Coordinated multi-battery control for single-stage islanded AC microgrids

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ABSTRACT

Reliable power management is essential for islanded AC microgrids integrating photovoltaic (PV) generation and battery energy storage, particularly under variable solar irradiance and load conditions. This paper proposes a coordinated multi-battery control strategy using a single-stage AC-coupled configuration to ensure uninterrupted power supply while improving system reliability. The proposed topology employs two PV arrays: one directly connected to a battery inverter to supply the AC load and another dedicated to battery charging. Four battery units are coordinated through a fuzzy logic controller (FLC), which sequentially regulates battery discharge based on PV generation and load demand. Simulation studies were conducted under two operating scenarios. In the first scenario, at a solar irradiance of 1000 W/m², the PV system generated approximately 1200 W, and the proposed controller maintained power balance as the load demand increased. In the second scenario, when PV output decreased due to reduced solar irradiance or complete source interruption, the FLC coordinated battery operation at 0.07 s, 0.34 s, 0.64 s, and 0.93 s, ensuring continuous power delivery to the load. The simulation results demonstrate that the proposed coordinated control strategy effectively enhances power continuity, operational stability, and energy management in single-stage islanded AC microgrids.

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1. INTRODUCTION

The increasing demand for electrical energy, driven by population growth and rapid technological development, has accelerated the transition from fossil fuel-based generation to renewable energy sources. Among the available renewable resources, photovoltaic (PV) systems have emerged as one of the most promising solutions because of their environmental sustainability, abundant availability, and declining installation costs. Since alternating current (AC) loads dominate residential, commercial, and industrial applications, integrating PV systems into AC microgrids has become an effective approach for improving energy sustainability and supply reliability. In addition to reducing greenhouse gas emissions, AC microgrids improve power quality, increase energy efficiency, reduce transmission losses, and enhance grid resilience through islanded operation during utility disturbances or outages [1].

To improve the reliability and operational efficiency of AC microgrids, numerous power management and control strategies have been proposed. Recent studies have investigated decentralized power management schemes for hybrid AC/DC microgrids, enabling interconnected subgrids to cooperate while maintaining acceptable power quality under varying load conditions [2], [3]. Hierarchical control frameworks have also been developed for community microgrids to coordinate multiple AC and DC subgrids under both islanded and grid-connected operating modes, thereby improving operational flexibility and economic performance [4], [5]. Furthermore, temporal energy management strategies considering renewable energy generation, bidirectional AC/DC converter characteristics, and time-of-use electricity pricing have been introduced to optimize microgrid operation while minimizing operating costs [6]–[10]. Although these approaches have significantly improved energy management and power sharing, maintaining continuous power supply under fluctuating PV generation remains a major challenge in islanded microgrids. Variations in solar irradiance directly affect PV output, leading to power imbalance, voltage deviations, and reduced supply reliability if battery energy storage is not properly coordinated. Consequently, an effective battery coordination strategy is required to ensure stable power flow and uninterrupted operation under dynamic operating conditions.

Recent studies have further improved the operation of hybrid AC/DC microgrids through advanced control and energy management strategies. Hybrid AC/DC microgrids have demonstrated superior flexibility, efficiency, and economic performance compared with conventional AC or DC microgrids, particularly when coordinated using hierarchical control architectures consisting of primary, secondary, and tertiary control levels [11], [12]. However, the integration of interlinking converters and multiple distributed energy resources increases the complexity of power management and requires more sophisticated control strategies than those employed in conventional microgrids [13]. To address these challenges, several intelligent and decentralized control methods have been proposed. Intelligent agent-based energy management systems have been developed to coordinate AC and DC subgrids through bidirectional communication, enabling optimal demand shifting, load shedding, and power exchange while improving system reliability and reducing operational costs [14]–[16]. In addition, decentralized voltage-supporting control strategies have been introduced to maintain stable AC and DC bus voltages during islanding events and to achieve proper power sharing between interconnected subgrids with minimal frequency deviation [17].

Recent research has also focused on improving battery energy storage coordination and system stability. Approaches such as virtual supercapacitor control based on battery state of charge (SOC), cloud energy storage systems (CESS), intelligent ANFIS-based controllers, and optimal PV–battery sizing have been proposed to enhance transient stability, improve voltage regulation, optimize energy utilization, and extend battery lifetime [18]–[21]. Although these methods have significantly improved microgrid performance, they primarily emphasize system-level energy management and storage optimization. Limited attention has been given to coordinated operation of multiple battery units within a single-stage AC-coupled architecture to ensure uninterrupted power supply under fluctuating PV generation. Recent studies have increasingly focused on battery energy management to improve the reliability, efficiency, and operational flexibility of islanded microgrids. Various approaches have been proposed, including residential microgrids with surplus PV generation for community energy sharing, battery energy management systems (BEMS) that coordinate diesel generators and PV systems, and autonomous control strategies that regulate PV-battery units through droop control to maintain power balance during islanded operation [22]–[24]. Intelligent charging and discharging techniques based on fuzzy logic have also been developed to improve battery utilization and extend battery lifetime by adapting battery operation to varying load and generation conditions [25]. Furthermore, decentralized power management strategies have been proposed to coordinate PV-battery systems while maintaining voltage and frequency stability in islanded microgrids [26].

Recent developments have also addressed battery degradation, coordinated operation of multiple hybrid units, and advanced energy storage architectures. Battery wear models have been incorporated into day-ahead energy management algorithms to optimize battery utilization and prolong service life [27]. Coordinated power management methods for multiple PV-battery hybrid units have been developed by considering the available PV generation, battery SOC, dispatchable generation capacity, and load demand to improve power sharing among distributed energy resources [28]–[30]. In addition, dual-battery energy management strategies have been proposed to separate long-term energy storage from short-term voltage regulation, thereby enhancing system stability and operational flexibility [31]–[34]. Although these studies have significantly advanced battery energy management in microgrids, most approaches focus on optimizing charging/discharging strategies, battery lifetime, or distributed power sharing. Limited attention has been given to coordinated control of multiple battery units within a single-stage AC-coupled islanded microgrid, where batteries operate sequentially to maintain continuous power supply during fluctuations or interruptions in PV generation. Addressing this limitation is essential for improving power continuity, simplifying converter architecture, and enhancing the reliability of standalone renewable energy systems.

