Chapter 9
Fuel Cell and Converters

Learning Objectives
On completion of this chapter the reader will have knowledge on:

- Need for Fuel Cell and types of fuel cell.
- Comparative Analysis and Characteristic behaviour of fuel cells.
- MATLAB/SIMULINK implementation of fuel cell model.
- Types of converters and their implementation using MATLAB/SIMULINK.
- Series architecture, DC bus distribution architecture, High frequency AC (HFAC) distribution architecture, Multilevel architecture models for high power and high voltage applications.

9.1 Introduction

Depletion of fossil fuels, increasing energy consumption and rising public awareness for environmental pollution effects have turned the focus of research work towards alternative renewable energy sources. Fuel cells are one of the most promising sources of energy because of their high efficiency and low environmental impact. Fuel cell is a device which was invented in nineteenth century, but it took so long to turn our minds towards fuel cell due to several challenges in implementing it in various applications. As it is focussed only in recent years and considered as a relatively new technology, the perception of risk and lack of user experience are obstacles. The capital expense of fuel cell systems may have been the most significant barrier in the past, but as technology improves, this may no longer be the case. Some tedious obstacles are: (i) No acceptance of reverse current, (ii) Low output voltage and its degradation with age and current, (iii) Low efficiency with output ripple current, (iv) Limited overload capability and (v) Respond sluggishly to step variation in load. To overcome these technical challenges, power converters

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are often necessary to boost and regulate the output voltage to provide an applicable DC power source. In this chapter, the fuel cell technology, converter types and their MATLAB/SIMULINK models are discussed. Architecture for multiple fuel cell for applications with high power are also delineated.

9.2 Fuel Cell Technology

Fuel cells actually have been known to science for more than 150 years. Though generally considered a curiosity in the 1800s, fuel cells became the subject of intense research and development during the 1900s. The basic operation of fuel cell is very simple. In 1839, lawyer and scientist, William Groove discovered the reverse electrolysis of water. By combining hydrogen and oxygen in a particular configuration, electricity could be produced. A fuel cell is an electrochemical cell that derives electrical energy from spontaneous redox reaction taking place within the cell. It is similar to that of battery as it converts the chemical potential energy into electrical energy by means of electrochemical process. Both batteries and fuel cells convert chemical potential energy into electrical energy and also, as a by-product of this process, into heat energy. However, a battery holds a closed store of energy within it and once this is depleted the battery must be discarded, or recharged by using an external supply of electricity to drive the electrochemical reaction in the reverse direction. A fuel cell, on the other hand, uses an external supply of chemical energy and can run indefinitely, as long as it is supplied with a source of hydrogen and a source of oxygen (usually air). A basic schematic of fuel cell is shown in Fig. 9.1.

Fuel cell uses hydrogen-rich fuel and oxygen from air to produce electricity. It continues to generate electric power until these substances are fed into the cell. The process is implemented by using two electrodes. At one electrode, hydrogen fuel is oxidised and at the other electrode oxygen is reduced. Electrolyte which is in between two electrodes transmits ions from anode to cathode but does not allow movement of electrons. Thus the reactions exchange electrons through an external circuit which gives the electrical power to the load. The reactants flow into the cell and the reaction products flow out of it, while the electrolyte remains within it. The basic reactions involved in energy conversion of Hydrogen-Oxygen fuel cell are:

$$\text{At Anode} : 2H_2 \rightarrow 4H^+ + 4e^- \tag{9.1}$$

$$\text{At Cathode} : O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \tag{9.2}$$

$$\text{Net reaction} : 2H_2 + O_2 \rightarrow 2H_2O \tag{9.3}$$

When pure hydrogen is used as fuel the products are thus water and energy which makes it advantageous. The fuel cell provides DC voltage which can be used for various applications directly or by converting to AC with the help of inverter. Pure Hydrogen can be obtained by using fuel reformer which consumes natural gas, coal and biomass to generate hydrogen.

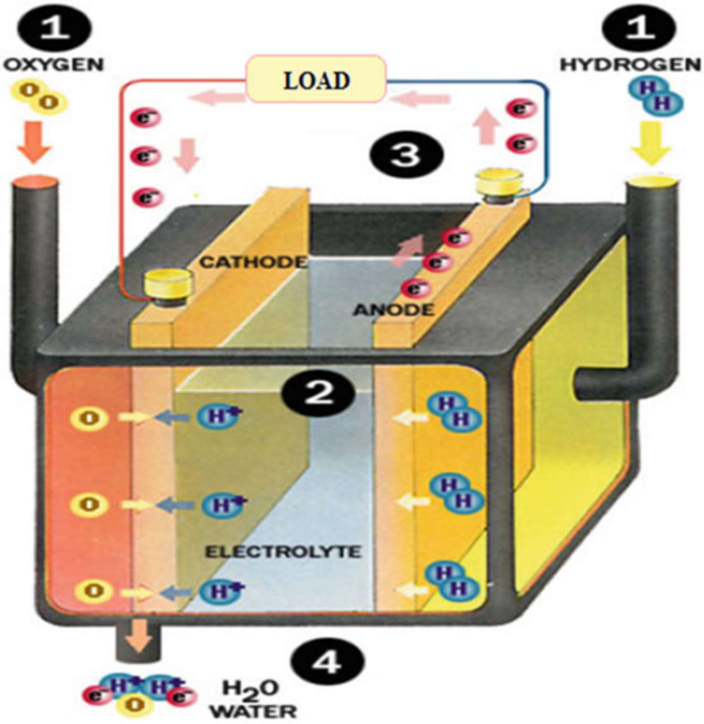

Fig. 9.1 Fuel cell process ((i)-Fuel supply inlet; (ii)-hydrogen through ion transfer electrolyte; (iii)-electron transfer through external circuit; (iv)- reaction product water outlet)

As per the required power rating fuel cells are bundled together in series and parallel combinations known as Stack. Its rating ranges from a few kilowatts to a hundred kilowatts (Fig. 9.2).

9.2.1 Importance of Fuel Cell

At present the entire world is in energy and environment crisis which forces people to go for a clean and more efficient renewable energy sources. Generating renewable electricity is an important way to reduce carbon dioxide (CO_2) emissions and many countries are installing wind and solar power plants to meet the targets for reducing CO_2 emission. One drawback of these energy sources is their variability: the wind tends to blow intermittently and solar power is only available during the daytime. Storing excess renewable energy generated during times of plenty is a difficult task. One of the alternative sources of power is fuel cell. Excess electricity can be fed into an electrolyser to split water into its constituent parts, oxygen and hydrogen. The hydrogen is then used in fuel cells to produce electricity when

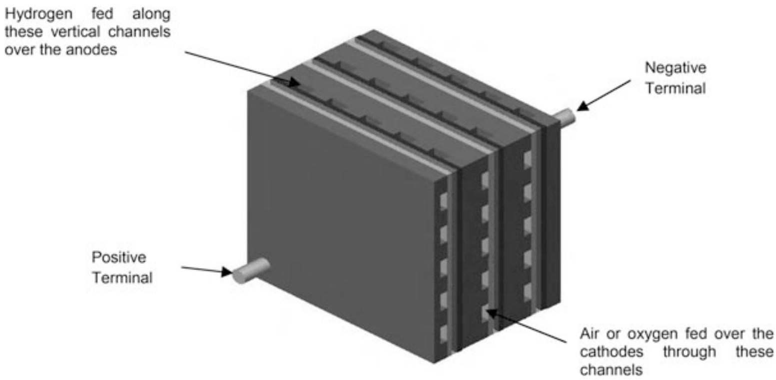

Fig. 9.2 Fuel cell stack connection using bipolar plates

needed, releasing the stored energy. Fuel cells also promise greater operating efficiency with lower emissions over conventional power sources used today. Unlike internal combustion engines, the fuel is not combusted the energy instead being released electro catalytically. This allows fuel cells to be highly energy efficient, especially if the heat produced by the reaction is also harnessed for cogeneration. The advantages of fuel cell are its high efficiency, low environmental impact, reliable and very quiet operation. But it has some technical challenges which includes expensiveness in manufacturing, production and storage of hydrogen-a difficult task and extreme heat generation in some models.

The major applications are: (i) Stationary (A.C. Applications)-Power plants, Residential use and Commercial use; (ii) Enclosed Environments (D.C. Applications)-Auxiliary power unit, Space Station, Space vehicles (space shuttle) and Underwater vehicles (submarine); (iii) Transportation and portable electronics (D.C. Applications)-Personal Vehicles (ZEV's -Zero Emission Vehicles), Public Transportation, Commercial and Military Vehicles.

9.2.2 *Types of Fuel Cells*

There are many different types of fuel cells which are mainly distinguished by the electrolyte/fuel that is used, though there are other important differences in performance parameter as well. The general classifications of fuel cells are: (i) Alkaline Fuel Cell (AFC); (ii) Proton Exchange Membrane Fuel Cell (PEMFC); (iii) Phosphoric Acid Fuel Cell (PAFC); (iv) Molten Carbonate Fuel Cell (MCFC); (v) Solid Oxide Fuel Cell (SOFC).

Table 9.1 shows the comparison of different fuel cells based on various parameters. The operating temperature of the fuel cell can be determined by the choice of electrolyte and the type of material used for it. Liquid electrolytes limits the operating temperature to about 250 °C or below because of the rapid degradation

Table 9.1 Comparison of different fuel cells

	AFC	PEMFC	PAFC	MCFC	SOFC
Electrolyte	Solution of KOH in water	Solid polymer (Nafion)	Liquid phosphoric acid in SiC matrix	Lithium and potassium carbonates in porous matrix	Solid oxide electrolyte (Yttria stabilised Zirconia)
Fuel	Pure H_2	Pure H_2	Pure H_2	H_2, CO, hydrocarbons	H_2, CO, hydrocarbons
Operating temperature, °C	50–100	30–80	160–220	600–700	600–1,000
Catalyst	Platinum	Platinum	Platinum	Electrode material (Nickel)	Nickel
Cell reaction	At anode: $2H_2 + 4OH^- \rightarrow 4H_2O + 4e^-$	At anode: $2H_2 \rightarrow 4H^+ + 4e^-$	At anode: $2H_2 \rightarrow 4H^+ + 4e^-$	At anode: $CO_3^{2-} + H_2 \rightarrow H_2O + CO_2 + 2e^-$	At anode: $O^{2-} + H_2 \rightarrow H_2O + 2e^-$
	At cathode: $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$	At cathode: $O_2 + 4H^+ + 4e^- \rightarrow H_2O$	At cathode: $O_2 + 4H^+ + 4e^- \rightarrow H_2O$	At cathode: $CO_2 + \frac{1}{2}O_2 + 2e^- \rightarrow CO_3^{2-}$	At cathode: $O_2 + 4e^- \rightarrow 2O^{2-}$
Mobile ion	OH^-	H^+	H^+	CO_3^{2-}	O^{2-}
Efficiency	About 55 %	40–50 %	Around 45 %	60–70 %	About 60 %
Advantages	High efficiency, low oxygen reduction reaction losses	Rapid start up, high hydrogen power density	Good quality waste heat, 1.5 % CO tolerance, simple and stable	Fuel flexibility, good quality waste heat, inexpensive nickel catalyst, CO tolerance	Fuel flexibility, CO_2 tolerance, waste heat can be recycled, inexpensive nickel catalyst

(continued)

Table 9.1 (continued)

	AFC	PEMFC	PAFC	MCFC	SOFC
Disadvantages	Small amount of CO and CO_2 in the atmosphere degrade the operation, expensive catalyst used	Expensive platinum catalyst used, fuel used must be purified from CO, poor quality waste heat	Expensive platinum catalyst used, internal parts must withstand corrosive acid, slow start up, loss of electrolyte	CO_2 injection necessary at the cathode, extremely long start up, electrolyte maintenance	Inactivity of electrolyte below 600 °C, long start up time
Applications	(i) Apollo space craft to provide both electricity and drinking water	(i) Mainly automotive applications	(i) Extraordinary premium stationary power system	(i) large stationary power plants	(i) Large stationary power plants
	(ii) Space missions	(ii) Portable applications	(ii) Waste heat used for cogeneration systems	(ii) Waste heat used for cogeneration systems	(ii) Waste heat used for cogeneration systems
					(iii) Auxiliary power

and vaporization of fluids at higher temperatures. Low temperature fuel cells include AFC, PAFC and PEMFC types. The rate of chemical reaction is too slow in low temperature fuel cells and hence it requires precious nobel metals such as platinum at any one electrode or both to catalyse the reaction. As low temperature fuel cells cannot tolerate CO concentration in the fuel which causes degradation of the operation, it requires external reformer to purify the hydrogen. Their applications are mainly focused on vehicle applications which requires quick start up and higher power density.

Higher temperatures fuel cells include MCFC and SOFC which has an operating temperature of 500 ° C and above typically promote faster reactions. As high temperature fuel cells react more readily and efficiently, it does not require the precious nobel metal catalyst. It is also fuel flexible and do not necessitate the use of external reformer as hydrocarbon fuels can be internally converted to hydrogen or even directly oxidized electrochemically during cell reaction.

Fuel cell is also classified based on the type of fuel used. Direct Methanol Fuel cell (DMFC) uses liquid form of Methanol or alcohol as fuel directly instead of pure hydrogen. So it operates without reforming. DMFC is a subtype of PEMFC which uses polymer as electrolyte and other operations are similar to that of it. It suits for some applications where the power density can be low but the energy density must be high such as portable electronic systems of low power and running for long times. It operates at a low temperature range of 20–60 °C.

9.2.3 Electrical Behaviour of Fuel Cell

The cell potential vs current density behaviour of the fuel cell predominantly determines the performance of fuel cell systems. The theoretical open circuit voltage (E) of a hydrogen fuel cell is given by the formula

$$E = (-\Delta G)/2F \tag{9.4}$$

where ΔG indicates the Gibbs free energy and F indicates the Faraday's constant.

The open circuit voltage value of a single fuel cell is about 1.2 V. When the amount of current is increased, the voltage drop is also increased. This drop in voltage is due to the losses such as activation losses, fuel crossover, ohmic losses and concentration losses at the electrode and in the electrolyte.

Activation losses are dominant when the current density is low. It is due to the slowness of the electrochemical reaction of hydrogen and oxygen at the surface of the electrode. Some of the voltage is lost in transferring electrons between the electrodes which makes this loss as highly non linear with the increase in current. Fuel crossover and internal currents contribute less to the voltage losses when the cell is operated at high temperature. It takes place due to the passing of fuels and electron conduction through the electrolyte. Ohmic losses take place due to the resistance offered by the electrode and various interconnections to the flow of

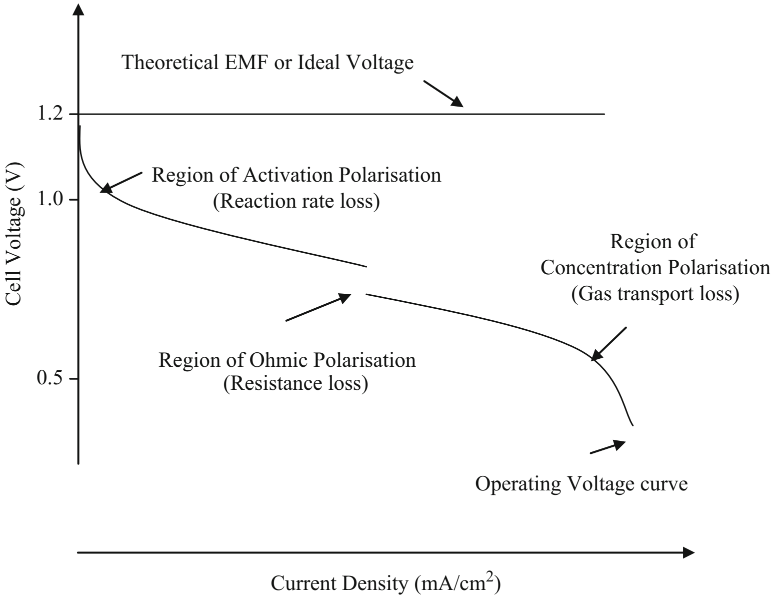

Fig. 9.3 Polarization curve of low temperature fuel cell, 70 °C

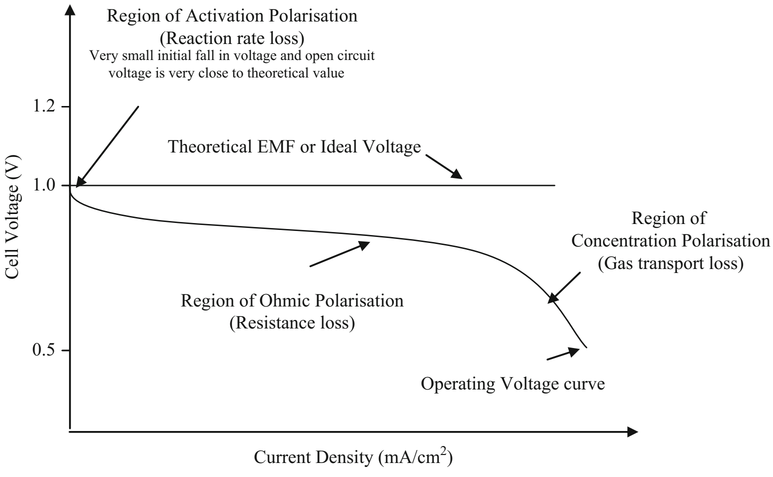

Fig. 9.4 Polarization curve of high temperature fuel cell, 800 °C

electron and also by the resistance to the flow of ions through the electrolyte. Ohmic losses are highly linear as it is purely dependent on the resistance. Concentration losses are due to the difference in the concentration of the reactants as the fuel is consumed. Only at high current densities, this loss will be dominant (Figs. 9.3 and 9.4).

