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PV GENERATION-ENERGY STORAGE COORDINATION WITH ADAPTIVE DROOP CONTROL IN ISOLATED DC MICROGRID

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Abstract. *Photovoltaic (PV) generators and energy storages are critical components for supplying electricity and ensuring system stability, particularly in isolated DC microgrid. Coordination of PV generators and energy storages plays an important role to avoid voltage instability, overcharge and overdischarge of energy storages. To develop PV generators-energy storage coordination, this paper proposes a distributed control method based on the SoC (state of charge) battery level and the DC bus voltage signalling. The proposed control method is equipped with adaptive droop control for both energy storage system and PV generators. Droop control for energy storage is responsible for ensuring the balance of stored energy, which can avoid overcharging or deepdischarging of certain energy storage units. Meanwhile, droop control for PV is used to minimize load sharing error when line resistance is considered. To restore the DC bus voltage due to the use of droop control, secondary control is also proposed in this paper. The results of the proposed technique are simulated completely using Matlab/Simulink, even under fluctuating PV power and the load changes.*
Keywords: PV generator, Energy storage, Adaptive droop control, DC microgrid

1. **Introduction.** Fossil fuels have been widely used as an energy source to produce electrical energy; nevertheless, this has an impact on increasing global warming. Solar energy is one solution to get electrical energy with no pollution, and its availability is very abundant [1,2]. Hence, a lot of electrical loads both for homes and industries are supplied by photovoltaic (PV) generator. Therefore, the installation of PV generator (PVG) has increased in recent years. Nowadays, the use of PVG can be combined with an energy storage system (ESS) to form an isolated DC (direct current) microgrid system, in which this system is able to supply more DC power sources, even though the utility system is not connected. Moreover, the DC microgrid (DCMG) system has no skin effect and reactive power, so its efficiency is higher than the AC (alternating current) microgrid system [3,4].

In addition, the isolated DCMG has the disadvantage that it is susceptible to DC bus voltage deviation and instantaneous power imbalance. This is due to the unexpected load fluctuations combined with intermittent nature of solar. Therefore, several distributed ESSs are needed to ensure the availability of electrical energy and voltage stability [5,6].

Coordination control between PVG and ESS is also required when the PVG generated power exceeds the load power and the ESS is fully charged. This is to avoid a power

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imbalance in the DCMG system. On this matter, the PVG control switches from MPPT (maximum power point tracking) to a droop control technique for limiting power generation so that restoration of DC bus voltage is achieved [7,8]. Moreover, a hierarchical control structure with a cascade control loop is the most efficient battery charging control where proportional load power sharing is considered [9]. Given the explanation above, each PVG and ESS in the DCMG system must be operated using a decision-making technique to change its control mode.

In terms of coordination between generators and storages, many studies have been proposed and developed. In [10] a decentralized control strategy for modular PVG and ESS is proposed. This control strategy switches the control mode of the PV generator and energy storage based on DC bus signaling. However, multiple batteries are not considered for providing redundancy, so there is no coordination algorithm between batteries. Besides that, restoration of DC bus voltage is not assured. Mao [11] presented an adaptive coordinated control method with multiple PVGs and ESSs in DCMG. Switching control mode on PVGs and ESSs based on DC bus link voltage level. Then, each PVG and battery can work independently to share resources with the load. However, this control technique does not consider the SoC of the battery.

An adaptive droop technique for balancing the SoC of multiple storages is proposed in [12]. Parameter droop coefficients are adjusted based on the SoC battery. The battery with the highest SoC supplies the most power and another battery with the lower SoC absorbs more power, and vice versa. However, the proposed technique was applied only to the control of multiple batteries, while coordination between PVG and battery was not considered. Furthermore, the control mode of the battery must be changed during the charging and discharging process, which is not practically desirable. Nasir et al. [13] proposed a multi-mode adaptive algorithm with a double control loop to regulate the coordination between DC nanogrids, where each DC nanogrid has a PVG and a battery. This algorithm is able to manage resource sharing between DC nanogrids, so that the battery SoC balance is achieved and the DC bus voltage deviation can be minimized. However, this proposed control mode does not take account of the exchange of information between unit converters, may cause battery SOC balance is less accurate and better load power sharing is not obtained. [14] also proposed modified droop control with a single control loop. This control has a faster dynamic response performance than conventional droop control. However, the proposed droop control utilizes fixed droop resistance, so there is no guarantee of a proportional balance of load power sharing between sources when differences in transmission line resistance are considered.

From the problems mentioned above, this paper presents a distributed PV generators-ESS coordination control technique according to the level of the DC bus voltage and battery SoCs for isolated DCMG. First, the energy balance between several ESS is guaranteed by adaptive droop control based on the fuzzy logic. Particularly, fuzzy logic controllers have the ability to manage multiple control objectives at the same time [15]. Therefore, the proposed fuzzy logic controller (FLC) tunes the droop resistance of the droop controllers based on the SoC at each battery and the average SoC. Also, the FLC is able to adjust the droop resistance in accordance to the current output at each converter and the average current output, in order to ensure the better proportional load power sharing. Second, when the PVGs power is abundant and all batteries reach the maximum SoC level, the proposed control strategy disables MPPT and limits the PVG generated power by considering proportional load power sharing between sources. Then, overcharged battery can be avoided. PVG control returns to MPPT mode when the SoC of all batteries begins to decrease. This paper also presents the secondary control to reduce the DC bus voltage dissipation due to the effect of using droop control.

The remainder of this paper includes four sections. Section 2 explains the system configuration of the DC microgrid in islanded operation mode. Section 3 shows the proposed control stategy, which includes (a) the primary control and the secondary control (b) the adaptive droop method using fuzzy logic controllers. Then, the result of the test under different scenarios is presented in Section 4. The test of the proposed technique is on a low voltage DCMG under isolated operation. Finally, Section 5 concludes the paper.

