2.1 INTRODUCTION

Fuel cells based DG system is considered an alternative to centralized power plants due to their nonpolluting nature, high efficiency, flexible modular structure, safety and reliability. At present, they are under extensive research investigation as the power source of the future, due to their characteristics. A fuel cell converts chemical energy directly to electrical energy through an electrochemical process. As opposed to a conventional storage cell, it can work as long as the fuel is supplied to it. There are many motivations in developing this method of energy generation and it needs further development to have a realistic system analysis combining various subsystems and components [100].

Among the various types of fuel cells discussed in the literature, PEMFC and SOFC fuel cells are in wide use and have been widely commercialized. A number of research have been undertaken in the modeling, control and performance of PEMFCs, which are best suited to mobile and residential applications. Because of their lower efficiency and dependence on pure hydrogen as fuel, they have not found much use in stationary power applications [101], [102]. SOFCs, which work at high temperatures, however, are ideal for DG applications, wherein power is generated at the load site itself.

A suitable dynamic model of a fuel cell considering the electro-chemical-thermodynamic process and electrical performance is necessary with respect to DG technology application of SOFC. In this respect, an SOFC under transient state was modeled and simulated by the author of [103], which included both electrochemical and thermal aspects of the cell performance treating fuel input as constant. The model
was also not suitable for power system analysis. Following their work, the authors in [55] described a simulation model for a SOFC power plant, where the different plant sub-subsystems were modeled from a power system point of view. In their work, the FC operating temperature was assumed constant and the voltage drop due to ohmic losses were also considered. The authors approximated the electrochemical and thermodynamic processes using first order transfer functions. The model was also amenable to a power system analysis package.

Later in [58], the authors included a fuel processor in their investigation and used their model to study the load tracking capability of the SOFC plant wherein it was suggested that the pressure of hydrogen and oxygen in the gas compartments of the anode and the cathode should be restricted to $4kP_a$ under normal conditions and to $8kP_a$ under transient conditions. However, they did not indicate how the Fuel Cell plant was to be controlled. The dynamic model discussed in [55] was adapted by the authors of [11] and [59], which proposed the development of a non-linear dynamic model of an SOFC, where effects of temperature variations of the cells were introduced. The control of frequency fluctuation and supply power were reported by them, but they failed to examine the most important fuel cell parameter, the fuel utilization factor.

The control of an SOFC in stand-alone and grid connected mode with a DC/DC boost converter followed by a DC/AC inverter using fuzzy logic control were discussed in [104]. The use of a flux-vector controlled inverter to connect the SOFC to the grid was explained in [105]. Two control strategies namely constant utilization control which is accomplished by controlling the input fuel in proportion to the stack current and other using constant voltage control accomplished by incorporating an additional voltage control loop for the SOFC was discussed in [60] while independent control of active and reactive power were elucidated in [82]. Work in [106] presented the dynamic model of a prototype solid oxide fuel cell and a PWM-based inverter which serves as an interface between the fuel cell and the power distribution system.
In this chapter, the fuel cell has been taken up in detail and various concepts that result in the conversion of chemical energy to electrical energy have been dealt with. The operation of a fuel cell has been discussed with special emphasis on Solid Oxide Fuel Cells and various chemical equations that occur in the FC have also been discussed. Next, the mathematical model and the various equations pertaining to the fuel cells have been derived, followed by the development of the dynamic model of SOFC based DG system, in MATLAB/SIMULINK environment. Suitable control techniques are then designed and modeled in order to interface the FC to the isolated load as well as to grid, and the different topologies thereof discussed in detail.

2.2 BASICS OF A FUEL CELL

The basic components of a typical fuel cell include two electrodes, an anode and cathode where the reactions take place. An electrolyte is sandwiched between anode and the cathode which allows the ions to cross over, while blocking the electrons. The electrolyte also allows the ions that are formed to cross-over to the other electrode, which happens because of the tendency of charged particles migrating to regions of lower electrochemical energy. The electrical energy is produced when the electrons traverse the external circuit, flowing from the anode to the cathode. The end products of a fuel cell are heat and electricity, which make them suitable for CHP (Combined Heat and Power) applications. The most commonly used fuel in a fuel cell is hydrogen and the oxidant is usually oxygen and the product of chemical reaction is water which is produced either at the cathode or at the anode, depending on the type of fuel cell used.

Fig. 2.1 Basic Electrochemistry of an SOFC
In this work, SOFC has been considered and its operation is investigated in detail. For SOFC, the particular electrochemical reaction employed is illustrated in Fig.2.1. Solid oxide fuel cell is based on the concept of oxide ion migration through an oxygen ion conducting electrolyte from the oxidant electrode (cathode) to fuel electrode (anode) side. It operates at temperatures in the range of 600 – 1000°C, which makes them highly efficient as well as fuel flexible. In case of SOFC the electrolyte is a dense solid that involves ceramic materials like Yttrium-stabilized zircon dioxide whose function is to prevent electrons from crossing over while allowing passage to the charged oxygen ions.

The reduction reaction is carried out at the cathode where molecular oxygen reacts with the electrons supplied from external circuit to produce oxide ions. The oxygen ions migrate through the solid electrolyte to anode where they combine with the hydrogen molecule to produce water, CO₂ and electrons. The electrons flow through the externally connected circuit to reach the cathode, doing electrical work and producing electrical energy in the process. Water is produced at the anode on recombination of oxygen ions and electrons with hydrogen, as opposed to PEMFCs where water is produced at the cathode. Under operation, SOFC can use either an oxygen ion-conducting electrolyte or a proton conducting electrolyte. Here the SOFC with the oxygen ion-conducting electrolyte (SOFC – O²⁻) has been considered rather than with proton-conducting electrolyte (SOFC – H⁺) as Solid Oxide fuel cells are based on concept of an oxygen ion conducting electrolyte. The high temperature operation of SOFC enables it to work with hydrogen as well as hydrocarbon-based gases as fuel. In addition, SOFCs show a high tolerance to fuel impurities such as natural gas. They permit internal reforming, and also use less expensive catalysts for the dissociation of the oxidant. The chemical reactions that take place inside the SOFC which are directly involved in the production of electricity are as follows [59], [103].