Although considerable progress has been made in the development of energy management and battery control strategies for hybrid microgrids, several challenges remain. Existing studies primarily focus on decentralized power management, battery charging and discharging optimization, or distributed energy sharing. However, limited attention has been given to the coordinated operation of multiple battery units within a single-stage AC-coupled architecture to mitigate the intermittency of PV generation. Consequently, fluctuations in solar irradiance may still result in power imbalance, voltage variations, and interruptions in power supply, particularly under islanded operating conditions. To address these limitations, this paper proposes a coordinated multi-battery control strategy for a single-stage islanded AC microgrid. The proposed AC-coupled configuration employs four battery units connected in parallel to the battery inverter, where battery operation is coordinated sequentially using a fuzzy logic controller (FLC). During PV power fluctuations or complete source interruptions, the controller regulates the discharge sequence of Battery 1 (B1), Battery 2 (B2), Battery 3 (B3), and Battery 4 (B4) to maintain a stable DC/AC bus voltage and ensure continuous power delivery to the load. In addition, B1 is charged using surplus PV power available on the AC bus, whereas B2, B3, and B4 are charged independently by dedicated PV sources. This coordinated charging and discharging mechanism improves battery utilization while enhancing the reliability and stability of the islanded microgrid. The proposed coordinated control strategy provides a practical solution for improving power continuity in renewable energy-based islanded microgrids. By combining a single-stage AC-coupled configuration with intelligent multi-battery coordination, the proposed system effectively compensates for PV intermittency, maintains stable bus voltage, and ensures uninterrupted power supply under varying operating conditions.

2. METHOD

Conventional droop control is widely employed for power sharing in DC and hybrid microgrids because of its simple implementation and decentralized operation. However, the output voltage reference decreases linearly as the output current increases, making the control performance sensitive to line resistance and load variations. Consequently, unequal power sharing and bus voltage deviations may occur under dynamic operating conditions [35]–[39]. To overcome these limitations, this study employs a FLC to coordinate the operation of multiple battery units, providing adaptive power regulation and improved voltage stability during fluctuations in PV generation and load demand.

The proposed research methodology consists of six stages. First, a DC–DC boost converter is designed to increase the PV output voltage to the required DC bus level. Second, a single-stage AC-coupled microgrid configuration incorporating multiple battery units is developed. Third, an FLC-based coordinated control strategy is designed to regulate the sequential charging and discharging of the battery units according to the available PV power and load demand. Fourth, the proposed configuration and control strategy are evaluated through MATLAB/Simulink simulations under various operating scenarios. Fifth, a laboratory-scale hardware prototype is developed to validate the proposed system experimentally. Finally, the simulation and experimental results are analyzed to evaluate the effectiveness of the proposed coordinated multi-battery control strategy in maintaining stable bus voltage and uninterrupted power supply.

2.1. DC/DC converter design

The proposed single-stage AC microgrid employs DC/DC converters to regulate the voltage levels of the PV arrays and battery energy storage system before power is delivered to the battery inverter. Proper voltage regulation is essential to ensure stable power flow, improve energy conversion efficiency, and maintain a constant DC bus voltage under varying solar irradiance and load conditions. As illustrated in Figure 1, a buck converter is employed on the PV charging branch to regulate the charging voltage according to the battery requirements, while a boost converter is connected to the battery discharge branch to increase the battery output voltage to the required DC bus level.

This configuration enables the batteries to provide sufficient input voltage to the inverter during periods of reduced PV generation or complete PV interruption. Both converters consist of an insulated-gate bipolar transistor (IGBT), an inductor, a diode, a capacitor, and appropriate filtering components. The passive components are designed to achieve continuous conduction mode (CCM), thereby minimizing current ripple and improving voltage stability. The converter parameters are selected based on the required output voltage, switching frequency, allowable current ripple, and load demand. The circuit configuration of the proposed buck converter is presented in Figure 1, while the corresponding design equations are described in the following subsection.

The output voltage value depends on the component parameters used. The parameter values of duty cycle (D), capacitor (C), and inductor (L) can be calculated using the following (1). Meanwhile, the component values of the buck converter are shown in Table 1.

$$D = \frac{V_R}{V} \quad (1)$$

Table 1. Buck converter parameters

Parameter	Value
Fs	10 kHz
D	67%
L	1.347 mH
C	27.87 uF

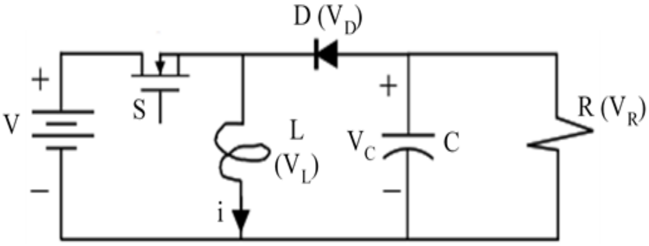


Figure 1. Buck converter design

The DC-DC boost converter might be used in CCM and discontinuous condition mode from an operating perspective (DCM). While in the boost converter circuit shown in Figure 2, the component values are calculated as follows in Table 2.

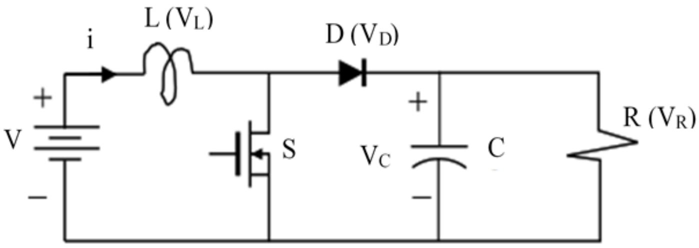


Figure 2. Boost converter design

Table 2. Boost converter parameters

Parameter	Value
Fs	10 kHz
D	75%
L	9.38 mH
C	3600 uF

2.2. Proposed single-stage model configuration

In the conventional AC Coupling model, the installed PV serves to supply power to the load through the inverter. When there is excess power on the AC bus, it will be stored in the battery using a bidirectional DC-DC converter. In the conventional configuration, the availability of battery power is very limited, due to the power stored in the battery when there is an excess of power on the AC bus. In the new model AC Coupling uses a single-stage configuration with a multi-battery source. The first battery is charging from PV1, the second battery is charging from PV2, the third battery is charging from PV3 and the fourth battery is charging from PV4. When the PV output power is cut off, the first to fourth batteries coordinate in supplying power to the AC bus. The PV used has the specifications in Table 3, while the battery used has the specifications in Table 4.

The first PV is a PV array and consists of 12 PV modules connected in parallel, so that the output voltage is 18 V DC. The first PV output power capacity is 720 W. While the second to fourth PV is a PV array with a total of 6 PV modules. This PV array has a configuration connected in parallel. The PV configuration is shown in Figure 3. In Figure 3, each PV uses MPPT to produce maximum output power for charging the battery. Each PV is controlled separately using MPPT. The output voltage of PV is reduced by using a buck converter, PV1 using a battery buck converter 1 (BCB1), PV2 being reduced using a battery buck converter 2 (BCB2), PV3 being reduced using a battery buck converter 3 (BCB3), PV4 being reduced using a battery buck converter 4 (BCB4). The voltage controller functions to produce a PWM control signal, to trigger the transistor signal on the buck converter. The comparison between the MPPT set point and the PV current is used as input for the voltage controller.