2. **System Configuration.** The configuration of DCMG is composed by two PVGs, two batteries, and DC load, as illustrated in Figure 1. A low voltage DCMG can be built around a 100V DC bus voltage. This low voltage has been commonly used in residential installations as well as for powering DC loads [16,17]. In particular, the DCMG will be examined under isolated mode because this mode is crucial for remote and rural applications [18], and PVG-ESS coordination has a very important role [19]. Power converters are used to manage the produced power of the PVG, manage the power buffering of the ESS, regulate the DC bus voltage, and share the power across numerous PVG and ESS systems. Typically, a boost power converter links PVG while a bi-directional power converter links the storage system to the DC bus. The battery is a prosumer whereas it can either generate or absorb energy. In this configuration, there are 4 transmission lines (R_{Line1}-R_{Line4}) which represent a conductor cable that carries current to the load. The control strategy should be configured to avoid overcharging and undercharging, thereby preserving battery life.

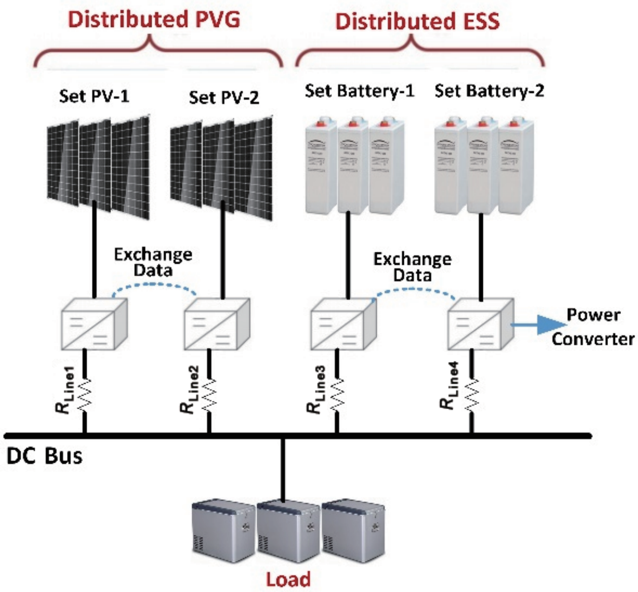


FIGURE 1. System configuration of DCMG

This system configuration performs data exchange between converter units via low bandwidth communication (LBC). This aims to produce a better proportional load power sharing and a more accurate SoC balance. In addition, to prove the reliability of this system, the difference in line resistance is also considered.

3. **Proposed Control Strategy.** The goal of this research is to provide an algorithm for power management in isolated DC microgrids. Figure 2 depicts the proposed block diagram. Multiple sources can be coordinated through two levels of control, such as primary control and secondary control. Each level has command-level responsibilities and supervises lower-level structures.

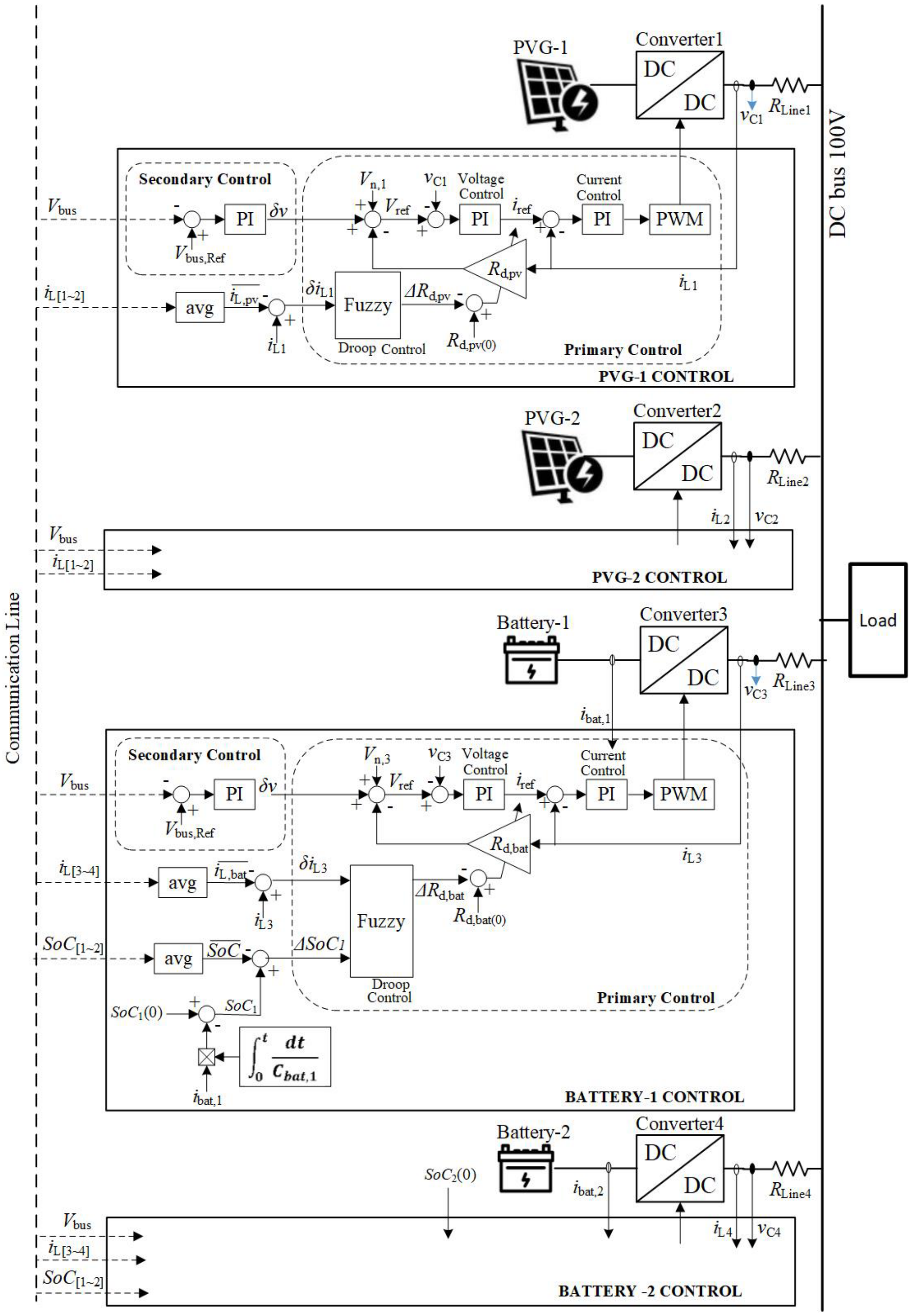


FIGURE 2. Diagram of the proposed adaptive droop control for PVG and ESS

3.1. **Primary control.** Figure 3 depicts that the primary control is the first level of control which consists of the droop control and control loops. The primary control is responsible for regulating the system voltage and current by tuning the current supplied to the DC bus [20]. The distributed control techniques can also be applied at this level to sharing the load power between DC generators with communication links [21].

