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A NOVEL HIGH-GAIN DC-DC CONVERTER APPLIED IN FUEL CELL VEHICLES

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Abstract: **Fuel cell vehicles (FCVs) require DC-DC converters with high-gain, low voltage stress, and high efficiency to efficiently manage the power conversion between the fuel cell stack and the electric drivetrain. Conventional boost converters, including two-level, three-level, and cascaded topologies, struggle to meet these stringent demands, particularly in terms of voltage gain and efficiency.This paper proposes a novel non-isolated DC-DC converter that incorporates switched-capacitor and switched-inductor techniques to achieve high voltage gain with a wide input range, low voltage stress across components, and a common ground structure. The converter's operating principles, component design, and comparative performance analysis with other high-gain topologies are presented. Additionally, the state-space averaging and small-signal modeling methods are employed to develop a dynamic model of the proposed converter.Simulation and experimental results validate the proposed converter's performance. The experimental prototype operates with an input voltage range of 25V to 80V, delivering a rated output of 200V with a power rating of 100W and a peak efficiency of 93.1%. The novel converter is particularly suitable for fuel cell vehicle applications due to its high efficiency, reduced size, and the ability to handle wide input voltage variations, contributing to improved energy management in FCV powertrains.**

Keyword: **Fuel cell vehicles, DC-DC converter, switchedcapacitor and switched- inductor, high-gain, low voltage stress.**

I. INTRODUCTION

The rapid advancement of the transportation industry plays a crucial role in economic development worldwide. However, the heavy reliance on conventional fuel vehicles has led to a substantial increase in oil consumption and significant environmental issues, such as air pollution and greenhouse gas emissions. To address these concerns, there is a growing global interest in clean energy alternatives, especially in the automotive sector, where fuel cell vehicles (FCVs) represent a promising solution.

Fuel cell vehicles are considered a key technology for the future of transportation due to their ability to generate electricity through an electrochemical reaction that combines hydrogen and oxygen, producing water as the only byproduct. FCVs offer several advantages, including zero emissions, high energy efficiency, and minimal environmental impact. These benefits position FCVs as a vital component in reducing global carbon emissions and achieving a sustainable energy future.

Despite these advantages, the practical implementation of FCVs faces several technical challenges, particularly in managing the power conversion between the fuel cell stack and the vehicle's electrical systems. One of the critical issues is the lowand variable output voltage of fuel cells, which is often insufficient to meet the high voltage requirements of modern electric vehicles. Additionally, fuel cells exhibit a"soft" voltage characteristic**,** where the output voltage decreases significantly as the output current increases. These characteristics create the need for a high-gain, efficient, and compact DC-DC converter to step up the fuel cell voltage to a stable, usable level for the vehicle's drive system.

Traditional DC-DC converter topologies, such as boost converters, cascaded converters, and three-level converters**,** face limitations when applied to fuel cell systems. These converters either offer limited voltage gain**,** high voltage stress across components**, or** increased size and complexity. Moreover, isolated DC-DC converters, which utilize transformers, introduce additional issues such as electromagnetic interference (EMI)**,** leakage inductance**,** and higher costs due to the bulky nature of transformers. As a result, there is a clear need for a more efficient and optimized solution tailored to the specific demands of fuel cell vehicles.

II. PRINCIPLE OF THE PROPOSED CONVERTER

The proposed DC-DC converter for fuel cell vehicles utilizes a combination of switched-capacitor and switched-inductor techniques to achieve high voltage gain while maintaining a simple and efficient topology. The main objective of this converter is to boost the low and variable output voltage from the fuel cell to a higher, more stable voltage that can be utilized by the vehicle's electrical system, such as the DC bus and inverter. Additionally, the converter minimizes voltage stress on components, avoids extreme duty cycles, and maintains a common ground structure between the input and output.The working principle of the proposed converter can be explained in several key stages, focusing on how energy is transferred, stored, and boosted during each part of the switching cycle:

1. Basic Structure:

- Switched capacitors: These help in stepping up the voltage by charging and discharging through various stages.
- Switched inductors: These act to store and transfer energy during the switching process, further enhancing the voltage gain.
- Power switches (MOSFETs): These switches control the charging and discharging cycles of the capacitors and inductors.
- Diodes: These are used to control the current flow, preventing reverse current and aiding in the energy transfer process.

