State of Charge Balancing Analysis Using Droop Control on Energy Storage System

Muhammad Cahyo Bagaskoro[1], Ariprihata[1*], Muhammad Afnan Habibi[1], Gabrielley Ferdhiansyah Riyadi[1]

[1] *State University of Malang*
Jl. Semarang No.5, Malang, 65145, Indonesia
[*]*Corresponding author. Email: ariprihata.ft@um.ac.id*

Abstract— The growing energy crisis has driven the global shift toward renewable energy development. Governments are taking significant steps by promoting diverse sources such as photovoltaic (PV), wind turbines, and battery systems. Among these, Battery Energy Storage Systems (BESS) play a crucial role in decentralized energy generation, especially in DC microgrids. Within BESS, Battery Energy Storage Units (BESUs) are vital components, where monitoring the State of Charge (SOC) is essential. The Coulomb Counter (CC) method is widely used due to its reliability in SOC estimation. This study introduces a dynamic SOC balancing strategy using droop control, aiming to maintain uniform SOC across multiple BESUs. The proposed method regulates BESU discharge behaviour to achieve SOC parity and optimize energy distribution throughout the microgrid. Simulations under various operating scenarios charging and discharging modes with different SOC levels were conducted using the MATLAB/SIMULINK® environment. The results show that the control approach effectively equalizes SOC levels under non-uniform initial conditions. The balancing duration varied according to the initial SOC difference, highlighting the controller's adaptability. Although the study did not directly measure battery lifespan or energy efficiency, enhanced SOC uniformity is expected to reduce current imbalances and operating stress, potentially improving long-term system reliability. This research offers valuable insights into the control and management of BESS, supporting the stable integration of renewable energy in modern microgrid applications.

Keywords— Battery; Bidirectional DC-DC Converter; Coulomb Counter; Droop Control

I. Introduction

Different renewable power sources and power storage devices are employed in a DC micro power grid to keep the load powered continuously. To prevent a decline in battery health, batteries must be charged and drained to their maximum potential. Energy storage devices can also be a part of DC microgrids with medium or big power. Several batteries with several DC-DC converters are found in big power microgrids; the power between them must be distributed effectively based on their power rating and state of charge. To maintain all batteries operating for the same amount of time and reduce power fluctuations, the batteries should ideally be charged or discharged in the same period of time [1].

The flow of energy through each microgrid source has been managed using a variety of energy management techniques. Battery operation is used to balance the generation mismatch at the load and control the DC bus voltage, while renewable power sources are typically used to extract their greatest potential [2]. One of the biggest issues with microgrids is battery longevity. Coordinating the charging and draining of various batteries in a micro power grid is necessary. The current charging capacity will drop if some batteries are loaded prematurely. Under such circumstances, a higher charging rate must be applied to the remaining uncharged batteries as power generation rises. As a result, the charging is not ideal overall. To preserve the battery's integrity, synchronization of battery charge and discharge must be achieved.

To maintain the stability and dependability of the microgrid, the DC micro power grid's renewable power generation must be coordinated and controlled, as the battery's renewable energy source varies [3]. One key indicator of a battery's performance is its level of charge. One significant metric for estimating battery longevity is the state of charge, or SOC [4]. For energy storage to last a long time and operate safely, the battery's state of charge must be accurate [5]. is the proportion of the battery's remaining capacity that remains. In microgrids, partial energy battery storage systems (BESS) are typically set up to guarantee a dependable DC power supply. Owing to the comparison of BESS capacity and aging degree, a certain BESS's SOC indicates when it is going to surpass its previous limit and leave the DC microgrid. In the event that the residual BESS capacity is inadequate to sustain the DC microgrid's functioning, the DC microgrid system will exhibit instability. [6]. For this reason, developing a SOC control strategy for BESS is essential.

The 2-way BESS converter typically utilizes conventional droop control for energy balancing in DC microgrids [7]. However, this method fails to achieve SOC balancing in multi-BESS systems. Jones et al. proposed coordinated control using variable droop coefficients to address static SOC issues [8], but their approach neglected the limitations of droop coefficient variations, which may compromise system stability. To overcome this, [9] introduced a functional model linking droop coefficients to SOC, aiming to restrict coefficients within safe operating limits [10]. Recent studies have shifted toward adaptive and decentralized SOC control. Belal et al. developed an adaptive droop mechanism that dynamically adjusts coefficients to reduce SOC imbalance [11], while Wu et al. focused on balancing SOC among heterogeneous BESS units

Received 27 June 2024, Revised 7 July 2025, Accepted 21 July 2025.
DOI: https://doi.org/10.15294/jte.v16i2.8280

via dynamic SOC feedback [12]. These approaches emphasize scalable and responsive SOC management in modern microgrids.

