A BIDIRECTIONAL DC-DC CONVERTER FOR FUEL CELL ELECTRICAL VEHICLE DRIVING SYSTEM

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ABSTRACT

This paper presents a bidirectional DC-DC converter for a fuel cell electric vehicle driving system. A new isolated bidirectional DC-DC converter topology has differing fuel cell characteristics from traditional chemical-power battery. Fuel cell generates continues electricity when hydrogen as a fuel is supplied and the advantage of fuel cell is that it has clean electricity generation. This converter has the advantages of high efficiency, simple circuit, and low cost. A dc–dc converter is used to draw power from the auxiliary battery to boost the high-voltage and to feedback and stored energy during the regenerated braking.

Keywords –Bidirectional dc-dc converter, electric vehicle, fuel cell

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1. Introduction

In recent years, growing concerns about environmental issues have demanded more energy efficient non-polluting vehicles. The rapid advances in fuel cell technology and power electronics have enabled the significant developments in fuel cell powered electric vehicles. The fuel cells have numerous advantages such as high density current output ability, clean electricity generation and high efficiency operation. However, the fuel cell characteristics are different from that of the traditional chemical powered battery. The fuel cell output voltage drops quickly when first connected with a load and gradually decreases as the output current rises. The fuel cell also lacks energy storage capability. Therefore, in electric vehicle applications, an auxiliary energy storage device (i.e.lead-acid battery) is always needed for a cold start and to absorb the regenerated energy fed back by the electric machine. A bidirectional dc-dc converter allows transfer of power between two dc sources, in either direction. A bidirectional dc–dc converter is needed to draw power from the auxiliary battery to boost the high-voltage bus during vehicle starting. Until the fuel cell voltage raises to a level high enough to hold the high-voltage bus, the excess load from the battery will be released. The regenerated braking energy can also be fed back and stored in the battery using the dc–dc converter.

This system has the advantages of high efficiency, simple circuit and low cost. Isolating the low and high voltage sides satisfies the safety requirements. According to the power flow directions, there are two operation modes for the proposed converter. When power flows from the low-voltage side (LVS) to the high-voltage side (HVS), the circuit operates in boost mode to draw energy from the battery. In the other power flow direction, the circuit operates in buck mode to recharge the battery from the high-voltage dc bus. When the dc bus voltage in the HVS is not at the desired high level, such as during a cold start, the power drawn from the low-voltage battery flows into the high-voltage dc bus. During this mode, the proposed converter is operated as a current-fed circuit to boost the HVS bus voltage. Different from the traditional electric vehicle driving system, the fuel cell powered system needs an additional energy storage device to absorb the feedback power from the electric machine. This energy storage device may be a lead-acid battery then the circuit works in buck mode to recharge the battery from high-voltage dc bus. During this mode, the proposed converter is operated as an asymmetrical half bridge circuit.

2. Literature Survey

2.1 Bidirectional DC-DCConverters

Most of the existing bidirectional dc-dc converters fall into the generic circuit structure as shown in fig..2.1which is characterized by a current fed or voltage fed on one side. Based on the placement of the auxiliary energy storage, the bidirectional dc-dc converter can be categorized into buck and boost type. The buck type is to have energy storage placed on the high voltage side, and the boost type is to have it placed on the low voltage side [1], [2].

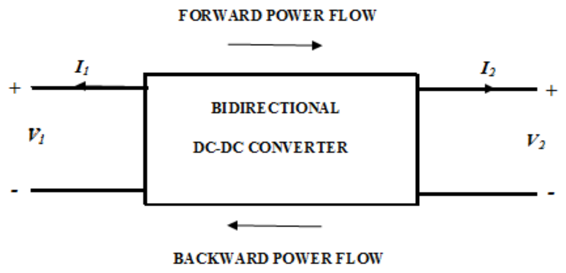

Fig.2.1 Power Flow in Bidirectional DC-DC Converter

There two types of bidirectional dc-dcConverters namely non-isolated bidirectional dc-dc converters andisolatedbidirectional dc-dc converters.