In general, an inner control and an outer control are the main part of control loops. A current control represents the inner control loop that controls the current, while the

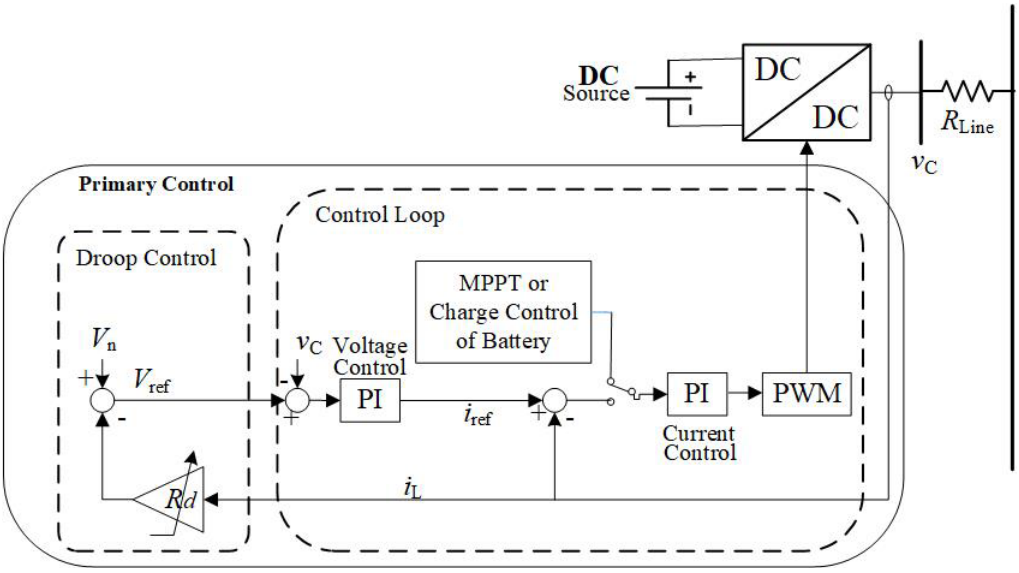


FIGURE 3. Primary control of DCMG

outer control can be used as an MPPT for the PVG system [22], voltage droop control or a charger control technique of the storage system. The voltage control function is to set the reference current, while the output current is regulated by the inner control which follows the reference value.

The reference voltage of the voltage control can be written as

$$V_{ref,y} = V_{n,y} - R_{d,y} \cdot i_{L,y} \tag{1}$$

where $V_{n,y}$ represents the converter's output voltage with no load, $R_{d,y}$ is the droop resistance, and $i_{L,y}$ is the inductor current of the converter $\#y$ $(y = 1, 2, 3, 4)$, respectively. The droop resistance is adjusted using the FLC to improve the proportional load power sharing accuracy. The maximum droop resistance is restricted by the maximum permissible DC bus voltage deviation and the converter's full load current [23]. Therefore, the droop resistance variation of each converter is as follows:

$$R_{d,y} \leq \frac{\Delta v_{\max}}{i_{c,y,\max}} \tag{2}$$

The $\Delta v_{\max}$ and $i_{c,y,\max}$ are the maximum DC voltage deviation and maximum load current of the yth converter, respectively.

The proposed coordination between the generator and the energy storage system can be divided into two, namely PVG control and battery control. As a resource, PVG is responsible for providing power support, while the ESS as a voltage source is responsible for regulating the DC bus voltage [24]. This coordination is based on the SoC battery and the DC bus voltage level. The droop curve of the two sources is also depicted in this coordination as shown in Figure 4.

When the SoC of battery has not reached the maximum level ($\text{SoC}_{\max}$), the PVG output power is maximized through MPPT mode. If the power generated by the PVG is greater than the load ($V_{bus} > V_{bus,ref}$), then the surplus power is ensured for charging the battery using droop charging mode. When all batteries reach $\text{SoC}_{\max}$, converter battery is operated under charger control technique, in which, the charging current will taper to the minimum value [25].

Once the $\text{SoC}_{\max}$ of all batteries is reached, the voltage droop control mode of PVG replaces the MPPT mode to restrict the PVG power generated. When the power generated

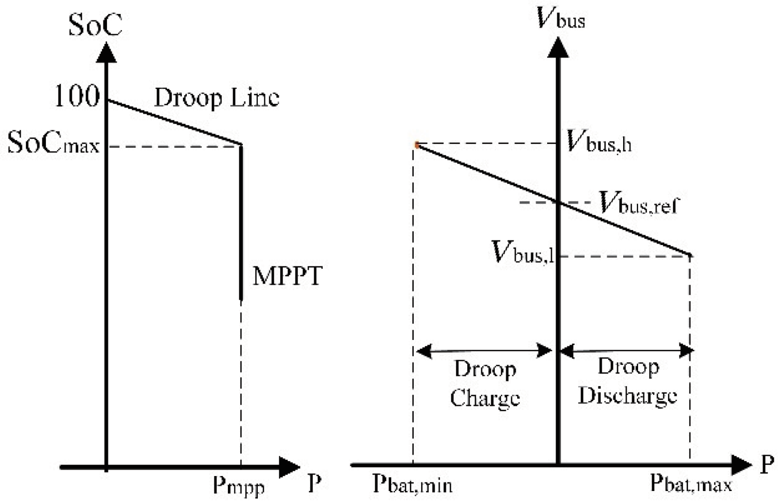


FIGURE 4. Droop curves from two sources

by the PVG is less than the load, it can be ascertained that the battery is discharging in droop discharging mode.

