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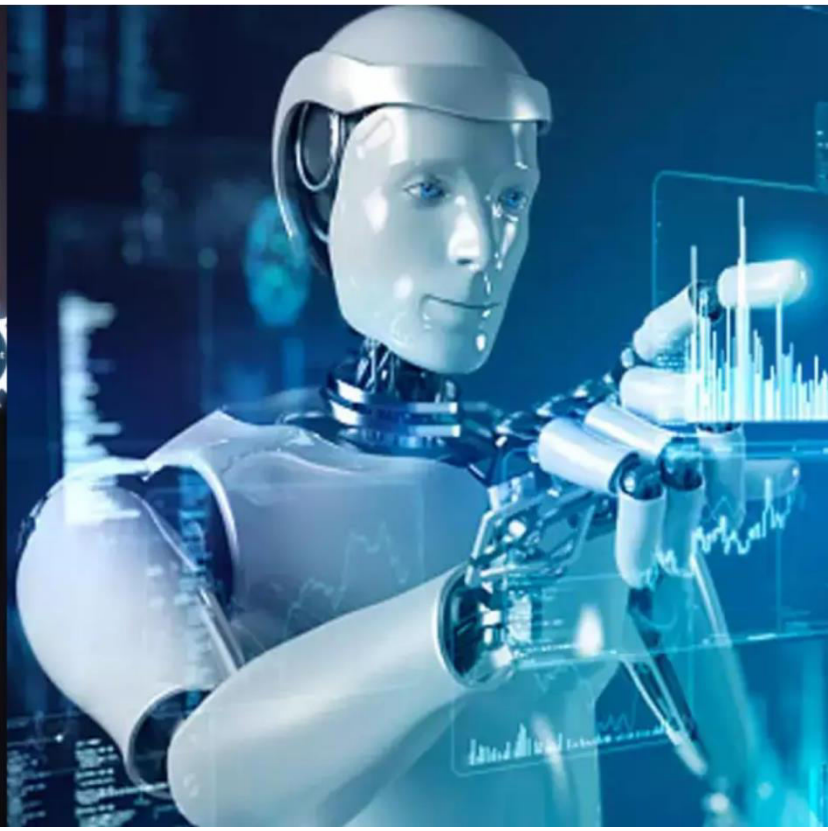
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AI-Based Adaptive Control of A Bidirectional DC–DC Converter for Electric Vehicle Energy Storage Systems

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ABSTRACT: The increasing demand for electric vehicles (EVs) has created a need for efficient, reliable, and intelligent energy management systems to improve battery performance and overall vehicle efficiency. This project proposes an AI-Based Adaptive Control of a Bidirectional DC–DC Converter for Electric Vehicle Energy Storage Systems. The proposed system utilizes a bidirectional DC–DC converter to enable efficient power transfer between the battery energy storage system and the DC bus during charging and discharging operations. Artificial Intelligence (AI)-based adaptive control techniques are implemented to dynamically adjust the converter's switching control based on real-time operating conditions, including battery voltage, current, state of charge (SOC), and load variations. Voltage and current sensors are employed to continuously monitor electrical parameters, while the AI controller analyzes the collected data to optimize power flow, maintain stable output voltage, and improve energy conversion efficiency. The system supports both buck and boost operating modes, allowing controlled battery charging and efficient energy delivery during vehicle operation. Additionally, the proposed approach aims to reduce voltage fluctuations, minimize switching losses, improve battery utilization, and enhance system reliability compared with conventional control techniques. The performance of the proposed system can be evaluated through simulation and experimental analysis under different load and battery operating conditions. The proposed AI-based adaptive control strategy offers an intelligent and efficient solution for advanced electric vehicle energy storage applications, contributing to improved energy management, battery protection, and sustainable electric transportation.

I. INTRODUCTION

The rapid development of electric vehicles (EVs) has significantly increased the demand for advanced energy storage systems and efficient power management technologies. Electric vehicles are considered an environmentally friendly alternative to conventional fuel-based vehicles because they reduce dependence on fossil fuels and contribute to lower greenhouse gas emissions. The battery energy storage system plays a crucial role in determining the performance, driving range, reliability, and efficiency of an electric vehicle. However, variations in battery voltage, charging conditions, load requirements, and power demand create challenges in maintaining stable energy transfer. To overcome these challenges, bidirectional DC–DC converters are widely employed in electric vehicle applications. These converters enable power transfer in both directions between the battery and the DC bus, supporting battery charging and discharging operations. By operating in buck and boost modes, the converter regulates voltage levels according to system requirements, ensuring efficient energy utilization and improved overall vehicle performance.

