Islanding Management of Microgrid with Multi-renewable Energy Sources

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***Abstract*— *The energy management and control strategies of microgrid system with multi-renewable energy sources, during islanding condition, are demonstrated in this paper. The test system consists of small-scale hydro generator, photovoltaic (PV) system and battery energy storage system. In addition, the hydro generator is using synchronous machine while PV and battery are interfaced with the grid through power converters. To operate microgrid system with satisfied frequency and voltage, four different control strategies are examined, which depending on technologies and functionalities of available energy sources in the system. The performance of each control strategy is simulated by using the time-sweep load flow calculation on DIgSILENT PowerFactory softwere. The simulation results show that the cooperation of frequency and voltage controls among hydro generator, PV and battery can increase the availability of electricity supply of microgrid system, during the islanding condition. This is found that the frequency and duration of sustained interruptions are decreased. Additionally, the Volt-Var controllability from PV system, and the active power curtailment of hydro generator and PV system are required for this solution.*

***Keywords*— Energy management and control, islanding mode, microgrid, renewable energy sources, Volt-Var control.**

1. INTRODUCTION

Many rural areas, such as small islands and mountain regions, are typically connected to the main utility via the long radial overhead networks which making the network strength is relatively weak. The long line lenghth and high exposure to elements and harsh weather conditions (strong winds, heavy snows and rains, severe floods) cause the customers who live in those areas are easy to face the power quality problems. The limitations in availability of technical support and reqair crews, as well as the lack of redundancy in the network design, influence the rural areas to experience very frequent and excessively long interruption of supply, resulting in a poor reliability performanace. Furthermore, the lack of energy storage systems or alternative generations in many rural areas, resulting in a much higher frequency of both short and long supply interuptions and the significantly longer supply restoration time.

The growth of distributed generation (DG), both conventional and renewable energy sources, can improve power quality, reliability and security of supply to existed distribution networks, in the form of microgrid system. In addition, the microgrid system is an interconnected network of loads and DG units that can function whether they are connected to or separated from the main utility system [1]. The microgrid system can enhance power quality, such as voltage level improvement and loss reduction, to the network during the grid connecting mode, whilst it increases stability and reliability to the network in the islanding mode.

There are many practical microgrid projects, across the globe, implemented by integrating with several renewable energy sources. It is found that, in 2013, North America has thus far built the majority of microgrid capacity, as can be seen in [2]. In the United States, The Consortium for Electric Reliability Technology Solution (CERTS) microgrid concept is developed to demonstrate the test bed including autonomous load following, local islanding and re-synchronising with the grid, voltage and frequency control [3]. This microgrid system consists of fuel cell, photovoltaic (PV) and micro-turbines as the energy sources, and adding battery, a fast static switch and power factor correcting capacitor to enable microgrid operation.

An alternative approach is taken by the European Union MicroGrid projects [4]. This microgrid system includes PV, fuel cell and micro-turbines, which those are interfaced through inverters, while small wind turbines connected directly to the grid. Furthermore, a central flywheel is used as energy storage unit to support frequency stability during islanding condition. Another example of microgrid project is in Sendai, Japan [5]. This project is defined as the multi power quality concept which both DC and AC loads are supplied by fuel cell, PV and micro-turbines. Additionally, a dynamic voltage restorer is employed to improve the power quality to high value loads. During the great east Japan earthquake in 2011, the Sendai microgrid could operate in the islanding mode to supply electricity to selective loads, such as hospital and school/university, during the outage.

Although the microgrid concept can enhance power generation and reliability of distribution networks, especially in the rural areas, the control and management strategy is an attentive issue in case that the microgrid system connects with many types of renewable energy sources, such as hydro, wind or PV systems. The uncertainty of many renewable resources causes the

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difficulty to the microgrid system when operating the instantaneous power balancing process and to maintaining the voltage level within the statutory limits, particularly during the islanding condition. Therefore, the energy storage system, such as battery or supercapacitor, is necessary to dealing with the fast fluctuations of frequency and voltage level in the system. In grid-connecting mode, the battery can support additional power when the supply from the main grid and DG is insufficient. On the other hand, it can absorb the surplus power when the power generated by DG is excessive than the total load demand. Many energy management and control strategies among the energy storage system and DG such as PV and micro-turbine in the microgrid system are examined in [6]-[8]. The results showed that the fast active frequency and voltage controls from converter connected DG and battery can provide the power balancing performance effectively during the microgrid system is separated from the main grid.

The islanding management is required to maintain the microgrid system with satisfied frequency and voltage level, while the load shedding should be a few. The battery is generally selected as the main controllable device to deal with the suddenly changes of frequency and voltage, after the islanding condition is detected. The renewable energy sources remain connect to the system if they can provide frequency and voltage control abilities. Additional, the active power curtailments are applied in some energy sources, to prevent an excessive power supplied into the system. When the battery condition is low, the load shedding is then processed and all DG units are disconnected, resulting the microgrid system becomes loss of supply. In this situation, if the sunlight is available, the PV system will charge the battery. Later, selective loads and DG units will be re-connected again after the battery condition is high enough to supply the power, making the microgrid system is restored.

From the reviews, it was found that the small hydro power plants are not involved in many practical microgrid projects. Most of microgrid systems is implemented based on converter-connected DG such as micro-turbine and PV system. However, many rural areas, especially in South-East Asia, have a high potential to include the small hydro generator in the microgrid system to support the energy balancing process under the islanding mode. In this work, the test system consists of small hydro generator, PV and battery systems. The study aims to demonstrate the performances of microgrid system in terms of energy management and voltage control, when various control strategies are applied. The results from simulation studies based on practical load demand and PV generation will benefit the relevant person, such as the planning engineer, to consider the suitable control solution, as well as the choice of controller's functions, which should be applied to operate the islanded microgrid system.

