EXPERIMENTAL AND SIMULATION STUDIES OF A GRID CONNECTED SOLID OXIDE FUEL CELL

by

Seyfullah FEDAKAR

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Seyfullah FEDAKAR

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I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

____

Prof. Dr. Murat UZAM
Head of Electrical and
Computer Engineering Division

This is to certify that I have read this thesis and that in my opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

____

Prof. Dr. Tankut YALÇINÖZ
Supervisor

Examining Committee

Prof. Dr. Tankut YALÇINÖZ ________________________

Assoc. Prof. Dr. Saffet AYASUN ________________________

Assist. Prof. Dr. Gökhan ÖZGÜR ________________________

It is approved that this thesis has been written in compliance with the formatting rules laid down by the Graduate Institute of Sciences and Engineering.

____

Associate Prof. Dr. Halidun KELEŞTEMUR
Director

August 2012

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M.S. Thesis – Electrical and Computer Engineering
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Supervisor: Prof. Dr. Tankut YALÇINÖZ

ABSTRACT

In recent years, an interest toward fuel cell studies has grown because of increasing energy demand. Fuel cells are clean and efficient sources of electricity, and have wide range of residential and stationary applications.

In this study, the electrical characteristic of solid oxide fuel cell (SOFC) is analyzed by experimental and simulation studies. The dynamic model of solid oxide fuel cell is developed using PSCAD software. The simulation studies of SOFC are performed by using parameters taken from literature. Experiments on the electrical characteristics of SOFC are performed. The dynamic performance of SOFC is tested under variable load conditions.

The DC power consumption of the load is measured using fuel cell test station. In the light of this fuel cell experiments, the parameters of the fuel cell are obtained. The experimental results are compared with the results of the SOFC model implemented in PSCAD software.

Moreover, the power conditioning unit, which includes DC – DC converter and DC – AC inverter, is modeled using PSCAD. The DC and AC performances of SOFC are tested under various loads using PSCAD. Then, the grid connected solid oxide fuel cell system is modeled using PSCAD. The fuel cell system is simulated under different AC load conditions. Finally, a three-bus system, which includes infinite bus, load bus and fuel cell bus, is implemented in PSCAD.

Keywords: Solid Oxide Fuel Cell, PSCAD, Grid, Converter, Inverter

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Seyfullah FEDAKAR

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ÖZ

Son yıllarda, artan enerji talebinden dolayı yakıt pillerine olan ilgi artmıştır. Bunun yanısıra yakıt pilleri temiz ve verimli bir elektrik kaynağıdır ve yakıt pillerinin yaygın bir şekilde evsel ve sabit uygulamarı vardır.

Bu çalışmada katı oksit yakıt pillerinin (KOYP) elektriksel karakteristiği deneysel ve simulasyon çalışmaları yapılarak incelenmiştir. PSCAD yazılımı kullanılarak katı oksit yakıt pilinin dinamik modeli geliştirilmiştir. Yapılan simülasyon çalışmalarında literatürdeki parametreler kullanılmıştır. Ayrıca KOYP'un elektriksel karakteristik deneyleri gerçekleştirilmiştir. Bu deneylerde KOYP'un dinamik performansı çeşitli yükler altında test edilmiştir. Deney sonuçlari PSCAD yazılımı ile oluşturulan modelden elde edilen sonuçlar ile karşılaştırılmıştır.

Buna ek olarak DC–DC konverter ve DC–AC inverteri içeren güç işleme birimi PSCAD yazılımı ile modellenmiştir. Yakıt pili sisteminin DC ve AC performansı PSCAD kullanılarak simüle edilmiştir. Daha sonra, şebekeye bağlı katı oksit yakıt pili sistemi PSCAD ile modellenmiştir. Yakıt pili sistemi farklı AC yüklerde simüle edilmiş ve bu yükler altındaki davranışı incelenmiştir. Son olarak, yük barası, yakıt pili barası ve sonsuz barayı içinde bulunduran üç baralı sistem PSCAD'de uygulandı.

Anahtar Kelimeler: Katı oksit yakıt pili, PSCAD, Şebeke, Konverter, İnverter

DEDICATION

Dedicated to my parents for their endless support and patience during the forming phase of this thesis.

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CHAPTER 1

INTRODUCTION

1.1 Distributed Generation

Distributed Generation (DG) includes small – scale, environmentally friendly and reliable technologies such as photovoltaic (PV), fuel cells, microturbines, or small wind turbines that are installed on and designed primarily to serve a single end user's site [1].

Distributed generation system (DGS) technologies can be used for various applications such as a standalone, a grid interconnection, cogeneration, standby, and peak shavings. Also, these systems have many benefits such as being eco-friendly, modular electrical generation, increased reliability, high power quality, uninterruptible power supply, cost savings, on-site generation [2]. DG by itself is not a new concept. A small number of consumers have been installing their own generation on-site for decades. Recently, new generation technologies including fuel cells and microturbies, have become widespread in developed countries. Thanks to new generation technologies, some DG can provide significant benefits, including reduced transmission and distribution costs, reduced emissions, and enhanced reliability. DG can be faster to build and easier to move, need less existing infrastructure, and require less up-front capital investment than large central station generators; some DG technologies could have an enormous role to play internationally in less developed countries [3].

The most popular distributed generators include microturbines, fuel cells, biomass, small wind, PV and diesel generators. Climate conditions have remarkable effects on power generation. Power generation of the sources such as wind turbines and PVs depends on wind and solar radiations. Diesel generators produce emission which is harmful to the environment.

Among different types of DGs, fuel cells are so appealing because of their high efficiency, high power quality, being eco-friendly and continuous power generation without the effects of weather conditions [4].

There are various technologies available for DG among these technologies; the use of fuel cells for distributed generation is attracting more and more attention due to its unique environmentally friendly features in recent years. In 1839, William Grove discovered that by combining oxygen and hydrogen in a particular configuration, electricity could be generated. Although this discovery was made more than 160 years ago, the basic operating principle of fuel cell discovered still applies. It is known that the 19th century was the century of the steam engine and the 20th century was the century of the internal combustion engine. On the other hand, the 21st century will be likely to be the century of the fuel cell [5].

In recent years, an interest toward fuel cell studies has grown, as fuel cells are a clean and efficient source of electricity, and have a wide range of transportation and stationary applications. Fuel cells convert chemical energy directly into electrical energy by an electro-chemical reaction between hydrogen and oxygen. The by-products are water and heat. Fuel cells are similar to batteries containing electrodes and electrolytic materials to generate electricity [6]. A positive electrode (anode), a negative electrode (cathode), and an electrolyte are essential to take place for the reaction. In principle, a fuel cell can operate with a variety of fuels and oxidants. Hydrogen has long been recognized as the most effective fuel for practical use because of its high electrochemical reactivity. Oxygen is the preferred oxidant due to its abundance in the atmosphere [7].

1.2 Objective of The Thesis

In this thesis the electrical characteristics of the solid oxide fuel cell (SOFC) is analyzed by experimental and simulation studies. In these SOFC experiments the effect of fuel quantity and temprature are examined. The dynamic model of Solid Oxide Fuel Cell is generated using the parameters of the experimental results. The charateristic DC and three phase AC load of this SOFC model is simulated using the PSCAD software. Then, the electrical energy from solid oxide fuel cell is converted to three phase AC voltage with a converter and an inverter implemented in PSCAD. Next, the behaviour of grid connected solid oxide fuel cell system is studied. Finally, simulation and experimental results are compared.

CHAPTER 2

FUEL CELLS

2.1 Overview

Fuel cell technology has been developing in recent years as an environmental friendly and low pollution power source. Among the various distributed generation technologies available, fuel cells are being considered as a potential source of electricity because they can be placed anywhere on a distribution system. Fuel cells have significant advantages which make them superior compared to the other technologies. Benefits include improving efficiency, high power quality, reliability, operation characteristic and zero emision. The efficiency of a fuel cell system is one of the most important aspects of that fuel cell.

Because of their attractive properties, fuel cells have already been developed and demonstrated in many applications. Fuel cells serve as a power source in remote locations where utility transmission lines cannot be reached. Fuel cells have no location limitations so they find application in transportation purposes as in cars, trucks and buses. Lower temprature fuel cells like the PEMFC (proton exchange membrane fuel cell) and PAFC (phosphoric acid fuel cell) are well suited for transformation applications. The higher temprature fuel cells like the SOFC (solid oxide fuel cell) and MCFC (molten carbonate fuel cell) produce high grade waste which can be used to residential application [8]. Fuel cells can also be used in utility vehicles, portable power, airplane, locomotives, boats and underwater vehicles. Many hospitals, credit card centres, police stations and banks are now using fuel cells to provide backup power to their facilities [9].