3.2. **Secondary control.** The second control level is secondary control as shown in Figure 5.

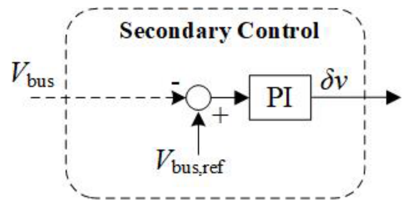


FIGURE 5. Secondary control of DCMG

The main disadvantage of using the droop control method is the emergence of voltage deviations in the DC bus voltage when the power generated and power consumed have inequalities. To minimize the voltage deviation on the DC bus voltage, the secondary level control based on PI (proportional-integral) controller is utilized to apply a suitable voltage deviation compensation δv, and the following formula is obtained:

$$\delta v = K_p(V_{bus,ref} - V_{bus}) + K_i \int (V_{bus,ref} - V_{bus})\, dt \tag{3}$$

where K_p is the proportional gain, K_i is the integral gain, V_{bus} is the measured DC bus voltage, and $V_{bus,ref}$ is the reference bus DC voltage, respectively. With the voltage deviation compensation, the droop curve in Figure 4 can be shifted according to the value of δv and the reference voltage in each primary control is given by

$$V_{ref,y} = V_{n,y} - R_{d,y} \cdot i_{L,y} + \delta v \tag{4}$$

3.3. **Fuzzy tuning of the droop resistance.**

3.3.1. *Fuzzy tuning for SoC balancing with accurate power sharing.* Droop control mode regulates the SoC balance of the batteries during charge and discharge. Then, to maintain the energy balance in the DC microgrid, the battery with the highest $R_{d,bat}$ will extract less current [26,27]. Because of that reason, the battery with the highest $R_{d,bat}$ will be charged or discharged with the least current.

For the above reason, it is expected that the battery with the highest SoC is discharged with the most current, in order to balance the stored energy. Then, a bigger $R_{d,bat}$ should be defined to that battery. The same, when batteries are absorbing the DC microgrid, it is expected that a smaller $R_{d,bat}$ is defined to the battery with the highest SoC for assuring stored energy balance.

Furthermore, to minimize the error load power sharing due to the line resistance differences, a bigger value for $R_{d,bat}$ is expected when the line resistance is decreased. On the contrary, when the line resistance is increased, the smallest $R_{d,bat}$ is expected.

All the above-mentioned qualitative knowledge may be simply summarized using a fuzzy logic controller (FLC). Indeed, it is easy for the fuzzy controller to handle multiple control purposes at once, in this specific case, the balance of the SoC battery and the proportional load power sharing. Thereby, a fuzzy logic controller can utilize the knowledge of an expert and the experience about the expected behavior of the system in order to adjust the droop resistance at each droop control. The fuzzy controller diagram shown in Figure 6 in which the droop resistance $R_{d,bat}$ can be adjusted.

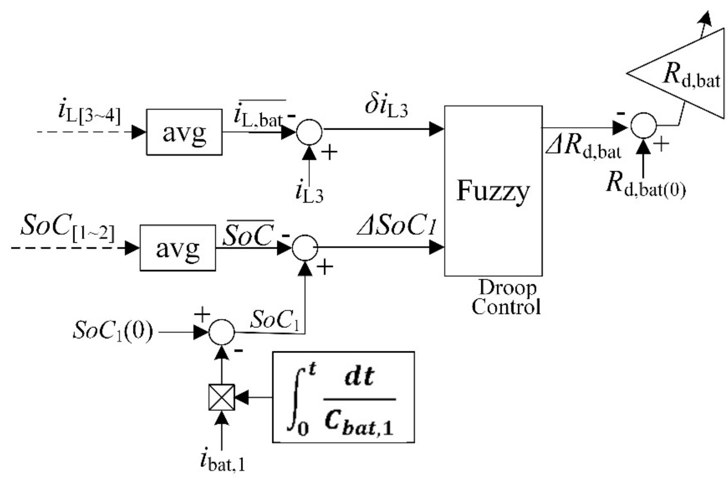


FIGURE 6. Control diagram of the fuzzy for SoC balancing

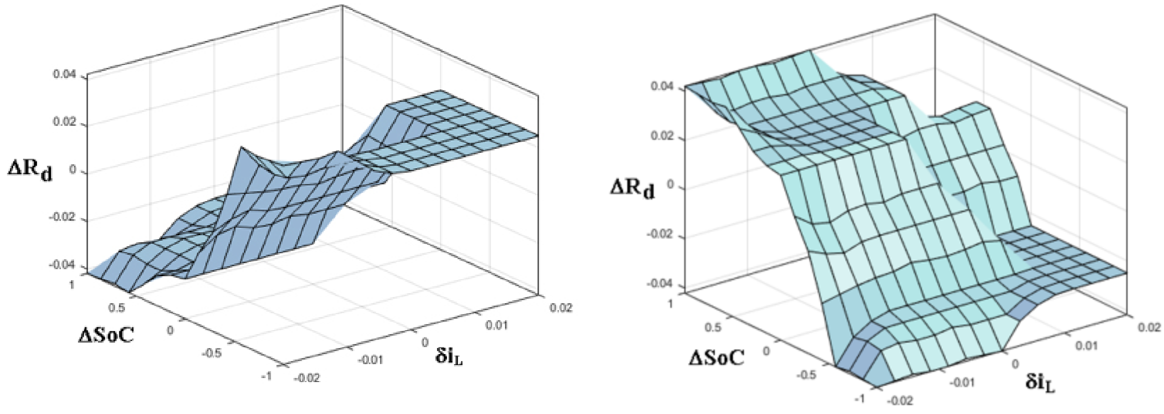
Given the aforementioned reasons, this paper proposed a Mamdani FLC for tuning the droop resistance $R_{d,bat}$ at each converter system in the ESS. The FLC consists of two inputs, the inductor current difference of converter ($\delta i_{L,j}$) and the SoC difference of battery (ΔSoC_k) expressed in (5) and (6), and the incremental signal ($\Delta R_{d,bat}$) as the output. The SoC of the battery is estimated by a simple Coulomb counting method formulated in (7):

