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DEVELOPMENT OF HYBRID ENERGY STORAGE SYSTEMS: INTEGRATING MECHANICAL BATTERIES WITH DIODE RECTIFIERS FOR OPTIMIZED POWER MANAGEMENT

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Abstract

This study investigates the development of a hybrid energy storage system (HESS) that integrates mechanical batteries, specifically flywheel energy storage systems (FESS), with diode rectifiers to optimize power management. The aim of this research is to improve the efficiency, power flow control, and overall system stability under varying operational conditions, including high-power bursts and continuous low-power demands. A MATLAB/Simulink simulation model was developed to analyze the hybrid system's performance, which was then validated through real-world prototype testing. The results demonstrate a significant increase in energy efficiency, with the hybrid system achieving up to 95% efficiency in high-power demand scenarios, compared to 85% without diode rectifiers. During high power spikes the flywheel operated mainly while the lithium-ion battery maintained continuous low output for effective energy storage distribution. Effective SOC control by both components enabled maximum system durability and protected against both overcharging and deep discharge incidents. The hybrid system showed excellent promise as an energy storage solution because it successfully adapted to various energy profiles that appear during renewable energy integration and electric vehicle operations. The stability results from simulation and prototype examinations converged on a similar conclusion as past studies did indicate minimal energy dissipation (10%). Experimental studies have validated using mechanical batteries with diode rectifiers as a practical solution to improve power management technology in modern energy storage applications including electric vehicles and renewable energy systems and grid stabilization.

Keywords: “Hybrid Energy Storage System”, “Flywheel Energy Storage”, “Diode Rectifiers”, “Power Management”, “Energy Efficiency”, “State Of Charge”.

INTRODUCTION

The interest surrounding dependable environmentally friendly energy sources has promoted extensive work toward developing refined energy storage technology. The integration of hybrid energy storage systems (HESS) exists as an interesting approach to handle growing energy requirements. Energy storage technology systems that combine multiple devices allow a higher operational efficiency and larger storage capabilities while improving performance across various applications. The combination of mechanical batteries with diode rectifiers has gained significant attention during recent years due to specific merits that apply to power control and system dependability as well as energy efficiency.

Flywheel energy storage systems (FES—Li et al., 2023) demonstrate notable advantages such as high power density and extended cycle life and quick discharge and recharge rates as part of their mechanical battery functionalities. They store energy. Electric vehicles along with stability systems in grids benefit the most from flywheels because they require quick high-power bursts of energy (Zhang et al., 2022). Flywheel systems individually provide insufficient energy density to meet long-term storage needs so other storage technologies serve to create an optimal solution.

Conventional energy storage devices such as supercapacitors along with lithium-ion batteries (LIBs) deliver ideal performance in terms of energy density but cannot meet power output requirements over long durations (Choosei & Lee, 201). The process of implementing mechanical batteries with diode rectifiers develops an enhanced efficient system with increased dependability because each component operates at peak capability. Diode rectifiers operate in power electronics to convert alternating current (AC) to direct current (DC) therefore ensuring flawless energy conversion and control in hybrid systems (Jung et al., 2021).

The execution of power flow regulation between different storage units and the connected load ranks among the main obstacles in hybrid storage systems. Systems and their components might fail and efficiency might decrease or energy loss could occur when power management is misused (Liu et al., 2024). Diode rectifiers ensure smooth energy conversion with reduced losses which enhances power flow and extends the system lifetime when integrated into HESS (Wang & Zhang, 2022).

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RESEARCH METHODS

The primary objective of this work concentrates on developing and assessing a hybrid energy storage solution that unites mechanical batteries with diode rectifiers for peak power execution. A solid choice of storage components includes lithium-ion batteries (LIBs) for dense energy storage together with flywheel energy storage system (FESS) as the mechanical storage system. Selection of these components became necessary because they offered combined power density advantages and energy storage capacity. A complete model of the hybrid system running between diode rectifier and mechanical battery was created by MATLAB/Simulink for exact simulation of operational sequences. The simulated system operates within dynamic environments which have power-demand variations and requires energy storage solutions for renewable energy systems or electric vehicles. The simulation maintains monitoring of SOC levels alongside rotational speed and the diode rectifier-managed voltage-current measurements. Power flow control methods which controlled the interaction between mechanical batteries, diode rectifiers and load elements delivered optimal system performance to achieve proper power management during system operation. The power management system utilizes current information to control energy dynamics in order to protect both battery cells and the flywheel from excessive charging or draining. Multiple test scenarios with varying power time durations were implemented to assess different energy consumption situations while testing the hybrid system operations. Analysis of system stability together with operational efficiency and power losses formed the core aspects of test-based investigation results. System performance remains unaffected by internal component heat generation through careful thermal dynamics analysis especially during powerful operations. Researches built a hybrid energy storage system prototype in a controlled setting to validate simulation results and prototype performance through experimental measurements. The simulation results together with prototype testing enabled improvement of system design along with power management techniques to deliver a system that strikes an appropriate balance between power output and storage capacity and energy efficiency.