Although the fuel cell stack is a good source of electricity, it has major disadvantages which present difficulties in connecting to the grid or for use in standalone applications. Fuel cells have a slow elctrochemical and thermo dynamic response. Sudden load changes may result in bad water management and reactant starvation phenomena due to slow response of the fuel cell. This flow response may be regulated for fuel cell stack to modify chemical reaction parameters. Furthermore, fuel cells have to be connected to power conditioning devices, which enhance their performance in order to be connected to the power grid [10].

In spite of the benefits, fuel cells are unable to penetrate the market owing to their high capital cost. The cost of fuel cell depends on the cost of materials that makes the components. Considerable efforts are being made in specific areas to reduce the capital cost. These specific areas include material reduction, exploration of low–cost materials, minimizing temprature constraints, increasing power density, streamling the manufacturing processes [11].

2.2 Fundamentals of Fuel Cell System

A fuel cell is a static energy conversion device that converts the chemical energy of the input fuel into electrical energy [12]. Fuel cell functioning is similar to that of a battery except that the fuel can be continuously fed into the cell. The waste products of fuel cells are water and heat. This conversion of the fuel into energy occurs without combustion. Generally efficiency of the fuel cell ranges can be improved to 80-90% in cogeneration applications. Fuel cells are capable of operation at efficiencies greater than traditional energy methods. Moreover, the scalability of fuel cell has allowed for applications almost every field.

2.2.1 Operation Principle

The fuel cell consist of two electrodes, anode and cathode seperated by an electrolyte. Fuel is fed into the anode where electrochemical oxidation takes place and the oxidant is fed into cathode where electrochemical reduction take place to produce electric current and water is the primary product of the cell reaction. Figure 2.1 shows the follows of reactants in a simplified fuel cell [13].

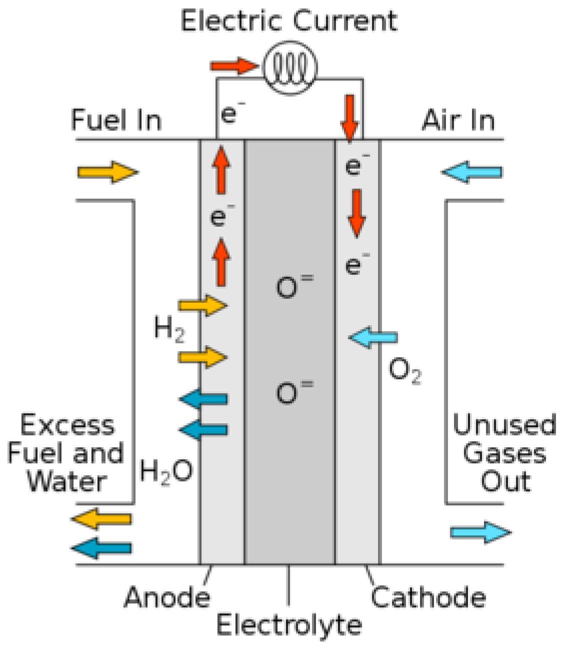


Figure 2.1 : Schematics of Fuel Cell [13]

The hydrogen which enters the anode side is divided into hydrogen ions and electrons thanks to catalyst. In case of lower temperature cells like the PEMFC and the PAFC, the hydrogen ions pass through the electrolyte thereby the electrons flow through the external circuit. The oxygen which enters through the cathode, combines with these hydrogen ions and electrons to form water as shown in the figure 2.1. In the SOFC, the hydrogen oxidation within a fuel cell occurs partly at the anode and cathode. The hydrogen adsorbed at the anode is ionised and the electrons are used within an external electrical work. Oxygen is adsorbed at the cathode and ionised by the electrons of the load. The electrolyte leads the oxide ion from the cathode to the anode. The hydrogen ions and oxide ions form a molecule of water [14]. In case of MCFC carbon dioxide combines with the oxygen and electrons to form carbonate ions, which are transmitted through the electrolyte [15].

The typical anode and cathode reactions for a hydrogen fuel cell are given by Equations (2.1) and (2.2), respectively.

$$H_2 \rightarrow 2H^+ + 2e^- \quad (2.1)$$

$$\frac{1}{2} O_2 + 2e^- + 2H^+ \rightarrow H_2O \quad (2.2)$$

2.2.2 Fuel Cell Voltage and Nernst Equation

Fuel cell voltage is determined by chemical reactions because there is no combustion in a fuel cell. Hydrogen heating value is used as a measure of energy input in a fuel cell. All the energy input can not be converted into electricity. The portion of the reaction enthalpy that can be converted to electricity in a fuel cell corresponds to Gibbs free energy. Gibbs free energy is the energy available to do external work which involves moving electrons around an external circuit. Enthalphy of formation is the sum of Gibbs free energy and the energy connected with entropy. Gibbs free energy is given by the following equation:

$$\Delta G = \Delta H - T\Delta S \quad (2.3)$$

ΔG= Difference between entropies of products and reactants

T= Temperature

ΔS= difference between the heats of formation of products and reactant

In operating fuel cell, in general, a higher temperature results in a higher cell potential. Because the voltage losses in fuel cells decrease with temperature [15].

2.2.3 Theoretical Fuel Cell Potential

In a lossless system, electrical work done is equal to the change in Gibbs Free Energy. Electrical work done to move a charge of 2F (Faraday's Constant) for a voltage of E is given by the following equation:

$$W_{el} = -\Delta G \quad (2.4)$$

$$W_{el} = -nFE \quad (2.5)$$

Therefore the potential E_0 can be written as shown in equation (6). This potential is the theoretical open circuit voltage of the fuel cell [16]:

$$E_0 = \frac{-\Delta G}{nF} = \frac{237.340\ J\ mol^{-1}}{2 \times 96{,}485\ A\ s\ mol^{-1}} = 1.23\ Volt \quad (2.6)$$

W_{el}: Electrical work done

ΔG : Gibbs free energy

n : Number of electrons

F : Faraday's Constant

E_0 : Potential

For any chemical reaction

jA + kB → mC + nD where j moles of A and k moles of B react with each other to produce m moles C and n moles of D. These reactants and products have an activity associated with them. This activity is the ratio of the partial pressure of the gas and the standart pressure [16].

$$\Delta = \; G_0 + RTln\frac{P}{P_0} \tag{2.7}$$

$$\Delta = \; G_0 + RTln\left[\frac{\frac{P_c}{P_0}^m \frac{P_d}{P_0}^n}{\frac{P_a}{P_0}^j \frac{P_b}{P_0}^k}\right] \tag{2.8}$$

where P is the partial pressure of the reactant or product species and P_0 is the referance pressure.

For the hydrogen / oxygen fuel cell reaction, the Nernst equation becomes [16]:

$$E = \; E_0 + \frac{RT}{nF}\; ln\frac{P_{H2}P_{O2}^{0.5}}{P_{H2O}} \tag{2.9}$$

2.2.4 Types Of Fuel Cell

The different types of fuel cells are generally classified according to their electrolyte. These fuel cells have different operating conditions such as temperature, material and type of chemical reaction. Because of the differences in some of the operating charactristics, the different types of fuel cells are suited for different applications.

Proton Exchange Membrane (PEM) Fuel Cell

PEM fuel cells use a thin proton conductive polymer membrane as the electrolyte. This type of fuel cell has attracted a lot of attention in the last few years [17]. The temprature of operating is typically between 60 and 80 ℃ . The advantages of the PEM fuel cell are a higher power density and lower operating temprature. Because of lower operating temprature the PEM fuel cell has a quick response which is very important for a lot of applications. Their long life is the attractive characteristic of PEM fuel cells [18].

Phosphoric Acid Fuel Cell (PAFC)

Phosphoric acid fuel cell (PAFC) uses a liquid fhosphoric acid as an electrolyte. Operating temprature is typically between 150 and 220 ℃ . Operating temprature cannot be too high because the phosphoric acid will begin to decompose at about 250 ℃ . PAFC is very tolerant to impurities in the reformed hydrocarbon fuels. This tolerant reduces the cost of reformer.

PAFC technology is the most experienced fuel cell technology in terms of system development and commercialization. The disadvantages of phosphoric acid fuel cells are its relatively low current and power densities and its size. The designs of the PAFC are rather large and heavy. PAFC are already semicommercially available in container packages for stationary electricity generation and vehicle applications [19].

