Fig. 9. Active and reactive powers of solar hybrid on/off grid inverter and grid-tied PV inverter in Case 1.

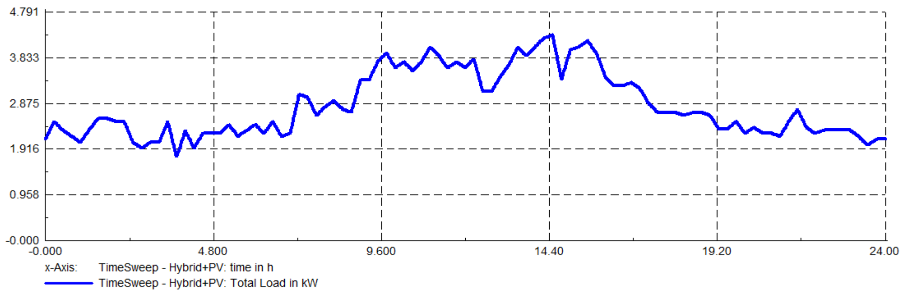
The proposed power curtailment controller attempts to automatically adjust the power set-point in power limiting function found in many commercial grid-tied PV inverters, in order to balance PV generation and load demand during off-grid condition. It is found that the use of load consumption and solar irradiance information for power limiting control, comparable to the usage of *P/f* droop controller [6], [17], [18], can also prevent the surplus PV feeding in isolated system effectively. As a result, the system frequency and voltage may be kept within the statutory limits. The controller, measuring instruments, and communication system, on the other hand, must be fast enough to deal with rapid variations in load demand and solar irradiation. Furthermore, the safety margin would be considered, with the power output of the grid-connected PV inverter being lower than the predicted value in (4) to guarantee that no excess PV injection occurs.

6. CONCLUSION

The study found that a particular power curtailment controller, which is the combination of smart meter and solar irradiance sensor, can allow the grid-tied PV inverter to collaborate with the solar hybrid on/off grid inverter in the event of loss of main grid. Based on the simulation results, the proposed active power controller can successfully adjust the output power of grid-tied PV inverter to avoid exceeding PV generation during islanding operation. The usage of a grid-connected PV inverter with suggested power limiting control can boost PV generation while decreasing the use of battery, especially during the day. As a result, this would be helpful for extending the building's uninterrupted operation when the energy supplied by the main grid is unavailable.

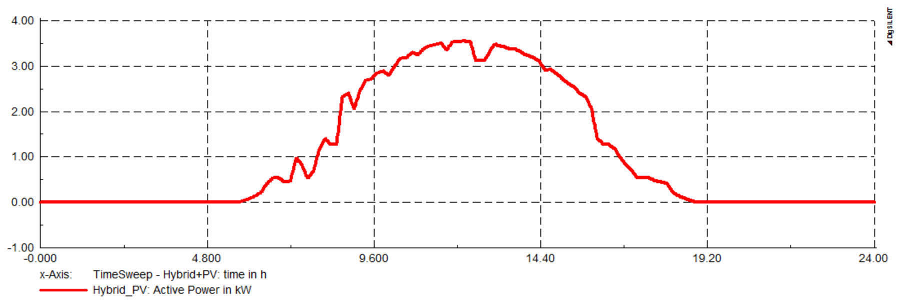


(a) Voltage at PCC.

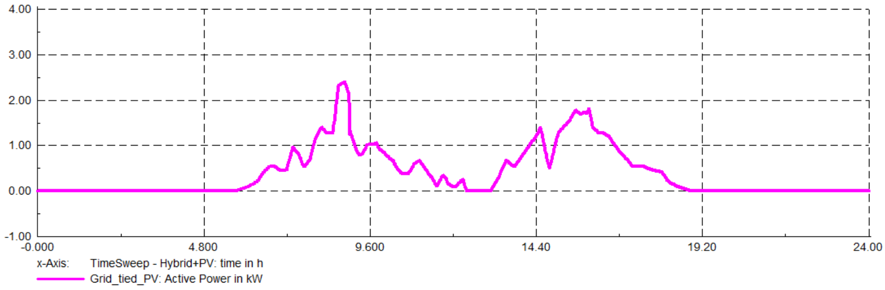


(b) Supplied load.

