Optimization of Battery Charging and Discharging in Hybrid Power Generation Systems

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Abstract : The increasing global demand for energy and the need for sustainable power generation have accelerated the integration of renewable sources such as solar and wind into hybrid power systems. However, the intermittent nature of these sources leads to instability in the charging and discharging cycles of energy storage units, primarily batteries. This study focuses on optimizing the charging and discharging processes of lithium-based batteries in a hybrid renewable energy system (solar–wind) using an intelligent Battery Management System (BMS) integrated with a Maximum Power Point Tracking (MPPT) solar charge controller and Low Voltage Disconnect (LVD) protection. The research involves prototype implementation consisting of four 3.3 V, 20 Ah $LiFePO_4$ cells configured in series (12.9 V total) and a 300 Wp photovoltaic module. Experimental results show that the developed BMS effectively balances cell voltages and prevents overcharging or overdischarging. During charging tests, voltage deviation among cells was maintained within 0.46%–1.63%, while in discharging tests, deviation remained below 2.61%, indicating stable and balanced performance. The integration of MPPT and LVD controllers improved overall energy conversion efficiency and prevented deep discharge damage, enhancing battery lifespan and system reliability. The study concludes that optimal battery management significantly improves hybrid system performance, ensuring efficient renewable energy utilization for off-grid or standalone power applications.

Keywords: Battery Management System (BMS), hybrid energy system, charging optimization, renewable energy, MPPT, LVD, $LiFePO_4$.

1. INTRODUCTION

The rapid escalation of global energy demand over the past several decades has intensified the pursuit of sustainable and environmentally friendly energy solutions. Renewable energy sources—such as solar, wind, and biomass—have become increasingly attractive due to their abundant availability and low environmental impact. However, the inherent intermittency and variability of renewable energy outputs remain major challenges to ensuring power system reliability, particularly when supply patterns do not align with dynamic load demands [1], [2]. This mismatch frequently

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results in voltage fluctuations, frequency instability, and difficulty in maintaining continuous power delivery, especially in remote or off-grid regions.

To address these operational challenges, hybrid renewable energy systems (HRES) or hybrid power generation systems have emerged as a promising solution. By integrating multiple renewable sources—typically photovoltaic (PV) and wind turbines—alongside energy storage systems (ESS), hybrid configurations can exploit complementary energy profiles and enhance the overall reliability of electricity supply [3], [4]. Within such systems, the battery energy storage system (BESS) plays a vital role as an energy buffer, smoothing out fluctuations and maintaining balance between supply and demand. Consequently, the performance, longevity, and efficiency of the entire hybrid system are strongly influenced by how the battery is charged and discharged [5].

Improper battery management, including overcharging, over-discharging, and high-rate cycling, can accelerate degradation, reduce State of Health (SOH), and decrease effective storage capacity [6], [7]. These issues not only undermine system efficiency but also increase operational costs due to frequent battery replacement. Therefore, advanced energy management strategies are essential for optimizing charging and discharging processes and ensuring that battery operation remains within safe, efficient boundaries. Key parameters such as State of Charge (SOC), SOH, temperature, and current must be continuously monitored to prevent degradation and extend the lifespan of energy storage assets [8].

Recent advancements in optimization algorithms and intelligent control systems have opened new opportunities for improving hybrid system performance. Approaches such as fuzzy logic controllers, genetic algorithms, model predictive control, and machine-learning-based forecasting models have shown significant potential for enhancing energy dispatch, predicting renewable generation patterns, and optimizing battery scheduling [9], [10]. Furthermore, the integration of Internet of Things (IoT) and distributed sensor networks enables real-time monitoring and communication, facilitating smarter and more adaptive energy management frameworks.

Given these developments, optimizing the charging and discharging strategy of batteries within hybrid renewable systems is essential to maximizing renewable energy utilization, advancing system reliability, and lowering lifecycle costs. This study aims to develop a comprehensive optimization strategy that enhances energy use efficiency, extends battery lifetime, and ensures stable power delivery, ultimately contributing to reliable and economically viable hybrid renewable energy solutions suitable for remote and underserved regions.

2. METHODOLOGY

The initial phase of this research involved identifying the primary issues within the Hybrid Renewable Energy System (HRES), particularly those associated with battery management. Observations on the existing system revealed that the charging and discharging processes were not yet operating at optimal levels, resulting in decreased overall system efficiency and potential degradation of battery performance. This problem identification stage served as the foundation for determining the necessary optimization approach. Following this, a comprehensive literature study was conducted to review theoretical concepts and previous work related to hybrid power systems, battery management systems (BMS), charging–discharging strategies, and optimization techniques. The literature review established a scientific basis for designing an improved battery management strategy and provided insights into suitable control algorithms and system architectures relevant to the study.

