



Design and Optimization of a Battery Management System for Enhanced Charging Performance in Solar Photovoltaic Systems

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Abstract : The integration of battery energy storage systems with solar photovoltaic (PV) technology plays a critical role in improving energy reliability and utilization. However, the effectiveness of such systems is highly dependent on the performance of the battery charging mechanism and management strategy. This study proposes the design and optimization of a Battery Management System (BMS) to enhance charging performance in PV-based energy systems. The proposed system integrates a PV module, a DC–DC charger controller, and a lithium-ion battery pack equipped with a BMS capable of real-time monitoring and control of key parameters, including voltage, current, temperature, and state of charge (SOC). An adaptive charging strategy is implemented to regulate charging current based on battery conditions and PV output characteristics. Experimental results under varying charging currents 1.4 A to 5.2 A demonstrate that the BMS effectively maintains voltage balance among battery cells, with deviations ranging from 0.46% to 1.63% and an average below 2%. This indicates a significant improvement in cell balancing performance compared to conventional systems without BMS. Furthermore, the proposed system enhances charging efficiency, reduces energy losses, and improves battery safety by preventing overcharge and thermal stress. The results confirm that the optimized BMS provides a reliable and efficient solution for battery charging in solar PV applications, contributing to improved system performance and extended battery lifespan.

Keywords: Battery Management System, Charging optimization, Energy storage system, Lithium-ion battery, Solar photovoltaic.

1. INTRODUCTION

The increasing penetration of solar photovoltaic (PV) systems in modern energy infrastructure is driven by the need for sustainable and low-carbon energy sources [1]. However, the inherent intermittency and variability of solar irradiance lead to fluctuating power output [2], which limits system reliability and efficiency [3], particularly in standalone and microgrid applications [4].

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A. Yulianto et al. (eds.), *Proceedings of the International Conference of Inland Water and Ferries Transport Polytechnic of Palembang on Technology and Environment (IWPOSPA-TE 2025)*, Advances in Engineering Research 302,

https://doi.org/10.2991/978-94-6239-731-6_3

To mitigate these issues, battery energy storage systems (BESS) are integrated with PV systems to store excess energy and stabilize power supply [5]. The effectiveness of PV-BESS systems is highly dependent on the efficiency of battery charging strategies and energy management approaches [6]. Conventional charging methods such as constant current–constant voltage (CC–CV) are widely applied but are not optimal for PV applications due to their inability to adapt to dynamic and stochastic solar generation profiles [7], [8].

In addition, improper charging control can accelerate battery degradation, reduce usable capacity, and shorten lifespan due to factors such as overcharging, thermal stress, and cycling effects [9]. Therefore, advanced control strategies that consider real-time operating conditions and battery states are required to ensure optimal performance and safety [10].

The Battery Management System (BMS) plays a critical role in monitoring key parameters such as state of charge (SOC), state of health (SOH), voltage, and temperature, while also implementing charging control strategies [11]. Recent developments in BMS focus on intelligent and adaptive approaches [12], including model predictive control, fuzzy logic, and machine learning techniques, to optimize charging efficiency and extend battery life under variable PV conditions [13].

Furthermore, the integration of optimization algorithms and energy management systems (EMS) enables coordinated control between PV generation and battery storage [14], improving energy utilization and system reliability [15]. Data-driven and forecast-based strategies have shown significant potential in enhancing charging performance and reducing energy losses in PV systems [16].

Based on these challenges, this study aims to design and optimize a Battery Management System (BMS) to enhance charging performance in solar PV systems by improving energy efficiency, maximizing solar utilization, and extending battery lifespan.