2. TYPICAL MICROGRID ARCHITECTURE

The typical microgrid architecture is showed in Fig. 1, adapted from [9], which consists of four parts: including,

Distribution network: The microgrid is usually a low voltage (LV) system, which can be DC or AC system depending on the load type. It is either interconnected to or isolated from a medium voltage (MV) network, with the fast response, by using the static disconnected switch.

DG units: The DG units in the microgrid system are normally small energy sources, such as PV, wind and micro-turbines, which typically interfaces to the AC system through the power electronic converters. The grid-side inverter of DG units can be used for supporting fast frequency and voltage controls.

Energy storage units: The energy storage devices typically are rechargeable battery or supercapacitor. The supercapacitor is used to support the power for the short-term disturbances, while the battery can supply bulk energy over a longer duration. Both energy storage devices connect to the AC network via bi-directional converters which the energy can be stored or taken from the energy storage devices.

Controlled and uncontrolled load: The high value loads, such as hospital, should stay connect to the LV system during the islanding condition, while some loads can be reduced the energy consumption or to be disconnected from the microgrid system when the lacking of power generation from DG and energy storage units.

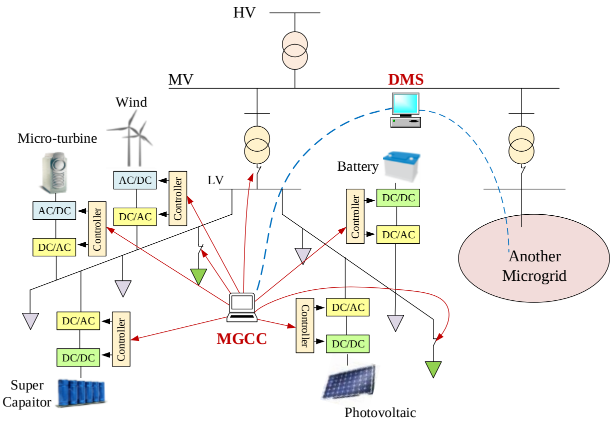

Fig.1. Typical Microgrid Architecture.

The microgrid control and management system, based on centralized control structure, typically consists of three level: device level at DG and energy storage units, microgrid central control (MGCC) and distribution management system (DMS) [10]. At the device level, DG and energy storage units try to generate power to the microgrid system that meet the grid requirement, both frequency and voltage. There are two control strategies are commonly used in this level. One is the peer-to-peer control which each DG and energy storage unit has an equivalent status and no single component is critical for the operation of microgrid. The DG and energy storage units can continue operating if the energy requirements are still satisfy, and thus plug-and-play capability is achieved. The other strategy is the master-slave control, which the slave modules receive instructions from the master through communication channels. Additionally, a single DG or energy storage unit is selected as the master, to take the primary control action, while the other units are slaves. All controllable devices in both control schemes are also supervised by the central controller.

The MGCC is the key level in the centralized control scheme. In this level, the central controller can command and exchange information with other controllable devices in the microgrid system via communication links, such as optical fiber cable. The MGCC is used to coordinate power references of DG units and controllable loads, while each individual DG controller ensures that the set-point from the MGCC level is reached. In islanding mode, the MGCC will manage the power production from DG and energy storage units to match with the total load demand in the microgrid system. Thus, the voltage and frequency are regulated to not exceed their limits. Moreover, the MGCC is able to disconnecting the uncontrollable DG and specific loads with the aim to maintain the reliability of the system. Moreover, weather information (such as temperature, solar irradiance, water lever) and load forecasting data, are required to make the MGCC can handle the microgrid system, under either on- or off-grid condition, effectively.

At the DMS level, which is the top level, the power productions of microgrid systems in the same distribution network are managed to meet the over grid demands. Furthermore, the DMS can be included in the wide-active network management or acting as virtual power plant, which allow the very large numbers of small DG units to be aggregated, to enhance the network performances in terms of power quality, reliability and stability [11].

3. OPERATING STRATEGIES OF RENEWABLE ENERGY SOURCES AND STORAGE SYSTEM

Small hydro generator and PV system are employed as renewable energy sources in this work, while the battery is chosen as the energy storage device. The hydro generator is based on synchronous machine and directly connecting to the network. On the other hand, both PV and battery are DC sources which will be connected to the grid through power electronic converter.

Small Hydro Generator

The small scale hydro generators are widely used in the rural areas. The power plant is commonly based on run-of-river design, which lacking of significant water storage, as seen in Fig. 2. The power output is decide by the water level which varies with rainfall. The power output of hydro turbine is given by, [1]

$$P = QH\eta\rho g \tag{1}$$

where P is output power (W), Q is flow rate (m^3/s), H is effective head (m), η is overall efficiency, ρ is density of water (1000 kg/m^3) and g is acceleration due to gravity.

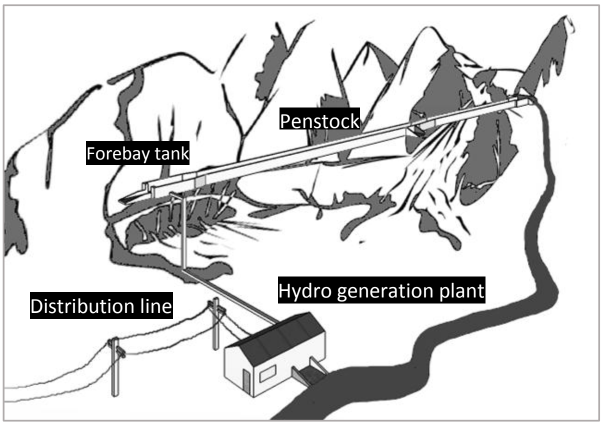

Fig.2. Run of River Hydro Power Plant.