Subsequently, the design phase focused on developing the battery system architecture tailored for HRES applications. This included determining battery configuration, selecting appropriate charging and discharging methods, and defining control algorithms for energy flow management. The system architecture was iteratively refined based on technical requirements, initial simulation results, and performance specifications to ensure compatibility with the power demand of the hybrid system. Once the design was validated, the implementation phase began with the construction of a functional prototype. Hardware components were assembled, integrated with the control system, and embedded with the proposed battery management algorithm. Any discrepancies encountered during implementation were resolved through iterative modifications to guarantee proper system operation.

The next stage involved conducting charging and discharging experiments to evaluate system performance under real operating conditions. Tests were performed to assess charging of the battery from hybrid renewable sources—solar photovoltaic panels and wind turbines—as well as discharging behavior under predetermined load conditions. Key parameters, including voltage, current, capacity, efficiency, and cycle time, were recorded to assess the dynamic response of the battery system. When test results did not meet the targeted performance criteria, further adjustments were applied to the implementation to achieve optimal functionality. Finally, data obtained from the experiments were analyzed to determine the degree of improvement provided by the optimization method. Performance before and after optimization was compared in terms of energy efficiency, battery durability, and power supply stability. The analysis established the effectiveness of the proposed strategy in enhancing battery operation and improving the overall reliability of the hybrid renewable energy system.

3. DISCUSSION

a. System Design

The design of the Battery Management System (BMS) for mitigating voltage drop in the solar-powered training vessel was developed using a prototype-based approach. The onboard renewable energy supply is generated by a 300 Wp solar panel, while the storage system consists of four 20 Ah batteries connected at a nominal voltage of 12 V. The overall BMS architecture is illustrated in the system block diagram, which outlines the interaction between the solar energy source, charge controller, battery pack, and BMS unit. In this configuration, electrical energy produced by the solar panel is delivered as a direct current (DC) output, which is first routed through a charge controller before entering the battery system. The charge controller functions to regulate the voltage and ensure that the electrical characteristics match the requirements of the battery pack, thereby preventing inappropriate charging conditions and protecting the battery from damage.

Once the voltage and current have been conditioned by the charge controller, the electrical energy is directed to the battery through the BMS. The BMS plays a critical role in balancing the charging process across individual battery cells to prevent overcharging, excessive discharging, and voltage imbalances that could otherwise occur due to varying cell characteristics. In addition to managing cell voltage, the BMS continuously monitors temperature at each battery cell, allowing the system to detect abnormal heating conditions. If any cell exhibits overheating, the BMS initiates corrective action by isolating the affected cell or interrupting the charging and discharging process to maintain operational safety and prevent thermal damage.

The BMS also controls the discharge process when electrical energy is drawn from the battery to supply onboard loads. During discharge, the system monitors the real-time voltage and temperature of each cell, ensuring that all cells remain within safe operating limits and that no individual cell experiences excessive voltage drop. This continuous monitoring enables the BMS to maintain uniform energy distribution and protect the battery pack from degradation caused by electrical stress or thermal instability. Through these integrated control and protection mechanisms, the designed BMS enhances the reliability of the energy storage system, mitigates voltage drop issues, and ensures stable power availability for the solar-powered training vessel.