Alkaline Fuel Cell (AFC)

Alkaline fuel cell (AFC) uses concentrated potassium hydroxide as the electrolyte for high temprature operation and less concentrated for lower temprature operation [20]. Generally the limiting reaction in a fuel cell is the cathode reaction because it takes more time to react than anode reaction. But AFC cathode reactions occur much faster than other types of fuel cells which improve the overall performance of the AFC. Alkaline fuel cell is intolerant to CO_2 present in either fuel or oxidant. Because of this AFC cannot use normal outside air to provide the oxygen.

The use of corrosive electroliyte is also a disadvantage in AFC. This fuel cell has been used in the space program and under development by the military which has helped to increase their efficiencies and decrease cost.

Molten Carbonate Fuel Cell (MCFC)

Molten carbonate fuel cells (MCFC) have the electrolyte consisted of a mixture of alkali carbonates. Operation tempratures of MCFC are between 600 and 700 ℃ where the carbonates form a excellent conductive molten salt with carbonate ions providing ionic conduction [21].

Solid Oxide Fuel Cell (SOFC)

Solid oxide fuel cell uses dense yttria – stabilized zirconia (YSZ) which is a solid ceramic material as its electrolyte. These cells operate at 800 to 1000 ℃ where ionic conduction by oxygen ions takes place. SOFCs are being developed for portable power and auxilary power in automobiles [22].

2.3 Fuel Cell Applications

Due to the growing concerns on the depletion of petroleum – based energy resources and climate change, fuel cell technologies have received much attention in recent years owing to their high efficiencies and low emissions. As a result of these characteristics the fuel cell technology could be used in applications with a broad range of power needs.

The major application of fuel cell focused on transportation primarily because of their potential impact on the environment such as the control of emission of the green hause gases [23]. Almost every car manufacturer has already developed and demonstrated at least one prototype vehicle and many have already gone through several generations of fuel cell vehicles. Daimler Benz released a methanol fuelled car with 640 km range which very first such vehicle fuelled with hydrogen and in 1997 [24]. It is shown in figure 2.2.

Figure 2.2 : The First Bus Vehicle Fuelled With Hydrogen [25]

Fast growing vehicle market causes for air pollution and climate change. In addition, these issues are associated with the internal-combustion engines which primarily depend on hydrocarbon fuels. Fuel cells have the potential to replace conventional engines due to their potentials of achieving higher efficiency and lower emissions [26]. Fuel cells are maybe employed in several other applications within transportation sector. These applications include electric powered bicycles, material handling vehicles such as forklifts [27]. Hwang et. al. developed an electric bicycle powered by 40-cell, which exhibits a peak power 378 W, a maximum speed of 16.8 km/h and an efficiency of up to %35 [28].

In addition to transportation applications, fuel cells are used several other applications for example portable electronic equipments. Some fuel cell portable applications are shown in figure 2.3.

Miniature fuel cells could replace batteries that power consumer electronic product such as cellular telephones, portable computers and video cameras.

Figure 2.3 : Fuel Cell Portable Electronic Applications [29]

Small fuel cells could be used to power telecommunications satellite, replacing or augmenting solar panels. The typical power range for portable electronic devices is 5-50W and several development focus on a level of <5W for micro power application [26]. Fuel cells also receive a great deal of attention for military application to power portable electrical devices such as radios [23]. As a result, fuel cell can offer a viable alternative to batteries and several low power fuel cells are currently being manufactured for this application [30]. Fuel cells are also used for stationary and residential applications and it is shown in figure 2.4.

Figure 2.4 : Fuel Cell Residential Applications [31]

Fuel cells power plants are also being developed by several manufactures to provide electricity and heat to single family homes. They don’t provide enough power to supply the total electrical demands of a residence but they do shift a portion of the demand from the electrical grid to natural gas.

Current stationary electric power is primarily generated by large central power. Large scale central power station has many benefits but exhibits several inherent disadvantages such as the waste heat that usually cannot be efficiently utilized and power loss during transmission. Distributed power decentralized generation is a way to resolve these disadvantages [23]. Consequently global production of fuel cells has continuously grown because of the fuel cell advantages.

CHAPTER 3

SOLID OXIDE FUEL CELLS

3.1 Solid Oxide Fuel Cell

The SOFC is a high-temperature operating fuel cell which has high potential in stationary applications. The efficiency of SOFC is in the range of 45-50% and when integrated with a gas turbine, it reaches a high efficiency of 70-75%. It is a solid-state device that uses an oxide ion-conducting non-porous ceramic material as an electrolyte. Two different geometries which are being developed are tubular and planar.

Tubular designs are more costly and advanced compared to the planar designs and are closer to commercialization. SOFCs have fuel-flexibility, for example the input to the anode can be hydrogen, carbon monoxide or methane. Hydrogen or carbon monoxide may enter the anode. At the cathode, electrochemical reduction takes place to obtain oxide ions. These ions pass through the electrolyte layer to the anode where hydrogen is oxidized to obtain water. In case of carbon monoxide, it is oxidized to carbon dioxide [32].

3.2 Literature Survey

Most of the studies in the literature have been centered on the electrical management of single cells or SOFC stacks as well as their performance. There have been lots of modeling studies in the literature to examine the critical parameters such as thermal behavior, partial pressure of oxidant, fluid flow and electrical response of solid oxide fuel cells. SOFC types and components also have become available in the literature. Some of models have focused on the behavior of only SOFC plant but other models have considered electrical behaviors of grid connected solid oxide fuel cells.

Padulles et al. [33] presented a simulation model of a fuel cell based power plant. They purposed that a study of how a fuel cell power plant should operate, prior to the production of the final model general characteristic of their model in the following

- The dynamics of the model could be explained in the Laplace transform
- The model is focused on the system operation in normal conditions
- The main model outputs must be real power and reactive power
- The purpose of the model is the description of the system performance rather than to be a helpful tool to the plant designer.

Their plant structure consists of two blocks. The first one related with network relationship. The second one is sending the appropciate instructions to execude controller. Their structure is shown in figure 3.1.

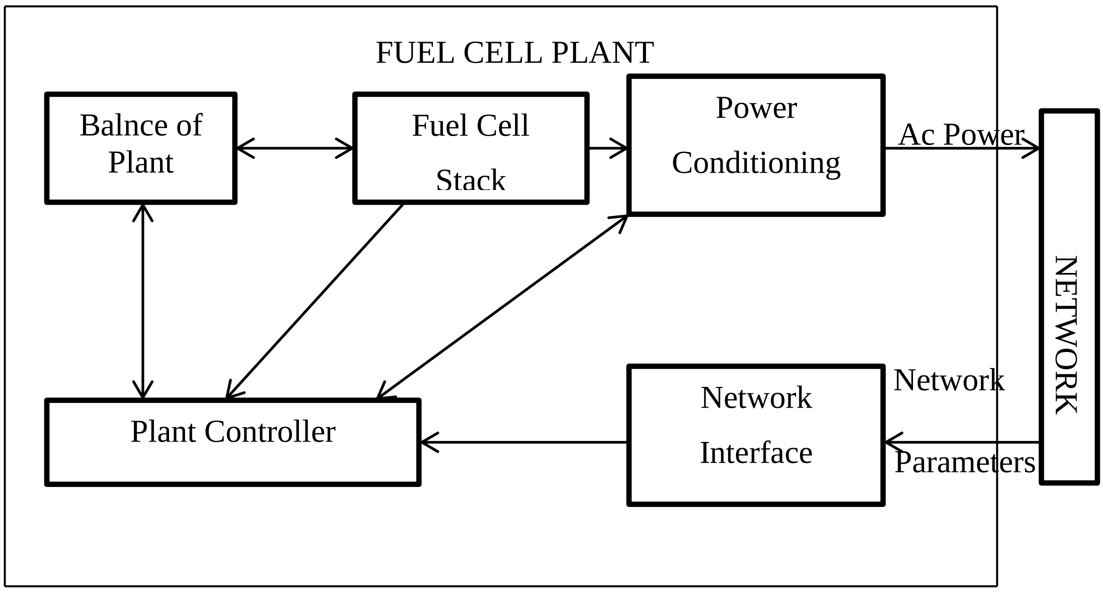


Figure 3.1 : Structure of a fuel cell power plant

In this study fuel cell stack model are based on the following assumptions

- The stack is fed with hydrogen and air. If natural gas instead of hydrogen is used as fuel the dynamics of the fuel processor must be included in the model.
- The channels that transport gases along the electrodes have a fixed volume
- The only source of losses is ohmic

- The Nernst Equation can be applied.

Characterization of the channels and calculation of the partial pressure are calculated using some equations. Stack output voltage is represented by applying Nernst Equations and Ohm’s Law. The stack model can be used to generate voltage-current and power-current curves at different fuel flow rates using given the parameters.