At anode (fuel electrode):

\[
2H_2 + 2O^{2-} \rightarrow 2H_2O + 4e^-
\]  

(2.1)
At cathode (air electrode):

\[ O_2 + 4e^- \rightarrow 2O_2^- \] (2.3)

Overall cell reaction:

\[ H_2 + \frac{1}{2}O_2 \rightarrow H_2O \] (2.4)

2.3 CLASSIFICATION OF FUEL CELL [107].

Fuel cells can be classified depending on the parameters which include the nature and types of fuel used, external and internal reforming of fuel and the temperature operation. However, the common classification of fuel cells is based upon the electrolyte they use. These different types have different operating temperatures, materials, and a slightly different interaction, but the same basic reaction is the backbone of all of them. Because of the differences in some of the operating characteristics, the different types of fuel cells are suited for different applications. The low temperature FCs are limited to within 200°C, as higher temperatures cause rapid degradation of the electrolytes used. In high temperature cells, the temperature can be as high as 1000°C. There are several types of Hydrogen based fuel cells available which are being studied [107]. These include alkaline, proton exchange membrane, phosphoric acid, molten carbonate and solid oxide. Another category of fuel cells that utilize non-hydrogen fuels without any form of reforming are direct methanol fuel cell (DMFC ), direct alcohol fuel cell (DAFC) and direct carbon fuel cell (DCFC).

- **Alkaline Fuel Cell (AFC):** It uses a liquid solution of potassium hydroxide as an electrolyte and operates at low temperature between 70-90°C. The fuel used for AFC is \( H_2 \) and removal of \( CO_2 \) from both gas streams is necessary. Its electrical efficiency is high about 60% which makes it more competitive. It is used in
military applications, trucks, boats and submarines. Some of the advantages of these fuel cells are faster cathode reaction and higher overall efficiency.

- **Proton exchange membrane fuel cell (PEMFC):** This fuel cell makes use of solid polymer as electrolyte such as sulphonated organic polymer. The membrane is made of a Teflon-like material, which are an excellent conductor of protons and an insulator of electrons. It operates at temperature about 80°C with high power density and electrical efficiency of 30 – 40%. These are used in dedicated power and heat production, buses and service vehicles. Some of the advantages are quick system start-up and shut-down, outstanding resistance of the electrolyte to gas crossover and highest power density among all fuel cells. Disadvantages of this FC are expensive catalyst, difficulties in thermal/water management, poor tolerance towards CO and NH₃ and complex system configuration.

- **Phosphoric acid fuel cell (PAFC):** It uses a liquid phosphoric acid as an electrolyte. The acid is contained in a Teflon matrix, which keeps the acid in place during the reactions. The operating temperature is between 175-200°C which is almost double of PEMFC. Since PAFC has higher operating temperature, cogeneration can be used more effectively than other low temperature fuel cells. This cogeneration increases the efficiency of PAFCs to close to 85%. Some of the advantages of these fuel cells are cogeneration applications, excellent reliability and relatively inexpensive electrolyte. Disadvantages are slow reduction half reaction, needs platinum, corrosive electrolyte and complex system configuration.

- **Molten carbonate fuel cell (MCFC):** A molten carbonate salt mixture such as molten lithium or sodium carbonate is used as an electrolyte in MCFC. It uses natural gas, H₂, CO₂, CH₄ other hydro-carbons as fuel. It operates at very high temperature about above 600°C with electrical efficiency of 45 –55%. Its cogeneration efficiency is very high [107]. These fuel cells can be used for stationary applications for combined power and vapor production and for utility use. Some of the advantages are fuel flexibility, non-precious metal catalyst and
higher efficiency than PEMFC / PAFC. Disadvantages are corrosive electrolyte, high contact cathode resistance and limit in power density

- **Direct Methanol Fuel Cell (DMFC):** DMFC is hybrid of PEMFC. DMFC still use the same polymer membrane used in the PEMFC, but the difference is that DMFC uses liquid methanol as fuel instead of reformed hydrogen. The anode catalyst itself draws the hydrogen from the liquid methanol. The DMFC technology is relatively new compared to the rest of the types of fuel cell, but it does have potential. These fuel cells can be used for portable and micro power applications. The advantages are simple structure and good for low power / long period operations. Some of the disadvantages are poor cell efficiency and are not suited for high power and short term operations.

### 2.4 WHY SOFC?

In this work SOFC has been considered as they find wide applications in general, as enumerated above. While each fuel cell has their advantages and fields of application, this research concentrates upon SOFC. The main reasons why the SOFC has been given precedence over other fuel cell are as follows:

- SOFCs are suitable for stationary power applications with step load changes.
- They provide higher system efficiency and higher power density
- The design of SOFCs is simpler than a fuel cell based on liquid electrolytes.
- The exhaust heat in case of SOFC can be utilized for co-generation application in industries.
- Internal reforming of natural gas reduces the cost considerably.
- Since an SOFC operates at a high temperature (500°C to 1000°C), it has high reactant activities which helps in reduction of activation polarization, thus increasing the cell efficiency.
- SOFCs are flexible in the choice of fuel such as carbon-based fuels, like natural gas.
• SOFC technology is best suited for Distributed Generation application because of its high conversion efficiency.

• They have the ability to integrate with other power generating systems, such as automotive engines or gas turbines of various sizes.

2.5 MATHEMATICAL MODEL OF SOFC

The following assumptions are made in developing the mathematical model of fuel cell stack:

• Fuel cell is fed with hydrogen and oxygen.

• The gases considered are ideal, that is, their chemical and physical properties are not co-related to the pressure.

• Nernst equation is applicable.

• Fuel cell temperature is stable at all times.

• The electrode channels are small enough that pressure drop across them is negligible.

• The ratio of pressures between the inside and outside of the electrode channels is sufficient to consider choked flow.

• Ohmic, activation, and concentration losses are considered.

2.5.1 Concept of Gibbs’ Free Energy

The concept of Gibbs’ free energy is very important in the development of a fuel cell model. The Gibbs’ free energy can be defined as the energy available to do the external work, neglecting any work done by changes in the pressure and/or volume of the reactants and products of the fuel cell. In this case, the ‘external work’ involves moving electrons around the external circuit, and any work done by a change in volume between the input and output is not harnessed by the fuel cell. The external work is also referred to as the electrical work done. Under standard operating conditions (temperature of 25°C and pressure of 0.1 MPa) the Gibbs’ free energy is referred to as the Gibb’s free energy of formation, $G_f$. It is that change in this
parameter $G_f$ that is important in considering the energy released. This change is the difference between the Gibbs' free energy of formation of products and reactants, and is given as [71].

$$\Delta G_f = G_f^{\text{product}} - G_f^{\text{reactant}}$$  \hspace{1cm} (2.5)