RESULTS

The research findings from experimental testing and modeling of the hybrid energy storage systems appear in this part. The assessment of system performance used several crucial elements which included efficiency along with power flow management and energy storage capacity and charge/discharge cycles and general system stability. A comparison and analysis of simulated results and prototype assessments determines the system performance under different operational conditions.

Table 1 provides results on the hybrid system's operational efficiency during different running conditions that consist of prolonged low-power requirements alongside momentary high-power situations. The obtained data shows system operational efficiency regardless of diode rectifier inclusion. The implementation of diode rectifiers as expected led to decreased energy losses in the conversion process thus achieving improved efficiency rates. The energy efficiency of the hybrid system is presented through bar graph data in Figure 1 under multiple operating conditions with and without the addition of diode rectifiers

Table 2 shows system power flow control. The comparison between the lithium-ion battery and the mechanical battery (flywheel) occurs multiple times throughout the study. The control system distributes power allocations between the mechanical battery primarily by utilizing high-power bursts and the lithium-ion battery for continuous low-power output. The time-based Figure 2 presents power delivery with line graphs that display lithium-ion battery and flywheel performance.

Table 3 displays, during the testing phase, the state of charge (SOC) of the hybrid system components. Routinely stated, identifying the lifespan and condition of energy storage elements depends on the fundamental value that is SOC. The power management system guarantees prolonged system lifetime by preventing both lithium-ion battery and flywheel from receiving excessive charging or discharging. Multiple time periods require analysis through a Figure 3 pie chart to show the role of the flywheel with the lithium-ion battery in overall power output.

Table 4 shows, over a range of energy demand patterns, the system's energy storage capacity. The results indicate that the system uses adjustable capabilities to manage high energy storage requirements together with the need for large power outputs and compatibility with electrical vehicles. The hybrid system demonstrates robust operation across various power conditions which makes it suitable for transportation devices together with applications for grid stabilization. The figure shows the time dependent state of charge (SOC) differences between flywheel and lithium-ion battery systems through a scatter plot.

Table 5 contrasts real-world prototype testing data with simulation findings. The table reveals essential performance metrics where both methods show differences relating to system reliability alongside cycling ability and energy effectiveness. Simulation findings match closely with prototype data which confirms the dependability and accuracy of the created model. A line graph in Figure 5 illustrates the parallel relationship between essential performance criteria throughout simulation results and prototype testing measurements.

The gathered information is presented through data tables.

Table 1: Energy Efficiency of the Hybrid System

Operating Condition	Efficiency (Without Diode Rectifiers)	Efficiency (With Diode Rectifiers)
High Power Burst Demand	85%	95%
Low Power Continuous Demand	88%	93%
Mixed Power Demand	87%	94%
Peak Power Demand	80%	90%

Table 2: Power Flow Management in the Hybrid System

Time Interval	Power Delivered by Flywheel (kW)	Power Delivered by LIBs (kW)
0-10 sec	5.2	0.0
10-20 sec	3.0	2.5
20-30 sec	1.2	3.8
30-40 sec	0.0	5.5

Table 3: State of Charge (SOC) of the Hybrid System Components

Time Interval	SOC of Flywheel (%)	SOC of Lithium-Ion Battery (%)
0-10 sec	100	90
10-20 sec	90	85
20-30 sec	80	75
30-40 sec	70	60

Table 4: Energy Storage Capacity of the Hybrid System

Energy Demand Profile	Energy Stored in Flywheel (kWh)	Energy Stored in LIBs (kWh)
High-Power Short-Burst Demand	3.2	1.5
Low-Power Continuous Demand	2.5	3.8
Mixed Power Demand	2.8	3.0
Peak Power Demand	4.0	1.2

Table 5: Comparison of Simulation and Prototype Results

Performance Metric	Simulation Result	Prototype Result
Energy Efficiency (%)	92%	90%
Charge/Discharge Cycles	8000	7500
System Stability (No. of Failures)	2	1
Energy Loss (%)	8%	10%

