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Energy Management System for Isolated PV Microgrid focusing on the Remote Areas

Remote or rural areas are often excluded from the power planning expansion due to their isolated location and not cost-benefit. Nonetheless, the electricity to remote or rural areas is complemented and necessary. Thus, the isolated microgrid can be developed from the renewable energy sources of solar PV associated with battery energy storage. However, in isolated PV microgrids, the energy management for controlling power flow due to the inconstant energy sources and load variation is one of the crucial aspects that need to be appropriately addressed. This factor not only can affect the performance of the microgrid but would shorten the life cycle of the battery energy storage. Thus, this paper proposed a strategy to manage the energy sources in the isolated PV microgrid with a less complex approach through energy management system (EMS). Furthermore, the proposed approach is intended to prevent the situation of overcharging and discharging by considering the level of the current charge/discharge. The proposed isolated PV microgrid has been developed and analyzed through a simulation environment. As a result, the proposed EMS can manage the operation of the isolated PV microgrid with proper power flow and energy sharing to the load variations.

Keywords: Isolated microgrid; PV; Battery energy storage; Energy management system.

1. Introduction

Power energy distribution called microgrid has brought a new solution in providing electricity to the end-users. As the definition, the microgrid consists of a unit of distribution generation (DG) that includes several types of distributed energy resources (DER) working in one system grid [1]. To date, the renewable energy source (RES) from PV has been widely used as DER compared to other RES [2]. The dominance of RES contributes to enhancing the microgrid power efficiency by minimizing the power losses in transmission, as well as running at a reasonable cost. Consequently, the economic view and power reliability are two prominent objectives in microgrids that most utilities aim to develop.

In rural and remote areas, the efficient electricity supply is often neglected due to less significant interest. Thus, isolated microgrids are the best solution for providing electricity to these areas. As the RES from solar energy is dominant in isolated microgrids, it is essential to look at the problem of power fluctuation that causes intermittent power supply [3][4]. The popular photovoltaic (PV) system has been employed in harvesting solar energy, hence the variation caused by nature such as passing clouds, shadows, and electromagnetic effects, are also the factors that degrade the energy conversion and fluctuation. Thus, the use of energy storage is vital in solving the power fluctuation and power mismatch in the isolated microgrid [5][6].

It has been noted that the problem of insufficient energy can be solved by using several methods and techniques [7][8][9]. However, the researcher agreed that battery energy storage had been emphasized as a better solution for delivering power in short-term to mid-term applications [5][6][10]. Nevertheless, the life span cycle of battery energy storage is one of the limitations in battery energy storage in providing the power continuously [11].

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The appropriate control strategies are needed to prolong the life cycle of the battery, which can be subjected to overcharging, high charge/discharge rate, deep discharge, and an unappropriated technique of handling. Therefore, the key to improving the life cycle of the battery is to control the charge/discharge rate and maintain the level of state of charging (SoC).

In [12] and [13], the problem can be solved by adding the regulator or limiter into the systems, but as load suddenly increases, the battery cannot provide enough power to the system. Meanwhile, in [6], the life cycle of the battery depends on the design of the utilization, and it may interrupt the overall operations if the battery is not monitored wisely. Therefore, the supercapacitor (SC) bank can be used with battery energy storage to overcome the aforementioned problem. The SC can accept and deliver faster charging and tolerate the cycle of charging/discharging compared to the battery [14][15]. The combination of battery and SC will significantly impact the system and improve the overall performance in the isolated microgrid. However, the rate of self-discharge for SC is considerably higher compared to the battery energy storage and requires a complex and tedious control approach. Another drawback for the SC is the amount of energy stored per unit, in which the amount of energy stored per weight is lower than the battery energy storage [16]. Thus, it requires a series of connections in order to set up a higher voltage. In addition, it also has a low energy density when compared to the battery's energy density

Nowadays, many methods and strategies have been done for managing microgrid energy sources. Nevertheless, in rural or remote areas, a straightforward and less complex energy management algorithm without degrading the overall performance and operation is preferred for compensating the initial cost. Such in [3],[4],[8] and [9], heuristic approaches are employed for optimum scheduling and configuration the microgrid operation. While in [7], the stochastic-based algorithm has been proposed, significantly increasing the complexity energy management system. These approaches are worthy for the critical areas and high penetration at the end-users in terms of the cost-benefit operation.