The Gibbs energy of formation per mole is given by

$$\Delta g_f = g_f^{\text{product}} - g_f^{\text{reactant}}$$  \hspace{1cm} (2.6)

$$\Delta g_f = \left(\frac{g_f}{H_2O}\right) - \left(\frac{g_f}{H_2}\right) - \frac{1}{2}\left(\frac{g_f}{O_2}\right)$$  \hspace{1cm} (2.7)

The reversible open circuit voltage of fuel cell at standard temperature and pressure (STP) is given by:

$$E = -\frac{\Delta g_f}{2F}$$  \hspace{1cm} (2.8)

Where, $F$ is the Faraday’s constant (96487 C/mol)

**2.5.2 Pressure Variation**

The change in Gibbs free energy varies with pressure and temperature of the fuel cell, which in turn changes the voltage of fuel cell. The equation shows how $\Delta g_f$ varies from its standard value which is stated at STP [71].

$$\Delta g_f = \Delta g_f^0 - RT \ln \left( \frac{P_{H_2} P_{O_2}^{0.5}}{P_{H_2O}} \right)$$  \hspace{1cm} (2.9)

Where,

$T$ is the operating temperature of fuel cell in Kelvin, $R$ is the universal gas constant (8.314 J/mol K) and $\Delta g_f^0$ is the change in Gibbs free energy of formation per mole at standard pressure.
Using \( E^0 = -\frac{\Delta g^0_i}{2F} \) and substituting the value of \( \Delta g^0_i \) from Equation (2.9) in Equation (2.8) gives the following equation, which shows the effect of pressure on Nernst equation at standard temperature:

\[
E = E^0 + \frac{RT}{2F} \ln \left( \frac{P_{H_2}P_{O_2}^{0.5}}{P_{H_2O}} \right) \tag{2.10}
\]

The above equation gives reversible voltage (open circuit voltage) of each cell, also known as Nernst voltage at standard temperature and varying pressure.

### 2.5.3 Characterization of the Exhaust of the Channels

The development of dynamic model of fuel cell begins with choked flow equation [55].

\[
\frac{m_f}{P_u} = K \sqrt{M} \tag{2.11}
\]

where,

- \( m_f \): Mass flow rate (Kg / s)
- \( P_u \): Upstream pressure
- \( K \): Valve constant
- \( M \): Fluid molar mass

The utilization factor \( (U_f) \) is defined as the ratio of amount of hydrogen that reacts with oxygen to the amount of hydrogen which enters the anode.

\[
U_f = \frac{m_{f,H_2,r}}{m_{f,H_2,in}} \tag{2.12}
\]

Where,

- \( U_f \): Utilization factor
- \( m_{f,H_2,r} \): Hydrogen which reacts with oxygen
- \( m_{f,H_2,in} \): Hydrogen which enters anode.
The following equations can be obtained by considering the molar flow of any gas through valve to be proportional to its partial pressure inside the channel [55].

\[
\frac{q_{H_2}}{p_{H_2}} = \frac{K_{an}}{\sqrt{M_{H_2}}} = K_{H_2} \tag{2.13}
\]

\[
\frac{q_{H_2O}}{p_{H_2O}} = \frac{K_{an}}{\sqrt{M_{H_2O}}} = K_{H_2O} \tag{2.14}
\]

Where,

- \(q_{H_2}\) and \(q_{H_2O}\): molar flow rate of hydrogen and water through the anode valve respectively.
- \(p_{H_2}\) and \(p_{H_2O}\): partial pressures of hydrogen and water in atm respectively.
- \(K_{an}\): anode valve constant,
- \(M_{H_2}\) and \(M_{H_2O}\): molecular masses of hydrogen and water respectively
- \(K_{H_2}\) and \(K_{H_2O}\): valve molar constant for hydrogen and water respectively

By substituting equations (2.12), (2.13), and (2.14) in (2.11), the equation can be expressed as,

\[
\frac{m_f}{p_{an}} = K_{an} \left[ (1 - U_f) \sqrt{M_{H_2}} + U_f \sqrt{M_{H_2O}} \right] \tag{2.15}
\]

### 2.5.4 Calculation of Partial Pressure

The ideal gas law is used to calculate the partial pressure of all the gases [55]. For hydrogen,

\[
p_{H_2} V_{an} = n_{H_2} RT \tag{2.16}
\]
where

\[ V_{an} \]: volume of anode-channel

\[ n_{H_2} \]: hydrogen moles in the channel

\[ R \] and \[ T \]: universal gas constant and operating temperature of the fuel cell stack respectively.

From equation (2.16)

\[ p_{H_2} = \frac{n_{H_2}RT}{V_{an}} \]  \hspace{1cm} (2.17)

Taking the first derivative of equation (2.17)

\[ \frac{d}{dt} \left( p_{H_2} \right) = \frac{d}{dt} \left( \frac{n_{H_2}RT}{V_{an}} \right) \]  \hspace{1cm} (2.18)

\[ = \frac{q_{H_2}RT}{V_{an}} \]  \hspace{1cm} (2.19)

Where, \( q_{H_2} \) is the time derivative of \( n_{H_2} \) and it represents the molar flow (kmol s\(^{-1}\)) of hydrogen. The hydrogen molar flow is further divided into three parts and their relationships can be expressed as follows [55], [108].

\[ \frac{d}{dt} \left( p_{H_2} \right) = \frac{RT}{V_{an}} \left( q_{H_2}^{in} - q_{H_2}^{out} - q_{H_2}^{r} \right) \]  \hspace{1cm} (2.20)

Where,

\[ q_{H_2}^{in} \]: molar flow rates of hydrogen in the channel

\[ q_{H_2}^{out} \]: molar flow rate of hydrogen out of the channel and

\[ q_{H_2}^{r} \]: molar flow rate of hydrogen reacting in the channel
According to the electrochemical relationships, the quantity of hydrogen that reacts is given by [55], [58].

\[ q_{H_2}^r = \frac{N_0 I_k}{2F} = 2K_r I_k \]  

(2.21)

Where,

- \( N_0 \): number of cells connected in series in the stack
- \( I_{fc} \): stack current
- \( F \): Faraday’s constant
- \( K_r \): modeling constant which is given as follows

\[ K_r = \frac{N_0}{4F} \]  

(2.22)

Substituting (2.21) in (2.20), the time derivative of hydrogen partial pressure can be expressed as

\[ \frac{d}{dt} (p_{H_2}) = \frac{RT}{V an} \left( q_{H_2}^{in} - q_{H_2}^{out} - 2K_r I_k \right) \]  

(2.23)

