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DESIGN AND MODELLING OF FUELCELL BASED ULTRA-VOLTAGE GAIN BOOST CONVERTER FOR ELECTRIC VEHICLE

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ABSTRACT

Renewable energy-powered electric vehicles (EVs) have become increasingly popular due to the growing need for environmentally friendly transportation. Proton exchange membrane (PEM) fuel cells stand out among them due to their compact design, minimal emissions, and excellent efficiency. However, a significant problem with fuel cells is their low output voltage, which makes high voltage gain DC-DC converters necessary. An innovative ultra-high voltage gain boost converter created especially for fuel cell usage in EVs is proposed in this study.To achieve voltage gain while preserving high efficiency, small size, and lower component stress, the converter combines linked inductors and switching capacitor techniques. The converter is a viable option for real-world EV integration since simulations confirm its performance in terms of gain, efficiency, and voltage regulation.The growing adoption of electric vehicles (EVs) has increased demand for efficient charging infrastructure. Transformers have disadvantages such expensive cost, complicated design, and increased weight, even though they can produce large voltage gains. An other method for achieving high voltage gain is presented in this article: a switching inductor circuit. This circuit lowers size, weight, and cost while improving overall system performance.

Keywords —*Hydrogen Fuel Cell, Boost Converter, Electrical Vehicle, PI Controller.*

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1. INTRODUCTION

Fuel Cell Electric Vehicles (FCEVs) are an advanced type of electric vehicle that use hydrogen fuel cells to generate electricity onboard, which powers an electric motor. Unlike conventional battery EVs, FCEVs generate electricity through an electrochemical reaction between hydrogen and oxygen, emitting only water vapor as a by-product, making them a clean alternative to fossil fuel-based transportation. However, to make FCEVs more competitive and practical, especially against battery electric vehicles, it is essential to improve their efficiency and voltage output.

As the world transitions toward cleaner and more sustainable modes of transportation, Fuel Cell Electric Vehicles (FCEVs) have emerged as a promising source. FCEVs use hydrogen fuel cells to generate electricity through a chemical reaction between hydrogen and oxygen. This electricity powers an electric motor that drives the vehicle, emitting only water vapor and heat as by-products, making FCEVs an environmentally friendly transportation solution.

Fuel-cells operate on the principle of electrochemical conversion, which is more efficient than combustion-based energy conversion. The core component of an FCEV is the Proton Exchange Membrane (PEM) fuel cell, which combines hydrogen with oxygen from the air to produce electricity.

The cascading boost converter topology offers the advantage of achieving higher voltage gain without the need for a maximum duty cycle, unlike the conventional boost converter. However, it is important to note that the switches in this topology are subjected to intense voltage and current stress. Another approach to increase voltage gain is through the use of switched inductors and capacitors converter topologies exhibit double the voltage gain compared to typical step-up converters, but the use of semiconductors leads to higher voltage stress. To address these challenges and enhance voltage gain while minimizing stress on the switches, the voltage lift approach is employed.

In scenarios where conversion ratio is high, a larger number of diodes and capacitors are employed. Limited topologies such as linked inductors and flyback converters utilize the turns ratio and duty cycle to regulate the converter's voltage gain.

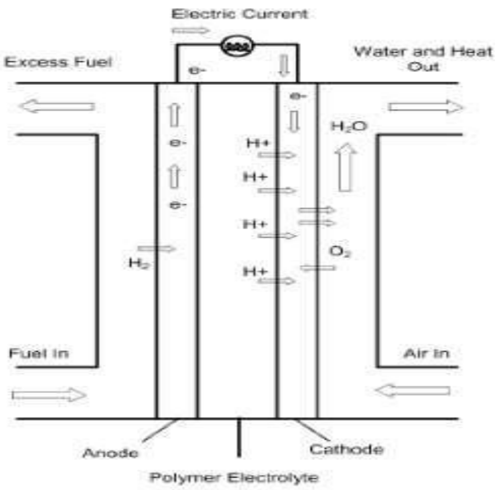

Fig 1. Basic Hydrogen Fuel-Cell

2. FUEL CELL MODELLING

The transformation of hydrogen-based chemical energy into electrical energy occurs through the utilization of fuel cells, which are electrochemical devices. Unlike thermal or electromechanical mechanisms, fuel cells facilitate the conversion of oxygen and hydrogen into water and power. When subjected to an electric field, the anode and cathode of the fuel-cell undergo specific processes. The movement of ions across the electrodes takes place once equilibrium is established. The fundamental chemical reaction of the Proton Exchange Membrane Fuel Cell (PEMFC) involves oxidation and reduction reactions occurring at the anode and cathode, respectively. At the anode, hydrogen undergoes oxidation to generate protons and electrons, while at the cathode, water is produced through the combination of two protons and two electrons. The overall chemical reaction can be represented as…