2.1.1 Non-Isolated Bidirectional Dc-Dc Converter

Non-isolated bidirectional dc-dc converters are simpler than isolated bidirectional dc-dc converter and can achieve better efficiency. The transformer less type is more attractive in high power applications. For the present high power density bidirectional dc-dc converter, to increase its power density, multiphase current interleaving technology with minimized inductance has been found in high power applications

2.1.2Isolated Bidirectional Dc-Dc Converters

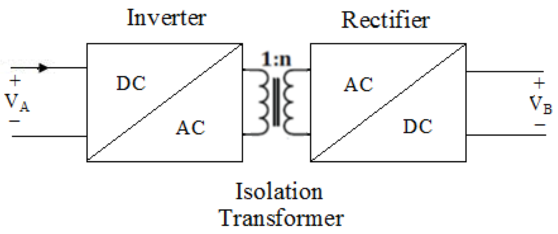

Fig.2.2 Block diagram of bidirectional DC-DC Converter

Galvanic isolation between multi-source systems is a requirement mandated by many standards. Personnel safety, noise reduction and correct operation of protection systems are the main reasons behind galvanic isolation.In the bidirectional dc-dc converters, isolation is normally provided by a transformer. The block diagram for isolated bidirectional dc-dc converters is shown below.

2.2 Fuel Cell

The fuel cell concept was first introduced in 1839 by Sir William Robert Grove, who realized that reversing the process of electrolysis (splitting water to form hydrogen and oxygen using electricity) could result in a process that would create electricity

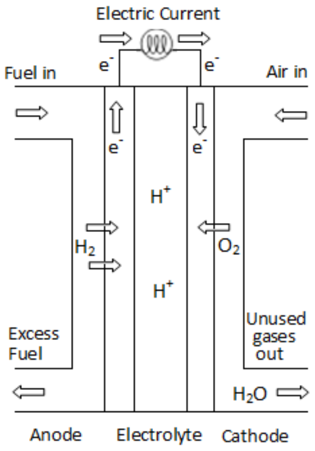

Fig.2.3 Circuit diagram of fuel cell

Although there are several different types of fuel cells, they all operate on the same basic concept of electrochemical reaction of fuel and oxygen to produce water, direct current electricity and heat. Fuel cells (essentially) consist of an anode, cathode, electrolyte, external electrical circuit, and fuel/air supply. Fuel is delivered to the anode, and an oxygen-rich mixture is delivered to the cathode. Ions migrate through the electrolyte and electrons flow through the external circuit, creating the electrical current.

There different types of fuel cell and they are classified as follows [3].

2.2.1. Solid Oxide Fuel Cells

Solid Oxide Fuel Cells (SOFCs) are high temperature fuel cells that use a solid electrolyte to conduct oxygen ions. The two geometries of SOFCs that are being developed are (a) tubular and (b) planar types. The cell is constructed with two porous electrodes that sandwich an electrolyte.

Air flows along the cathode. When an oxygen molecule contacts the cathode/electrolyte interface, it acquires electrons from the cathode. The oxygen ions diffuse into the electrolyte material and migrate to the other side of the cell where they contact the anode. The oxygen ions encounter the fuel at the anode/electrolyte interface and react catalytically, giving off water, heat, and electrons. Carbon dioxide is another product of SOFC operation where hydrocarbon fuels are employed. Also it has higher operating temperature capacity.

2.2.2Polymer Electrolyte Membrane Fuel Cell

PEMFCs have high power density, rapid start-up and low temperature operation. This makes them ideal for use in transport and battery replacement. The present cost of PEMFC systems is high and does not assist its cause in the stationary power generation market. Polymer Electrolyte Membrane Fuel Cells operate in a temperature range of 60-80^oC and use a solid, proton conducting fluorinated sulfuric acid or similar polymer as electrolyte, such as NaFion from DuPont. This solid electrolyte allows a compact construction of the fuel cell and also allows more straight forward operation under pressure, which can improve the performance considerably.

2.2.3 Direct Methanol Fuel Cell

The Direct Methanol Fuel Cell (DMFC) is closely related to PEM systems: the structure of the fuel cell is almost identical and Nafion has often been used as a membrane. The main drawbacks of the DMFC are the excessive use of expensive materials like platinum and ruthenium, and the toxicity of CH_3OH. Low cell voltage, resulting in low current density, is caused by cross-over of neutral methanol from anode to cathode side. DMFC can be used as a substitution for the classical batteries in small scale, portable appliances such as cell phones, laptops, CD players, etc.

2.2.4. Phosphoric Acid Fuel Cell

Together with the SOFC and the Molten Carbonate Fuel Cell (MCFC), the Phosphoric Acid Fuel Cell (PAFC) is one of the high temperature fuel cells. Its operating temperature is approximately 200°C and it uses concentrated phosphoric acid as the electrolyte. The oxidant for terrestrial applications is air and the cell usually operates at ambient pressure. The electrodes most important material is platinum but the use of high surface area graphite structurally supporting the platinum has resulted to significant reduction of the platinum loading without reducing the electrodes performance.

3. Research Elaboration

The fig. 3.1 and fig. 3.2 shows the block diagram and circuit diagram of the system respectively.