Fig. 10. Voltage at PCC and supplied load in Case 2.

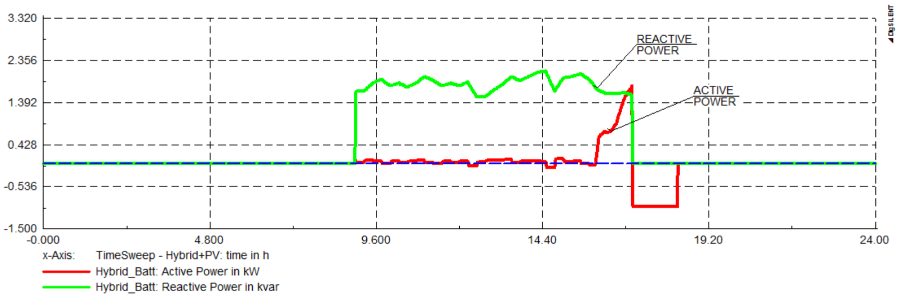


(a) PV power of solar hybrid on/off inverter.

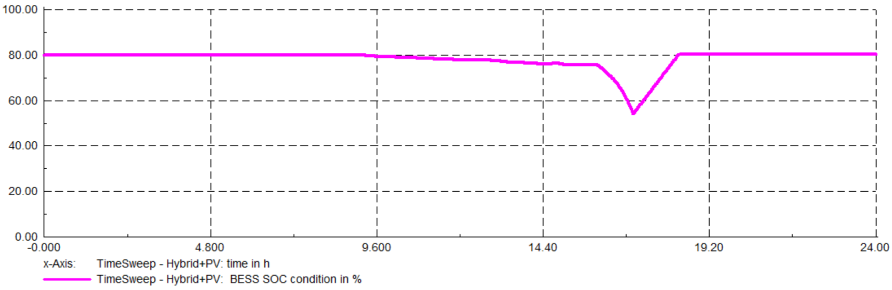


(b) PV power of grid-tied PV inverter.

Fig. 11. PV powers supplied by solar hybrid on/off grid inverter and grid-tied PV inverter in Case 2.



(a) Active and reactive powers of battery.



(b) Battery %*SoC.*

Fig. 12. Battery power and the level on *SoC* in Case 2.

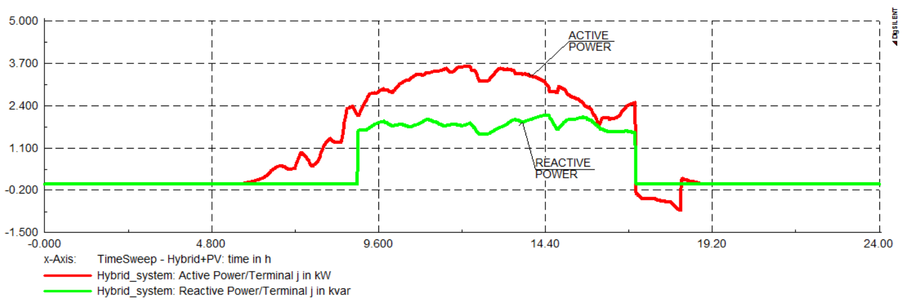


Fig. 13. Active and reactive powers of solar hybrid on/off grid inverter and grid-tied PV inverter in Case 2.

ACKNOWLEDGEMENT

This research was supported by the Centre of excellence on Energy Technology and Environment (CETE), Faculty of Engineering, Naresuan University and the Mastering Energy Supply focusing on Isolated Areas (MESfIA) project co-funded by the Erasmus+ Programme of the European Union. The European Commission support for the production of this publication does not constitute an endorsement of the contents which reflects the views only of the authors, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

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