$$\delta i_{L,j} = i_{L,j} - \overline{i_{L,bat}} \tag{5}$$

$$\Delta SoC_k = SoC_k - \overline{SoC} \text{ where } k = 1, 2 \tag{6}$$

$$SoC_k = SoC_k(0) - \int_0^t \frac{I_{bat,k}(t)}{C_{bat,k}} dt \tag{7}$$

where $i_{L,j}$ is the inductor current of the converter $\#j$ ($j = 3, 4$), $\overline{i_{L,bat}}$ is the average inductor current of all converters $\#j$, $SoC_k(0)$ represents the initial value of the battery's SoC $\#k(1, 2)$, $\overline{SoC}$ is the average SoC of all batteries $\#k$, $C_{bat,k}$ is the capacity of the battery $\#k$, and $I_{bat,k}$ is the output current of the battery $\#k$.



(a) Droop charging (b) Droop discharging

FIGURE 7. Control surface for battery control

Figures 7(a) and 7(b) depict the control surface of the proposed FLC that represent the process of droop charging and droop dicharging, respectively. The proposed FLC summarizes the fuzzy logic controller's behavior, where the droop resistance ($R_{d,bat}$) is tuned based on the previously described expected behavior.

The SoC balancing plays an important role in the system performance as proved in Figures 7(a) and 7(b). Therefore, FLC tries to improve SoC balancing and minimize the load sharing error.

3.3.2. *Fuzzy tuning for accurate power sharing among PVG.* When the SoC of all batteries reaches the maximum SoC threshold and the DC bus voltage is higher than V_{ref}, the PVGs are in charge of regulating the DC bus voltage. At this point, droop mode will be active on both PV sets to limit the power generated. Similiarly, the droop resistance $R_{d,pv}$ at each unit can be tuned for reducing error power sharing among PVGs due to line resistance differences. $R_{d,pv}$ is tuned using a fuzzy inference system with an incremental signal as the output ($\Delta R_{d,pv}$). Then, depending on the difference in the inductor current of converter $\#i$ $(i = 1, 2)$ and the average inductor current of all converters $\#i$ $\left(\delta i_{L,i} = i_{L,i} - \overline{i_{L,pv}}\right)$, the droop resistance will fluctuate. Figure 8 depicts control diagram of the fuzzy for PVG and Figure 9 shows the inference system's control surface.

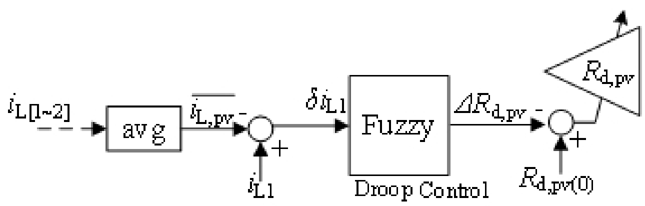


FIGURE 8. Control diagram of the fuzzy for PVG

4. **Proposed Control Strategy.** The proposed DC microgrid system using the fuzzy logic controller is simulated via Matlab/Simulink in order to prove the effectiveness of the control scheme. The system performance was tested by comparing the droop control using fixed droop resistance ($R_{d(0)} = 1\ \Omega$) with the adaptive droop control. The parameters of the DC microgrid system are listed in Table 1.

The PVG becomes the main priority for supplying the load when using the proposed control method. The battery compensates for any power surplus or shortfall. Two cases

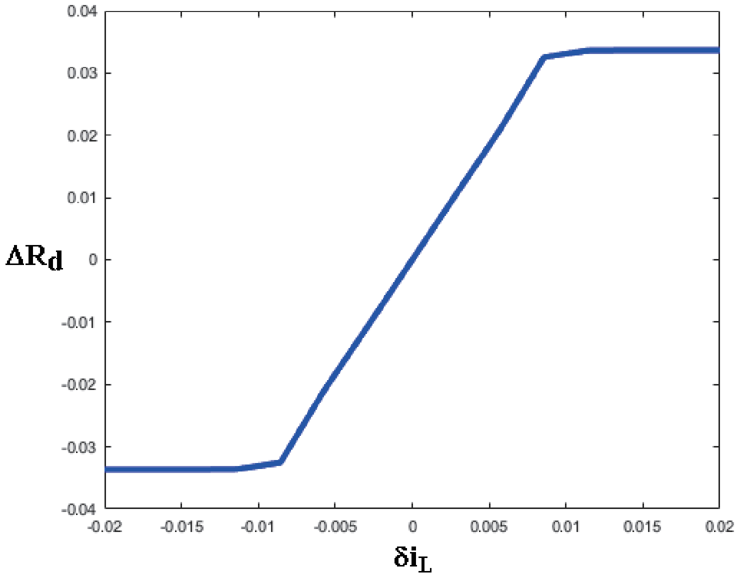


FIGURE 9. Control surface for PVG control

TABLE 1. Parameters of the DC microgrid

Parameter	**Symbol**	**Value**
Nominal DC bus voltage	$V_{bus,ref}$	100 V
Maximum power from PVG_1, PVG_2	P_{max} PVG_1, P_{max} PVG_2	500 W, 500 W
Maximum SoC of battery	SoC_{max}	98%
Battery capacity	C_{bat}	2.5 Ah
Line resistance	R_{Line1}, R_{Line2}, R_{Line3}, R_{Line4}	0.1 Ω, 1.0 Ω, 0.7 Ω, 0.2 Ω

were selected to evaluate the functioning of the system. The first case is associated with the changes in the power generated by PV while the second case is related to changes in load power.