This work designs the BESS control strategy based on the aforementioned situations and the microgrid operation of the control strategy based on the BESS SOC. 4 examples are examined in this study: case 1 battery without using controller, in case 2 discharge mode with SOC capacity of 70% < SOC < 72% with balancing controller, case 3 in discharge mode with SOC capacity of 50% < SOC < 52% with balancing controller, case 4 in discharge mode with SOC capacity of 20% < SOC < 22% with balancing controller, case 5 in charge mode with SOC capacity of 25% < SOC < 22% with balancing controller, case 6 in charge mode with SOC capacity of 55% < SOC < 52% with balancing controller. The strategy control designed BESS fulfills the SOC balancing among BESU. Micro grid designed operation control fulfills the energy balancing in micro power grid. The scheme has been tested using MATLAB/SIMULINK® platform.

Several writers have also put forth different control solutions in related literature to mitigate power fluctuations in micro power grids. The authors of [13] discuss the use of isolated DC microgrids and utilize battery energy storage systems to reduce power fluctuations. A control strategy focusing on the state of charge (SOC) of the battery has been shown to be effective in suppressing power fluctuations in DC microgrids [14].

II. METHOD

This study proposes an SOC balancing control system for multiple batteries in DC grids using a modified Droop control method. As shown in Figure 1, the system consists of batteries, bidirectional DC-DC converters, and SOC controllers. Each Battery Energy Storage System (BESS) is managed by a dedicated SOC controller that uses Coulomb Counting to estimate the battery's state of charge based on current and voltage readings. The controller adjusts charging and discharging via PWM signals to maintain SOC balance across all units. Integrated with droop control, this approach ensures efficient energy distribution and enhances DC microgrid stability through real-time, modular coordination.

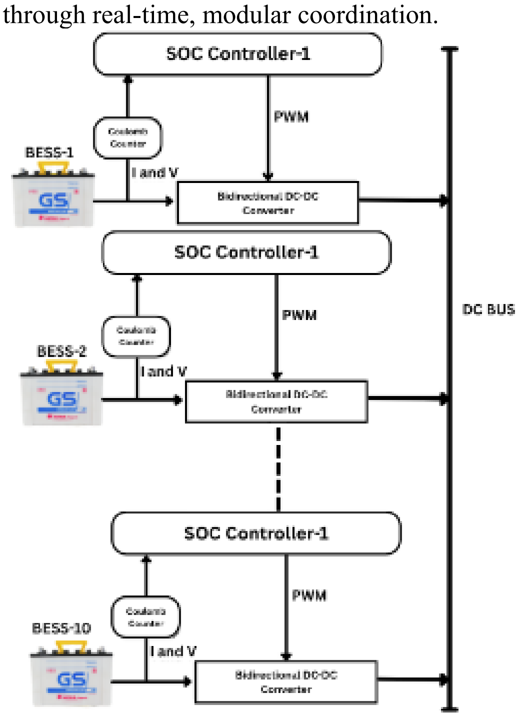

Figure 1. Proposed system for charging 10 BESS

A. Battery Specification

TABLE I. SPECIFICATION OF BATTERY

No.	BEES	Voltage (V)	Capacity (Ah)	Dimention (mm)
1	BESS-1	12	3.4	150 x 64 x 94
2	BESS-2	12	2.2	250 x 54 x 94
3	BESS-3	12	1.3	152 x 68 x 81
4	BESS-4	12	7.2	153 x 62 x 101
5	BESS-5	12	12	153 x 72 x 101
6	BESS-6	12	17	201 x 66 x 115
7	BESS-7	12	17	201 x 66 x 115
8	BESS-8	12	20	201 x 66 x 115
9	BESS-9	12	23	193 x 81 x 113
10	BESS-10	12	1.2	151 x 99 x 99

The design of this SOC balancer is compatible with various battery configurations, as detailed in Table 1, which presents the specifications of the batteries used in the system.

Table 1 outlines the technical specifications of the Battery Energy Storage Systems (BESS) utilized in the SOC balancing experiments. Each BESS unit operates at a standard nominal voltage of 12 V, while their capacities vary significantly, ranging from 1.2 Ah to 23 Ah. The diversity in capacity and physical dimensions among the batteries measured in millimetres (mm) is intentional, as it allows the proposed SOC balancing controller to be tested under heterogeneous conditions. By simulating a microgrid scenario with non-uniform battery characteristics, the system's ability to manage and equalize the SOC across multiple storage units can be effectively evaluated.

Due to their long lifespan, high energy density, and efficiency under various load conditions, lithium-ion batteries are selected as the main energy storage units in this study. Their durability and stable performance over multiple cycles make them ideal for DC microgrid applications. Most battery models assume steady-state operation to simplify analysis while preserving control accuracy. Figure 2 presents the equivalent circuit of the lithium-ion battery, which includes a voltage source, internal resistance, and an RC network to represent transient behaviour.

There are various types of batteries used in the system, each with distinct characteristics and charging stages that must be managed individually to ensure optimal performance and longevity. In this study, the temperature conditions of all ten batteries are maintained consistently within approximately 25°C, ensuring thermal stability during operation.

