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Z – Source Inverter for Fuel Cells

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1. *ABSTRACT*

This paper presents a Z-source converter also known as impedance-source (or impedance-fed) power converter and its control method for implementing dc-to-ac, ac-to-dc, ac-to-ac, and dc-to-dc power conversion. The Z-source Inverter employs a unique impedance network (or circuit) to couple the converter main circuit to the power source, thus providing unique features that cannot be obtained in the traditional voltage-source (or voltage-fed) and current-source (or current-fed) converters where a capacitor and inductor are used, respectively. The Z-source Inverter overcomes the conceptual and theoretical barriers and limitations of the traditional voltage-source converter (abbreviated as V-source converter) and current-source converter (abbreviated as I-source converter) and provides a novel power conversion concept. The Z-source concept can be applied to all dc-to-ac, ac-to-dc, ac-to-ac, and dc-to-dc power conversion. To describe the operating principle and control, this paper focuses on an example: a Z-source inverter for dc-ac power conversion needed in fuel cell applications. Simulation and experimental results will be presented to demonstrate the new features.

2. Z-SOURCE INVERTER

2.1 Introduction

There exist two traditional converters: voltage-source (or voltage-fed) and current-source (or current-fed) converters (or inverters depending on power flow directions). Fig. 1shows the traditional three-phase voltage-source converter (abbreviated as V-source converter) structure. A dc voltage source supported by a relatively large capacitor feeds the main converter circuit, a three-phase bridge. The dc voltage source can be a battery, fuel-cell stack, diode rectifier, and/or capacitor. Six switches are used in the main circuit; each is traditionally composed of a power transistor and an antiparallel (or freewheeling) diode to provide bidirectional current flow and unidirectional voltage blocking capability. The V-source converter is widely used.

It, however, has the following conceptual and theoretical barriers and limitations. The ac output voltage is limited below and cannot exceed the dc-rail voltage or the dc-rail voltage has to be greater than the ac input voltage. Therefore, the V-source inverter is a buck (step-down) inverter for dc-to-ac power conversion and the V-source converter is a boost (step-up) rectifier (or boost converter) for ac-to-dc power conversion. For applications where over drive is desirable and the available dc voltage is limited, an additional DC-DC boost converter is needed to obtain a desired ac output. To overcome the above problems of the traditional V-source and I-source converters, this paper presents an impedance-source (or impedance-fed) power converter (abbreviated as Z-source converter) and its control method for implementing dc-to-ac, ac-to-dc, ac-to-ac, and dc-to-dc power conversion. Fig. 3 shows the general Z-source converter structure proposed. It employs a unique impedance network (or circuit) to couple the converter main circuit to the power source, load, or another converter, for providing unique features that cannot be observed in the traditional V- and I-source converters where a capacitor and inductor are used, respectively. The Z-source converter overcomes the above-mentioned conceptual and theoretical barriers and limitations of the traditional V-source converter and I-source converter and provides a novel power conversion concept.

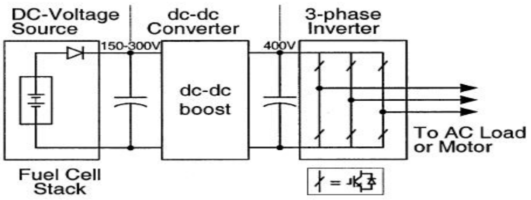


Fig 1: Traditional two-stage power conversion for fuel-cell applications.

In Fig 1, a two-port network that consists of a split-inductor L1and L2 and capacitors C1and C2 connected in X shape is employed to provide an impedance source (Z-source) coupling the converter (or inverter) to the dc source, load, or another converter. The dc source/or load can be either a voltage or a current source/or load. Therefore, the dc source can be a battery, diode, rectifier, thyristor, converter, fuel cell, an inductor, a capacitor, or a combination of those. Switches used in the converter can be a combination of switching devices and diodes such as the anti-parallel combination as shown in the series combination figure. As examples, two three-phase Z-source inverter configurations. The inductance L1andL2 can be provided through a split inductor or two separate inductors.

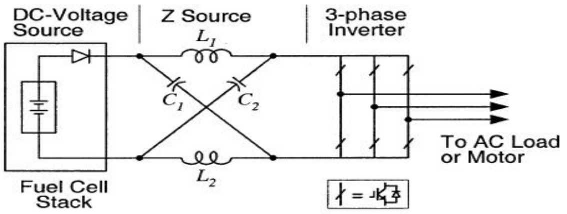


Fig 2: Z-source inverter for fuel-cell applications.