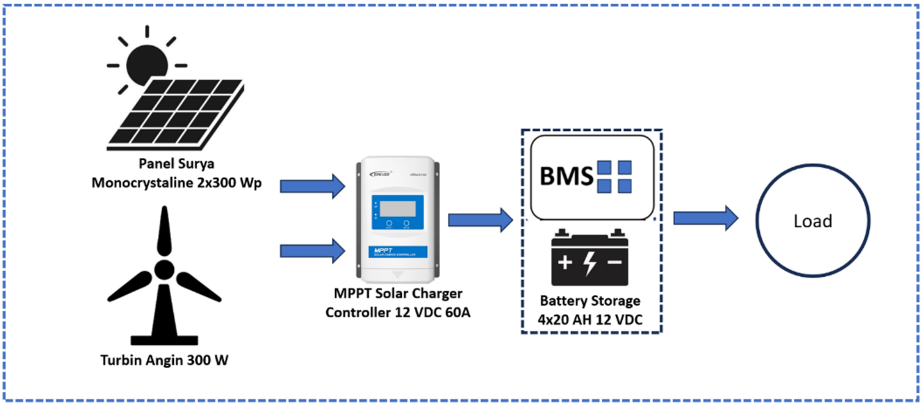


Figure 1. Diagram block BMS and HRES

The design of the Battery Management System (BMS) was carried out to ensure that the system operates in accordance with the required specifications as in figure 1. In this stage, the number of batteries, their individual capacities, and the appropriate type of BMS were determined to ensure compatibility with the intended operational needs. The energy storage system consists of four battery units, each with a capacity of 20 Ah and a nominal cell voltage of 3.3 V. The batteries are connected in series to form a single pack, resulting in a total output voltage of approximately 12.9 V while maintaining the same capacity of 20 Ah. The series configuration allows the individual cell voltages to be summed directly, providing the required operating voltage for the system.

The BMS architecture includes multiple monitoring and control pins that interface with each battery cell. The B- pin is connected to the negative terminal of the entire series battery pack, serving as the reference point for system grounding and cell monitoring. Pin B1 is connected to the positive terminal of the first battery cell and is responsible for measuring and regulating the voltage of Cell 1. Pin B2 is connected to the positive terminal of the second cell to monitor its voltage condition, while pins B3 and B4 are connected to the positive terminals of Cells 3 and 4, respectively, to provide continuous voltage monitoring for these cells. By assigning dedicated pins to each cell, the BMS is able to balance the charging and discharging processes across the battery pack, prevent overvoltage or undervoltage events, and maintain stable operation of the energy storage system, as in figure 2.

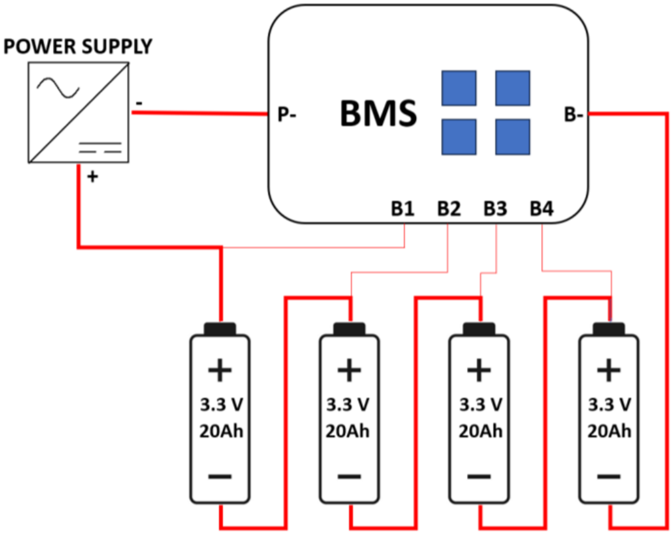


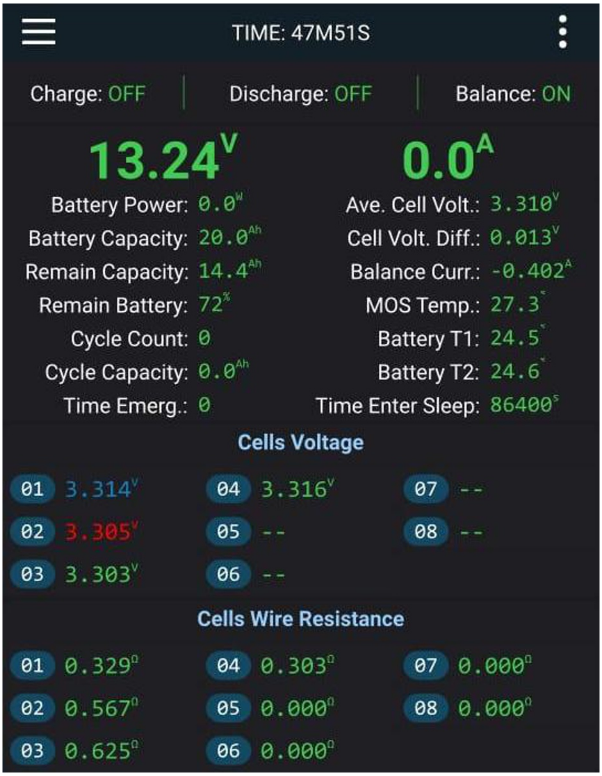
Figure 2. BMS system design

b. Implementation

The implementation phase was carried out after the system design was validated and deemed suitable for operational requirements. During this stage, the planned design was translated into a functional system, with the objective of enabling the Battery Management System (BMS) to operate as intended. The implementation began with the assembly of the battery pack using four cylindrical battery cells, each rated at 20 Ah with a nominal voltage of 3.3 V. These four cells were connected in a series configuration, resulting in a total output voltage of approximately 12 V while maintaining a constant current capacity. The series arrangement was selected since it increases the overall voltage by summing individual cell voltages while keeping the current unchanged, thereby meeting the voltage requirements of the system.

