Application of Negative DC Bus Embedded Type Z-Source Inverters in Hybrid Electrical Vehicles

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Abstract

This paper presents a Z-source inverter control approach used to control power from the fuel cell, power to the motor, and state of charge (SOC) of the battery for fuel cell (FC)—battery hybrid electric vehicles FCHEV). Traditional pulse width modulation inverter always requires an extra dc/dc converter to interface the battery in FCHEV's.Z-source inverter has the capability to boost voltage and invert at single stage itself. By substituting one of the capacitors in the Z-source with a battery and controlling the shoot through duty ratio and modulation index independently, one is able to control the FC power, output power, and SOC of the battery at the same time. The advantage of negative dc bus type embedded type was reducing the requirement of battery size in vehicular applications. These facts make the proposed Z-source inverter highly desirable for use in FCHEVs, as the cost and complexity is greatly reduced when compared to traditional Z-source inverters. These new concepts will be demonstrated by simulation results.

Keywords: Z-source inverter, negative dc bus embedded type Z-source inverter Fuel cell hybrid electric vehicles (FCHEV), pulse width modulation (PWM), state of charge (SOC).

1. INTRODUCTION

Fuel cells (FCs) have attained global attention as an alternative power source for hybrid electric vehicles (HEVs) [4] . Fuel cell vehicles (FCVs), are being developed by auto manufacturers [7], [8], [10]–[14], and have generated interest among industry, environmentalists, and consumers. A FCV promises the air quality benefits of a battery-powered electric vehicle, with the driving range and convenience of a conventional internal combustion engine vehicle. Because of its nature, a FC prefers to be operated under constant power to prolong its lifetime and it is also more efficient in this way. However, the traction power the vehicle demands is ever changing. To balance the difference of these two and also to handle the regenerative energy, a battery is often used as an energy storage device in FCVs, which forms a FC-battery hybrid electric vehicle (FCHEV). Therefore, basically the traction drive system of a FCHEV consists of a FC stack, a battery pack, a controller (power inverter), and a traction motor. The main source of the vehicle's power is the FC. The secondary power source is the battery, which also stores excess energy from the FC, and from regenerative braking. The four utilized operating modes and the power flow diagrams are outlined in the following.

The type of connections are clearly showed given Fig.1,those connections are respectedly applicable to all modes showed at Fig.2 to Fig.5.active power flow was uncontrolled flow and conditional flow was controlled by set of conditions at time of operating the vehicle by suitable PWM technique.

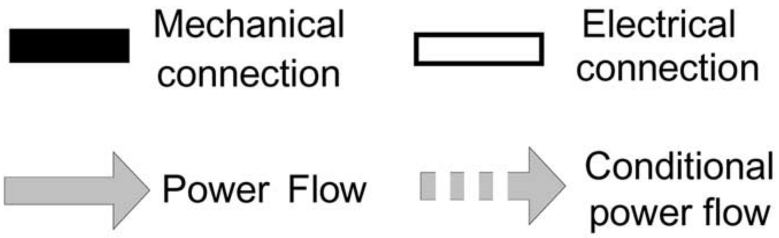


Fig. 1. Type of connections in hybrid vehicle.

1.1. Mode 1, Medium Power (Fig. 2)

Under medium power, the vehicle traction motor only receives power from the FC. The FC can also provide power to the battery if its state of charge (SOC) is low.

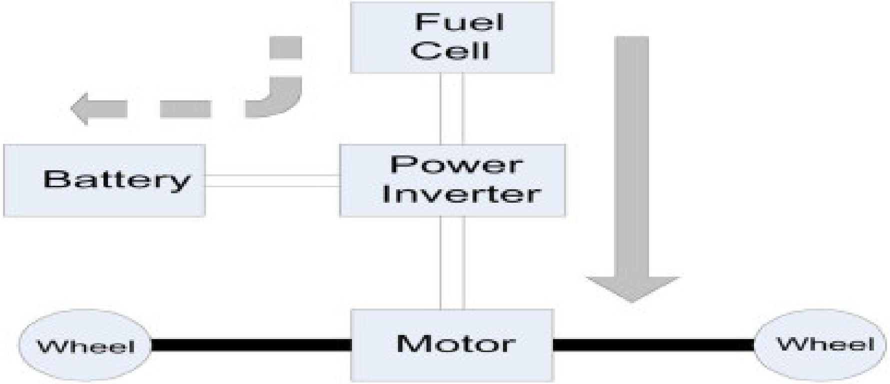


Fig. 2. Medium power operating mode 1.

1.2. Mode 2, High Power (Fig. 3)
During acceleration, or uphill driving, both the FC and the battery provide power to the traction motor. The battery speeds up the vehicle's response time for a request of acceleration, because the FC typically has a slow response time. This also allows the FC to maintain a safe and efficient operating point.