The Z-source concept can be applied to all dc-to-ac, ac-to-dc, ac-to-ac, and dc-to-dc power conversion. To describe the operating principle and control, this paper focuses on an application example of the Z-source converter: a Z-source inverter for dc-ac power conversion needed for fuel-cell applications. Fig 2 shows the traditional two-stage power conversion for fuel-cell applications. Because fuel cells usually produce a voltage that changes widely (2:1 ratio) depending on current drawn from the stacks. For fuel-cell vehicles and distributed power generation, a boost dc–dc converter is needed because the V-source inverter cannot produce an ac voltage that is greater than the dc voltage. Fig. 7 shows a Z-source inverter for such fuel-cell applications, which can directly produce an ac voltage greater and less than the fuel-cell voltage. The diode in series with the fuel cell in Figures is usually needed for preventing reverse current flow.

2.2 Advantages Of Z-Source Inverter Over Traditional Inverters:

- It can used for any type of power conversion.
- Can be used as both V-source as well as I-source inverters.
- Higher efficiency & more reliability
- It can Buck-boost the voltage.
- Self boost phenomenon can be controlled using a battery in the system.

2.3. Elements In Circuit Diagram:

2.3.1 Fuel Cells:

A fuel cell is a device that generates electricity by a chemical reaction. Every fuel cell has two electrodes, one positive and one negative, called, respectively, the anode and cathode. The reactions that produce electricity take place at the electrodes. Every fuel cell also has an electrolyte, which carries electrically charged particles from one electrode to the other, and a catalyst, which speeds the reactions at the electrodes.

Working of Fuel Cells:

The purpose of a fuel cell is to produce an electrical current that can be directed outside the cell to do work, such as powering an electric motor or illuminating a light bulb or a city. Because of the way electricity behaves, this current returns to the fuel cell, completing an electrical circuit. (To learn more about electricity and electric power, visit “Throw The Switch” on the Smithsonian website Powering a Generation of Change.) The chemical reactions that produce this current are the key to how a fuel cell works.

2.3.2 Insulated Gate Bipolar Transistor

It is a three-terminal power semiconductor device, noted for high efficiency and fast switching. It switches electric power in many modern appliances: electric cars, trains, variable speed refrigerators, air-conditioners and even stereo systems with switching amplifiers . An IGBT cell is constructed similarly to a n-channel vertical construction power MOSFET except the n+ drain is replaced with a p+ collector layer, thus forming a vertical PNP bipolar junction transistor.

2.3.3 Diode:

A modern semiconductor diode is made of a crystal of semiconductor like silicon that has impurities added to it to create a region on one side that contains negative charge carriers (electrons), called n-type semiconductor, and a region on the other side that contains positive charge carriers (holes), called p-type semiconductor. The diode's terminals are attached to each of these regions. The boundary within the crystal between these two regions, called a PN junction, is where the action of the diode takes place. The crystal conducts a current of electrons in a direction from the N-type side (called the cathode) to the P-type side (called the anode), but not in the opposite direction. However, conventional current flows from anode to cathode in the direction of the arrow (opposite to the electron flow, since electrons have negative charge).

2.3.4 Inductor:

An **inductor** (or **reactor** or **coil**) is a passive two-terminal electrical component used to store energy in a magnetic field. An inductor's ability to store magnetic energy is measured by its inductance, in units of henries. Any conductor has inductance although the conductor is typically wound in loops to reinforce the inductor magnetic field. Due to the time-varying magnetic field inside the coil, a voltage is induced, according to Faraday's law of electromagnetic induction, which by Lenz's Law opposes the change in current that created it. Inductors are one of the basic components used in electronics where current and voltage change with time, due to the ability of inductors to delay and reshape alternating currents and can be used to block AC signals from passing through a circuit.

2.3.5 Capacitor:

A **capacitor** (formerly known as **condenser**) is a passive two-terminal electrical component used to store energy in an electric field. When there is a potential difference (voltage) across the conductors, a static electric field develops across the dielectric, causing positive charge to collect on one plate and negative charge on the other plate. Energy is stored in the electrostatic field. The capacitance is greatest when there is a narrow separation between large areas of conductor, hence capacitor conductors are often called "plates," referring to an early means of construction.

