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Comparative Analysis and Optimization of Interleaved DC-DC Converters for Fuel Cell Electric Vehicles

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Abstract— ***This paper presents a comprehensive study on the application of bidirectional DC-DC converters in fuel cell systems. The selection of a suitable bidirectional DC-DC converter is crucial for efficient power management in fuel cell systems. To evaluate the performance and efficiency of the selected converters, MATLAB simulations are conducted using different parameters. The simulation analysis provides valuable insights into the behavior and characteristics of the converters, aiding in the selection process. The findings from this study can provide valuable insights for researchers, engineers, and practitioners involved in the design and implementation of fuel cell systems for various applications.***

Index Terms— Comparative Analysis, Electric Vehicles, Fuel Cell, Interleaved DC-DC Converters, Optimization.

I. INTRODUCTION

Many nations continue to heavily depend on unsustainable fossil fuels for energy production, resulting in significant environmental consequences. The depletion of non-renewable resources, alongside their adverse effects such as greenhouse gas emissions on the energy industry and the environment, remains a critical concern. To address the increasing energy demands of a growing global population, transitioning to alternative and sustainable energy sources is crucial. Despite ongoing efforts toward sustainability, fossil fuels are still projected to dominate energy production, with an estimated 75% share by 2050 [1].

An electric vehicle (EV) uses one or more electric motors for propulsion and can be powered by a collector system, or it can be powered autonomously by a battery. Application of EVs is not limited to road and rail vehicles, they are used in surface and underwater vessels, electric aircraft and electric spacecraft [2]. Fuel cell vehicles (FCVs) are a type of zero-emission vehicle that utilize fuel cell technology to generate electricity and power an electric motor. FCVs use hydrogen as their primary fuel source, resulting in significantly reduced environmental impact. The core component of a fuel cell vehicle is the fuel cell stack, which contains multiple individual fuel cells. Each fuel cell consists of an anode, a cathode, and an electrolyte membrane in between. When hydrogen gas is supplied to the anode and oxygen from the air is provided to the cathode, a chemical reaction occurs in the fuel cell, producing electricity, heat, and water as by-products. The electricity generated by the fuel cell is used to power an electric motor, which propels the vehicle. Since the conversion of hydrogen and oxygen into electricity is an electrochemical process, it occurs without any combustion, resulting in zero greenhouse gas emissions. The only by-product of this process is pure water vapor, making fuel cell vehicles a clean and sustainable transportation option [2].

The integration of fuel cells with electric vehicle (EV) powertrains has gained significant attention as a promising alternative to conventional internal combustion engines. In recent years, researchers have explored the utilization of bidirectional dc-dc converters to efficiently interface fuel cells with electric motors [3].

M. A. Khan, A. Ahmed, Hussain, Y. Sober and M. Badawy in [4] proposes an integration of renewable energy sources based on a modular multi-input bidirectional DC/DC buck-boost converter. C.-C. Lin, L.-S. Yang, and G.-W. Wu in [5] proposes a non-isolated bidirectional DC–DC converter, which has simple circuit structure. The control strategy is easily implemented. Also, the synchronous rectifier technique is used to reduce the losses. Yu-En Wu, and Bo-Hau Pan in [6] proposes a converter which is an enhancement of the conventional Buck-Boost converter. By integrating a three-winding coupled inductor and switched-capacitor into the power stage, the converter offers advantages such as isolation and bidirectional power flow.

Yun Zhang, Wei Zhang, Fei Gao, Shenghan Gao, and Daniel J. Rogers in [7] proposes a switched-capacitor interleaved bidirectional dc–dc converter that combines a three-phase interleaved structure with switched-capacitor cells. Yun Zhang, Qiangqiang Liu, Yongping Gao, Jing Li, and Mark Sumner in [8] introduces a hybrid switched-capacitor/switched-quasi-Z-source bidirectional DC-DC converter designed for electric vehicles (EVs) with hybrid energy sources. The converter offers a wide range of voltage gain for bidirectional energy flows.