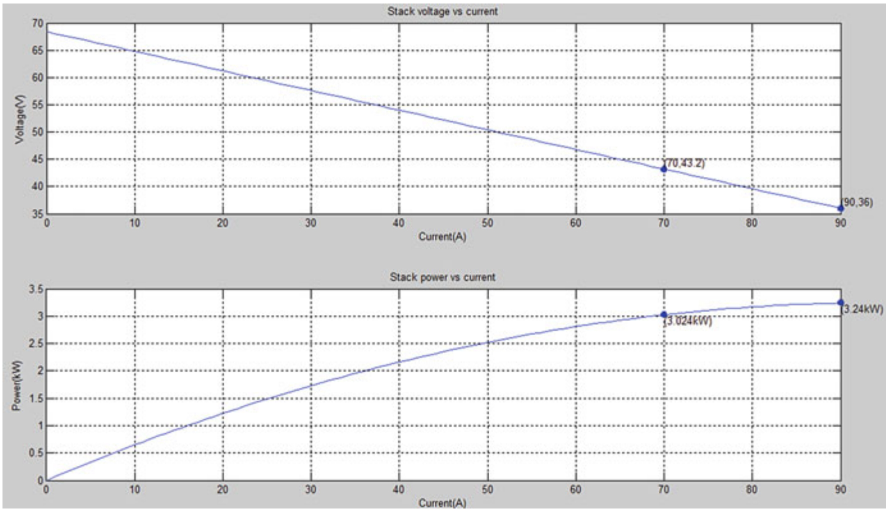

Fig. 9.5 Polarization curve of PEMFC

For low temperature fuel cell operating below 100 °C the open circuit voltage is less than the theoretical ideal value. When the current density increases the voltage decreases and losses will be high at high current densities.

For high temperature fuel cell operating about 800 °C the open circuit voltage is identical to its ideal value which is generally less than the ideal voltage value of low temperature fuel cell. But this is compensated when the fuel cell operates as the losses are less when compared with operating at low temperature. There will not be any sudden drop in voltage at the beginning which indicates no effect of activation losses.

Figure 9.5 shows the polarization curve of the selected PEM fuel cell stack using MATLAB/SIMULINK. The fuel cell stack produces an open circuit voltage of 68 V and 3 KW power at nominal operating point.

9.2.4 Need for Power Electronic Converters

All electrical power sources generate voltage which varies with time, temperature and other factors such as current. But fuel cells are badly regulated when compared to the other sources which is evident from its electrical characteristics (Figs. 9.3 and 9.4). Since the voltage of an elementary cell is only about 0.6–0.7 V at the rated current, the fuel cells are connected in series known as stack to produce a useful voltage. But higher stacking has a disadvantage of higher production cost, reducing the reliability and lifetime. Even when there is a small variation in one of its cell in stack the output will get heavily affected. Therefore the fuel cell stack output

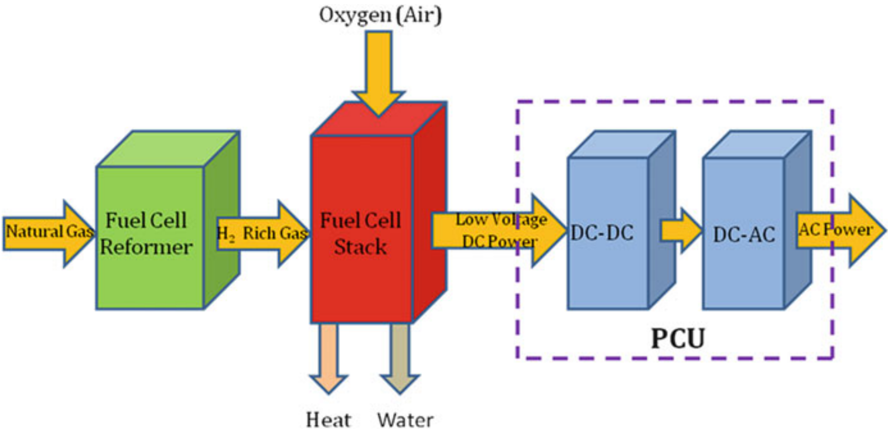

Fig. 9.6 Block diagram of fuel cell system

voltage is mostly limited to a maximum of 100 V to improve the lifetime and reliability. But various applications such as electric vehicles require high DC-bus voltage of few hundred volts to drive the power train. Therefore an effective DC-DC converter is needed to interface fuel cell stack with utility DC-bus (Fig. 9.6).

As fuel cell strongly varies with the load, the DC-DC converter should also serve as a voltage conditioning unit. The dynamic response of the fuel cell during load variations is very slow i.e. the output voltage cannot match the required demand and fluctuates. Typically, the cell voltage varies from 1 V to 400 mV, so a 60 % voltage variation must be managed. Then high stresses can be imposed on the switching devices. Also a diode is connected in series with the fuel cell module as fuel cells obstruct reverse current flow and do not absorb power back. Thus an additional energy storage system such as battery or super capacitor is required to store braking energy in vehicles and to manage high power transients. To implement this functionality Bidirectional DC-DC converter is linked in interfacing the energy storage system with the fuel cell system. One major problem with the DC-DC converter is the injection of ripple onto the fuel cell which affects the performance of the fuel cell. This ripple current is the result of switching characteristics of the electronic devices used in the power conditioning system which generates two components: a low frequency component and a high frequency component. The low frequency component has a frequency twice that of the output a.c frequency, generally in the range of 100 or 120 Hz. The high frequency component is in the range of kHz and is caused by the internal switching characteristics of the electronic devices. If the capacitor bank is added at the output of the fuel cell to absorb ripple current, the capacitor should be selected properly to avoid over stress on it. Moreover it increases the cost, size and reliability of the converter. The ripple factor must be lower than 5 % and switching frequencies must be greater than 1.25 kHz for the fuel cell output current to have mirror impact to the fuel cell operating conditions. The

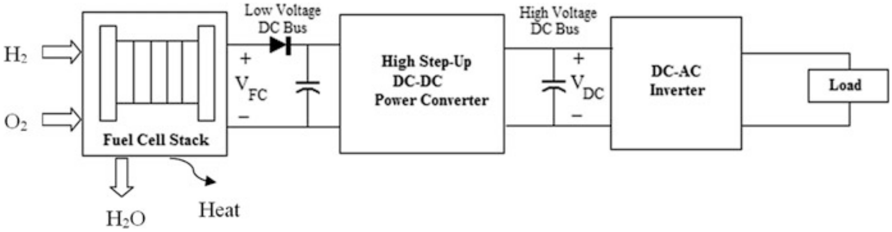

Fig. 9.7 General fuel cell power conditioning system

power electronic devices need to be thermally isolated from the fuel cell modules especially from high temperature fuel cells because power electronic units have high losses and it may even get failure under high temperature. Sometimes to provide electrical isolation between the low output voltage of the fuel cell and the high voltage DC-link, transformer will be added in DC-DC converters which protects the fuel cell. Thus the power conditioning unit plays an important role in all types of fuel cell applications. The basic power conditioning unit (Fig. 9.7) generally consists of a DC-DC converter to raise DC output voltage to DC bus voltage followed by a DC/AC inverter to convert DC bus voltage to AC voltage.

The power conditioning unit should be capable of controlling the fuel cell voltage and convert the fuel cell output to the appropriate type. It should be able to operate efficiently under all conditions which mainly depend upon the conduction losses and switching losses. To reduce the conduction losses, the number of components used in the converter and their operating ranges has to be reduced. The switching losses can be efficiently reduced by adapting soft switching techniques. Thus the configuration particularly number of stages and efficiency of individual components determine the overall efficiency of the power conditioning unit. It also depends on the mode of operation and it varies with the operating point of the system. Efficiencies close to 90 % can be achieved for a well-designed power conditioning system, and probably higher for single stage conversion without transformers. A limitation in power electronic interface is that it cannot perform efficiently beyond certain limit of voltage gain. Hence the fuel cell modules have to be designed in such a way to produce its minimum output voltage more than the least value required by the power electronics unit for the providing voltage gain during interfacing.

9.2.5 DC-DC Converters

DC-DC converters play an important role in fuel cell system to control and regulate the power output. Input to these converters is an unregulated DC voltage from fuel cell stack. It converts the unregulated DC voltage to a regulated voltage based on application.

The different DC-link voltage level based on its applications are 270 or 350 V for electric aircrafts, 270–540 V for electric vehicles, 350–750 V for locomotives, 48, 120 or 400–480 V for stand-alone or parallel grid connections. Therefore, a high step-up DC-DC converter is required to boost the low voltage output of the fuel cell stack into the high voltage at the DC bus. Due to non ideal characteristics of fuel cell the development and designing of power conditioning units play an important role to interface the fuel cell system with the end user. The main characteristics required for dc-dc converter are: (i) High efficiency in power conversion; (ii) High power density;(iii) Small size and light weight; (iv) Low electromagnetic interference (EMI); (v) Reduced ripple current to avoid the FC damage and increase its lifetime; (vi) Low cost.

The selection of proper switching devices also contributes to the efficient operation of the converter. Among all switching devices MOSFET and IGBT plays a wide role in efficient conversion especially the latter combines the advantages of MOSFET, BJT and GTO. Hence IGBT has a significant advantages such as fast switching, much less parasitic power to perform the switching function and reducing complexity by eliminating commutation circuits. But if the switching loss is the major constraint MOSFET is preferred than IGBT.

9.2.5.1 Types of DC-DC Converters

There are various topologies of unidirectional and bidirectional DC-DC converters suitable for fuel cell interface. Based on the existence of electrical barrier between the input and output, DC-DC converters are classified as Isolated and Non-Isolated Converters. The operation of a semiconductor device, during a given turn-on or turn-off switching transition, can be classified as hard switched, zero-current switched, or zero-voltage switched. Zero current switching (ZCS) and Zero voltage switching (ZVS) are the soft switching techniques in which zero-voltage switching comes at the expense of increased conduction loss. Based on switching topology used, DC-DC converters classified as soft and hard-switched converters. Soft switched converters are mainly adopted to reduce the switching losses over the device, to overcome the problems of switching stress and the EMI and to improve the efficiency at higher switching frequency.

9.2.6 Conventional Boost Converter

Among the DC-DC converters the efficiency of the conventional boost converter (Fig. 9.8) is always greater than the other converter topologies because it has reduced number of components and simplicity in control. It consists of an inductor for energy storage, a switch to control the output, a diode to isolate the output stage when the switch is on and a capacitor to reduce ripple. When the switch is closed (t_{on}) the input current flows through the inductor L and switch S. Hence inductor

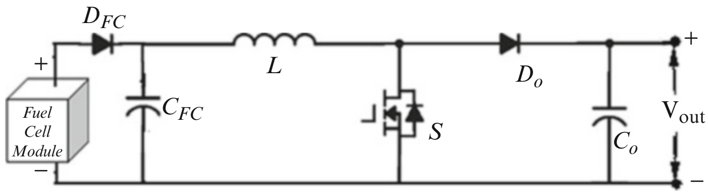

Fig. 9.8 DC-DC boost converter

stores some energy during this operating mode. When the switch is open (t_{off}) the current changes its path as inductor, diode, capacitor and load. The energy stored in the inductor is transferred to the load.

$$\text{During switching-on period } DT_s, \ \frac{di_L}{dt} = \frac{V_{in}}{L} \tag{9.5}$$

$$\text{During switching-off period } (1\text{-}D)T_s, \ \frac{di_L}{dt} = \frac{V_{in} - V_O}{L} \tag{9.6}$$

where i_L is the inductor current, V_{in} is the input voltage and V_o is the voltage across the load.

The output voltage for the selected duty cycle (D) is given by

$$V_o = \frac{V_{in}}{1 - D} \tag{9.7}$$

Some design parameters such as duty cycle, inductor values and design of output filter are to be considered for boosting the voltage to the required level.

Inductor selection is based on the changes in inductor current,

$$\Delta I_L = \frac{V_{in} D T_s}{2L} \tag{9.8}$$

Capacitor selection is based on the output ripple voltage,

$$\Delta V_o = \frac{V_o D T_s}{2RC} \tag{9.9}$$

where T_s is the switching time period.

The voltage gain of this boost converter is extremely high when the duty ratio is close to one. However, the switch turn-off period becomes short when the duty cycle increases and also large duty ratio leads to losses in power switches and diodes. It also cause reverse-recovery problem of diode. As the output voltage is very sensitive to changes in duty cycle it is difficult to stabilize the regulator. For high step-up conversion the current ripples on the devices are large which increases the power device conduction losses and turn-off current. The voltage stresses of the

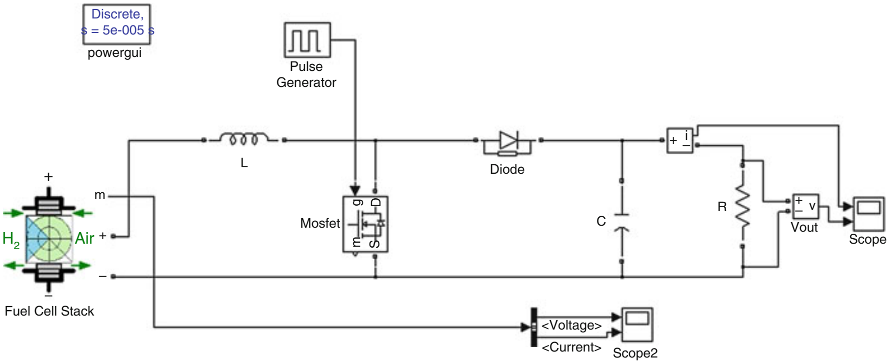

Fig. 9.9 MATLAB/SIMULINK model of the DC-DC boost converter

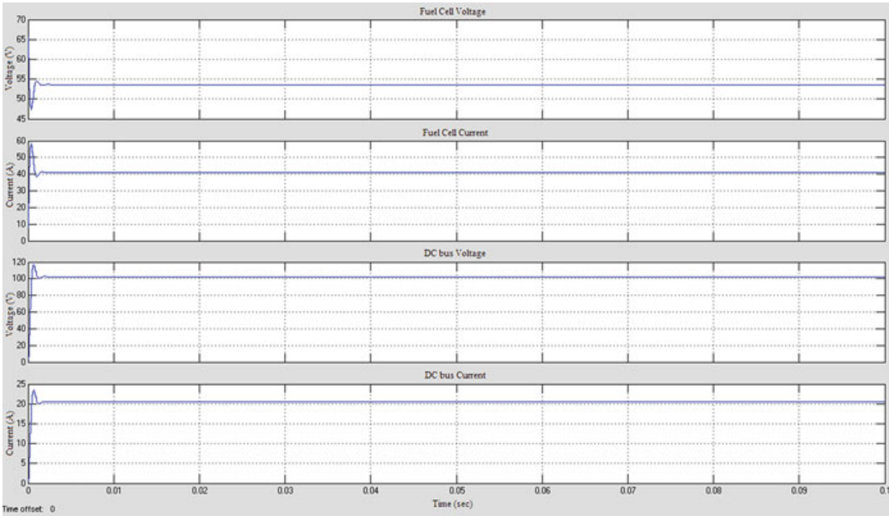

Fig. 9.10 Simulation results of DC-DC boost converter

switch and the diode are equal to the output voltage, which is large in high output voltage applications. Hence it requires high rating passive components. The cost of the switches with high voltage stress is rather higher than that of the switches with low voltage stress.

Figure 9.9 shows the MATLAB/SIMULINK model of the DC-DC boost converter.

Figure 9.10 shows the simulation results of the conventional DC-DC boost converter for 3 kW fuel cell stack input. For high conversion ratio greater than 5, the boost efficiency decreases drastically as a function of duty cycle. Thus conventional boost converter can be operated at reasonable duty cycle to achieve high efficiency and high voltage gain. Furthermore, the power level of the classical boost converter is limited and also it does not meet the criteria of electrical isolation.

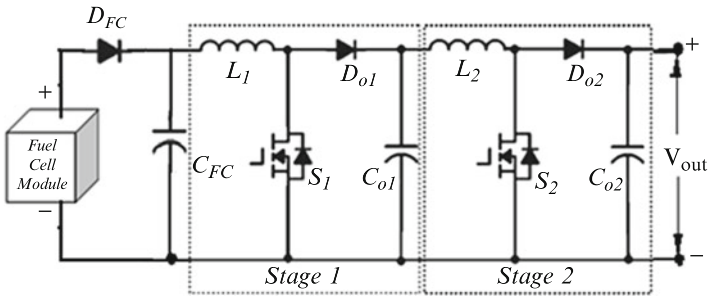

Fig. 9.11 Cascaded boost converter

9.2.7 Cascaded Boost Converter

The DC-DC converter should have a high voltage ratio to satisfy the requirements of various applications. The boost conversion ratio can be increased by connecting several boost components in series known as cascade connection. Important feature expected from the DC-DC converter is a low input current ripple. By cascading the current ripple can be significantly reduced to satisfy high step up requirements (Fig. 9.11). The first stage conversion is achieved with high switching frequency as the voltage stress on the devices is low. The second stage can be achieved with a low switching frequency to reduce the switching losses. The major limitation of cascade converters is the requirement of two sets of boost components, which is complex and expensive. However, the inductance requirement may be reduced if the switching frequency will increase, but this may be limited as semiconductor switching losses are increasing with frequency. Another issue in the cascade boost converters is the system stability which requires careful designing. Moreover, the output-diode reverse-recovery problem of the second stage is severe because a high voltage level should be sustained in the high output-voltage applications.