Response of the plant to load changes is very important for this model. If the stack is exposed to a current change, this change will be immediate although this means permanent damage to the stack. The control system can help to respond to the load change.

In conclusion, a SOFC stack model for power system simulation tolls has been proposed, as well as a model for the power condition unit of the plant. The use of voltage-current and power-current plots has been revealed as a useful tool to define the safe operation areas associated with the stack operation.

Bove and Ubertini [34] offer 3D, time dependent SOFC model considering all processes occurring in each cell component. The all mathematical model is independent from the cell geometry (planar, tubular) and the modeling approaches so can be conducted for any SOFC. The most commonly used numerical techniques are also well explained.

Behavior of SOFC based generation system is analyzed by D. Vera and F. Jurado [35]. A system generation model consists of SOFC, fuel processor and power conditioning unit. The first one is SOFC that describes electrochemical model of SOFC. The fuel cell output voltage is obtained using Gibbs free energy of the cell reaction. The losses are summation of three losses: activation, concentration and ohmic. The second one is fuel processor that is based on a methane reformer with steam. Reformer output depends on of the utilization factor and fuel cell current.

A PI control structure is used to control the flow rate in the reformer. The last power conditioning unit is consisted of DC-AC inverter and PI control blocks. The inverter inputs are fuel cell voltage, modulation index and phase angle on the AC voltage. The load terminal voltage is 400 V AC for residential and commercial applications. Owing to PI controller, load terminal voltage is kept constant 400 V AC. According to simulation results, voltage and power functions are not obtained instantaneously. There exists a delay of approximately 20 seconds. This is due to time responses of the SOFC system. In conclusion this study, a dynamic model of the fuel cell stack is presented and suitable control architecture is announced.

A.A. Salam et al. [38] analysed a dynamic model of solid oxide fuel cell. They believed that fuel cell systems can be easily placed at any site in power systems. A dynamic model of fuel cell power plant is connected to a distribution grid via DC-AC converter and it is shown figure 3.2.

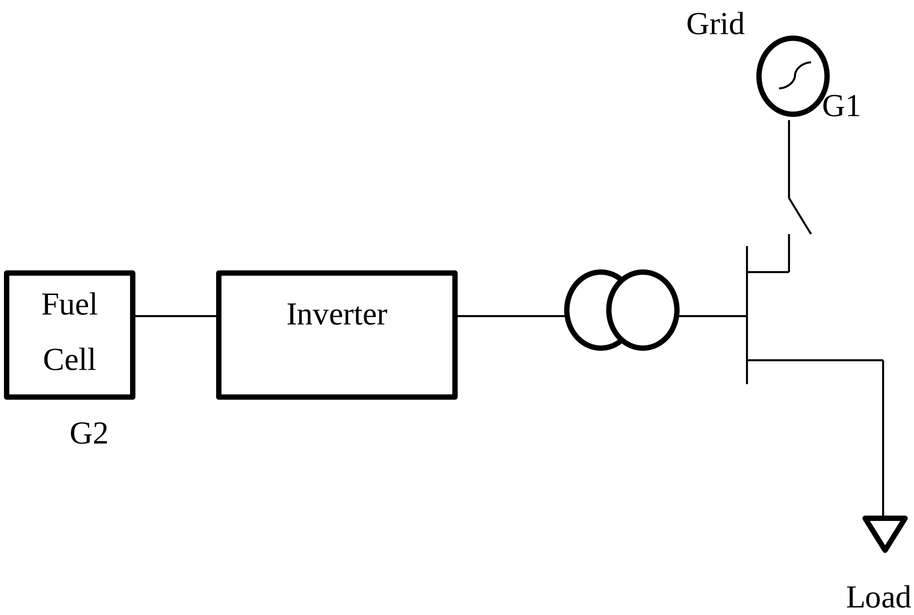


Figure 3.2 : Single Line Diagram of Grid Connected Fuel Cell

The proposed model includes the electrochemical and thermal aspects of chemical reactions inside the fuel cell stack. The fuel cell power plant is interfaced with the utility grid via boost DC-DC converter and three phase pulse width modulation (PWM) inverter. The VSI (voltage source inverter) plays a vital role in interfacing the fuel cell system.

A simulation model is developed for the SOFC. The output voltage of the stack is given by the Nernst equation. The ohmic loss of the stack is because of the resistance of the electrodes. PSCAD modeling of the proposed system consists of three part: fuel cell, VSI controller and grid connection. Measured three phase voltages are fed to the PLL (Phase Locked Loop) in order to detect the phase angles and position of the voltage in VSI. The PLL also provides the voltage synchronization signal in which it is multiplied by SPWM switching frequency. Output signals are passed through the low pass filter to reduce the voltage transients. In addition, output signal is compared with a reference voltage. According to simulation results, when the grid is disconnected from the system, the SOFC immediately increases its power and the inverters controls respond accordingly with the load voltage returning its pre-disturbance value.

Yalcinoz et al. [36] worked on air breathing PEM fuel cell. The air breathing fuel cells have many features when compared to other types of fuel cells. A dynamic model of an air breathing PEM fuel cell is presented in this work. They used a new dynamic model based on one dimensional model described by O'Hayre et al. [37]. The model is examined for portable devices such as a laptop computer. The power requirement varied significantly under different operation conditions for this study.

Air breathing PEM fuel cell consists of four main blocks; temperature, ohmic overvoltage, activation overvoltage and the Nerns Voltage blocks. The fuel cell current is limited by a current limiter. The simulation results show that, the membrane conductivity is not linear with the current density. Because of higher current density ohmic voltage loss is higher than that is in the O'Hayre model. A dynamic performance of the fuel cell was tested under various load conditions. Feedback control system kept the load voltage at 20V under various operational canditions. The air breathing PEM fuel cell produced output powers and voltages based on the feedback current. In conclusion, the proposed fuel cell system model can be considered as a viable alternative energy sources for portable applications.

M.M. Hussian et al. [39] is studied about mathematical modeling of planar SOFC. They focused on fuel choice and thickness of layers. They not only use pure H_2 but also use composition consisting of multi-component species for SOFCs. Solid oxide fuel cells have some problems due to high operation temperature. If the operation temperature is reduced, many of the problems can be resolved. Mathematical modeling is a necessity for SOFC development period. A numerical method simplifies research and improvement by minimizing the repetitive experimentation.

Numerical simulation of SOFCs provides how cell performance is affected by different design parameters such as temperature, pressure and thickness. Numerical models of SOFCs exist in the literature. The common model is used reaction zone layers as the mathematical model of SOFC satisfying the requirements such as fuel flexibility, finite reaction zone layers. SOFC numerical model formulation is made up using electrode, electrolyte and reaction zone layer boundary conditions equations. The developed SOFC model can be used to analyze the effect of manufacture parameters on the cell performance. In conclusion, a mathematical model of SOFC has been developed using conventional equations such as Maxwell and Laplace equations. According to simulation results, mathematical model most significant contribution to the cell potential loss is from the anode side of the cell in an anode-supported SOFC.

Reference [40] is interested in input current ripple reduction of converter for fuel cells. In general fuel cells operate with current ripple. The current ripple damages to the working life fuel capacity because the chemical reaction time when generates electricity is slower than commercial frequency.

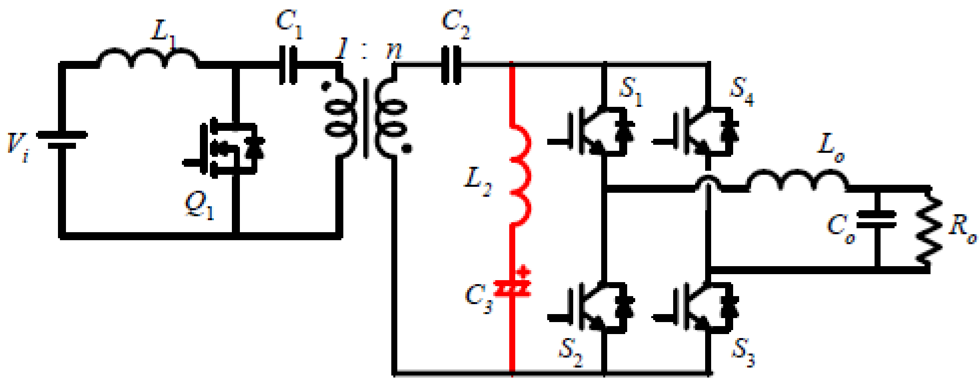


Figure 3.3 : Proposed Circuit Topology

Fuel cells need DC-AC converter for inverting DC signal. In classical DC-AC converter for fuel cells, a large smoothing capacitor is used in paralel between the boost DC-DC converter and PWM inverter. This capacitor scales up the size of this DC-AC converter. To overcome this problem Fukishima et al. has proposed a novel DC-AC converter topology called as Pulse Link DC-AC converter. In this topology, in order to reduce the current ripple, a series connected LC circuit is used in paralel between boost converter and PWM inverter as shown in figure 3.3. Furthermore, when duty ratio is controlled by sensing input current, input current ripple is reduced to less than 1Ampere.

