Comparison of Traditional Inverters and Z-Source Inverter for Fuel Cell Vehicles

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***Abstract:* In this paper, three different inverters: traditional PWM inverter, dc/dc boosted PWM inverter, and Z-source inverter for fuel cell vehicles were investigated. Total switching device power of each of these inverters was calculated. For purposes of comparison, an example of the total switching device power, requirement of passive components, efficiency, and the constant power speed ratio of the different inverters powered by the same fuel cell and loaded by the same motor were conducted. This comparison shows that the Z-source inverter is very promising for fuel cell vehicles.**

. INTRODUCTION

Fuel cells, as one of the most promising energy sources, have attracted attention from automotive engineers as well as power electronics engineers and have been used in a variety of areas, such as domestic applications, utility applications and traction applications [1-4]. Unlike batteries that have fairly constant output voltage, the fuel cell has a unique V-I characteristic and wide voltage change range as shown in Fig. 1.

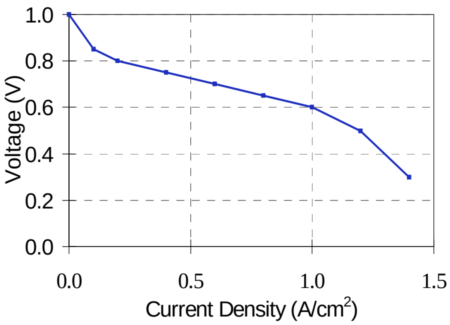


Fig.1. Typical fuel cell polarization curve

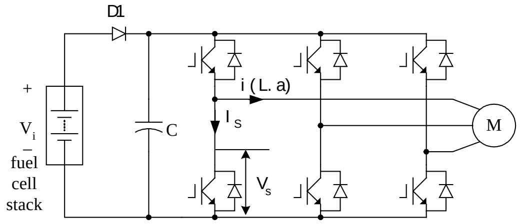
As can be seen from the figure, the output voltage of the fuel cell decreases as the output current increases. This results in difficulty for high-speed, and high-power operation to achieve a great Constant Power Speed Ratio (CPSR). In addition, a larger inverter is required.

Currently, there are two existing inverter topologies used for hybrid electric and fuel cell vehicles: the conventional 3-phase Pulse Width Modulation (PWM) inverter and a 3-phase PWM inverter with a dc-dc boost converter, which is also very popular in other applications [1-4]. Because of the wide voltage range and limited voltage level of fuel cell stack, the conventional PWM inverter topology imposes high stresses to the switching devices and motor, and limits the motor's constant power speed ratio. The dc/dc boosted PWM inverter topology can alleviate the stresses and limitations, however, suffers problems such as high cost and complexity associated with the two-stage power conversion.

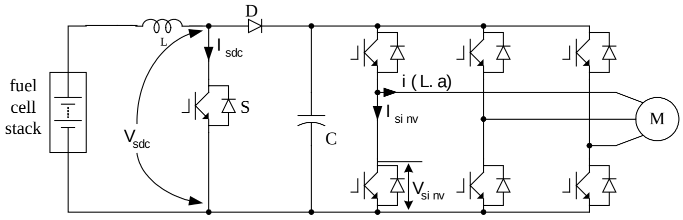
The newly proposed Z-source inverter [5-7] has the unique feature that it can boost the output voltage by introducing shoot through operation mode, which is forbidden in traditional voltage source inverters. With this unique feature, the Z-source inverter provides a cheaper, simpler, single stage approach for applications of fuel cell. Moreover, it highly enhances the reliability of the inverter because the shoot through can no longer destroy the inverter. This paper provides analysis and comparisons of the three inverters for fuel cell vehicle traction drives using total Switching Device Power (SDP), passive components requirement, efficiency, and CPSR as benchmarks.