In most areas, it is practical to locate PV due to its flexibility of installation and solar availability. Therefore, this paper proposes an energy management system (EMS) in an isolated PV microgrid integrating with the dual bank of battery energy storage. This paper discusses the configuration of isolated PV microgrid in section 2. The proposed EMS together with battery reference control is presented in section 3. Then, the results discussions of the proposed EMS are shown in section 4. The proposed approach and test system of isolated PV microgrid are analyzed and evaluated via simulation environment. The main objectives of the proposed EMS are to monitor and control the deep discharge state and charge/discharge rate by estimating the reference current for each energy storage (battery bank/unit) during charging or discharging mode. As a result, the proposed EMS can manage the operation of the isolated PV microgrid with proper power flow and energy sharing to the load variations.

2. Isolated PV Microgrid Configuration

2.1. Isolated Microgrid Topology

The PV system needs to be structured and designed properly due to the highly dynamic load change and unpredictable sun irradiation. The design topology of the system must be able to operate in reliable operation. In the early stage of the topology evolution, the battery directly connected the load by using a switch [17]. However, this kind of topology destabilizes the DC bus voltage in the system due to decreasing in the voltage during battery discharge. Moreover, the design does not have any control capability of charge and discharge operation. Therefore, the battery could degrade if there is a sudden load change in the system.

In order to solve the problem, the DC/DC converter is added to the system. The implementation of MPPT is adapted to the systems to track the maximum power output for the PV systems. However, as illustrated in Fig. 1(b), the battery is still directly attached to the DC bus. Usually, the value of the DC bus voltage is higher than the value of the single battery cell.

Therefore, a lot of the battery cells connected in series are needed in order to match the amount of DC bus voltage. To overcome the problem, PV system topology in Fig. 1(c) is proposed. The bidirectional DC/DC converter was used to manage the power flow in the battery. Thus, by employing the DC/DC converter, the value of total voltage for the battery bank can be designed smaller than the voltage DC bus. The control of the DC/DC bidirectional converter can manage the level state of charge/discharge rate. It also can monitor the operation condition of the battery charge/discharge within the acceptance boundary. These factors are significant in order to avoid overcharge and discharge. The maintenance cost is the most crucial issue in the isolated PV microgrid. Most of the cost comes from the battery units. Therefore, efficient EMS needs to be proposed to manage and control the energy supplies to the load demands.

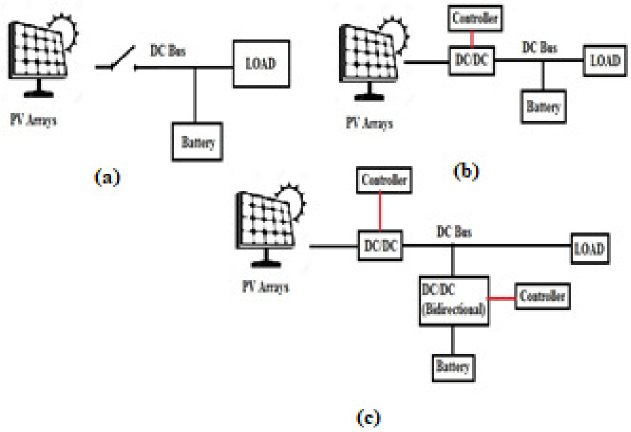

Fig. 1: Revolution topology of isolated PV microgrid

2.2. Proposed Isolated PV Microgrid

A small-scale isolated PV microgrid is proposed in Fig. 2 that aims to adopt in rural or remote areas. The objective of the energy supplies topology is to get a better power flow control from the energy storage units and enhance the capability control of charge and discharge current rate. The parameters of the proposed PV microgrid are shown in Table 1.

Two energy storage systems (ESS), which are battery banks with a capacity of 70kW each are used in the systems. The battery bank can hold the grid electricity up to two days of utilization without PV power. Lead-acid types of batteries are used and connected to the DC/DC converter. Converters 1 and 2 are buck-type converters, while converters 3 and 4 are boost-type converters. The maximum load test of the network is 62kW. In this topology, converter A used a maximum power point tracker (MPPT) controller to track the maximum power of the PV system while the ESS units supply the power if there is insufficient power caused by the uncertainty of PV power production and load demands.

In normal condition, The PV system delivers the power towards demand at the load and charge the battery when there is a surplus of power. In that case, the EMS is required to manage the input energies behaviour. The proposed EMS monitors the level of the state of charge, SoC of each bank in order to avoid overcharge/discharging conditions. When the PV system cannot deliver the power towards load demand due to weather conditions or load demand increase, the EMS manages the energy storage supplying the power to loads and monitoring the level of deep of discharge (DoD) of each energy storage. The proposed control in EMS defines the amount of current charging/discharging rate regarding the condition of SoC. The factory specification of boundary rate is taken into account for controlling the current charging/discharging for protecting the battery.