Conventional control techniques, such as Proportional–Integral (PI) and Proportional–Integral–Derivative (PID) controllers, are commonly used to regulate DC–DC converters.

II. OBJECTIVES

- Design and develop a bidirectional DC–DC converter capable of operating in buck and boost modes for efficient battery charging and discharging.
- Implement an AI-based adaptive control algorithm that dynamically adjusts the converter switching duty cycle according to real-time operating conditions.
- Integrate voltage and current sensors for continuous monitoring of battery voltage, charging current, discharging current, and DC bus voltage.

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- Monitor the battery State of Charge (SOC) and ensure effective energy management while preventing overcharging and excessive discharging.
- Maintain a stable DC bus voltage under varying load conditions, battery voltage fluctuations, and changes in power demand.
- Improve the dynamic response of the converter by reducing voltage fluctuations, current ripple, and transient disturbances.
- Optimize bidirectional power flow between the battery energy storage system and the electric vehicle's electrical network.
- Minimize switching losses and conduction losses through intelligent switching control strategies.

III. LITERATURE SURVEY

[1] Review of Bidirectional DC–DC Converter Topologies for Hybrid Energy Storage System of New Energy Vehicles. Green Energy and Intelligent Transportation. Wang and colleagues presented a comprehensive review of bidirectional DC–DC converter topologies used in hybrid energy storage systems for electric vehicles. The study examined isolated and non-isolated converters and evaluated their performance in terms of efficiency, voltage gain, power density, and energy transfer capability. The researchers emphasized the importance of bidirectional power flow between batteries, supercapacitors, and vehicle loads. The study provides a strong foundation for selecting a suitable converter topology for intelligent battery energy management systems.

[2] Review of Bidirectional DC-DC Converters and Trends in Control Techniques for Applications in Electric Vehicles. IEEE Latin America Transactions. Martínez-Vera and Bañuelos-Sánchez reviewed different bidirectional DC–DC converter structures and their associated control techniques for electric vehicle applications. The research compared converter topologies based on switching frequency, power capacity, voltage gain, operating modes, and semiconductor technology. The study also discussed emerging intelligent control approaches and wide-bandgap power devices. This research highlights the importance of selecting advanced control techniques for maintaining reliable power conversion under varying electric vehicle operating conditions.

[3] DC-DC Converters for Transportation Electrification: Topologies, Control, and Future Challenges. This research reviewed the role of DC–DC converters in electric and autonomous vehicle applications. The article discussed various converter configurations, control methodologies, and practical challenges associated with transportation electrification. Particular attention was given to improving conversion efficiency, reducing converter size, increasing power density, and minimizing system cost. The study identified future developments in power electronic converter technology and demonstrated the importance of efficient converter control in electric vehicle energy storage applications.

[4] Bi-directional DC/DC Converters Used in Interfacing ESSs for RESs and Evs.Jaga and colleagues presented an extensive analysis of bidirectional DC–DC converters used to connect energy storage systems with renewable energy sources and electric vehicles. The study classified converter architectures into isolated and non-isolated configurations and compared their component requirements, voltage gain, efficiency, and reliability. The authors explained how bidirectional converters enable charging and discharging operations while maintaining controlled energy transfer. This study supports the design and selection of efficient power conversion circuits for advanced battery energy management applications.