Table 3. PV module spesifications

Parameter	Value
Nominal volatge	18 V
Maximum power	60 W
Number of cells Ns	36
Standard light intensity S0	1000 W/m2
Ref. temperature (Tref)	25 °C

Table 4. Lithium ion battery specifications

Parameter	Value
Nominal volatge	3.7 V
Rated capacity	5.4 Ah
Discharge current	1.08 A
Internal resistance	0.05 ohm
Discharge cut-off voltage	2.5 V

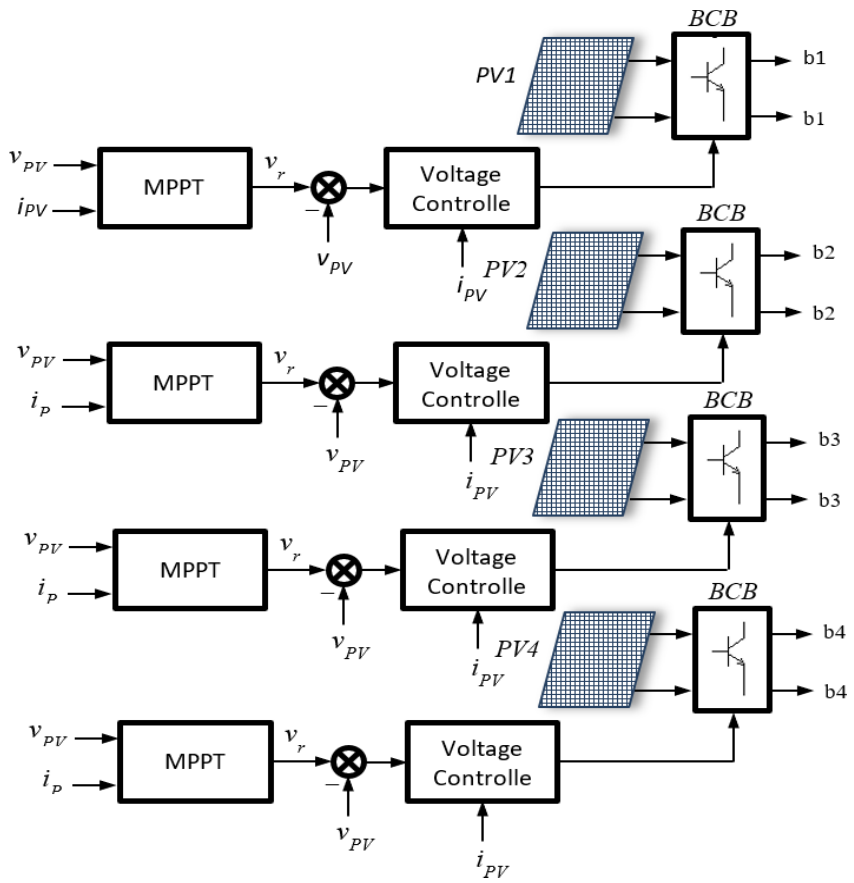


Figure 3. PV configuration for battery charging

The solar energy conversion system is obtained using a PV connected AC bus via a DC-link and boost converter. This can be expressed by the following equation

$$\frac{dV_{PV1}}{dt} = \frac{I_{PV1}}{C_C} - \frac{I_L}{C_C} \quad (2)$$

$$V_{ref} = \frac{P_L - I_{PV1}}{I_{PV1}} \quad (3)$$

2.3. Battery control design using FLC

Traditionally, the battery energy storage system requires a two-stage converter to create the pulsing charging/discharging current for the battery and to achieve the DC/AC function for the AC bus connected inverter. Sadly, it will lower the priceless energy storage's ability to convert power. Additionally, to determine the battery module output power for the output power regulation, expensive current sensors are needed. The two-stage setup and the pricey current sensor end up being the main obstacles for the battery energy storage system. Therefore, in this multi-battery coordination study it is proposed to use a battery-inverter, which is shown in Figure 4. In this study, no current sensor is used. The battery-inverter used can regulate the flow of power to the AC bus. In Figure 4 it can be seen that each battery is connected to the boost converter. The output power of each battery is regulated alternately using a FLC.

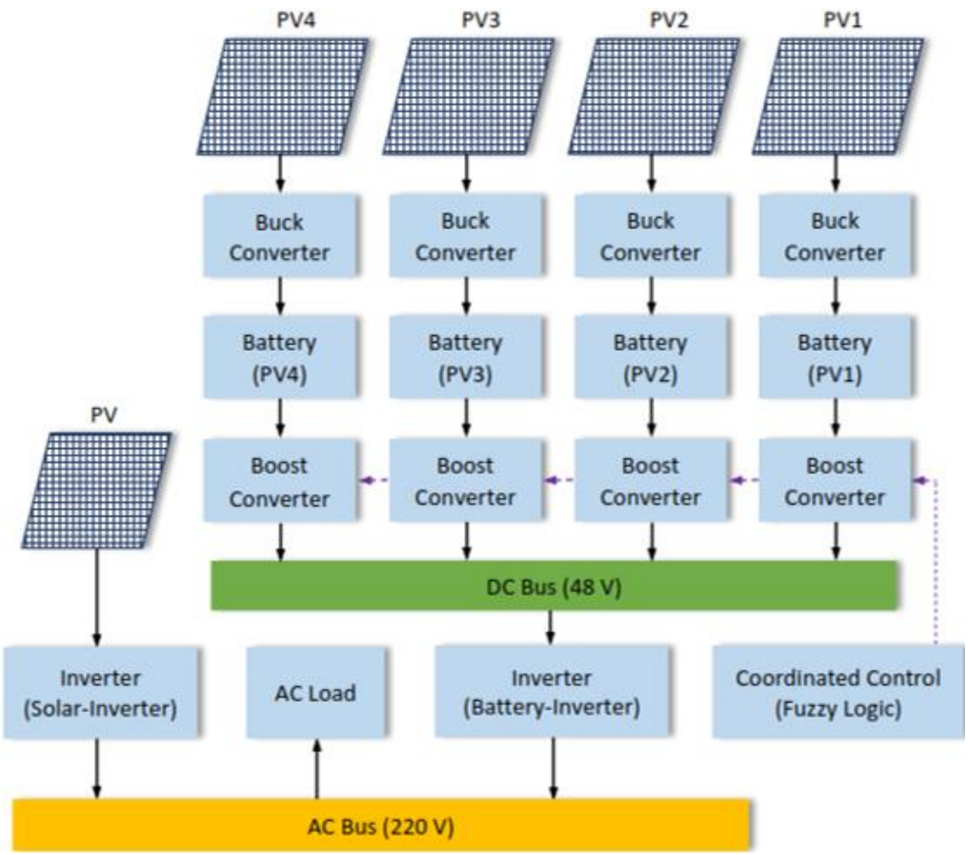


Figure 4. Proposed AC coupling model

Figure 5 shows a coordinated control strategy for distributing battery power to the AC bus using a FLC. Battery 1 (b1), battery 2 (b2), battery 3 (b3), and battery 4 (b4) work sequentially with the initial supply of battery power using battery 1. When battery 1 decreases, battery 2 will work to supply power to the battery. AC bus, and so on until battery 4. In this study, the data for the load of one residential house has a total power usage for one day of 1,118 Wh. Taking into account the 80% depth of discharge (DOD) of the battery, the capacity of one battery unit used is 260 Ah. Each battery unit is composed of 60 battery cells.