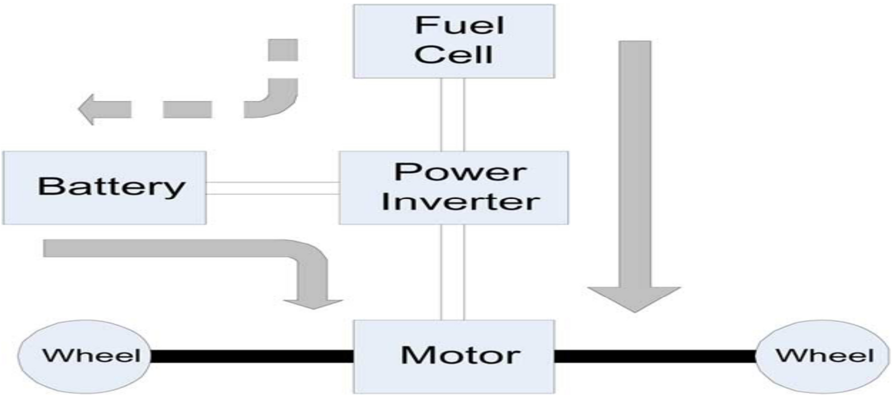


Fig. 3. High power operating mode 2.

1.3. Mode 3, Low Power (Fig. 4)
Because of the parasitic loads, such as the air compressor, associated with the FC, the FC system efficiency decreases when operated under low power [8]. Thus the vehicle will be operated strictly as a battery powered electric vehicle under low power by turning off the FC stack.

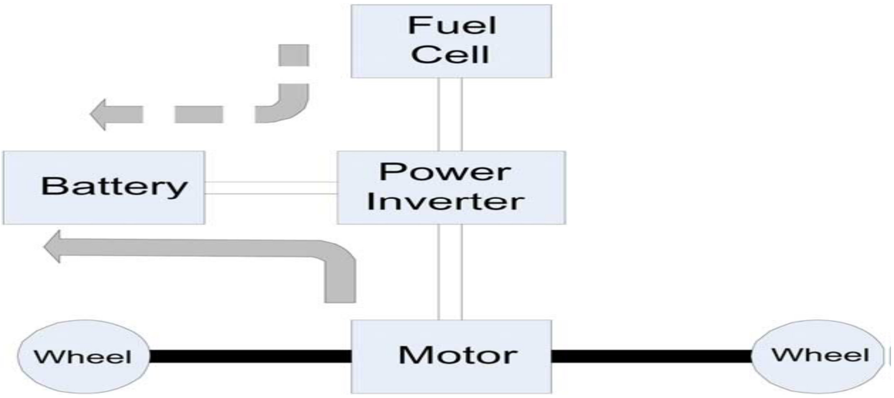


Fig. 4. Low power operating mode 3.

1.4. Mode 4, Regenerative Braking (Fig. 5)
During regenerative braking, the FC produces no power, and the electric motor acts as a generator, using the wheels to apply torque to the motor to generate electrical power, this torque in turn slows the vehicle down. The electrical energy generated during regenerative braking is stored in the battery until needed. It is important to

mention that in any of the operating modes, if the SOC of the battery becomes too low, the FC will provide power to recharge the battery.

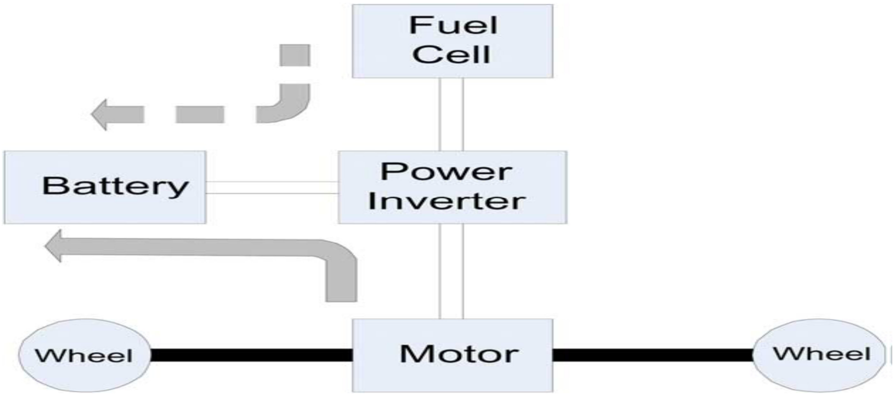


Fig. 5. Regenerative braking operating mode 4.

2. FC AND BATTERY CHARACTERISTICS

Although there are many complex subsystems and parasitic loads associated with a FC, we are mainly concerned with the voltage and current. The FC's voltage (and power) is determined by two main factors. First the rate at which hydrogen flows through the FC establishes the level of the – polarization curve.