IV. EXISTING & PROPOSED SYSTEM

4.1 EXISTING SYSTEM

The existing electric vehicle energy storage systems primarily utilize conventional bidirectional DC–DC converters controlled by traditional control techniques such as Proportional–Integral (PI), Proportional–Integral–Derivative (PID), and Pulse Width Modulation (PWM). These converters are responsible for regulating the flow of electrical energy between the battery energy storage system and the DC bus during charging and discharging operations. In conventional systems, the converter operates in buck mode when the battery requires charging and boost mode when electrical energy is supplied from the battery to the vehicle load. The switching duty cycle is regulated using predefined control parameters to maintain the required output voltage and current levels. Although these control methods are relatively simple, cost-effective, and easy to implement, their performance may become less effective under rapidly changing

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load conditions, variations in battery voltage, and nonlinear operating characteristics. Fixed controller parameters may not provide optimal performance across different charging and discharging conditions, resulting in increased voltage fluctuations, slower transient response, and reduced power conversion efficiency. In existing battery energy management systems, voltage sensors and current sensors are commonly employed to monitor electrical parameters such as battery terminal voltage, charging current, discharging current, and DC bus voltage.

4.2 PROPOSED SYSTEM

The proposed system, "AI-Based Adaptive Control of a Bidirectional DC–DC Converter for Electric Vehicle Energy Storage Systems," introduces an intelligent and efficient power management approach for improving battery performance, voltage regulation, and energy conversion efficiency in electric vehicles. The system integrates a bidirectional DC–DC converter with an Artificial Intelligence (AI)-based adaptive control algorithm to regulate the flow of electrical energy between the battery energy storage system and the DC bus. Unlike conventional control methods that depend on fixed controller parameters, the proposed AI-based controller dynamically adjusts the converter switching duty cycle according to real-time operating conditions. The system supports both buck and boost operating modes, allowing controlled battery charging and efficient energy delivery during vehicle operation. The integration of intelligent control techniques helps improve the converter's response to variations in battery voltage, electrical load, charging current, and discharging requirements. This adaptive approach aims to achieve stable power conversion, reduce voltage fluctuations, minimize energy losses, and enhance the overall reliability of electric vehicle energy storage systems.

