Design of Efficient DC-DC Converter for Fuel Cell Hybrid Electric Vehicles

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Abstract

In recent years, fuel cells are becoming an attractive power source in automotive applications with dc/dc converter topology. Multiphase converter topologies are used in high performance applications and have received an increasing interest in recent years. This paper proposes the design of dc/dc converter for interfacing with hybrid electric vehicles. The module is designed with two capacitors and one coupled inductor with reduced number of switches to achieve a high step up voltage gain. The proposed dc/dc converter is compared with Multi Device Interleaved Boost Converter (MDIBC) to verify its performance. The dc/dc converter topologies and their controllers are designed using MATLAB/Simulink. The simulation results proved that the proposed converter is more efficient than other dc/dc converter topologies in achieving high performance and reliability for high-power dc/dc converters.

Keywords: DC-DC converter, MDIBC, Fuel cells, Hybrid Electric Vehicles

1. Introduction
In recent years, Fuel Cell (FC) technologies are becoming an attractive power source for automotive applications because of their cleanliness, high efficiency, and high reliability. The massive usage of fossil fuels like oil, coal, and gases results in environmental pollution, global warming, and the rapid depletion of the earth’s petroleum resources, which have a great influence in the world. With the increasing demand for environmentally friendlier and higher fuel economy vehicles, automotive companies are focusing on electric vehicles, hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell hybrid electric vehicles (FCHEVs) to replace conventional vehicles [1,2]. These vehicles enable us to meet the demands for electrical power due to the increasing use of the electronic features to improve vehicle performance and fuel economy. A fuel cell system designed for automotive applications must have low weight, high power density, very high performance, good fuel economy, easy access and safety considerations with respect to fuel handling [3]. Fuel cells proton exchange membrane (PEM) fuel cells are gaining importance for automotive applications due to high power density and smaller size, simple structure and maintenance. However, FCs has the some of the following drawbacks: 1) It cannot store energy; 2) the response is slow; 3) its output voltage fluctuates with the load; and 4) it is difficult to cold start. Although hybrid electric trucks (pickups and tractors) and buses also exist, the most common form of HEV is the hybrid electric car. Some varieties of HEVs use their internal combustion engine to generate electricity by spinning an electrical generator, to either recharge their batteries or to directly power the electric drive motors [4,5].

This paper is organized as follows. Section 2 describes the objective of the work. Section 3 illustrates the conventional design of multi device interleaved boost converter. Section 4 highlights the design of proposed dc-dc converter and fuel cell hybrid electric vehicle. Section 5 presents the results and discussions of the work. Finally, section 6 concludes the work.

2. Research Objectives

The objective of the work is to design a bidirectional isolated dc-dc converter controlled by phase-shift and duty cycle for the fuel cell hybrid energy system. The proposed topology is focused to minimize the number of switches and their associated gate driver components by using two high frequency transformers which combine a half-bridge circuit and a full-bridge circuit together on the primary side. The voltage doubler circuit is to be employed on the secondary side and the current-fed input can limit the input current ripple that is favorable for fuel cells. A phase-shift and duty cycle modulation method is to be utilized to control the bidirectional power flow flexibly and also to make the converter operate under a quasi-optimal condition over a wide input voltage range.

3. Design of Multi Device Interleaved Boost Converter
The main aim of the work is to design and analyze the Multi Device Interleaved Boost Converter to enhance the performance of fuel cell applications. A digital dual-loop control is designed for fast transient response. Several power stages are connected in parallel and driven with gate signals shifted for $360^\circ/(n \times m)$. Interleaving includes the additional benefits such as reduced ripples in both the input and output circuits. The concept of interleaving enables the converter topology to operate at increased power levels[6,7].

![Fig.3.1. Block diagram of the FCHEV.](image)

The block diagram consists of polymer electrolyte membrane fuel cell, dc/dc converter (MDIBC, bidirectional converter), inverter, storage system (ESS) such as battery or super capacitors and motor. The fuel cell converts chemical energy into electrical energy and given as input to MDIBC [8,9]. The DC energy will be given to inverter through bidirectional DC bus and the excessive amount of power is given to bidirectional converter and the energy storage system. The motor gets supply from the inverter. The inverter is used to convert the DC to variable voltage and variable frequency in order to energize the load. DC/DC converter allows the desired level of dc voltage to be obtained without increasing the size of components. The design converter is used to boost the fuel cell voltage and also this converter the amount of power flow between the input and output can be controlled by adjusting the duty cycle. This is done to maintain the constant power for controlling the power regulation particularly for a common DC bus.