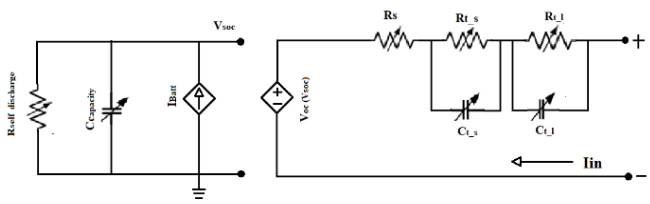

Figure 2. Equivalent Circuit

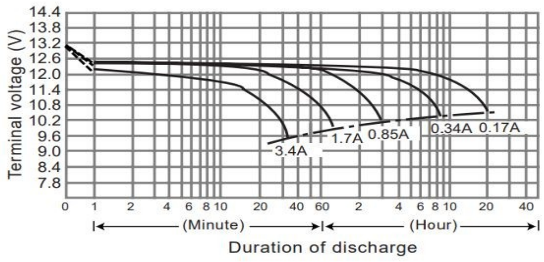

Figure 3. Battery Discharge Curve

Figure 3 presents a representative discharge curve, highlighting the voltage behaviour of the batteries over time during the discharge process and serving as a reference for evaluating performance and state of charge.

B. SoC Coulomb Counter Estimation

A fairly common technique for determining SOC is the coulomb counting method, which is also referred to as ampere hour counting and current integration. Throughout the usage period, battery current data are mathematically integrated to determine the SOC value using this method. The following is the equation (1) for this method [16]:

$$\mathrm{SOC} = \mathrm{SOC}(t_0) + \frac{I}{\mathrm{X}_{\rho\alpha\tau\varepsilon\delta}} \int_{to}^{t_0+\pi} I_b + I_{loss} \quad (1)$$

In this method, $\mathrm{SOC}_{\mathrm{rated}}$ refers to the battery's rated capacity, I_b is the battery current, I_{loss} represents the loss-related current, and $\mathrm{SOC}(t_0)$ denotes the initial SOC. The remaining capacity is calculated using the Coulomb Counting method, which integrates the charge entering and leaving the battery. This approach relies heavily on accurate initial SOC estimation and precise current measurement. By summing the charge and discharge currents over time, SOC can be computed based on a known capacity, which is either estimated or predefined during system setup. However, in repeated charge-discharge cycles, the extractable charge is often less than the initially stored charge.

C. Bidirectional DC-DC Converter

Several power sources are combined in renewable power systems using multiple-input bidirectional DC-DC converters. Current must be able to pass through the converter's switch in both directions. Typically, a unidirectional semiconductor energy switch, like a MOSFET or IGBT, is used to apply the converter.

Figure 4 illustrates the circuit configuration of a bidirectional DC-DC converter used in the multi-BESS system. This converter facilitates two-way energy flow—charging and discharging—between each battery and the DC bus. Controlled by SOC signals, it regulates power transfer to match energy demand and SOC levels in real time. Its bidirectional capability enhances system flexibility, supports SOC balancing, and maintains DC microgrid stability. The complete converter circuit is shown in Figure 4 [15].

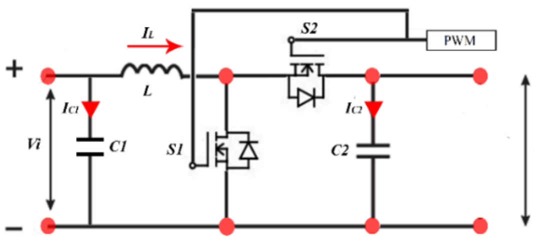

Figure 4. Bidirectional DC- DC Converter Circuit

D. Battery Controller Design

Distributed control, commonly used in ESS strategies, reduces system stress while maintaining a simple structure, such as in U-I droop control. An enhanced approach combines the ESU's SOC with a dynamic droop coefficient. The local controller adjusts this coefficient in real time based on each ESU's SOC. Figure 5 shows the parallel configuration of ESUs in an islanded DC microgrid. The droop control based on SOC can be defined using the following equation (2) [17]:

$$U_{dc-i} = U_{\mathrm{dc-ref}} - I_{\mathrm{dc-i}} \,.\, R_{\mathrm{i}}(\mathrm{SOC}) \quad (2)$$

$$R_{\mathrm{i}}(\mathrm{SOC}) = \frac{C_{\max}}{C_i} K_i(\mathrm{SOC}) \quad (3)$$

Charging:

$$K_i(\mathrm{SOC}) = \mathrm{e}^{(soc_i^2 - \overline{soc^2})} \quad (4)$$

Discharging:

$$K_i(\mathrm{SOC}) = \mathrm{e}^{-(soc_i^2 - \overline{soc^2})} \quad (5)$$

The mathematical formulation used in the SOC balancing strategy involves several key parameters related to battery operation within a DC microgrid. The variable U_{dc-i} represents the voltage measured at the DC bus for the i-th battery, while $U_{\mathrm{dc-ref}}$ denotes the reference voltage used to maintain stability across the bus. The current flowing through the i-th battery is denoted by $I_{\mathrm{dc-i}}$. The droop coefficient, which is a function of the battery's SOC, is expressed as $R_{\mathrm{i}}(\mathrm{SOC})$ or alternatively $K_i(\mathrm{SOC})$, and it dynamically adjusts power sharing based on the SOC level. The battery's actual capacity is given by C_i, whereas $C_{\max}$ refers to the maximum capacity among all batteries in the system. The individual State of Charge is denoted as SOC_i, and the average SOC across all connected BESS units is indicated by $\overline{\mathrm{SOC}}$. Together, these variables form the basis of the control logic, enabling adaptive and balanced energy distribution within a heterogeneous battery network.