. SYSTEM CONFIGURATIONS

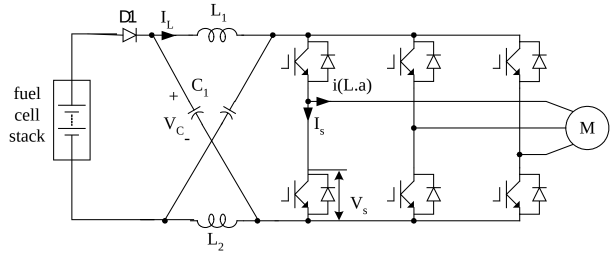
As previously mentioned, three different inverter system configurations are to be investigated: the conventional PWM inverter, the dc/dc boosted PWM inverter, and the Z-source inverter. Their system configurations for fuel cell vehicles are shown in Fig. 2 (a), (b), and (c), respectively.



(a) System configuration using conventional PWM inverter



(b) System configuration using dc/dc boost + PWM inverter



(c) System configuration using the Z-source inverter

Fig. 2. Three inverter system configurations for comparison

In the traditional PWM inverter, the dc bus voltage, which is also the output voltage of fuel cell stack, varies with the load. The boost converter in the dc/dc boosted PWM inverter system outputs a constant dc voltage that is equal to or higher than the maximum output voltage of the fuel cell regardless of the load. The Z-source inverter outputs a required voltage by adjusting the shoot through duty cycle with the restriction to keep the voltage across the switches not to exceed its limit [8].

. COMPARISON ITEMS, CONDITIONS, EQUATIONS, AND RESULTS

1. Total Switching Device Power Comparison

In an inverter system, each switching device has to be selected according to the maximum voltage impressed and the peak and average current going through it. To quantify the voltage and current stress (or requirement) of an inverter system, switching device power is introduced. The SDP of a switching device/cell is expressed as the product of voltage stress and current stress. The total SDP of an inverter system is defined as the aggregate of SDP of all the switching devices used in the circuit. Total SDP is a measure of the total semiconductor device requirement, thus an important cost indicator of an inverter system. The definitions are summarized as follows:

Total Average SDP = $(SDP)_{av} = \sum_{i=1}^{N} V_i I_{i\_average}$, and

Total Peak SDP = $(SDP)_{pk} = \sum_{i=1}^{N} V_i I_{i\_peak}$, where N is the number of devices used, and V_i is the peak voltage induced on the devices.

To derive the SDP of the different inverters, we define some parameters that are necessary for derivation. P_o is the maximum output power; V_{max} is the maximum output voltage of the fuel cell stack; cosφ is the power factor of the motor at maximum power; V_i is the fuel cell stack output voltage at maximum power; M is the modulation index; V_{dc} is the output voltage of the boost converter in the dc/dc boosted inverter, which is equal to or greater than V_{max}.

In our comparison, the input end diode D1 is not considered, because it's hard to compare the cost of the diode and switch of the same rating.

a. Traditional PWM inverter

For the traditional PWM inverter, the output phase RMS voltage at peak power is

$$V_p = \frac{V_i}{2\sqrt{2}} M \,. \qquad (1)$$

With motor power factor of cosφ, the output line RMS current is

$$I_p = \frac{P_o}{3\cos\varphi V_p} \,. \qquad (2)$$

Because the line current is evenly shared by two switches in a line cycle, the average current through each switch is:

$$I_{av} = \frac{P_o}{3\cos\varphi V_i/(2\sqrt{2})M} \sqrt{2} * \frac{2}{2\pi} = \frac{4P_o}{3\cos\varphi V_i \pi M} \qquad (3)$$

The maximum voltage stress of the switches occurs when the output power is zero, and the fuel cell voltage reaches its maximum value, which is

$$V_s = V_{\max} \,. \qquad (4)$$

The total average switching device power of the circuit is

$$(SDP)_{av} = 6 * V_s * I_{av} = \frac{8V_{\max}P_o}{\cos\varphi V_i \pi M} \,. \qquad (5)$$