2. Switching States

The operation of the converter can be broken down into two main switching states:

State 1 (Switch ON)

- When the power switch is turned ON, the inductors start charging from the input power source (the fuel cell in this case).
- During this time, the capacitors discharge, transferring energy to the load, which helps in boosting the output voltage.
- This phase is crucial for storing energy in the inductors, which will later be released when the switch is turned off.

State 2 (Switch OFF)

- When the power switch is turned OFF, the energy stored in the inductors is released.
- The inductors transfer this stored energy to the output side, which is further boosted by the capacitors.
- The diodes help control the direction of current flow, ensuring that energy flows towards the output without reverse leakage.
- The capacitors are recharged during this phase, preparing for the next cycle.

This two-stage energy transfer process allows the converter to achieve a much higher voltage gain compared to conventional boost converters.

3. Voltage Gain

The voltage gain of the proposed converter is significantly higher than that of a traditional boost converter. The gain can be controlled by adjusting the duty cycle of the power switch and the number of capacitors and inductors used in the design. Unlike conventional boost converters, which experience severe voltage stress on components and limited voltage gain at high duty cycles, the proposed converter achieves higher gain without extreme stress on any single component.

4. Low Voltage Stress

A major advantage of the proposed converter is that the voltage stress across the power switches and diodes is much lower compared to traditional boost converters. This is achieved by distributing the voltage across multiple capacitors and inductors, rather than concentrating it on a single switch or diode. This lowers the risk of component breakdown, increases reliability, and allows the use of lower-cost components with lower voltage ratings.

5. Common Ground Structure

The converter maintains a common ground between the input and output, which simplifies the control and feedback mechanism. This common ground structure also helps to reduce electromagnetic interference (EMI), which can be a significant issue in high-power applications such as fuel cell vehicles.

6. Dynamic Response and Stability

In addition to high voltage gain and low voltage stress, the proposed converter offers fast dynamic response and stable output voltage, even when the input voltage varies significantly (as in the case of fuel cells). This stability is achieved through proper selection of component parameters and advanced control techniques, such as pulse-width modulation (PWM), ensuring that the DC bus voltage remains constant under varying load and input conditions.

7. Operating Modes

- Continuous Conduction Mode (CCM): The converter operates in this mode when the inductors carry current continuously, leading to smoother voltage conversion and reduced switching losses.
- Discontinuous Conduction Mode (DCM): In this mode, the inductor current falls to zero during each switching cycle. Although less efficient than CCM, this mode can be useful for light load conditions.

III. RESULT & DISCUSSION

This block diagram represents a high-gain DC-DC converter suitable for fuel cell vehicles. The converter efficiently steps up low DC input voltage to a much higher level through a combination of switched-inductor and switched-capacitor networks, MOSFET switching, and precise PWM control. This design also incorporates feedback mechanisms to maintain voltage regulation and protect the system under varying load conditions, making it an ideal solution for the fluctuating power characteristics of fuel cells.

Dynamic Operation of the System:

1. **High-Gain Boost Conversion**: The converter's main job is to boost the low voltage from the fuel cell or battery (e.g., 25-80 V) to a much higher output voltage (e.g., 200 V). This is achieved through the combination of switched inductors and capacitors, which provide the necessary voltage gain beyond that of a traditional boost converter.
2. **Voltage Regulation**: The feedback loop continuously senses the output voltage and adjusts the duty cycle of the PWM to maintain the desired output voltage despite fluctuations in input voltage or load conditions.
3. **Current Flow**: Current flows through the inductors during the switch "on" phase, storing energy in the magnetic field, and when the switch is turned "off," this energy is transferred to the output through the capacitors and diodes.