The total load in the microgrid system with a battery source is the sum of the power of each battery unit, which can be expressed by:

$$\sum_{j=1}^{n=4} P_{Bj}(t) = P_{B1}(t) + P_{B2}(t) + P_{B3}(t) + P_{B4}(t) \quad (4)$$

The battery when charging is expressed by (5) and when it is discharging it is expressed by (6).

$$\sum_{j=1}^{n=4} P_V(t) - P_L(t) \geq \sum_{t=1}^{T} P_b(t) \quad (5)$$

$$\sum_{j=1}^{n=4} P_V(t) - P_L(t) \leq \sum_{t=1}^{T} P_b(t) \quad (6)$$

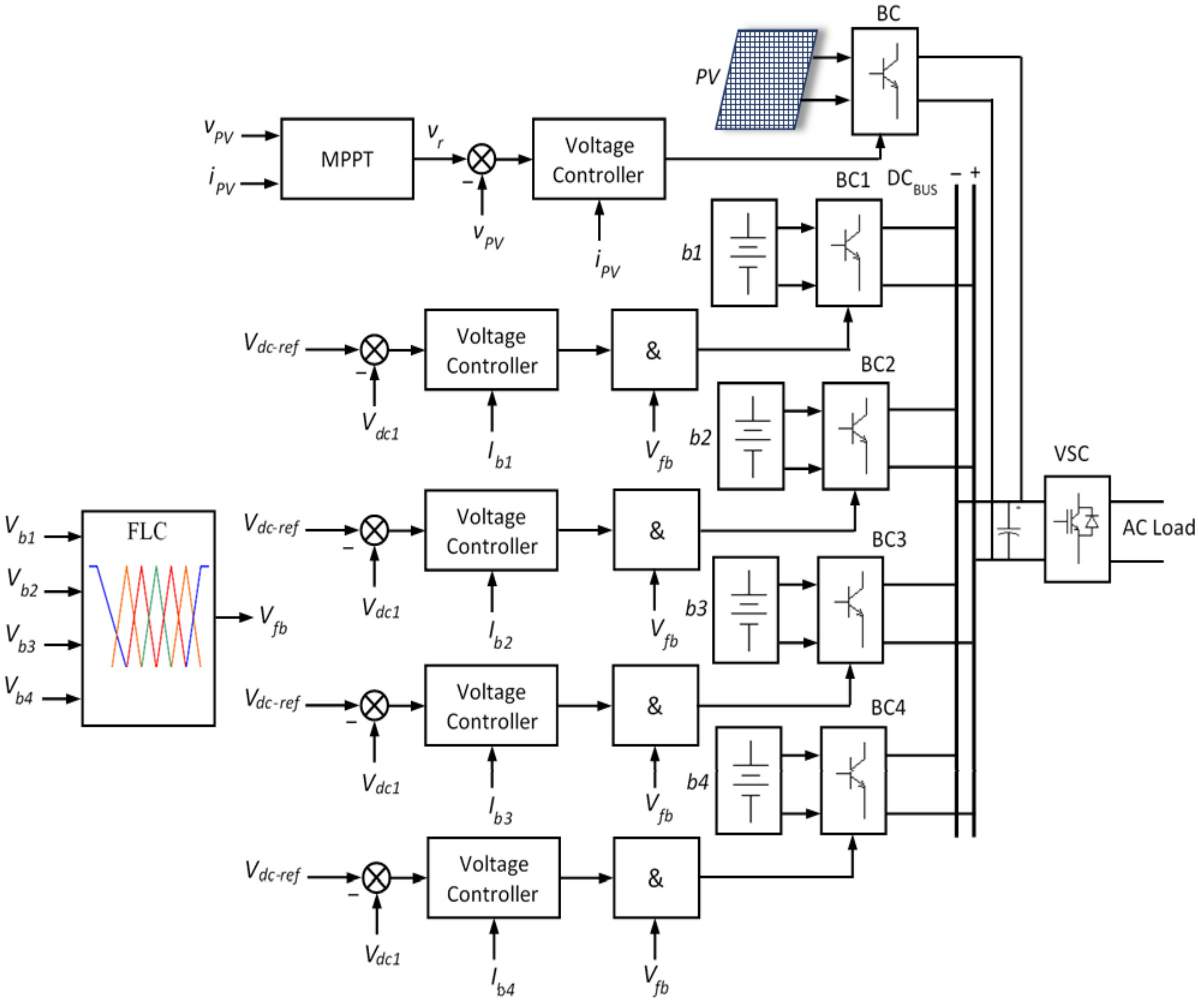


Figure 5. Coordinated control battery with FLC

The fuzzy rule base in this study consists of if-then rules as shown in Table 5. The table shows that FLC is designed with four inputs and each input uses seven membership functions. While the FLC output is the battery output power (BOP), as the battery-inverter input. Figure 6 shows the battery coordinated control flowchart.

Table 5. Rules of coordinated control battery

e/de (b1-b4)	NB	NE	NS	ZE	PS	PE	PB
NB	PB	PB	PB	PB	PE	PS	ZE
NE	PB	PB	PB	PE	PS	ZE	NS
NS	PB	PB	PE	PS	ZE	NS	NE
ZE	PB	PE	PS	ZE	NS	NE	NB
PS	PE	PS	ZE	NS	NE	NB	NB
PE	PS	ZE	NS	NE	NB	NB	NB
PB	ZE	NS	NE	NB	NB	NB	NB

FLC is designed to use four inputs and one output. The four FLC inputs consist of first battery power (PB1), second battery power (PB2), third battery power (PB3), and fourth battery power (PB4). In this study, the control of the BOP that affects the load power is simulated using Matlab, with the simulink shown in Figure 6. Figure 7 shows the FLC design using Matlab, seen in controlling the output power of the battery is done sequentially. Therefore, in Matlab's Simulink design, four battery inputs and an inverter output are used. When there is a fluctuation in the PV output power, battery 1 will supply power to the inverter. When the output power of battery 1 decreases, battery 2 will supply power to the inverter. And so on battery 3 and battery 4 will supply power to the inverter sequentially.