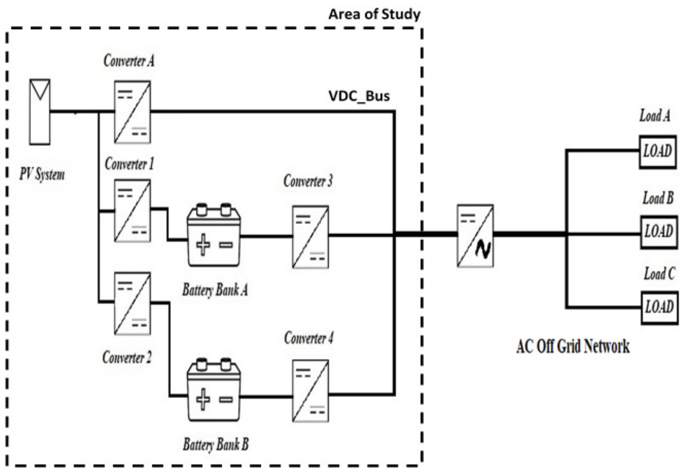

Fig. 2: Proposed topology of isolated PV microgrid

Table 1: Parameter of the isolated PV microgrid

Item	Parameter
PV system	35 kW
Battery Bank A (ESS_1)	70 kW
Battery Bank B (ESS_2)	70 kW
Maximum Load test	62 kW
Total load per day	140 kW
Voltage DC Bus	680 V
Inverter	68kW

3. Proposed Energy Management System (EMS)

3.1. Battery Reference Control

In Fig. 3(a), the charging control is proposed. The total string voltage for both battery banks is 370V, 200Ah. The fuzzy control is adopted to allow the battery bank to charge according to the accepted boundary from the manufacturer in order to protect the battery. Usually, the value of charging the battery is ranged between 10% to 30% of the battery capacity [18]. While in Fig. 3(b), the input parameters for fuzzy control are determined. The input parameters, which are the output power from PV (P_{pv}), power of load demand (P_l), and percentage *SoC* (SoC%) are classified into three categories, i.e., low (*L*), medium (*M*), and high (*H*). The reference current of the charging current (I_{BC_Ref}) is determined based on the behaviour of the input parameters which then decide the amount of current to be supplied to the battery. The PI controller is utilized for generating the PWM to switch on the converter. The mode of supply current is divided into three groups, which are low (2 to 10 A), medium (11 to 30 A), and high (31 to 52 A). Based on the defined output range, the fuzzy rules are proposed as shown in Table 2.

Table 2: Fuzzy rule table decision state

P_{PV}	P_l	$Soc\%$	I_{BC_Ref}
L	L	L	L
L	H	H	L
M	L	L	M
M	L	H	M
M	H	L	M
M	H	H	M
H	L	L	H
H	L	H	L
H	H	L	H
H	H	H	L

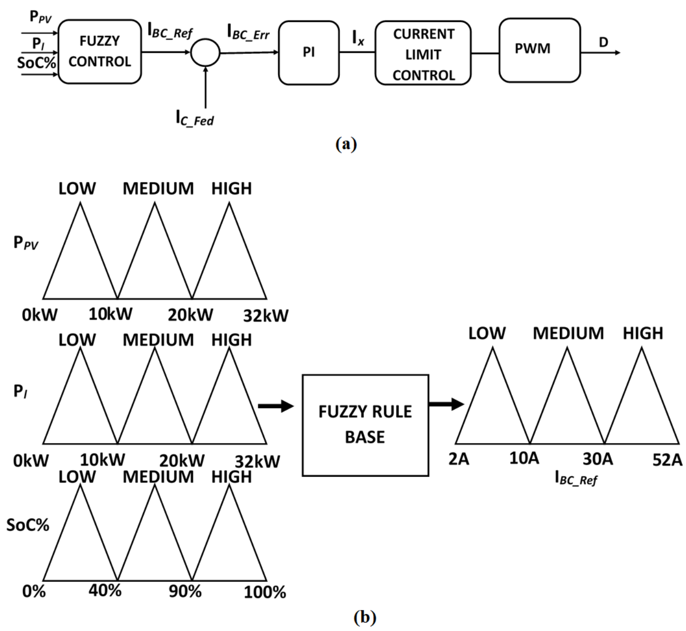

Fig. 3: (a) The control block diagram for charging and (b) The fuzzy membership function for charge control.