The BMS implementation employed a Jikong JK-BD4A8S-4P module, which serves as the core component for monitoring and regulating the battery pack. In the assembled configuration, the negative terminal of the battery series was connected to the B- pin of the BMS module. The P- pin was connected to the negative terminal of either the power source or the load, depending on the operating condition. The B+ pin of the BMS was connected to the positive terminal of the battery pack and paralleled with the positive terminal of the input power source or load. Each positive terminal of the individual battery cells was then connected to the corresponding B1, B2, B3, and B4 pins on the BMS module. This connection scheme enables the module to perform real-time monitoring and balancing of the voltage across each cell, ensuring uniform energy distribution during charging and discharging.

In addition to voltage monitoring, the BMS module was equipped with a temperature sensor to track the thermal condition of the battery pack. This feature enables the system to detect excessive temperature rise, which could potentially damage the cells. In such cases, the BMS automatically intervenes by disconnecting charging or discharging currents to prevent thermal runaway and preserve battery integrity. The implemented BMS system also incorporates wireless communication capabilities, allowing operational data to be transmitted to the user's mobile device via Bluetooth. The displayed information includes the total series voltage, individual cell voltages, battery temperature, and additional safety-related parameters, providing comprehensive visibility into the operational state of the battery system, as in figure 3.



TIME: 47M51S

Charge: OFF | Discharge: OFF | Balance: ON

13.24^{V} 0.0^{A}

Battery Power: 0.0^{W}
Battery Capacity: 20.0^{Ah}
Remain Capacity: 14.4^{Ah}
Remain Battery: 72$^{\%}$
Cycle Count: 0
Cycle Capacity: 0.0^{Ah}
Time Emerg.: 0

Ave. Cell Volt.: 3.310^{V}
Cell Volt. Diff.: 0.013^{V}
Balance Curr.: -0.402^{A}
MOS Temp.: 27.3°
Battery T1: 24.5°
Battery T2: 24.6°
Time Enter Sleep: 86400^{s}

Cells Voltage

01	3.314^{V}	04	3.316^{V}	07	--
02	3.305^{V}	05	--	08	--
03	3.303^{V}	06	--		

Cells Wire Resistance

01	0.329$^{\Omega}$	04	0.303$^{\Omega}$	07	0.000$^{\Omega}$
02	0.567$^{\Omega}$	05	0.000$^{\Omega}$	08	0.000$^{\Omega}$
03	0.625$^{\Omega}$	06	0.000$^{\Omega}$		

Figure 3. BMS implementation reading results

c. analysis

The analysis of the battery charging process was conducted to evaluate whether the Battery Management System (BMS) operated according to the expected performance criteria. A key indicator of proper BMS functionality is its ability to regulate and balance the voltage of each battery cell to ensure that the voltage difference between cells remains minimal. During the testing phase, several charging scenarios were executed using different input current levels as predefined in the experimental setup. These variations allowed assessment of the BMS's response to fluctuating charging conditions and its capability to maintain voltage uniformity across the battery pack.

Based on experimental data, the voltage of each battery cell was recorded throughout the charging process. The collected values were tabulated to determine the highest and lowest voltage for each cell, followed by calculating the percentage difference between them. Analysis of the recorded data shows that the minimum voltage deviation among the batteries was 0.46%, while the maximum deviation reached 1.63%. Overall, the average voltage difference among cells remained below 2%, demonstrating that the BMS successfully maintained balanced cell voltages during charging. This result confirms that the BMS effectively minimizes voltage imbalance, which is critical for preventing overcharging and ensuring uniform energy distribution.