V. BLOCK DIAGRAM

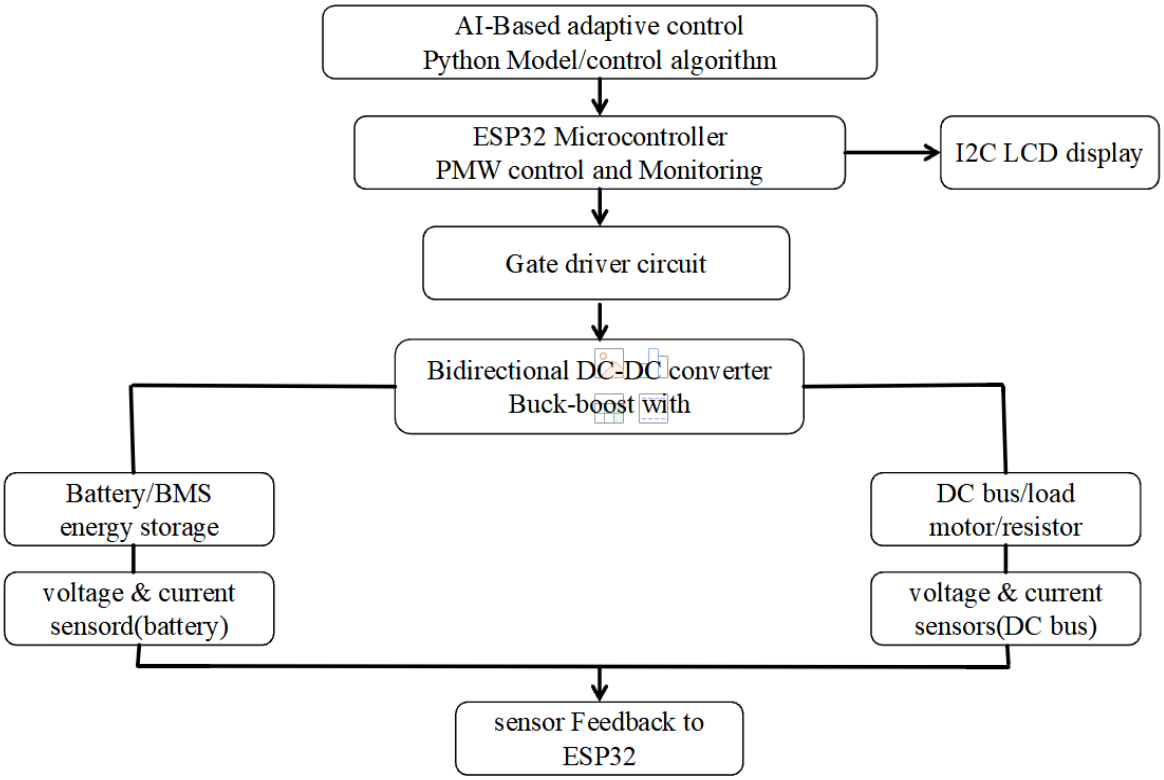


Fig No: 1 Software block diagram

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VI. HARDWARE REQUIREMENTS

6.1. POWER SUPPLY

The power supply is an essential component of the proposed AI-Based Adaptive Control of a Bidirectional DC–DC Converter for Electric Vehicle Energy Storage Systems. It provides the required electrical energy for the ESP32 microcontroller, voltage sensors, current sensors, LCD display, and other electronic components. A regulated DC power supply is used to ensure a stable and reliable voltage level during system operation. The power supply converts the available input electrical energy into a suitable DC voltage required by the control and monitoring circuits. Proper voltage regulation is necessary to prevent fluctuations that may affect the accuracy of sensor measurements, microcontroller performance, and converter switching operations. The proposed system uses an appropriate regulated power source to support continuous monitoring, intelligent control, and reliable operation of the power electronic components.



Fig.No:2 Power adapter

6.2. ESP32 DEVELOPMENT BOARD

The ESP32 Development Board is a powerful, low-cost, and energy-efficient microcontroller platform widely used in embedded systems, Internet of Things (IoT), automation, and intelligent control applications. In the proposed AI-Based Adaptive Control of a Bidirectional DC–DC Converter for Electric Vehicle Energy Storage Systems, the ESP32 acts as the central processing and control unit responsible for monitoring electrical parameters and regulating the operation of the bidirectional buck–boost converter. The ESP32 is equipped with a dual-core 32-bit processor, integrated Wi-Fi and Bluetooth connectivity, analog-to-digital converters (ADC), and Pulse Width Modulation (PWM) capabilities.

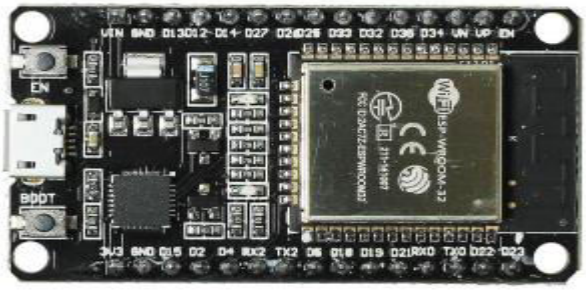


Fig No:3 Esp32 wifi device

6.3.BIDIRECTIONAL DC–DC CONVERTER (BUCK–BOOST CONVERTER MODULE)

The Bidirectional DC–DC Converter is an essential power electronic component used in the proposed AI-Based Adaptive Control of a Bidirectional DC–DC Converter for Electric Vehicle Energy Storage Systems. It enables electrical energy to flow in both directions between the battery energy storage system and the DC bus. The converter operates in two modes, namely buck mode and boost mode, depending on the charging and discharging requirements of the battery. During buck operation, the converter steps down the DC bus voltage to a suitable level for charging the

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battery, whereas during boost operation, it increases the battery voltage to maintain the required DC bus voltage for supplying electrical power to the connected load.



Fig no: 4 Buck-Boost converter module

6.4VOLTAGE SENSOR

The Voltage Sensor is an essential component used in the proposed AI-Based Adaptive Control of a Bidirectional DC–DC Converter for Electric Vehicle Energy Storage Systems. It is responsible for measuring the voltage levels of the battery and DC bus during charging and discharging operations. The sensor converts the measured voltage into a suitable analog signal that can be processed by the ESP32 microcontroller. Continuous voltage monitoring helps maintain stable power conversion and supports safe battery operation.



Fig No:5 Voltage sensor

6.5 CURRENT SENSOR

The Current Sensor is an important component used in the proposed AI-Based Adaptive Control of a Bidirectional DC–DC Converter for Electric Vehicle Energy Storage Systems. It measures the electrical current flowing between the battery, bidirectional converter, and connected load. The sensor detects charging and discharging currents and converts them into an analog voltage signal suitable for microcontroller processing. Continuous current monitoring helps maintain efficient power transfer and supports battery protection during different operating conditions.