The fuel cell hybrid electric vehicle (FCHEV), as shown in Fig.3.1, utilizes FC as the main power source and the ESS (e.g., batteries and super capacitors) as the auxiliary power source to assist the propulsion of the vehicle during transients and to recuperate energy during regenerative braking. A fuel cell system designed for automotive applications must have low weight, high power density, very high performance, good fuel economy, easy access and safety considerations with respect to fuel handling[10]. Among several kinds of fuel cells proton exchange membrane
(PEM) fuel cells are gaining importance for automotive applications due to relatively high power density, smaller size, simple structure and maintenance. However, FCs has the following several shortcomings: 1) It cannot store energy; 2) the response is slow; 3) its output voltage fluctuates with the load; and 4) it is difficult to cold start. Therefore, an auxiliary energy storage systems (ESS) such as a battery or a super capacitor can be hybridized with FC power system to improve the dynamic characteristics. In this configuration, the FC is connected to the DC bus through a boost converter, whereas the ESS is connected to the DC bus via a bidirectional dc/dc converter[11,12]. As mentioned, the dc/dc converter is one of the most important components in a FC powered system. It allows a desired level of dc voltage to be obtained without having to increase the stack size. As a result, this work focused on a non-isolated dc/dc converter that interfaces the FC with the power train of HEVs. In high-power boost converters, the major design aspect is the selection of the boost inductor and the output capacitor[25]. The major concern is the size, cost, and weight of such a high power inductor that is perhaps the single heaviest component in the entire dc/dc converter. To reduce the inductor size and weight, a small inductance value is preferred[13,14]. In addition, the dc/dc converter performance directly influences the characteristics of the FC stack or the ESS (e.g., batteries). Indeed, the ripple and harmonic content of the current is one of the major phenomena that influences FC lifespan as well as battery lifetime. Hence the main objective of this work is to minimize inductor size, capacitor, current/voltage ripples, and harmonic content. The digital control plays an important role in improving the control efficiency in high-power interleaved converter applications and also its better dynamic response[15].

4. DESIGN OF PROPOSED DC-DC CONVERTER

The basic boost converter circuit consists of only a switch, a diode, an inductor, and a capacitor as shown in Fig.4.1. This converter is designed with the input of 24V and it thus produces the output voltage of 400V. The boost converter can provide a high voltage gain with an extremely high duty cycle. In practice, the step up voltage gain is limited by the effect of power switch, rectifier diode and equivalent series resistance of the inductors and capacitors. Also, the extreme duty cycle operation may result in series reverse recovery and electromagnetic interference problems[16,17]. The main aim of this converter design is to reduce the number of power switches and getting maximum efficiency by using a coupled inductor technique. Hence the voltage stress across the switches gets reduced.
A high voltage gain can be achieved by the use of switched capacitor and coupled inductor technique, the converters use coupled inductor technique to achieve a high step up gain. However, the leakage inductor leads to a voltage spike on the main switch and affects the conversion efficiency. For this reason, the converters using a coupled inductor technique have been proposed. Also, several converters combine output voltage stacking to increase the voltage gain and use multiple coupled inductors.

In CCM operation, there are five operating modes in one switching period. The main operating principle is that, when the switch is turned on, the coupled-inductor-induced voltage on the secondary side and magnetic inductor Lm is charged by Vin [18]. The induced voltage makes Vin, VC1, VC2, and VC3 release energy to the output in series. The coupled inductor is used as a transformer in the forward converter. When the switch is turned off, the energy of magnetic inductor Lm is released via the secondary side of the coupled inductor to charge capacitors C2 and C3 in parallel. The coupled inductor is used as a transformer in the flyback converter.