4.1. **Case 1: Changes of PVG power.** In this case, both PV generators have the same rating with a fixed power load of 500 W. Battery-1 and battery-2 have initial SoCs of 97% and 96%, respectively. The performance of the DC microgrid is depicted by Figures 10 and 11 when the power produced by PVs fluctuates throughout time, with fixed droop resistance value and with fuzzy tuning of the droop resistance. Afterward, it is possible to examine the performance of the suggested solution during droop mode on PV, battery charge and discharge.

At the beginning of the analysis, during the first event (E1), PVG operates in MPPT mode and the power generated by the two PV sets is 900 W. Since the load power is less than the generating power, then the batteries are in charging condition. The system using fuzzy controller shows that the battery-1 absorbs less current than battery-2 (Figure 11(d)), so that the SoC of battery-1 can be approached by the SoC of battery-2 asymptotically (Figure 11(c)). This condition does not occur in the fixed droop resistance system (Figure 10(c) and Figure 10(d)).

During the second event (E2), the power generated by the PVG has been reduced to 450 W, causing the battery converter to activate droop discharging mode to meet the load's power requirements. At the begining of this event, adaptive droop control is able

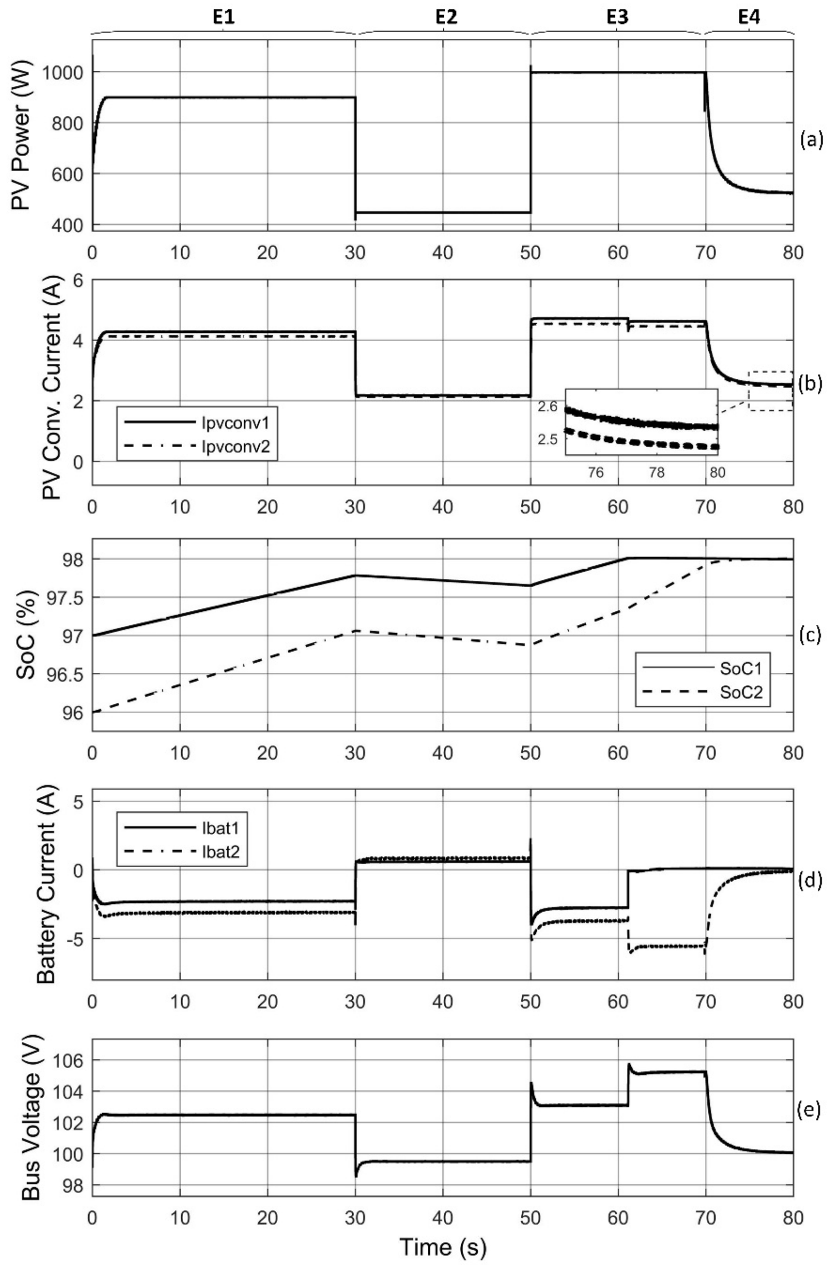


FIGURE 10. Simulation result when PVG changes using fixed droop

to maintain the balance of all storage SoCs. Even, at the end of this event, the SoC of the two batteries reached a balance of 100% (see Figure 11(c)). However, the SoC balance of all batteries has not reached 100% when using fixed droop resistance (see Figure 10(c)).

During the third event (E3), the power produced by PVGs has been increased to 1000 W, the batteries are in charging condition, and the PVGs are still in MPPT mode. In Figure 11(c), the SoC imbalance in the storages energy remains constant at 0% when using FLC, even though the line resistance is different. On the contrary, the SoC imbalance between batteries has not reached 0% when fixed droop control is used (Figure 10(c)).

In the last event (E4), SoC of all batteries has reached maximum level. Therefore, the PVGs change its inner control loop from MPPT mode to droop control mode. Thus, the current sharing error between PV converters can reach 0% when using FLC (see Figure 11(b)), and this condition does not appear in Figure 10(b).