Replacing the output flow by (2.13) and taking the Laplace transform both sides followed by isolation of hydrogen partial pressure; it gives the expression for partial pressure of hydrogen as

\[ P_{H_2} = \frac{1}{1 + \tau_{H_2} s} \left( q_{H_2}^{in} - 2K_r I_k \right) \]  

(2.24)

Where, \( \tau_{H_2} \) is the value of system pole associated with the hydrogen flow [55], expressed in seconds and is given as

\[ \tau_{H_2} = \frac{V_{as}}{K_{H_2} RT} \]  

(2.25)
In similar way, the partial pressure for the reactant, oxygen and product, water can be expressed as follows

\[ p_{O_2} = \frac{1/K_{O_2}}{1 + \tau_{O_2}s} \left( q_{in}^{O_2} - K_r I_k \right) \]  
\[ (2.26) \]

\[ p_{H_2O} = \frac{1/K_{H_2O}}{1 + \tau_{H_2O}s} \left( 2 K_r I_k \right) \]  
\[ (2.27) \]

where

\[ K_{O_2} : \text{Valve molar constant for oxygen} \]

### 2.5.5 Calculation of Stack Voltage

The expression for stack output voltage \( V_{fc} \) of a fuel cell can be obtained applying Nernst’s equation and also taking into account the voltage losses such as the ohmic, activation and mass transportation (concentration) losses as: [55], [71], [109].

\[ V_{fc} = E_{fc} - V_{act} - V_{conc} - V_{ohmic} \]  
\[ (2.28) \]

where,

\[ V_{fc} : \text{is the stack voltage of fuel cell} \]

\[ E_{fc} : \text{is the reversible open circuit voltage (V)} \]

\[ V_{act} : \text{is the activation over voltage (V)} \]

\[ V_{conc} : \text{is the concentration overvoltage (V)} \]

\[ V_{ohmic} : \text{is the ohmic voltage loss (V)} \]

The value of the Nernst voltage equation \( E_{fc} \) is found from Nernst equation

\[ E_{fc} = N_0 \left[ E^0 + \frac{RT}{2F} \ln \left( \frac{p_{H_2} p_{O_2}^{0.5}}{p_{H_2O}} \right) \right] \]  
\[ (2.29) \]
\[ V_{fc} = E_{fc} - A \ln(i) - m(\exp(ni)) - rI_{fc} \]  
\[ (2.30) \]

\[ V_{fc} = N_0 \left( E^0 + \frac{RT}{2F} \ln \left( \frac{P_{H_2}P_{O_2}}{P_{H_2O}} \right)^{0.5} \right) - A \ln(i) - m(\exp(ni)) - rI_{fc} \]  
\[ (2.31) \]

2.5.6 Calculation of Voltage Losses

2.5.6.1 Activation voltage losses

The reason for this loss in SOFC is the sluggishness of chemical reaction that takes place on the surface of electrodes. A certain amount of voltage produced by fuel cell is lost in carrying the reaction forward that transfers the electrons to or from the electrode. Activation losses are estimated using Tafel equation [71]. This equation was derived by physical experimentation on various electrochemical reactions. It provides a relationship between the overvoltage at the surface of an electrode and the natural logarithm of the current density and can be used to calculate the activation voltage loss for the fuel cell [71], [109].

\[ V_{act} = B \ln(i) \]  
\[ (2.32) \]

where

\[ V_{act} \]: is the activation voltage loss

\[ B \]: is the slope of Tafel line (constant specific for SOFC)

\[ i \]: current density (current/electrode area)

2.5.6.2 Concentration voltage losses

These losses are also known as mass transport losses and are caused due to the reduction in concentration of reactants in the region of electrode as the fuel is
consumed. The consumption of reactants at respective electrodes, i.e. hydrogen at the anode and oxygen at the cathode leads to a slight reduction in concentrations of the reactants. Due to the reduction in concentrations, there is a drop in partial pressure of gases which will result in a reduction of voltage that portion of the electrode can produce. Unfortunately this loss cannot be calculated analytically with enough accuracy. Therefore, experimental results are used to estimate the loss. Following equation (2.33) has been developed on an experimental basis and is accepted as a good approximation of the mass transport losses.

$$V_{\text{conc}} = m \exp(ni)$$  \hspace{1cm} (2.33)

where, \(m\) and \(n\) are constants.

### 2.5.6.3 Ohmic voltage losses

These losses in SOFCs are caused due to the resistance both to flow of electrons through the electrodes and to the migration of ions through the electrolyte. In addition, the fuel cell interconnects or bipolar plates also contribute to the ohmic losses [71]. Ohmic loss is given as

$$V_{\text{ohmic}} = rI_{\text{fc}}$$  \hspace{1cm} (2.34)

where, \(r\) is the internal resistance.

Ohmic losses can be minimized by reducing the internal resistance of the cell, which can be done in the following ways:

- Making electrolyte as thin as possible
- Using electrodes with highest possible conductivity.
- Using appropriate materials for bipolar plates or cell interconnect.
2.5.7 Implementation of SOFC Model in Simulink /MATLAB

A comprehensive dynamic model of a SOFC has been developed and simulated in the MATLAB / Simulink environment as shown in Fig.2.3. The SOFC model is based on [55], [58] in respect of expression for partial pressures hydrogen, oxygen, water, Nernst’s voltage, ohmic loss, activation loss and mass transportation loss. The different model parameters such as maximum fuel utilization, minimum fuel utilization, optimum fuel utilization fuel system response time, electrical response time and so on as mentioned in Table 2.2 in Appendix. Fuel cells can be operated in two basic modes, viz.

(i) Constant input mode

(ii) Constant utilization mode.