2.4 Inductor And Capacitor Requirement Of The Z-Source Network

For the traditional V-source inverter, the dc capacitor is the sole energy storage and filtering element to suppress voltage ripple and serve temporary storage. For the traditional I-source inverter, the dc inductor is the sole energy storage/filtering element to suppress current ripple and serve temporary storage .The Z-source network is a combination of two inductors and two capacitors. This combined circuit, the Z-source network is the energy storage/filtering element for the Z-source inverter. The Z-source network provides a second-order filter and is more effective to suppress voltage and current ripples than capacitor or inductor used alone in the traditional inverters. Therefore, the inductor and capacitor requirement should be smaller than the traditional inverters. When the two inductors(L1andL2) are small and approach zero, the Z-source network reduces to two capacitors(C1andC2) in parallel and becomes a traditional V-source. Therefore, a traditional V-source inverter's capacitor requirements and physical size is the worst case requirement for the Z-source network. Considering additional filtering and energy storage provided by the inductors, the Z-source network should require less capacitance and smaller size compared with the traditional V-source inverter. Similarly, when the two capacitors(C1andC2) are small and approach zero, the Z-source network reduces to two inductors(L1andL2) in series and becomes a traditional I-source. Therefore, a traditional I-source inverter's inductor requirements and physical size is the worst case requirement for the Z-source network. Considering additional filtering and energy storage by the capacitors, the Z-source network should require less inductance and smaller size compared with the traditional I-source inverter.

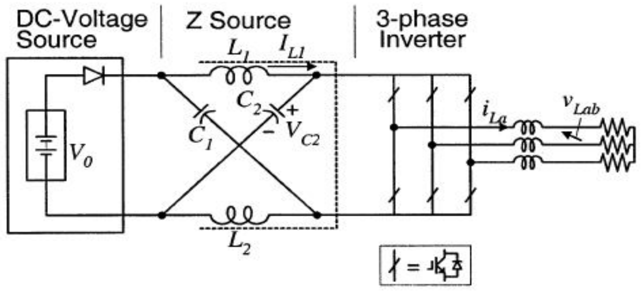


Fig 3: Z-Source Inverter

2.5 Z-Source Inverter Self-Boost Phenomenon:

The purpose of this project is to verify the Z-source inverter technology and examine the possibility of using it in fuel cell vehicles. The current configuration of the Z-source inverter prototype does not include the dispensable battery and is not able to handle transients. During the testing, the current Z-source inverter without a battery was discovered to have a voltage boost when operated at low speed, low modulation index, and low load power factor without intentional insertion of shoot-through. This self voltage boost was initially deemed a problem. However, theoretical analysis, simulation, and experiments have proved that it can be solved when a battery is incorporated into the Z-source inverter. A further, deeper investigation and discussions with fuel cell control experts revealed that the self voltage boost problem actually is a needed function for faster and more reliable fuel cell startup, especially for freeze startups. However, this self-boot phenomenon can be a problem for some applications other than FCVs. In addition, this self-boost has to be and can be controlled.

2.6 Z-Source Inverter Self-Boost:

During normal operation, there is no shoot-through. Assuming the inductor current is a pure dc value, for a system shown in the fig 4,

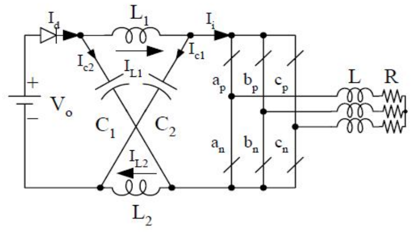


Fig 4: Z-source inverter with load.

Assuming the load current is *ILoad* and the load power factor is *cosφ*, the total power of the system current can be calculated. The inverter dc side current, *Ii*, is a pulse signal. The peak value of the current is the maximum load current, which is max(*Ii*) = 2*I Load* .

The inverter current *Ii* can be expressed as the combination of the inductor current *IL* and the diode current *Id*

$$Ii = I_{L1} - Ic1$$

$$= I_{L1} - Ic2$$

$$= I_{L1} - (Id - I_{L1})$$

$$= 2I_L - Id ,$$

where Ic1 = Ic2, IL1 = IL2 = IL.

The current through the diode cannot be lower than zero; therefore, the maximum available current for *Ii* is 2*IL*. However, in the following condition, the load peak current can be higher.

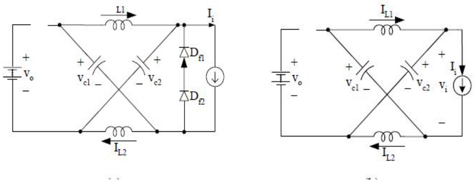


Fig 5: operation modes during self-boost.