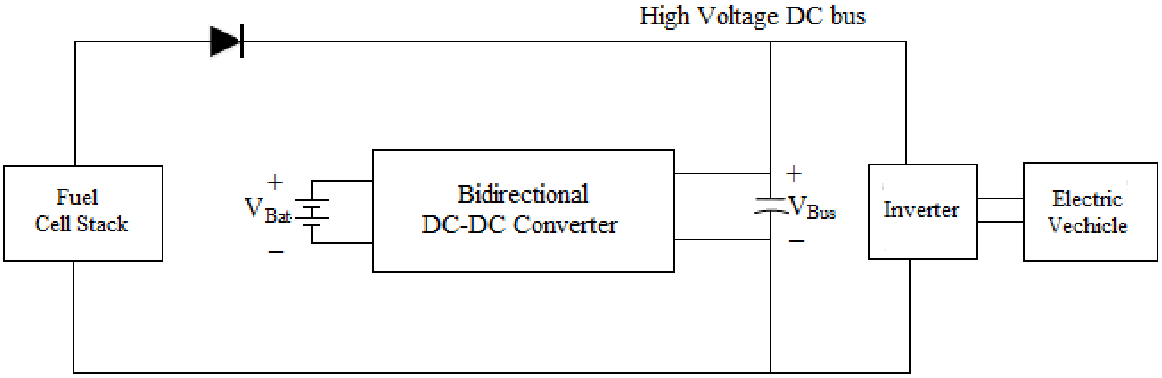

Fig. 3.1 Block diagram of the system

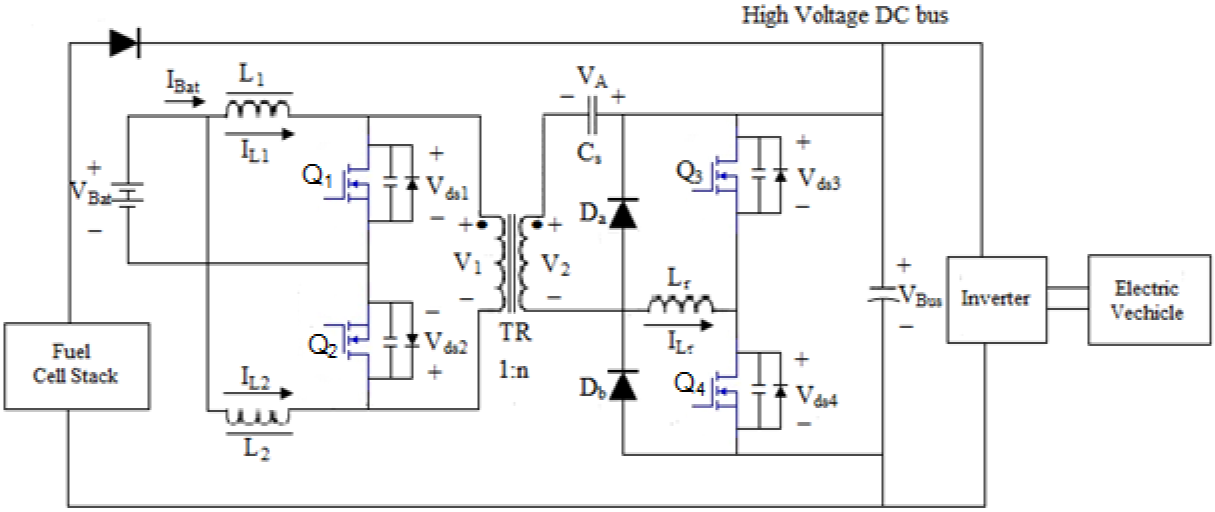

fig..3.2 Circuit diagram of the system

3.1Circuit Diagram Operation

The operational explanation of the circuit diagram in boost mode (discharging mode) and buck mode (charging mode) is given below. [4], [5], [6].

3.1.1Boost Mode (Discharging Mode) Operation

When the dc bus voltage in the HVS is not at the desired high level, such as during a cold start, the power drawn from the low-voltage battery flows into the high-voltage dc bus. During this mode, the proposed converter is operated as a current-fed circuit to boost the HVS bus voltage. The LVS switches Q_1 and Q_2 operate at asymmetrical duty ratios δ and $(1-\delta)$ which require a short overlapping conduction interval. Referring to the equivalent circuits for the boost mode operation in Fig. 3.2, the detailed operating principle can be explained as follows.