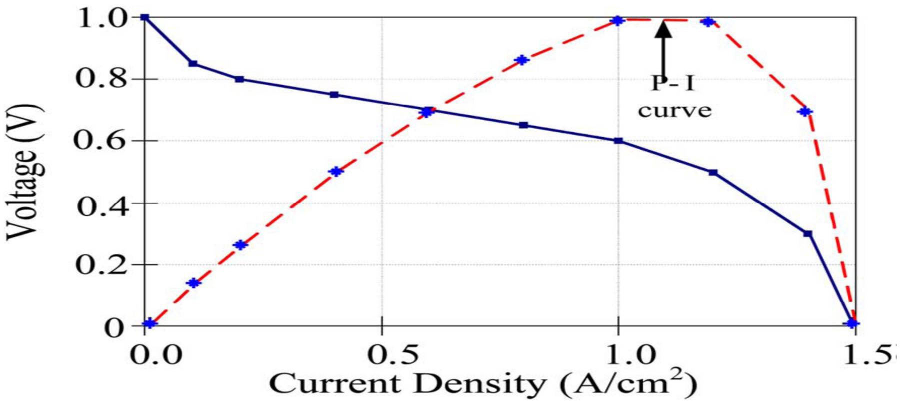


Fig. 6. Typical FC polarization curve.

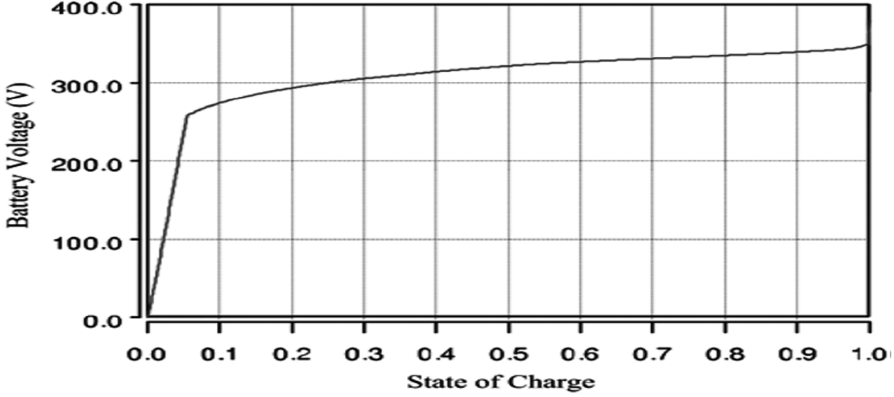
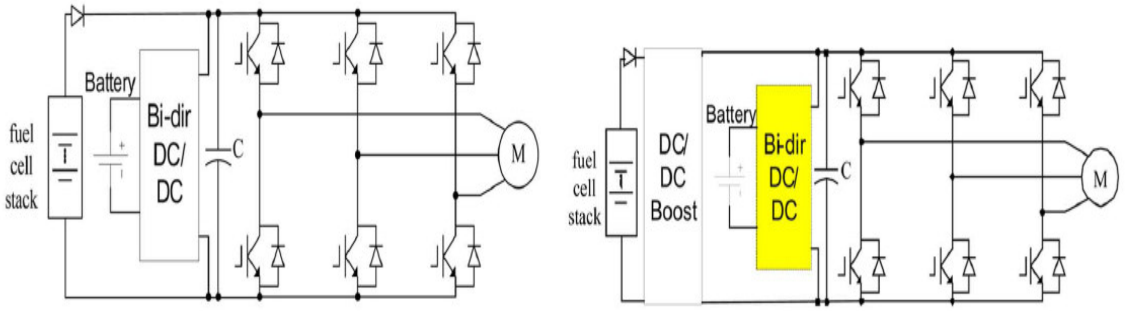


Fig. 7. Typical lithium–ion battery voltage versus SOC.

Second the amount of current drawn by the inverter determines the point on this curve where the FC will operate. Thus, by controlling the amount of current drawn by the inverter, the FC power can be controlled for given hydrogen flow rate. The typical steady state – polarization curve of the FC is shown in Fig. 6. As can be seen from Fig. 6, the output voltage of the FC is heavily dependent on the load current as so does the power. On the other hand, the output voltage of a battery is relatively less current dependent because of much smaller internal resistance. The voltage of a battery changes with the SOC of the battery. A typical curve of voltage versus SOC of a 330-V lithium-ion battery is shown in Fig. 8.

3 . TRADITIONAL SYSTEM CONFIGURATIONS

As can be seen from above analysis, the power inverter is the key component in the system to handle all power flow control. The inverter in FCHEV has to output the requested power to the traction motor, capture excess power from the FC, and to absorb energy from regenerative braking. There are typically two configurations available for this application shown in Fig. 8. The FCHEV using the conventional inverter Fig. 8(a) must use a bi-directional dc–dc converter to control the SOC of the battery, because the modulation index is the inverter's only control freedom. Also, the conventional inverter is a buck (step-down) inverter, the output ac voltage is limited below the FC voltage. Because of the wide voltage range of the FC, the conventional inverter imposes high stresses to the switching devices.