$H_2 + \frac{1}{2}O_2 \rightarrow 2H_2O +$ electrical energy + heat energy

An essential stage in assessing and estimating the performance of fuel cell electric vehicles (FCEVs) is fuel cell modeling in MATLAB. Proton Exchange Membrane Fuel Cells (PEMFCs), which are frequently utilized in automotive applications because of their high power density and rapid startup features, can dynamically-modele MATLAB / Simulink. The mathematical depiction of the fuel cell's electrochemical activity, including equations describing the voltage-current (V-I) relationship, activation losses, ohmic losses, and concentration losses, usually starts the modelling process.

3. METHODOLOGY

The methodology for integrating a boost converter in Fuel Cell Electric Vehicles (FCEVs) involves a systematic approach encompassing the modeling of the fuel cell, design of the DC-DC boost converter, development of the control strategy, and performance of analysis through simulation. Initially, a Proton Exchange Membrane Fuel Cell (PEMFC) model is developed in the MATLAB / Simulink using electrochemical equations to simulate voltage characteristics under various current loads. The dynamic behavior of the fuel cell is replicated using appropriate blocks, considering activation, ohmic, and concentration losses. Following this

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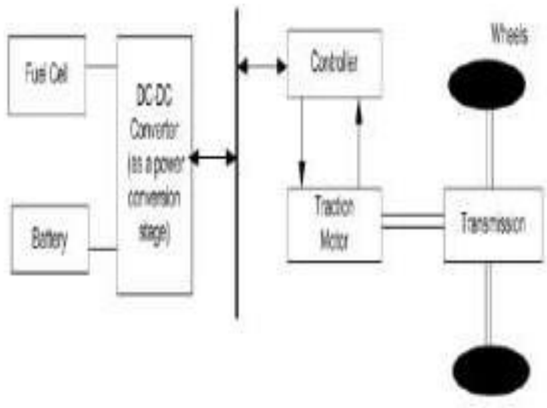
as a non-isolated interleaved boost converter is designed to step up the low voltage output from the fuel cell to a higher level suitable for propulsion systems. Key design parameters, such as inductance, switching frequency, duty cycle, and semiconductor ratings, are selected based on the desired output power and efficiency requirements. A dual-loop control strategy is implemented, consisting of an inner current loop for fast dynamic response and an outer voltage loop for maintaining output voltage stability. To maximize the efficiency of the fuel cell, a Maximum Power Point Tracking (MPPT) algorithm is also integrated. Finally, the complete system, including the fuel cell, converter, and control system, is simulated in MATLAB/ Simulink to analyze performance under steady-state and transient conditions. The results are evaluated in terms of voltage regulation, response time, and overall system efficiency.



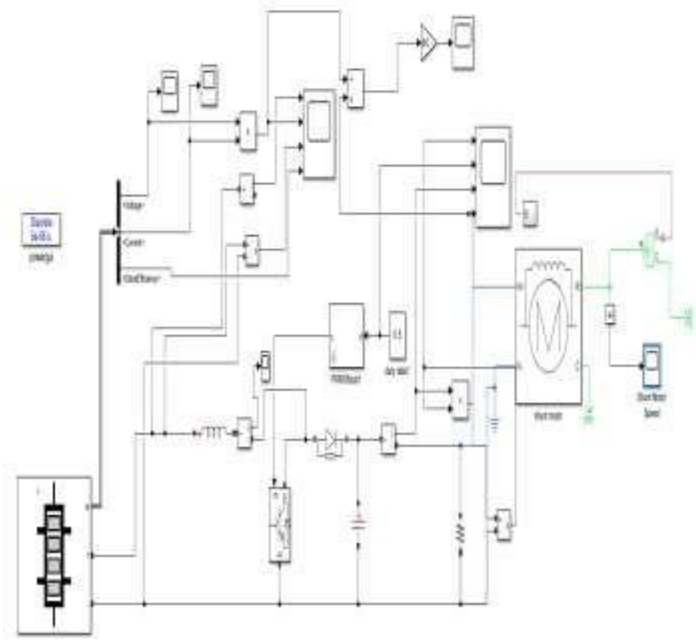
The simulation model in MATLAB/Simulink integrates a fuel cell, battery, DC-DC boost converter, traction motor, transmission, and controller to drive wheels:

- **Fuel Cell and Battery**: PEM fuel cell (e.g., 24 V, 50 A) and battery (e.g., 24 V) provide input power.
- **DC-DC Converter**: Boosts voltage from 24 V to 48 V using L=1mH L=1,L=1mH, C=1000μF,C=1000,C=1000μF, and fs=20 kHz fs = 20 fs=20kHz with D=0.5 D = 0.5 D=0.5.
- **Traction Motor and Transmission**: DC motor or PMSM with a gear ratio drives the wheels.
- **Controller**: PID adjusts duty cycle based on output voltage and motor speed feedback.