During charging, the BMS continuously monitors the condition of each battery cell. If a significant voltage discrepancy is detected, the system actively redistributes energy by limiting charging to the cell with the highest voltage while allowing additional charging current to flow to cells with lower voltages. This balancing mechanism ensures that all cells reach an equal voltage level by the end of the charging cycle. If the BMS were not functioning properly, the system would only measure the total series voltage without recognizing individual cell imbalances. In such a case, an overvoltage in one cell could cause the system to prematurely interpret the entire battery pack as fully charged, thereby preventing optimal charging and reducing overall battery performance. The observed results confirm that the implemented BMS performs its balancing and monitoring functions effectively, contributing to improved charging efficiency and battery safety, as in table 1.

Table 1. Voltage between batteries in discharge condition

No	Discharge (Amperes)	Total Battery Voltage (Volts)	Voltage per Cell (Volt)				Difference between highest and lowest voltage
			Cell 1	Cell 2	Cell 3	Cell 4	
1	3.1	13.068	3.253	3.279	3.263	3.273	0,79%
2	3.9	12.931	3.258	3.249	3.251	3.173	2,61%
3	3.6	12.911	3.264	3.228	3.235	3.184	2,45%
4	3.9	13.051	3.262	3.271	3.269	3.249	0,67%

5	2.0	13.099	3.301	3.286	3.270	3.242	1,79%

4. CONCLUSION

Based on the results of this research, it can be concluded that the charging and discharging performance of batteries in a renewable energy–based power system is highly influenced by variations in energy sources as well as the characteristics of the connected electrical loads. Fluctuations in solar irradiation directly affect the output voltage and current of the photovoltaic panels, thereby determining the rate at which the battery is charged. Higher irradiation levels increase charging current and accelerate the charging process, while lower irradiation reduces current flow and prolongs charging duration. These findings demonstrate that the stability of renewable energy input plays a crucial role in maintaining balanced battery charging and discharging cycles, which are essential for ensuring the reliability and efficiency of the overall energy storage system.

The observations also show that varying load conditions significantly impact the battery's discharge behavior. Under high-load conditions, battery voltage drops more rapidly, whereas light-load conditions allow the battery to retain its stored energy for a longer period. This highlights the importance of effective load management to preserve battery lifespan and operational efficiency. Continuous exposure to excessive load can accelerate deep discharge events and negatively affect system performance. Overall, the study confirms that both renewable energy variability and load dynamics must be carefully managed to optimize battery operation and enhance the performance of hybrid or stand-alone renewable energy systems.

References

[1] M. J. Khan, M. T. Iqbal, and H. Qu, "Analysis of renewable energy based hybrid energy system for a remote area in Newfoundland," IEEE Access, vol. 7, pp. 174584–174593, 2019.

[2] X. Luo, J. Wang, M. Dooner, and J. Clarke, "Overview of current development in electrical energy storage technologies and the application potential in power system operation," Applied Energy, vol. 137, pp. 511–536, 2015.

[3] H. Lund, P. A. Østergaard, D. Connolly, and B. V. Mathiesen, "Smart energy and smart energy systems," Energy, vol. 137, pp. 556–565, 2017.

[4] A. Khalid, H. Shareef, M. S. Ahmed, and U. Khan, "A review on optimization methods for hybrid renewable energy systems," Int. J. Energy Research, vol. 43, no. 13, pp. 6599–6632, 2019.

[5] M. Y. Suberu, M. W. Mustafa, and N. Bashir, "Energy storage systems for renewable energy power sector integration and mitigation of intermittency," Renew. Sustain. Energy Rev., vol. 35, pp. 499–514, 2014.

[6] D. Anseán et al., "Fast charging technique for high power lithium iron phosphate batteries: A cycle life analysis," Appl. Energy, vol. 160, pp. 484–495, 2015.

[7] K. Shah, K. W. E. Cheng, and B. K. T. Ho, "Battery management system for electric vehicle applications," Energy Procedia, vol. 75, pp. 1920–1925, 2015.

[8] M. Dubarry, N. Vuillaume, and B. Y. Liaw, "From single cell model to battery pack simulation for Li-ion batteries," J. Power Sources, vol. 186, pp. 500–507, 2009.

[9] S. B. Kjaer, J. K. Pedersen, and F. Blaabjerg, "A review of single-phase grid-connected inverters for photovoltaic modules," IEEE Trans. Ind. Appl., vol. 41, no. 5, pp. 1292–1306, 2005.

[10] Q. Shafiee, V. K. Sood, and P. W. Lehn, "Energy management in modern power systems: A review of forecasting and optimization approaches," Electric Power Systems Research, vol. 192, 2021.