This means that when the product of the modulation index and the load power factor is lower than 2/3, the inverter might have some new operation modes. During the traditional zero state, the current to the inverter, *Ii*, is zero. When the inverter turns into an active state, and the current required to the inverter, *Ii*, is higher than what is available—2*IL* when Equation is met—the free-wheeling diode *Df1* and *Df2* will be turned on to provide the required current to the load, which forms an undesired shoot-through state as shown in Fig. During the shoot-through state, the inductor current increases linearly, until $2I_L = Ii$ .Then the inverter turns into the active state shown as in Fig. in which the input end diode is still reverse biased, and the current to the load is provided by the capacitor only until the next switching action to turn the inverter into a zero state or another active state. The unwanted shoot-through state will boost the output voltage.

2.7 Shoot-Through Pwm Control:

Several control methods have been proposed: simple control , maximum boost control ,and maximum constant boost control. In our design, to minimize the size of the inductor, the inductance was selected to be 50 μH; therefore, maximum constant boost was the most suitable control method to minimize current ripples. The original method presented in the paper increases the equivalent frequency for the inductor side, but it also increases the real switching frequency. To minimize the switching loss, a modified PWM method that achieves maximum constant boost and minimum switching loss was proposed and implemented in the prototype.

2.7.1 Control Methods for Z-Source Inverter:

Compared with a traditional voltage source inverter, the Z-source inverter has an extra switching state: shoot-through. During the shoot-though state, the output voltage to the load terminals is zero, the same as traditional zero states. Therefore, to maintain sinusoidal output voltage, the active-state duty ratio has to be maintained and some or all of the zero states turned into shoot-through state.

2.7.1.1 Simple Control:

The simple control uses two straight lines to control the shoot-through states, as shown in Fig 6. When the triangular waveform is greater than the upper envelope, Vp, or lower than the bottom envelope, Vn, the circuit turns into shoot-through state. Otherwise it operates just as traditional carrier-based PWM. This method is very straightforward; however, the resulting voltage stress across the device is relatively high because some traditional zero states are not utilized.

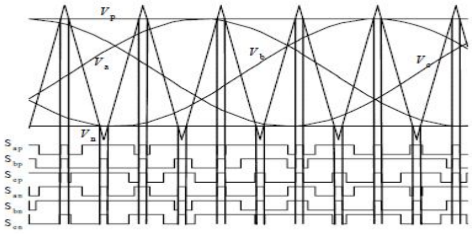
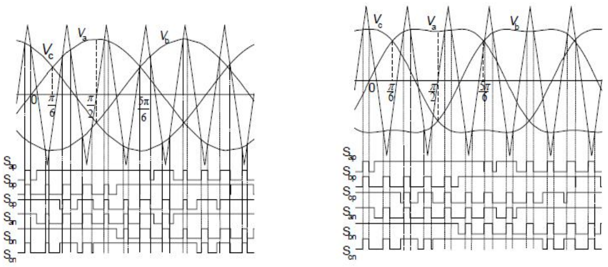


Fig 6: sketch up map of simple control

2.7.1.2 Maximum Boost Control:

To fully utilize the zero states so as to minimize the voltage stress across the device, maximum boost control turns all traditional zero states into shoot-through state, as shown in Fig. Third harmonic injection can also be used to extend the modulation index range. Indeed, turning all zero states into shoot-through state can minimize the voltage stress; however, doing so also causes a shoot-through duty ratio varying in a line cycle, which causes inductor current ripple. This will require high inductance for low-frequency or variable-frequency applications.



(a) Maximum boost control. (b) Maximum boost control with third harmonic injection.

Fig 7: sketch map of maximum boost control

2.8 Equivalent Circuit, Operating Principle, And Control:

The unique feature of the Z-source inverter is that the output ac voltage can be any value between zero and infinity regardless of the fuel-cell voltage. That is, the Z-source inverter is a buck–boost inverter that has a wide range of obtainable voltage. The traditional V- and I-source inverters cannot provide such feature. To describe the operating principle and control of the Z-source inverter, let us briefly examine the Z-source inverter structure.