Then, the discharge current control is proposed such as in Fig. 4, which is functioning to determine the current reference I_{BD_Ref} of the load demands. The voltage error V_{DC_Err} is determined by comparing with the measured DC bus voltage V_{DC_Bus} and the voltage reference V_{DC_Ref} before passing through the PI controller for stabilizing the bus voltage. It is then compensated with load current I_l to provide the compensation load current I_x. The voltage reference value is respected to the amount of V_{DC_Bus} of the system. The I_{BD_Ref} is used to compare with circuit current I_{DB} to determine the limit of the discharging current of each battery bank. The value of current load I_l, the percentage SoC of battery bank *A* (SoC$\%_1$), and battery bank *B* (SoC$\%_2$) are employed in the algorithm to calculate the current reference.

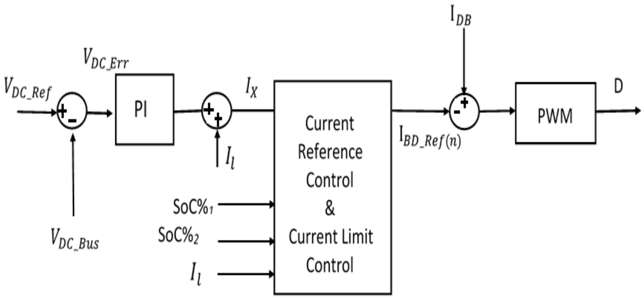

Fig. 4: The block of control for discharge state

The algorithm of discharge current reference control is shown in Fig. 5. In this algorithm, the discharging current for each ESS unit is determined by monitoring the level of SoC% of each ESS. The current reference (I_{BD_Ref}) is computed by the given information of load current I_l and the level of SoC% for each ESS. At first, the data of I_l, SoC%$_{1,}$ and SoC%$_2$ are defined.

If the value of SoC % for both batteries is at the same level, the value of the I_l that is needed in the system is divided into two from each battery unit to supply the current. While if the value of SoC%$_1$ is higher than the SoC%$_2$, ESS_1 is functions to discharge more current than the ESS_2 and vice versa. The algorithm control allows controlling the level of SoC% of each battery unit. This is important to ensure all the battery unit is utilized in optimum condition. The unbalanced use of the battery unit can impact the life of the battery and maintenance operation costs.

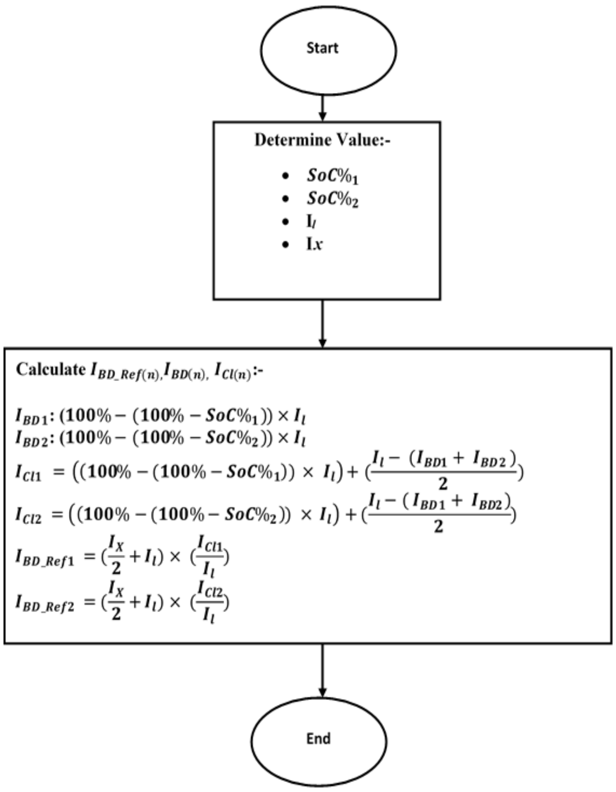

Figure 5: Current reference control algorithm for discharge control

3.2. Energy Management System (EMS) Configuration

As illustrated in Fig. 6, each ESS is either in a charging or discharge state depending on output PV power, $P_{PV,}$ and load demand power, P_l. The value of I_{BC_Ref1} for ESS_1 and I_{BC_Ref2} for ESS_2 is the value of current charging, while I_{BD_Ref1} and I_{BD_Ref2} are the amounts of current discharge from ESS_1 and ESS_2 to the load demand P_l respectively. The value of charging I_{BC_Ref1} or I_{BC_Ref2} are products with the voltage of the ESS (V_{EES}) to produce the power of the ESS (P_{EES}), while the value of discharging I_{BD_Ref1} and I_{BD_Ref2} are multiple with bus voltage V_{DC_Bus} to draw the power from each ESS to the load demand $P_{l.}$ The proposed isolated PV microgrid system has been divided into four operation modes to configure the EMS. Consequently, the value of P_{PV} and P_l are required for monitoring and used as parameters to decide the operation. If the PV output is higher than the total load demands, the ESS works in charging mode; otherwise, the ESS works in a discharged state.