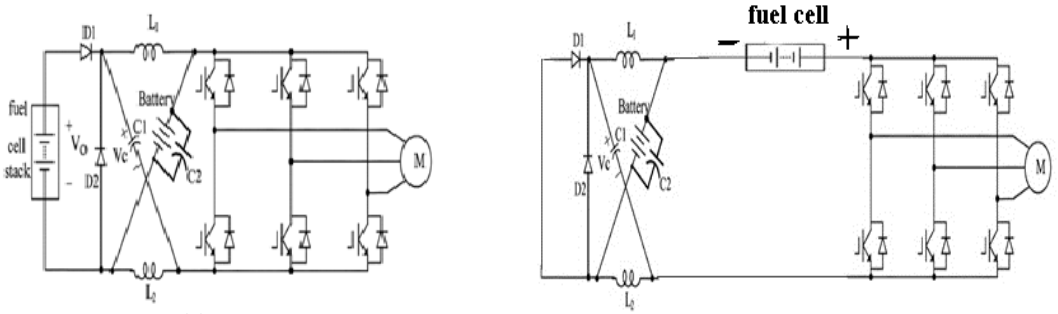
(a) (b)

Fig. 8. Traditional configurations of FCVs. (a) System configuration using a conventional inverter. (b) System configuration using a dc–dc boosted inverter.

The dc–dc boosted inverter Fig. 8(b) can improve these stresses, at the price of higher cost and complexity. The dc–dc boost converter is used to boost (step-up) the voltage from the FC, to a steady dc bus voltage, and the inverter's output ac voltage is controlled by the modulation index. The system configuration using the dc–dc boosted inverter typically uses a bi-directional dc–dc converter to control the SOC of the battery [6]. Both configurations use an inverter bridge and at least one dc–dc converter, which increases the cost and system complexity and reduces the system reliability.

4. CONFIGURATION AND CONTROL OF Z-SOURCE

The recently presented Z-source inverter [1] is suitable for many applications [1]–[3], including FCHEVs. The Z-source inverter is attractive for three main reasons. First, the traditional pulse width modulation (PWM) inverter has only one control freedom, used to control the output ac voltage [4], [5]. However the Z-source inverter has two independent control freedoms [1]: shoot-through duty cycle and modulation index, providing the ability to produce any desired output ac voltage to the traction motor, regulate battery SOC, and control FC output power (or voltage) simultaneously. Second, the Z-source inverter provides the same features of a dc–dc boosted inverter (i.e., buck/boost), yet its single stage is less complex and more cost effective. Third, the Z-source inverter has the benefit of enhanced reliability due to the fact that momentary shoot-through can no longer destroy the inverter (i.e., both devices of a phase leg can be on for a significant period of time). By replacing one of the capacitors in the Z-source network with a battery as shown in Fig. 9(a), the Z-source inverter can be used in FCHEVs. This paper reveals the basic control method for the Z-source inverter in FCHEVs and its unique features. By using the Z-source inverter, extra dc–dc converter is no longer needed. This can be achieved because the Z-source inverter has two independent control freedoms: modulation index and shoot through duty ratio. In this system, there are three power sources/consumers: FC, battery, and the motor, as long as we can control the power flow of two of them, the third element automatically matches the power difference.



(a) **(b)**

Fig. 9. Different Configurations Z-source inverter for FC HEV.

The Z-source inverter again modified in this paper such a way that the requirement of battery has low. The battery driven vehicles are limited to short distances, because of bulkiness of battery. That was addressed by Z-source inverter. The proposed topology reduces capacitor size further. In traditional Z-source inverter has a drawback of over stressed capacitor at shoot through state and input dc source is opened out. It's going to disturb the principle of MPPT in any practical sources like PV cell, fuel cell, etc. That drawback was overcome by proposed negative dc bus embedded type Z-source inverter, where dc source supplies power both the states, it makes to maintain MPPT algorithm easy and also reduces the stresses across capacitor.

The essentials of proposed topology clearly explained with help of table I. The outputs of two topologies exactly same and inductor stress also same, but the proposed topology shows extreme reduction in the capacitor requirement. Application of Z-source inverter in hybrid vehicular needs the replacement of capacitor by battery.