The enhanced droop control factor includes the battery capacity in addition to the SOC for determining the droop coefficient [18]. on the grounds of attaining battery SOC balance. Figure 6 displays the enhanced droop control's control flow diagram.

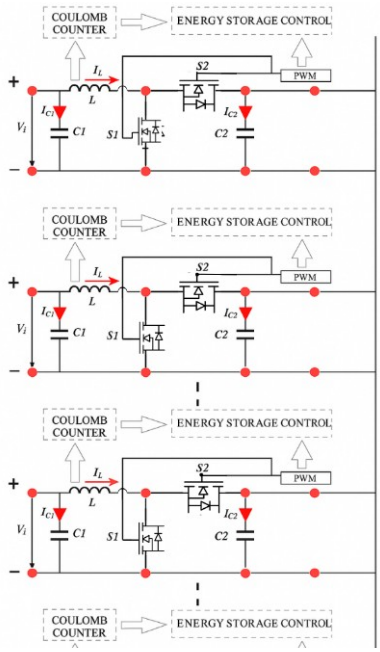

Figure 5. Structure Of the Battery Control

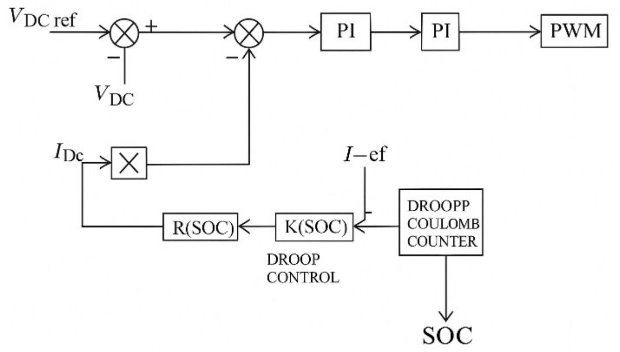

Figure 6. Block Diagram of Droop Control with SOC

Figure 6 illustrates the block diagram of a droop control system integrated with SOC-based feedback. The system regulates the output by comparing the reference DC voltage V_{DC} ref with the actual DC bus voltage V_{DC} , and the resulting error signal is processed through two cascaded Proportional-Integral (PI) controllers to generate a PWM signal for converter control. Simultaneously, the current I_{DC} is used to compute the droop response based on two functions: R(SOC) and K(SOC), which are SOC-dependent droop coefficients. These coefficients adapt the control behaviour based on the real-time SOC, measured using a Coulomb Counter integrated into the droop mechanism. The output current reference I_{ref} is then adjusted accordingly, ensuring dynamic power sharing and SOC balancing among battery units. This approach enhances system responsiveness while maintaining voltage regulation and battery health within a distributed energy storage system.

III. Results and Discussion

Testing of SOC balancing using the droop control method was conducted through MATLAB-based simulations, where the system was carefully modeled to closely replicate real-world battery operating conditions, as illustrated in Figure 7. The simulation aimed to evaluate the system's ability to maintain uniform SOC levels across multiple batteries under varying initial charge conditions. Figures 8, 9, and 10 present the simulation results, highlighting the differences in charging behavior with and without SOC balancing for initial SOC ranges of 21%–23%, 51%–53%, and 71%–73%. Additionally, Figures 11, 12, and 13 provide a more detailed analysis of the SOC balancing performance during the charging process, specifically for battery groups within the SOC ranges of 22%–25% and 52%–55%. These results demonstrate that the effectiveness of the droop control strategy is strongly influenced by the dynamic interaction of charge and discharge currents, which directly determine the speed and accuracy of SOC balancing in real-time across the battery array.

