Design and Simulation of Solar-Powered Battery Charging Using a Multi-Loop Control Approach

Kadelianto Ramba, Zuraida Tharo

Abstract

This study discusses the design and simulation of a solar cell-based battery charging system by applying a multi-loop control strategy. The proposed system is a PV-battery hybrid system with a topology of two independently operating DC-DC converters, consisting of a PV converter and a bidirectional battery converter. The multi-loop control strategy uses a Proportional-Integral (PI) control approach to maintain DC bus voltage stability and regulate the charging current limit and battery State-of-Charge (SoC). The system was tested under various load variations and solar irradiation intensities to evaluate its power control performance. Simulation results show that the proposed control strategy is capable of maintaining the bus voltage stable at the reference value and adaptively regulating the power flow between the PV and the battery. The system is classified into four main operating modes representing charging, idle, and discharging conditions, based on the combination of SoC, PV power, and load requirements. Simulations on a 200 Wpeak PV system prove that this control strategy is effective in maintaining system efficiency and reliability, as well as supporting optimal operation of standalone PV systems.

Keywords: Solar Cell, Battery, Hybrid PV System, Multi-Loop Control, Bidirectional Converter, PI Controller, MPPT.

Kadelianto Ramba[1]
[1]Department of Electrical Engineering, Universitas Pembangunan Panca Budi, Indonesia
e-mail: kadelianto@gmail.com[1]

Zuraida Tharo[2]
Department of Electrical Engineering, Universitas Pembangunan Panca Budi, Indonesia
e-mail: zuraidahtharo@dosen.pancabudi.ac.id[2]

Introduction

Lead-acid batteries are still the primary choice for solar panel systems due to their advantages, such as being maintenance-free, relatively low cost, ability to deep discharge up to 80% of their capacity, and lower risk compared to other types of batteries. However, the main drawback of lead-acid batteries is their relatively short lifespan compared to lithium-ion batteries. The lifespan of these batteries will decrease further if charging is done with a high current that exceeds their maximum capacity.

To overcome these problems, a control strategy is needed that can regulate the power flow on the DC bus, the charging current, and the State-of-Charge (SoC) of the battery in order to extend its service life. A study in reference [4] has proposed a control strategy for a PV-battery hybrid system that maintains maximum charging current and SoC without requiring discrete conditions. However, this method results in a voltage deviation on the DC bus of up to 5%.

A power management strategy for PV-battery systems using three converters has been proposed previously. Unfortunately, this approach introduces high control complexity, without regulating the maximum charging current limit or taking into account the battery SoC limit.

Based on the above issues, this study proposes a **multi-loop** control method for PV-battery hybrid systems, taking into account charging current limitations and battery SoC capacity. Each DC-DC converter is controlled by a two-loop control system using a Proportional-Integral (PI) controller. PI control was chosen because it is a conventional control method that is simple and easy to implement, and is more efficient than PID control in converter systems.

The proposed strategy aims to maintain voltage stability on the DC bus, regulate the maximum charging current limit, and maintain the battery's state of charge (SoC) without certain conditions so that control can operate optimally. The system used in this simulation has a peak power of 200 W to prove the effectiveness of the developed method.

A Buck Converter is a type of step-down DC-DC converter that functions to reduce the DC voltage from the input to a lower output voltage level [12]. The basic circuit of a Buck Converter is shown in **Figure 1**.

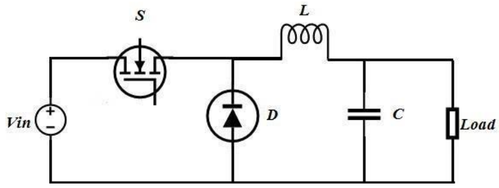

Figure 1. Buck Converter Circuit

A buck converter operates in two main conditions: when the switch is **closed** and when it is **open**. When the switch **is closed**, the diode is **reverse-biased**, and current flows from the voltage source through the switch to the inductor, then to the capacitor and load, before returning to the source. When the switch **is open**, the diode is **forward-biased**, and the current stored in the inductor flows to the load through the freewheeling diode, then returns to the inductor.

In order for the Buck Converter to operate in **Continuous Conduction Mode (CCM)**, the inductor value used must be greater than the minimum required value (L > Lmin), to ensure that the inductor current never drops to zero during the operating cycle.