Table I: Summary of different Z-source hybrid vehicle configurations

slno	Voltage across elements	Traditional ZSI (Fig.9a)	Proposed ZSI (Fig.9b)
1	Voltage across capacitor (V_c)	(1-D)*$V_{fuel\ cell}$/(1-2D)	D*$V_{fuelcell}$/(1-2D)
2	Voltage across dc link ($V_{dc\ link}$)	$V_{fuel\ cell}$/(1-2D)	$V_{fuel\ cell}$/(1-2D)
3	Voltage across output load (V_{ac})	05*M*$V_{fuel\ cell}$/(1-2D)	05*M*$V_{fuel\ cell}$/(1-2D)

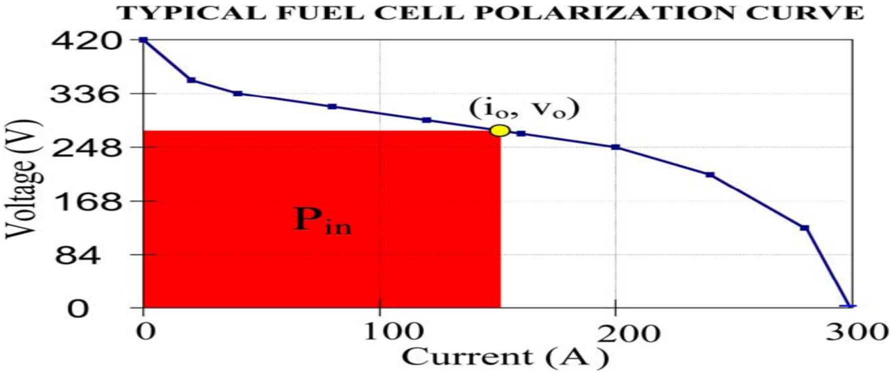


Fig.10. Power control of FC by controlling the voltage.

For Z-source inverter, the relationship of the capacitor voltage and the input voltage [1] is

$$V_c = \frac{1-D_0}{1-2*D_0} * V_0 \quad \text{for traditional Z-source inverter shown by Fig.9(a)} \tag{1}$$

$$V_c = \frac{D_0}{1-2*D_0} * V_0 \quad \text{for proposed Z-source inverter shown by Fig.9(b)} \tag{2}$$

Where D_0 is the shoot through duty ratio,V_0 is the FC voltage,V_c is the voltage across the capacitor in Z-source network. In this system, the battery voltage, V_b, equals to the capacitor voltage V_c. From Figs. 5 and 6, the battery voltage is relatively constant at certain SOC and the FC voltage is highly current dependent, therefore, for a given battery voltage,V_b , the FC voltage is controlled to be

$$V_0 = \frac{1-2*D_0}{1-D_0} * V_b \tag{3}$$

For given hydrogen and air flow rates, the – characteristic of the FC is determined. As a result, the FC voltage determines the output current and power of the FC. Fig. 9 shows the – curve of a typical 30 kW FC, with the controlled FC voltage,V_0 , the shaded area illustrates the output power of the FC. At the same time, the output power can be controlled by manipulating the modulation index to produce the desired output voltage. The output peak phase voltage of the inverter is

$$V_{phase} = (2V_b - V_0) * \frac{M}{2} \tag{4}$$

where is the modulation index defined as the ratio of the magnitude of the reference waveform and the triangular waveform in traditional SPWM.

The output power can be expressed as

$$P_{out} = \frac{3*pf}{\sqrt{2}} * V_{phase} * I \tag{5}$$

Where is the rms load current and pf is the load power factor. Therefore the system is able to control the FC output power and the output power to the motor at the same time, as a result, the power charging the battery is

$$P_b = V_0 * I_0 - P_{out} \tag{6}$$

Thus we are able to control the SOC of the battery and drive the vehicle at the same time. In corresponding to the four vehicle operation modes shown in Fig. 1, the inverter has different operation methods too. For mode 1 and 2, the inverter operation is very similar: the FC power is controlled by shoot through duty ratio, the output power is controlled by the output voltage and current. The only difference is that the output power is higher than the FC power and the battery is being discharged in mode 2, the FC power can be slightly higher/lower than or equal to the output power to charge/discharge or maintain the battery based on the battery SOC in mode 1. For mode 3, the FC is turned off and the diode D2 bypasses the FC. To maintain the inductor current at certain level, the shoot through duty ratio has to be slightly higher than 50% [15], and the modulation index is still used to control the output voltage/power. For mode 4, to maintain a certain inductor current, the shoot through duty ratio also has to be around 50%, and the power is being charged back to the battery.

Maximum Constant Boost PWM control strategy

Constant boost method achieves the maximum voltage gain while always keeping the shoot-through duty ratio constant. This method requires the minimum inductance & capacitance because the inductor current and the capacitor voltage contain no low-frequency ripples associated with the output voltage, thus reducing the cost, volume and weight of the Z-source network. Fig.11.shows the maximum constant boosting method.

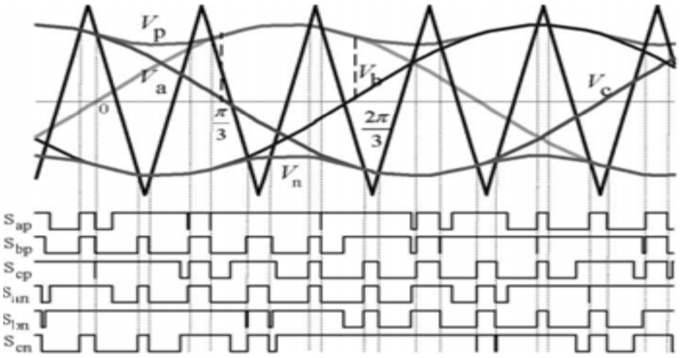


Fig.11**:** pulse pattern for Maximum constant boost

The Table II demonstrates the PWM topologies to ZSI, and comparative analysis going on by taking switching stresses, boost voltage as main concerns.