In this model, constant utilization mode is considered. The fuel utilization is defined as the ratio between fuel flow that reacts and the fuel flow injected to the stack [58] and is expressed as:

\[ U_f = \frac{q_{H_2}^r}{q_{H_2}} \]  

(2.35)
It has been shown that the fuel utilization ranging from 0.8 to 0.9 yields better performance and prevents overused and underused fuel conditions [58]. Considering the above specified fuel conditions, \( U_f > 0.9 \) can cause permanent damage to the cell because of fuel starvation and \( U_f < 0.7 \) leads to higher cell voltage rapidly. For definite hydrogen input flow, the demand current of fuel cell system can be limited in the range given as: [58]

\[
\frac{0.8q_{\text{in}}^{\text{H}_2}}{2K_t} \leq I_e \leq \frac{0.9q_{\text{in}}^{\text{H}_2}}{2K_t} \quad (2.36)
\]

The optimum utilization factor assumed for this model is 0.85 [58]. The fuel utilization can be set at this value by regulating the input fuel flow depending on the real output current recorded in the fuel cell system. Therefore, the value of fuel input flow, depending on fuel cell output current is given as

\[
q_{\text{in}}^{\text{H}_2} = \frac{2K_t I_e}{0.85} \quad (2.37)
\]
With reference to (2.4), the stoichiometric ratio of hydrogen to oxygen is 2:1. Excess oxygen is continuously taken in order that hydrogen can react with oxygen completely [58]. The flow rate of oxygen input is controlled by the hydrogen-oxygen molar flow ratio $r_{H-O}$. The parameters of the chemical reaction do not change instantly with the change in the flow rate of reactants, but require some time. Because of this, the chemical response of the fuel processor is slow. This response is characterized by a first order transfer function with a time constant, $T_f$ and the dynamic electrical response of fuel cell is modeled using first order transfer function with a time constant, $T_e$. Electrical response is associated with speed of the chemical reaction at which charge is restored, which is drained by the load. The power output of fuel cell system is the product of stack current and voltage. The various dynamic behaviors of the developed SOFC model with step change in reference input have been obtained which are discussed in the next chapter.

### 2.6 POWER ELECTRONICS INTERFACE TOPOLOGIES

A variety of topologies have been discussed in the literature in order to utilize the power generated by a fuel cell. The power output of a fuel cell cannot be used directly, and needs to be properly conditioned before interfacing to the load or to the grid. Thus, power conditioning units (PCU) are employed that convert the power generated by the FCs into a usable form. The components of the PCU and the way they are connected constitute a number of topologies. The basic components of any of such topologies include:

- The power source (Fuel Cell)
- The DC-DC Converter
- The DC-AC Inverter
Other additional components that may be used include

- A support battery
- A bidirectional buck/boost converter
- Transformers
- L-C filters at input/output
- Static Switches

2.6.1 DC to DC Converters

A number of designs for the DC/DC converter have been suggested, which may be single or dual stage. Single stage converters do not provide isolation between the input and the output, and do not perform any inversion of the voltage. The types of single stage DC/DC converters used are [110], [111].

- Boost Converter
- Synchronous Boost Converter
- Buck-Boost Converter
- C’uk Converter
- Fly-back converter

The other types of DC/DC converters, that have a multistage operation, first convert the DC power to AC and again back to DC. The AC signal can be easily boosted with the help of a high frequency transformer incorporated in the design. This system offers electrical isolation between the input and the output, as the transformer uses different grounds. This also facilitates continuous noise filtering from the primary side, resulting in reduction of the electrical noise emitted. The converter topologies under this scheme include:

- Push-Pull DC to DC boost converter
- Unidirectional Full-bridge DC to DC power converter.

Out of the above mentioned converters a few of them are described in brief.
2.6.1.1 Push–Pull DC to DC converter [110], [112]

The push–pull DC to DC converter has a simple structure in its gate drive circuits and power circuits. They are usually recommended for power capacities less than 1 kW with a low input voltage. However, the active switches are hard-switched, and the dissipative losses which occur due to the passive clamp circuit for suppressing the voltage spikes caused by the leakage inductance of the high frequency transformer are quite high, bringing down the efficiency and power density at the higher power levels.

By exchanging the diodes for IGBTs on the secondary side, bidirectional operation can be made possible with a few modifications in the circuit, as shown in fig. 2.4. This topology requires a clamping circuit for limiting the voltage stress on the MOSFETS on the primary side. The main advantage of the push – pull converter is that the current is naturally limited by the inductor on the primary side, avoiding the possibilities of shoot through and voltage clamping of rectifier diodes to the DC link voltage.

Fig.2.4 Unidirectional push-pull converter
2.6.1.2 The full bridge DC–DC converter [113]

For fuel cell application a voltage fed full bridge two stage converters with an intermediate high frequency transformer is shown in Fig. 2.6. The first stage consists of a single phase inverter that is based on four switches which are controlled using a controller. The high frequency transformer ensures a proper voltage gain and transmits power from the primary to the secondary. The second stage is a single phase rectifier with an RL filter that supplies the DC link. A capacitor is added in parallel with the FC stack to reduce the current harmonics.
The full bridge converter is suitable for high power applications as transistor voltage and current stresses are not very high, and the device current rating and transformer turns ratio can be reduced by one half compared to other topologies. The input and output current ripples and the voltage ripples are low and they favour zero voltage switching (ZVS) with PWM techniques. However, the conduction losses can be quite high due to an increased number of components. They can be either of voltage fed type or current fed types. The current fed converters require a clamping circuit, consisting of a diode and a capacitor.

2.6.1.3 Unidirectional/Bidirectional full bridge converters [113]

If a backup power source like a battery is involved, two phase-shifted full bridge DC-DC Converters can be used, one a unidirectional full bridge DC to DC boost converter and other a bidirectional full bridge DC to DC buck boost converter for the battery. A static switch on the battery side to control the power flow in both directions can also be incorporated for smooth functioning. The circuit diagram of this topology is shown in Fig. 2.7.

![Fig. 2.7 Unidirectional / Bidirectional DC – DC power converter](image-url)
The unidirectional power converter system as shown in the above figure consists of a fuel cell, an input filter, a full bridge power converter, a high frequency transformer, a bridge diode and an output filter. The bidirectional power converter for the battery consists of a static switch and two full bridge power converters made up of IGBTs along with a high frequency transformer, apart from the supporting battery. The main purpose of the dual full bridge converters is to boost the low DC voltage of the fuel cell and the battery and tightly regulate the value of the output voltage even if the FC output voltage or the load fluctuates. While the unidirectional converter only allows power to flow from the fuel cell to the load as a reverse current can damage the fuel cell, the bidirectional converter allows power flow in both directions to facilitate discharging and recharging of the battery. Its response should also be fast enough to compensate for the slow dynamics of fuel cell during start up or sudden load changes.

The main purpose of the battery is to cater to the instantaneous power demand of the load until the fuel cell reaches its full operation state, after which the fuel cell feeds power to the load. During the recharge mode, the battery absorbs the energy overflowed from the fuel cell to prevent the DC link voltage from being overcharged during a sudden load decrease, and then the battery is recharged by the fuel cell in a steady state until it reaches its nominal voltage. A full bridge converter presents certain advantages over other types of DC-DC converters. On the primary side, there is no need to use a high current inductor and the voltage and current constraints of the switch are reduced with respect to the other structure. The two stages are also isolated from each other through a high frequency transformer.