Sajjad Yahyazadeh, Mehdi Khaleghi, Saleh Farzamkia, and A Khoshkbar Sadigh in[9] proposes a new multi-input multi-output bidirectional DC-DC converter suitable for electric and hybrid vehicles applications. The key advantage of this new structure is its ability to accommodate various energy sources with different voltage-current characteristics. Nour Elsayad, Hadi Moradisizkoohi, and Osama A. Mohammed in [10] introduces a new transformerless bidirectional buck-boost converter. The converter is designed with a simple circuit structure, a minimal number of components, low voltage stress on the power transistors, and a wide range of voltage gain. Sin-Woo Lee and Hyun-Lark Do in[11] proposes an isolated single-ended primary-inductor converter (SEPIC) DC-DC converter, which achieves ripple-free input current and incorporates a lossless snubber. Interleaving multiple converter phases can help distribute the current and reduce the size of components such as inductors and capacitors. However, finding the optimal interleaving strategy for a given application needs to be addressed.

Jianwu Zeng, Wei Qiao, Liyan Qu, and Yanping Jiao in [12] introduces an isolated multiport DC-DC converter for efficient management of multiple renewable energy sources with varying types and capacities.Young-Rok Kang, Ji-Chang Son, and Dong-Kuk Lim[13] introduces an autotuning elliptical niching genetic algorithm as a solution to finding multimodal solutions for the optimal design of interior permanent magnet synchronous motors (IPMSMs) in fuel cell electric vehicles.Hosseini, R. Ghazi and H. Heydari Doostabad in [14] introduces a Voltage Quadruple bidirectional DC-DC converter designed for electric vehicle applications. Hadi Moradisizkoohi, Nour Elsayad, and Osama A. Mohammed in [15] proposes an interleaved-converter that provides a wide range of voltage conversion ratios, making it suitable for connecting the energy storage unit to the DC bus in electric vehicle applications. By utilizing a capacitive voltage-divider stage, the converter achieves high voltage gain and minimizes voltage stress on the switches.

The literature review indicates that interleaving multiple converter phases can effectively distribute current and reduce the size of components such as inductors and capacitors. However, determining the optimal interleaving strategy for specific applications remains a crucial challenge. Interleaved bidirectional converters offer significant potential for high efficiency due to their reduced current ripple and improved thermal management, yet further optimization opportunities for efficiency may still exist

Switched-capacitor circuits are attracting attention for their ability to achieve high voltage gain by storing and releasing energy in capacitors during different switching intervals. Nevertheless, these circuits often have a high component count, which can result in increased costs, size, and power losses. Therefore, a thorough analysis aimed at minimizing losses within the converter—encompassing both conduction and switching losses—is essential.

Additionally, the dynamic response and stability of bidirectional converters in fuel cell systems are vital for ensuring reliable operation. Investigating the converter's behavior under varying load conditions, along with its transient response and control strategies, can help identify areas for improvement, ensuring stable and efficient operation.

A suitable interleaved DC-DC converter, capable of boosting input voltage and regulating output voltage for electric vehicle (EV) applications, has been selected based on an extensive literature review. This converter has been optimized specifically for integration with fuel-cell-powered EV systems. In this paper, we analyze the performance of the optimized converter using three different types of fuel cells, evaluating key metrics such as efficiency, voltage regulation, and dynamic response. Section 2 outlines the design and optimization process of the selected DC-DC converter. Section 3 presents the results of the Simulink-based simulations, followed by conclusions and future research directions in Section 4.

II. DESIGN AND WORKING OF POWER-BOOST INTERLEAVED CONVERTER

The schematic diagram of the Power-Boost Interleaved Converter (PBIC) is depicted in Fig. 1 [15], showcasing the overall design of the converter. The proposed topology consists of two primary stages that work in tandem to achieve the desired voltage boost and interleaving functions.

The first stage is the conventional interleaved structure, which plays a critical role in reducing input current ripple and distributing the load between multiple phases. This stage comprises two inductors, L1 and L2, and two switches, S1 and S2. The interleaving of these components ensures that the current is shared effectively, reducing stress on individual components and improving overall efficiency.

The second stage, known as the Power-Boost stage, is responsible for providing the high-voltage gain required for the electric vehicle (EV) application. This stage includes key components such as capacitors Cm1, Cm2, CH1, and CH2, along with switches S3, S4, S5, and S6. These capacitors and switches form the core of the voltage-boosting mechanism, allowing the converter to step up the voltage from the energy storage unit (ESU) to meet the high-voltage requirements of the EV's DC bus.

Additionally, the low voltage side (LVS) includes a filter capacitor, CL, which helps smooth out the voltage and further reduces ripple, ensuring a stable input to the converter. The combination of these stages and components makes the PBIC highly efficient and suitable for fuel-cell-based EV applications, where high voltage gain and low ripple are essential for optimal performance.