Table II: Summary of different PWM control methods expressions

Control Method	Simple	Max. Boost	Max. Constant Boost
D_0	1-M	$2-3\sqrt{3}M$	$\frac{2-3\sqrt{3}M}{2}$
B	$\frac{1}{2M-1}$	$\frac{\pi}{3\sqrt{3}-\pi}$	$\frac{1}{\sqrt{3}M-1}$
G	$\frac{M}{2M-1}$	$\frac{\pi M}{3\sqrt{3}M-\pi}$	$\frac{M}{\sqrt{3}M-1}$
M_{max}	$\frac{G}{2G-1}$	$\frac{\pi G}{3\sqrt{3}G-\pi}$	$\frac{G}{\sqrt{3}G-1}$
V_s	$(2G-1)*V_{in}$	$\frac{3\sqrt{3}M-\pi}{\pi}*V_{in}$	$(\sqrt{3}G-1)*V_{in}$

5. SIMULATION RESULTS

To verify the above mentioned feature of the Z-source inverter for FCHEVs, three cases are examined and simulated. In these cases the circuit parameters are $L_1 = L_2 = 200\mu H$, $C_1 = 400\mu F$, C2 has been replaced (or connected in parallel) with a 6.5-Ah lithium-ion battery with a nominal voltage of 330 V, switching frequency of 10 kHz, and using constant boost control with third harmonic injection [9], [16]. The characteristics of the battery and FC are shown in Figs. 7 and 10. An RL load is used in the simulation.

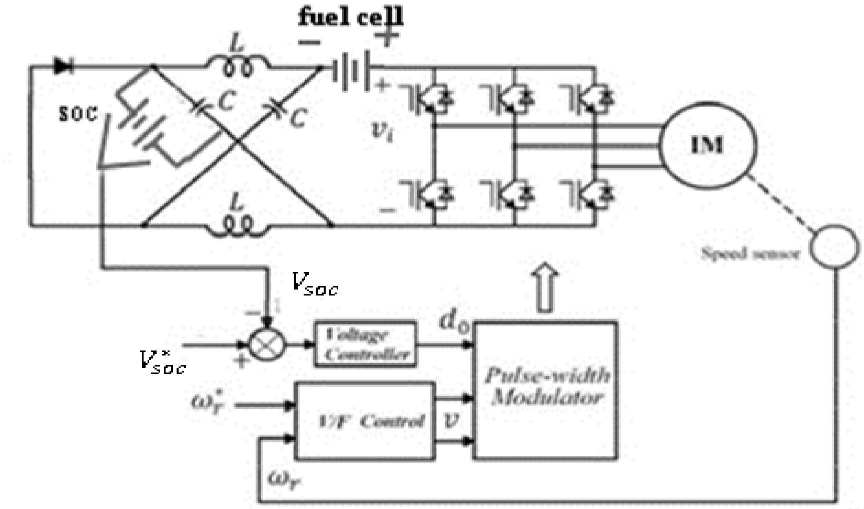


Fig. 12. Different Configurations Z-source inverter for FC HEV.

1) Case 1: The FC voltage is kept constant at 300 V (P=30 kW), and the load power is varied from 30 kW to 55 kW, to 5 kW, back to 30 kW. As one would expect the battery SOC should remain constant while the load is at 30 kW (P_{in}=P_{out}) . When the load is increased to 55 kW (P_{in}<P_{out}) the battery should supply the additional power requested by the load, thus the SOC will decrease. When the load is decreased to 5 kW (P_{in}>P_{out}) the additional power provided by the FC will charge the battery, increasing the SOC. These results are verified by simulation, Fig. 11, starting from the top, the FC voltage is constant, and the FC current is fairly constant. Next are the battery voltage, SOC, load voltage, load current, and load power. Initially the load absorbs 30 kW, and the SOC stays constant. The load is then increased to 55 kW and the SOC decreases. Next the load is decreased to 5 kW, and the SOC increases. Finally the load is returned to 30 kW and the SOC remains constant.