The peak current through the switches is the peak line current

$$I_{pk} = \sqrt{2} I_p = \frac{4P_o}{3\cos\varphi V_i M} \,. \qquad (6)$$

The total peak switching device power of the traditional PWM inverter is

$$(SDP)_{pk} = 6 * V_s * I_{pk} = \frac{8V_{\max}P_o}{\cos\varphi V_i M} \,. \qquad (7)$$

b. dc/dc boosted PWM inverter

For the switch in the boost converter, treating the switch and the diode as a switch cell, the maximum voltage it sustains is V_{DC} and the average current through it during maximum power is

$$I_{avs} = \frac{P_o}{V_i} \,. \qquad (8)$$

The average switching device power of the dc/dc converter is

$$(SDP)_{DCav} = \frac{P_o}{V_i} * V_{DC} . \tag{9}$$

Suppose the current through the inductor in the boost converter is constant, the peak current through the switch is the same as the average current. The peak switching device power is

$$(SDP)_{DCpk} = \frac{P_o}{V_i} * V_{DC} . \tag{10}$$

The voltage stress of the inverter switches is $V_{DC.}$ The RMS phase voltage at modulation index of M is

$$V_p = \frac{V_{DC} M}{2\sqrt{2}} . \tag{11}$$

The RMS line current is:

$$I_p = \frac{P_o}{3 V_p \cos\varphi} \tag{12}$$

The average current through switches under maximum power is

$$I_{avinv} = \frac{I_p \sqrt{2}}{\pi} = \frac{4 P_o}{3 \cos\varphi V_{DC} \pi M} . \tag{13}$$

The average switching device power of the system is

$$\begin{aligned} (SDP)_{av} &= 6 * V_{DC} * I_{avinv} + (SDP)_{DCav} \\ &= \frac{8 P_o}{\cos\varphi \pi M} + \frac{P_o}{V_i} * V_{DC} \end{aligned} \tag{14}$$

The peak switch current of the inverter is

$$I_{pkinv} = \sqrt{2} I_p = \frac{4 P_o}{3 \cos\varphi V_{DC} M} . \tag{15}$$

The peak switching device power of the system is

$$\begin{aligned} (SDP)_{pk} &= 6 * V_{DC} * I_{pkinv} + (SDP)_{DC\,pk} \\ &= \frac{8 P_o}{\cos\varphi M} + \frac{P_o}{V_i} * V_{DC} \end{aligned} . \tag{16}$$

c. Z-source inverter

For the Z source inverter, the current through the inverter switches consists of two elements, one is the current to the load and the other is the current through them during the shoot through state. Because of the symmetrical structure of the inverter, the current during shoot through in terms of average is evenly distributed in three parallel paths. The current through the inverter during shoot through is twice of the inductor current. Therefore, the average current value in shoot through period through each switch is

$$I_{avss} = \frac{2}{3} I_L , \tag{17}$$

where I_L is the inductor current. From the input end, the average current through the diode equals to the sum of the average current through inductor L_1 and capacitor C_1. In steady state, the average current through the capacitor is zero, the average current through the inductor equals to that of the diode. The output power of the fuel cell stack under maximum power is P_o, therefore, the average current through the diode as well as the inductor is:

$$\bar{I}_d = I_L = \frac{P_o}{V_i} . \tag{18}$$

While in active states, the average current is the same as a conventional PWM inverter, therefore the overall average current through inverter switches is

$$\begin{aligned} I_{avs} &= \frac{2}{3} I_L * \frac{T_0}{T_s} + \frac{\sqrt{2} P_o}{3 V_o \cos\varphi\pi} (1 - \frac{T_0}{T_s}) \\ &= \frac{2}{3} I_L * \frac{T_0}{T_s} + \frac{4\left(\sqrt{3}M - 1\right) P_o}{3 V_i \cos\varphi\pi M} (1 - \frac{T_0}{T_s}) \end{aligned} , \tag{19}$$

where T_0 is the shoot through period in a switching cycle T_s, V_o is the RMS output phase voltage. With the control method presented in [8], T_0 and V_o can be expressed as