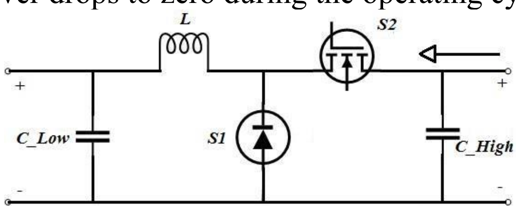

Figure 2. Bidirectional DC-DC Converter Buck Mode

Literature Review

1 Solar Energy Systems and Lead-Acid Batteries

Photovoltaic (PV) systems are one of the fastest growing renewable energy sources. To ensure continuity of power when the sun is not shining, PV systems are usually combined with batteries as a means of energy storage. One type of battery commonly used is the Lead-Acid battery due to its advantages such as low cost, ease of maintenance, and the ability to perform deep discharging up to 80% of total capacity (Nema & Agnihotri, 2010). However, its disadvantage is a short service life if charging is not properly controlled (Rahman et al., 2014).

2 State-of-Charge (SoC) and Power Management

State-of-Charge (SoC) is an important parameter that indicates the remaining energy capacity in a battery. Proper SoC management can extend battery life and prevent overcharging and excessive deep discharging (Chen & Rincon-Mora, 2006). Therefore, a power management strategy is necessary in hybrid PV-battery systems to maintain system stability and battery performance. A study by Lu et al. (2013) proposed a method for controlling current and SoC in PV-battery systems using a fuzzy logic-based strategy, but it is highly complex. A simpler and more effective alternative is the PI (Proportional-Integral) control-based method.

3 Multi-Loop Control and PI Control

Multi-loop control refers to the use of several separate control loops that work simultaneously to control different variables, such as DC bus voltage and battery charging current. This approach improves system stability and dynamic response compared to single control (Zhang et al., 2015). PI control is widely used in power converter systems due to its simplicity and ability to reduce steady-state errors. Compared to PID control, PI control is more suitable for applications with less complex dynamics such as DC-DC converters (Kundur, 1994).

4 DC-DC Converters and Buck Converters

A buck converter is a type of DC-DC converter that functions to reduce voltage from the input to the output. Its operation depends on the switching cycle (MOSFET) and the interaction between the inductor, capacitor, and diode. Buck converters are commonly used in battery charging systems due to their high efficiency and ability to regulate output voltage with precision (Erickson & Maksimovic, 2001).

5 Simulation and Implementation of PV-Battery Systems

PV system simulation with battery charging is generally performed using software such as MATLAB/Simulink. This environment allows for integrated multi-loop control simulation, voltage and current analysis, and SoC analysis (Amin et al., 2016). In this study, simulation was used to evaluate the effectiveness of multi-loop control strategies with a 200 Wpeak power configuration as a case study.

Research Methodology

In the system design process, it is very important to develop a block diagram that can comprehensively explain the relationships between components and the workflow of the system. Block diagrams provide a visual representation of the functions of each part and the interactions between subsystems involved in the overall operation of the system.

This study proposes a hybrid PV-battery system designed with a topology of two DC-DC converters that work independently. This system aims to manage the power flow from the solar panels (PV) and batteries to the DC bus to ensure a stable and efficient power supply. The block diagram of this system is shown in Figure 3.