If the voltage across the capacitor C_1 is charged to V_1 and the voltage across the capacitor C_2 is charged to V_o, the current flowing through inductor L_2 increases with V_1 during the switching-on period DT_s and decreases with voltage $-(V_o-V_1)$ during the switching-off period (1–D) $T_{s.}$ Thus the inductor selection is based on the ripple current ΔI_{L2} and ΔI_{L1} given by,

$$\Delta I_{L2} = \frac{I_{L2} D\left((1-D)^2\right) R}{f L_2} \tag{9.10}$$

$$\Delta I_{L1} = \frac{I_{L1} D\left((1-D)^4\right) R}{f L_1} \tag{9.11}$$

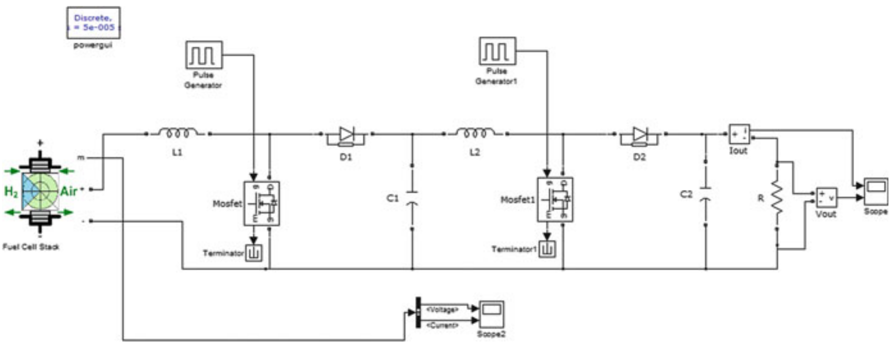

Fig. 9.12 MATLAB/SIMULINK model of cascaded boost converter

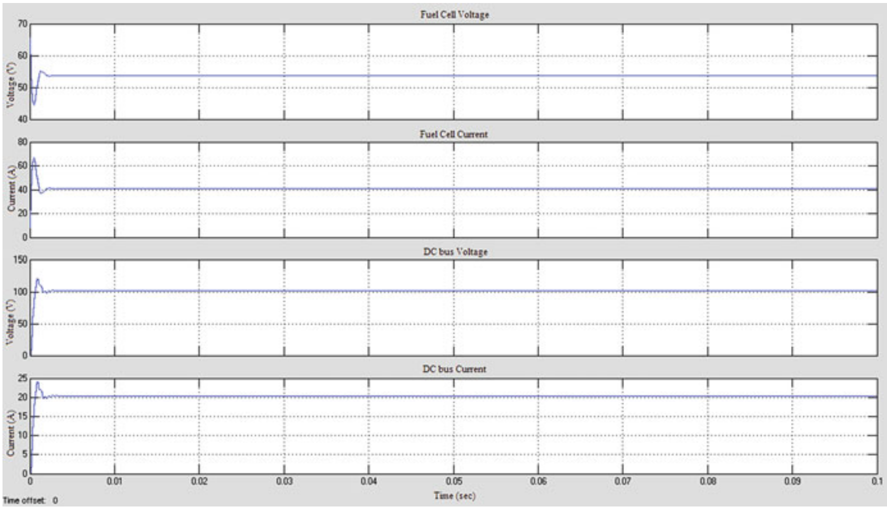

Fig. 9.13 Simulation results of cascaded boost converter

The capacitor selection is based on the ripple voltage

$$\Delta V_o = \frac{V_o(1 - D)}{Rf\,C_2} \tag{9.12}$$

Figure 9.12 shows the MATLAB/SIMULINK model of the cascaded boost converter. The model is designed for 3 kW fuel cell stack input. Figure 9.13 shows the simulation results of cascaded boost converter obtained for the fuel cell input.

In order to reduce the circuit complexity the two switches can be integrated into one switch. The integrated cascade boost converter is shown in Fig. 9.14. When switch S turns on the inductors $L1$ and $L2$ stores energy. When switch S turns off $L1$

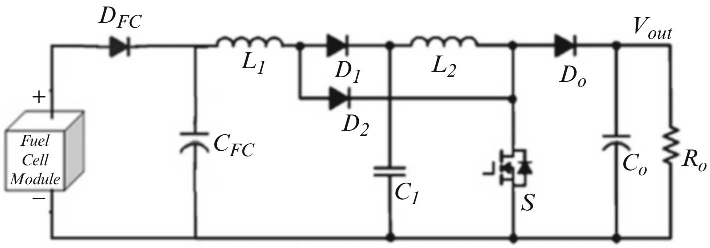

Fig. 9.14 Integrated cascaded boost converter

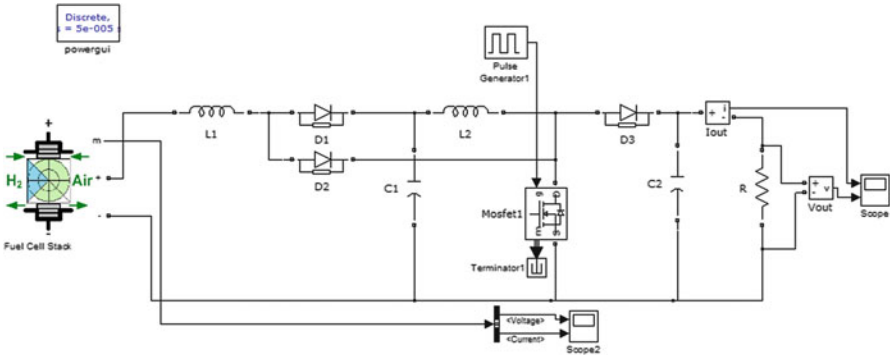

Fig. 9.15 MATLAB/SIMULINK model of the integrated cascaded boost converter

transfers stored energy through diode $D1$ to capacitor $C1$ and $L2$ transfers stored energy through diode $D0$ to the load. The circuit is simplified, and the instability caused by the cascade structure is avoided, compared with the cascade boost converter.

Figure 9.15 shows the MATLAB/SIMULINK model of the integrated cascaded boost converter. Figure 9.16 shows the simulation results of integrated cascaded boost converter obtained for 3 kW fuel cell stack input.

An integrated cascade boost converter with active clamping circuit is shown in Fig. 9.17. The auxiliary circuit is composed of a small inductor Ls, a resonant capacitor Cc, and a power MOSFET Sc, which is used to realize the soft switching (ZVS) for both main and clamp switches. The voltage stress of main switch can be effectively limited by the active clamp circuit. Therefore low-voltage stress of power switches with low Rds, on can be used to further reduce the conduction losses.

However, the switch voltage stress of the integrated cascade boost converters is equal to the high output voltage, and the current stress is large because the current of the inductors $L1$ and $L2$ flows through the switch when it turns on. These two factors increase the conduction losses and reduce the circuit efficiency. An auxiliary circuit is often necessary to improve the efficiency.

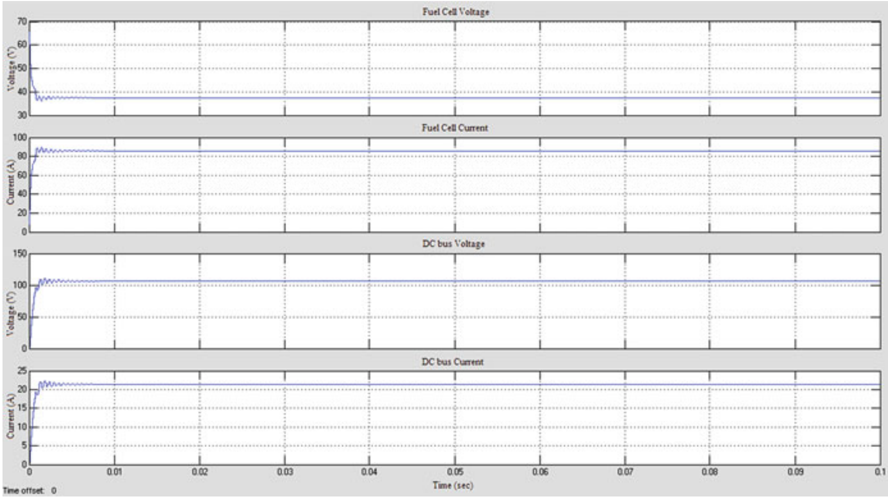

Fig. 9.16 Simulation results of integrated cascaded boost converter

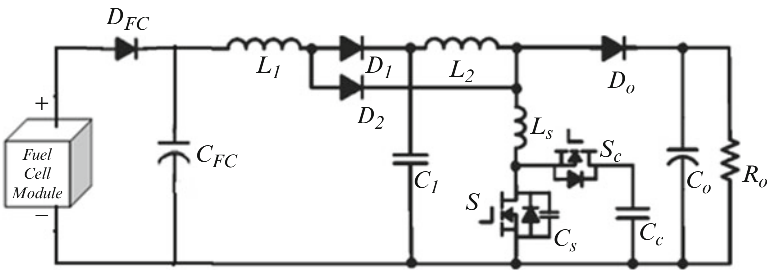

Fig. 9.17 Integrated cascaded boost converter with active clamping circuit

Figure 9.18 shows the MATLAB/SIMULINK model of the integrated cascaded boost converter along with the active clamping circuit. The model is designed to reduce the voltage stress. Figure 9.19 shows the simulation results of integrated cascaded boost converter along with the active clamping circuit obtained for 3 kW fuel cell input.

9.2.8 Interleaved Boost Converter

The interleaved boost converter structure is another effective solution for dc-dc power conversion. This structure can be used to increase the power level, minimize the current ripple, can reduce the passive component size, minimize the current stress on the power electronic devices, can improve the transient response, and can realize the thermal distribution.

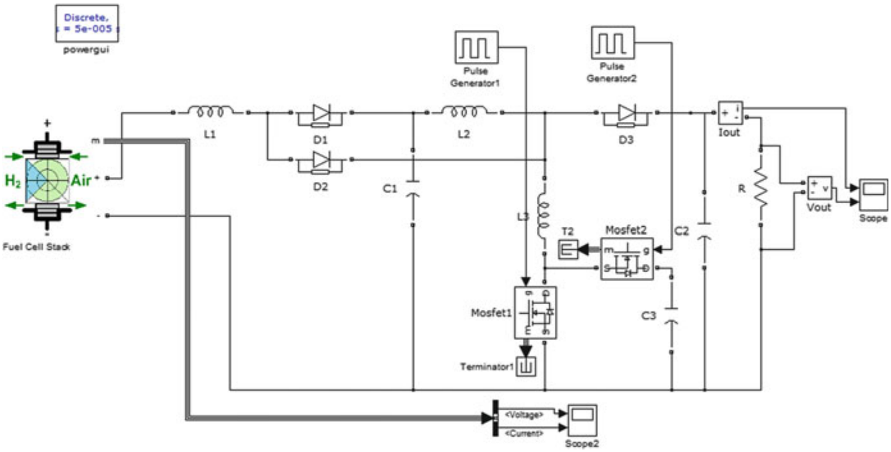

Fig. 9.18 MATLAB/SIMULINK model of the integrated cascaded boost converter with active clamping circuit

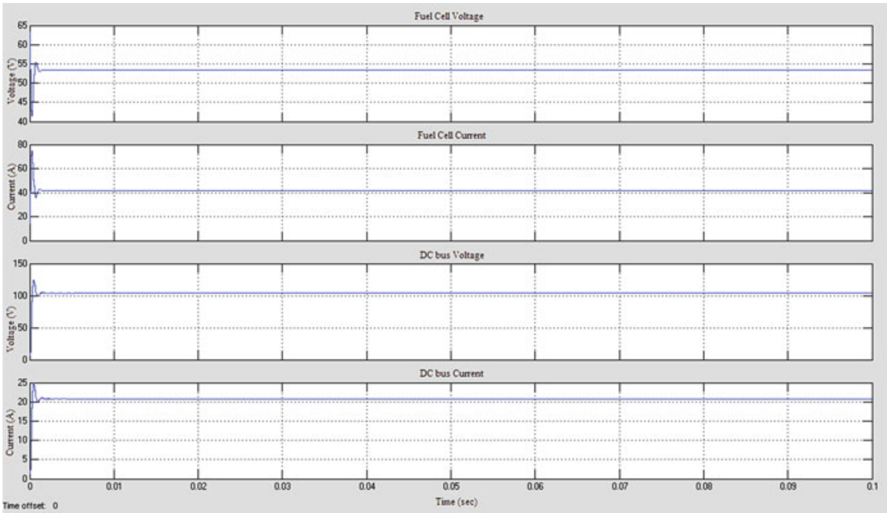

Fig. 9.19 Simulation results of integrated cascaded boost converter with active clamping circuit

The converters can be designed with multiple legs interleaving each other by means of input coupling inductors. It reduces the size and weight of the passive components and high efficiency can be obtained. For high-power applications, interleaved boost converters are preferable to increase the output current and to reduce the input current ripple. Since the currents through the switches are just fractions of the input current, current stress also can be minimized.

The Design parameters to be considered are decision of duty ratio and number of phases, selection of inductor values and the design of output filter. Ripple content is

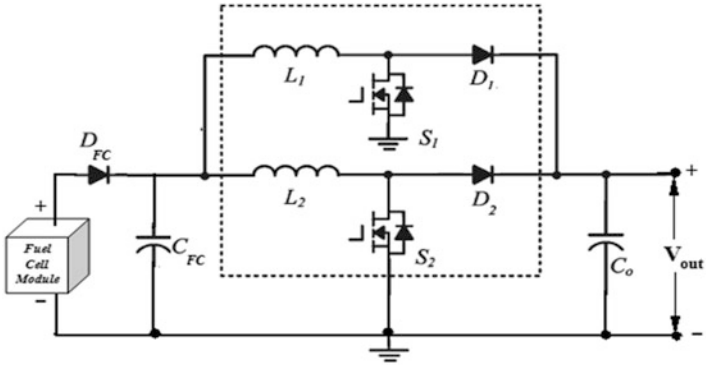

Fig. 9.20 Interleaved boost converter

inversely proportional to the number of phases (N). Ripple content decreases with increase in N. But if the number of phase is increased more the circuit complexity and cost increases so high without much decrease in ripple content. So the number of phase is limited to 2. Inductor values can be calculated based on the ripple current requirement which is given by

$$\Delta I_L = \frac{V_{in} D T_s}{L} \tag{9.13}$$

Capacitor serves the purpose of output voltage filtration. Thus its design calculation plays a major role in the elimination of ripples at the output which is based on the ripple voltage tolerable (ΔV_o).

$$\Delta V_o = \frac{V_o D T_s}{RC} \tag{9.14}$$

Figure 9.20 shows the conventional interleaved boost converter. However, the power devices still operate at hard switching which causes switching losses. The efficiency is limited because the output diode reverse-recovery problem is still serious in high-output voltage applications. Figure 9.21 shows the MATLAB/SIMULINK model of the conventional interleaved boost converter. Simulation results for the interleaved boost converter are shown in Fig. 9.22. The output is obtained for a fuel cell stack of 3 kW power.

By adding a set of auxiliary commutation circuit to each phase switch turn off which happens at maximum current conduction can be reduced. The auxiliary circuit consists of an active switch, a capacitor, and an inductor. The interleaved boost converter with auxiliary commutation circuits is introduced in Fig. 9.23. Turning on of the main switches occurs naturally at zero current, and the output-diode reverse-recovery problem is alleviated due to the critical discontinued current mode (DCM) operation. The auxiliary commutation circuits provide Zero Current

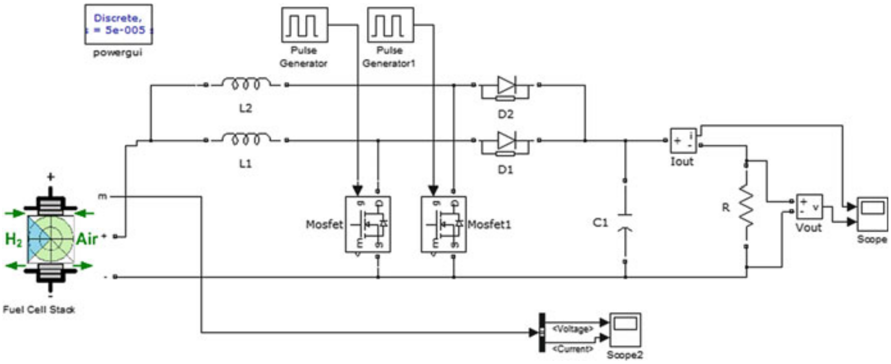

Fig. 9.21 MATLAB/SIMULINK model of the interleaved boost converter

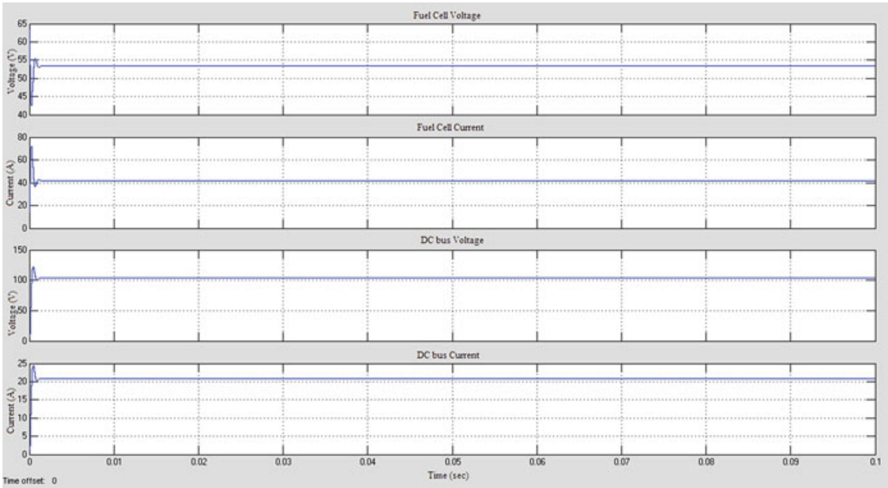

Fig. 9.22 Simulation results of interleaved boost converter

Transition (ZCT) when the main switch turns off. However, a variable frequency control is mandatory for this converter, which is difficult for the electromagnetic interference (EMI) filter design.