$$T_o = \left(1 - \frac{\sqrt{3}}{2} M\right) T_s \tag{20}$$

$$V_o = \frac{M}{\sqrt{3}M - 1} \frac{V_i}{2\sqrt{2}} . \tag{21}$$

Voltage stress of the inverter switches is

$$V_s = B V_i = \frac{V_i}{\sqrt{3}M - 1} . \tag{22}$$

The average switching device power of the inverter is

$$\begin{aligned} (SDP)_{av} &= 6 I_{avs} V_s \\ &= 4 I_L V_i \frac{T_0}{T_s (\sqrt{3}M - 1)} + 8 \frac{P_o}{\cos\varphi\pi M} \left(1 - \frac{T_0}{T_s}\right) \\ &= \frac{2 P_o (2 - \sqrt{3}M)}{(\sqrt{3}M - 1)} + \frac{4\sqrt{3} P_o}{\cos\varphi\pi} \end{aligned} \tag{23}$$

The peak current through the switches occurs during shoot through. To calculate the peak current through the switches, we suppose that when the switches are on they are pure resistors with the same resistance, which is shown in Fig.3.

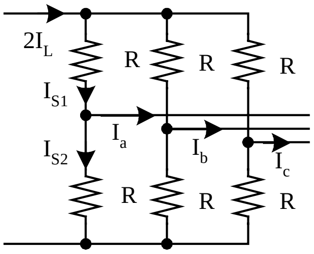


Fig.3. Inverter model during shoot through

Based on this model, we can have the following equations

$$I_{s2} + I_{s1} = \frac{4}{3} I_L \tag{24}$$

$$I_{s1} - I_{s2} = I_a \, . \tag{25}$$

From which we can get

$$I_{s1} = \frac{1}{2} I_a + \frac{2}{3} I_L \, . \tag{26}$$

The peak current through the switch S1 occurs when the line current of phase A is at its peak, which is

$$I_{lpk} = \frac{\sqrt{2}P_o}{3\cos\varphi V_o} = \frac{4P_o}{3\cos\varphi MBV_i} \, . \tag{27}$$

The peak switching device power of the inverter is

$$\begin{aligned} (SDP)_{pk} &= 6I_{pk}V_s \\ &= 6\frac{V_i}{\sqrt{3}M-1}\left(\frac{2}{3}\frac{P_o}{V_i} + \frac{1}{2}\frac{4P_o}{3\cos\varphi MBV_i}\right) \\ &= \frac{4P_o}{\sqrt{3}M-1} + \frac{4P_o}{\cos\varphi M} \end{aligned} \tag{28}$$

Based on all these equations, a comparison example for a system with the following specifications is conducted.

Fuel cell output voltage at maximum power: 250 V;

Maximum fuel cell output voltage: 420 V;

Maximum power: 50 kW;

Motor power factor at maximum power: 0.9;

Output voltage of the boost converter: 420 V;

Modulation index of conventional PWM inverter and dc/dc boosted PWM inverter is 1;

Modulation index of Z source inverter is 0.92 at maximum output power. (To keep the voltage stress of the switches lower than 420 V)

Table 1: SWITCHING DEVICE POWER COMPARISON EXAMPLE

Inverter Systems	Total Average SDP (kVA)	Total Peak SDP (kVA)
PWM inverter	238	747
PWM plus boost dc/dc	225	528
Z source inverter	191	577

The Z-source inverter's average SDP is the smallest among the three while the conventional PWM inverter's SDPs are the highest in both average and peak values. The average SDP also indicates thermal requirements and conversion efficiency.