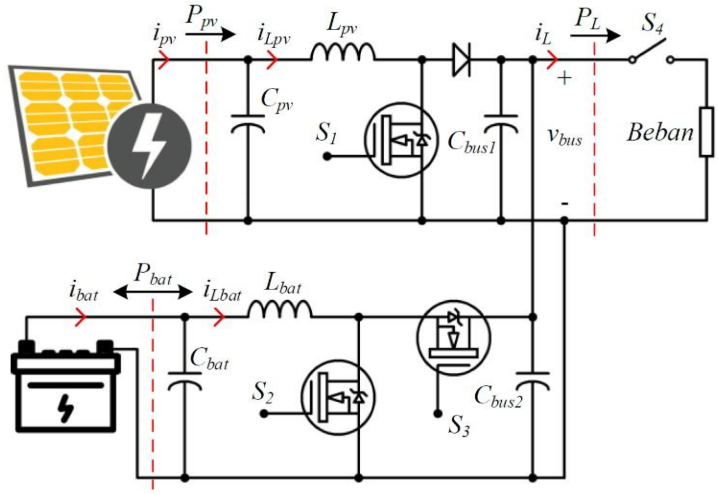

Figure 3. Proposed PV Battery Hybrid System Circuit

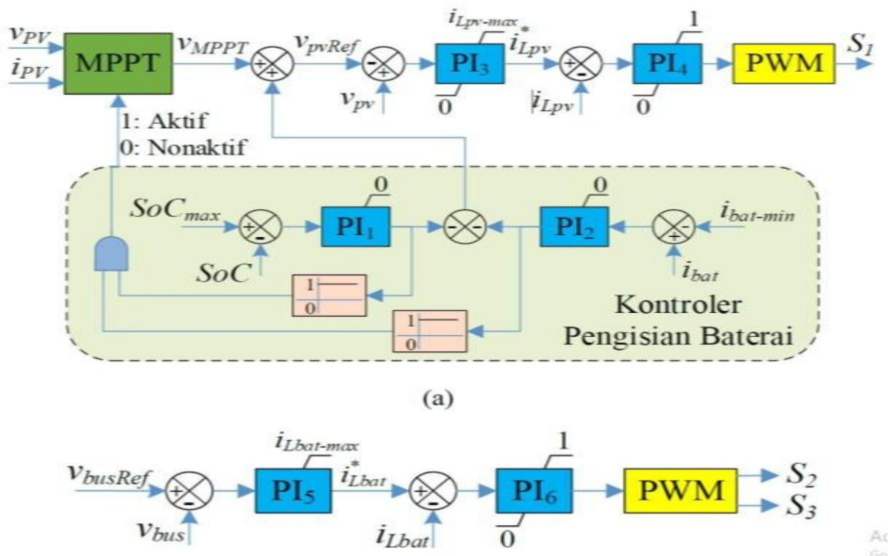

Figure 4. Proposed Control System Block Diagram

One of the main components in this system is a bidirectional DC-DC converter, which is responsible for regulating the DC bus voltage (denoted as vbus). This converter is connected directly to the battery, allowing two-way power flow between the battery and the DC bus, depending on the system conditions. Based on the configuration used, the nominal battery voltage must be lower than the DC bus voltage for the converter to operate efficiently in both modes.

This bidirectional converter is capable of operating in two modes, namely:

1. Buck Mode (Step-Down): When the voltage on the DC bus (vbusv) is higher than the reference voltage (vbusRefv), the converter will lower the voltage from the bus to the battery to store energy (charging). In this condition, energy from PV or other sources can be stored in the battery with precise current control.
2. Boost Mode (Step-Up): When the vbusv voltage is lower than the vbusRef reference value, the converter will operate in boost mode, raising the voltage from the battery to the DC bus level. This allows the battery to supply energy to the system when the power from the solar panels is insufficient, such as during cloudy weather or at night.

The combination of these two modes allows the system to operate automatically and adaptively, maintaining voltage stability on the DC bus and ensuring that the battery is not overcharged or over-discharged. This strategy also optimizes battery life by keeping the State-of-Charge (SoC) within safe limits.

Overall, this system offers an efficient solution for power management in renewable energy-based applications, and provides a strong foundation for the implementation of a digital river flow measurement system that relies on energy availability from solar panels.

Results

In the initial testing phase, the system enters the maximum power point tracking (MPPT) process. When MPPT first starts working, the PV converter is not yet able to meet all of the load's power requirements. Therefore, part of the load's power requirements are supplied by the battery. Over time, the output power from the PV that is successfully absorbed by the converter gradually increases until it exceeds the power required by the load. This excess power is then used to charge the battery. This condition is known as Mode-1.

Mode-1 (Charging Mode)

Mode-1 runs from 0.6 seconds to 5 seconds, with a load value of 20 Ohms. In this mode, after the system reaches a steady state, the power absorbed by the load is 115.3 W, while the power entering the battery (charging) is 79.82 W. The battery current (ibati_{bat}ibat) is recorded at -3.19 A. The negative sign on the battery current and power indicates that the battery is charging.

Mode-2 (Equilibrium Mode)

At the 5th second, the load value suddenly changed from 20 Ω to 11.84 Ω, causing an increase in load power requirements. Under these conditions, the load power becomes proportional to the power generated by the PV converter, which is 194.6 W, so that the battery is in a static state (neither charging nor supplying power), with a current value of ibat=0i_{bat} = 0ibat=0 A. Nevertheless, the MPPT algorithm continues to run and successfully finds the maximum power point of 199.9 W. The difference between the input and output power of the PV converter is due to power losses that are normal in the energy conversion process.