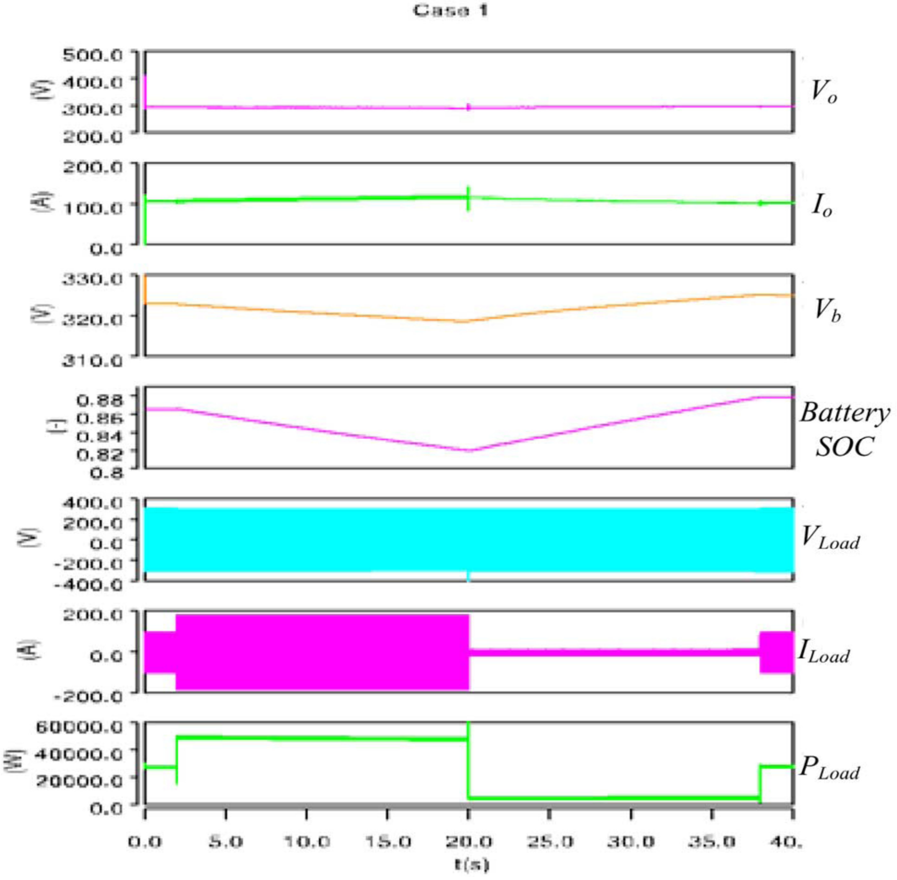


Fig. 11. Simulation case 1.

This simulation shows that we can operate the FC at an efficient operating point, while the battery handles the load dynamics. This also verifies the Z-source inverter can be used to provide the medium, and high power operating modes.

2) Case 2: The load power is kept constant at 30 kW, and the FC power is varied between 30 kW, 50 kW, and 20 kW. Again the battery SOC should remain constant while the FC is producing 30 kW. The battery will be charged when the FC power is increased to 50kW , increasing the SOC. When the FC power is decreased to 20 kW , the battery will supply the additional power requested by the load, decreasing the SOC.

This can be verified in Fig. 12. Starting from the bottom, the load power, current, and voltage are constant, where the power is at approximately 30 kW. Next are the battery SOC, battery voltage, FC current, and FC voltage. Initially the FC produces 30 kW, and the SOC stays constant. Then the FC power is increased to 50k(P_{in}>P_{out})Wand the SOC increases. Again the FC produces 30 kW, and the SOC stays constant. Next the FC power is decreased to 20 kW(P_{in}<P_{out}), and the SOC decreases. Finally, the FC again produces 30 kW, and the SOC stays constant. Case 2 shows that we can control the FC power, thus controlling the battery SOC.