2. Requirement of Passive Components Comparison

In this comparison, we are going to compare the inductors and capacitors requirement in the systems. The inductors are designed based on the current ripple limit, and the capacitors are designed based on the current ripple capacity requirement and capacitance requirement due to voltage ripple range.

a. Traditional PWM inverter

Because of the internal impendence of the fuel cell, it outputs constant DC current. The peak voltage ripple of the capacitor in traditional PWM inverter occurs at maximum power, when the power factor of the motor is pretty high and there is no current fed back to the capacitor from the inverter. The voltage across the capacitor increases when the inverter is in zero state when capacitor current equals to that from the fuel cell. In a line cycle, the maximum voltage ripple across the capacitor occurs when the longest zero state happens. The maximum interval of open circuit in one cycle is

$$\begin{aligned} T_o &= T_s * \max(1-(M\sin(\alpha) - M\sin(\alpha - \frac{2}{3}\pi)))\Big|_{\frac{\pi}{6}}^{\frac{\pi}{2}} \, . \\ &= (1-\frac{3}{4}M)T_s \end{aligned} \tag{29}$$

During this interval, the current through the capacitor is the current from the fuel cell, which is

$$I_f = \frac{P_o}{V_i} \, . \tag{30}$$

Therefore, the maximum voltage ripple across the capacitor is

$$\Delta V_c = \frac{T_0 I_{DC}}{C} = \frac{P_o T_s}{V_i C}(1-\frac{3}{4}M) \, . \tag{31}$$

b. dc/dc boosted PWM inverter

Similar to the conventional PWM inverter, the maximum voltage ripple occurs at maximum power and maximum zero states. Suppose the dc/dc converter and the inverter share the same carrier. In the period when the switch in dc/dc converter is off, the current flows into the capacitor from boost converter is the inductor current, which is

$$I_{c1} = \frac{P_o}{V_i}. \quad (32)$$

In the active state at this instant, the output voltage of one phase is at its maximum value, the current flowing into the inverter is

$$I_{c2} = \cos\varphi I_{pk} = \cos\varphi \frac{4P_o}{3V_{DC}M}. \quad (33)$$

During the period when the switch in dc/dc converter is off, there is no current from the capacitor to the inverter for $(1-\frac{3}{4}M)T_s$, and amount of current I_{c2} flows to the inverter for the rest of the time. Therefore, the voltage ripple across the capacitor is

$$\begin{aligned}\Delta V_c &= (I_{c1}(1-D) - I_{c2}(\frac{3}{4}M - D))\frac{T_s}{C} \\ &= \frac{P_o T_s}{V_i C}(1-D) - \cos\varphi \frac{4P_o T_s}{3V_{DC}MC}(\frac{3}{4}M - D)\end{aligned}. \quad (34)$$

This equation works when $\frac{3}{4}M \geq D$ only, which will be the case in our comparison example.

For the inductor in the boost converter, the current ripple can be calculated by the current increase during the switch is on.

$$\Delta I_L = \frac{V_i}{L}DT_s = \frac{V_i(V_{DC} - V_i)}{LV_{DC}}T_s, \quad (35)$$

where D is the duty cycle.

c. Z-source inverter

For the Z-source inverter, during the shoot through interval, the capacitor charges the inductor and gives out current. The voltage ripple across the capacitors can be estimated

$$\Delta V_C = \frac{I_L T_0}{C}, \quad (36)$$

where

$$T_o = \left(1 - \frac{\sqrt{3}}{2}M\right)T_s, \quad (37)$$

and

$$I_L = \frac{P_o}{V_i}. \quad (38)$$

We have

$$\Delta V_C = \frac{\frac{P_o}{V_i}\left(1 - \frac{\sqrt{3}}{2}M\right)T_s}{C} \quad (39)$$

When the inverter is in a shoot through state, the voltage across the inductor is the voltage across the capacitor. Therefore the current ripple of the inductor can be calculated as

$$\Delta I = \frac{V_c}{L}T_o, \quad (40)$$

where V_c is the voltage across the capacitor C

$$V_c = \frac{V_i}{2}(1+B) = \frac{V_i}{2}\frac{\sqrt{3}M}{\sqrt{3}M - 1}. \quad (41)$$

We have

$$\Delta I = \frac{V_i\sqrt{3}M}{2L(\sqrt{3}M - 1)}\left(1 - \frac{\sqrt{3}}{2}M\right)T_s. \quad (42)$$

Based on above equations, we can design inductors with requirement of current ripple level. The capacitors are designed to take the ripple current through them based on the ripple current level, which can be calculated by certain programs.