Mode 1: For insufficient power drawn from PV to the load demand, the ESS provides the power to the power network to ensure a consistent supply in the voltage bus. The amount of current supply to the load depends on the level of SoC% of each ESS unit.

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Mode 2: For PV power increases due to the reaction of the sun irradiation while the load demand is minimum. The excessive energy is triggered to charge the ESS unit through converters 1 and 2. The controller algorithm calculates the amount of current from the ESS (refer to Fig. 5), and it depends on the value of the SoC% of each ESS.

Mode3: For charging protection mode. The ESS is working within the current limit to prevent the battery from overcharging. This happens when P_{PV} increases while load demand is at the minimum zone. The controller ceased the charging mode when the value of SoC% of the ESS reached the maximum setting.

Mode 4: For discharging protection mode, the P_{pv} condition decreases while load demand increases. The ESS is needed to discharge power to the systems and stabilize the DC bus voltage. To protect the ESS from over-discharge, the controller function to limit the discharge current within the maximum value of protection boundary, which is in this case, the value maximum of current can be drawn to the maximum current that allowed in the inverter (i.e. 150 A).

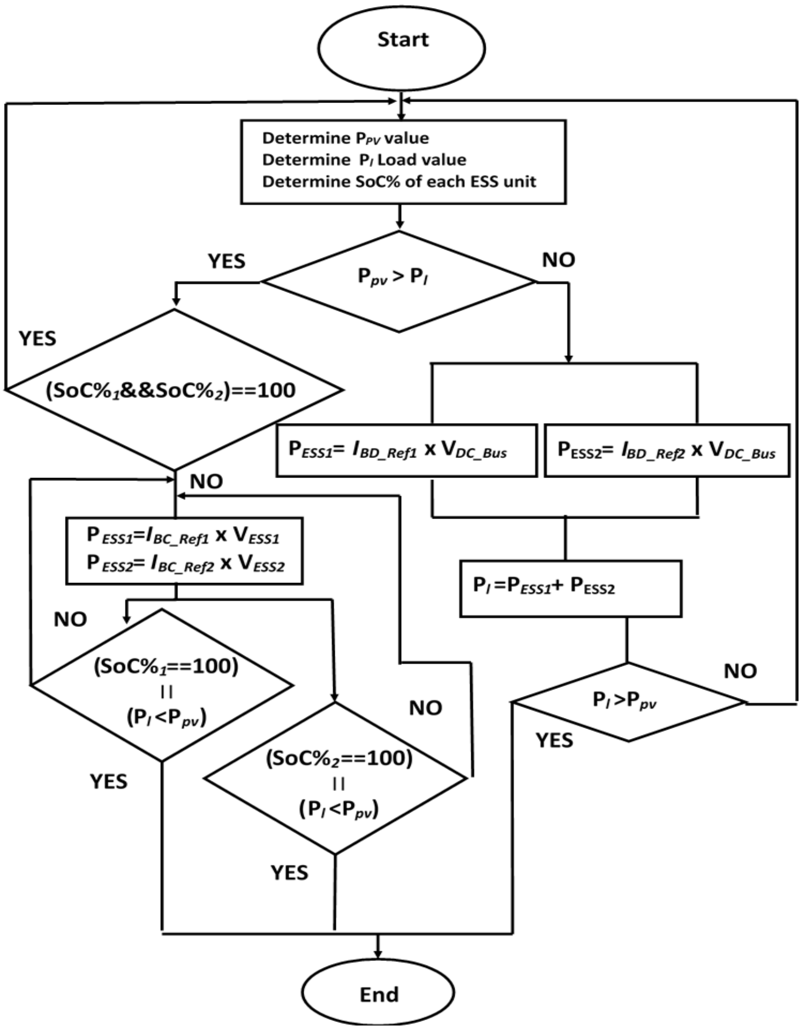

Fig. 6: Configuration of Energy Management system (EMS) algorithm for charging and discharging ESS.

4. Results and Discussion

The proposed EMS in isolated PV microgrid is developed following the parameters in Table 1 and analyzed through the simulation environment using Matlab/SIMULINK. The objective of the analysis is to validate the capability of the EMS operation in the proposed isolated PV microgrid topology with load changes.