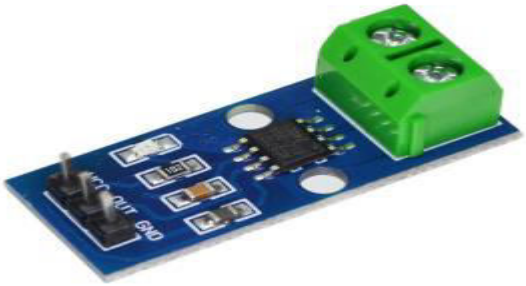


Fig No 6: Current Sensor Module

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6.6.INDUCTOR (POWER INDUCTOR)

The Power Inductor is an essential component used in the proposed AI-Based Adaptive Control of a Bidirectional DC–DC Converter for Electric Vehicle Energy Storage Systems. It stores electrical energy in the form of a magnetic field when current flows through its coil and releases the stored energy during converter switching operations. The inductor plays a significant role in regulating current flow, reducing current ripple, and supporting efficient energy transfer between the battery and DC bus. Its inductance value is selected based on the converter switching frequency, operating voltage, current rating, and allowable current ripple.

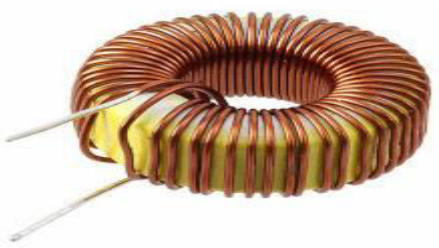


Fig No 7: Power Inductor for Bidirectional DC–DC Converter

6.7.DISPLAY UNIT (16×2 LCD DISPLAY WITH I2C MODULE)

The 16×2 LCD Display with I2C Module is an important output device used in the proposed AI-Based Adaptive Control of a Bidirectional DC–DC Converter for Electric Vehicle Energy Storage Systems. It consists of two rows, each capable of displaying 16 characters, allowing real-time monitoring of electrical parameters. The I2C communication interface reduces the number of connections required between the LCD and ESP32 microcontroller. The display provides a simple and effective method for presenting battery voltage, current, converter operating mode, and system status.

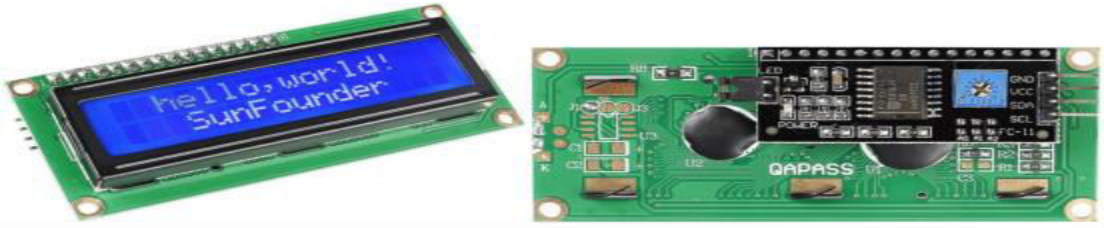


Fig No 8: 16×2 LCD Display with I2C Module

6.8.BATTERY (BATTERY ENERGY STORAGE SYSTEM)

The Battery is an essential energy storage component used in the proposed AI-Based Adaptive Control of a Bidirectional DC–DC Converter for Electric Vehicle Energy Storage Systems. It stores electrical energy in chemical form and supplies DC electrical power to the converter during discharging operations. A rechargeable lithium-ion battery is suitable for electric vehicle applications because of its high energy density, long cycle life, and efficient charging characteristics. The battery is connected to the bidirectional buck–boost converter to enable controlled energy transfer between the battery and DC bus. Its voltage, current, and State of Charge (SOC) are monitored to support efficient energy management and safe operation.