Palle et al. [41] examined a novel integration of a doubly fed induction generator (DFIG) and a fuel cell. In this study, it is possible to inject power from a DC power source like a fuel cell into the AC grid without using inverter. Dynamic models of DFIG and PEM fuel cell are derived which are used in the integrated system. Simulation results showing the interaction of DFIG and fuel cell with each other and with the AC grid were studied. Experimental setup was built to confirm the simulation results. Experimental research showed active and reactive power control in the induction generator. The results of experimental set up were very well when the fuel cell was connected across the DC link.

Yakaba et al. [42] developed a single unit with a double channel model for a counter flow pattern of the anode of the Ni/YSZ anode supported SOFC. Ji et al. [43] developed a 3D mathematical model, studied the dependence of the temperature, the mass transport, the local current and power densities on the gas channel size for a planar SOFC and considered the cathode and the electrolyte. Iwata et al. [44] predicted temperature and current density distributions in a planar SOFC with co-flow and counter flow (2D), and with cross flow (3D) configurations. When the cell outer surfaces are modeled by considering the radiative heat transfer, corresponding to an SOFC in a furnace, almost flat temperature profiles were observed.

Burt et al. [45] discovered the cell to cell variation of the voltage in a planar SOFC stack with 5 cells numerically. They found that the radiative heat transfer mode gives uniform temperature distribution which is essential for a higher cell performance. Damm and Federov [46] numerically investigated the temperature variations in the SOFC during start up and shut down. On the other hand, the temperature gradient inside the planar SOFC under different load conditions which is one of the important operating parameters has been studied by Inui et al. [47]. The authors have proposed a new cell temperature control method that is based on the optimization of the air utilization and the inlet gas temperature for each average current density. This new method enables SOFCs to operate under variable load conditions.

CHAPTER 4

POWER CONDITIONING UNIT

4.1 Power Conditioning Unit

Power electronic interfacing circuits, also called power conditioning units, are essential for a fuel cell based system to condition its output dc voltage and convert the dc into ac [48]. Fuel cells can be connected to grid using power conditioning unit and its block diagram is shown figure 4.1.

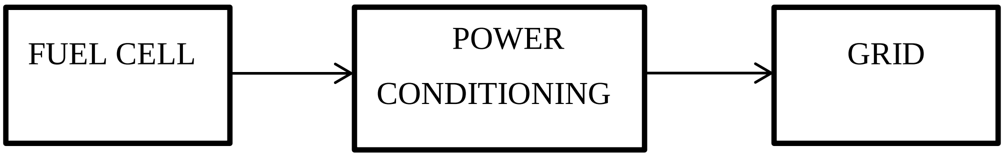


Figure 4.1 : The Use of Power Conditioning Unit For Fuel Cell

The Power Conditioning Unit should:

- Control the fuel cell voltage
- Deliver a high power factor
- Convert the fuel cell output to the appropriate type and magnitute
- Operate efficiently under various load conditions
- Add little to the cost of the overall seystem [49]

Power conditioning unit for solid oxide fuel cells generally is used DC – DC converter and DC – AC inverter to boost the fuel cell voltage.

4.2 DC–DC Converter

There are many types of dc to dc converters in literature. In general, converters can be classified into isolated and non–isolated converters. Several new dc to dc converter circuits have been presented in literature for fuel cell systems [50].

The DC input from the fuel cell is unregulated. The DC-DC converter converts the unregulated DC input into regulated and controlled DC output at a desired voltage magnitude [48].

A fuel cell stack cannot be directly connected to the load because fuel cell has slow response time. Thus, the voltage generated by the stack is low. This voltage must be boosted to a higher level in order to invert this dc voltage into ac voltage for grid connection [50], so a boost converter is required to be connected between the solid oxide fuel cell and the inverter. Figure 4.2 shows the circuit diagram of non – isolated boost converter.

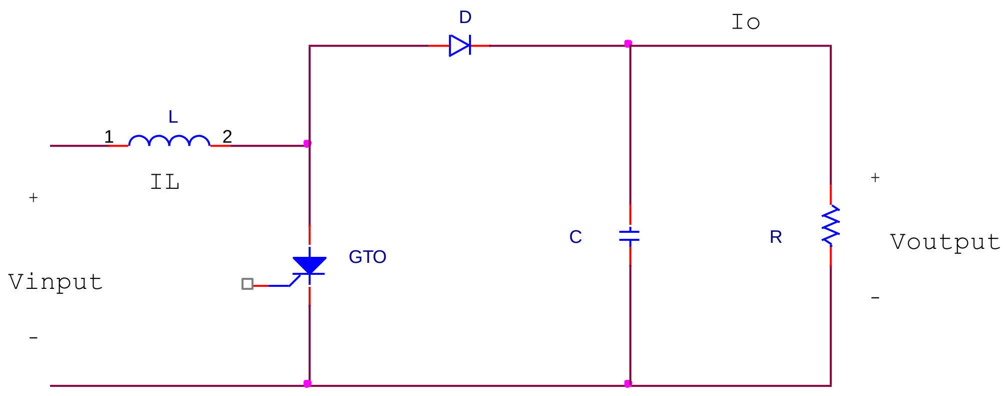


Figure 4.2 : Boost DC–DC Converter [48]

Boost converter is preferred due to higher range of input voltage control and smoother output voltage. This converter can have higher output voltage based on the duty cycle. Boost converter operating principle is shown figure 4.3.

When the switch is on state, the current in the boost inductor (i_L) increases linearly. The diode is off at the same time and circuit model is shown figure 4.3 (a). When the switch is turned off, the energy stored in the inductor is released through the diode to the input RC circuit and circuit model is shown figure 4.3 (b) [48].