Stage 1 (t_0–t_1): At t_0, the LVS switch Q_2 is turned off and the HVS switch Q_3 is turned on. The current from the inductor flows through Q_1 and the transformer LVS winding, closing the loop via the battery. Therefore, the transformer LVS winding carries only I_{L2}. The voltage amplitude across the transformer HVS winding can be clamped to the dc voltage, on the series blocking capacitor with negative polarity while the diode conducts. Thus, the voltage across the transformer LVS winding, is clamped to $(-V_A / n)$. The “ n ” is the transformer turn ratio. The current I_{L2} increases linearly while I_{L1} decreases linearly. Because the battery current I_{Bat}, is the sum of the two inductor currents, the ripple currents cancel each other to produce relatively ripple free dc current that is desirable for the low-voltage battery.

Stage 2 (t_1–t_2): At t_1, the LVS switch Q_2 is turned on and the HVS switch Q_3 is turned off. During this interval, the switches Q_1 and Q_2 are on simultaneously. The voltage across L_2 also becomes negative and its amplitude equals the battery voltage. The inductance current, I_{L2} decreases linearly like the current I_{L1}, The voltage across the transformer winding become zero and the diode is reverse-biased. The voltage on the series blocking capacitor, V_A will force the inductance current $I_{Lr}$to change its direction at t_2.

Stage 3 (t_2–t_3):The inductor L_r resonates with and during this interval. The voltage V_{ds4} across the HVS switch, Q_4 continues to decrease to zero at t_3.
Stage 4 (t_3–t_4): At t_3, the inductor I_{Lr} current starts to flow through the body diode D_4. As long as the switch Q_4 is turned on at t_4, zero-voltage switching can be assured.

Stage 5 (t_4–t_5):At t_4, the LVS switch Q_1 is turned off and the HVS switch Q_4 is turned on. The current from the inductor L_1 flows through Q_2 and the transformer LVS winding, closing the loop via the battery. Therefore, the transformer LVS winding carries only I_{L1}. The voltage amplitude across the transformer HVS winding, V_2 can be clamped to $(V_{Bus}-V_A)$ while the diode D_b conducts. Thus the voltage across the transformer LVS winding, V_1 is clamped to $(V_{Bus}-V_A) / n$. The current increases linearly while decreases linearly. The ripple currents on two inductors cancel each other to produce relatively ripple free dc current for the low-voltage battery.

Stage 6 (t_5–t_6):At t_5, the LVS switch Q_1 is turned on and the HVS switch Q_4 is turned off. During this interval, the switches Q_1 and Q_2 are simultaneously on. The voltage across L_1 also becomes negative and its amplitude equals the battery voltage. The inductance current, I_{L1} decreases linearly like the current $I_{L2.}$ The voltage across the transformer winding becomes zero and the diode is reverse-biased. The voltage across the inductor Lr, $(V_{Bus}-V_A)$ will force the inductance current I_{Lr2} to change its direction at t_6.

Stage 7 (t_6–t_7):The inductor L_r resonates with C_{P3} and C_{P4} during this interval. The voltage across the HVS switch, Q_3 continues to decrease to zero at t_6.

Stage 8 (t_7–t_8): At t_7, the inductor currents I_{Lr} starts to flow through the body diode. As long as the switch Q_3 is turned on at t_8, zero-voltage switching can be assured. The circuit will then precede back to stage 1 after completing one operating cycle T_S.

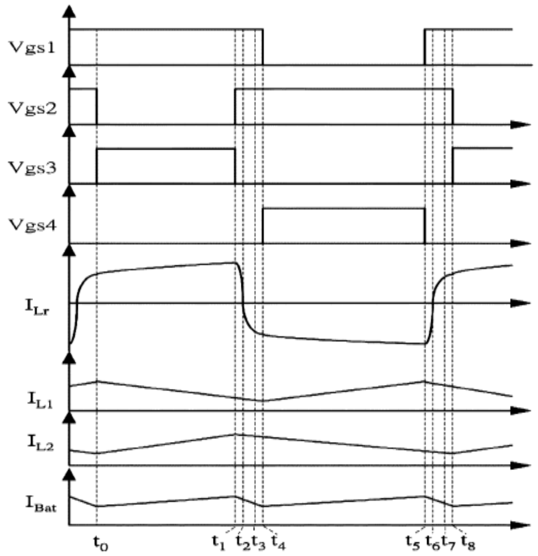

fig.3.3 Theoretical waveforms under boost mode operations.