In boost mode, energy flows from the low voltage side (LVS) to the high voltage side (HVS), with the converter raising the voltage of the energy storage unit (ESU) to the target 800 V required for the EV's DC bus. Switches S1 and

S2 are controlled by gate pulses with an identical duty cycle and a phase shift of 180° to achieve interleaved operation. Switches S3 and S6 receive complementary gate pulses to those of S1, while switches S4 and S5 receive complementary gate pulses to S2. The steady-state analysis assumes continuous conduction mode (CCM) operation, with a duty cycle greater than 0.5, which ensures the high step-up voltage gain characteristic of this topology—an advantage for EV applications using ESUs. The expected waveforms generated by the proposed PBIC can be referred from [15].

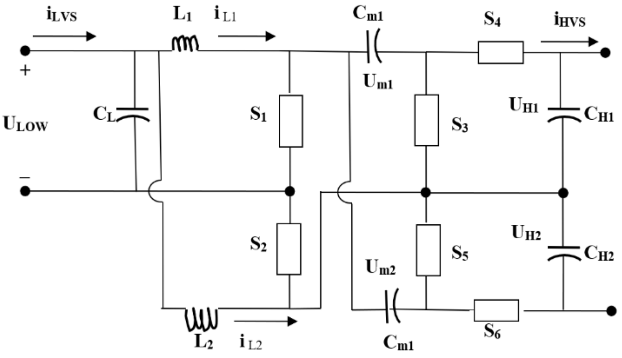

Fig.1 Power-Boost interleaved boost converter

III. SIMULATION AND RESULTS

Fig. 2 illustrates the Simulink model of the proposed DC-DC converter, showcasing its key components and configuration. This model serves as a foundation for analyzing the performance and efficiency of the converter under various operating conditions. Table 1 summarizes the simulation parameters utilized in the model, providing essential details for replicating the simulation and understanding its outcomes.

Fig. 3 shows the output voltage waveform obtained from the proposed Converter (PBIC). Its value is measured to be 820V with the input being 100V. In forward mode, the Interleaved Boost Converter was operated by charging capacitors in parallel and then distributing the energy through separate paths during the discharging process. This principle enabled the converter to achieve a high voltage conversion ratio in forward mode. Conversely, in backward mode, the capacitors were charged in series and discharged in parallel.

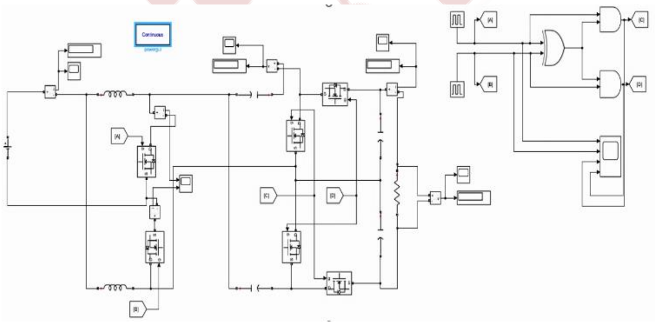

Fig. 2 Simulink model of power-boost interleaved converter (PBIC)

Table 1. Simulation Parameters

Parameters And Components	Values
Switches	MOSFET
Switching Frequency f_s	100kHz
High-side voltage U_{High}	800 V
Low-side voltage U_{Low}	50-100 V
Inductors L_1, L_2	100μH
Capacitors C_{m1}, C_{m2}	10μF
Capacitors C_{H1}, C_{H2}	220μF

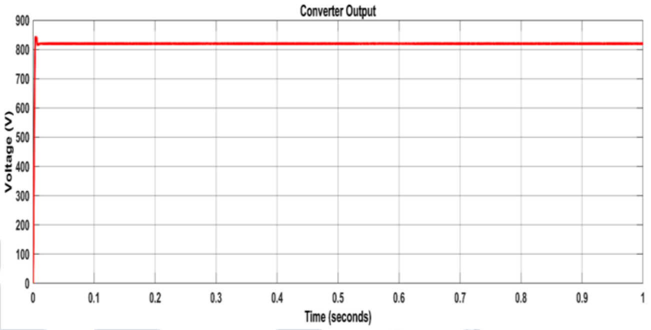

Fig. 3 Output voltage of the interleaved boost converter (IBC)

A. Case 1: Fuel Cell PEMFC providing Input Voltage as 24V DC

The PEMFC (Proton Exchange Membrane Fuel Cell) is a type of fuel cell that operates at relatively low temperatures and uses a solid polymer membrane as the electrolyte. It is a highly efficient and environmentally friendly energy conversion device that converts the chemical energy of hydrogen fuel into electrical energy through an electrochemical reaction.