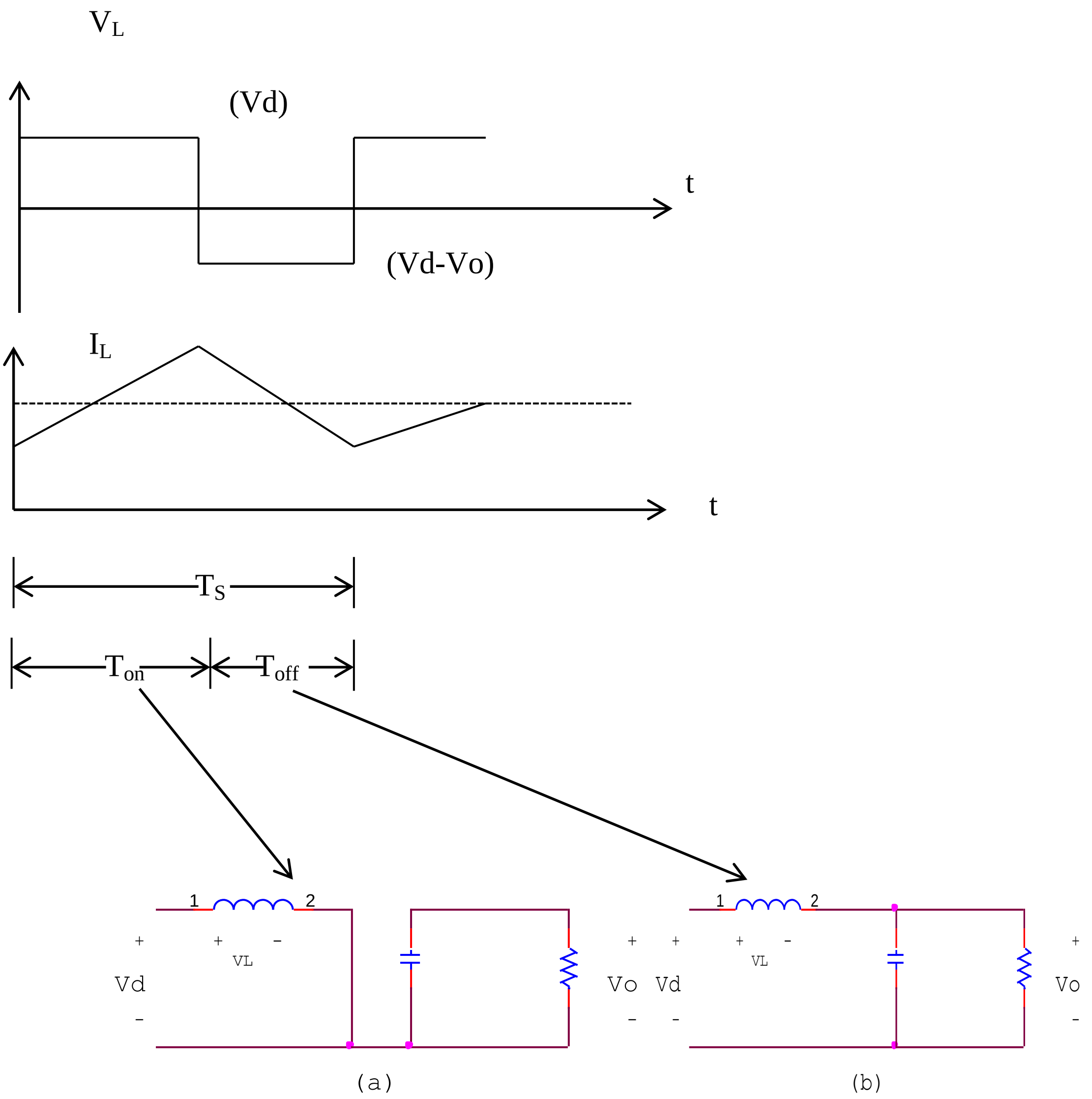


Figure 4.3 : Converter conduction mode; (a) Switch on (b) Switch off [48]

$$\frac{V_0}{V_d} = \frac{1}{1\text{-}D} = \frac{T_s}{T_{off}}$$

V_0:Converter Output Signal

V_d:Converter Input Signal

D:Duty Cycle

T_s:Switch Operation Time

T_{off}:Switch Off Time

If the duty cycle (D) is less than 0.5 converter operates like a buck converter otherwise it operates like a boost converter. Design of the boost converter involves determination of the inductance L and the capacitance C. R is the load resistance. L and C can be obtained by Equation (4.1) and (4.2)

$$L > \frac{(1\text{-}D)^2 DR}{2f} \tag{4.1}$$

$$C > \frac{D}{Rf\,(\frac{\Delta V}{V_0})} \tag{4.2}$$

where D is the duty cycle, f is the switching frequency and $\frac{\Delta V}{V_0}$ is the voltage ripple.

Figure 4.4 shows the block diagram model of the boost converter conncted to the fuel cell system with the feedback control system using pulse width modulation (PWM).

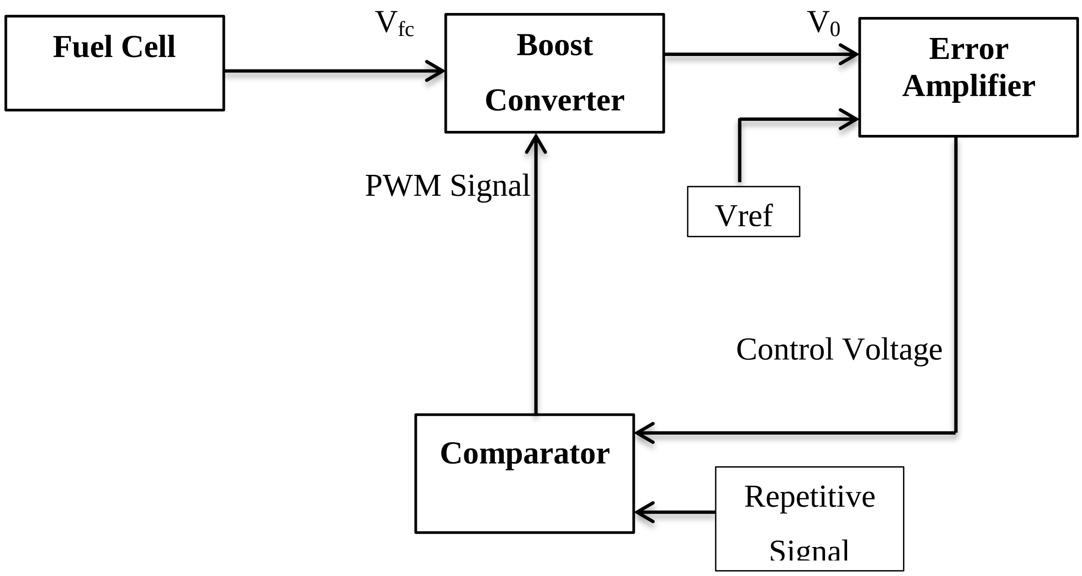


Figure 4.4 : Boost Converter Feedback Control System [51]

Fuel cell voltage (V_{fc}) is the input of the converter. The output voltage of the converter (Vo) is subtracted from an external reference output voltage (V_{ref}) in an error amplifier. The error ampilifier produces a control voltage and it is compared with the repetitive signals to obtain the PWM control signal. This control signal is used to adjust the desired converter output voltage.

The duty ratio of the PWM signal depends on the value of the control voltage. The frequency of the PWM signal is the same as the frequency of the triangular waveform. The error amplifier reacts fast to changes in the output voltage. Thus the voltage control provides effective load regulation.

4.3 DC – AC Inverter

The fuel cell and converter system is connected to the grid through a DC – AC inveter in which a typical 3-phase 6-switch pulse width modulation (PWM) voltage source inverter (VSI). The VSI is used to convert the power from a DC voltage source to 3-phase AC output with 120^o phase displacement to each other.

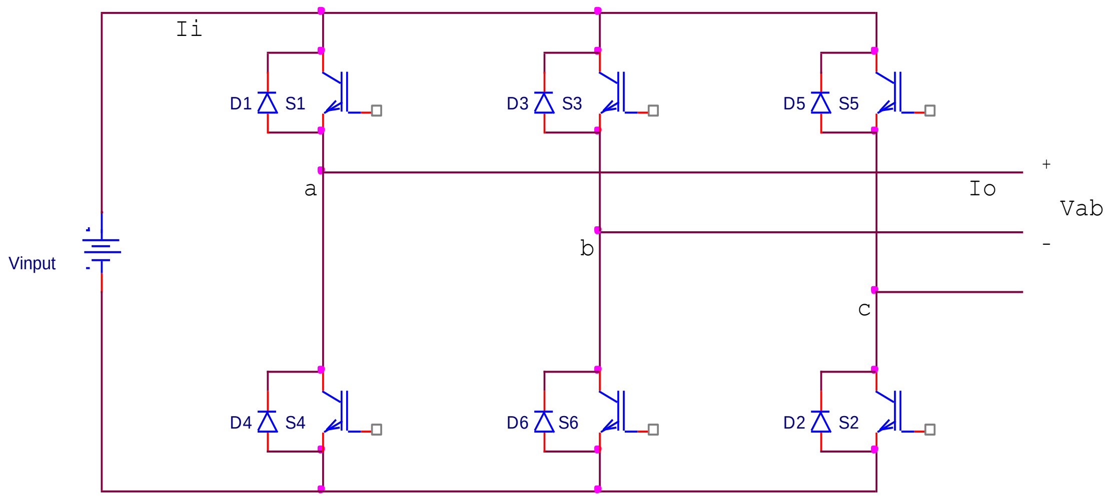


Figure 4.5 : Three Phase DC–AC Voltage Source Inverter

As shown in figure 4.5, the inverter has three arms, one for each phase. Each arm has two power electronic switches, the upper switch (+) and the lower one (-). There are many modulation types for inverters in literature. In order to control the magnitute, SPWM is used to generate to appropriate switching signals to control the six switches in the inverter. Three-phase PWM VSI waveforms is shown in figure 4.6. The triangular waveform is at a switching frequency f_s, which is generally much higher than the frequency of the control voltages. The control signals with the same frequency f_1 are used to modulate the duty ratios of the switching pulses [50].