2.6.1.4 Design of DC – DC boost converter

In this work, the boost converter has been considered for providing a regulated dc output voltage at its terminals. DC–DC boost converter is the integral part of fuel cell power conditioning unit. The design of DC–DC boost converter and their controller plays important role to control power regulation particularly for common DC bus. The converter operates in the linear region operation of fuel cell stack. Beyond the linear region, the fuel cell cannot be operated as electrolyte membrane of fuel cell may get damaged. The main advantages of the boost converter include higher efficiency and a
reduced number of components. The duty cycle has been varied at a high switching frequency to convert the unregulated voltage into a regulated supply. The values of inductor and capacitor have been chosen appropriately to reduce the ripples. However, the large inductance tends to increase the startup time slightly while small inductance allows the coil current to ramp up to higher levels before switch turns off [110], [111]. A circuit diagram of boost converter is shown in Fig. 2.7. The following assumptions have been made in the analysis:

- Steady state conditions exist.
- The switching period is $T$, and the duty ratio is $D$, so that the switch remains open for time $(1-D)T$ and closed for time $DT$.
- The inductor current is continuous and always positive.
- The capacitor is very large and the output voltage is held constant at $V_o$.
- All components are ideal with no voltage drops across them.

![Boost converter circuit diagram](image1)

**Fig. 2.8 Boost converter circuit diagram [110]**

- **Analysis when switch is in closed condition**

Fig. 2.9 shows the equivalent circuit of the DC–DC boost converter during switch on time.

![Equivalent circuit for DC–DC boost converter during switch ON time](image2)

**Fig. 2.9 Equivalent circuit for DC–DC boost converter during switch ON time**
During the time period $DT$, when the switch is closed, the inductor voltage can be written as

$$V_L = V_S = L \frac{di}{dt} \quad \text{or} \quad \frac{di}{dt} = \frac{V_S}{L}$$  \hspace{1cm} (2.38)$$

The change in inductor current is given as

$$\Delta i_L \text{_{closed}} = \frac{V_S DT}{L}$$  \hspace{1cm} (2.39)$$

- **Analysis when switch is in open condition**

When the switch is open for time period $(1-D)*T$, the equivalent circuit is as shown in Fig.2.10.

Fig.2.10 Equivalent circuit for DC–DC boost converter during switch off time

Assuming that the output voltage $V_O$ is a constant, the voltage across inductor is given as

$$V_L = V_S - V_O = L \frac{di}{dt} \quad \text{or} \quad \frac{di}{dt} = \frac{V_S - V_O}{L}$$  \hspace{1cm} (2.40)$$

The change in inductor current while switch is open is given as

$$\Delta i_L \text{_{open}} = \frac{(V_S - V_O)(1-D)T}{L}$$  \hspace{1cm} (2.41)$$
The net change in inductor current must be zero, from equations (2.39) and (2.41)

\[(\Delta i_L)_{closed} + (\Delta i_L)_{open} = 0\]

\[\Rightarrow V_o = \frac{V_s}{1-D}\]  \hspace{1cm} (2.42)

Equation (2.42) gives the expression of the output voltage as a function of the duty cycle. The average current inductor is determined by considering that the power supplied by source must be same as power absorbed by the load.

\[P_o = \frac{V_o^2}{R_L}\]  \hspace{1cm} (2.43)

and \[V_s I_s = V_s I_L\]  \hspace{1cm} (2.44)

Now from (2.42), (2.43) and (2.44), the inductor current is obtained as

\[I_L = \frac{V_s}{(1-D)^2 R_L}\]  \hspace{1cm} (2.45)

Where, \(R_L\) is the load resistance.

Maximum and minimum inductor currents are determined as

\[I_{max} = I_L + \frac{\Delta i_L}{2} = \frac{V_s}{(1-D)^2 R_L} + \frac{V_s DT}{2L}\]  \hspace{1cm} (2.46)

\[I_{min} = I_L - \frac{\Delta i_L}{2} = \frac{V_s}{(1-D)^2 R_L} - \frac{V_s DT}{2L}\]  \hspace{1cm} (2.47)

And the minimum value of inductance, obtained from the limiting value of the current to ensure continuity in conduction is given as

\[L_{min} = \frac{D(1-D)^2 R_L}{2f_s}\]  \hspace{1cm} (2.48)
Where $f_s$ is switching frequency in hertz.

A ripple in the output will always be present whenever a capacitance is involved in the circuit. The voltage ripple due to the capacitor can be considered as

$$\frac{\Delta V_O}{V_O} = \frac{D}{R_L C f_s}$$  \hspace{1cm} (2.49)

The size of reactive elements of Boost converter can be determined from the rated voltage, voltage ripple and switching frequency of the converter based on the equations from (2.42) to (2.49) with voltage ripple < 0.1% and switching frequency $f_s = 20000$ hertz.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage ripple</td>
<td>0.1%</td>
</tr>
<tr>
<td>Inductance: $L$</td>
<td>19.188 μH</td>
</tr>
<tr>
<td>Capacitance: $C$</td>
<td>419.88 μF</td>
</tr>
<tr>
<td>Switching frequency: $f_s$</td>
<td>20KHz</td>
</tr>
<tr>
<td>Desired DC Output Voltage</td>
<td>776 V</td>
</tr>
</tbody>
</table>

Table 2.1 Boost converter parameters
A Simulink model of PI controlled DC–DC boost converter based on the designed parameters given in Table 2.1 is shown in Fig.2.11. The DC–DC converter is an integral part of fuel cell power conditioning unit hence modeled PI boost converter has been used in SOFC based DG to maintain a constant voltage of 776 V output which is required as an input to inverter, irrespective of variation in the load and fuel cell terminal voltage. The PI controller minimizes steady state error to zero. The process of sensing the control variable and transformation of dimensionless measured quantities compared with reference signals are incorporated in Fig2.11 (a) and Fig.2.11 (b) [114],[115]. The change in duty cycle for varying load is obtained by controlling the suitable PI parameter values of voltage controller. The set parameters of PI controller are $K_p$ and $K_i$ are 0.15 and 1.15 respectively.