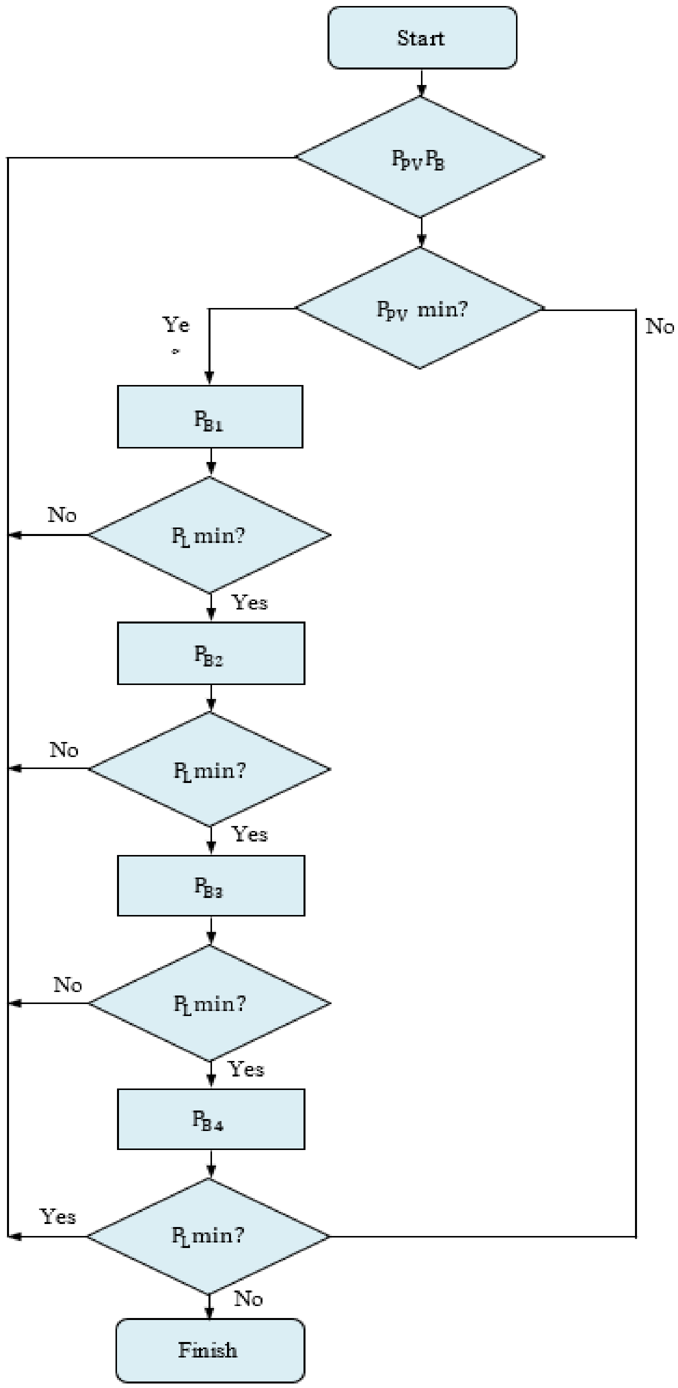


Figure 6. Flowchart on battery coordinated control

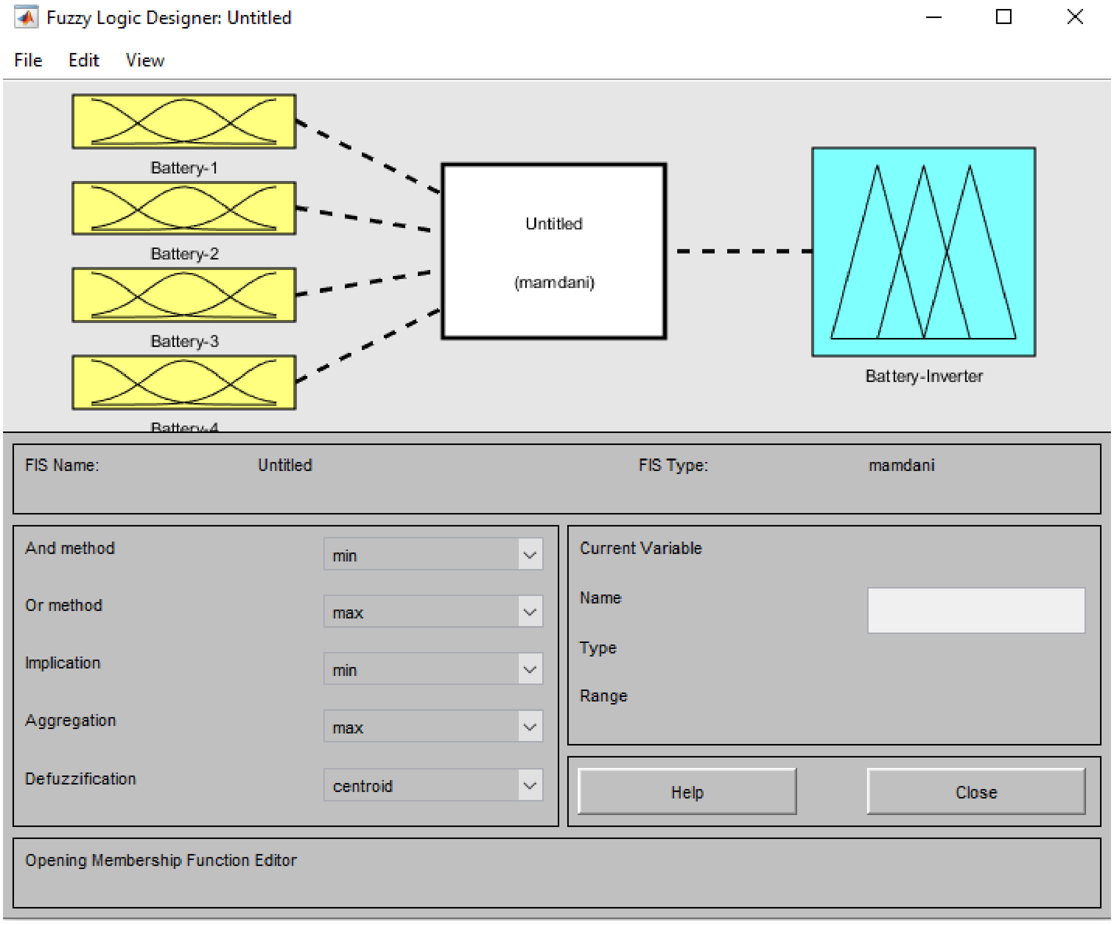


Figure 7. Simulink design for battery coordinated control

3. RESULTS AND DISCUSSION

This section explains the results of research using simulation and implementation of coordinated control hardware on a microgrid system with multi-batteries.

3.1. Solar power (PV) to load (case study 1)

In case 1 the PV output power supplies to the load through the inverter, in this case PV1 through PV4 supplies power to the battery. Figure 8 shows the intensity of solar radiation as a PV input source. In this simulation, the intensity of solar radiation is 1000 W/m^2 with a temperature of 25°C.