The MATLAB/SIMULINK model of the interleaved boost converter with auxiliary commutation circuit is shown in Fig. 9.24. Auxiliary commutation circuit reduces the maximum current conduction. Figure 9.25 shows the obtained simulation results for the interleaved boost converter with auxiliary commutation circuit.

To achieve the requirements of high efficiency and high power applications, an auxiliary circuit with an inductor and capacitor can be added along with the input filter inductor, a switch leg and diode leg. It reduces the voltage stresses of switches and diodes and enables soft switching which can eliminate losses and reverse recovery problem of Diode. Number of legs can be extended to desired voltage

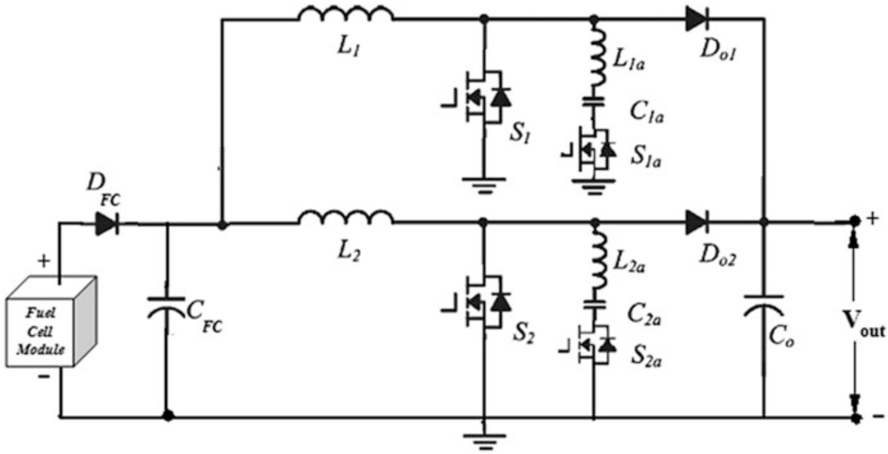

Fig. 9.23 Interleaved boost converter with an auxiliary commutation circuit

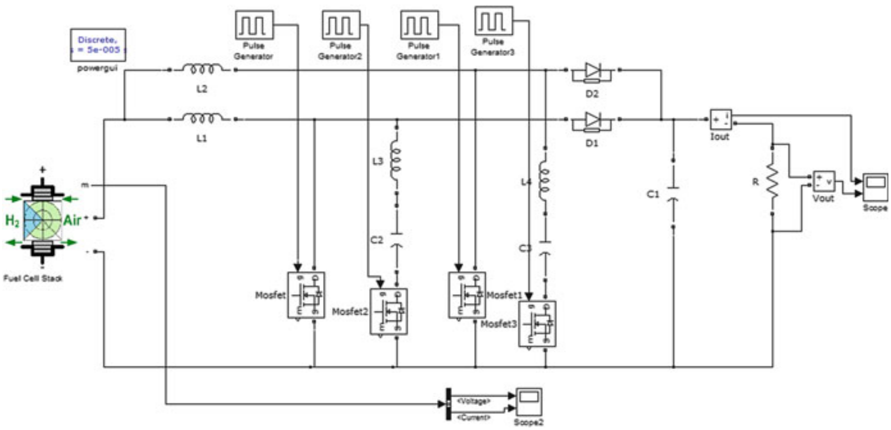

Fig. 9.24 MATLAB/SIMULINK model of the interleaved boost converter with auxiliary commutation circuit

gain and power level. However the converter circuit becomes complex and the overall cost increases. Two leg interleaving boost converter is shown in Fig. 9.26 and its MATLAB/SIMULINK model is shown in Fig. 9.27.

Figure 9.28 shows the simulation results of the interleaved boost converter which can be used for high step up applications with high efficiency. The input is given from the fuel cell stack of 3 kW power.

Integrated circuit methodology can be adapted to improve the performance of the interleaved converter. A high step-up converter shown in Fig. 9.29 consists of two phase circuits with interleaved operation. The first phase is a boost integrated Cuk-type converter, which includes a shared inductor $L1$ and switch $S1$ for the

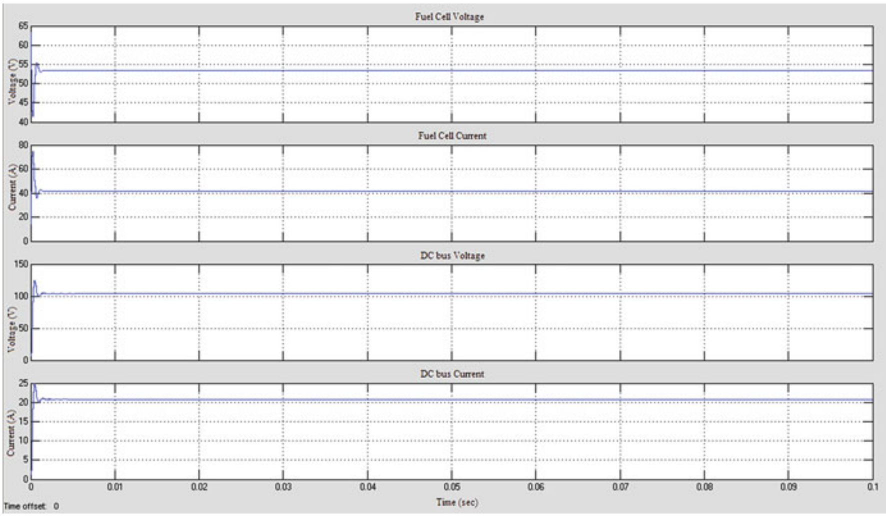

Fig. 9.25 Simulation results of interleaved boost converter with auxiliary commutation circuit

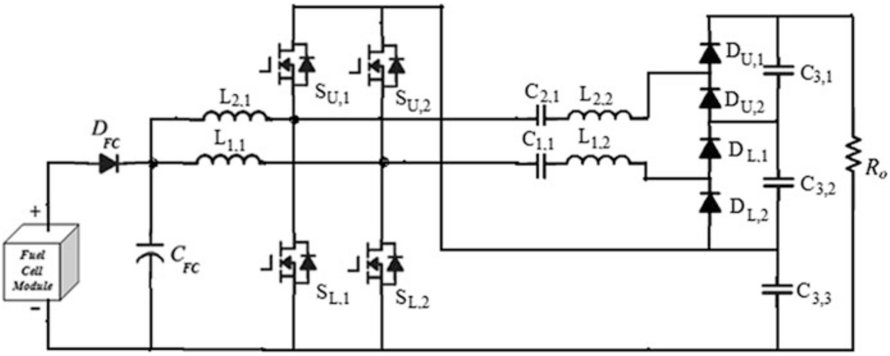

Fig. 9.26 Interleaved boost converter for high step up applications

boost and the isolated Cuk converter with turn ratio N to achieve a much higher voltage conversion ratio and avoid operating at extreme duty ratio. In addition, additional capacitors are added as voltage dividers for the two phases for reducing the voltage stress of active switches and diodes, which enables one to adopt lower voltage rating devices to further reduce both switching and conduction losses. The second phase of the proposed converter is a boost circuit which contains inductor $L2$, switch $S2$, blocking capacitor $C2$, and diode $D2$ followed by the common output capacitor Co.

However, current sharing among the parallel paths is a major design problem. Auxiliary circuits can be used but it increases the system cost and the overall converter circuit becomes bulky.

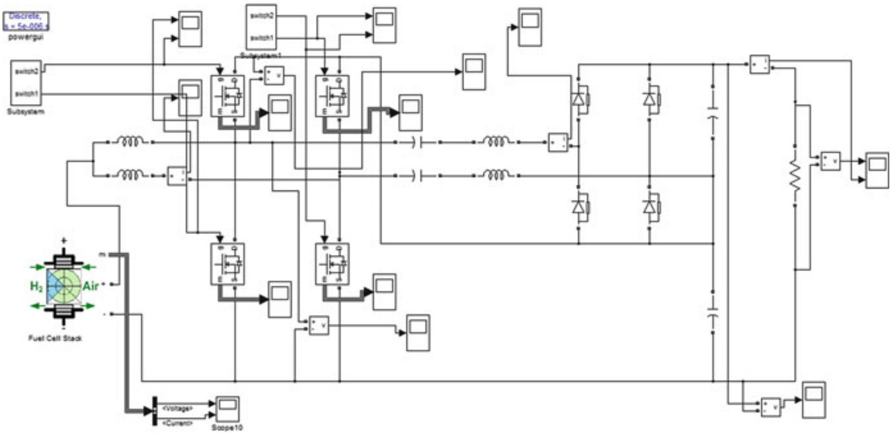

Fig. 9.27 MATLAB/SIMULINK model of the interleaved boost converter for high step up applications

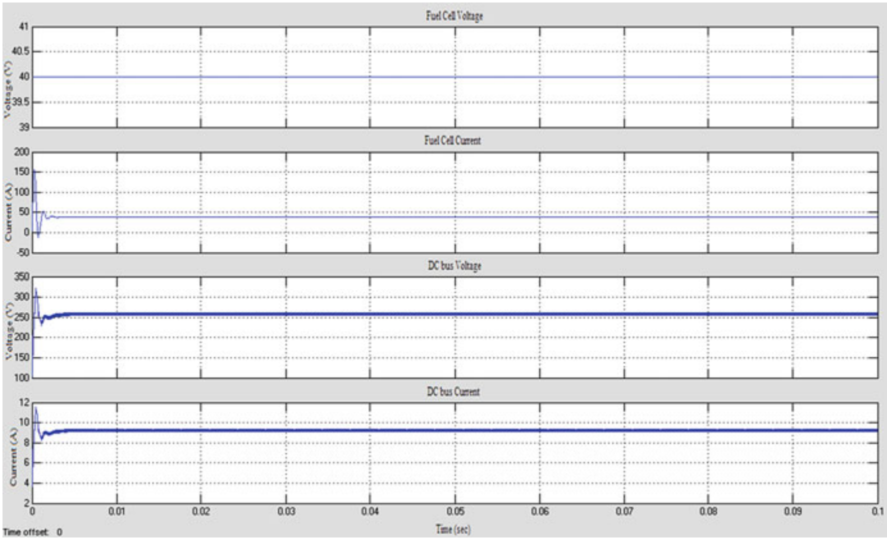

Fig. 9.28 Simulation results of interleaved boost converter for high step up applications

9.2.9 Isolated Converters

Both unidirectional and bidirectional DC-DC converters are preferred to be isolated to provide safety for the loading devices. In this view, most of the DC-DC converters incorporate a high frequency transformer. Isolated converters type of converters uses high frequency circuits with transformers which provide galvanic isolation. But inclusion of a transformer leads to the major issues such as high

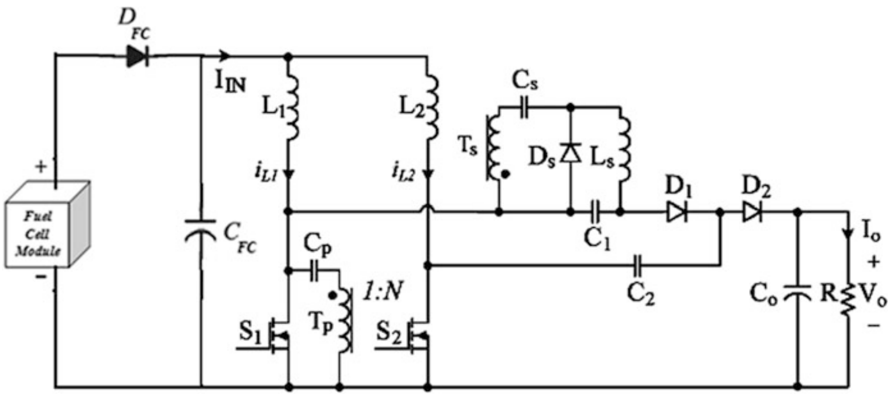

Fig. 9.29 Interleaved high step-up converter with low switch voltage stress

voltage stresses across the converter switches and diodes caused by the leakage inductance and the transistor/diode output capacitance, increase in converter area, volume, cost and increase in EMI. Most of the DC-DC converter designs are aimed to overcome these problems to yield highly efficient, cost effective converters. The current or voltage stresses imposed on the switches and diodes can be minimized by choosing appropriate transformer turns ratio, which may lead to an improved efficiency and lower cost. Various types of Isolated DC-DC converters are discussed below:

9.2.10 Flyback Converter

The topology of a flyback converter is shown in Fig. 9.30. This flyback converter has a large core size because of its single switch unipolar operation. It is an isolated version of the buck-boost and does not contain a transformer. It utilizes a coupled inductor arrangement. When the switch is turned on, current builds up in the primary and energy is stored in the core. This energy is then released to the output circuit through the secondary when the switch is turned off. All of the output power of the flyback has to be stored in the core as $\frac{1}{2}LI^2$ energy thus the core size and cost will be much greater than in the other topologies, where only the core excitation energy, which is normally small, is stored. This means that the transformer bulk is one of the major drawbacks of the flyback converter. In order to obtain sufficiently high stored energy, the flyback primary inductance has to be significantly lower than required for a true transformer, since high peak currents are needed. This is normally achieved by gapping the core. The gap reduces the inductance, and most of the high peak energy is then stored in the gap, thus avoiding transformer saturation. In the flyback converter, the secondary inductance is in series with the

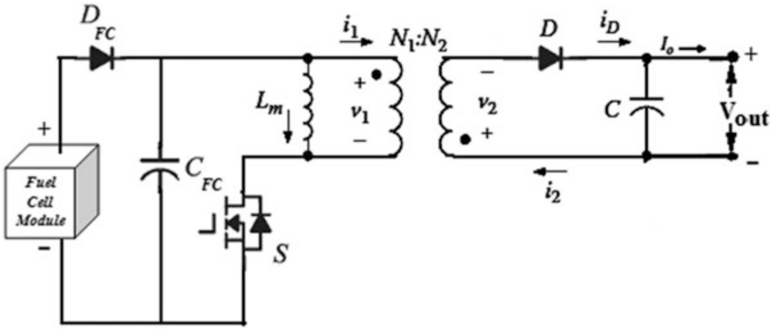

Fig. 9.30 Flyback converter

output diode when current is delivered to load. Hence, each output requires only one diode and output filter capacitor.

Flyback is the ideal choice for generating low cost, multiple output supplies. Flyback is also ideal for generating high voltage outputs. However, there is a voltage spike at turn-off due to the stored energy in the transformer leakage inductance. The switches must be capable of blocking approximately twice the supply voltage plus the leakage spike. Flyback converters have inherently much higher output ripples than other topologies. This, together with the higher peak currents, large capacitors, and transformer, limits the flyback to lower output power applications in the 20–200 W range. The flyback converter has a low number of components and a simple structure. The main drawbacks of this topology are high input current ripple, current and voltage stress on the power electronic devices, and discontinuous source current. However, such a topology is suitable for low power applications.