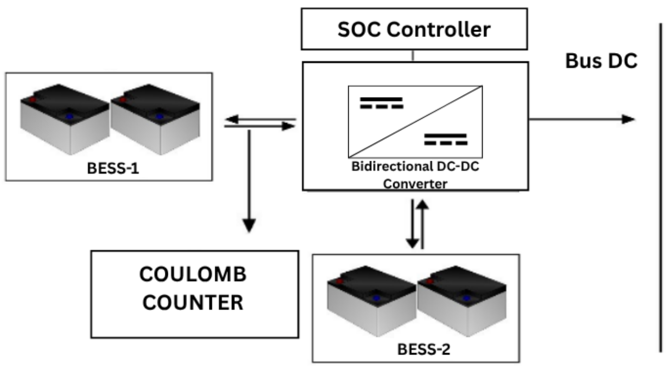

Figure 7. Simulation Of Battery SOC Balancing Using Droop Control

1) Case 1

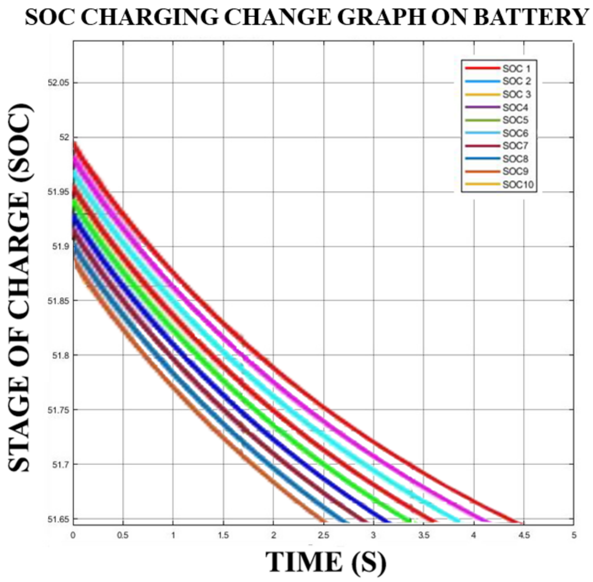

Figure 8. Battery SOC Capacity at The Time of Discharge Without Using SOC Control

Case 1, as illustrated in Figure 8, represents the initial test scenario for evaluating the SOC balancing performance using droop control. In this case, batteries are initialized with a specific SOC range that exhibits moderate imbalance, allowing observation of the controller's response to unequal charge distribution. The results shown in Figure 8 demonstrate the system's ability to gradually equalize the SOC levels among the batteries, highlighting the effectiveness of the proposed control strategy under these conditions.

2) Case 2

Case 2, as shown in Figure 9, investigates the performance of SOC balancing during the battery discharge phase with initial SOC values ranging from 21% to 23%. This low SOC condition tests the droop control strategy under critical energy levels, where effective balancing is crucial to prevent deep discharge and ensure system stability. The results in Figure 9 indicate that the SOC control method successfully minimizes the SOC gap between batteries, enabling coordinated energy management and improved discharge uniformity across the BESS units.

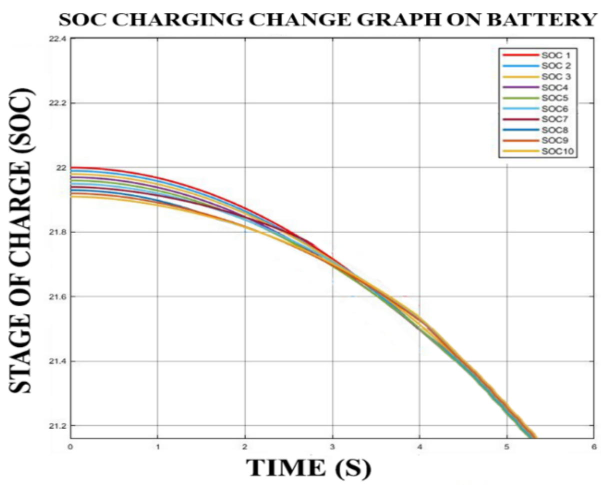

Figure 9. Battery SOC Capacity at the Time of Discharge is 21% < SOC < 23% Using SOC Control

3) Case 3

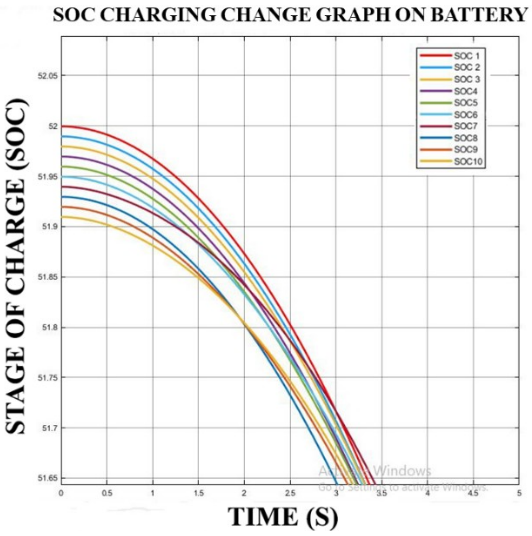

Figure 10. Battery SOC Capacity at the Time of Discharge is 51% < SOC < 53% Using SOC Control

Case 3, as illustrated in Figure 10, evaluates the SOC balancing performance during the discharge process when the initial SOC values range between 51% and 53%. This medium-level SOC condition provides a balanced scenario to assess how the droop control strategy maintains synchronization among battery units during energy release. The results demonstrate that the SOC control mechanism effectively aligns the discharge behaviour, ensuring uniform SOC reduction across the BESS units and maintaining operational consistency within the microgrid.