2. METHODOLOGY

This study employs an experimental and computational approach to design and optimize a Battery Management System (BMS) for improving battery charging performance in solar photovoltaic (PV) systems. The proposed system consists of a PV module as the primary energy source, a DC–DC converter functioning as a charger controller, a lithium-ion battery pack, and a BMS unit for monitoring and control. The PV system is modeled using a single-diode equivalent circuit to represent its current–voltage characteristics under varying irradiance and temperature conditions. Meanwhile, the battery is modeled using an equivalent circuit model (ECM) that incorporates key parameters such as state of charge (SOC), internal resistance, and dynamic charging behavior. The BMS is designed to continuously monitor cell-level voltage, current, and temperature, and to estimate SOC in real time. An adaptive charging strategy is implemented by modifying the conventional constant current–constant voltage (CC–CV) method, where the charging current is dynamically adjusted based on PV output and battery condition. System performance is evaluated through simulation and experimental testing under varying charging current scenarios, ranging from 1.4 A to 5.2 A. Key performance indicators include charging efficiency, voltage deviation among cells, energy utilization, and system stability. The effectiveness of the

proposed method is validated by comparing its performance with conventional charging approaches without BMS, focusing on improvements in voltage balancing, safety, and overall battery lifespan.

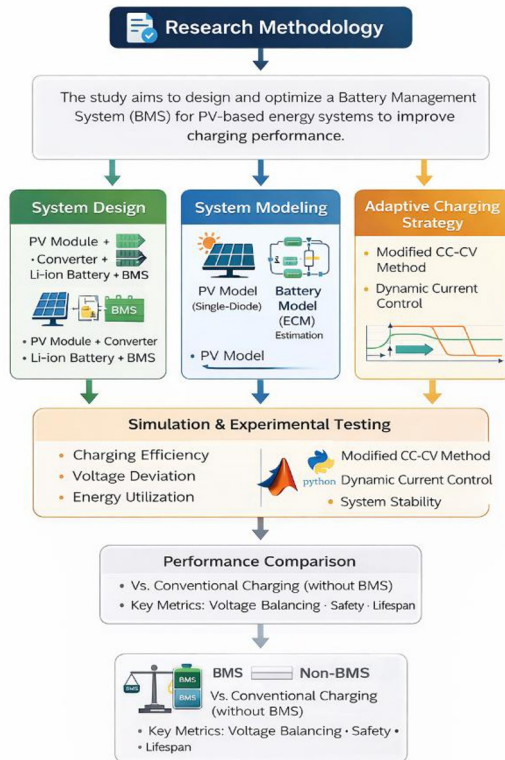


Figure 1. Research methodology

3. DISCUSSION

The proposed Battery Management System (BMS)-based charging system is designed to utilize energy generated from a solar photovoltaic (PV) source for efficient and controlled battery charging. The overall system consists of a PV module, a DC–DC converter (charger controller), a lithium-ion battery pack, and a BMS unit.

The PV module generates a variable DC output depending on solar irradiance and temperature conditions. This output is regulated by a DC–DC converter, which functions as a charger controller to stabilize the output voltage and control the charging current supplied to the battery. The converter operates under a controlled charging scheme to ensure safe and efficient energy transfer.

The charging process follows an adaptive current control mechanism. When the battery is in a low state of charge (SOC), the controller supplies a higher charging current to accelerate the charging process. As the battery approaches its upper SOC limit, the charging current is gradually reduced to prevent overcharging and minimize thermal stress. This approach is a modified constant current–constant voltage (CC–CV) strategy adapted to variable PV output conditions.

The BMS plays a critical role in monitoring and managing battery conditions at both pack and cell levels. Key parameters such as cell voltage, current, temperature, state of charge (SOC), and state of health (SOH) are continuously measured and processed. Based on this information, the BMS provides feedback signals to the charger controller to dynamically adjust the charging profile.

In contrast to conventional systems without BMS, where charging control is based solely on overall battery voltage, the proposed system enables cell-level monitoring and balancing. This reduces the risk of cell overvoltage, undervoltage, and imbalance, which are major factors contributing to battery degradation and reduced lifespan.

Furthermore, the BMS incorporates protection mechanisms, including overcharge, overdischarge, overcurrent, and overtemperature protection, ensuring safe operation under varying environmental and load conditions. The integration of BMS with the charger controller allows for a closed-loop control system, improving charging efficiency, energy utilization, and battery longevity.