### 2.6.2 Three-phase Voltage Source Inverter

Since fuel cell (FC) generates DC output voltage, it must be inverted using a DC to AC for household application as well as for distributed generation. Inverters can be either voltage source or current source inverters (VSI or CSI). In VSI, the DC source has negligible impedance and the terminal voltage remains almost constant with load variations. Any short circuit across the terminals causes current to rise very fast, and to clear the faults, fast acting fuse links must be incorporated. The CSI, on the other hand, is supplied with a controlled current from a high impedance DC source. Here, the inverter output voltage is dependent on the load impedance and thus terminal voltage can change substantially with changes in the load. However, inherent protection against short circuits is provided in this topology, thus fault protection is not required.
On the basis of the output waveform, inverters can be classified as Square wave or Pulse-width Modulated (PWM) inverters. Square wave inverters produce a square wave AC voltage which is of a constant magnitude, and the output can be varied controlling the input DC voltage. To obtain a sinusoid, filter circuits at the output can be used, however, this increases the cost and weight of the inverter and efficiencies also fall due to additional losses in the filter. The PWM inverters, on the other hand, employ a switching scheme in order to obtain a sine wave at the output. A constant DC voltage is supplied to the inverter and by adjusting the on and off times of the inverter devices, an AC output can be obtained. No additional devices are used here and lower order harmonics can be easily minimized or eliminated. The input power factor in this case is also good at all frequencies. The commonly used PWM techniques include single, multiple and sinusoidal PWM methods.

The voltage switching used with PWM inverters can be either bipolar or unipolar voltage switching. In bipolar switching, the output voltage switches between the positive and negative of the maximum value of the DC voltage, viz. $+V_{dc}$ and $-V_{dc}$. In unipolar switching, the polarity of the PWM output voltage can be at three levels, at the maximum positive or negative value or at zero, viz. $+V_{dc}$, zero or $-V_{dc}$. A circuit model of a three phase DC to AC PWM inverter is described in Fig. 2.12, with low pass series RL filter placed at the output terminals of the inverter to supply sinusoidal output voltage for the three phase isolated load as it is important to keep the output voltage sinusoidal as far as possible.

![Fig. 2.12 Three-phase PWM inverter with RL output filter](image-url)
The topology consists of the DC power which is being fed to the inverter; six IGBT switches S1 to S6, an output series RL filter and a load. The input power source has been shown as a DC voltage source while in reality, this stage consists of a fuel cell and a DC to DC boost converter.

In this thesis, a three phase Sinusoidal PWM (SPWM) inverter using unipolar voltage switching scheme is considered. A three phase six switch Unipolar PWM voltage source inverter (VSI) followed by a low pass series RL filter is considered to interface the SOFC fuel cell to a three phase isolated load. Filter circuit is used to eliminate the current harmonics around the switching frequency and to comply with the required standards, for example IEEE 1547. Ideally, the filter with low cut-off frequency and high attenuation at the high switching frequency is used to eliminate switching ripple effectively [117]. The topologies of such filters, as suggested in the literature, may contain only inductive elements or inductive elements in combination with capacitive elements. However an RL series filter has been adopted for interfacing SOFC to an isolated load/utility grid. The most commonly used three-phase inverter circuit consists of three legs, one for each phase as shown in Fig. 2.12. The output of each leg depends on $V_{dc}$ and the switching status. The switching scheme in this type of power converter conversion is based on the pulse width modulation technique.

2.6.3 Pulse Width Modulation (PWM)

The working of a SPWM inverter is discussed next. A three-phase SPWM inverter requires a balanced set of three sinusoidal signals along with the triangular carrier signal of high frequency. In its simplest form, an SPWM inverter involves comparison of a high frequency triangular carrier voltage with three sinusoidal controlled voltages.
For this reason, it requires a balanced set of three sinusoidal signals which are 120° out of phase. Wave generator is used to generate these signals which are then compared using a comparator, to get the pulse width modulated output, as shown schematically in Fig. 2.13. The triangular wave generator generates a high frequency carrier signal, which decides the switching frequency of the inverter and the modulating wave generator produces sinusoidal signals that determine the width of the pulses and therefore, the RMS voltage output of the inverter. A comparator is used to compare the carrier wave with the reference signal, considering the following conditions:

\[
V_{AN} = \begin{cases} 
V_{dc} & v_{controlA} \geq v_{tri} \\
0 & v_{controlA} < v_{tri} 
\end{cases}
\]  

(2.50)

The output voltage is generated with the condition that two switching devices in the same leg do not conduct at the same time. For example, in phase A, when control voltage \(v_{controlA} \geq v_{tri}\) the upper switch S1 in Figure 2.12 is ON (closed) and lower switch S4 is off (open). As a result, the output voltage of phase A with respect to the negative terminal of the DC source is \(V_{AN} = V_{dc}\) and \(V_{AN} = 0\) when \(v_{controlA} < v_{tri}\). The same arguments hold good for voltage \(v_{BN}\), that is, if \(v_{controlB} \geq v_{tri}\), \(V_{BN} = V_{dc}\) and \(V_{BN} = 0\) when \(v_{controlB} < v_{tri}\), as shown in Figure 2.14. The output voltage of phase C is modulated similar to phase A and B.
For three phase applications, line to line voltages are of main interest and harmonics in the line to line voltages are of greater concern. The harmonics in the line to line voltage $v_{AB}$ are suppressed as the phase difference between the harmonics in $v_{AN}$ and $v_{BN}$ is zero. The DC component and the harmonics that correspond to multiples of three of the fundamental frequency are cancelled, when line to line voltages are concerned. In this way, some of the dominant harmonics of one leg of the inverter can be eliminated from the line-to-line voltage from a three-phase inverter. The resulting output waveforms are shown in Fig. 2.14.

Fig. 2.14 Three phase PWM waveforms
The modulation index of a SPWM inverter is defined as the ratio of the peak magnitudes of the modulating waveform to the carrier waveform. It is used to change the switching frequency, which in turn changes the inverter output voltage

\[ m_a = \frac{V_{\text{modulating}}}{V_{\text{carrier}}} \]  \hspace{1cm} (2.51)

The frequency modulation ratio is defined as the ratio between the frequency of the carrier wave \( f_s \) and the fundamental (modulating) frequency \( f_1 \).

\[ m_f = \frac{f_s}{f_1} \] \hspace{1cm} (2.52)

For linear modulation, \( (m_a \leq 1) \), the RMS value of line to line voltage at fundamental frequency \( f_1 \), due to a 120° displacement between the phase voltages is

\[ V_{LL} = \frac{\sqrt{3}}{\sqrt{2}} V_{AN} \] \hspace{1cm} (2.53)

The fuel cell base quantities (DC) are derived from voltage source converter with SPWM modulation. The AC side line to line RMS voltage is proportional to the fuel side DC converter output voltage as

\[ V_{LL} = \frac{\sqrt{3}}{2\sqrt{2}} m_a V_{dc} \] \hspace{1cm} (2.54)

Where, \( m_a \) is the amplitude modulation.

\[ V_{LL} = 0.612 m_a V_{dc}, m_a < 1 \] \hspace{1cm} (2.55)

where \( V_{dc} \) is the regulated voltage output from DC-DC converter.

