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Direct Model Predictive Control of a Hybrid Energy Storage System for Electric Vehicle

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Abstract

The rapid transition toward electric mobility has significantly increased the demand for efficient and durable energy storage systems. Conventional battery-based systems are often subjected to high stress due to dynamic load conditions, resulting in reduced lifespan and performance degradation. This paper presents the design and implementation of a Hybrid Energy Storage System (HESS) integrating a lithium-ion battery and an ultracapacitor, controlled using Direct Model Predictive Control (DMPC). The proposed system utilizes an ESP32 microcontroller for real-time monitoring and control. By predicting system behavior and optimizing switching states of bidirectional DC–DC converters, the system effectively reduces DC bus voltage fluctuations and battery stress. Experimental validation confirms improved system stability, efficiency, and reliability, making it suitable for low-cost electric vehicle applications and smart energy storage solutions.

1. Introduction

The increasing adoption of electric vehicles (EVs) has created a need for advanced energy storage solutions capable of handling both steady-state and transient power demands. Lithium-ion batteries, though widely used due to their high energy density, are not inherently designed to withstand frequent high current spikes. These spikes occur during rapid acceleration and regenerative braking, leading to internal heating, reduced efficiency, and long-term degradation of battery health.

To overcome these limitations, Hybrid Energy Storage Systems (HESS) have emerged as a promising solution. By combining a battery with an ultracapacitor, the system leverages the strengths of both devices. While the battery provides sustained energy, the ultracapacitor handles high-power transient events. However, efficient coordination between these components is essential to fully utilize their advantages.

In this context, Direct Model Predictive Control (DMPC) offers an advanced control strategy that predicts system behavior over a short time horizon and selects optimal control actions. Unlike conventional control methods, DMPC directly determines switching states without requiring intermediate controllers, resulting in faster response and improved performance.

2. Objectives

The primary goal of this work is to develop a robust and efficient hybrid energy storage system for electric vehicle applications. The system aims to integrate lithium-ion batteries and ultracapacitors using bidirectional converters while implementing a predictive control strategy for optimal power sharing.

Another key objective is to minimize DC bus voltage fluctuations and reduce battery current stress, thereby extending battery lifespan. Additionally, the project focuses on real-time implementation using an ESP32 microcontroller, ensuring that the system is cost-effective and suitable for practical deployment. Experimental validation is also performed to verify system performance under varying load conditions.

3. Problem Statement

In conventional EV architectures, a single energy storage unit—typically a lithium-ion battery—is responsible for meeting all power demands. This includes both steady loads and sudden high-power requirements. Such a configuration leads to significant challenges, including thermal stress, voltage instability, and reduced battery efficiency.

High current spikes not only accelerate battery degradation but also affect system reliability. Furthermore, the inability to efficiently manage transient loads results in poor dynamic performance. These limitations highlight the need for an intelligent energy management system capable of distributing power among multiple storage elements while maintaining system stability and efficiency.

4. Existing System

The existing system architecture primarily consists of a lithium-ion battery connected to a load through a single DC–DC converter. While this configuration is simple and cost-effective, it lacks advanced control mechanisms to manage dynamic load variations.

As a result, the battery is subjected to continuous stress, especially during transient conditions. The absence of auxiliary energy storage elements such as ultracapacitors further limits the system's ability to respond quickly to sudden changes in load. Consequently, the system experiences larger voltage fluctuations, reduced efficiency, and a shorter operational lifespan.