Typically, there are no automatic power and voltage controllers in the small hydro power plant. This means that the hydro turbine will product the power as much as possible to the microgrid system. Therefore, it may cause the surplus of power generation during islanding condition. To prevent this situation, the hydro generator will be disconnected or to be asked for the power curtailment if the active power controller is available. In addition, the power production of hydro generator can be reduced by adjusting the penstock valve position to dropping the water flow rate.

Photovoltaic and Battery

The modern grid-connected PV and battery systems are typically based on voltage source converter (VSC) which consists of DC/DC converter cascading with DC/AC inverter, as illustrated in Fig. 3. The energy source-side VSC establishes the maximum power extraction function whilst the grid-side VSC performs the grid interface control. The active and reactive powers from grid-side converter can be controlled follows the supervision from the MGCC. Although both PV and battery have the same converter configuration, the PV is using uni-directional power converter while the bi-directional power converter is employed for the battery system.

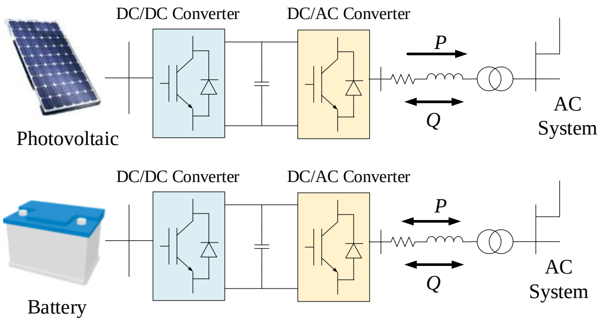

Fig.3. Configurations of Grid-connected PV and Battery.

For the PV system, the active power from PV is variable depending on the weather conditions, such as temperature and solar irradiance. The PV system will operate in maximum power extraction mode, which is the energy captured from the sun according to the maximum power extraction algorithm. During the grid-connecting condition, the power converter of PV system can operate in either *PQ* or *PV* mode [9]. In *PQ* mode, the reactive power of PV system is controlled at the fixed value or to be generated by the MGCC demand while the active power is still produced according to a maximum power extraction rule. Alternatively, the *PV* mode will arrow the PV system providing voltage control, to maintaining the AC voltage of inverter at a desired value. The voltage controllability is limited by the maximum allowable reactive power ($Q_{\max}$) of PV system, which depends on the output power (P_{pv}) and the rated power of PV system (S_{rated}). This allowance reactive power is calculated by,

$$Q_{\max} = \sqrt{S_{rated}^2 - P_{PV}^2} \tag{2}$$

In case of battery energy storage system, the direction of active power of the battery is depending on it is charged or discharged. The battery sends active power to the microgrid system during the discharge mode, while, in the charge mode, the battery creates negative active power. The battery will be operated in charge or discharge mode is depending on the level of state-of-charge (SOC). If SOC is high, the battery has been filled with electricity and ready to discharge power the system. Conversely, the battery should be recharged immediately when SOC is lower than the permission value. In term of reactive power produced by the battery, it is similar to the PV system which it is decided by the operating mode of the battery (*PQ* or *PV* mode) and the rated power of the grid-side converter. Moreover, the fast charging and discharging characteristics of the battery can be used to stabilize the power fluctuation from the PV generation, affected by the uncertain characteristic of sun intensity over the day.

In islanding mode, the grid-side inverter of either PV or battery, especially the one chosen as the master device, will operate as a grid-forming inverter aiming to emulate the behavior of a synchronous machine by providing a reference for voltage and frequency when the microgrid system is isolated from the main grid [12]. If two or more converter based PV and energy storage units participate in grid frequency and voltage controls, the droop control methods are applied to share active and reactive power among those PV and battery units. The frequency-droop and voltage-droop characteristics can be written as;

$$P = -\frac{(f - f_0)}{K_P} \quad \text{and} \quad Q = -\frac{(V - V_0)}{K_Q} \tag{3}$$

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.

4. TEST SYSTEM AND CASE STUDY

The test system is 22 kV, 50 Hz distribution network which includes 100 kW hydro generator, 100 kW PV system and 100 kWh battery, as shown in Fig. 4. The battery's depth of discharge is 80%. A group of customers in the system has the daily aggregated demand as demonstrated in Fig. 5. Assuming the power output of hydro generator is constant for the whole day, while the PV generation varies following the availability of sunlight. Fig. 6, illustrates the power output characteristic of 100 kW PV system. The MGCC will detect the islanding condition, and the switches M1, M2, S1 can be disconnected by the decision of MGCC to keep reliability and stability of microgrid system during the islanding condition. Furthermore, the MGCC is able to adjust the power dispatched from battery and PV system, for load balancing process, to control the system frequency and voltage level within the statutory limits.