Design Parameters

- Input Voltage: 24 V
- Output Voltage: 48 V
- Power Rating: 1 kW
- Switching Frequency: 20 kHz
- Load:Variable (e.g.,10Ω or dynamic torque).

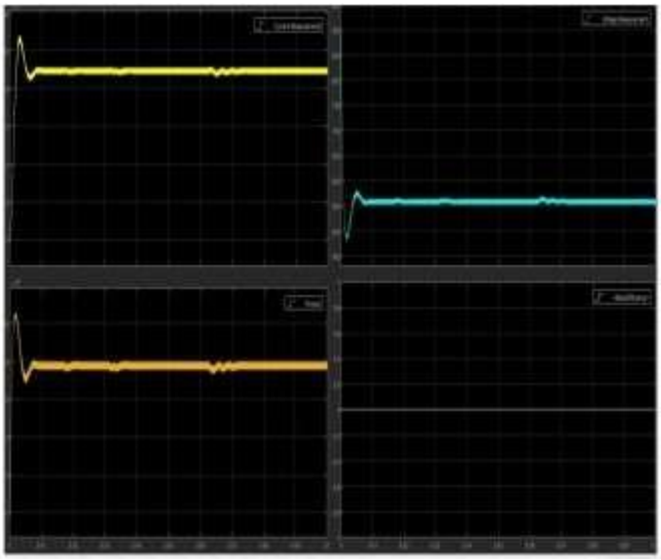
4. SIMULATION MODELS



The simulation setup in MATLAB/Simulink integrates a fuel cell model, represented by a block outputting voltage, current, and efficiency, with a DC-DC boost converter designed to step up the input voltage (e.g., 24 V) to a higher level (e.g., 48 V)using an inductor, capacitor, diode, and MOSFET switch controlled by a PWM block with an initial duty ratio of 0.5. A controller, featuring a gain block (e.g., 60) and feedback loop, adjusts the duty cycle based on the shunt motor's output voltage and speed, ensuring stability under varying loads, while the "Discrete powergui", block (set to 5e-6 s) manages discrete simulation settings. The shunt motor, modelled with electrical components and a speed output block, converts the boosted voltage into mechanical power, with feedback lines enabling closed-loop control. The design parameters include a switching frequency of approximately 20 kHz and a motor load defined by its resistance and inertia, with simulation scenarios focusing on steady-state performance, dynamic response to load changes, and efficiency analysis of power losses across the system.

5. RESULTS

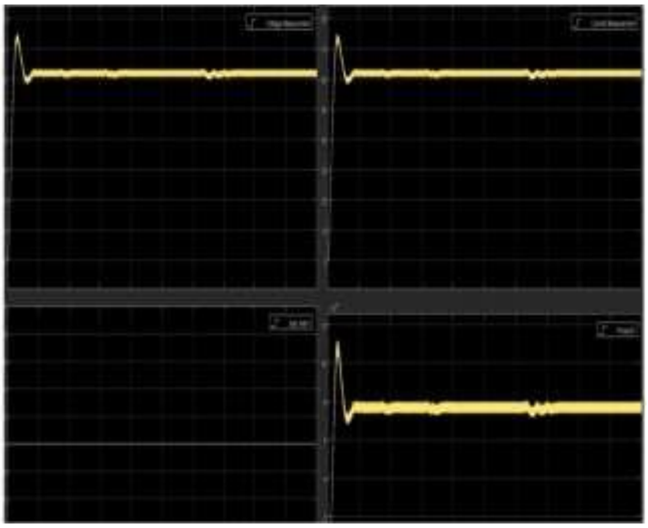
5.1 Input to Fuel Cell:



- Voltage: Variable output (e.g., ~24 V nominal, depending on load and operating conditions).
- Stack Efficiency: Calculated metric (e.g., percentage of chemical energy converted to electrical energy, influenced by operating parameters).
- Currents are high initially before boost converter action.
- Power is of similar value as of voltages and current, i.e:-Power = Voltage * Current.

The fuel cell's output voltage (e.g., ~24 V) varies with load and operating conditions, reflecting its electrochemical performance, while the current output (e.g., ~50 A) depends on the stack design and demand, influencing power delivery. Stack efficiency, a key metric, indicates the percentage of chemical energy converted to electrical energy, influenced by factors such as temperature, pressure, and fuel utilization.