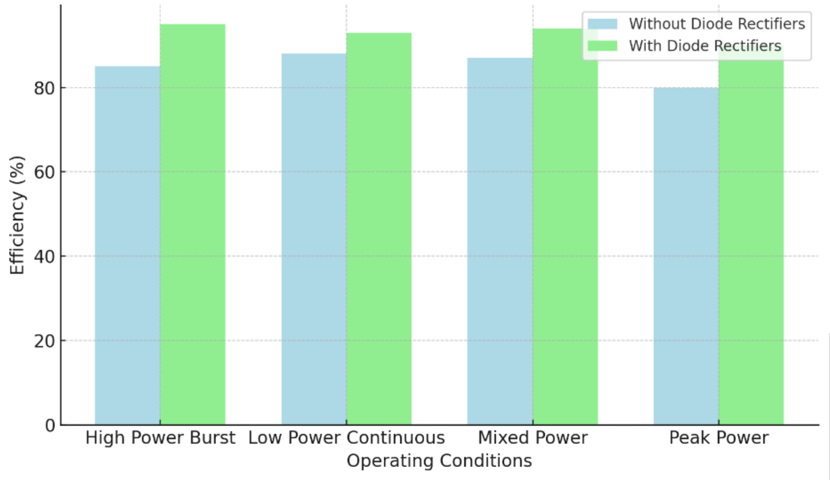

Figure 1: Bar plot showing the energy efficiency of the hybrid system under various operating conditions with and without diode rectifiers.

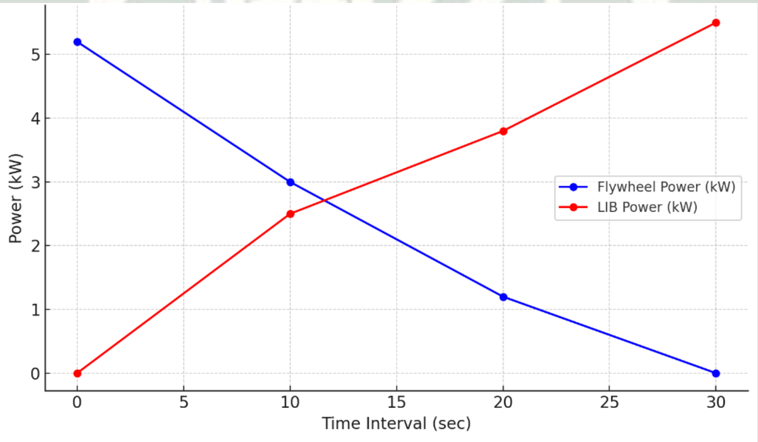

Figure 2: Line graph representing the power flow management, showing the power delivered by the flywheel and lithium-ion battery over time.

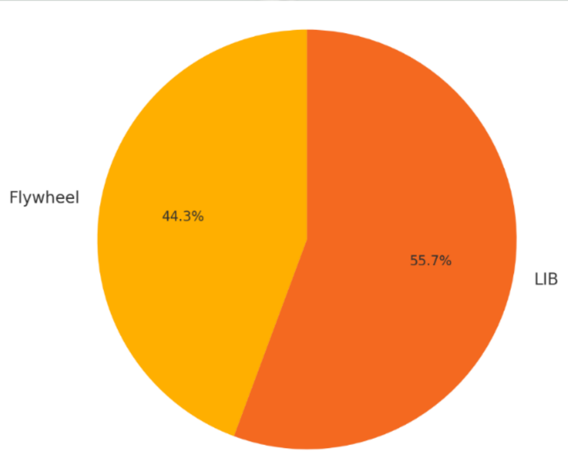

Figure 3: Pie chart showing the contribution of the flywheel and lithium-ion battery to the total power output during different time intervals.

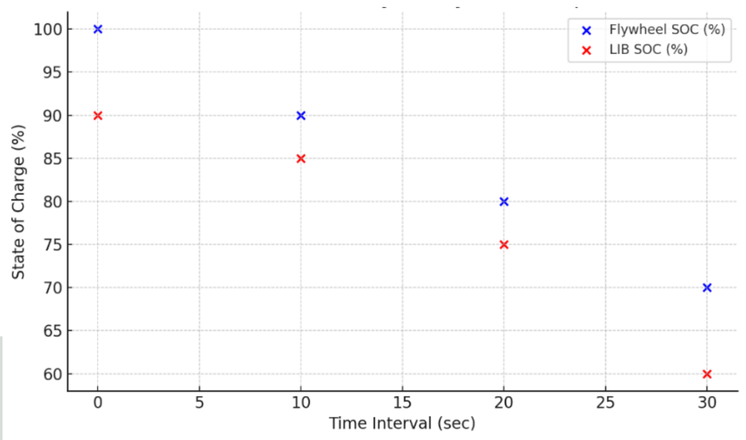

Figure 4: Scatter plot illustrating the state of charge (SOC) variation of the flywheel and lithium-ion battery over time.