Mode-3 (Discharging Mode - Partial Support)

At the 10th second, the load suddenly changed again from 11.84 Ω to 9.57 Ω. This change triggered a transient response in the bus voltage signal (vbus). This transient phenomenon commonly occurs due to drastic changes in load within a short period of time. Since the load power at this point exceeds the power that can be supplied by the PV converter, the battery converter begins to operate to supply the power shortage so that the bus voltage remains stable according to the reference (setpoint). In steady state Mode-3, the power supplied by the battery is 45.48 W, while the total power consumed by the load is 240.7 W.

Mode-4 (Full Battery Support)

From the 15th to the 16th second, the irradiation level received by the PV panel gradually decreased to zero, causing the PV output power to slowly decrease and eventually stop completely. During this irradiation decrease process, the battery converter gradually took over the power supply for the load. When the irradiation completely disappears (the PV does not generate power), the battery becomes the sole energy source for the system. In Mode-4, the power supplied by the battery is recorded at 241.9 W, while the load power remains at 240.7 W, indicating that the battery successfully meets all of the system's energy needs.

Bus Voltage Stability and the Role of the Bidirectional DC-DC Converter

Test results show that the DC bus voltage (vbus) consistently remains at the reference voltage (vbusRef), despite changes in load and fluctuations in solar irradiation intensity. This indicates that the MPPT algorithm remains active at all times and that the system successfully maintains bus voltage stability under various operating conditions.

This voltage stability can be achieved because the bidirectional DC-DC converter effectively regulates the power flow between the solar panels, batteries, and loads. When the power generated by the PV panels exceeds the load requirements and causes the vbusv_{bus}vbus voltage to be higher than the reference voltage vbusRefv_{busRef}vbusRef , the PI5 control loop will generate a negative error value. This activates the bidirectional converter to operate in buck (step-down) mode, where the battery absorbs the excess power (charging process) so that the bus voltage returns to the reference value.

Conversely, when the vbus voltage drops below the reference voltage, the battery, through the bidirectional converter, supplies power to the load, i.e., it operates in boost (step-up) mode to keep the bus voltage stable.

Overall, the performance of the PI control loop and the dynamic operation of the bidirectional converter proved capable of maintaining the bus voltage at the expected value, both in conditions of excess power (surplus) and power shortage (deficit).

These findings are consistent with the results reported in previous studies, as described in references [4], [8], and [9], where the use of a bidirectional converter with a PI control strategy ( ) demonstrated reliable performance in maintaining voltage stability and power flow efficiency in hybrid PV-battery systems.

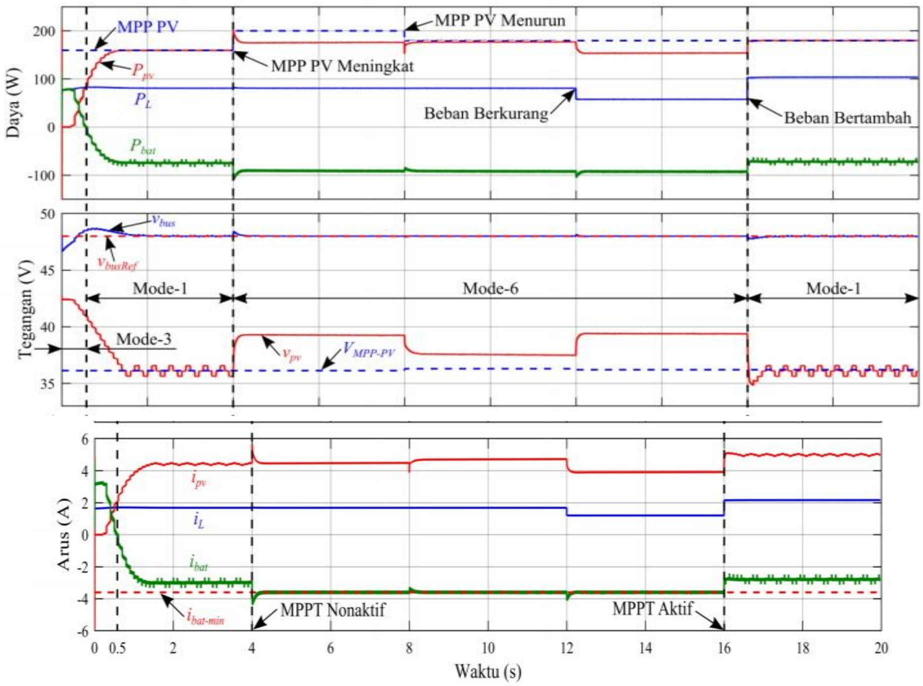

Figure 5. Charging Current Control System Graph

Table 1. Simulation Test Results of the PV-Battery System with a Multi-Loop Strategy