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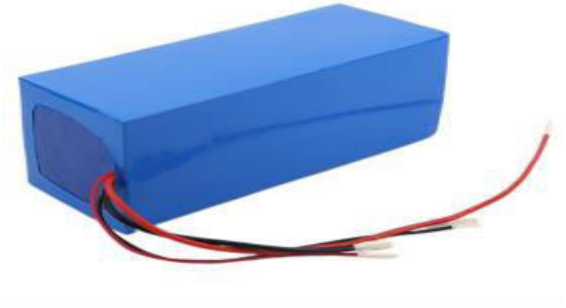


Fig No 9: Lithium-Ion Battery Energy Storage System

VII.RESULT

To provide intelligent and efficient energy management during battery charging and discharging operations. The system integrates an ESP32 microcontroller, bidirectional buck–boost converter, voltage sensors, current sensors, battery energy storage unit, and 16×2 LCD display. The AI-based adaptive control algorithm processes real-time electrical parameters and regulates the converter switching duty cycle according to battery conditions and load requirements. During boost operation, the converter increases the battery voltage to supply the required DC bus voltage, while during buck operation, it regulates the voltage and current supplied to the battery from an appropriate charging source.The proposed system enables continuous monitoring of battery voltage, charging and discharging current, and converter operating conditions. The voltage and current sensors provide electrical measurements to the ESP32 microcontroller, which processes the information and generates suitable Pulse Width Modulation (PWM) signals for controlling the converter through gate-driver circuits.

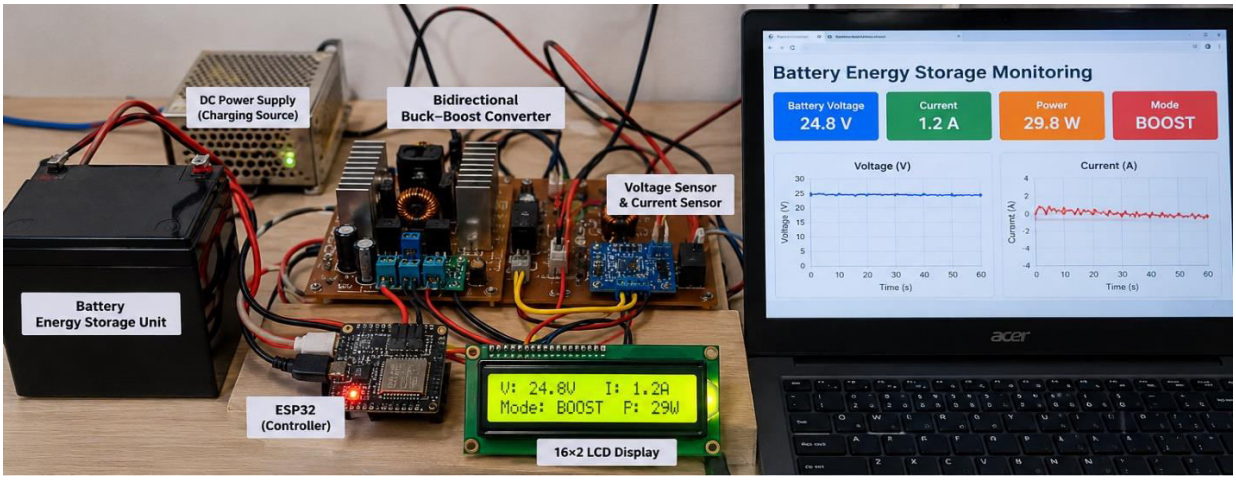


Fig No 10: Prototype Model picture

VIII. CONCLUSION

AI-Based Adaptive Control of a Bidirectional DC–DC Converter for Electric Vehicle Energy Storage Systems presents an intelligent approach to improving energy management, battery performance, and power conversion efficiency in electric vehicles. The system integrates an ESP32 microcontroller, bidirectional buck–boost converter, voltage and current sensors, battery energy storage system, and 16×2 LCD display for effective monitoring and control. The AI-based adaptive control algorithm is designed to regulate the converter switching duty cycle according to real-time battery conditions and load requirements. The bidirectional converter supports both buck and boost operations, enabling controlled battery charging and efficient power delivery during discharging. Continuous monitoring of voltage and current parameters helps maintain stable DC bus voltage and supports battery protection. The proposed adaptive

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control technique aims to reduce voltage fluctuations, current ripple, switching losses, and transient disturbances compared with conventional control methods.

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