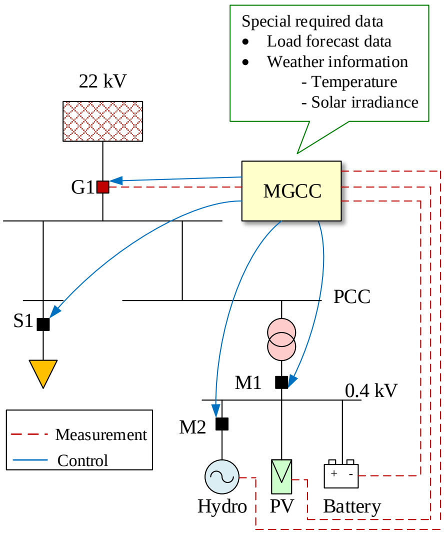

Fig. 4. Test System.

During grid-connecting condition, hydro generator and PV system dispatch active power according to the maximum extraction from their resources. There is no voltage control for hydro generator and PV system, which the PV system operates in *PQ* mode. The battery stays in healthy condition, assuming that the level of SOC is in high condition all the time. In addition, the battery may operate in *PV* smoothing mode to compensate the output fluctuation from PV system.

When the load break switch, G1, is opened, the MGCC receives the islanded command. The grid-side converters of energy sources are operated in islanding mode. The MGCC will find the optimal control strategy to manage the microgrid system during the off-grid condition, which depending on the availability and control functions of energy sources in the system. If hydro generator and PV system cannot provide active controllability, they will be forced to shut down by the MGCC. Then, the battery is a controllable device to support voltage and frequency controls. On the other hand, the hydro generator with power curtailment ability can be used as the base load generator of the microgrid system, due to the power output is quite steady.

The grid-side converters of PV and battery can be used to support frequency and voltage controls, based on the droop control methods. Additionally, the power curtailment control is required for the PV system to prevent over producing active power to the system, especially during the peak of solar intensity. The battery is able to support energy balancing and voltage control until the SOC is in the low condition. After that, the MGCC will disconnect all DG units and loads, and then the microgrid system becomes outage. In this situation, the PV system is used for charging the battery if the sunlight is available. The microgrid operation is back to work after the battery SOC is ready to discharge again. Otherwise, it needs to wait until the main ultility is re-connected.

At initial condition, hydro generation supplies the power of 55 kW into the network, while the battery is fully charged at 100 %. The PV system operates in the *PQ* mode at unity power factor. The islanding condition is defined by tripping the switch G1, to disconnect the utility system from the microgrid system.

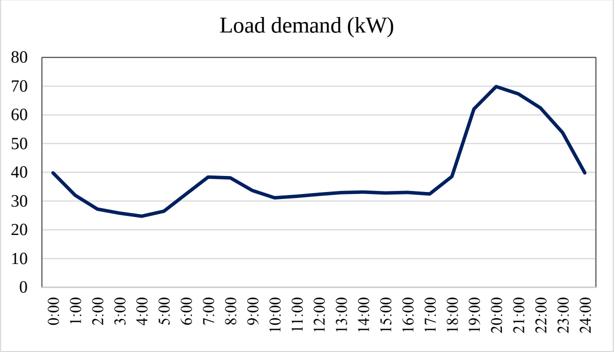

Fig. 5. Load Demand Profile.

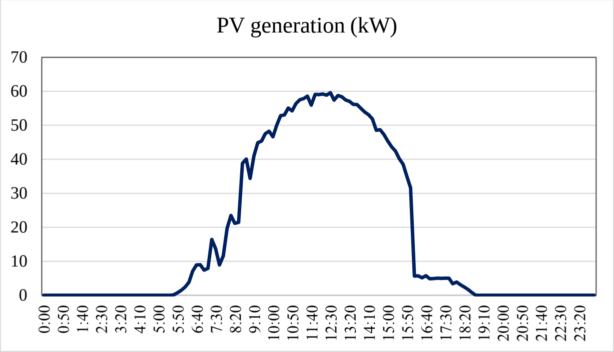

Fig. 6. PV Generation Profile.

The performances of microgrid operation during islanding condition are simulated by using the time-sweep load flow calculation on DIgSILENT *PowerFactory* software. Assuming the utility system is separated from the microgrid system at 9.00 a.m., and then it is reconnected again at 21.00 p.m., on the same day (12 hours of islanding mode). During the isolation from the main grid, the load shedding is requested when the battery has the SOC is lower than 20 %. Consequently, the microgrid will be restarted after the battery is charged by PV system, until the level of SOC is 100 %. Alternatively, the battery is allowed to discharge energy if the SOC is over 50 %, in case of the sunlight has gone before the fully charged. In this study, the islanding management of microgrid system is exercised in four different strategies, as followings;

Case 1: No support from hydro generator and PV system, only battery storage system is used to operate the microgrid (i.e. the base case).

Case 2: No support from PV system, using hydro generator and battery system to operate the microgrid.

Case 3: Hydro generator, PV and battery systems are used to operate the microgrid, but PV system only support reactive power for the voltage control.

Case 4: Hydro generator, PV and battery systems are used to operate the microgrid. In this case, PV system can support both active and reactive power, which the power curtailment is available.

Note that the hydro generator can be adjusted only active power by reducing the water flow rate, while battery and PV systems are possible to support either active or reactive powers into the microgrid system.

5. SIMULATIONS AND RESULTS

The simulation results of each case include the voltage profile, total load demand and power dispatched by energy sources, as can be seen from Fig. 7 to Fig. 10. The frequency and total duration of sustained interruptions that occur in each case are shown in Table 1. The performances of islanded microgrid system in four different control strategies are discussed as followings.