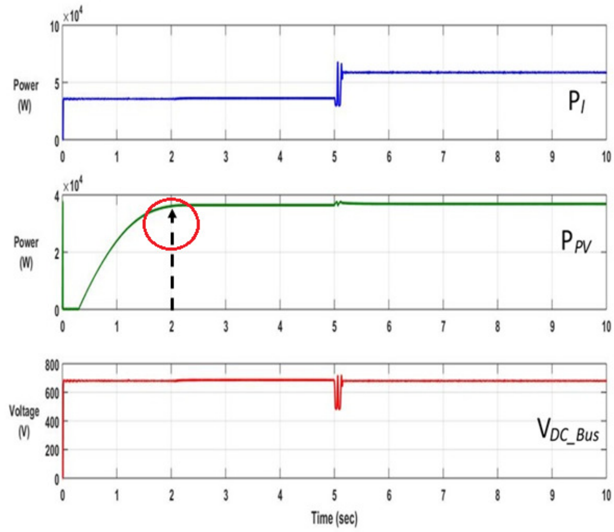

Fig. 7: P_l , $P_{pv,}$ and V_{DC_Bus}

Fig. 7 shows the power of load demand P_l, the power generated by PV, $P_{PV,}$ and DC bus voltage in the systems. The system is tested at 5 sec in a sudden increase of load demand from 36 kW up to 62 kW. The PV system receives a maximum of sun irradiation I_r = 1000 W/m^2. The result shows that the PV power increased and reached maximum PV power which is steady-state after 2 sec. The DC bus voltage is essential to be maintained regarding the variation of load demand in the microgrid. As a result, it is observed that 680 V_{DC_Bus} is maintained even there is a sudden increase in load. Then, in Fig. 8, it can be seen that from 0 sec to 2 sec and from 5 sec to 10 sec, the load demand is supplied by the ESS unit.

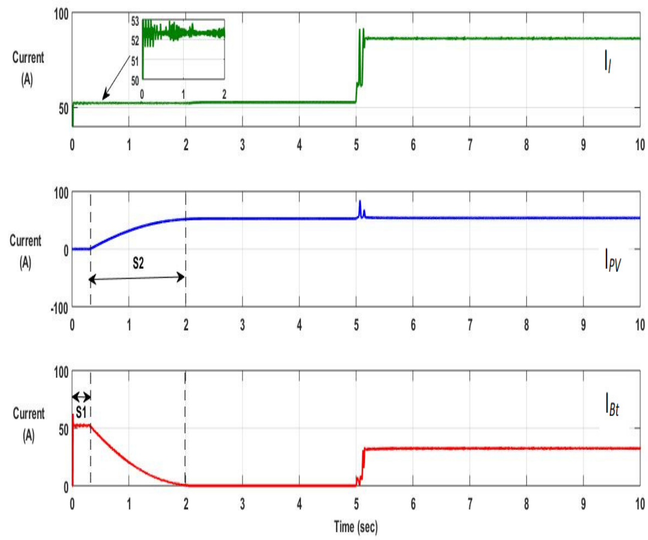

Fig. 8: I_l and I_{pv} and I_{Bt} battery discharge

In Fig. 8, the load current I_l is increased from 52 A to 92 A. It has been shown that the current spike up to 92 A after 5 sec due to the increase of current in load demand in a microgrid. At the beginning of range S1 (0s to 0.3s), the result shows that the microgrid gets the total current from ESS units I_{Bt}, which is 52 A due to insufficient current from the P_{PV}. At range S2, it can be seen that P_{PV} raise to steady-state as the solar irradiation increase to full capacity (0.3s to 2s) where P_{PV} has gained enough current to deliver, in which the load demand only receives the current from P_{PV} system and there is no current provide to the load by the ESS units. When the current load demand spike at 5 sec, the P_{PV} current inadequacy is added up from the ESS units (40 A) to the microgrid.

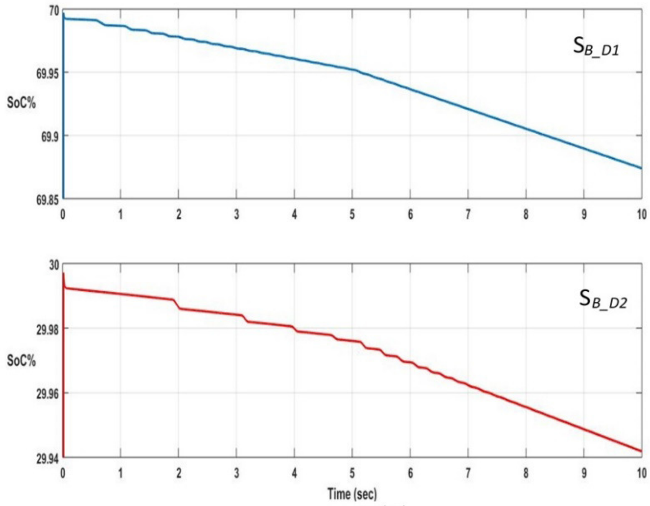

Fig. 9: SoC% profile for ESS$_1$ (S_{B_D1}) and ESS$_2$ (S_{B_D2}) during discharging