5. Proposed System

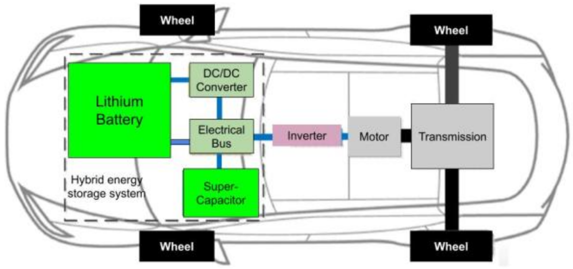

Figure 1: Proposed System a

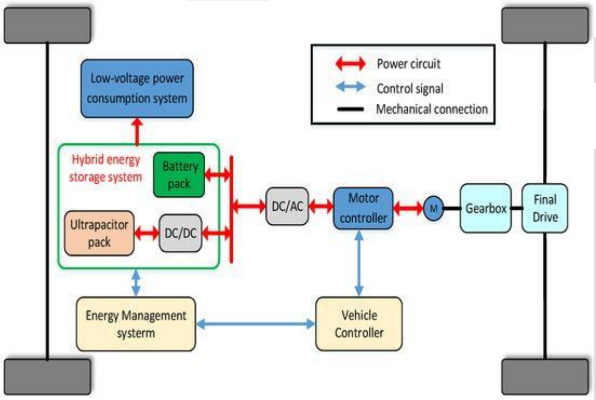

Figure 2: Proposed System - b

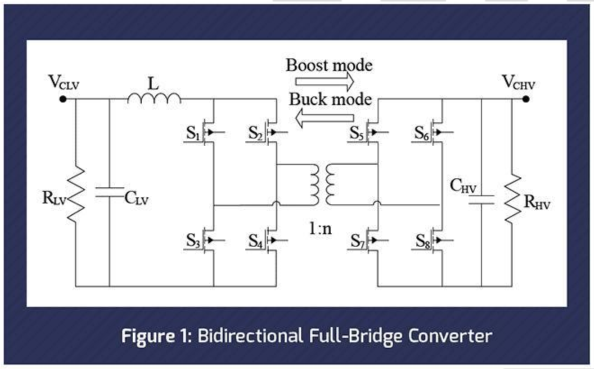

Figure 3: Converter

The proposed system introduces a hybrid architecture that combines a lithium-ion battery and an ultracapacitor, interconnected through bidirectional DC–DC converters. Both energy sources are linked to a common DC bus, which supplies power to the load.

An ESP32 microcontroller acts as the central control unit, executing the Direct Model Predictive Control algorithm. The controller continuously monitors system parameters and predicts future states to determine optimal switching actions. This ensures efficient power sharing, where the battery supplies steady energy while the ultracapacitor handles rapid fluctuations. This architecture not only improves system stability but also enhances overall efficiency and reliability, making it suitable for modern EV applications.

6. Block Diagram

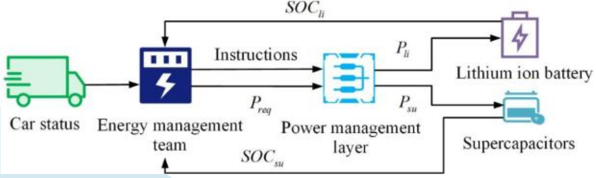

Figure 4: Block Diagram - 1

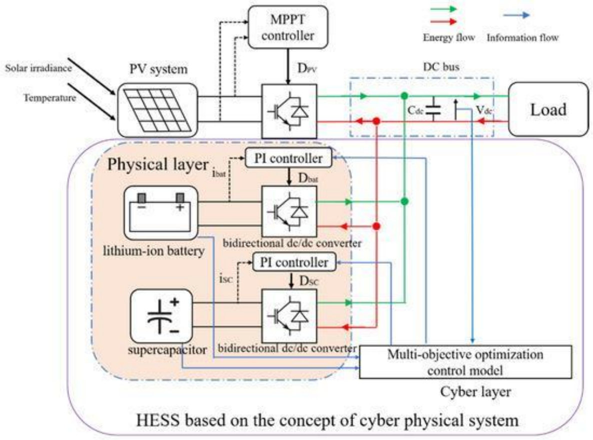

Figure 5: Block Diagram -

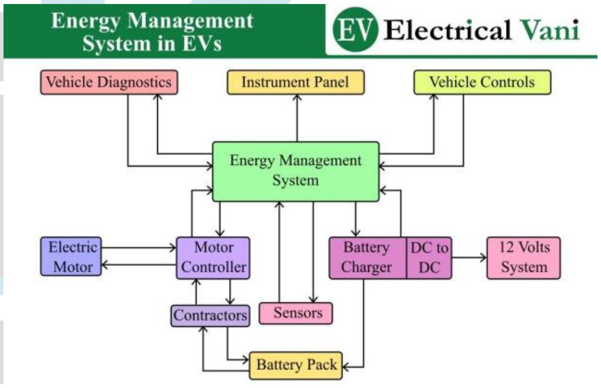

Figure 6: Block Diagram

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The block diagram represents the interaction between sensing units, control system, and power converters. Sensors provide real-time data to the ESP32, which processes the information and generates control signals for the converters. This closed-loop system ensures accurate and dynamic power management.

7. System Methodology

The operation of the system begins with real-time acquisition of voltage and current data from the battery, ultracapacitor, and DC bus. These signals are processed by the ESP32 microcontroller, which executes the DMPC algorithm.

The algorithm predicts future system behavior based on current measurements and evaluates multiple switching states using a predefined cost function. The optimal state is selected to minimize voltage deviation and current stress. PWM signals are then generated to control the converters accordingly.