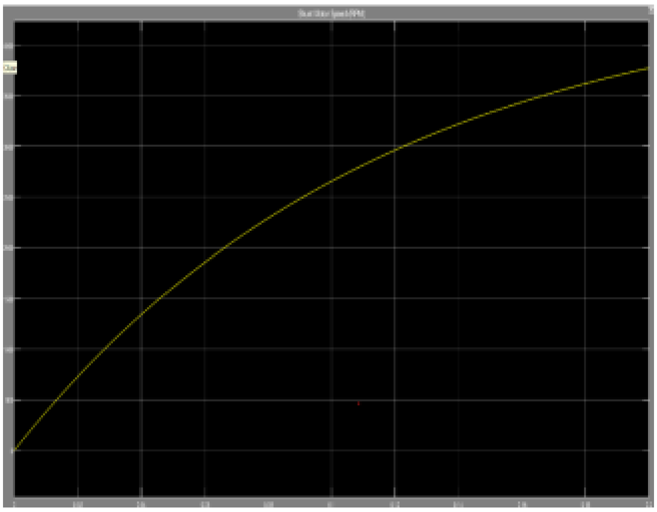
5.2 Output of fuel cell EV:



- Voltage: Stepped up to ~48 V to 400V DC (depending on duty cycle, e.g., D = 0.5).
- Current: Reduced proportionally (e.g., ~25 A, based on power conservation).
- Efficiency: Overall system efficiency ~90%, accounting for converter losses.
- Power: Increased to ~1 kW (product of boosted voltage and current).

The output of the fuel cell after boosting through the DC-DC converter sees the voltage stepped up to approximately 48 V, depending on the duty cycle (e.g.,D =0.5), significantly enhancing its usability-for higher-load applications.The current is correspondingly reduced to around 25 A due to power conservation principles, ensuring the system maintains energy balance. The overall efficiency of the system is approximately 90%, reflecting minor losses in the conversion process. The resulting power output reaches about 1 kW, calculated as the product of the boosted voltage and current, demonstrating the effectiveness of the boost converter. These outputs collectively enable the system to meet the demands of devices like the shunt motor in the simulation.

5.3 EV Rpm:



The graph depicting the shunt motor speed (RPM) of the electric vehicle (EV) shows an exponential increase over time, as indicated by the upward-curving yellow plot, which rises from 0 RPM to over 3500 RPM within a short duration (approximately 0.2 seconds). This rapid acceleration reflects the efficient power delivery from the fuel cell and boosted voltage through the DC-DC converter, enabling the motor to respond dynamically to the load. The single red data point suggests a specific measurement or initial condition, emphasizing the steep rise in speed as the system stabilizes and the controller adjusts effectively.

6. CONCLUSION AND FUTURE SCOPE

The integration of a fuel cell with a DC-DC boost converter, as simulated in MATLAB/Simulink, demonstrates a robust and efficient power delivery system for driving a shunt motor in an electric vehicle (EV) application. The simulation results, including the exponential increase in motor speed from 0 to over 3500 RPM within 0.2 seconds, highlight the system's ability to provide rapid and stable power output.

The boost converter successfully steps up the fuel cell's nominal 24 V to 48 V, with an efficiency of approximately 90% and a power output of around 1 kW, validating the design's effectiveness in meeting the dynamic load demands of the motor. The PID controller's role in adjusting the duty cycle ensures voltage stability and responsive motor performance, making this setup a promising solution for EV propulsion.

In conclusion, this project lays a solid foundation for further optimization and real-world implementation of fuel cell-based EV systems. The observed exponential speed increase underscores the potential for high-performance applications, though challenges such as thermal management and converter losses warrant additional investigation. Future work could explore hybrid configurations with batteries, refine control algorithms for enhanced efficiency, and validate the model with experimental data to bridge the gap between simulation and practical deployment. This study affirms the viability of fuel cell technology integrated with power electronics for sustainable transportation, aligning with the growing demand for clean energy solutions.

The successful simulation of a fuel cell integrated with a DC-DC boost converter opens several avenues for future research and development. One promising direction is the incorporation of hybrid energy systems, combining fuel cells with batteries or ultracapacitors to enhance power density and manage peak loads more effectively, potentially improving overall efficiency and extending operational range in EVs. Advanced control strategies, such as model predictive control (MPC) or adaptive algorithms, could be explored to optimize the duty cycle and voltage regulation under varying environmental conditions, further reducing energy losses and enhancing system reliability.

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