Mode	Time (s)	Load Value (Ω)	PV Irradiation	Load Power (W)	PV Power (W)	Battery Power (W)	Battery Status	Operation Description

Mode 1	0.6 – 5	20	Increasing	115.3	195.1	-79.82	Charging	PV surplus, battery absorbs excess power
Mode 2	5 – 10	11.84	High stability	194.6	194.6 – 199.9	≈ 0	Idle	PV balanced with load, battery idle
Mode 3	10 – 15	9.57	Highly stable	240.7	≈ 195	+45.48	Discharging	PV deficit, battery supply power shortage
Mode 4	15 – 16	9.57	Decreasing → 0	240.7	0	+241.9	Full discharge	

Description:

1) Battery Power (negative) = battery in charging mode
2) Battery Power (positive) = battery in discharging mode
3) PV Irradiation = describes the lighting conditions that affect PV power
4) MPPT is active throughout the entire test to optimize power from the solar panel.

The simulation results show that the solar panel-based battery charging system with a multi-loop control strategy is able to work well under various load and irradiation conditions. This system is divided into four operating modes, each of which shows how the power flow is controlled between the solar panels, batteries, and loads.

In Mode 1 (0.6–5 seconds), the power from the solar panels exceeds the load requirements, so the excess power is used to charge the battery. The battery current is negative, indicating the charging process, and the bus voltage remains stable according to the reference.

In Mode 2 (5–10 seconds), the power from the PV is equal to the load power. The battery does not charge or supply power, so it remains idle. The bus voltage remains stable, and MPPT remains active to regulate optimal power.

In Mode 3 (10–15 seconds), the load increases and the PV power is insufficient. The battery begins to supply power (discharging) to cover the shortfall, and the system is still able to maintain bus voltage stability quickly despite momentary transients.

In Mode 4 (15–16 seconds), solar irradiation drops to zero, causing the PV to stop generating power. All load power is supplied entirely by the battery. The system remains stable, and the bus voltage remains at its reference value. In general, the multi-loop control strategy is capable of automatically and responsively managing mode transitions, maintaining stable bus voltage, and protecting the battery from overcharging or over-discharging. This system has proven effective in handling changes in load and irradiation conditions.

Conclusion

Based on the results of the design and simulation that has been carried out, it can be concluded that the multi-loop control strategy in the solar cell-based battery charging system has been successfully designed and tested effectively. This strategy is capable of controlling the PV power converter and bidirectional battery power converter by considering the charging current limit and the State-of-Charge (SoC) condition of the battery, without causing voltage deviation on the DC bus. The system can adapt to load changes and solar irradiation fluctuations, while maintaining the bus voltage at its reference value. Based on a combination of battery SoC parameters, maximum PV power, and load power requirements, the system was successfully classified into four main operating modes that reflect the efficient power flow mechanism between the PV, battery, and load. Simulation results on a 200 Wpeak PV system show that the proposed control strategy is capable of maintaining system stability and efficiency under various operating conditions. Thus, this multi-loop control approach has been proven effective in improving the performance and battery life of standalone solar energy systems.

References

[1] Anisah, S., Tharo, Z., Hamdani, H., & Butar, A. K. B. (2023). Optimization Analysis Of Solar And Wind Power Hybrid Power Plant Systems. Proceedings of Dharmawangsa University, 3(1), 614-624.

[2] Hamdani, H., Sastra, A., & Firmansyah, D. (2023). Study of the Development of a 50 Kg Capacity Smart Goods Lift with Solar Power Generation (PLTS). INTECOMS: Journal of Information Technology and Computer Science, 6(1), 429-433.