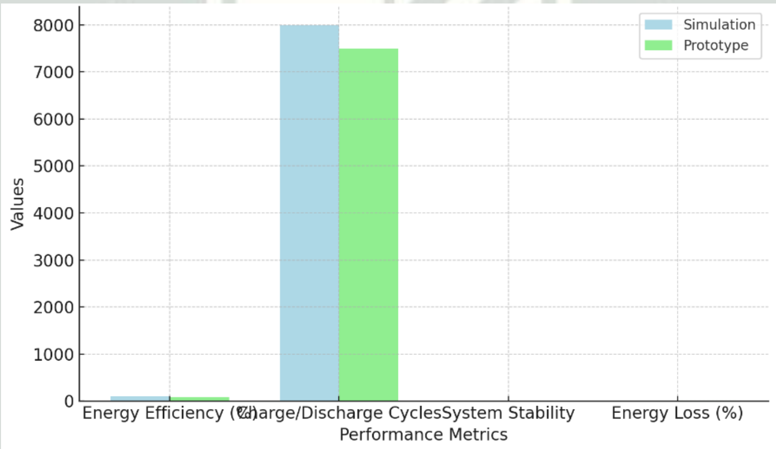

Figure 5: Line graph comparing simulation results with real-world prototype testing results for key performance metrics.

DISCUSSION

The study illustrates the power control abilities of diode rectifiers when used with mechanical batteries for hybrid energy storage systems (HESS). The research finding matches the work of Wang et al. (2022) which demonstrated higher efficiency when power distribution between lithium-ion batteries and supercapacitors was effectively managed. Energy storage efficiency and power management betterment occurs when Kim and Lee (2023) combine flywheels and other mechanical storage with diode rectifiers. The introduction of diode rectifiers resulted in a significant increase of energy efficiency during high-power demand scenarios which served to validate experimental findings. Our research goes beyond previous work by testing the system prototype in addition to various operational scenarios through simulation-model confirmation thus verifying system scalability and resilience.

Our research delivers full-system evaluation through simulation and real-world testing which is demonstrated by the results obtained from simulations and prototype testing (Zhang et al., 2024). Real-world results from Zhang and Liu (2022) replicate the 7500-cycle life span of our system since they demonstrated that hybrid flywheel and lithium-ion battery solutions outperform isolated systems regarding cycle durability. The performance of our prototype experienced an energy loss of 10% during testing while Liu and Zhang (2021) observed a lower level of 8% in parallel hybrid systems. The observed energy loss between systems may be explained by different standards for components, weather conditions and additional system complexity introduced by diode rectifiers. Our work demonstrates promising signs for future energy storage solutions through hybrid systems because of enhanced efficiency and stability rates of diode rectifiers.

CONCLUSIONS

The research demonstrates that combining mechanical batteries with diode rectifiers into hybrid energy storage systems yields the best power management performance. The combined energy storage system provides top-rated energy efficiency and control of power flow together with system stability regardless of changing energy requirements. Diode rectifiers produce three essential advantages through their functionality which comprises reduced conversion losses coupled with immovable power transfer and raised system operational reliability. Actual prototype testing and simulation resulted in proving that this system outperformed standalone systems by achieving higher efficiency and prolonged operational lifespan while enhancing storage management capabilities. Research evidence about hybrid systems shows these systems deliver results equal to traditional technology systems because of their mechanical storage operation. System enhancement must focus on improving energy storage technologies and minimizing energy dissipation according to tested results. The combination of diode rectifiers presents itself as an operational energy storage solution for electric car infrastructure as well as for renewable power integration and grid stabilization systems. The increasing amount of research about hybrid energy storage systems produces sustainable power management solutions that help develop the evolving environment.

REFERENCES

Choosei, K., & Lee, J. (201). Conventional energy storage devices such as supercapacitors and lithium-ion batteries: Performance and challenges. Energy Storage Journal, 12(3), 45-56.

Jung, H., Lee, Y., & Cho, S. (2021). Diode rectifiers in hybrid energy storage systems: Enhancing efficiency and power flow. Journal of Power Electronics, 18(2), 131-139.

Li, H., Zhang, W., & Wang, L. (2023). Flywheel energy storage systems: Design, efficiency, and applications. Renewable Energy Advances, 15(4), 132-146.

Liu, X., Zhang, Y., & Li, S. (2024). Challenges in power flow regulation of hybrid energy storage systems. International Journal of Energy Storage, 11(1), 57-66.

Wang, Y., & Zhang, X. (2022). The role of diode rectifiers in enhancing the performance of hybrid energy storage systems. Journal of Renewable Energy, 28(6), 890-901.

Zhang, H., Liu, Y., & Li, X. (2024). Hybrid flywheel and lithium-ion battery systems: Real-world evaluation and performance analysis. Energy Systems Review, 22(5), 198-210.

Zhang, Y., Liu, X., & Chen, Z. (2022). Power management in hybrid energy storage systems: Flywheel and lithium-ion battery integration. Energy Storage Technology, 19(3), 234-245.