9.2.11 Forward Converter

The forward converter is also a single-switch isolated topology (Fig. 9.31). This is based on the buck converter. In contrast to the flyback, the forward converter has a true transformer action, where energy is transferred directly to the output through the inductor during the switch on time. When the switch turns off, the secondary voltage reverses, D1 goes from conducting to blocking mode, and the freewheel diode D2 then becomes forward biased and provides a path for the inductor current to continue to flow. This allows the energy stored in L to be released into the load during the switch off time. The forward converter is always operated in continuous mode, because this produces very low peak input and output currents and small ripple components. Since the transformer in this topology transfers energy directly, there is negligible stored energy in the core compared to the flyback. However, there is a small magnetization energy required to excite the core, allowing it to

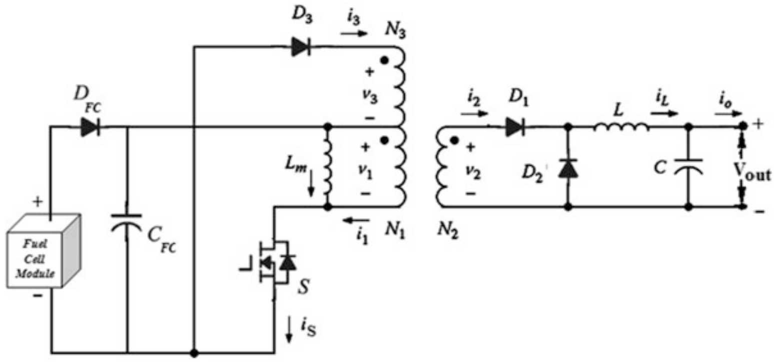

Fig. 9.31 Forward converter

become an energy transfer medium. This energy is very small and only a very small primary magnetization current is needed. This means that a high primary inductance is usually suitable, with no need for the core air gap required in the flyback. Standard ungapped ferrite cores with high permeability are ideal for providing the high inductance required. Negligible energy storage means that the forward converter transformer is considerably smaller than the flyback, and core loss is also much smaller for the same throughput power. However, the transformer is still operated asymmetrically, which means that power is only transferred during the switch on time, and this poor utilization means the transformer is still far bigger than in the symmetrical types. In addition, a major problem is how to remove the core magnetization energy by the end of each switching cycle. This path is provided by adding an additional reset winding of opposite polarity to the primary. If this did not happen, there would be a net DC flux build-up, leading to core saturation and possible destruction of power electronic devices.

For the forward topology a third winding is placed on the transformer core allowing for the demagnetization of the transformer due to any remaining energy in the core which may lead to saturation problems.

This topology has also a low number of components and a simple structure. Its main drawbacks are the presence of two magnetic components, misuse of the magnetic circuit of the transformer, and similar to flyback, current and voltage stress on the power electronic devices and discontinuous source current. This converter is also suitable for low power applications.

9.2.12 Push-Pull Converter

The primary concept of the push-pull converter (Fig. 9.32) is a center-tapped arrangement and each switch is driven alternately, driving the transformer in both directions. The push-pull transformer is typically half the size of that for the

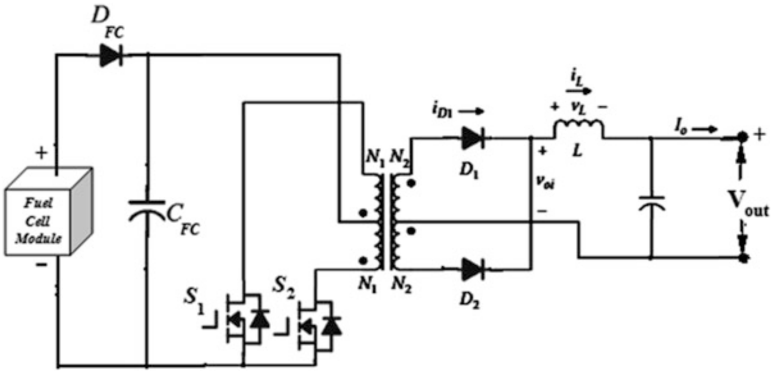

Fig. 9.32 Push-pull converter

single-ended types, resulting in a more compact design. This push-pull action produces core resetting during each half cycle hence, no clamp winding is required. Power is transferred to the buck type output circuit during each switch conduction period. The push-pull configuration is normally used for output power in the 100–500 W ranges. Push-pull converters are thus excellent for high power density, low ripple output. The push-pull offers very compact design of the transformer and output filter, while producing very low output ripple. So if space is a premium issue, the push-pull could be suitable. However, one of the main drawbacks of the push-pull converter is the fact that each switch must block twice the input voltage due to the doubling effect of the center-tapped primary, even though two switches are used. A further problem with the push-pull is that it is prone to flux symmetry imbalance. If the flux swing in each half cycle is not exactly symmetrical, the volt-second will not balance and this will result in transformer saturation, particularly for high input voltage. Symmetry imbalance can be caused by different characteristics in the two switches such as storage time in a bipolar and different on state losses. The center-tape arrangement also means that extra copper is needed and very good coupling between the two halves is necessary to minimize possible leakage spikes. It should also be noted that if snubbers are used to protect the device, the design must be very precise since they tend to interact with each other. This is true for all symmetrically driven converters. These advantages usually makes the push-pull to normally operated at lower voltage inputs such as 12, 28, or 48 V. DC-DC converters found in the automotive and telecommunication industries are often push-pull designs. At these voltage levels, transformer saturation is easier to avoid.

Push-pull converters use only one switch at any time to interface fuel cell stack voltage to DC bus which reduces the conduction loss. But the issue is that the device handles twice of the input voltage. This can be handled by the use of high voltage switching devices. The major problem with these types of converters is the transformer saturation which results in converter failure because the two half portions of the center tap transformer cannot be equal or symmetrically wound. Therefore these converters are suitable for low voltage and low power applications.

9.2.13 Half Bridge Converter

The half-bridge converter (Fig. 9.33) is also referred to as the single ended push-pull, and in principle is a balanced version of the forward converter. Again it is a derivative of the buck type. The half-bridge has some key advantages over the push-pull, which usually makes it first choice for higher power applications in the 500–1,000 W range. As shown in Fig. 9.17, the two main bulk capacitors C_1 and C_2 are connected in series, and an artificial input voltage mid-point is provided. The two switches are driven alternately, and this connects each capacitor across the single primary winding each half cycle. Vin/2 is super imposed symmetrically across the primary in a push-pull manner. A full wave buck output filter rather than a half wave filter is implemented. This again results in very efficient core utilization. The waveforms are identical to the push-pull, except that the voltage across the switches is halved. This means that the half-bridge is particularly suited to high voltage inputs, such as off-line applications. Another major advantage over the push-pull is that the transformer saturation problems due to flux symmetry imbalance do not occur. By using a small capacitor, DC build-up of flux in the transformer is blocked, and only symmetrical AC is drawn from the input. A less obvious exclusive advantage of the half-bridge is that the two series reservoir capacitors already exist, and this makes it ideal for implementing a voltage doubling circuit. The bridge circuits also have the same advantages over the single ended types that the push-pull possesses, including excellent transformer utilization, very low output ripple, and high output power capabilities. The limiting factor in the maximum output power available from the half bridge is the peak current handling capabilities of present day power switching devices. The upper power limit is typically 1,000 W. For higher output powers the four-switch full-bridge is normally used.

However, the need for two 50 or 60 Hz input capacitors in the half-bridge are a drawback because of their large size. The top switch must also have isolated drive, since the gate or base is at a floating potential. Furthermore, if snubbers are used

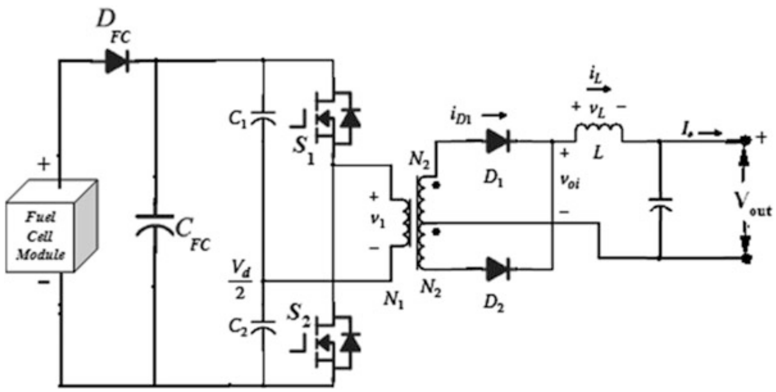

Fig. 9.33 Half bridge converter

across the power semiconductor switches, great care must be taken in their design because the symmetrical action means that they will interact with one another. The circuit cost and complexity have clearly increased and must be weighed against the advantage gained. In many cases, this normally excludes the use of the half-bridge at output power levels below 500 W. The two switches are driven alternately, and this half bridge converter is suitable for high power applications. The number of the active components is reduced, but the semiconductor devices have to handle twice of the current. Also split capacitors may cause some balancing issues. It also requires large value of transformation ratio to obtain the desired output voltage and large value of dc link capacitors to eliminate transformer saturation. This increases the cost of the converter. Single silicon device or transformer has to handle large value of current which causes current stress. In addition, interconnect and parasitic inductances will induce significant i^2R and Li^2 losses, which decreases the converter efficiency.

9.2.14 Full Bridge Converter

In the half-bridge converter, the maximum current rating of the switch will eventually determine the upper limit of the output power. The switches are driven alternately in pairs: T1 and T3 simultaneously, and then T2 and T4. The transformer primary is now subjected to the full input voltage. The current levels flowing are halved compared to the half-bridge for a given power level. Hence, the full-bridges will double the output power of the half-bridge using the same switch types (Fig. 9.34). The secondary circuit operates in exactly the same manner as the push-pull and half-bridge, producing very low ripple outputs at very high current levels. Therefore, the waveforms for the full-bridge are identical to the half-bridge waveforms, except for the voltage across the primary, which is effectively doubled. The full-bridge converter is ideal for the generation of very high output power level.

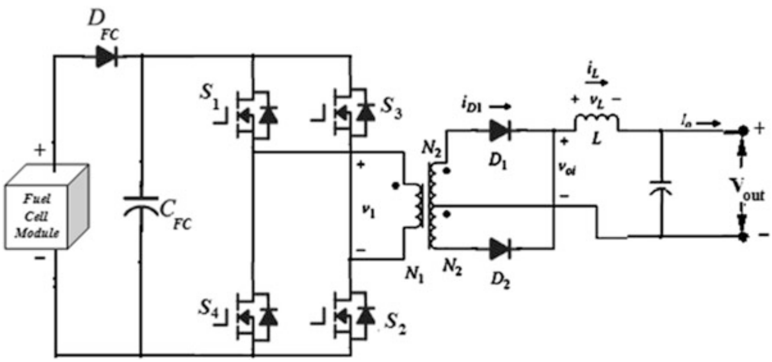

Fig. 9.34 Full bridge converter

The increased circuit complexity normally means that the full-bridge is reserved for applications with power output level of 1 kW and above. For such high power requirements, designers often select Darlington power, since its superior current rating and switching characteristics provide additional performance and in many cases a more cost-effective design. The full-bridge also has the advantage of only requiring one main smoothing capacitor compared to two for the half-bridge, hence saving space. Its other major advantages are the same as for the half-bridge. However, four switches and clamp diodes are needed instead of two for the other symmetrical types. The full-bridge has the most complex and costly design of any of the converters discussed, and should only be used where other types do not meet the requirements. Full bridge converters are suitable for high power applications. The main advantage of the full-bridge converter is reasonable device voltage and current ratings. It also has low transformer turns ratio and the voltage and current stress are minimum. It has more number of components which increases the cost and the control is also complex. But it has a good efficiency which makes this converter acceptable for suitable high power applications.

9.3 Inverters

In almost every application, AC power is required demanding the utilisation of an inverter in the power-conditioning system. The dc-ac converter, also known as the inverter, converts dc power to ac power at desired output voltage and frequency. The dc power input to the inverter is obtained from a fuel cell through dc-dc converter. The filter capacitor across the input terminals of the inverter provides a constant dc link voltage. The inverter therefore is an adjustable-frequency voltage constant dc link voltage. The inverter therefore is an adjustable-frequency voltage link converter.

Inverters can be broadly classified into two types, voltage source and current source inverters. A voltage–fed inverter (VFI) or more generally a voltage–source inverter (VSI) is one in which the dc source has small or negligible impedance. The voltage at the input terminals is constant. A current–source inverter (CSI) is fed with adjustable current from the dc source of high impedance that is from a constant dc source. A voltage source inverter employing thyristors as switches, some type of forced commutation is required, while the VSIs made up of using GTOs, power transistors, power MOSFETs or IGBTs, self commutation with base or gate drive signals for their controlled turn-on and turn-off.

9.3.1 Single Phase Inverter

A standard single phase voltage or current source inverter can be in half- bridge or full-bridge configuration. The single-phase units can be joined to have three-phase or multiphase topologies.

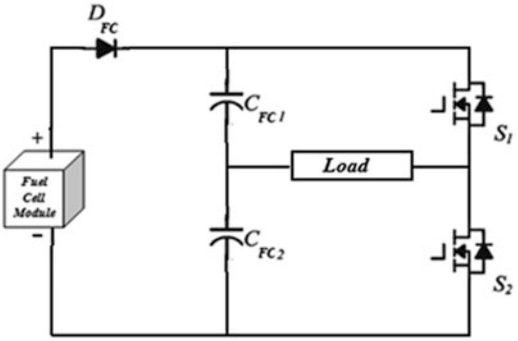

Fig. 9.35 Single phase half bridge inverter

9.3.2 Half-Bridge Configuration

Figure 9.35 shows the half-bridge or a single leg inverter, which is the simplest Topology. It is used to produce a two-level square wave output waveform using two semiconductor switches S1 and S2. A center tapped voltage source supply is needed; it may be possible to use a simple supply with two well-matched capacitors in series to provide the center tap.

9.3.3 Half Bridge with Resistive Load

A half-bridge voltage source-inverter with resistive load can be considered with representing load by only resistance. The circuit is operated by switching S1 (T1 & D1) and S2 (T2& D2) alternatively at 50 % duty cycle. It is seen that for $0 < t < \pi$ S1 conducts and the load is subjected Vs/2 due to the upper voltage source Vs/2. At $t = \pi$, switch S1 is commutated and S2 is gated on. During the period $\pi < t < 2\pi$, S2 conducts and the load is subjected to a voltage (–Vs/2) due to the lower voltage source Vs/2. Figure 9.36 shows simulation circuit by MATLAB/SIMULINK of a single phase half bridge inverter and Fig. 9.37 shows voltage and current waveforms.

9.3.4 Half Bridge with RL Load

A half-bridge voltage source-inverter with inductive-resistive load can be considered with representing load by only resistance and inductance. The circuit is operated by switching S1 and S2 alternatively at 50 % duty cycle. To understand the operation of the circuit, the inverter is started by giving signal to S1. There was no current in any part of the circuit earlier. A signal to S1 turns it on and connects

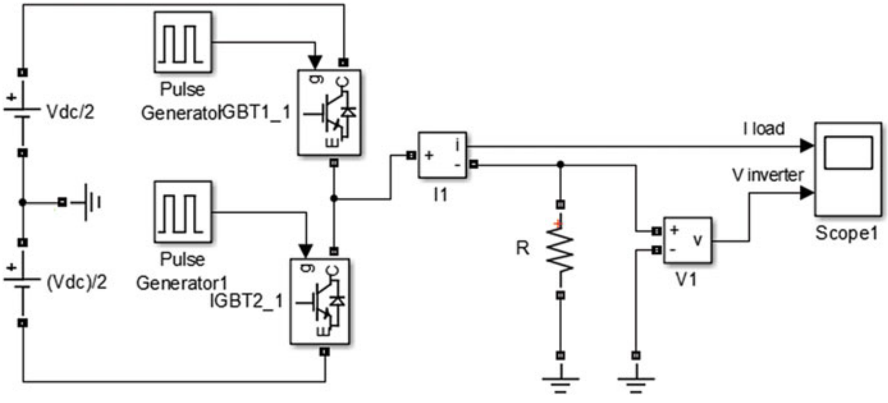

Fig. 9.36 MATLAB/SIMULINK model of single phase half bridge inverter with R load

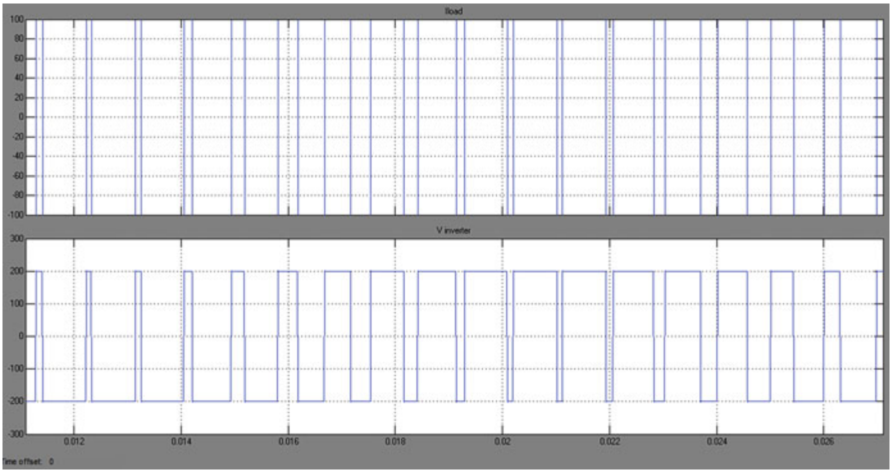

Fig. 9.37 Simulation results of single phase half bridge inverter with R load

the load to upper Vs/2. A positive current develops form upper Vs/2 through S1 to load. During the time period $0 < t < \pi$ current through the load (through S1 and upper Vs/2) has grown from zero to Imax. The current will be reduced to zero through D2. S2 is forward biased now; the current grows in the negative direction and the current flows through D2, load, lower Vs/2 until the current falls to zero. Similarly, when S2 is turned off at 2π, the load current flows through D1, load, and upper Vs/2. The energy will be fed back to DC source when D1 and D2 conduct. Figure 9.38 shows simulation circuit by MATLAB/SIMULINK and Fig. 9.39 shows the voltage and current waveforms.