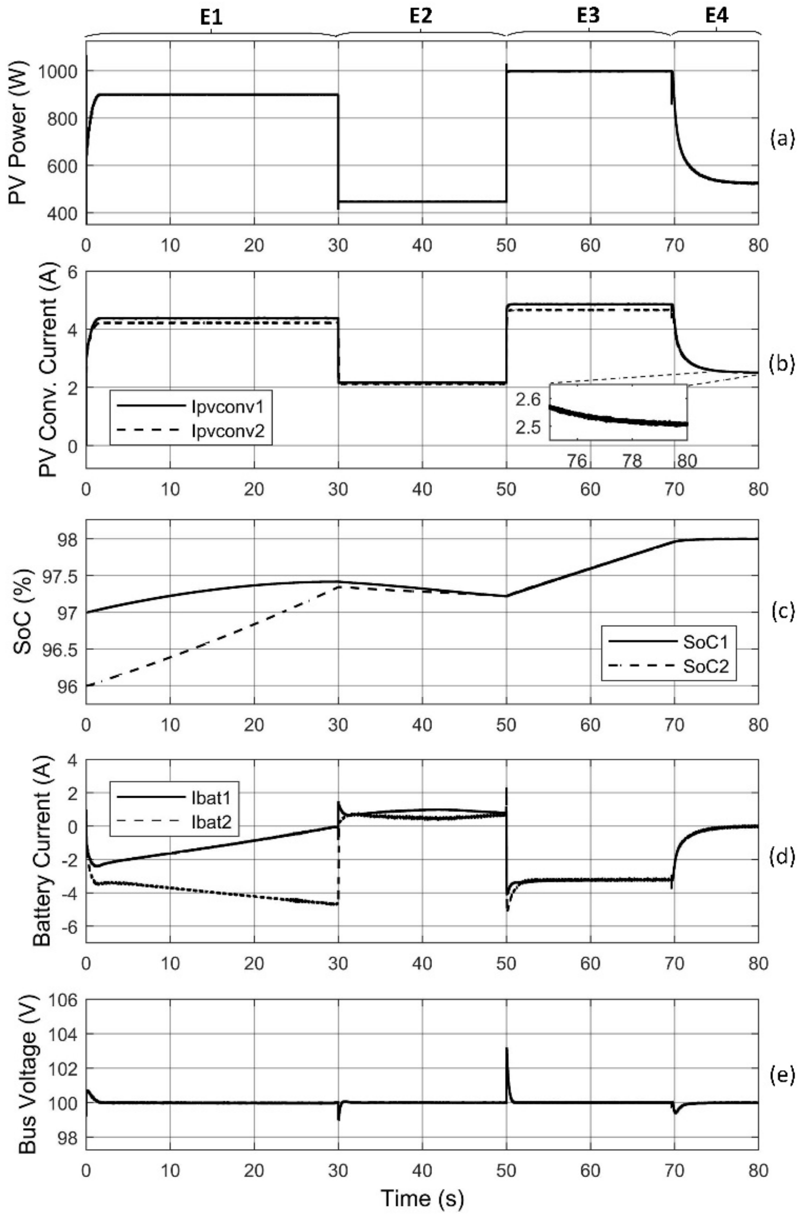


FIGURE 11. Simulation result when PVG changes using adaptive droop control

In all events, it can be seen that the fuzzy logic controller is better than the fixed droop resistance system in terms of minimizing the DC bus voltage deviation (see Figures 10(e) and 11(e)).

4.2. **Case 2: Changes of load power.** The performance of the DC microgrid system is also shown in Figures 12 and 13 when the load power fluctuates and the PVGs produce a fixed power of 1000 W, with fixed droop resistance and adaptive droop resistance, respectively. Initially, the SoC of battery-1 and battery-2 is set to 97% and 96%.

This analysis starts from event-1 (E1), initialization of load power is 600 W and MPPT mode on PVGs is enabled. Since the load power is less than the power generated by the PVGs, both batteries are charging. Figure 13(c) indicates that the SoC of battery-1 is approaching the SoC of battery-2. It is proven that the battery-2 absorbs more current than the battery-1 (Figure 13(d)). On the other hand, the SoC imbalance in the ESS is still maintained as shown in Figure 12(c).