An example of required passive components at input power of 50 kW is shown in Table 2 based on the same system specification as above and requirement to limit the inductor current ripple to be less than 10% of its average value, and capacitor voltage ripple less than 3% of its average value at switching frequency of 10kHz. The Z-source's two inductors can be built in one core to minimize the size and weight. The required L and C of the Z-source are quite similar to (slightly greater than) those of the dc/dc boosted PWM inverter.

3. Efficiency Comparison

Efficiency is an important criterion for any power converter. High efficiency can reduce thermal requirements and cost. A comparison example is conducted. The fuel cell is the one with characteristic shown in Fig. 1, with I_{pu} (per unit) =200 A, and V_{pu} (per unit)=420 V. The following operation principles of the inverters are implemented in order to make a fair comparison: the conventional PWM inverter is always operating at modulation index of 1; the dc-dc boosted PWM inverter boosts the dc voltage to 420 V, the inverter always operates with modulation index of 1; the Z source inverter outputs the maximum obtainable voltage while keeping the switch voltage under 420 V. With these assumptions, the obtainable motor phase voltage and motor current are shown in table.3. The efficiencies of the inverter-

Table 2. REQUIRED PASSIVE COMPONENTS

Inverter Systems	Number of inductors	Inductance (μH)	Average inductor current (A)	Number of capacitors	Capacitance of the capacitors (μF)	Capacitor rms ripple current (A)	Capacitor voltage rating (V)
conventional PWM inverter	0	N/A	N/A	1	667	106	420
dc/dc boosted PWM	1	510	200	1	556	124	420
Z - source inverter	2 (1)	339	200	2	405	111	420

Table 3 OPERATION CONDITIONS AT DIFFERENT POWER

Power Rating		50 kW 56 kVA	40kW 47kVA	30 kW 38 kVA	20 kW 27 kVA	10 kW 14 kVA
Fuel cell voltage (V)		250	280	305	325	340
Motor Phase voltage (V)	Conventional PWM inverter	88.4	99	107.8	117.9	120.2
	Dc/dc boost +PWM inverter	148.5	148.5	148.5	148.5	148.5
	Z – source inverter	136.8	142.9	148	152.1	155.2
Motor current (A)	Conventional PWM inverter	209.4	158.5	115.9	77.3	39.7
	Dc/dc boost +PWM inverter	124.7	105.6	84.2	59.9	32.1
	Z – source inverter	129.5	105.3	81.1	56.2	29.6

motor systems are also compared. To calculate the motor efficiency, a simple model is developed as shown in Fig.4, where R_c is corresponding to the core loss, R_s and R_r are the stator and rotor resistance respectively, L_m is the magnetizing inductance, L_L is the leakage inductance and $\frac{1-S}{S}R_r$ is corresponding to the output power. With the assumptions in Table.3, and the following parameters measured from an induction machine, the efficiency of the motor for different operation conditions can be calculated.

$$R_c = 150\Omega;$$
$$R_s = 0.0117\Omega;$$
$$R_r = 0.082\Omega.$$

The selected devices for loss calculation are: The switches for the main inverters are FUJI IPM 6MBP300RA060, the switch for the dc/dc boost converter is FUJI 2MBI 300N-060, the input end diode of the traditional PWM inverter and the Z-source inverter is IXYS MEO 500-06DA.

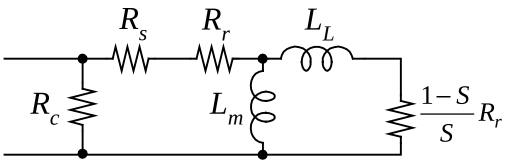


Fig.4. Simplified motor model for each phase

Only the semiconductor devices loss is considered. Traditional PWM inverter and the Z-source inverter are calculated twice with/without considering the input end diode. The calculation results are shown in Fig. 5 and Fig. 6 respectively. The input end diodes are considered for the system efficiency shown in Fig.6.