In case 1, it is assumed that the battery energy storage system (BESS) is only available device to offer active and reactive power to mictrogrid system during islanding condition, whilst the small hydro generator is tripped, by opening switch M2, and no support from PV system. The results in Fig. 7, shows that the battery can operate the system safely until the level of SOC is below 20 %, at 11.20 a.m. Hence, the MGCC will open switches S1 and M1, making all customers experience the outage. The PV system will start charging battery until the SOC is back to 100 % at 12.50 p.m.. When the battery is ready again, switches S1 and M1 are closed. The battery will support active and reactive powers to all loads again until it is in low condition at 15.00 p.m., and then the PV system will resume charging the battery for the second time. However, due to the sun intensity in the late afternoon is very low, so the PV system is able to charge the battery to reach 79.75 kWh (SOC > 50 %) before the sunset at 19.00 p.m.. The battery then resumes to support system frequency and voltage controls again until it is out of service at 20.00 p.m.. Hence, the microgrid system will remain loss of electricity supply until the main grid is re-connected again, at 21.00 p.m.

In case 2 to case 4, assuming the hydro generator can provide active power adjustment. From the daily load profile in Fig. 5, it is found that the lowest demand in the microgrid system is about 25 kW. If the small hydro generator can decrease the output power to lower than that value, it can operate as the base load generator, and using either battery or PV system as the load following generator during the islanding condition. In this study, the active power from hydro generator will be reduced from 55 kW to 20 kW. To allow PV system supporting active and reactive powers, the MGCC will investigate the system frequency and voltage level, and then sending the control signals to the PV system. The active power of the PV system will be curtailed if the frequency is high, and the PV system will inject the reactive power if the voltage is low. Moreover, all load and DG units are disconnected when the battery condition is low.

The simulation results of case 2 are illustrated in Fig. 8. In this case, during the main utility has lost, the small hydro generator remains connecting to the microgrid system, whereas the PV system is not included in grid-forming process and to be deactivated by the MGCC demand. The power from hydro generator is reduced to 20 kW as the base load generation. The battery will product additional active and reactive powers for energy balancing and voltage control. Since the islanding mode started from 9.00 a.m., the hydro and PV systems can handle the microgrid system in a good manner until the SOC of battery is in the low condition, at 12.40 p.m.. Then, switches S1, M1 and M2 are opened to remove all loads and DG units from the microgrid system. The sustained interruption has occurred in the microgrid system for 1.30 hours during the PV system is charging the battery until the SOC resumes to 100%. Since 14.10 p.m., the microgrid system can re-supply electricity for all customers with the assist of hydro generator and battery storage system. It is found that battery can discharge energy until 17.30 p.m., after that all loads and DG units are disconnected again, for waiting PV system provides charging to the battery. However, the PV is unable to charge the battery to reach the SOC > 50 %, due to the sun intensity is very low in the evening. Therefore, there is no electricity in the microgrid system since 17.30 p.m. until the main utility is available again at 21.00 p.m.

In case 3, it assumes that if the power curtailment of PV system is unavailable, the active power should not be dispatched to prevent the surplus power generation, especially during the noon time which the sun intensity is relatively high. Thus, in islanding mode, the PV system is only used as the Volt-Var controller (droop controller gain is 1%), similar to the DSTATCOM, without supplying active power into the system. From Fig. 9, it can be seen that the additional reactive power supported by PV system is able to extend the used of battery, comparing to case 2. The battery only inject active power for power balancing when the sun is still available. Since the main grid was isolated at 9.00 a.m., all energy sources can supply the electricity to the microgird system until 15.35 p.m. After that, the battery condition is low. The MGCC afterward trips all loads and energy sources from the microgrid system, causing the sustained interruption has occured for more than 3 hours. When the sunset at 19.00 p.m., the battery charging by PV system is finish, which the SOC is raised to 50.5 %. Hence, the MGCC re-connects all loads and DG units and resuming the system frequency and voltage controls again, but this time has no PV support due to the lack of sunlight. The electricity is available in the microgrid system until 19.40 p.m., then the SOC of battery is lower than 20% and then the load shedding is requested. The interruption of supply has remained in the microgrid system until the main grid is able to supply again at 21.00 p.m.

In case 4, the small hydro generator will decrease the power output to 20 kW and the PV system will support additional active and reactive powers, after the islanding condition is detected. The battery is only providing system frequency and voltage controls when the supports from hydro generator and PV system are insufficient. The simulation results in Fig. 10, illustrate that the hydro generator acts as the base load machine in the islanding operation. The PV system will inject reactive power to control the voltage level, while the active power is curtailed, during the time that the sun intensity is relative high, to maintain the system frequency within the limit. Due to the solar irradiance is very low after 16.15 p.m., the dispatched powers from hydro and PV systems are lower than the total load demand. Hence, the battery will start to support additional active and reactive powers. All energy sources can provide the availability of supply in the microgrid system until 19.00 p.m., without any load shedding. After that, the sunlight is unavailable and PV system cannot provide the charging process to the battery. All load and DG units are then disconnected by opening switches S1, M1 and M2, and hence the microgrid system will be loss of supply until the system resumes to the grid-connecting condition again at 21.00 p.m..

From the Table 1, it can be seen that the control operation of case 1, which using only battery, has the highest number in terms of frequency (3 times) and the total duration (6 hours 30 minutes) of sustained interruption. On the other hand, in case 4, the use of all energy source to support active and reactive powers with power curtailment ability and Volt-Var control can increase the availability of electricity supply in the microgrid system. It is found that the number of interruption event is reduced to only one, as well as the loss of supply duration is reduced to 2 hours.