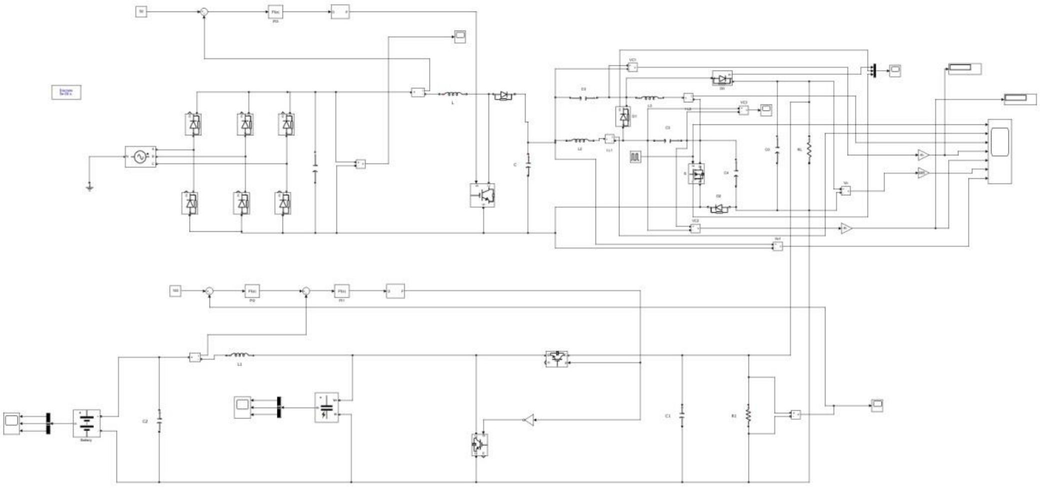

Fig.1: Block diagram

1. Input Power Source

- **Battery or Fuel Cell (DC Source)**:
  - The input power is likely coming from a fuel cell or battery. The fuel cell outputs a relatively low and unregulated DC voltage, which is passed through an input filter to smooth out voltage variations.
  - Capacitors (C1, C2) are used near the power source to filter out noise and stabilize the voltage.

2. Switched Inductor and Switched Capacitor Network

- The heart of the high-gain converter is a network of inductors (L1, L2) and capacitors (C1, C2, C3), combined with switches (S) and diodes (D). This network functions as a switched-capacitor and switched-inductor converter, responsible for stepping up the low input voltage to a much higher level.
- Switched-Inductor: Inductors are used to store energy when the switch is on, and then discharge it into the circuit when the switch is off, allowing for a higher voltage output.
- Switched-Capacitor: Capacitors charge and discharge in synchronization with the switching actions, contributing to the voltage multiplication effect.

3. Power Switches and Diodes

- MOSFETs (S): Power switches, typically MOSFETs, are used for the high-speed switching required for controlling the flow of energy between the input and output stages. The switches are controlled by PWM signals (Pulse-Width Modulation), which regulate how long the switches stay on/off, controlling the voltage gain.
- Diodes (D0, D1, D2): These components are used for energy direction and rectification, ensuring that current flows in the correct direction during the switching cycles.

4. Pulse-Width Modulation (PWM) Control

- PWM Blocks (such as PWM1, PWM2 in the diagram):
  - These generate the control signals for the switches (MOSFETs) by varying the duty cycle. The duty cycle controls how much time the switch stays in the "on" state during each cycle, directly affecting the output voltage.
  - A higher duty cycle typically results in a higher output voltage, and vice versa.

5. Output Voltage Sensing and Control

- Voltage Feedback (VC1, VC2): The system continuously monitors the output voltage (Vo). Feedback loops adjust the PWM signals to regulate the output voltage, ensuring stability and avoiding voltage spikes.

- Comparator and Operational Amplifiers: These components help compare the actual output voltage with the reference voltage and generate the error signal, which is used to adjust the switching duty cycle accordingly.

6. Load (RL)

- Resistive Load (RL): This represents the load (such as an electric motor or auxiliary systems in a fuel cell vehicle) that consumes the power generated by the DC-DC converter. The system is designed to ensure that even with fluctuating input (from the fuel cell), the load receives a stable high voltage.

7. Common Ground Structure

- The entire system shares a common ground, which simplifies the design and ensures that the converter can easily be integrated into the fuel cell vehicle’s existing electrical system.

8. Control and Protection

- The control blocks (VC3, etc.) likely contain safety mechanisms to protect the system from overvoltage, undervoltage, or short-circuit conditions. These can shut down the converter or adjust the switching mechanism in the case of an anomaly.

9. Capacitors and Inductors in the Output Stage

- The capacitors (C3, C4) and inductors (L3) near the output are likely there to smooth out the ripples in the output voltage, ensuring a steady, regulated DC voltage is provided to the load.