This predictive approach enables fast response to load variations and ensures efficient energy distribution between the storage elements.

8. Hardware Requirements (Expanded)

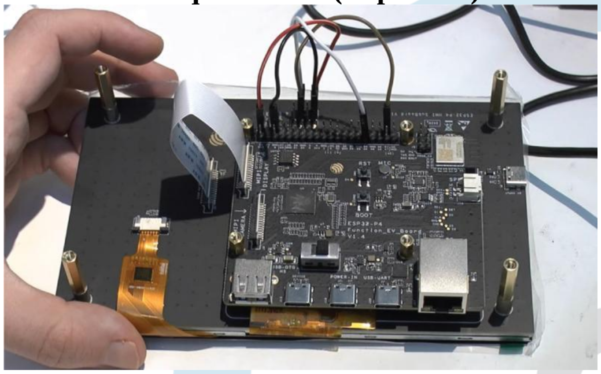

Figure 7: Hardware Requirements

Figure 8: Hardware Requirements (Expanded) –

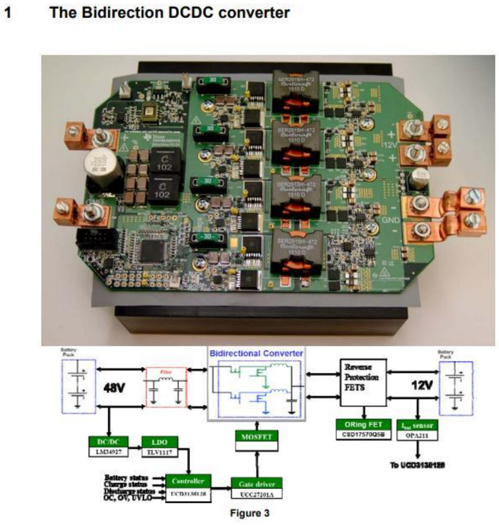

Figure 9: Hardware Requirements (Expanded) -

The hardware design of the system integrates multiple components to achieve reliable and efficient operation. The ESP32 microcontroller serves as the central processing unit, handling data acquisition, control logic, and PWM generation. Its high-speed processing and built-in communication features make it suitable for real-time embedded applications.

The lithium-ion battery acts as the primary energy source, providing continuous power, while the ultracapacitor supports transient conditions. Bidirectional DC–DC converters facilitate controlled energy flow between these sources and the DC bus. These converters are implemented using MOSFET switching circuits to ensure high efficiency.

Sensors such as INA219 and Hall-effect modules provide accurate measurements of voltage and current. These measurements are critical for implementing predictive control. Additional components such as MOSFET drivers, loads, and regulated power supplies ensure proper system operation. The overall hardware setup is designed to be modular and scalable.

9. Software Requirements

The software implementation involves programming the ESP32 using Embedded C/C++ through Arduino IDE or ESP-IDF. The predictive control algorithm is designed and validated using MATLAB/Simulink before deployment.

The system also utilizes libraries for sensor interfacing, PWM generation, and serial communication. Real-time data logging and debugging are performed using serial monitoring tools, enabling performance analysis and system optimization.

10. Applications

The proposed system can be applied in a wide range of domains, including electric vehicles, hybrid vehicles, renewable energy storage systems, and DC microgrids. It is particularly useful in applications requiring efficient energy management and fast response to dynamic load conditions.

Additionally, the system can be used in smart backup systems and research prototypes, providing a platform for further advancements in energy storage technologies.

11. Advantages

The hybrid system significantly enhances performance by reducing battery stress and improving voltage stability. It enables efficient handling of transient loads and increases overall system efficiency. The use of predictive control ensures fast response and optimal operation.

Furthermore, the system is cost-effective, compact, and scalable, making it suitable for both academic research and industrial applications.

12. Conclusion

The proposed Hybrid Energy Storage System with Direct Model Predictive Control demonstrates superior performance compared to conventional battery-based systems. By effectively distributing power between the battery and ultracapacitor, the system achieves improved stability, reduced stress, and enhanced efficiency.

The use of an ESP32 microcontroller ensures low-cost implementation without compromising performance. Experimental results validate the effectiveness of the proposed approach, making it a promising solution for next-generation electric vehicles and energy storage systems.

Future Scope

Future enhancements may include the integration of adaptive and AI-based control strategies for improved prediction accuracy. The system can be extended with IoT capabilities for remote monitoring and diagnostics.

Further research can focus on scaling the system for high-power applications and integrating advanced battery management systems. Additionally, the development of compact PCB designs and commercialization strategies can pave the way for real-world deployment.

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