When the peak magnitude of the modulating signal exceeds that of the carrier signal, i.e., \( m_a > 1 \), the PWM inverter operates under over modulation. Over modulation is generally not preferred because of the introduction of lower frequency harmonics in the output waveforms and subsequent disturbance of the load current.
2.7 DESIGN OF CONTROL SCHEME FOR 3 PHASE PWM INVERTER

In order to interconnect the SOFC system to an isolated load it is necessary to control the inverter output voltage in amplitude. For this a PWM controller has been designed for inverter under voltage controller mode using PI controller that adjusts the modulation index to maintain a constant voltage across the load.

2.7.1 $V_{abc}$ to $V_{dq}$ Conversion

For simplicity in calculations, the output voltage of the inverter is transformed into $dq$ coordinates for controlling the inverter voltage and frequency, wherein a $dq$ reference frame is used by controlling the $d$–axis and $q$–axis voltages respectively. In simulation, the “$abc$ to $dq0$” component available in the SIMULINK library performs the transformation of three phase stationary frame to a rotating two-phase dc system. The $abc$ to $dq0$ transformation block takes the voltage value in $abc$ coordinate from voltage measurement block and converts them into $dq$ values. The transformation decreases the number of control variables from 3 to 2 (Component 0 will be zero) if the system is balanced. The constant dc signals are used to achieve zero tracking error control. Due to this merit, the $abc/dq0$ transformation has been widely used in PWM converters/inverter.

The $abc/dq0$ transformation can be expressed as:

$$
\begin{bmatrix}
V_q \\
V_d \\
V_0
\end{bmatrix} = \begin{bmatrix}
\cos(\theta) & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\
\sin(\theta) & \sin(\theta - 2\pi/3) & \sin(\theta + 2\pi/3) \\
1/2 & 1/2 & 1/2
\end{bmatrix} \begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix} (2.56)
$$

Where,

$\theta$ : is the angular position and

$\omega$ : is the angular speed.

For $abc$ variables with a constant frequency of $f$ and with zero initial phase, the value of $\theta$ can be written as

$$
\theta = 2\pi f 
$$

(2.57)
$V_d$ and $V_q$ obtained from $abc/dq\theta$ transformation is compared with the respective reference values and the error signal generated is used as an input to the voltage regulator.

### 2.7.2 PI Controllers (Voltage Regulator)

A PI Controller is used to regulate the voltage output in the system. The integral part of PI controller minimizes error at low frequency, while proportional gain and zero placements are related to the amount of ripples. The PI controller used in this scheme keeps the inverter output voltage constant. The voltage across the load is regulated at 380 volt (1pu) by PI voltage regulator using $abc/dq$ and $dq/abc$ transformation. The parameters of PI controller are determined by using trial and error methods and set parameters $K_p$ and $K_i$ are 0.45 and 550 respectively. The general schematic of a PI controller is shown Figure 2.15.

![Fig.2.15 Schematic diagram of PI controller](image)

**2.7.3 $V_{dq}$ to $V_{abc}$ Conversion:** The controlled voltage $V_d$ and $V_q$ derived from PI controller is transformed back into controlled inverter voltage $V_{abc\text{inverter}}$ by using $dq/abc$ transformation block.

$$
egin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
\cos(\theta) & \sin(\theta) & 1/2 \\
\cos((\theta - 2\pi/3)) & \sin((\theta - 2\pi/3)) & 1/2 \\
\cos((\theta + 2\pi/3)) & \sin((\theta + 2\pi/3)) & 1/2
\end{bmatrix}
\begin{bmatrix}
V_d \\
V_q \\
V_0
\end{bmatrix}
\quad (2.58)
$$
This voltage is fed to the PWM generator wherein it compared with a triangular wave of high frequency (called the carrier wave) to generate required PWM pulses for the inverter which controls the inverter output voltage. The output voltage from the inverter is fed to the low pass RL filter which suppresses the harmonics. The output voltage of inverter can be controlled by modulation index $m_a$ and voltage across the load can be maintained constant even for step change in load.

### 2.8 SIMULATION MODEL OF SOFC BASED DG SYSTEM FOR ISOLATED OPERATION

SOFCs, one of the most developed fuel cells show great promise in stationary power generation applications. In isolated mode FCs based DG system can be used to supply power to remote areas or supply power during grid failure. The system may be supported by batteries or capacitors or other energy storage devices. The control of such a system is done by a master control system that mainly adjusts the voltage and frequency of the isolated load involved. The main characteristics of an isolated load connected to DG system are

- Low short circuit power
- Constant Fluctuation of load demand
- Difficulty in forecasting the load
- Ability to respond fast to changes in load
- High efficiency under part-load conditions
- Supply of hydrogen from a storage facility

The complete model of SOFC based DG system with power electronic for isolated three–phase resistive load is shown in Fig. 2.16. The individual component modeling including a stack of SOFC, a DC/DC Boost Converter, a three-phase PWM inverter, a PI Controller, is given in this chapter. A virtual phase locked loop (PLL) available in SymPower System of the MATLAB has been used to provide the angle reference for the control scheme.
Fig.2.16 Simulink Block diagram for SOFC based DG with PI controller for isolated operation

2.9 CONCLUSION

A dynamic model of SOFC based DG system has been developed in MATLAB/SIMULINK environment to supply power to an isolated load. The model incorporates the electrochemical reaction dynamics and major voltage losses in SOFCs. An overview of the operating principle of SOFC and its V–I characteristic has been discussed taking into account the various voltage losses. A constant utilization mode has been adopted for the operation of fuel cell in which the control of constant utilization is implemented using current feedback to adjust the hydrogen input flow rate. Various power electronic interface topologies that convert the power generated by the FCs into a usable form have been discussed. A DC-DC PWM boost converter model is developed and interfaced to fuel cell to boost SOFC voltage to a regulated dc voltage required for DC/AC PWM inverter to serve for an isolated load. A PI controller has been designed for dc/dc converter that minimizes the steady state
error to zero. A control strategy under voltage control mode using PI controller has been developed for three phase PWM inverter that interfaces the SOFCs to a three phase isolated load. Thus the developed model of SOFC based DG system can be used as a tool suitable for studying and for performing accurate analysis of most electrical phenomena that occur when it is interfaced to the isolated load.