3.1.2 Buck Mode (Charging Mode) Operation

Different from the traditional electric vehicle driving system, the fuel cell powered system needs an additional energy storage device to absorb the feedback power from the electric machine. This energy storage device may be a lead-acid battery. The proposed circuit works in buck mode to recharge the battery from high-voltage dc bus. During this mode, the proposed converter is operated as an asymmetrical half bridge circuit with synchronous rectification current doubler to recharge the battery from high-voltage dc bus. The HVS switches Q_3 and Q_4 operate at asymmetrical duty ratios δ and $1-\delta$ which require short and well defined dead time between the conduction intervals. The detailed operating principle of this mode can be explained as follows.

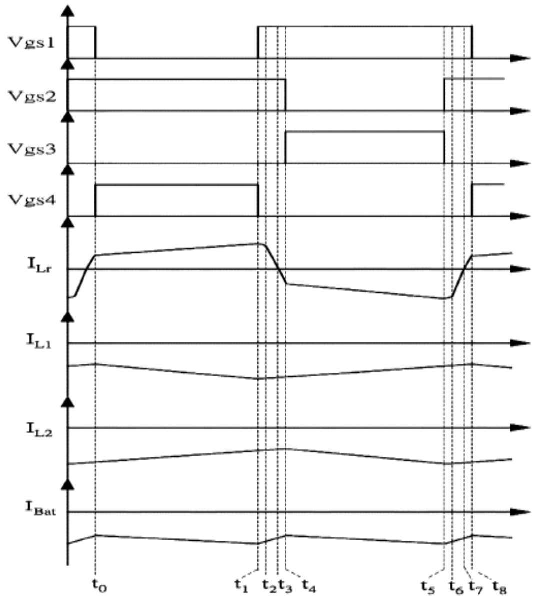

fig. 3.4 Theoretical waveforms under buck mode operations

Stage 1(t_0–t_1):At t_0, the HVS switch Q_4 and the LVS switch Q_2 stay on. The inductance current I_{Lr} is equal I_{L1}/n. The current from the inductor L_1 flows through Q_2 and the transformer LVS winding, closing the loop via the battery. Therefore, the transformer LVS winding carries only $-I_{L1}$. The current I_{L1} increases linearly while $-I_{L2}$ decreases linearly. Since the recharging current $-I_{Bat}$, is the sum of the two inductor currents, the ripple currents cancel each other to produce relatively ripple-free dc current that is desirable for the low-voltage battery.

Stage 2 (t_1–t_2):At t_1, the LVS switch Q_1 is turned on and the HVS switch Q_4 is turned off. During this interval, the switches Q_1 and Q_2 are simultaneously on. The recharging current, $-I_{Bat,}$ freewheels through both the switches, Q_1 and Q_2. The voltage across also becomes negative and equals the battery voltage. Therefore, the inductance current $-I_{L1}$ decreases linearly like the current $-I_{L2}$. The voltage across the transformer winding becomes zero; the inductor resonates with C_{P3} and C_{P4}. The voltage across V_{ds3} the switch, Q_3 continues to decrease to zero at t_2.

Stage 3 (t_2–t_3):At t_3, the current I_{Lr} starts to flow through the body diode D_3. As long as the HVS switch Q_3 is turned on before the inductor current changes its direction at t_3, zero voltage switching can be assured.

Stage 4 (t_3–t_4):While the HVS switch, Q_3 is zero-voltage turned on, the LVS switch, Q_2 is turned off. The resonance caused by inductor L_r and the stray transformer winding capacitor could be clamped while the diode, D_a is conducted. At t_4, D_a is released because the inductance current $-I_{Lr}$ stays at ($-I_{L2}/n$). The stages 5–8 are similar to stages 1–4, respectively. The circuit will then precede back to stage 1 after completing one operating cycle T_S.

4. Result

Due to the present high costof fuel cells as compared to batteries the overall cost of FCEV becomes high but this drawback can be minimized by using battery and ultra-capacitor or by using high efficiency and economical lithium-ion batteries with fuel cell as energy storage elements. These energy storage devices reduces the size of fuel cell and the fuel-cell–battery–ultra-capacitor vehicle has higher fueleconomy and can extend the battery lifetimeand this results in reduction in overall cost of FCEV.

5. Conclusion

In this paper, a high efficiency bidirectional isolated dc–dc converter for fuel cell electric vehicle driving systems is presented. A bidirectional dc–dc converter is used to draw power from the auxiliary battery to boost the high-voltage and to feedback and stored energy during the regenerated braking. This converter has the advantages of high efficiency, simple circuit and low cost over conventional converter.

The fuel cell has lacks energy storage capability and to absorb the regenerated energy fed back by the electric machine therefore, in electric vehicle applications, an auxiliary energy storage device (i.e., lead-acid battery) is used.

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