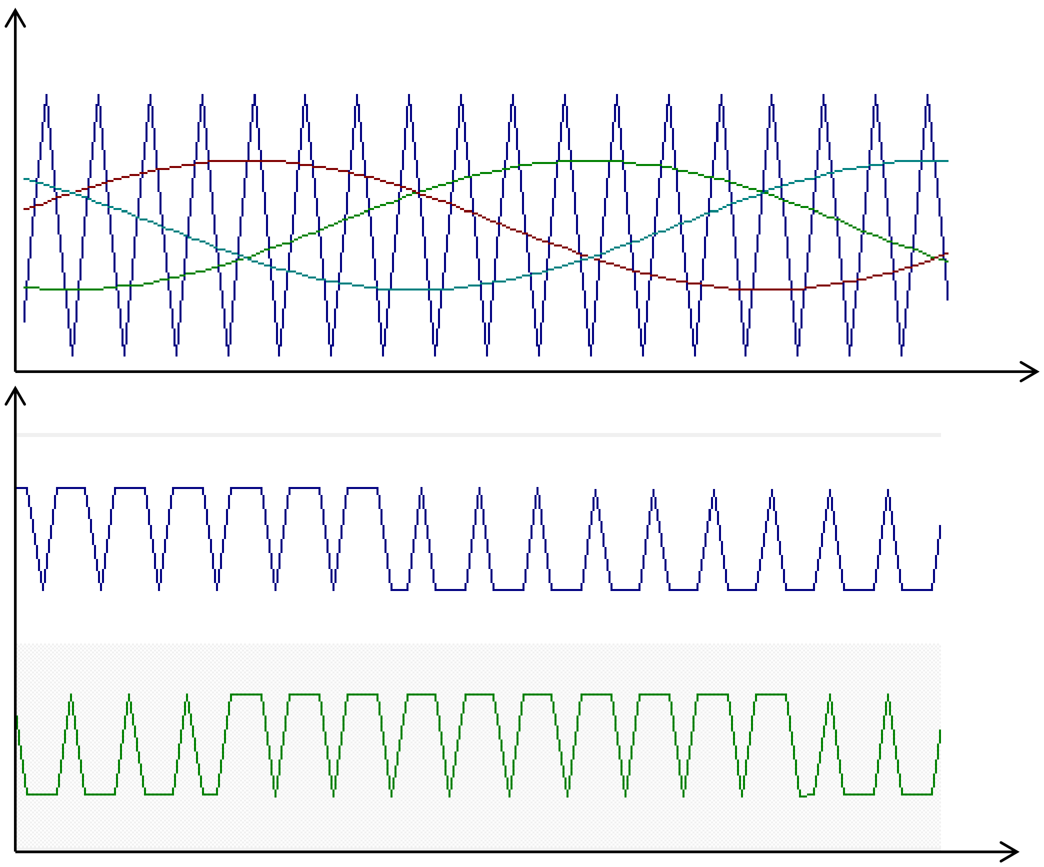
The frequency modulation ratio is

$$m_f = \frac{f_s}{f_1}.$$

The amplitude modulation index is

$$m_a = \frac{V_{p,crl}}{V_{p,tri}}.$$

Where $V_{p,crl}$ is the peak value of the control signal for each phase and $V_{p,tri}$ is the peak value of the triangular waveform.



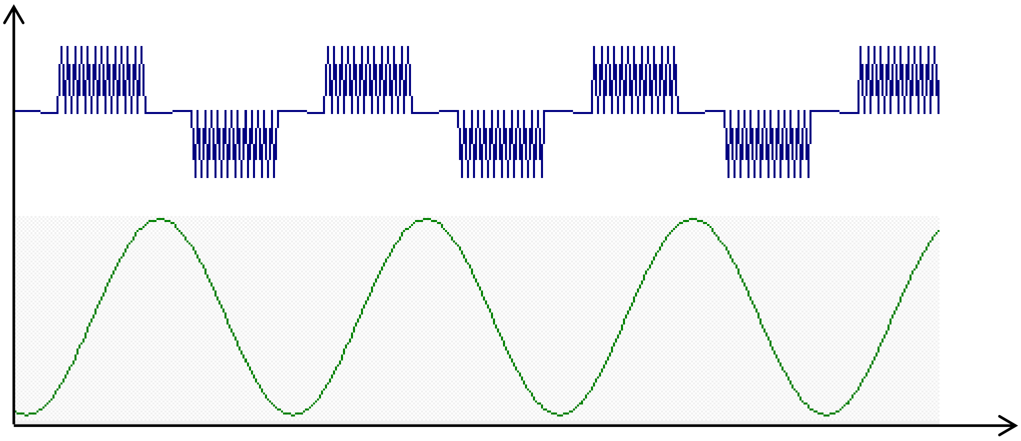


Figure 4.6 : Three-phase PWM VSI waveforms

In three phase inverter, maximum amplitude of the fundamental phase voltage in the linear region ($m_a < 1$) is $\frac{V_i}{2}$, the maximum amplitude of the fundamental ac output line voltage $\sqrt{3} * \frac{V_i}{2}$ therefore, we can write [48]

$$V_{line} = m_a \times \sqrt{3}\ \frac{V_i}{2} \qquad 0 < m_a \leq 1$$

m_a : modulation index

V_i : Three phase inverter input voltage

V_{line} : Three phase inverter line to line voltage

As the load conditions usually change the AC waveform should be adjusted to new conditions. Such adjustment can be done automatically by means of closed – loop control strategy. The proposed DC–AC inverter control scheme is PI control in this thesis. This controller controls the amplitude of output voltage. Figure 4.7 shows the block diagram of the inverter control system.

In a control system, the transformer output voltage is subtracted from an external referance voltage. The error signal is connected PI and blocks as per unit. The limiter block output is modulation index and it is between 0 and 1. Then the modulation signal is multiplied by the sinusoidal control voltages. The three balanced sinusoidal control voltages are compared with the triangular voltage. As a result, VSI switching signals are produced according to desired output voltage. K_p and K_i constants are obtained with trial and error method for PI control block.

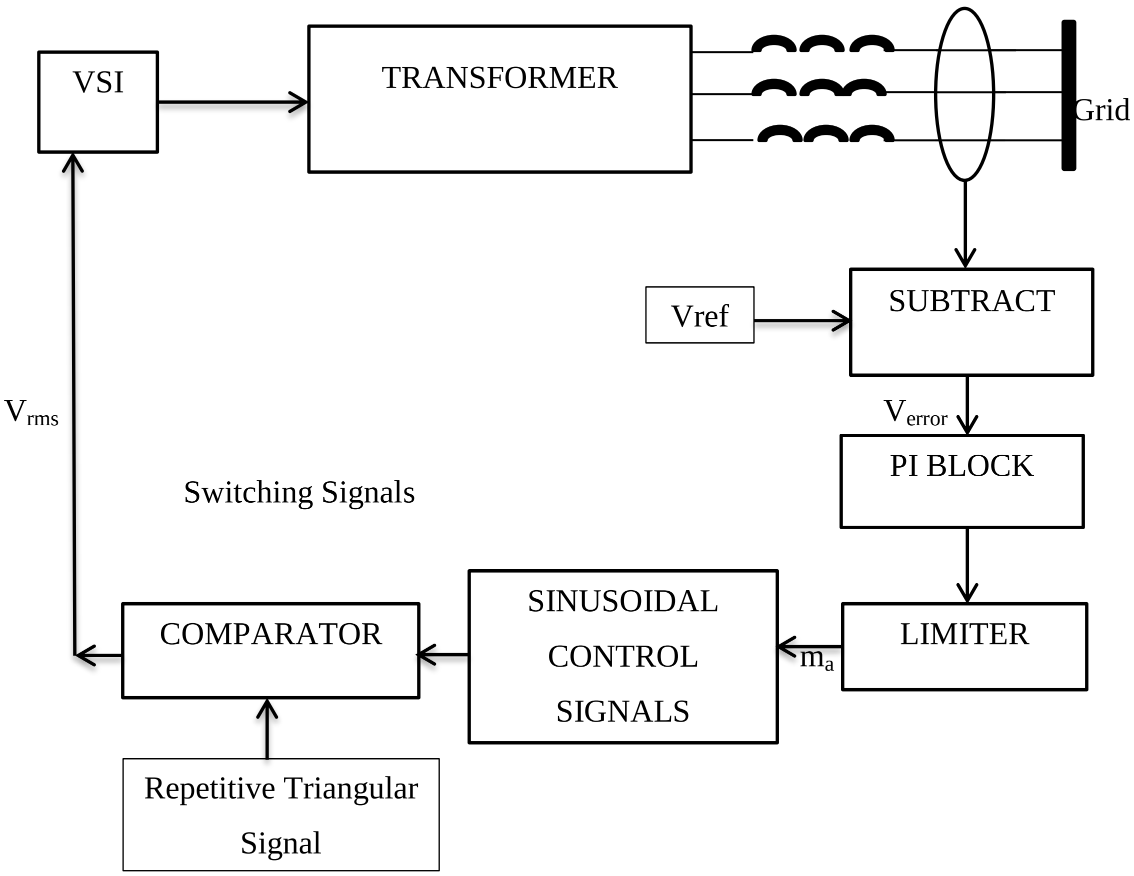


Figure 4.7 : Inverter Control Block Diagram

In a control system, the transformer output voltage is subtracted from an external referance voltage. The error signal is connected PI and blocks as per unit. The limiter block output is modulation index and it is between 0 and 1. Then the modulation signal is multiplied by the sinusoidal control voltages. The three balanced sinusoidal control voltages are compared with the triangular voltage. As a result, VSI switching signals are produced according to desired output voltage. K_p and K_i constants are obtained with trial and error method for PI control block.