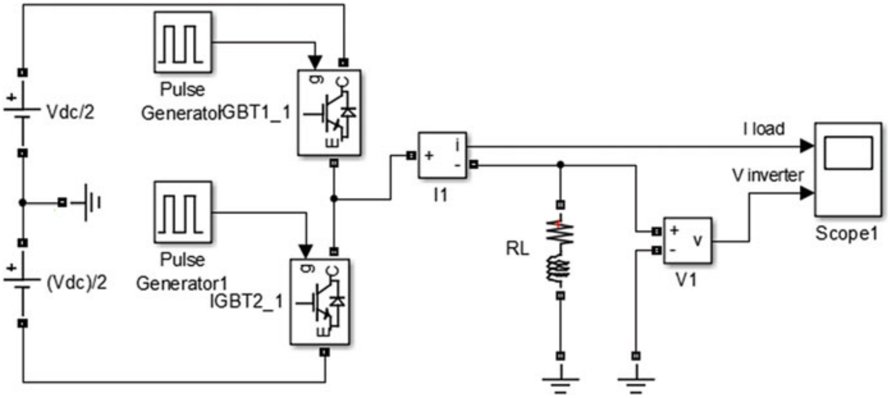

Fig. 9.38 MATLAB/SIMULINK model of single phase half bridge inverter with RL load

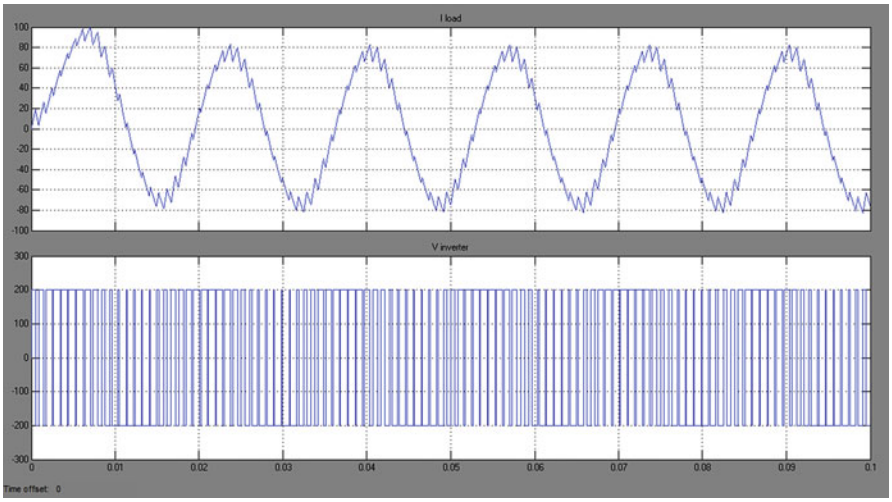

Fig. 9.39 Simulation results of single phase half bridge inverter with RL load

9.3.5 Full Bridge Configuration

The power circuit diagram of a single phase full bridge inverter is shown in Fig. 9.40. When S1 and S2 are connected, the input voltage Vs appears across the load. If S3 and S4 are connected the voltage across the load is –Vs. Table 9.2 shows the main principle of a single phase full bridge inverter.

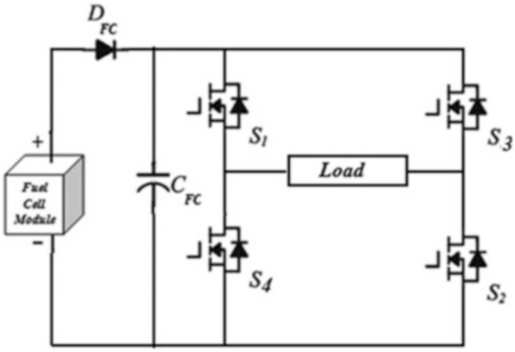

Fig. 9.40 Single phase full bridge inverter

Table 9.2 Switching sequence of single phase full bridge inverter

Switching states				Vout	Iout	
S1	S2	S3	S4		Iout > 0	Iout < 0
On	On	Off	Off	V_s	S1 and s2 conduct	D1 and D2 conduct
Off	Off	On	On	$-V_s$	D4 and D3 conduct	S3 and s4 conduct
On	Off	On	Off	0	S1 and D3 conduct	D1 and S3 conduct
Off	On	Off	On	0	D4 and S2 conduct	S4 and D2 conduct
Off	Off	Off	Off	$-V_s$	D4 and D3 conduct	–
Off	Off	Off	Off	V_s	–	D1 and D2 conduct

9.3.6 Full Bridge with Resistive Load

A full-bridge voltage source-inverter with resistive load can be considered with representing load by only resistance. The circuit is operated by switching S1, S2, S3, and S4. S1-S2 and S3-S4 are switched on and off at a 50 % duty cycle. When S1 and S2 are connected, the input voltage Vs appears across the load. If S3 and S4 are connected the voltage across the load is –Vs. Table 9.2 can be considered the operation table for a single-phase full-bridge Inverter with resistive load. Figure 9.41 shows simulation circuit by MATLAB/SIMULINK and Fig. 9.42 shows voltage and current waveforms.

9.3.7 Full Bridge with Resistive Load

A full-bridge voltage source-inverter with inductive-resistive load can be considered with representing load by only resistance and inductance. The circuit is operated by switching S1, S2, S3, and S4. S1–S3 and S2–S4 are switched on and off at a 50 % duty cycle. When S1 and S2 are connected, the input voltage Vs appears across the load. If S3 and S4 are connected the voltage across the load is –Vs. Fig. 9.43 shows simulation circuit by MATLAB/SIMULINK and Fig. 9.44 shows voltage and current waveforms.

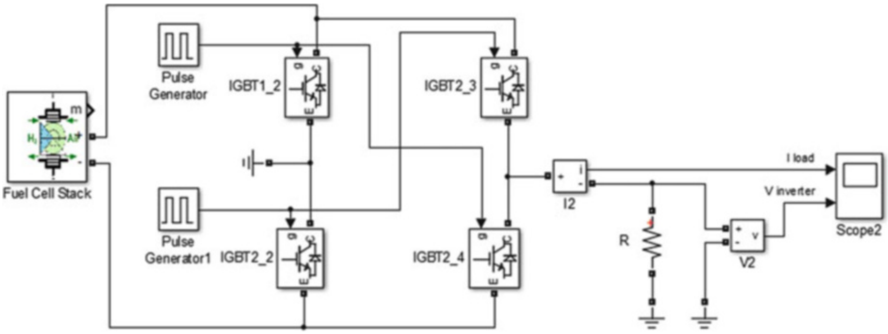

Fig. 9.41 MATLAB/SIMULINK model of single phase full bridge inverter with R load

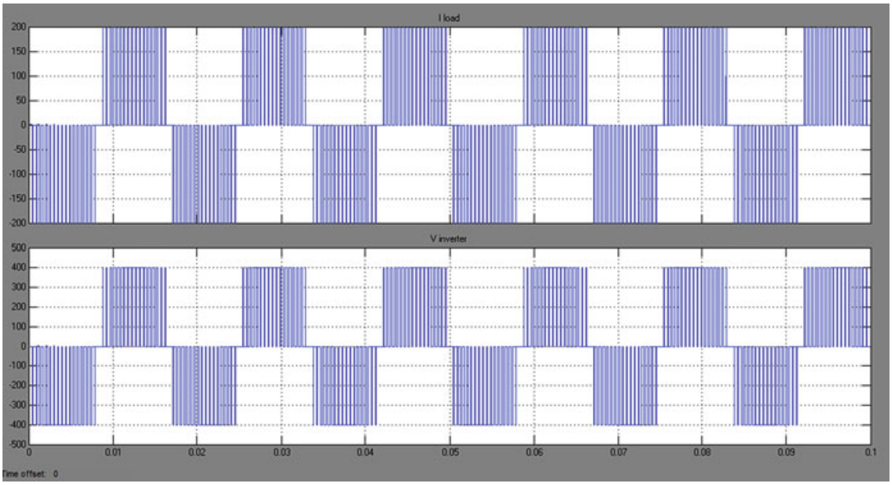

Fig. 9.42 Simulation results of single phase full bridge inverter with R load

9.3.8 Three Phase Inverter

A three phase inverters are used to provide industrial applications by adjustable frequency power. Three phase inverters are more common than single phase inverters. DC supply for three phase inverters is taken from a fuel cell or usually from DC-DC Converter. Three-phase counterparts of the single-phase half and full bridge voltage source inverters are shown in Figs. 9.45 and 9.46. Single-phase VSIs cover low-range power applications and three-phase VSIs cover medium to high power applications. The main purpose of these topologies is to provide a three-phase voltage source, where the amplitude, phase and frequency of the voltages can be controlled. The three-phase dc/ac voltage source inverters are extensively being used in motor drives, active filters and unified power flow controllers in power

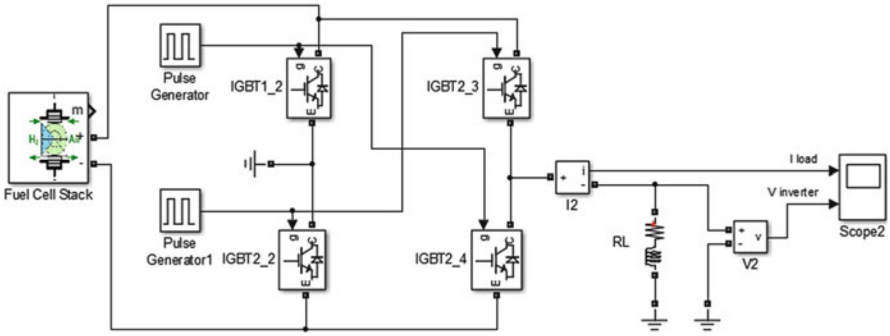

Fig. 9.43 MATLAB/SIMULINK model of single phase full bridge inverter with RL load

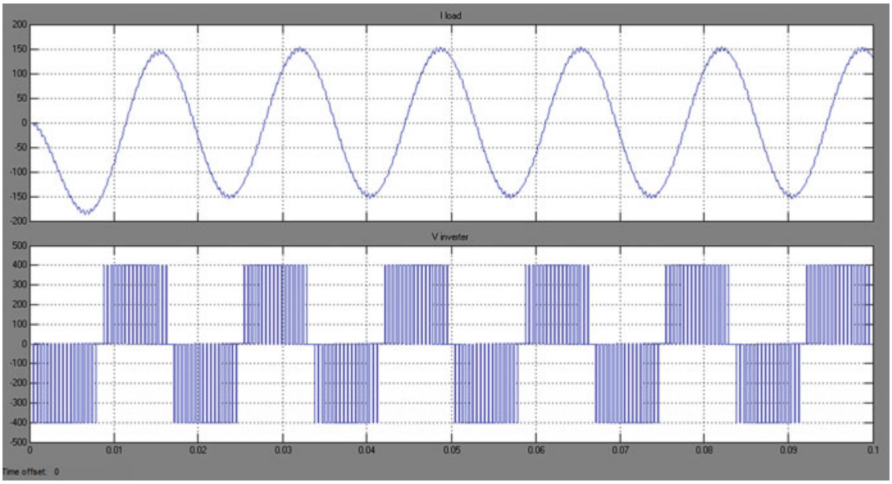

Fig. 9.44 Simulation results of single phase full bridge inverter with RL load

systems and uninterrupted power supplies to generate controllable frequency and ac voltage magnitudes using various pulse width modulation (PWM) strategies. The standard three-phase inverter has six switches the switching of which depends on the modulation scheme. A six steps bridge is used for three phase inverter by using six switches, two switches for each phase. Each step is defined as a change in the time operation for each transistor to the next transistor in proper sequence. For one cycle 360°, each step would be of 60° interval for a six step inverter. Figure 9.46 shows the power circuit diagram of a three phase bridge inverter using six IGBTs. Large capacitors are connected at the input terminal to make the DC input constant and also suppress the harmonics fed back to the source. The input dc is usually obtained from a single-phase or three phase utility power supply through a diode-bridge rectifier and LC or C filter. The nature of the two switches in the same leg is complementary.

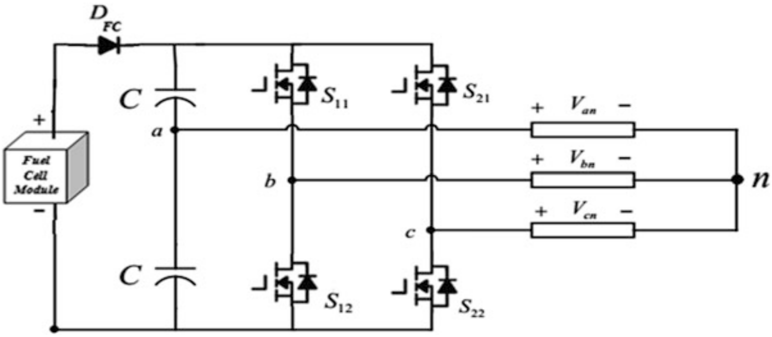

Fig. 9.45 Three phase half bridge inverter

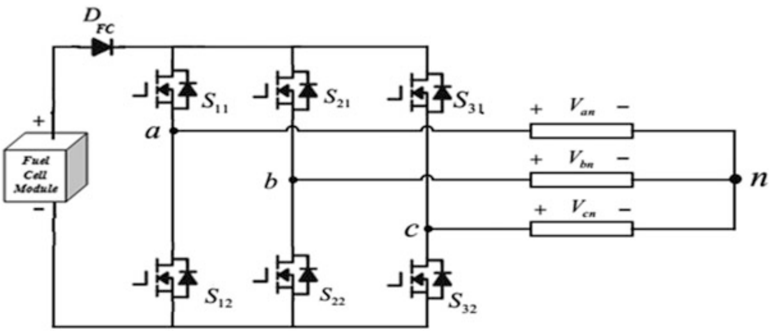

Fig. 9.46 Three phase full bridge inverter

Table 9.3 Switching sequence of three phase inverter

Switching states			Output voltage		
S11	S12	S31	Vab	Vbc	Vca
Off	Off	Off	0	0	0
Off	Off	On	0	$-V_S$	V_S
Off	On	Off	$-V_S$	V_S	0
Off	On	On	$-V_S$	0	$-V_S$
On	Off	Off	V_S	0	$-V_S$
On	Off	On	V_S	$-V_S$	0
On	On	Off	0	V_S	$-V_S$
On	On	On	0	0	0

Of the eight switching states as shown in Table 9.3 two of them produce zero ac line voltage at the output. In this case, the ac line currents freewheel through either the upper or lower components. The remaining states produce no zero ac output line voltages. In order to generate a given voltage waveform, the inverter switches from one state to another. Thus the resulting ac output line voltages consist of discrete values of voltages, which are $-V_{DC,}$ 0, and V_{DC}

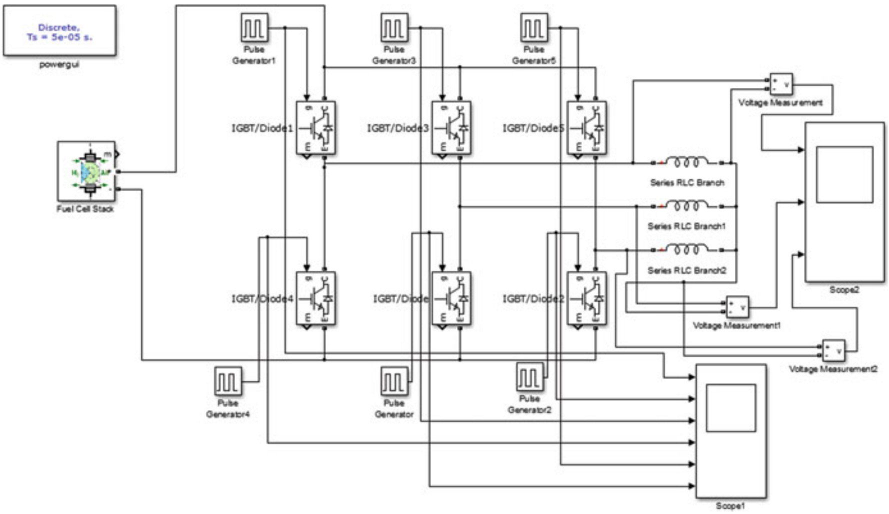

Fig. 9.47 MATLAB/SIMULINK model of three phase inverter

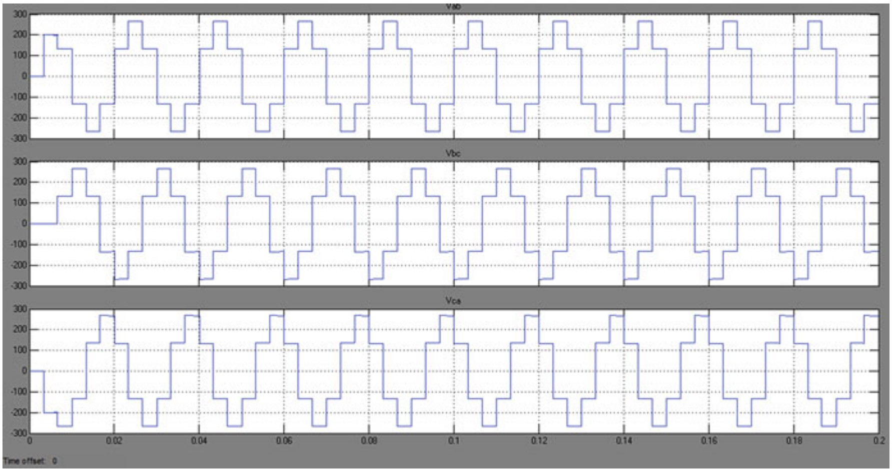

Fig. 9.48 Simulation results of three phase inverter

Figure 9.47 shows the MATLAB/SIMULINK Model of Three Phase Inverter and Fig. 9.48 shows the simulation results for three phase line-line voltage obtained for L load.