In Fig 8, the three-phase Z-source inverter bridge has nine permissible switching states (vectors) unlike the traditional three-phase V-source inverter that has eight. The traditional three-phase V-source inverter has six active vectors when the dc voltage is impressed cross the load and two zero vectors when the load terminals are shorted through either the lower or upper three devices, respectively. However, the three-phase Z-source inverter bridge has one extra zero state (or vector) when the load terminals are shorted through both the upper and lower devices of any one phase leg (i.e., both devices are gated on), any two phase legs, or all three phase legs. This shoot-through zero state (or vector) is forbidden in the traditional V-source inverter, because it would cause a shoot-through. We call this third zero state (vector) the shoot-through zero state (or vector), which can be generated by seven different ways: shoot-through via any one phase leg, combinations of any two phase legs, and all three phase legs. The Z-source network makes the shoot-through zero state possible. This shoot-through zero state provides the unique buck-boost feature to the inverter. Fig shows the equivalent circuit of the Z-source inverter shown in Fig when viewed from the dc link. The inverter bridge is equivalent to a short circuit when the inverter bridge is in the shoot-through zero state, as shown in Fig 8, whereas the inverter bridge becomes an equivalent current source as shown in Fig. 9 when in one of the six active states. Note that the inverter bridge can be also represented by a current source with zero value (i.e., an open circuit) when it is in one of the two traditional zero states. Therefore, Fig 9 shows the equivalent circuit of the Z-source inverter viewed from the dc link when the inverter bridge is in one of the eight non shoot-through switching states.

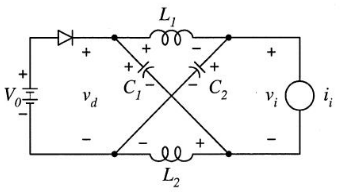


Fig 8: Equivalent circuit of the z source

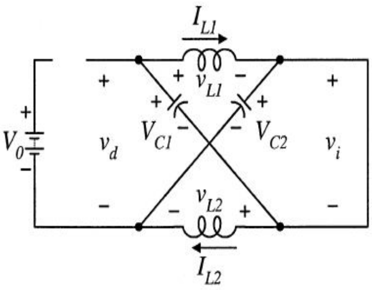


Fig 9: Equivalent circuit of z source during shoot through state

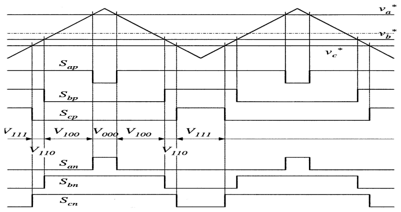


Fig 10: Traditional carrier-based PWM control without shoot-through zero states

All the traditional pulse width-modulation (PWM) schemes can be used to control the Z-source inverter and their theoretical input–output relationships still hold. Fig shows the traditional PWM switching sequence based on the triangular carrier method. In every switching cycle, the two non shoot-through zero states are used along with two adjacent active states to synthesize the desired voltage. When the dc voltage is high enough to generate the desired ac voltage, the traditional PWM is used. While the dc voltage is not enough to directly generate a desired output voltage, a modified PWM with shoot-through zero states will be used as shown in Fig 10 to boost voltage. It should be noted that each phase leg still switches on and off once per switching cycle. Without change the total zero-state time interval, shoot-through zero states are evenly allocated into each phase. That is, the active states are unchanged. However, the equivalent dc-link voltage to the inverter is boosted because of the shoot-through states. The detailed relationship will be analyzed in the next section. It is noticeable here that the equivalent switching frequency viewed from the Z-source network is six times the switching frequency of the main inverter, which greatly reduces the required inductance of the Z-source network.

2.9 Simulation Results

Simulations have been performed to confirm the above analysis. Fig 11 shows the circuit configuration and simulation waveforms when the fuel-cell stack voltage is V and the Z-source network parameters are H and F. The purpose of the system is to produce a three-phase 208-Vrms power from the fuel-cell stack whose voltage changes 150-340 V dc depending on load current. From the simulation waveforms of it is clear that the capacitor voltage was boosted to V and the output line-to-line was 208-Vrms or 294 V peak. In this case, the modulation index was set to and the shoot-through duty cycle was set to and switching frequency was 10 kHz. The shoot-through zero state was populated evenly among the three phase legs, achieving an equivalent switching frequency of 60 kHz viewed from the Z-source network. Therefore, the required dc inductance is minimized. From the above analysis, we have the following

$$B = \frac{1}{1-2\frac{T_0}{T}} = 3.52$$

$$V_{C1} = V_{C2} = V_C \frac{1-\frac{T_0}{T}}{1-2\frac{T_0}{T}} V_0 = 2.26 \cdot 150\ \text{V} = 339\text{V}$$

$$\hat{v}_{ac} = M \cdot B \cdot \frac{V_0}{2} = 0.642 \cdot 3.52 \cdot \frac{150\ \text{V}}{2} = 169.5\text{V}.$$