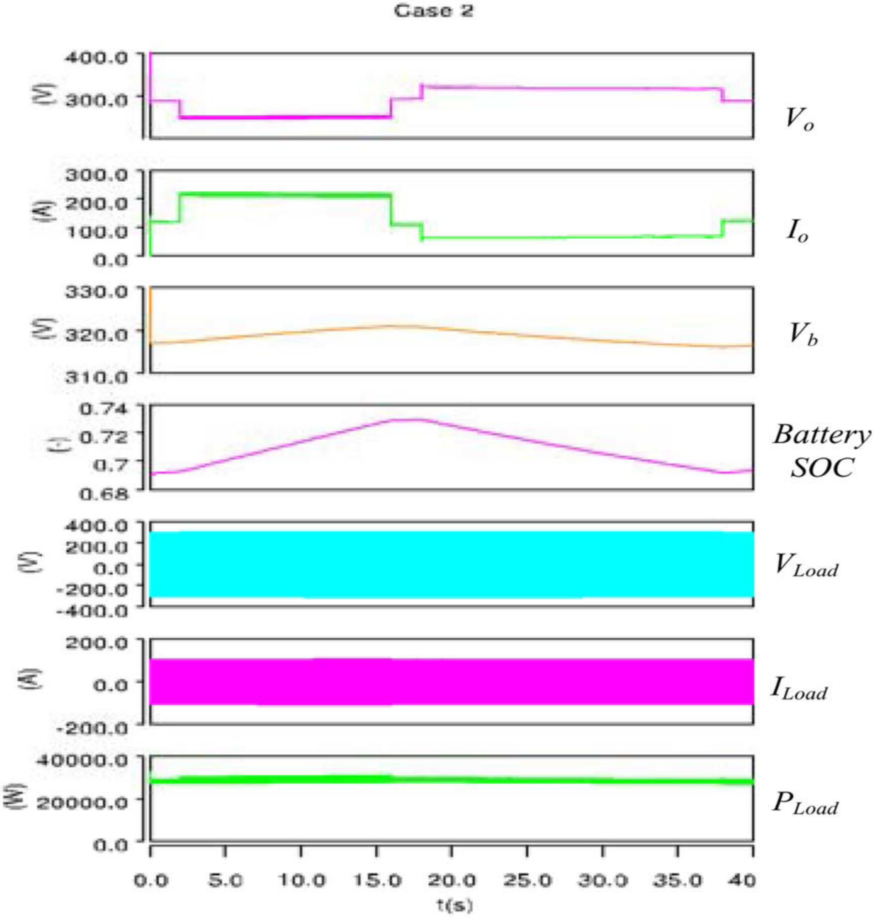


Fig. 12. Simulation case 2.

3) Case 3: The FC operation is stopped, and the load power is varied from 5 kW, to 20 kW. As one would expect the batterySOC should decrease. When the FC is turned off, D2 provides a current path for any possible current. These results are verified by simulation as seen in Fig. 13, starting from the top, the FC power is zero. Next are the battery voltage, SOC, load voltage, load current, and load power. Initially the load absorbs 5 kW, and the SOC decreases slowly. The load is then increased to 20 kW and the SOC decreases more rapidly. Case 3 verifies that the vehicle can be operated without using the FC, strictly as an electric vehicle, as in the low power mode. This also demonstrates the ability of the inverter to capture power during regenerative braking, when the FC is also turned off and the output voltage and current is out of phase.

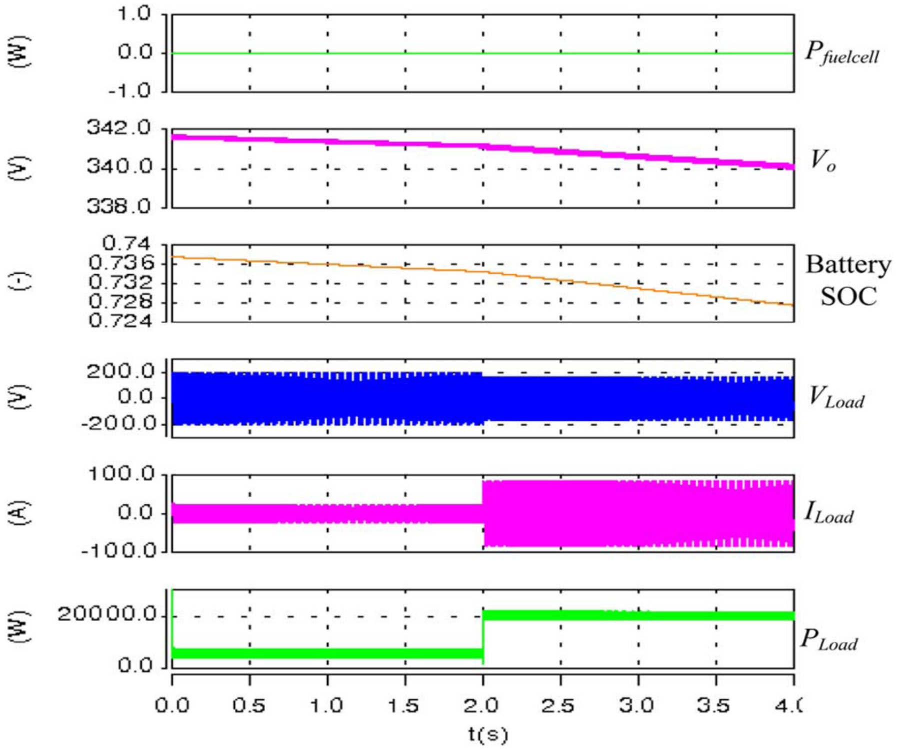


Fig. 13. Simulation case 3.

6. CONCLUSION

This paper has presented a FCHEV system power control strategy to control power from the FC, power to the motor, and SOC of the battery, using the proposed Z-source inverter. The negative dc bus embedded type Z-source inverter is very promising for use in FCHEVs because of the following unique features and advantages:

1) Less complex, and more cost effective than a dc–dc boosted inverter, while providing the same function (i.e., buck boost).

2) Greater reliability, because shoot-through can no longer destroy the inverter.

3) No need for any dc–dc converters to control the battery SOC, or boost the dc bus voltage, because the Z-source inverter ha two independent control freedoms.

4) Further reduction of capacitor stress by proposed Z-source inverter.

The basic control concept of using the proposed Z-source inverter for FCHEVs to realize all necessary functions is discussed in this paper and confirmed by simulation results.

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