9.3.9 Z-Source Inverter

Impedance-source (or impedance-fed) power converter (abbreviated as Z-source converter) employs a unique impedance network (or circuit) to couple the converter

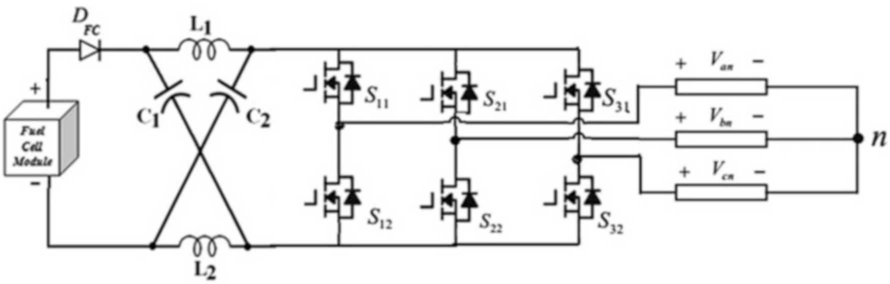

Fig. 9.49 Z-source inverter

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.

The Z-source concept can be applied to all dc-to-ac, ac-to-dc, ac-to-ac, and dc-to-dc power conversion. Because fuel cells usually produce a voltage that changes widely (2:1 ratio) depending on current drawn from the stack, for fuel-cell vehicles and distributed power generation, a boost dc–dc converter is needed as the V-source inverter cannot produce an ac voltage that is greater than the dc voltage. Figure 9.49 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 is usually needed for preventing reverse current flow.

The unique feature of the Z-source inverter is that the output ac voltage can be any value between zero and infinity regard-less 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. 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 across 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. This third zero state (vector) is called as 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. All the traditional pulse

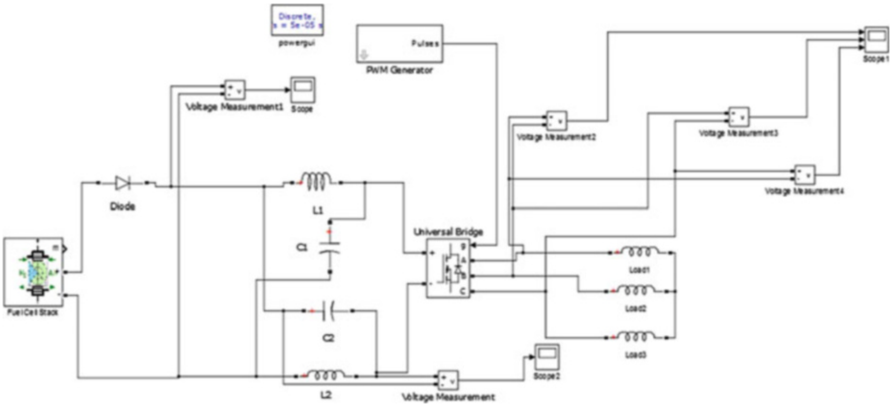

Fig. 9.50 MATLAB/SIMULINK model of Z-source inverter

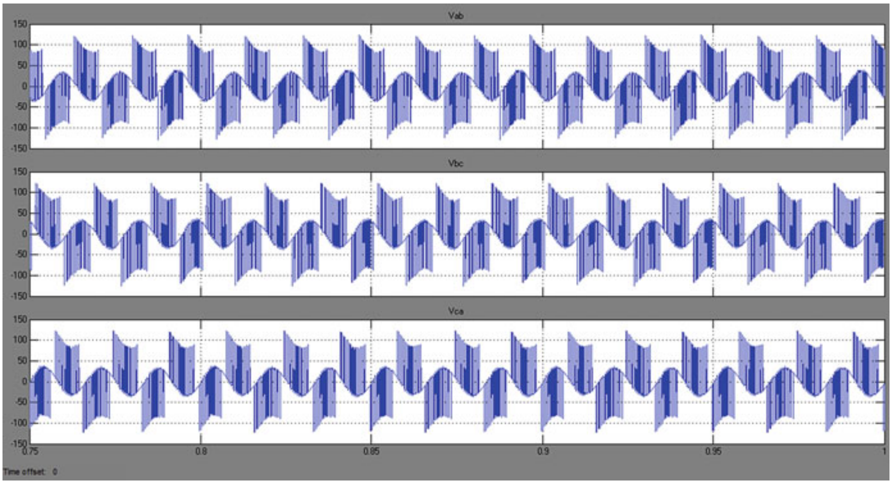

Fig. 9.51 Simulation results of Z-source inverter

width-modulation (PWM) schemes can be used to control the Z-source inverter and their theoretical input–output relationships still hold. Figure 9.50 shows the MATLAB/SIMULINK Model of Z-Source Inverter and Fig. 9.51 shows the simulation result of output voltage waveform.

9.3.10 LLCC Resonant Inverter

The diode at the output of the fuel-cell stack is necessary to prevent the negative current going into the stack. Due to the negative current, it is possible that the cell

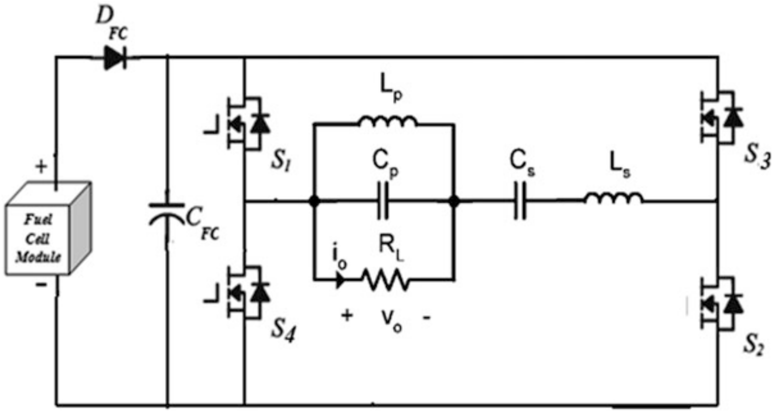

Fig. 9.52 LLCC resonant inverter

reversal could occur and damage the fuel-cell stack. The ripple current seen by the fuel-cell stack due to the switching of the boost converter has to be reduced. The power inverter circuit is composed of a boost dc/dc converter that uses PWM direct duty-cycle control and a newly designed LLCC resonant inverter. Because the output voltage of a fuel cell varies with the load variation, the boost dc/dc converter with dc voltage feedback control is utilized to provide the constant dc voltage for the inverter. The dc-link voltage amplitude is controlled by the boost dc/dc converter according to the control input. To provide stable sinusoid ac voltage output, the LLCC resonant circuit is operated at a geometric mean frequency such that the output voltage will not be influenced by the quality factor variation. This driving circuit has full-bridge switches (S1, S2, S3, S4), a series-resonant tank (Ls, Cs), and parallel-resonant tank (Lp, Cp, RL) as shown in Fig. 9.52. The LLCC inverter incorporates series and parallel combinations of inductors and capacitors otherwise known as a series-resonant tank (LS, CS) and parallel-resonant tank (LP, CP) to filter the voltage, remove some of the ripple current and provide a stable AC output. A half-bridge inverter converts the DC signal to AC using PWM with zero-voltage/zero-current switching. This reduces switching losses, thereby increasing the efficiency of the converter.

Unfortunately, the two capacitors and inductors increase the space and cost of the inverter. In addition, this resonant circuit highly depends on the parameters of the capacitors and inductances and may be influenced by their variation with operating conditions. Figure 9.53 shows the MATLAB/SIMULINK Model of LLCC Resonant Inverter and Fig. 9.54 shows the simulation result obtained using MATLAB.

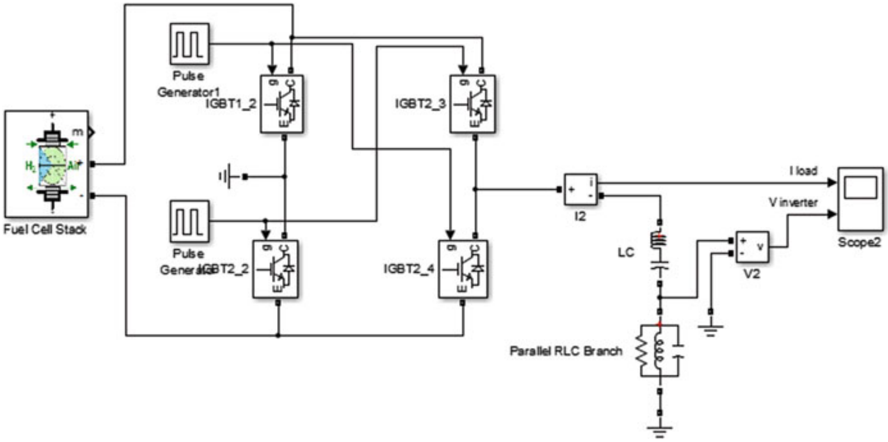

Fig. 9.53 MATLAB/SIMULINK model of LLCC resonant inverter

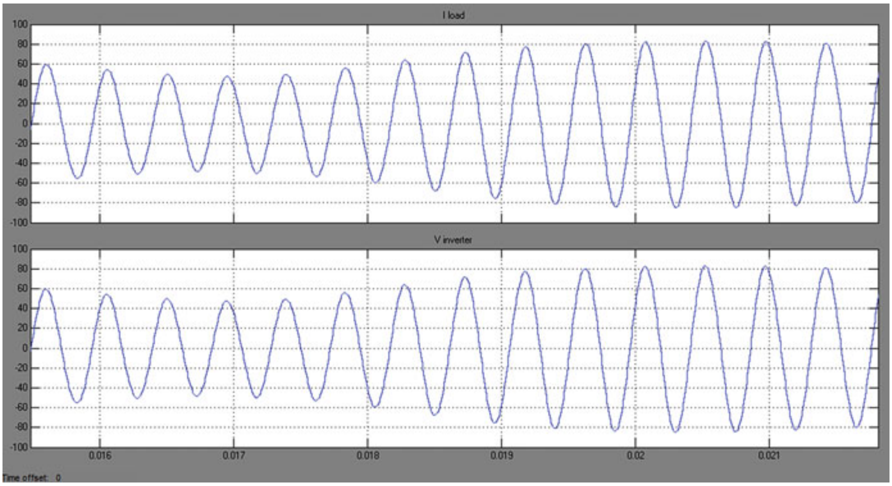

Fig. 9.54 Simulation results of LLCC resonant inverter

9.4 Fuel Cell System with Motor Load

As one of the most prominent sources of distributed energy in the future, fuel cells are under consideration for almost every application including both residential and industrial power generation. Yet, a power electronics interface must be incorporated between the fuel cell and output to provide flexibility due to the inherent restrictions fuel cells produce, such as low voltage, large voltage variation, low efficiency when ripple current is high, slow load step responsibility and no acceptance of reverse current. The topology selection is not an easy process as it requires many constraints to be considered. The non isolated converters allows for the minimum size design. It is preferred for automotive applications. The converter must provide a high efficiency over the wide load range and maintain a high efficiency. The isolated converters are recommended for all applications where electrical isolation is required for a safety reason. It would be the automotive charging units or any grid-connected high power system. The isolated DC-DC converters are usually not considered for a vehicle power train as they require additional voltage conditioning systems. In general, high power converters tend to be multiphase for current sharing. Also, multiphase structure allows for increased part-load efficiency. The non-isolated converter is the most optimal solution for a low size converter in a low to medium voltage gain range. If a high voltage gain is required, the floating or transformer-based converters are the most optimum solution. The lowest input current ripple is available from multiphase converters due to current ripple cancelation. Selection of DC-AC converter plays a major role while using fuel cell output for AC loads and when connected to grid.

Apart from finding solutions to reduce device stresses and to improve the converter efficiency, many other challenges are posed for a power electronic circuit designer. Before selecting the converter topology, the efficiency of the converter must be evaluated in comparison with the overall efficiency of the system. Based on this evaluation, hard-switched or soft-switched topology must be chosen. Thorough investigation of DC-DC converters regarding EMI must be carried out to satisfy the standard regulations. Temperature effects must be considered to ensure a safe and reliable operation.

A fuel cell system with conventional boost converter and three phase inverter are used to feed an asynchronous machine. Figure 9.55 shows the MATLAB/ SIMULINK model of the entire system and Fig. 9.56 shows the simulation result for speed, torque and stator current of asynchronous machine.

9.5 Architecture of Multiple Fuel Cells for High Voltage/ High Power Applications

If more power is wanted than what is available from the standard size fuel cell, then modules need to be aggregated. There is more than one approach to aggregate numerous fuel cell modules for high-voltage/high-power applications. Four different approaches of these architectures are

- Series architecture.
- DC bus distribution architecture.
- High frequency AC (HFAC) distribution architecture.
- Multilevel architecture.

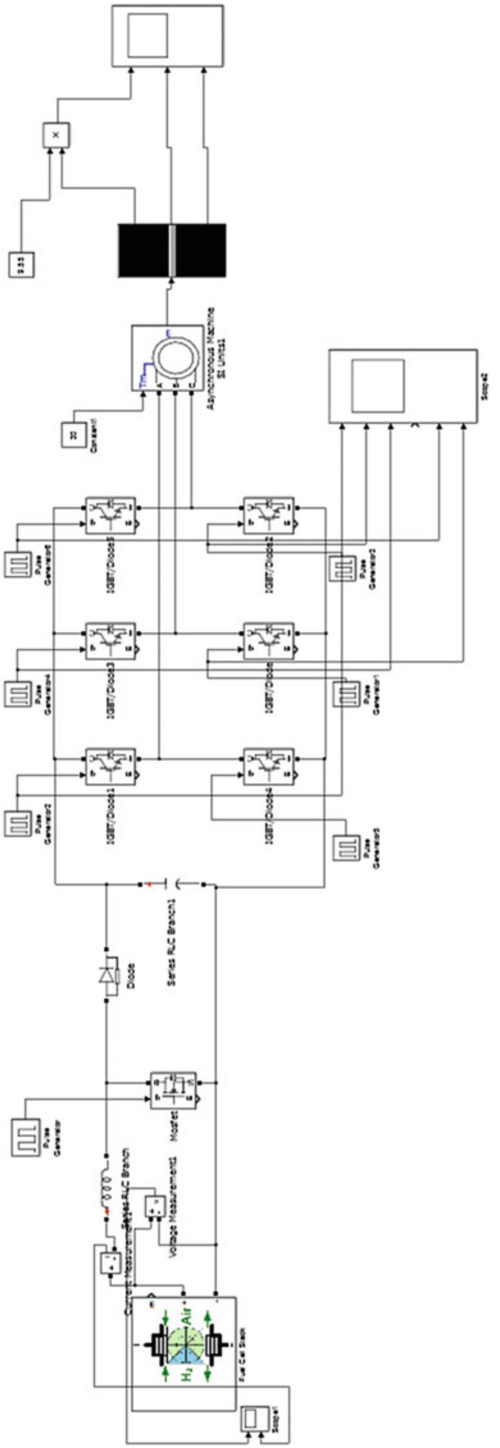

Fig. 9.55 MATLAB/SIMULINK model of fuel cell system to drive induction motor

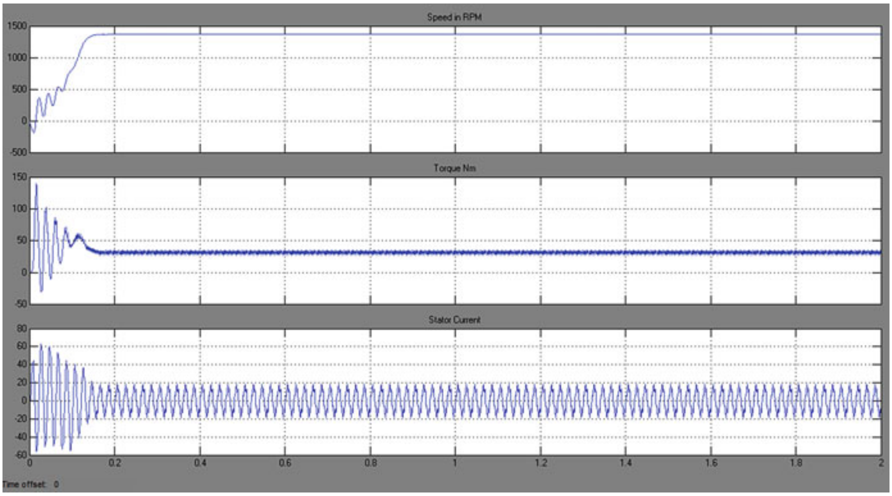

Fig. 9.56 Simulation results of the fuel cell system

9.5.1 Series Architecture

The series architecture, as shown in Fig. 9.57, simply connects all the fuel cell modules in series and interfaces the output with a power converter. The power converter can use any of the DC/DC converters and inverters. As the cumulative fuel cell module output voltage is enough for the inverter to produce AC grid level voltages, the DC/DC converter is used to regulate the DC voltage instead of boosting voltage. The DC/DC converter can also be removed and the modulation index of the inverter can be regulated to get a fixed output AC voltage. This architecture is the simplest of the topologies to be covered and is the most commonly used. The device count is low: only six power switches are required when no DC-DC regulator is used and sufficient fuel cell modules are aggregated. Three-phase inverter modules are commonly used and thus are inexpensive. Higher voltage- rated switches that need to handle no-load voltage levels would be more expensive. This is a modular architecture consisting of fuel cell modules, an inverter module, and a DC-DC converter module. To achieve the required power level, fuel cell modules can also be connected in parallel. The main quandary for this architecture is the failure mode. If one fuel cell module fails (open circuit), the whole system will stop working. The failing unit has to be replaced or bypassed externally. This causes reliability concerns.