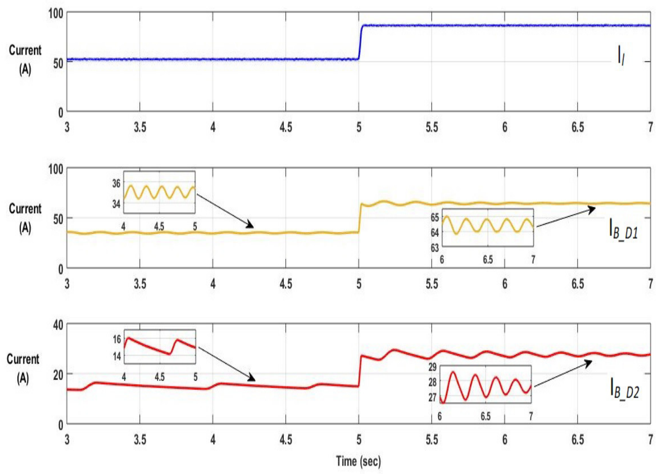

Fig. 10: Discharge current due to SoC% condition for each ESS.

Fig. 9 shows the level of SoC% during discharging for ESS$_1$ (S_{B_D1}) and ESS$_2$ (S_{B_D2}). The initial level of SoC% for ESS$_1$ is approximately 70% while the SoC% level for ESS$_2$ is around 30%. It is observed that the angle of discharge has dropped after 5 sec due to the increase of load demand. Meanwhile, in Fig. 10, the test run is carried out when there is no P_{PV} has been produced in the system ($P_{PV} = 0$), in which the total load current I_l is supplied from ESS units. The 52 A of load current I_l is observed until 5 sec. It is noticed that the current discharge from ESS$_1$ (I_{B_D1}) delivers to the microgrid network approximately in range 34 A to 36.4 A, which means 70% of the load current, while the other 30% is supplied from the ESS_2 (I_{B_D2}), which is 15.6 A. In a scenario of spike increase of load current I_l from 52 A to 92 A, the ESS units' response to increasing the current discharge up to 64.4 A and 27.6 A for ESS_1 and ESS_2, respectively.

Then in Fig. 11, the result shows the level of SoC% during charging for ESS_1 (S_{B_C1}) and ESS_2 (S_{B_C2}). Meanwhile, the charging current injected into the ESS units is shown in Fig. 12. The run test is carried out when there is no load demand ($P_l = 0$). In this case, the PV produces about 52A and use to charge both ESS units. The conditions are 60% and 40% of SoC% for ESS_1 and ESS_2, respectively (refer Fig. 11). It is observed the proposed charging algorithm response to draw about 31 A and 21 A to charge ESS_1 and ESS_2 respectively that follow each SoC% level. Hence, it has shown the effectiveness of the proposed algorithm for EMS which both ESS units can be controlled and function simultaneously at different SoC% levels. On the other hand, the speed of charging recovery is increased accordingly when one of the ESS units has reached the maximum level of SoC%.