Table 1. The Summary of Sustained Interruption Event and Duration during Islanding Condition

Case	Number of sustained interruption event	Total duration of sustained interruption
1	3	6 hours 30 minutes
2	2	6 hours
3	2	4 hours 45 minutes
4	1	2 hours

6. CONCLUSION

This work examines the islanded microgrid system with multi-renewable energy sources in different control and management strategies. The test system consists of hydro generator, PV and battery systems. The battery energy storage system is widely used as a main controllable device to dealing with power balancing mechanism and system voltage control when the main utility is disconnected. However, using only battery maybe not insufficient if the islanding condition is taking a longer restoration time. Then, the control operation among participated energy sources and energy storage devices is applied to increase the performance of microgrid system in terms of energy management and voltage control.

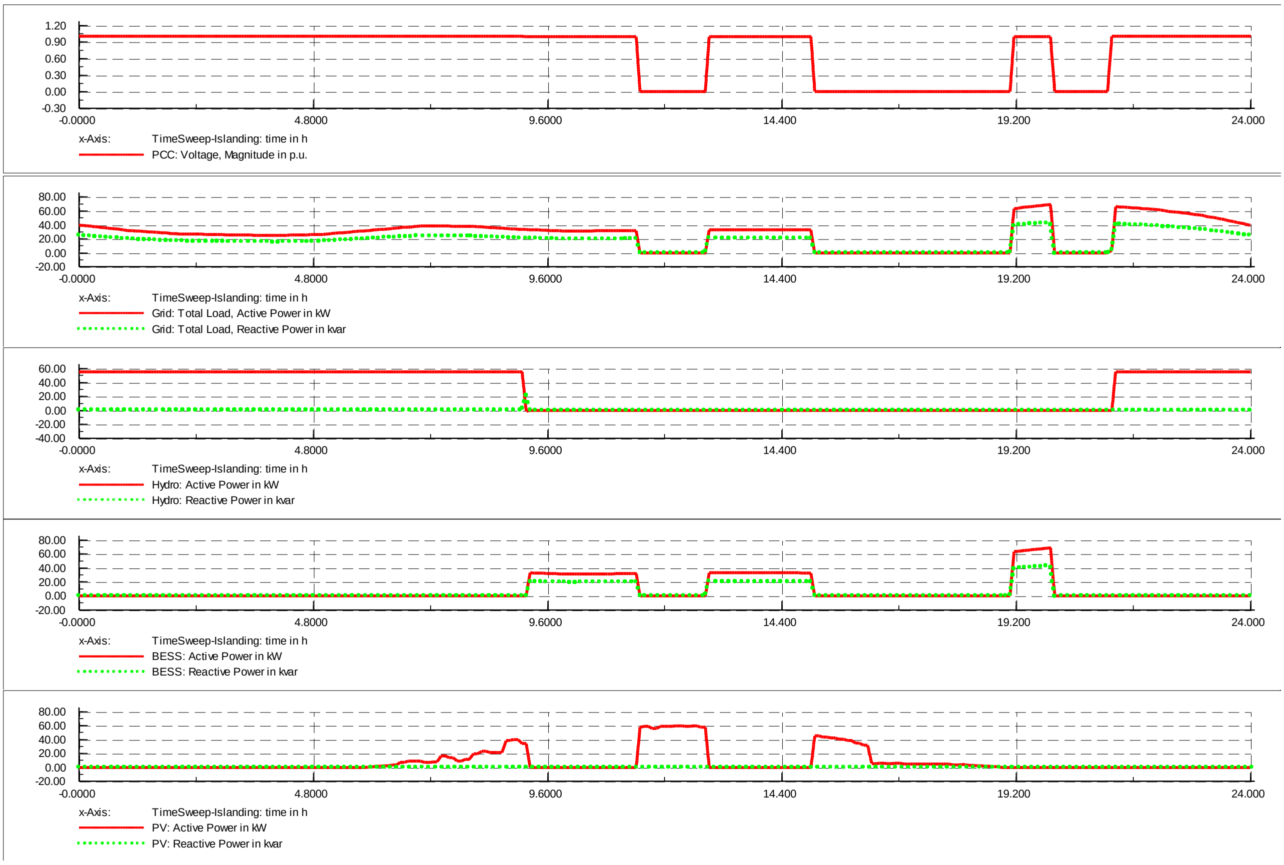

Fig. 7. Simulation Results of Case 1 (System voltage, Total demand, Outputs of Hydro generator, Battery and PV system).