4.1 Bidirectional Converter

The proposed topology minimizes the number of switches and their associated gate driver components by using two high frequency transformers which combine a half-bridge circuit and a full-bridge circuit together on the primary side. The voltage doubler circuit is employed on the secondary side. The current-fed input can limit the input current ripple that is favorable for fuel cells. The parasitic capacitance of the switches is used for zero voltage switching (ZVS) [19,20]. Moreover, a phase-shift and duty cycle modulation method is utilized to control the bidirectional power flow flexibly and it also makes the converter operate under a quasi optimal condition over a wide input voltage range. During the warming-up stage or load transient, super capacitors are utilized as the auxiliary power source for smoothing the output power. In addition, the fuel cell output voltage is varied widely, almost 2:1, depending on the load condition, and the terminal voltage of the super capacitor bank is also variable during charging and discharging periods.
As shown in Fig.4.2, a structure locates on the primary side of the transformer T1 and associates with the switches S1 and S2 operating at 50% duty cycle. The super capacitor bank is connected to the variable low voltage (LV) DC bus across the dividing capacitors, C1 and C2. Bidirectional operation can be realized between the super-capacitor bank and the high voltage (HV) DC bus. Switches S3 and S4 are controlled by the duty cycle to reduce the current stress and AC RMS value when input voltage VFC or VSC are variable over a wide range. A DC blocking capacitor Cb is added in series with the primary winding of T2 to avoid transformer saturation caused by asymmetrical operation in full-bridge circuit. The voltage doubler circuit utilized on the secondary side is to increase voltage conversion ratio further. The inductor L2 on the secondary side is utilized as a power delivering interface element between the LV side and the HV side. In the boost mode, the power is delivered from the fuel cells and super capacitors to the DC voltage bus. In the super-capacitor power mode, only the super capacitors are connected to provide the required load power. When the DC bus charges the super capacitors, the power flow direction is reversed which means the energy is transferred from the HV side to the LV side, and thereby the converter is operated under the super capacitor mode.

### 4.2 Fuel Cell Based Vehicle Propulsion System

A fuel cell system designed for vehicular propulsion applications must have a weight, a volume, a power density, a startup, and a transient response similar to present day ICE-based vehicles. Other requirements are: 1) very high performance for a short time; 2) rapid acceleration; 3) good fuel economy; and 4) easy access and safety considerations with respect to fuel handling. The cost and the expected lifetime are also very important considerations[21]. The output voltage of the fuel cell stack is conditioned to be compatible with the battery voltage using a power conditioner, which could be a step-up or step-down converter, depending on the voltage levels of the fuel cell and the battery. An inverter is used to convert the dc to variable voltage and variable frequency to power the propulsion motor. A battery or an ultra capacitor is generally connected across the fuel cell system to provide supplemental power and for starting the system. Proton Exchange Membrane PEM
fuel cells are gaining importance for automotive propulsion applications for the following reasons:

1) easy start at ordinary temperatures below 100 °C;
2) relatively high power density and smaller size;
3) simple structure and maintenance;
4) ruggedness to the shock and vibrations.

4.3 Hybrid Electric Vehicle

Hybrid vehicles have two or more sources of energy and/or two or more sources of power onboard the vehicle. The sources of energy can be a battery, a flywheel, etc. The sources of power can be an engine, a fuel cell, a battery, an ultra capacitor, etc. Depending on the vehicle configuration, two or more of these power or energy sources are used. Hybrid vehicles save energy and minimize pollution by combining an electric motor and an internal combustion engine (ICE) in such a way that the most desirable characteristics of each can be utilized. Hybrid vehicles are generally classified as series hybrids and parallel hybrids[22]. In a series hybrid vehicle, the engine drives the generator, which, in turn, powers the electric motor. In a parallel hybrid vehicle, the engine and the electric motor are coupled to drive the vehicle. A series hybrid vehicle can offer lower fuel consumption in a city driving cycle by making the ICE consistently operate at the highest efficiency point during frequent stops/starts. A parallel hybrid vehicle can have lower fuel consumption in the highway driving cycle, in which the ICE is at the highest efficient point while the vehicle is running at constant speed. Hybrid vehicles are also divided into mild hybrids, power hybrids, and energy hybrids, according to the role performed by the engine and the electric motor and the mission that the system is designed to achieve. A plug-in hybrid vehicle can be a series or parallel hybrid, with the battery being charged onboard the vehicle and being externally charged by the utility grid, thus increasing the range when operating in pure electric mode[24].

4.4 ENERGY STORAGE SYSTEMS

The peak power required in hybrid vehicles is met by devices like batteries, capacitors or a flywheel. These devices store energy and readily release it when needed.