The PEMFC (24V DC) fuel cell has a power output of 1.26 kW (1260 W). This means that it can generate a nominal voltage of 24.23V and a nominal current of 52A. Various other parameters of the fuel cell for simulation have been chosen from MATLAB.

Fig.4. shows the input voltage provided by the fuel cell which measures out to be 24Vand Fig.5. shows the Inverter output of simulated model and it comes out to be 392V.

The fuel cell stack provides a DC voltage to the boost converter and the boosted voltage is then converted to AC voltage via inverter and supplied to the Permanent Magnet Synchronous Motor (PMSM). The simulation is run for 1sec and inverter and motor outputs are measured. Various parameters of the PMSM motor were measured like rotor speed, rotor angle, and electromagnetic torque in the Fig. 6. Motor achieves a steady speed of 1500rpm at 0.13sec and a constant torque of 2.7Nm at 0.1sec. The rotor angle is measured in radians and it goes from 0 to 156.4 radians in 1 second.

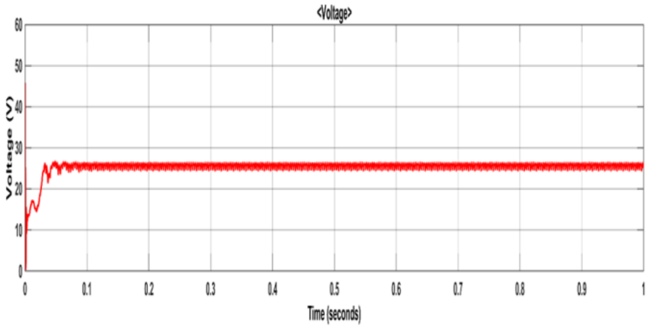

Fig. 4 Case 1: Input voltage provided by the fuel cell (24V)

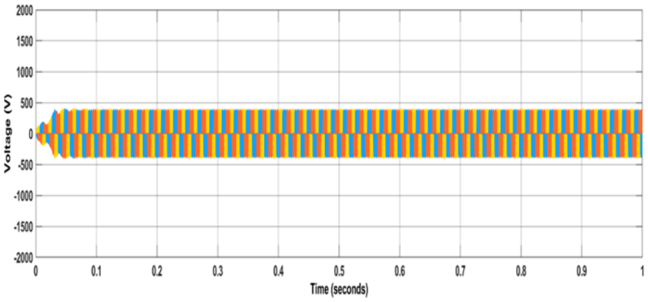

Fig. 5 Case 1: Inverter output (392V)

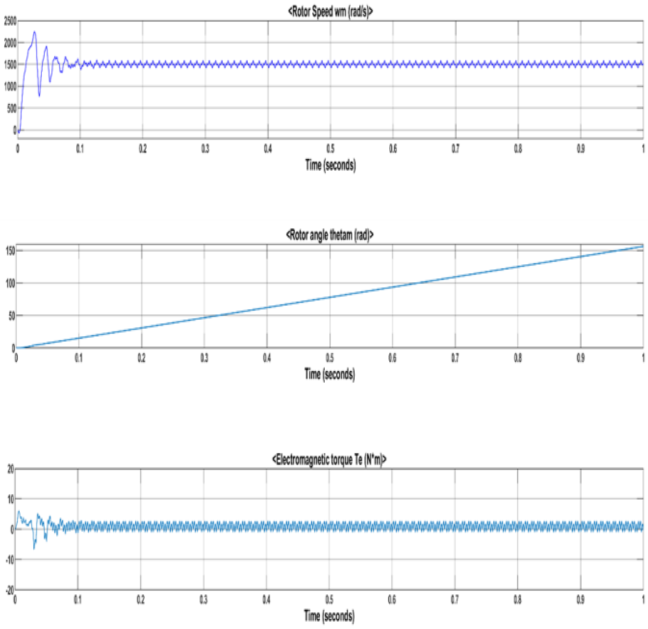

Fig. 6 Case 1: PMSM motor operating parameters

B. Case 2: Fuel Cell 2: PEMFC (45V DC)

In this case, a fuel cell similar to the one described in Case 1 is utilized, but with a slight modification. The main difference is that this particular variant of the fuel cell generates a DC voltage of 45V.