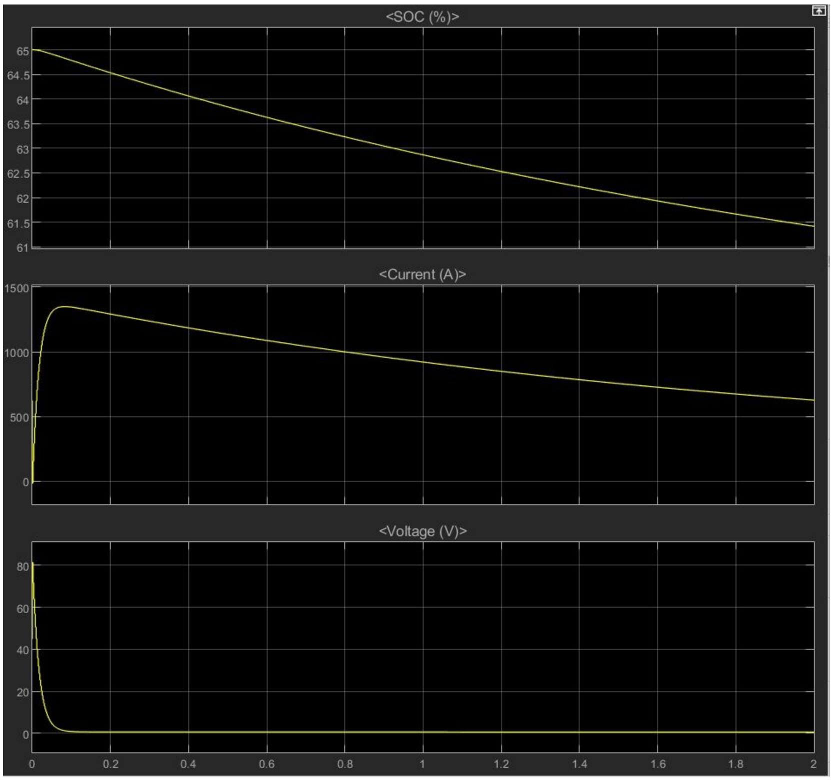

Fig.2: State of Charge (SOC %), Voltage (V), andCurrent (I) over time

1. SOC (%) - State of Charge

- **Y-axis (SOC %)**: This represents the state of charge of the battery or energy storage system (such as a fuel cell's auxiliary battery). It is expressed as a percentage.
- **X-axis (Time)**: The time over which the system is simulated, likely in seconds.
- **Graph Behavior**: The SOC (%) starts at around 65% and decreases gradually over time. This indicates that the battery or energy storage is discharging**,** which is expected during active operation where power is being drawn to supply the load.
  - **Interpretation**: This graph shows a steady decline in SOC, suggesting that the load is continuously drawing power from the energy source without any recharge phase. It also suggests that the system is working as intended, gradually consuming the available charge.

2. Current (A)

- **Y-axis (Current in Amps, A)**: This represents thecurrentbeing drawn from the power source.
- **X-axis (Time)**: Similar to the SOC graph, the time axis is also in seconds.
- **Graph Behavior**: The current spikes sharply to around 1500 A initially and then gradually decreases to stabilize around 1000 A over time. This type of behavior is typical when a system is first powered on or when a load is initially applied.
  - **Interpretation**: This shows a high initial inrush current**,** which can be expected when a converter is first activated or when the load is applied. After this inrush period, the current stabilizes, indicating that the system has reached a steady operating condition, with the load drawing current consistently.

3. Voltage (V)

- **Y-axis (Voltage in Volts, V)**: This shows the output voltage of the DC-DC converter.
- **X-axis (Time)**: Time over which the voltage is monitored, similar to the other graphs.
- **Graph Behavior**: The voltage rises sharply to about 80V within the first few milliseconds and then stays constant.
  - **Interpretation**: This indicates that the converter has rapidly stepped up the input voltage and stabilized it at around 80V. This behavior is typical of a boost converter**,** which increases the input voltage to a higher and stable output level. The system has reached a steady state, maintaining a consistent output voltage.
- **SOC**: The SOC graph shows that energy is gradually being consumed over time, indicating that the converter is supplying power to the load from the battery or fuel cell.
- **Current**: The initial inrush current is quite high, which is typical when the system first starts, but it quickly stabilizes. This indicates that the load has high power demand initially, which then reduces as the system stabilizes.
- **Voltage**: The voltage rises quickly to 80V and remains stable, demonstrating the ability of the DC-DC converter to maintain a constant output voltage after startup.

These graphs reflect the dynamic response of the system during startup and steady-state operation. The system behavior is consistent with typical high-gain DC-DC converters, which experience initial transients followed by stabilization.