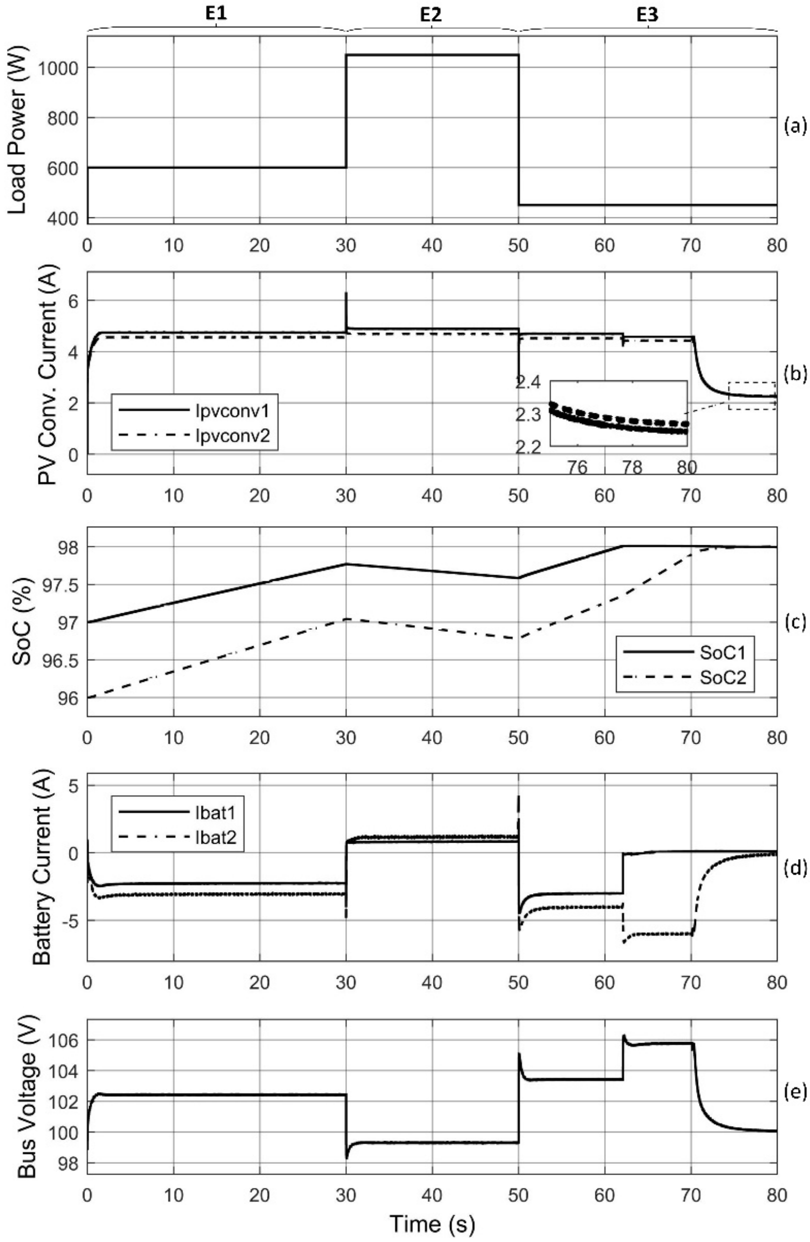


FIGURE 12. Simulation result when load changes using fixed droop control

During the second event (E2), the load power is greater than the generating power of the PVGs (1050 W); hence, there is an imbalance between consumed and generated power. Therefore, both batteries are in a state of discharging. During E2, the imbalance of stored energy is continuously reduced and the SoC imbalance of all batteries reaches 0% at the end of this event, as shown in Figure 13(c). On the other hand, as seen in Figure 12(c), the DC microgrid system with fixed droop control was unable to reduce the energy storage imbalance.

During the third event (E3), the load power drops to 450 W, the batteries are charged again until the SoC maximum is reached. During time 70-80 s, the droop control mode on the PV replaces the MPPT mode when the SoC battery reaches its maximum level. Then, the current sharing error of each PV converter with FLC is much smaller than without FLC (Figure 13(b)) even though the line resistance differences are considered. In this case, Figure 13(e) illustrates that FLC with the secondary control is able to stabilize

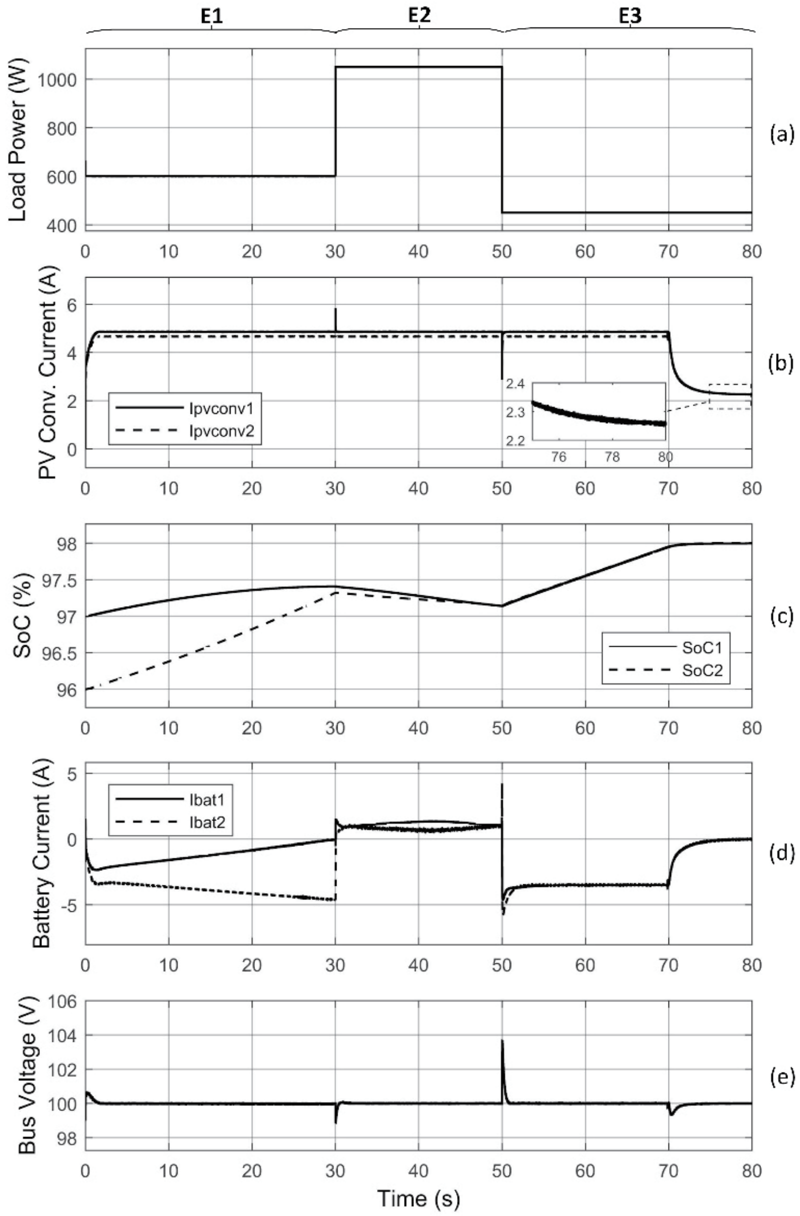


FIGURE 13. Simulation result when load changes using adaptive droop control

the DC bus voltage according to the reference voltage. However, the instability of the DC bus voltage can be seen in Figure 12(e).

5. **Conclusions.** A distributed PV generation-energy storage coordination control method based on battery SoC level and signaling DC bus voltage for isolated DC microgrids was proposed in this paper. The proposed control technique is also equipped with adaptive droop control using a fuzzy system. To ensure the energy balance of the batteries, the fuzzy system on the battery control adjusts the droop resistance so that the overcharge and deepdischarge of the batteries can be avoided. While the fuzzy system in PVG control is responsible for increasing the accuracy of load sharing in PVGs even though the line resistance is different. Furthermore, this paper also proposes a secondary control based on PI control which is able to minimize the deviation of the DC bus voltage due to the use of droop control, even when disturbances occur.

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