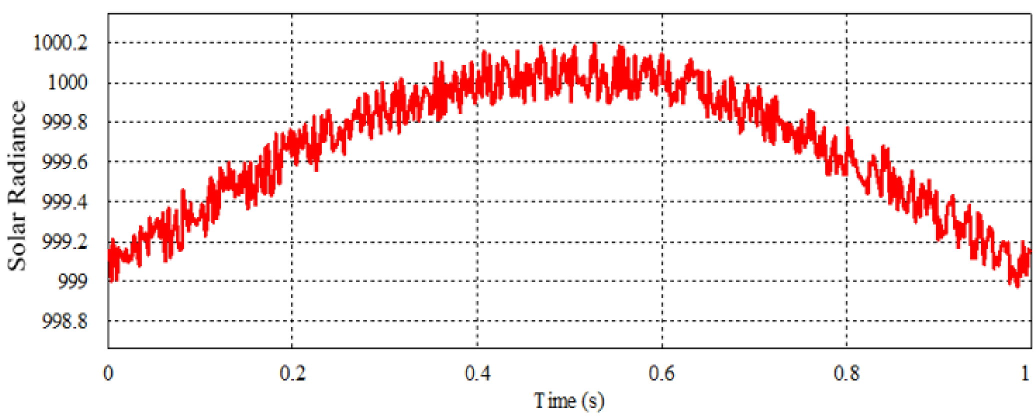


Figure 8. Intensity of solar radiation

With a solar radiation intensity of 1000 W/m^2, a PV output power of 1200 watts is generated, which can be seen in Figure 9. While Figure 10 shows the load power. In a start time of up to 0.4 seconds the PV output power decreases and the load power increases with a time of 0.4 seconds to 1 second. This shows that with an increase in load power, the output power of solar PV will decrease.

Figure 11 shows the DC boost converter output voltage and connected to the DC bus at 200 V. Therefore, the boost converter output voltage with a solar PV source is the same as the DC bus voltage. Figure 12 shows the battery-inverter output current connected to an AC load. When connected to a sinusoidal voltage inverter, the load current is 4.8 A. In case 1, battery 1, battery 2, battery 3, and battery 4 have not supplied power to the load. This is because solar PV is still able to supply power to the load. In this case 1, PV1 supplies power to battery 1. Likewise, PV2, PV3, and PV4 supply power to battery 2, battery 3, and battery 4, respectively.

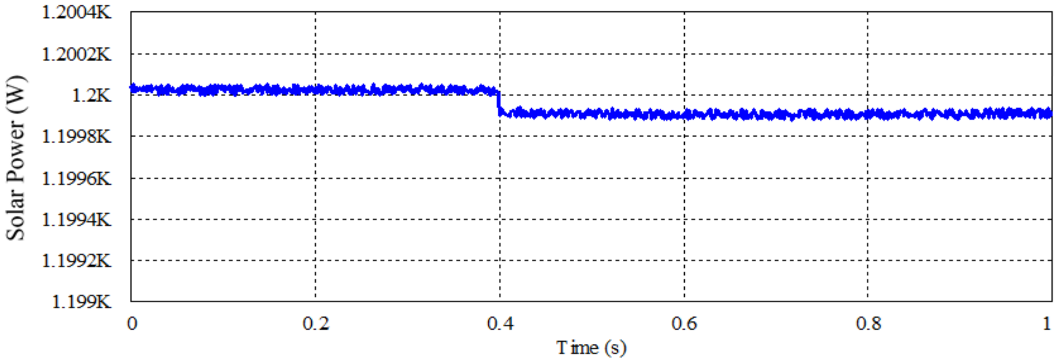


Figure 9. Solar PV output power

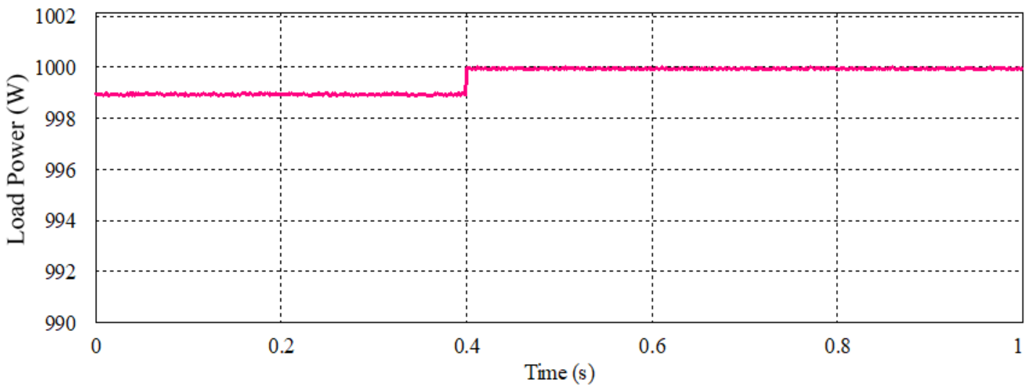


Figure 10. Load power with solar PV sources

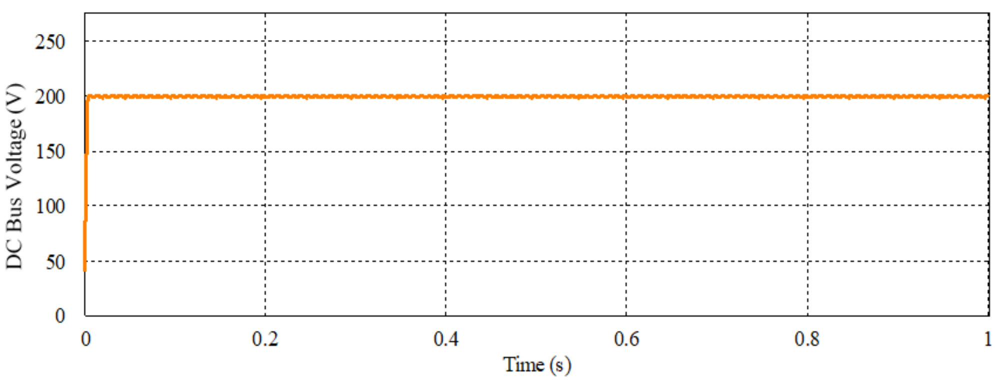


Figure 11. DC bus voltage

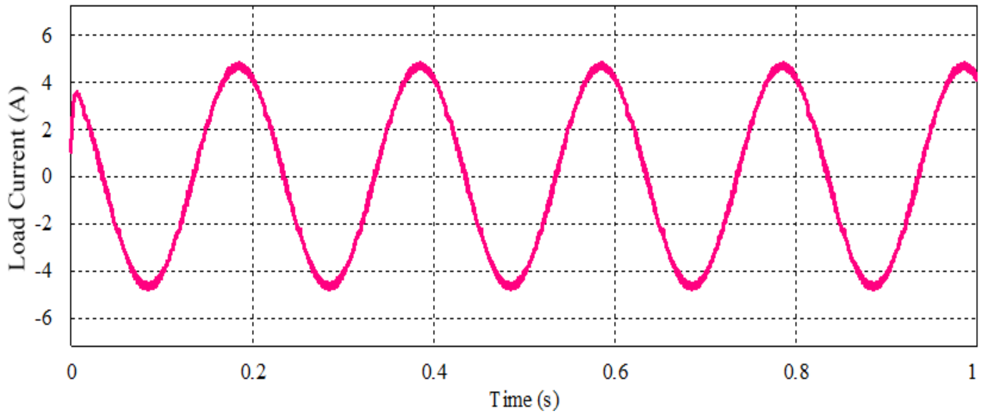


Figure 12. AC load current

3.2. Battery power to load (case study 2)

In the second case, when the solar PV output power is cut off or there is a change in the intensity of solar radiation, the solar PV is no longer supplying electrical power to the load. Likewise, the output power of PV1, PV2, PV3 and PV4 does not provide power to the battery or the battery charging is disconnected. In this case, the battery must be ready to supply power to the load. Figure 13 shows the PV output power stored in the battery. The PV used for charging the battery produces an output power of 720 W, in this case PV1, PV2, PV3, and PV4. While Figure 14 shows the battery output voltage through the boost converter. The battery output voltage is increased using a boost converter according to the DC bus voltage, which is 200 V. This voltage is the battery-inverter input voltage to be converted into AC voltage, according to the load voltage.