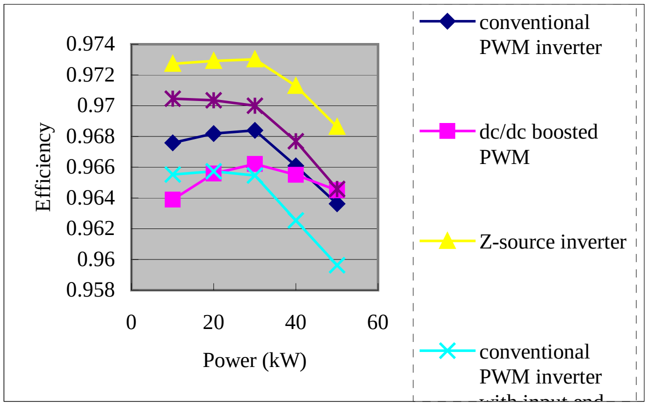


Fig.5. Calculated efficiency of inverters

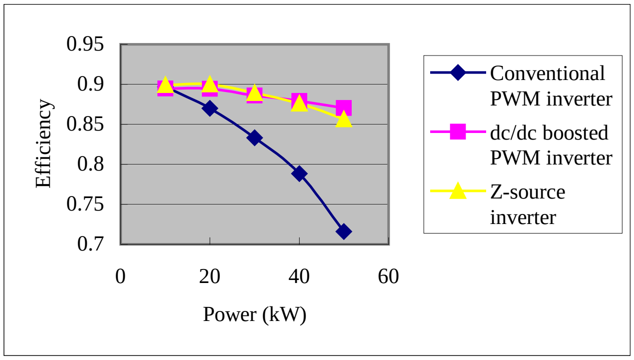


Fig.6. Calculated efficiency of inverters plus motor

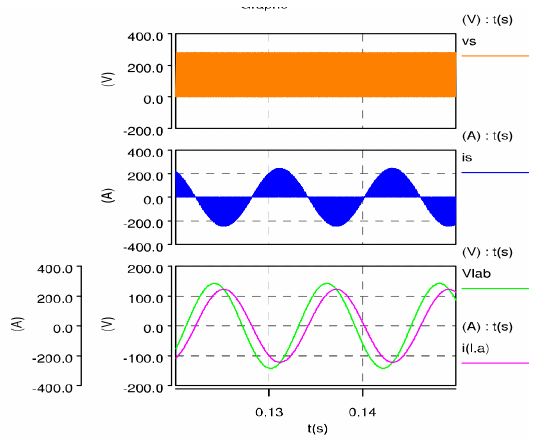
From the above comparison, the Z source inverter provides the highest efficiency of the inverter itself. At heavy load when the fuel cell voltage decreases, by keeping the switch voltage stress the same, the output voltage of Z-source inverter is a little bit lower than the dc/dc boosted PWM inverter. In order to keep the same power, the motor current is larger, which results lower motor efficiency.

4. CPSR Comparison

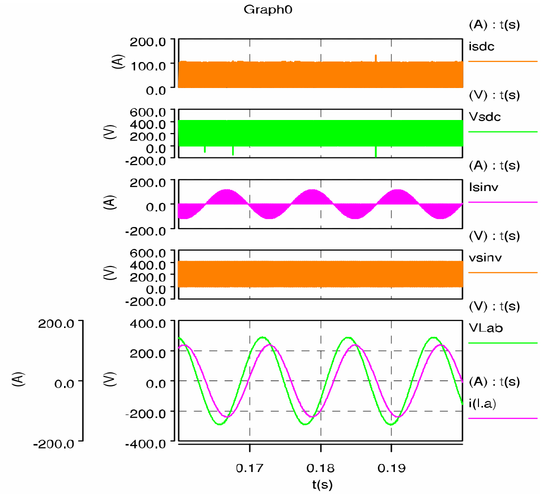
CPSR is limited mainly by available dc voltage of the PWM inverter. The fuel cell voltage decreases as the current drawn increases, which greatly limits the motor's power output and efficiency at high speed. For the conventional PWM inverter with the fuel cell model described above, the fuel cell voltage is the dc voltage of the inverter, which drops to 250 V at 200 A. From the 250 V dc, the conventional PWM inverter can only yield 170 V to the motor. This low motor voltage limits CPSR and lowers mechanical output power and efficiency. The PWM inverter with dc-dc boost can keep the dc voltage constant at or above 420 V, which in turn increases CPSR by a factor of 1.68. Theoretically the Z-source inverter can output whatever voltage as required. By the restriction of the same switch voltage stress as traditional PWM inverter and dc/dc boosted PWM inverter, the Z-source inverter can increase the CPSR by 1.55 times over the traditional PWM inverter. In other words, the motor voltage produced by these inverters is 1.55 times that produced by the conventional PWM inverter, thus the same motor can output 1.55 times the power than when driven by the conventional PWM inverter.