The PEMFC ($45V_{DC}$) fuel cell has a power output of 6 kilowatts (6000 watts). This means that it can generate a nominal voltage of 45V and a nominal current of 133.3A. Various other parameters of the fuel cell for simulation have been chosen from MATLAB.

Fig.7 shows Input voltage provided by the fuel cell which measures out to be 45V and Fig. 8 shows the inverter output of simulated model and it is measured to be 542V.

The fuel cell stack generates a direct current (DC) voltage, which is then supplied to a boost converter. The boost converter increases the voltage, and the resulting boosted voltage is converted into alternating current (AC) voltage using an inverter. The AC voltage is then provided to a Permanent Magnet Synchronous Motor (PMSM). During the simulation, which runs for 1 second, the outputs of the inverter and the motor are measured and observed. Rotor speed, rotor angle, and electromagnetic torque of the PMSM motor were measured as shown in the Fig. 9. Motor achieves a steady speed of 1500rpm at 0.05sec and a constant torque of 4Nm at 0.04sec. The rotor angle is measured in radians and it goes from 0 to 156.4 radians in 1 second.

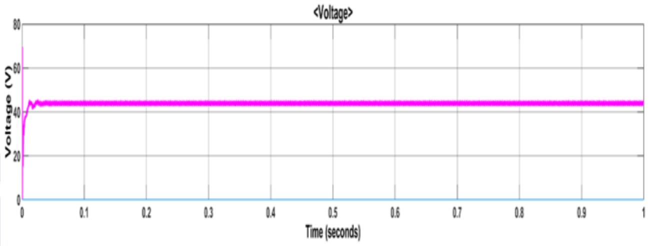

Fig. 7 Case 2: Input voltage (45V)

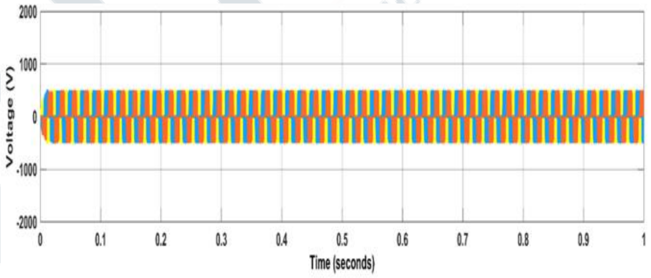

Fig. 8 Case 2: Inverter output (542V)

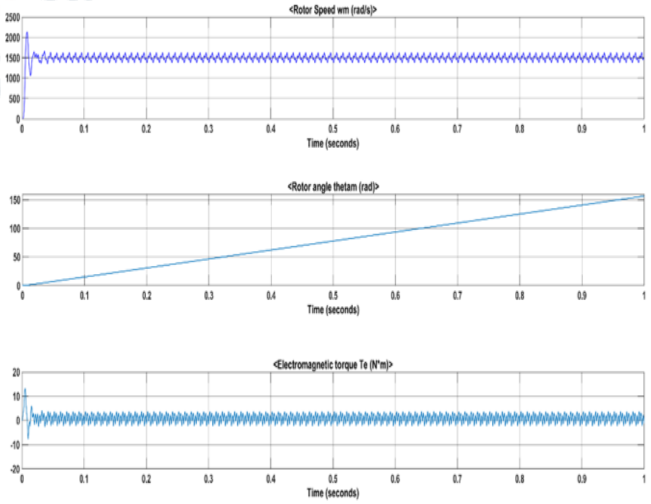

Fig. 9 Case 2: PMSM motor operating parameters

C. Case 3: Fuel Cell 3: SOFC (100V DC)

Solid Oxide Fuel Cells (SOFCs) are high-temperature fuel cells that operate at temperatures typically ranging from 500 to 1,000 °C (932 to 1,832 °F). SOFCs use a solid oxide electrolyte to conduct oxygen ions and typically operate on a variety of fuels, including hydrogen, natural gas, and biogas. They are known for their high efficiency, fuel flexibility, and potential for stationary and portable power applications.

The SOFC (100V DC) fuel cell has a power output of 3 kW (3000 W). Various other parameters of the fuel cell for simulation have been chosen from MATLAB.