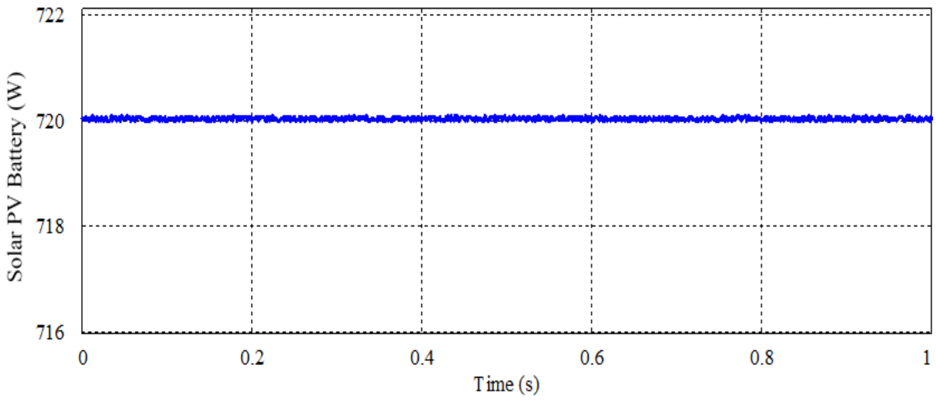


Figure 13. PV-BOP

When the battery provides power to the load, the FLC control will regulate each battery in supplying its power. Figure 15 shows the power changes that occur on the DC bus at 0.07 seconds, 0.34 seconds, 0.64 seconds and 0.93 seconds. When the DC bus power decreases at 0.07 seconds then battery 1 will supply power and when battery 1 has decreased power at 0.34 seconds then battery 2 will supply power to the DC bus. While Figure 16 shows the coordination of battery control 3 and battery 4 in supplying power through the boost converter. In Figure 16 it can be seen that at 0.64 seconds there is a change in the DC bus power and this is because the power on battery 1 and battery 2 has decreased. At 0.64 seconds battery 3 will supply power to the DC bus. When battery 3 has decreased, at 0.93 seconds, battery 4 will supply power to the DC bus. With this coordination method, the input power for the battery-inverter is always sufficient and the load can obtain input power without interruption.