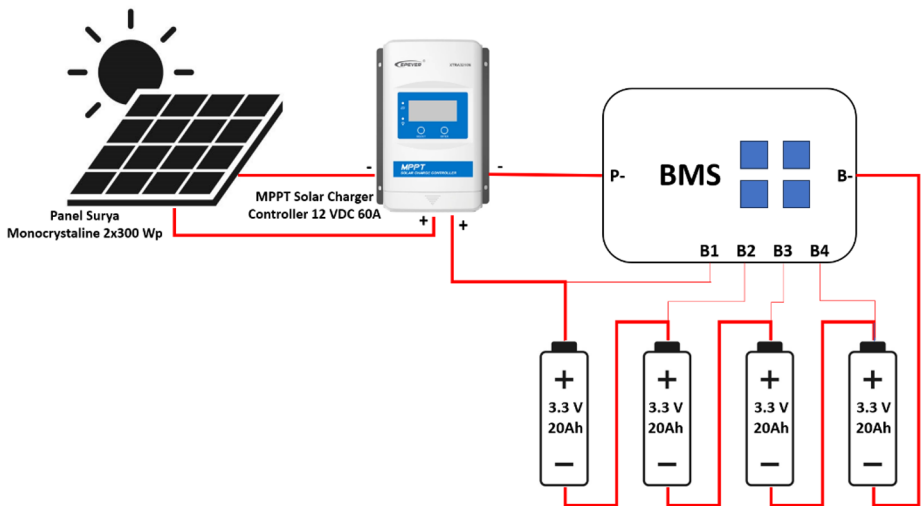


Figure 2. The role of the BMS charging system

The charging performance of the proposed Battery Management System (BMS) was evaluated by analyzing the voltage distribution across individual battery cells under varying charging current conditions. The primary objective of this analysis is to assess the effectiveness of the BMS in maintaining cell voltage balance during the charging process.

Experimental results show that the charging current varies between 1.4 A and 5.2 A, representing different operating scenarios of the photovoltaic (PV) system. For each

condition, the total battery voltage and individual cell voltages were measured. The voltage deviation between the highest and lowest cell voltage was calculated to quantify the level of imbalance.

Based on the data presented in Table 1, the voltage deviation ranges from 0.46% to 1.63%, with an average deviation below 2%. The smallest deviation (0.46%) occurs at a charging current of 4.3 A, indicating a highly balanced condition among cells. Meanwhile, the highest deviation (1.63%) is observed at 5.2 A, which can be attributed to higher charging current leading to increased dynamic imbalance. Nevertheless, all observed deviations remain within acceptable limits for lithium-ion battery operation, typically below 3%.

These results indicate that the proposed BMS is capable of effectively minimizing voltage imbalance among cells during charging. The BMS continuously monitors individual cell voltages and performs active or passive balancing by redistributing energy from higher-voltage cells to lower-voltage cells. This mechanism ensures uniform voltage distribution and prevents overvoltage or undervoltage conditions at the cell level.

Table 1. Voltage between batteries under charging conditions

No	Charging (Amperes)	Total Battery Voltage (Volts)	Voltage per Cell (Volts)				Difference between Highest and Lowest Voltage
			Cell 1	Cell 2	Cell 3	Cell 4	
1	1.4	13.10	3.293	3.293	3.269	3.243	1,52%
2	5.2	12.50	3.193	3.187	3.173	3.141	1,63%
3	3.2	12.92	3.286	3.270	3.248	3.272	1,16%
4	4.3	12.85	3.274	3.271	3.286	3.274	0,46%
5	3.1	12.90	3.232	3.230	3.210	3.227	0,68%

From a system perspective, the implementation of BMS significantly improves charging reliability compared to conventional systems without cell-level monitoring. In non-BMS systems, charging control is based solely on total pack voltage, which may mask internal cell imbalances. As a result, certain cells may experience overcharging while others remain undercharged, leading to accelerated degradation and reduced battery lifespan.