Fig. 10 shows Input voltage provided by the fuel cell which measures out to be 45V and Fig.11 shows the inverter output of simulated model and it is measured to be 850V.

The simulation results in this case shows rotor speed, rotor angle, and electromagnetic torque of the PMSM motor were measured as shown in the Fig.12. Motor achieves a steady speed of 1500rpm at 0.11sec and a constant torque of 5Nm at 0.1sec. The rotor angle is measured in radians and it goes from 0 to 156.4 radians in 1 second.

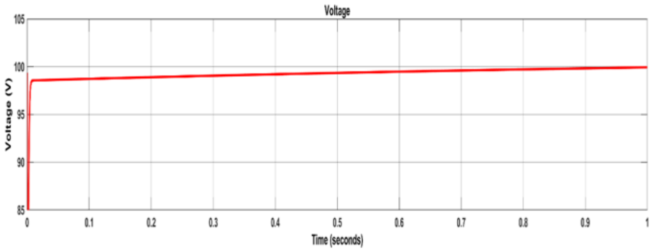

Fig. 10 Case 3: Input voltage from fuel cell (100V)

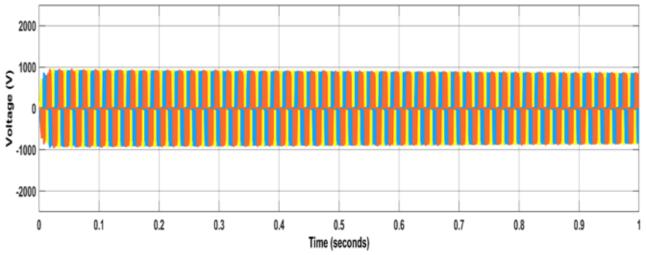

Fig. 11 Case 3: Inverter output (850V)

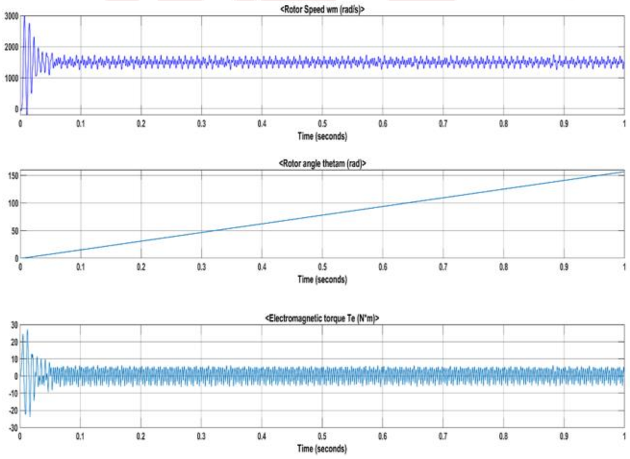

Fig. 12 Case 3: PMSM motor operating parameters

After observing the above simulated results of fuel cells with the PMSM motor, it is concluded that the PEMFC (45V DC) performs better than the remaining two fuel cells. It is because this fuel cell provides a better and stable operation of the motor compared to the other two fuel cells. The motor stabilizes faster and provides a steady response which is necessary for the smooth working of the fuel cell based electric vehicles.

IV. CONCLUSION AND FUTURE SCOPE

The simulation results of the Power-Boost Interleaved converter (PBIC) and the fuel cell integration with the PMSM motor have provided valuable insights into their performance and suitability for electric vehicle applications. The Simulink model accurately represented the behaviour of the converter and allowed for the analysis of various parameters and components for three types of most commonly used Fuel Cells. The Simulink models illustrated their integration with the boost converter, inverter, and PMSM motor. Based on the observed results, it can be determined that the PEMFC (45V DC) fuel cell outperformed the other two fuel cell types. It exhibited better and more stable operation of the PMSM motor, with faster stabilization and a steady response. These characteristics are crucial for ensuring the smooth functioning of fuel cell-based electric vehicles. The findings highlight the potential of fuel cells in electric vehicle applications, offering enhanced environmental performance, extended driving range, fast re-fueling, scalability, flexibility, and improved energy efficiency.

As future work, advanced control techniques, such as predictive control, model predictive control (MPC), or adaptive control, to enhance the converter's dynamic response, stability, and transient performance can be investigated. Research to enhance the durability and reliability of the proposed converter, fuel cell stack, and associated components in real-world operating conditions can also be carried out.

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