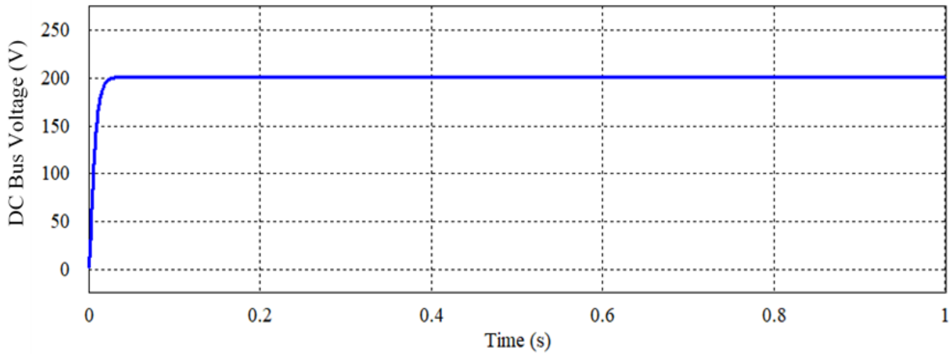


Figure 14. Battery converter output voltage

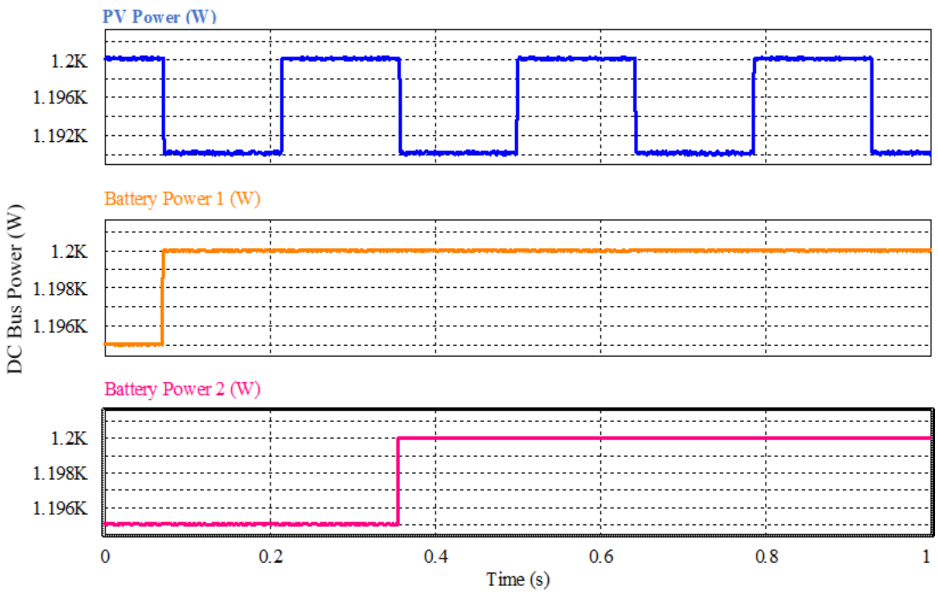


Figure 15. Coordination of battery 1 and battery 2

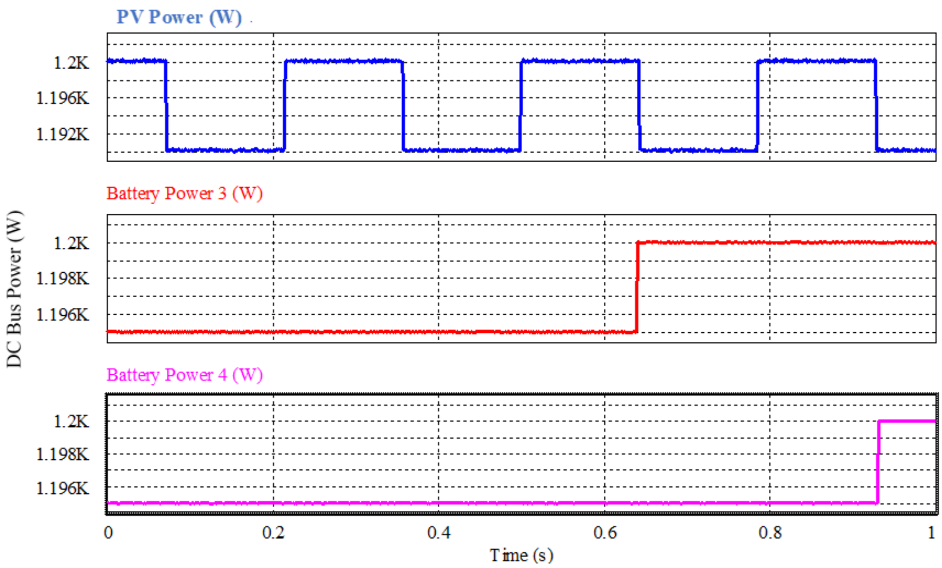


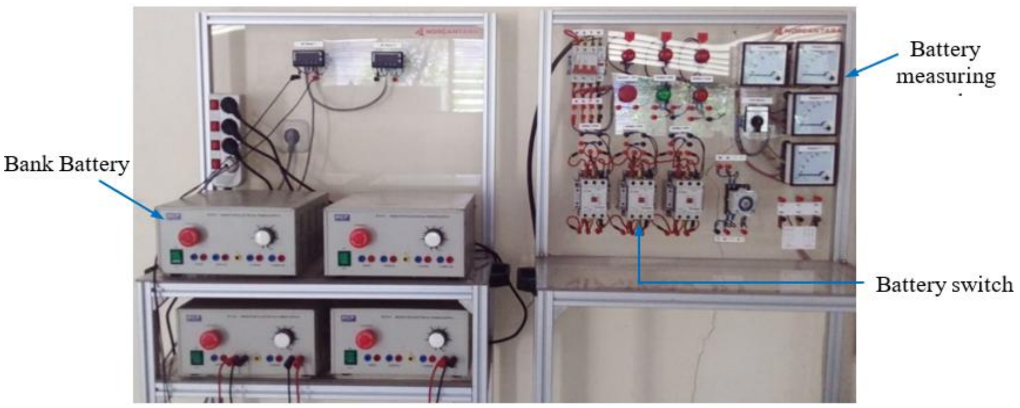
Figure 16. Coordination of battery 3 and battery 4

Based on the research objective in increasing power stability to the load using multi-batteries, this research has produced power and voltage stability on the DC bus by alternating the power flow of each battery. Table 6 shows the parameters and values used for the microgrid AC system. The results of the study using multi-battery with multi-PV sources will obtain uninterrupted load power availability. This can be seen in Figures 15 and 16, each battery alternately supplies 1200 W of power. Battery 1 supplies power in 0.07 seconds, battery 2 supplies power in 0.34 seconds, battery 3 supplies power in 0.64 seconds, and battery 4 delivers power in 0.93 seconds. With a coordinated control based on FLC the system is able to deliver uninterrupted power.

Table 6. Specifications of the system AC microgrid

Component	Parameter	Value
PV	Maximum power @ 1000 W/m2	720 W
PV1 – P4	Maximum power @ 1000 W/m2	720 W
Battery (B1-B4)	Capacity/ Voltage	@260 Ah/ @200 V
DC bus	Voltage	200 V
Utility grid	Power, Voltage, Frequency	1200 W, 220 V, 50 Hz
Load	Capacity	1000 W

Figure 17 shows the hardware implementation in the coordinated control design of an AC microgrid. Figure 17(a) shows a battery bank unit equipped with measuring instrumentation devices and control switches, while Figure 17(b) shows coordinated control hardware with a FLC. In this hardware test, an oscilloscope is used to measure voltage, current, and load power variables. This device is also equipped with voltage and current sensors and a DC source.



(a)

(b)

Figure 17. Coordinated control testing in the laboratory: (a) battery bank setup and (b) FLC-based coordinated control system

Compared with the hybrid microgrid architecture proposed in [2], the proposed single-stage AC-coupled configuration provides a simpler and more reliable battery charging mechanism by employing dedicated PV sources for battery charging while allowing one PV source to directly supply the battery inverter. This configuration improves the availability of stored energy during PV power fluctuations and reduces the dependence on centralized energy management. Furthermore, the hierarchical control approaches presented in [2] and [4] require coordination among multiple control layers, increasing implementation complexity and communication requirements. Similarly, the decentralized droop-control strategies proposed in [17] and [26] rely on voltage and frequency regulation to achieve power sharing among distributed energy resources. Although these methods effectively maintain power balance, their performance is sensitive to line impedance variations and often requires additional control mechanisms to improve voltage regulation under dynamic operating conditions.

As summarized in Table 7, the proposed coordinated multi-battery strategy demonstrates stable operation under varying power conditions. The FLC sequentially regulates the discharge of Battery 1 (B1) through Battery 4 (B4), enabling continuous power delivery while maintaining the DC bus voltage at 200 V. Each battery is capable of supplying approximately 1200 W, ensuring sufficient power to compensate for PV output fluctuations. Compared with existing decentralized and hierarchical control strategies, the proposed approach simplifies the control architecture by eliminating complex inter-subgrid coordination while maintaining stable bus voltage and uninterrupted power supply. These results demonstrate that the proposed single-stage AC-coupled configuration effectively enhances system reliability and operational stability for islanded AC microgrid applications.

Table 7. AC microgrid system output

Component	Value
PV	1200 W
PV1 – P4	2880 W
Battery B1	1200 W
Battery B2	1200 W
Battery B3	1200 W
Battery B4	1200 W
DC bus	200 V
Load current	6 A
Load power	1000 W

4. CONCLUSION

This paper proposed a novel single-stage AC-coupled microgrid configuration incorporating a coordinated multi-battery control strategy to improve the continuity and reliability of power supply under fluctuating PV generation. In the proposed architecture, one PV array directly supplies the battery inverter to feed the AC load, while additional PV arrays are dedicated to charging four battery units. A FLC was employed to coordinate the sequential charging and discharging of the battery units according to the available PV power and load demand. Simulation and experimental results demonstrated that the proposed coordinated control strategy effectively maintains stable bus voltage and power during PV power fluctuations and source interruptions. The sequential operation of Battery 1 through Battery 4 ensures continuous power delivery, minimizes power imbalance, and enhances the utilization of battery energy storage. Consequently, the proposed system improves the operational stability and reliability of the islanded AC microgrid while maintaining uninterrupted power supply to the connected load. Although the proposed strategy was validated under laboratory-scale operating conditions, further investigation is required to evaluate its performance in larger and more complex microgrid environments. Future research will focus on extending the proposed coordinated multi-battery strategy to hybrid AC/DC microgrids, incorporating battery state-of-charge (SOC) balancing, adaptive energy management, and predictive control based on artificial intelligence to optimize battery utilization, enhance system efficiency, and improve resilience under highly dynamic operating conditions.

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