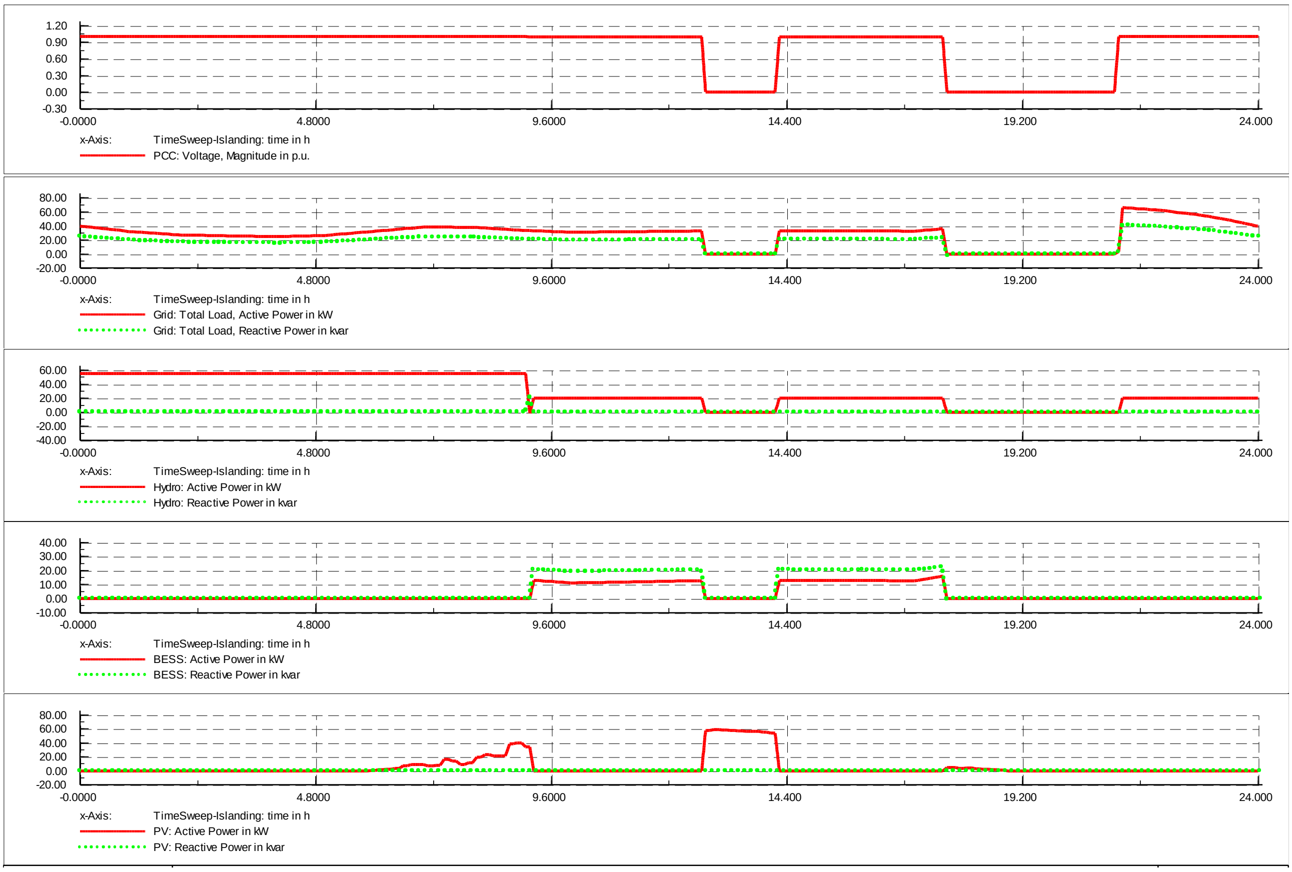

Fig. 8. Simulation Results of Case 2 (System voltage, Total demand, Outputs of Hydro generator, Battery and PV system)