[3] Hamdani, H., Tharo, Z., Anisah, S., & Lubis, S. A. (2020, September). Design of a Modified Sine Wave Inverter in Solar Power Plants for Residential Use. In Proceedings of the UISU National Engineering Seminar (SEMNASTEK) (Vol. 3, No. 1, pp. 156-162).

[4] Tharo, Z., Hamdani, H., & Andriana, M. (2019, May). Hybrid solar and wind power plants as an alternative source to address the fossil fuel crisis in Sumatra. In Proceedings of the UISU National Engineering Seminar (SEMNASTEK) (Vol. 2, No. 1, pp. 141-144).

[5] Tharo, Z., Hamdani, H., Andriana, M., & Yusar, J. H. (2022). Implementation of environmentally friendly generator sets based on solar panels in Tomuan Holbung Village. Journal of Higher Education Lecturer Service (Jurnal Deputi), 2(2), 98-101.

[6] Tharo, Z., Syahputra, M. R., Hamdani, H., & Sugino, B. (2020). Analysis of Medium Voltage Network Protection System Using Etap Application at Kualanamu International Airport. JOURNAL OF ELECTRICAL AND SYSTEM CONTROL ENGINEERING, 4(1), 33-42.

[7] Wibowo, P., Lubis, S. A., & Hamdani, Z. T. (2017). Smart home security system design sensor based on pir and microcontroller. International Journal of Global Sustainability, 1(1), 67-73.

[8] Yusup, M. (2022). Radio Frequency Identification (RFID) technology as a tool for automatic door opening systems in smart houses. Jurnal Media Infotama, 18(2), 367-373.

[9] M. R. Mojallizadeh and M. A. Badamchizadeh, "Adaptive Passivity-Based Control of a Photovoltaic/Battery Hybrid Power Source via Algebraic Parameter Identification," IEEE J. Photovoltaics, vol. 6, no. 2, pp. 532–539, 2016, doi: 10.1109/JPHOTOV.2016.2514715.

[10] Z. Yi, W. Dong, and A. H. Etemadi, "A unified control and power management scheme for PV-Battery-based hybrid microgrids for both grid-connected and islanded modes," IEEE Transactions on Smart Grid, vol. 9, no. 6, pp. 5975–5985, 2018, doi: 10.1109/TSG.2017.2700332.

[11] J. Hong, J. Yin, Y. Liu, J. Peng, and H. Jiang, "Energy Management and Control Strategy of Photovoltaic/Battery Hybrid Distributed Power Generation Systems with an Integrated Three-Port Power Converter," IEEE Access, vol. 7, pp. 82838–82847, 2019, doi: 10.1109/ACCESS.2019.2923458.

[12] H. Mahmood, D. Michaelson, and J. Jiang, "Control strategy for a standalone PV/battery hybrid system," IECON Proc. (Industrial Electron. Conf., pp. 3412–3418, 2012, doi: 10.1109/IECON.2012.6389351.

[13] M. Alramlawi and P. Li, "Design optimization of a residential pv-battery microgrid with a detailed battery lifetime estimation model," IEEE Trans. Ind. Appl., vol. 56, no. 2, pp. 2020–2030, 2020, doi: 10.1109/TIA.2020.2965894.

[14] S. Armstrong, M. E. Glavin, and W. G. Hurley, “Comparison of battery charging algorithms for stand alone photovoltaic systems,” PESC Rec. - IEEE Annu. Power Electron. Spec. Conf., pp. 1469–1475, 2008, doi: 10.1109/PESC.2008.4592143.

[15] S. Dhundhara, Y. P. Verma, and A. Williams, “Techno-economic analysis of the lithium-ion and lead-acid battery in microgrid systems,” Energy Convers. Management, vol. 177, pp. 122–142, 2018, doi: https://doi.org/10.1016/j.enconman.2018.09.030.

[16] A. Mirzaei, M. Forooghi, A. A. Ghadimi, A. H. Abolmasoumi, and M. R. Riahi, “Design and construction of a charge controller for stand-alone PV/battery hybrid system by using a new control strategy and power management,” Sol. Energy, vol. 149, pp. 132–144, 2017, doi: 10.1016/j.solener.2017.03.046.

[17] Wen, S. Wang, G. Liu, and R. Liu, “Energy management and coordinated control strategy of PV/HESS AC microgrid during islanded operation,” IEEE Access, vol. 7, no. c, pp. 4432–4441, 2019, doi: 10.1109/ACCESS.2018.2887114.