4) Case 4

Case 4, as presented in Figure 11, analyses the SOC balancing behaviour during the discharge phase with initial SOC values between 51% and 53%. Although the SOC range is similar to that in Case 3, this scenario may involve different battery configurations or time intervals to further assess the consistency of the SOC control strategy. The simulation results in Figure 11 confirm that the controller continues to perform effectively, maintaining SOC uniformity among the batteries and ensuring a balanced energy discharge across the system.

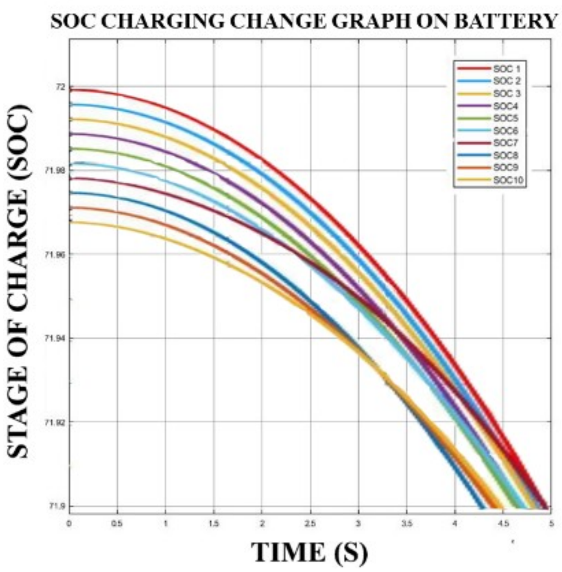

Figure 11. Battery SOC Capacity at the Time of Discharge is 51% < SOC < 53% Using SOC Control

5) Case 5

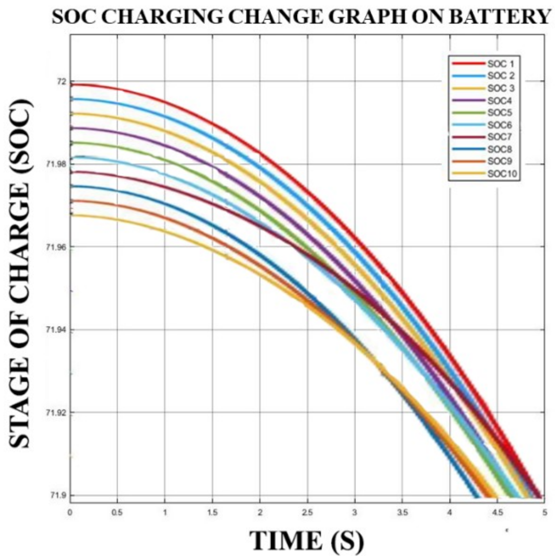

Figure 12. Battery SOC Capacity at The Time of Charge is 25% < SOC < 22% Using SOC Control

Case 5, as shown in Figure 12, investigates the SOC balancing performance during the charging phase, where the initial SOC of the batteries ranges between 22% and 25%. This low SOC condition presents a critical scenario in which the droop control strategy must respond promptly to restore energy levels while maintaining balance among the battery units. The results in Figure 12 demonstrate that the SOC control method effectively coordinates the charging process, progressively equalizing the SOC across all BESS units and preventing overcharging or charging delays in individual batteries.

6) Case 6

Case 6, as depicted in Figure 13, analyses the SOC balancing process during the charging phase with initial SOC values ranging from 52% to 55%. This mid-level SOC condition serves to evaluate how effectively the droop control strategy manages moderate disparities in battery charge levels during energy intake. The results in Figure 13 show that the SOC control mechanism successfully harmonizes the charging behaviour across the BESS units, gradually reducing the SOC gap and ensuring balanced energy distribution throughout the system.

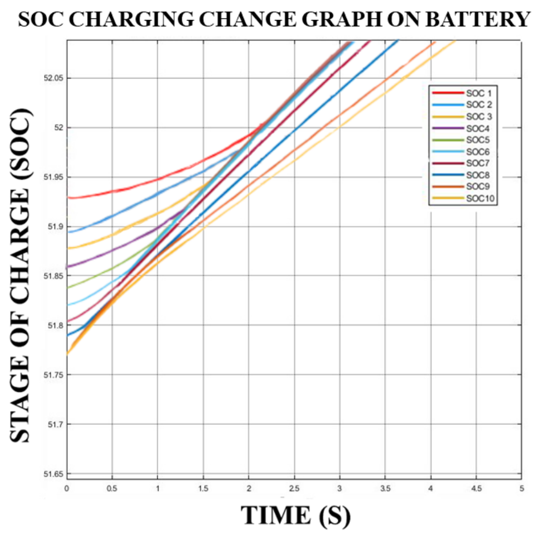

Figure 13. Battery SOC Capacity at The Time of Charge is 55% < SOC < 52% Using SOC Control