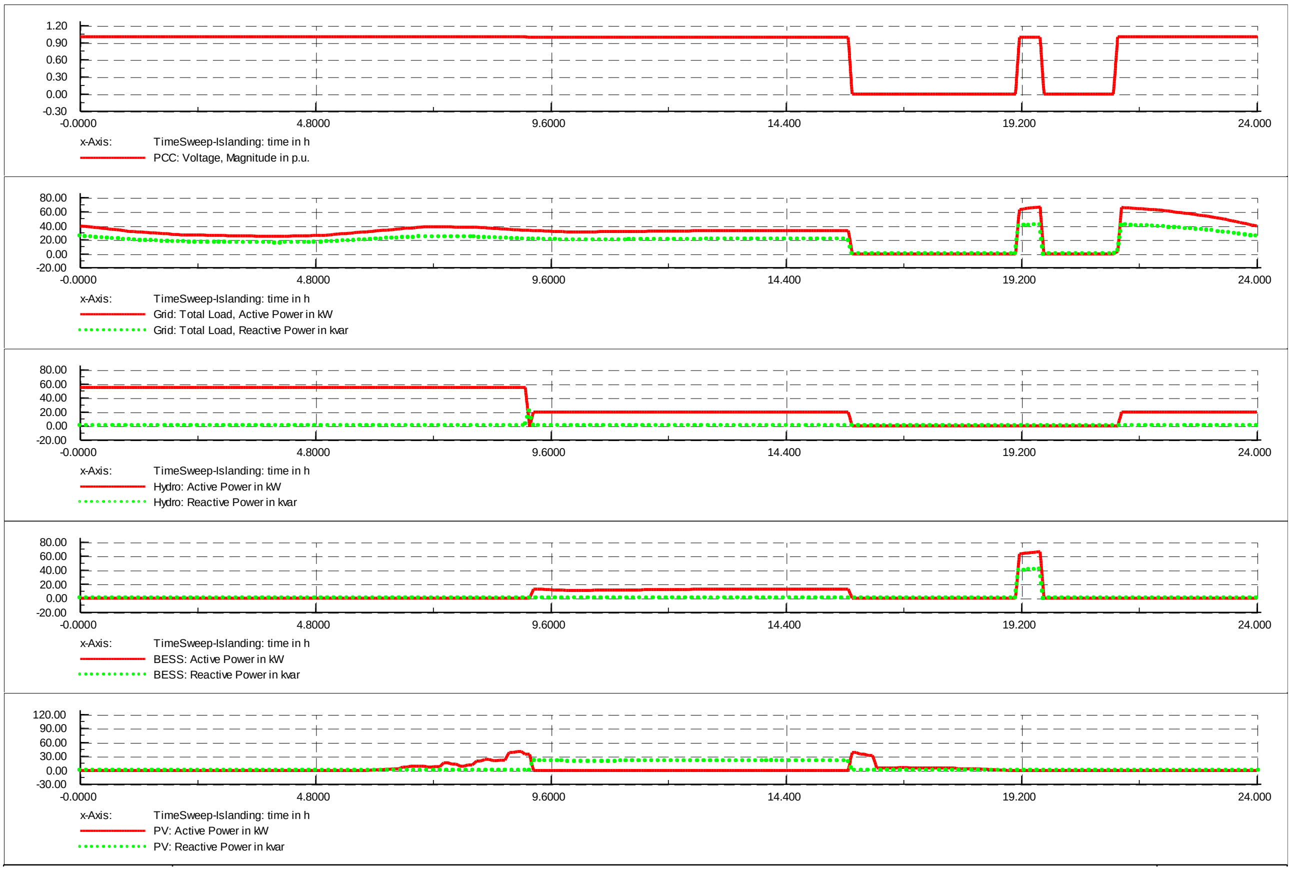

Fig. 9. Simulation Results of Case 3 (System voltage, Total demand, Outputs of Hydro generator, Battery and PV system).

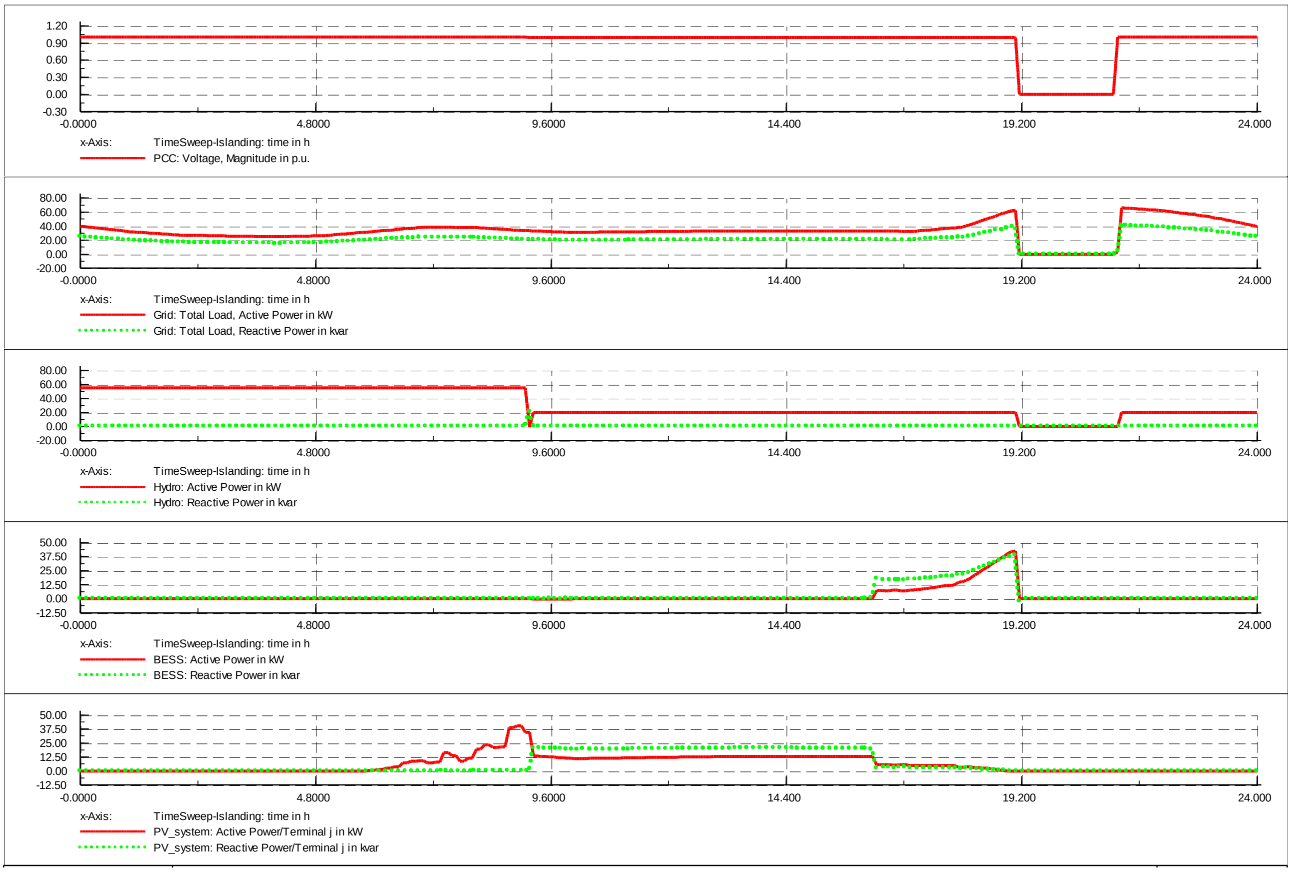

Fig. 10. Simulation Results of Case 4 (System voltage, Total demand, Outputs of Hydro generator, Battery and PV system).

From the simulation studies, it is found that the use of hydro generator, PV and battery to operate the microgrid system, with the cooperated manner, can enhance the use of battery during the islanding condition. This control strategy can reduce frequency and duration of sustained interruption, resulting in the improvement of reliability performance to the microgrid system. Additionally, the automatic voltage control from PV system, and the active power curtailment of hydro generator and PV system are necessary for this solution. Moreover, the MGCC should be fast and smart enough to manage the power balancing process between energy sources and load to dealing with the rapid changes of frequency and voltage under the islanding operation.

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