Equation is the phase peak voltage, which implies that the line-to-line voltage is 208 V rms or 294 V peak. The above theoretical values are quite consistent with the simulation results. The simulation proved the Z-source inverter concept. A prototype as shown in Fig. has been constructed. The same parameters as the simulation were used. Figs 12 show experimental results. When the fuel-cell voltage is low, as shown in Fig, the shoot-through state was used to boost the voltage in order to maintain the desired output voltage. The waveforms are consistent with the simulation results. When the fuel-cell voltage is high enough to produce the desired output voltage, the shoot-through state was not used, as shown in Fig 12, where the traditional PWM control without shoot-through was used. By controlling the shoot-through state duty cycle or the boost factor, the desired output voltage can be obtained regardless of the fuel cell voltage.

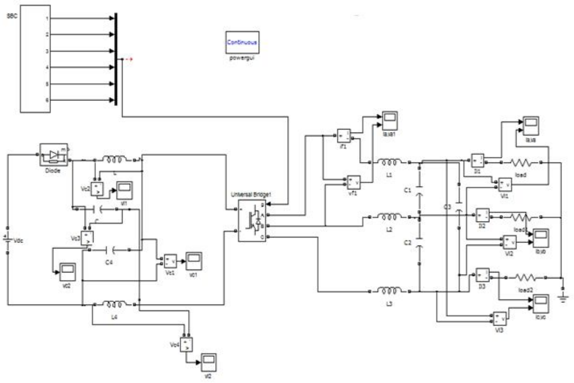


Fig 11: Simulink Of Z-Source Inveter:

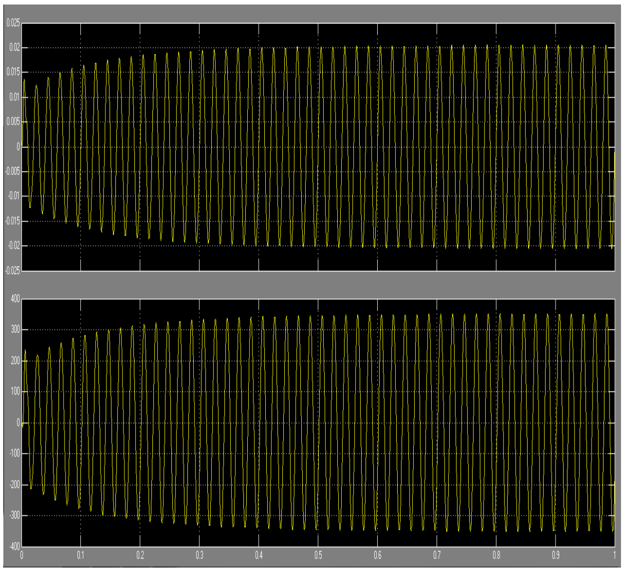


Fig 12: Output current and voltage waveforms

2.10 CONCLUSION

This paper has presented an impedance-source power converter for implementing dc-to-ac, ac-to-dc, ac-to-ac, and dc-to-dc power conversion. The Z-source converter employs a unique impedance network (or circuit) to couple the converter main circuit to the power source, thus providing unique features that cannot be observed in the traditional voltage-source and current-source converters where a capacitor and inductor are used, respectively. The Z-source converter overcomes the conceptual and theoretical barriers and limitations of the traditional voltage-source converter and current-source converter and provides a novel power conversion concept. This paper focused on an example—a Z-source inverter for fuel-cell applications. Through the example, the paper described the operating principle, analyzed the circuit characteristics, and demonstrated its concept and superiority. Analytical, simulation, and experimental results have been presented. The Z-source inverter can boost–buck voltage minimize component count, increase efficiency, and reduce cost.

2.11 FUTURE SCOPE

In this report, a Z-Source inverter fed induction motor for electric vehicle applications was presented. Only the power flow from DC source side to motor side was taken in to account. However a dc-dc converter is needed to accept a reverse power flow and to reduce the regenerative voltage to a battery voltage. Hence, the proposed inverter circuit can be modified to include a current fed Z-source dc-dc converter to make the Z-source circuit bi-directional in nature. Also, PID controller can be included for capacitor voltage control with an excellent transient performance which enhances the rejection of disturbance, including the input voltage ripple and load current variation, and have good ride-through for voltage-sags.

2.12 REFERENCES

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