. SIMULATION COMPARISON

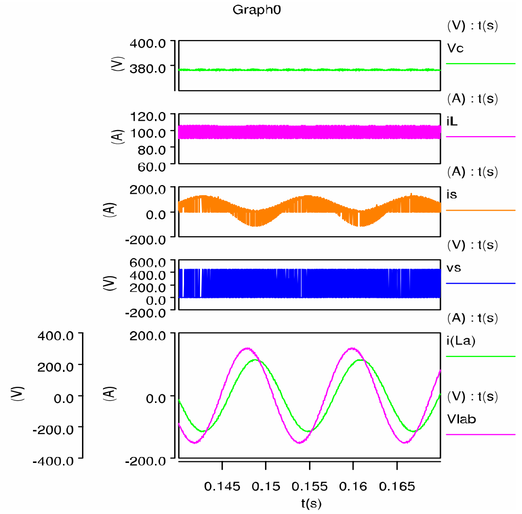
To verify the validity of the above comparisons, simulation models shown in Fig. 2 for the three inverters have been developed. As examples, simulation results at 30 kW are given in Fig. 7.



(a) Simulation results of voltage across the switch in the inverter (V_s), and current through the switch (I_s), output current I(L.a), and output voltage after LC filter (V_{Lab}) of conventional PWM inverter



(b) Simulation results of dc/dc converter switch current (I_{sdc}), voltage across the switch (V_{sdc}), the voltage (V_{sinv}) across and current (I_{sinv}) through the inverter switch, and the output current (I(l.a)) and voltage after LC filter (V_{lab}) of dc/dc boosted PWM inverter



(c) Simulation results of capacitor voltage (V_c), inductor current (i_L) of Z network, current (i_s) through and voltage (v_s) across the inverter switch, and output current (I(L.a)) and voltage after LC filter (V_{Lab}) of the Z - source inverter

Fig.7. Simulation results of different inverters at 30kW

Through simulation results and the models developed, we confirmed the validity of the comparisons performed. For example, the output current of the traditional PWM inverter is much higher than that of the other two cases, which means higher inverter losses, higher current devices are needed, and higher current to the motor. The obtainable output power to the motor is greatly limited by the dc voltage for the conventional PWM inverter.

. CONCLUSION

A comprehensive comparison of the three inverter systems has been performed. The comparison results show that the Z-source inverter can increase inverter conversion efficiency by 1% over the two existing systems and inverter-motor system efficiency by 1% to 15% over the conventional PWM inverter. The Z-source also reduces the total average SDP by 15%, which leads to cost reduction. Moreover, the constant power speed ratio is greatly (1.55 times) extended over the system driven by the conventional PWM inverter. Thus, the Z-source inverter system can minimize stresses and size of the motor and increase output power greatly. Along with these promising results, the Z-source inverter offers a simplified single stage power conversion topology and higher reliability because the shoot through can no longer destroy the inverter. The existing two inverter systems suffer the shoot through reliability problem. In summary, the Z source inverter is very promising for fuel cell vehicles.

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