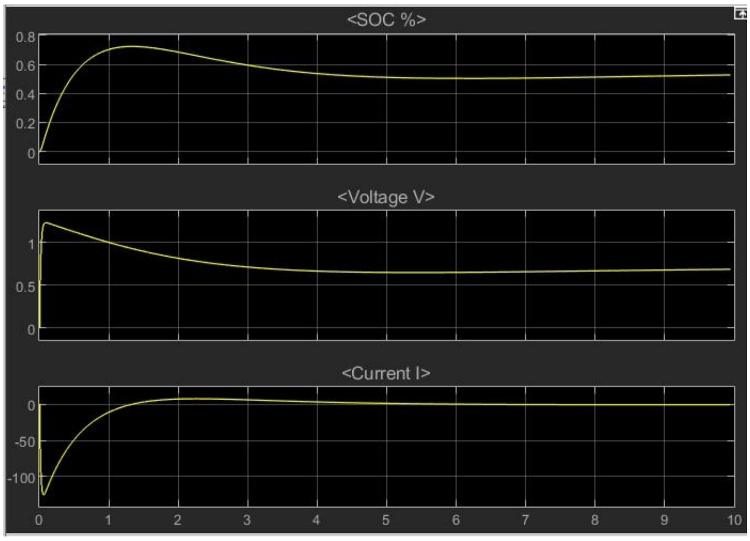

Fig.3: State of Charge (SOC)%, Current (A), and Voltage (V)

- **SOC (%)**: The system starts with a charging phase (initial rise in SOC), followed by a gradual discharge as power is drawn from the storage.
- **Voltage (V)**: The system experiences a quick voltage rise, which drops over time and stabilizes, showing that the converter is stepping up the voltage and then stabilizing it as needed.
- **Current (I)**: Initially, there is a strong current draw (negative value) during startup, which stabilizes as the system reaches steady-state operation.

1. SOC (%) - State of Charge

- **Y-axis (SOC %)**: The state of charge as a fraction or percentage.
- **X-axis (Time)**: Time measured in seconds.

- **Graph Behavior**: Initially, SOC rises sharply from 0 to around 0.65 (65%), then gradually drops over time before flattening out.
  - **Interpretation**: This behavior likely represents a charging phase, where the system first charges the energy storage (battery or capacitor), after which it begins to discharge gradually as power is drawn from it. The flattening suggests that the charge is stabilizing or reaching equilibrium.

2. Voltage (V)

- **Y-axis (Voltage in Volts, V)**: The output voltage across the load or the converter.
- **X-axis (Time)**: Time in seconds.
- **Graph Behavior**: The voltage spikes quickly to about 1.0V**,** then decreases steadily before stabilizing at around 0.6V.
  - **Interpretation**: This indicates a boost in voltage followed by a gradual drop as the load consumes power. The voltage stabilizes after some time, suggesting the converter is working to maintain a lower, steady-state voltage level after the initial transient surge.

3. Current (I)

- **Y-axis (Current in Amps, A)**: Current supplied by the source.
- **X-axis (Time)**: Time in seconds.
- **Graph Behavior**: The current initially drops below **-**100A**,** then quickly rises to about -50A and stabilizes.
  - **Interpretation**: The negative current suggests discharging or current flowing in the opposite direction, likely from the energy storage or fuel cell. The initial steep drop represents the inrush or initial charging phase, and then the current stabilizes at a moderate discharge level over time.

IV. CONCLUSION

The development of high-efficiency DC-DC converters is crucial for the successful integration of fuel cell technology into the transportation sector, particularly in light of the growing need for sustainable and environmentally friendly energy solutions. The proposed DC-DC converter design leverages switched-capacitor and switched-inductor techniques to address the specific challenges faced by fuel cell vehicles, including low output voltage and the requirement for a stable DC bus voltage. In summary, the proposed high-gain DC-DC converter represents a significant advancement in the field of power electronics for fuel cell applications. Its innovative design not only addresses the specific limitations of conventional boost converters but also paves the way for improved energy efficiency and sustainability in the transportation sector. As the industry moves toward greater adoption of clean energy vehicles, such converter technologies will play a pivotal role in ensuring reliable and effective power management systems. Future work will focus on further optimizing the design for enhanced performance, cost-effectiveness, and integration into commercial fuel cell vehicle platforms.

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