It can be seen from Figure 8 that when the SOC of the battery is in discharge mode without using the SOC balancing controller. It can be seen from SOC1 to SOC10 cannot balance the SOC. In case 2 in Figure 9 the capacity of 21% < SOC < 23% experienced SOC balancing at time 3 with a capacity of 21.78%. It can be seen in case 3 from Figure 10 that when the SOC of the battery is in discharge mode at a capacity of 51% < SOC < 53%, it experiences SOC balancing at time 3.4 with a capacity of 51.75%. It can be seen from Figure 11 in case 4 that when the SOC of the battery experiencing discharge mode is at a capacity of 71% < SOC < 73% experiencing SOC balancing at time 3.5 with a capacity of 71.7%. It can be seen from Figure 12 in case 5 that when the SOC of the battery experiencing charge mode is at a capacity of 25% < SOC < 22% experiencing SOC balancing at time 2 with a capacity of 24.05%. It can be seen from Figure 13 in case 5 that when the SOC of the battery experiencing charge mode is at a capacity of 75% < SOC < 72% experiencing SOC balancing at time 2 with a capacity of 24.05%. There is a difference in balancing time from Figure 12 and 13 where in Figure 12 the current entering the battery from the bus is greater than in Figure 13. Table 2 shows the battery voltage and current during discharge at different SOC capacities. It can be observed that the proposed controller successfully maintains the current distribution proportional to the SOC imbalance. At lower SOC ranges (e.g., 21–23%), the current magnitude is higher, indicating a stronger control response to balance the batteries. This highlights the adaptiveness of the modified droop control to respond to various SOC discrepancies in real time.

To further validate the effectiveness of the proposed SOC balancing strategy, a performance comparison with recent relevant studies is presented the adaptive droop control method [19] achieves moderate balancing with SOC deviation around ±2–3% and balancing times of about 4–5 seconds under limited conditions. However, its responsiveness decreases with greater SOC disparity due to centralized coordination. In contrast, [20] proposed a decentralized droop control method for multiple BESUs, which improved modularity but still produced deviations greater than 3% and longer balancing times. In comparison, the proposed method achieves significantly better performance, with SOC deviations reduced below 1% across all scenarios and faster response times between 2–3.5 seconds depending on the SOC range. These improvements are enabled by real-time adjustment of droop coefficients based on SOC levels and battery capacities, as detailed in the proposed controller design. The comparison highlights the superiority of the proposed SOC balancing method in terms of speed, accuracy, and modularity. These findings reinforce the method’s suitability for real-world applications in modern DC microgrids that require decentralized and adaptive control strategies.

IV. Conclusion

This paper investigates the battery's SOC balancing control strategy, which has been thoughtfully designed. Initially, the conventional battery control approach is examined, and advancements are implemented based on the traditional approach. The SOC balancing between batteries is completed by the enhanced battery control technique. The battery is then employed as the primary control unit and coordinates the control technique of the distributed power generation unit under the direction of the central controller based on its state of charge (SOC). This process is simulated using MATLAB/Simulink in order to guarantee the power balance of the DC microgrid. The battery control strategy based on battery SOC that is designed in this study can complete the SOC balance between batteries, according to the simulation findings. The microgrid's power balance can be maintained and the seamless transition between modes can be accomplished with the help of the operation control strategy that was devised based on the battery's state of charge. The next research project will canter on the renewable energy producing unit.

Acknowledgement

This work is supported by non-APBN UM 2024, Indonesia with contract 11.6.52/UN32.14.1/LT/2024.

References

[1] Y. Deng, C. Sun, S. Qiu, Y. Li, C. Sui, and W. Han, “SOC Balancing Control Strategy of DC Microgrid Energy storage System based on droop control,” *2021 International Conference on Power System Technology (POWERCON)*, pp. 01–05, Sep. 2023, doi: 10.1109/powercon58120.2023.10331322.

[2] A. Hussain, K. Raj, K. Rajashekara, H. Krishnamoorthy, and S. Atcitty, “A Voltage Droop-Based State of Charge Control among Split Batteries in Modular Multilevel Converter for Grid Energy Storage Interface,” *IEEE Industry Applications Society Annual Meeting*, pp. 1–14, Sep. 2019, doi: 10.1109/ias.2019.8911867.

[3] K. Wang, J. Zhang, X. Qiu, J. Wang, and C. Wang, “Accurate current sharing with SOC balancing in DC microgrid,” *Electric Power Systems Research*, vol. 232, p. 110386, Apr. 2024, doi: 10.1016/j.epsr.2024.110386.

[4] J. V. M. Caracas, G. C. Farias, J. G. De Matos, F. Simoes, and L. A. De S Ribeiro, “Adaptative droop control for balancing the state of charge of multiple energy storage systems in decentralized microgrids,” *IECON 2020 the 46th Annual Conference of the IEEE Industrial Electronics Society*, pp. 1658–1663, Oct. 2018, doi: 10.1109/iecon.2018.8591697.