Furthermore, the ability of the BMS to maintain voltage deviation below 2% demonstrates its effectiveness in enhancing battery safety and performance. Balanced cell voltages contribute to improved energy utilization, reduced thermal stress, and extended cycle life. The results also confirm that the adaptive charging control integrated with the BMS operates effectively under varying current conditions.

Overall, the experimental findings validate that the proposed BMS design achieves stable and balanced charging performance, making it suitable for solar PV-based energy storage applications.

4. CONCLUSION

This study presents the design and optimization of a Battery Management System (BMS) to enhance battery charging performance in solar photovoltaic (PV) systems by integrating a PV module, DC–DC charger controller, and lithium-ion battery with cell-level monitoring. The experimental results show that the proposed BMS effectively maintains voltage balance among battery cells, with voltage deviations ranging from 0.46% to 1.63% and an average below 2%, indicating good balancing performance under varying charging currents. The implementation of adaptive charging control based on real-time parameters such as state of charge (SOC), voltage, and temperature improves energy utilization compared to conventional methods while ensuring safe operation through protection against overcharge, overdischarge, and thermal stress. Overall, the proposed system demonstrates stable, efficient, and reliable performance, confirming that the integration of BMS significantly enhances charging efficiency, battery safety, and lifespan in solar PV-based energy storage applications.

References

- [1] International Energy Agency, Trends in Photovoltaic Applications 2023, Paris, France: IEA, 2023.
- [2] M. Mahmoud, A. Ramadan, and H. Ali, “Renewable energy integration trends and challenges,” *Renewable Energy*, vol. 190, pp. 123–135, 2022.
- [3] M. G. Osman, A. M. Hasan, and S. R. Fahmy, “Analysis of photovoltaic systems with battery storage and smart energy management,” *Sustainability*, vol. 17, no. 9, pp. 1–18, 2025.
- [4] S. Islam, M. R. Ahmed, and M. A. Hannan, “Optimized energy management of solar battery microgrids,” *Journal of Energy Storage*, vol. 72, pp. 1–12, 2024.
- [5] D. Stoica, R. Andrei, and C. Marinescu, “Exploring optimal charging strategies for photovoltaic battery systems,” *Batteries*, vol. 9, no. 9, pp. 1–15, 2023.
- [6] A. Khalid, M. Saeed, and F. Khan, “Battery charging optimization techniques for solar energy systems,” *Energies*, vol. 15, no. 10, pp. 1–20, 2022.
- [7] H. Z. Butt and X. Li, “Modeling of constant current–constant voltage charging in photovoltaic systems,” 2025.
- [8] A. Bermúdez and I. Padín, “Optimal control of photovoltaic systems with battery storage,” 2025.
- [9] J. Vetter, P. Novák, M. R. Wagner, C. Veit, and K. C. Möller, “Ageing mechanisms in lithium-ion batteries,” *Journal of Power Sources*, vol. 147, no. 1–2, pp. 269–281, 2020.
- [10] H. Z. Butt and X. Li, “Battery degradation modeling for energy storage systems,” 2025.
- [11] G. L. Plett, *Battery Management Systems, Volume I: Battery Modeling*,

Norwood, MA, USA: Artech House, 2021.

- [12] F. Aksan, M. Demir, and E. Kaya, "Artificial intelligence-based battery management systems: A review," *Energies*, vol. 17, no. 11, pp. 1–22, 2024.
- [13] L. Ullner, T. Schmidt, and P. Becker, "Deep reinforcement learning for photovoltaic-battery energy management systems," 2025.
- [14] H. Alhumade, M. Alshammari, and A. Alqahtani, "Advanced energy management strategies for hybrid renewable energy systems," *Sensors*, vol. 23, no. 4, pp. 1–18, 2023.
- [15] Y. Zhang, X. Liu, and Z. Wang, "Forecast-based battery charging strategy for photovoltaic systems," 2025.
- [16] M. Mahmoud, A. Ramadan, and H. Ali, "Optimization of hybrid photovoltaic-battery systems," *Renewable Energy*, vol. 195, pp. 456–468, 2022.

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