But in paralleling fuel cell modules, extreme caution should be taken, since it is undesirable to feed current to the cells (unless a reversible fuel cell module is involved); a diode should be inserted as shown in Fig. 9.58 to block any possible circulating currents between the fuel cell modules.

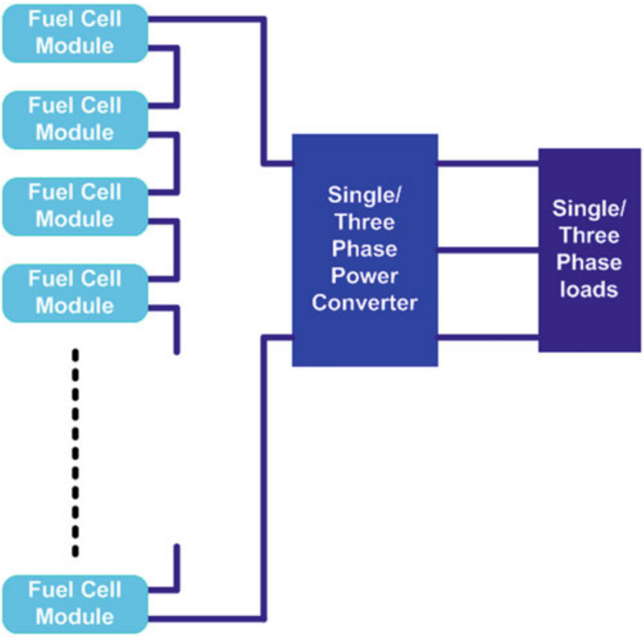

Fig. 9.57 Block diagram of series architecture

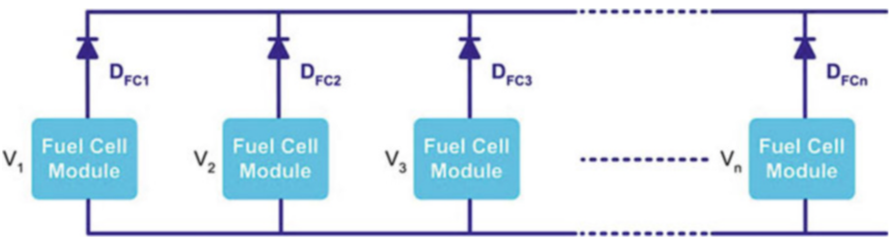

Fig. 9.58 Block diagram of parallel architecture

9.5.2 DC Bus Distribution Architecture

To overcome the disadvantages of the series architecture, a step-up DC-DC converter can connected to each fuel cell module; and the constant DC outputs of these converters can be connected in parallel, producing the DC bus distribution architecture shown in Fig. 9.59. In this architecture, each fuel cell module has its own power converter module. These DC-DC converters can be of the boost type if the fuel cell module voltage is less than the DC bus distribution voltage. The fuel cell module voltage can be equal to or greater than the DC bus distribution voltage if a sufficient number of cells are stacked together to form the fuel cell module. For such a scheme, a DC regulator should suffice to control the DC bus distribution voltage at a value best suited for the inverter. This architecture is inherently more reliable, as one individual fuel cell module's failure will not affect the whole system operation. Each subsystem can be designed as an individual module and stocked as

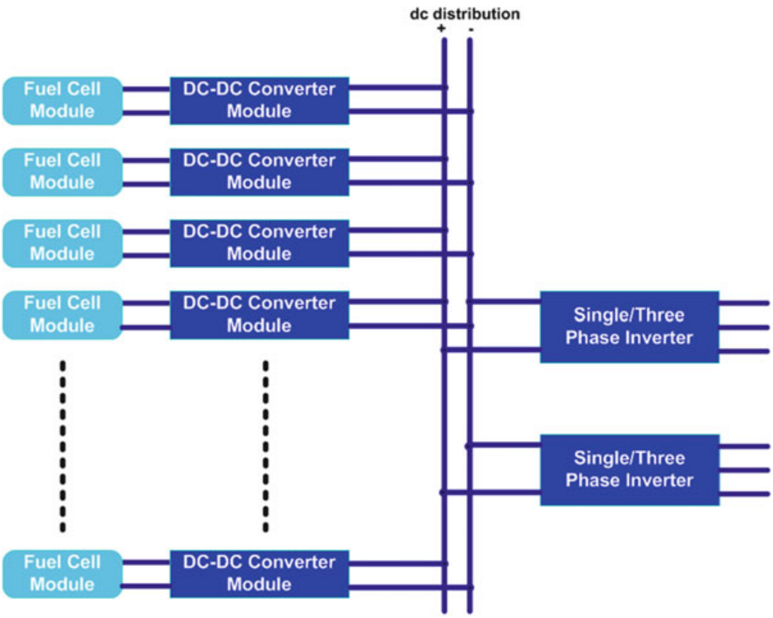

Fig. 9.59 Block diagram of DC bus distribution architecture

needed. The main dilemma of this converter is the higher device count. The addition of a DC-DC converter for every fuel cell multiplies the cost by a significant factor. In addition, each DC-DC converter's output voltage must be balanced with the other DC–DC converters to ensure that no circulating currents are present. To increase reliability, a redundant number of fuel cells can be connected in this architecture. Additionally, the constant voltage DC-link can also be used to feed one or several inverters, depending on the application.

The advantages of the DC Bus distribution architecture are: (i) each fuel cell can be controlled independently with the DC-DC converter module. The fuel cell modules can even be disconnected from the system for maintenance or replacement, and the rest of the system will continue the operation; (ii) Increased availability and fault-tolerant operation can be achieved by adding redundant fuel cell modules together with DC-DC converter modules. This architecture enhances the availability of fuel cell power, albeit at a reduced capacity while a fuel cell module is off-line for service or replacement; (iii) Each subsystem can be designed as an individual module, and they can be combined as needed. The list of modules would include the fuel cell module, the DC-DC converter module, and the inverter module. The inverter is already commercially available in a module. The disadvantages of the DC Bus distribution architecture are: (i) when the instantaneous voltages at the outputs of the DC-DC converters are not equal, circulating currents will occur. These will interfere with the operation of the system; therefore, they have to be prevented. Therefore, more complex control algorithms are required; (ii) This architecture requires a higher device count than the series architecture because of the DC-DC converters, but the devices have lower power ratings because more devices will be sharing the load current.

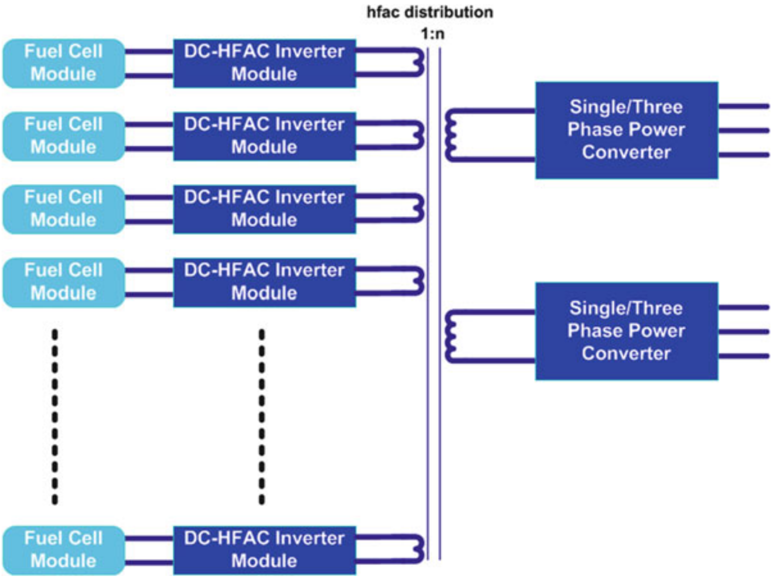

Fig. 9.60 Block diagram of HFAC distribution architecture

9.5.3 HFAC Distribution Architecture

The basic configuration of this architecture can be implemented through the use of the high-frequency link inverter as seen in Fig. 9.60. Each fuel cell is connected to a full-bridge inverter that converts the fuel cell DC voltage to a high-frequency AC. This AC is placed onto a small link and is shared among other fuel cells and their conditioning systems that are in parallel. Finally, a cycloconverter converts the high frequency link voltage to the appropriate output voltage. Unfortunately to place the converters in parallel, a strict control of the high-frequency output of the full-bridge converter must be in place adding severe complexity to this design.

The transformer brings the advantages of isolation, voltage boost, and the capability to add other power sources and loads through a power converter. Several converters can be connected to the extra primary and secondary taps, and the power can flow in different directions as required by the application. HFAC transformer is much smaller than a typical bulky 60 Hz transformer. As the frequency increases, the size of a transformer decreases. The challenge of fuel cell voltage variation with load also exists for the HFAC architecture. One solution to this problem is to insert a voltage regulator between fuel cell module and the DC-HFAC inverter. Another solution involves monitoring fuel cell voltages and modifying the control signals accordingly. The advantages of the HFAC distribution architecture are: (i) because of the high-frequency operation, the harmonics are at higher orders and it is easier to filter them with smaller, less-costly filters; (ii) The passive components required at high frequencies are smaller and lower cost just as in the case of the transformer;

(iii) Modularity is similar to the DC distribution case. The disadvantages of the HFAC distribution architecture are: (i) The HFAC transformer has to be specially designed; therefore, it will be expensive; (ii) If the transformer input voltage has a DC component, there will be a problem of transformer saturation. This can be eliminated with feedback control. Cycloconverters and matrix converters require AC switches, which are two switches connected back-to-back. They are not commonly available as modules. The control is complex because of the cycloconverter/ matrix converter control and its interaction with the H-bridge high frequency inverters.

9.5.4 Multilevel Architecture

Fuel cell modules can be connected to one single/three-phase multilevel inverter as shown in Fig. 9.61. In this case, there might not be a need for a voltage regulator if fuel cell voltages are monitored.

There are many variations of multilevel architectures. One typical multilevel inverter, the diode clamped multilevel inverter, is shown in Fig. 9.62 for four fuel cell modules. The advantages of multilevel converter architecture are: (i) They are

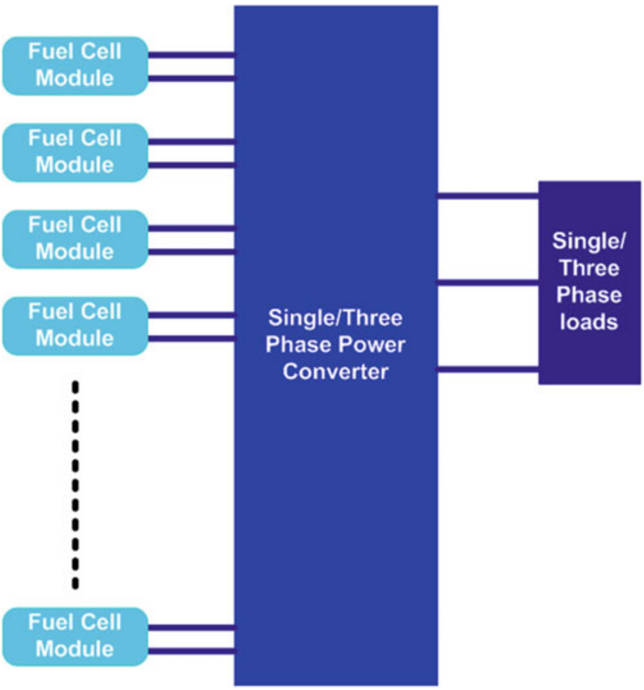

Fig. 9.61 Block diagram of the multilevel architecture

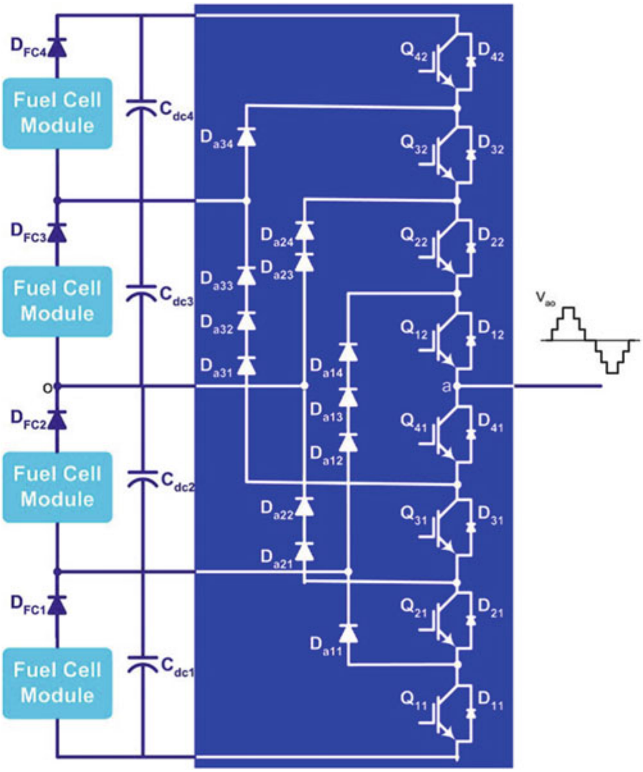

Fig. 9.62 One phase of a diode-clamped seven-level inverter

modular, lowering manufacturing costs. The cascaded multilevel converter is more modular than the other multilevel converters; (ii) Redundant levels can be added for increased reliability; (iii) Since each phase is built separately from the others, the final converter can be easily connected to be single-phase, multi-phase, or three-phase wye or delta; (iv) Fundamental frequency switching techniques can be applied to decrease the switching losses and to increase the converter efficiency; (v) Other control strategies, such as multilevel PWM or multilevel space vector PWM are possible. The disadvantages of multilevel converter architecture are: (i) the number of devices used in multilevel converters is high, but the voltage ratings of these devices are lower. An increased number of switches increase the price, but lower-rated switches are less-costly; (ii) Because of fundamental frequency switching, lower-order harmonics are higher; but there are techniques to reduce these harmonics. For example, the switching angles can be selected so that the required fundamental voltage is achieved with no 5th or 7th-order harmonics. Total harmonic distortion (THD) of 3 % has been achieved using fundamental frequency switching; (iii) for fuel cell applications, ripple current must be avoided. For a multilevel converter, care must be taken to reduce current ripple.

9.6 Summary

Uncertainty indeed remains as to the mix of technologies that will play the largest parts in meeting the challenges of global warming, energy security and economic efficiency in the longer term. Fuel cell could be a major and necessary source of energy within a decade. They have great potential as the basic elements of large and small stationary power plants and as the source of electricity for vehicles and smaller devices. Their shape and size are flexible and adaptable. They are modular having no moving parts, operate without combustion, are comparatively efficient and reliable, are nearly silent, generally do not pollute the environment and are quite safe. The technologies associated with hydrogen and with fuel cells are amongst those with the greatest potential, in particular, for the transport sector. Deployment of hydrogen infrastructure at this point would be premature, as some of the key technical issues that are still being worked on – such as fuel cell operating conditions and hydrogen on-board storage – may have a considerable impact on the choice of technologies for hydrogen production, distribution, and refuelling. As natural gas and coal are likely to remain the lowest-cost sources of hydrogen for many years to come, large-scale CO_2 capture and storage, already of the highest importance to mitigate emission in the power sector, is also a vital step towards the wider use of hydrogen. Fuel cells are under consideration for almost every application including both residential and industrial power generation. Yet, a power electronics interface must be incorporated between the fuel cell and output to provide flexibility due to the inherent restrictions fuel cells produce, such as low voltage, large voltage variation, low efficiency when ripple current is high, slow load step responsibility and no acceptance of reverse current. There are different types of fuel cell and based on the application the type of fuel cell has to be selected. Then the power electronic requirements of fuel cells have to be analysed and from various topologies of DC-DC boost converters and inverters best suited converters have to be used for fuel cells' power-conditioning system. Several architectures such as Series architecture, DC bus distribution architecture, High frequency AC (HFAC) distribution architecture, Multilevel architecture can be used to aggregate multiple fuel cells for high voltage/high-power applications.

Review Questions

1. What fuels can be used in a fuel cell?
2. How are fuel cells used to generate power for domestic purposes?
3. What is the present scenario of fuel cell energy?
4. Design a controller to control the fuel inputs to the fuel cell stack based on the feedback from the load output.
5. Develop a suitable power converter topology for efficient step up of voltage in fuel cells.
6. Mention the various switching techniques to control the switching operation with reduced switching losses.
7. Develop a MATLAB/SIMULINK model to implement the grid architectures using multiple fuel cells.

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