4.4.1 Batteries

Batteries are one of the most important parts of a hybrid vehicle. A battery produces electricity by means of chemical action. It consists of one or more electric cells. Each cell has all the chemicals and parts needed to produce an electric current. There are two types of batteries: primary and secondary (or storage) batteries. Primary batteries discharge and must be discarded after one or more of the chemicals is used up. Secondary batteries, on the other hand, can be recharged after they have delivered their electrical energy. Consequently, secondary batteries are ideal for hybrid application. They are able to supply power to the vehicle and be
re-used. The criteria used for battery selection are: temperature, energy density, power density, service life, shelf life, cost, reliability, cell configuration, charge/discharge cycle, safety, operating environment, recycling, minimal memory effect and efficiency[23].

4.4.2 Capacitors
A capacitor is a device that stores electrical energy in the form of an electrical charge. It consists of two metal plates with an insulating material called a dielectric between them. Wires usually connect the plates to a source of electric current such as a battery. When an electric charge flows through the wires from one plate of the capacitor to the other, both plates become charged one with a positive charge, and the other with a negative charge. The two plates then have potential difference in energy a voltage between them. The plates release their charge when their wires are disconnected from the source and touched together. The ability of the capacitor to store electric energy is its capacitance. The main difference between a battery and a capacitor is that a capacitor can be rapidly charged and discharged.

5. Results and Discussion
The main aim of this converter design is to reduce the number of power switches and getting maximum efficiency by using a coupled inductor technique. Hence the voltage stress across the switches gets reduced. This converter designed is interfaced with the fuel cell and the bidirectional converter is designed for charging and discharging of battery. Finally the proposed converter is compared with the conventional converter as Multi Device Interleaved Boost Converter.

Fig.5.1. Current waveforms of high step up dc-dc converter

Fig.5.2. Voltage waveforms of high step up dc-dc converter
The output voltage and current obtained as 400 V and 0.5 A. The waveforms settles at the respective values and the ripple factor is minimized to certain values with minimum number of switches.

### 5.1 Bidirectional Converter
The output voltage and reference voltage are given as the input voltage to the bidirectional converter. 500V reference voltage is considered as the minimum amount of voltage required to run the motor.

![Fig 5.3. Charging and discharging waveforms](image)

The charging and discharging of battery is shown in Fig.5.3. The battery is linearly discharge the energy for the HEV using bidirectional boost converter. Hence battery is mainly used for normal speed operations. When the vehicle goes beyond the speed limit the battery cannot able to withstand for discharging energy.

### 5.2 Fuel Cell Hybrid Electric Vehicle
The converter gets input from the fuel cell and gating signals from the dual loop control strategy. Voltage and current waveforms are given to inverter and the excessive charge flows to bidirectional converter through DC bus. Finally the motor is driven by signals obtained from inverter.
Fig.5.4. Voltage and Current waveforms of FCHEV

The above graph shows that the converter is connected to the motor load for fuel cell hybrid electric vehicle with the 460 V as output voltage.

<table>
<thead>
<tr>
<th>Type</th>
<th>Number of switches used</th>
<th>Ripple ratio</th>
<th>Steady state</th>
<th>Power taken by the switch(W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional (MDIBC)</td>
<td>4</td>
<td>13</td>
<td>0.08</td>
<td>7</td>
</tr>
<tr>
<td>Proposed (High step up dc-dc converter)</td>
<td>1</td>
<td>0.8</td>
<td>0.03</td>
<td>0.03</td>
</tr>
</tbody>
</table>

TABLE I results proved that the proposed high step up dc-dc converter design required less number of switches, less ripple ratio values and less power compared with the conventional MDIBC Converter.

6. Conclusion

A high step dc-dc converter has been modeled in this work. The simulation result shows that the maximum output voltage has been obtained by this converter technique. Moreover the voltage stress across the switch gets reduced due to the use
of single switch. Compared with Multi Device Interleaved Boost Converter, the proposed design utilized less number of switches. Therefore, the proposed converter seems to be very promising in high power FC systems to extend their lifespan as well as battery systems. The proposed converter can improve efficiency with reduced number of switches and leads to high reliability compared with other dc/dc converter topologies.

References