[5] S.-H. Choi, J.-S. Kim, J. Kim, J. Bang, and G.-W. Moon, *A Decentralized Control Method of Battery Energy Storage Units With Different State of Charge*. 2024, pp. 1736–1739. doi: 10.1109/ipemc-ecceasia60879.2024.10567059.

[6] J. Su, K. Li, Y. Li, C. Xing, and J. Yu, “A novel State-of-Charge-Based droop control for battery energy storage systems to support coordinated operation of DC microgrids,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 11, no. 1, pp. 312–324, Feb. 2022, doi: 10.1109/jestpe.2022.3149398.

[7] D. Li, Z. Wu, B. Zhao, and L. Zhang, “An improved droop control for balancing state of charge of battery energy storage systems in AC microgrid,” *IEEE Access*, vol. 8, pp. 71917–71929, Jan. 2020, doi: 10.1109/access.2020.2987098.

[8] Z. Huang, Y. Li, X. Cheng, and M. Ke, “A voltage-shifting-based state-of-charge balancing control for distributed energy storage systems in islanded DC microgrids,” *Journal of Energy Storage*, vol. 69, p. 107861, Jun. 2023, doi: 10.1016/j.est.2023.107861.

[9] P. Jangir, V. Sangwan, R. Kumar, and A. K. Rathore, “Droop control method in power converter system for balancing state-of-charge of energy storage units in EV,” *The Journal of Engineering*, vol. 2019, no. 18, pp. 4764–4769, Jun. 2019, doi: 10.1049/joe.2018.9271.

[10] N. Ghanbari and S. Bhattacharya, “SOC balancing of different energy storage systems in DC microgrids using modified droop control,” *IECON 2020 the 46th Annual Conference of the IEEE Industrial Electronics Society*, pp. 6094–6099, Oct. 2018, doi: 10.1109/iecon.2018.8592890.

[11] K. Bi, W. Yang, D. Xu, and W. Yan, “Dynamic SOC balance Strategy for modular energy storage system based on adaptive droop control,” *IEEE Access*, vol. 8, pp. 41418–41431, Jan. 2020, doi: 10.1109/access.2020.2976729.

[12] N. Qi, W. Fang, W. Wang, X. Liu, and S. Liu, “SoC balancing method for energy storage systems in DC microgrids using simplified droop control,” *Journal of Power Electronics*, vol. 21, no. 8, pp. 1200–1212, May 2021, doi: 10.1007/s43236-021-00260-6.

[13] X. Lu, K. Sun, J. M. Guerrero, J. C. Vasquez, and L. Huang, Droop-control-based state-of-charge balancing method for charging and discharging process in autonomous DC microgrids. 2014. doi: 10.1109/isie.2014.6864988.

[14] R. Yang and F. Yang, “An Adaptive Droop Control Method for SOC Balancing in DC Microgrids with Photovoltaic and Energy Storage Systems,” *2022 IEEE Transportation Electrification Conference and Expo, Asia-Pacific (ITEC Asia-Pacific)*, pp. 1010–1015, Oct. 2024, doi: 10.1109/itecasia-pacific63159.2024.10738620.

[15] N. Ghanbari and S. Bhattacharya, “A Droop Control Algorithm with Frequency Partitioning Capability and SoC Balancing for Different

Energy Storage Systems," *2022 IEEE Applied Power Electronics Conference and Exposition (APEC)*, pp. 1931–1938, Mar. 2022, doi: 10.1109/apec43599.2022.9773775.

[16] Q. Qu and G. Tan, *An improved method for energy storage droop control based on SOC equalization*. 2024, pp. 367–372. doi: 10.1109/icepet61938.2024.10625903.

[17] X. Lu, K. Sun, J. M. Guerrero, J. C. Vasquez, and L. Huang, "State-of-Charge balance using adaptive droop control for distributed energy storage systems in DC microgrid applications," *IEEE Transactions on Industrial Electronics*, vol. 61, no. 6, pp. 2804–2815, Aug. 2013, doi: 10.1109/tie.2013.2279374.

[18] Y. Li, D. Wang, Y. Ni, and K. Song, "A SOC balancing adaptive droop control scheme for multiple energy storage modules in DC microgrids," *Journal of Physics Conference Series*, vol. 2849, no. 1, p. 012102, Sep. 2024, doi: 10.1088/1742-6596/2849/1/012102.

[19] J. W. Lin, Z. X. Wang, L. X. Bao, and H. Qin, "An improved droop control method for energy storage module of DC microgrid," *IOP Conference Series Earth and Environmental Science*, vol. 342, no. 1, p. 012008, Oct. 2019, doi: 10.1088/1755-1315/342/1/012008.

[20] X. Lu, K. Sun, J. M. Guerrero, J. C. Vasquez, and L. Huang, "Double-Quadrant State-of-Charge-Based droop control method for distributed energy storage systems in autonomous DC microgrids," *IEEE Transactions on Smart Grid*, vol. 6, no. 1, pp. 147–157, Sep. 2014, doi: 10.1109/tsg.2014.2352342.