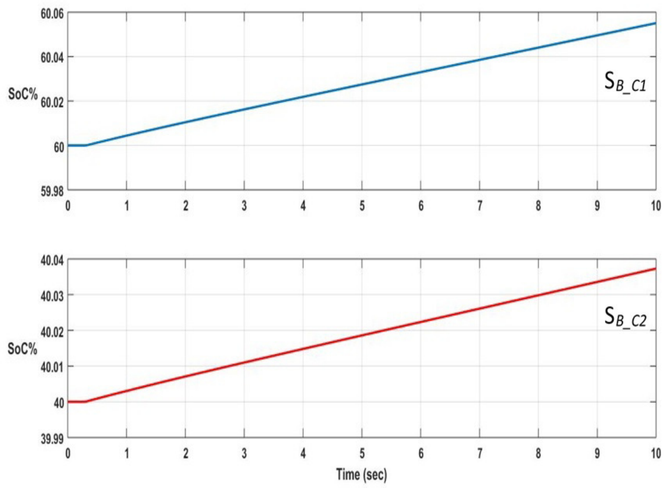

Fig. 11: SoC% for ESS_1 (S_{B_C1}) and ESS_2 (S_{B_C2}) during charging

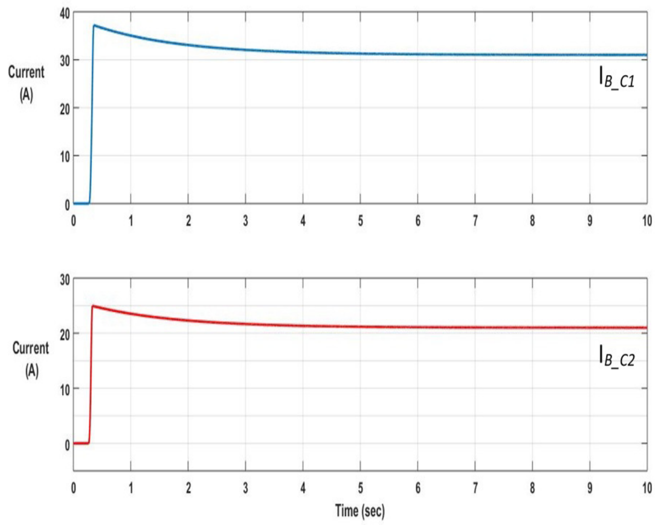

Fig. 12: Charging current inject to the ESS_1 (I_{B_C1}) and ESS_2 (I_{B_C2})

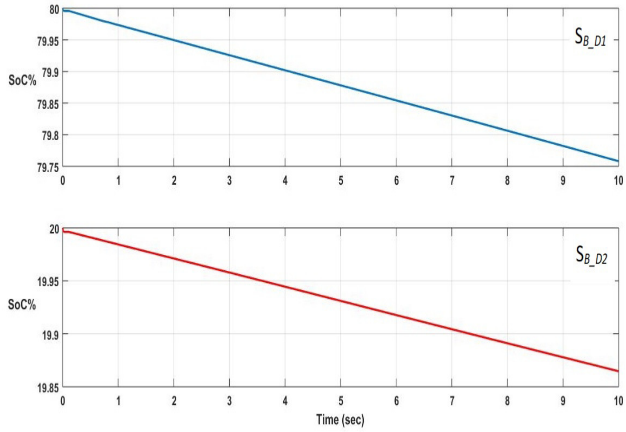

Fig. 13: SoC% value for ESS_1 and ESS_2 at discharging limit

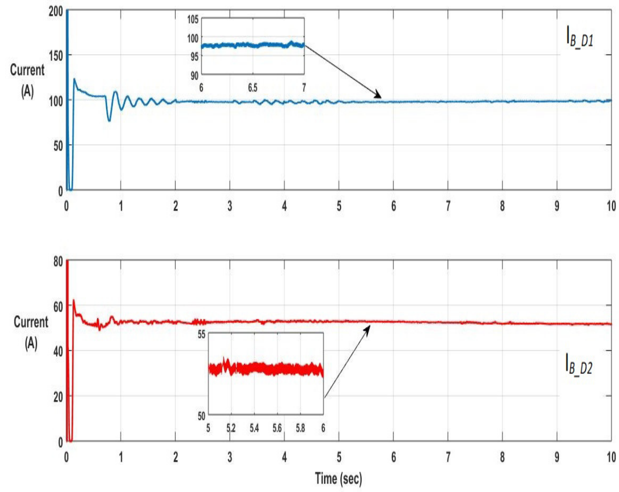

Fig. 14: Current discharging limit for both ESS units

Later, Fig. 13 shows the value of SoC% for ESS units during the discharge limit run test. As mentioned, the maximum current input allowed for the inverter is 150A, while the maximum current draw from each ESS unit is limited up to 100A. In this run test, the maximum current needed by the load demand is 150 A. Thus, from the algorithm calculation, if ESS_1 has 80% of SoC% level, the current should be drawn from the ESS_1 is 120A and the rest of 20% (30A) must be delivered by the ESS_2. However, in Fig. 14, it is observed that the current from ESS_1 has been set up to limit at 100 A due to the maximum current discharge setting, and the balance of the current is supplied from the ESS_2. This has shown the proposed EMS has obeyed the discharge current limit accordingly.

5. Conclusion

The isolated PV microgrid for rural or remote areas has been proposed and developed through a simulation environment. Two battery banks as energy storages system (ESS) are employed, which the PV plant is considered as a primary energy source. Taking into account the SoC% characteristics, the control for charging and discharging ESS has been implemented according to the reference current control. Afterward, the energy management system (EMS) is derived through the four-mode algorithm that considers the isolated microgrid operation. As result, the proposed isolated PV microgrid has demonstrated proper energy sharing to the load demands and capable to manage the DC bus voltage when the load changes. Besides that, the dual ESS can be operated simultaneously even at different SoC% levels with the charging and discharging are controlled accordingly to prevent overcharging and over-discharging.

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