CHAPTER 5

SYSTEM MODELING USING PSCAD

5.1 System Modeling

In this chapter, grid connected fuel cell system which is modeled using PSCAD software is explained. To analyze the characteristic of grid connected fuel cell system when operating a power system, a dynamic model which is suitable for the system simulation needs to be developed. The configuration of a grid – connected fuel cell power plant is illustrated in figure 5.1.

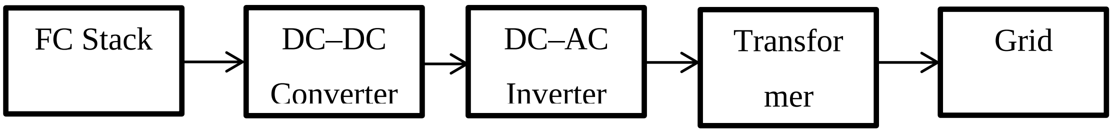


Figure 5.1 : Grid Connected Fuel Cell System

The fuel cell stack is connected to the DC–DC converter to boost the DC voltage. Then DC–DC converter is connected to the DC–AC inverter to give a sinusoidal output waveform at the required voltage and frequency. Three phase transformer is used for electrical isolation in fuel cell system. In addition, three phase transformer is connected to the grid.

The following assumptions have been made in this system:

- The three phase transformer has been considered to be ideal
- Switching losses of the inverter are neglected
- The stack is fed with hydrogen and air
- The temprature is stable at all times

5.2 SOFC Model

The dynamic model of the SOFC is shown in figure 5.2. The development of a dynamic model of a planar SOFC stack is presented based on its electrochemical and thermodynamic characteristics and the mass and energy conversation laws with emphasis on the fuel cell terminal electrical characteristics. SOFC's fuel flow is proportional to the stack current in this model. The partial pressure of hydrogen, oxygen and water are determined using the flow rates of hydrogen and oxygen. The output voltage of the fuel cell stack is based on the Nernst Equation which depends on the stack current and the partial pressure of the gases.

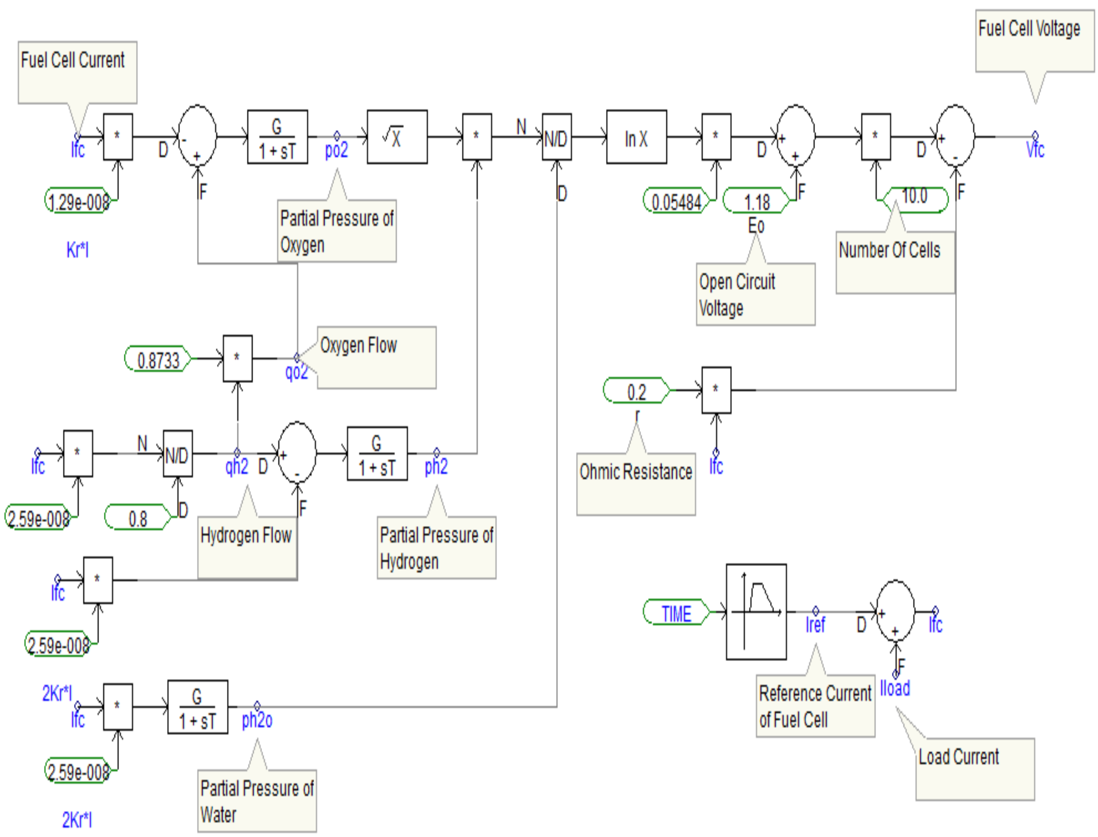


Figure 5.2 : Solid Oxide Fuel Cell Dynamic Model

5.3 DC–DC Converter Model

The fuel cell output voltage is the input voltage for DC–DC converter. A capacitor is used for smooting the output voltage. A filter inductor is connected in series with the load resistance which provides the output current to be smooth. The dynamic model of DC–DC boost converter is shown in figure 5.3

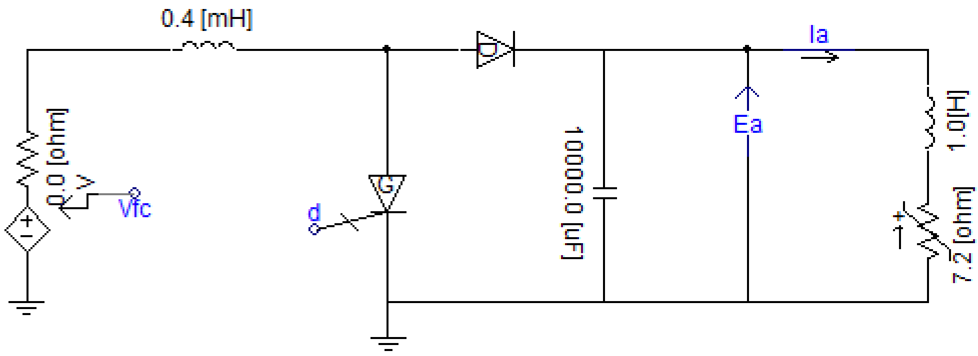


Figure 5.3 : DC – DC Converter Model

Closed loop feedback control system can be used for regulating the output voltage. A conventional PI controller is used for the boost DC–DC converter. The feedback control structure is shown in figure 5.4

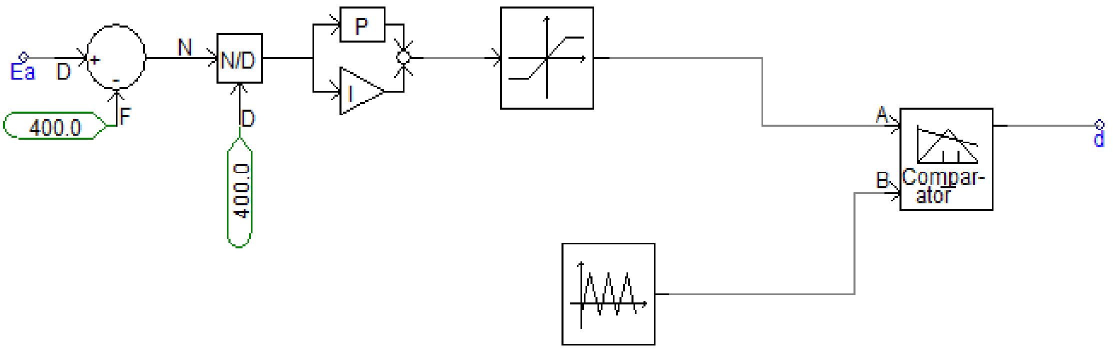


Figure 5.4 : DC–DC Converter Feedback Control

The gate signal is produced by the PI controller. The DC – DC converter's output and the referance voltage are subtracted and an error signal is obtained. Then the error signal is fed into the comparator to compare with the PWM signal to achieve the required gate signal.

5.4 DC–AC Inverter

The inverter takes the output of the DC–DC boost converter and delivers a sinusoidal output waveform at the required voltage and frequency.

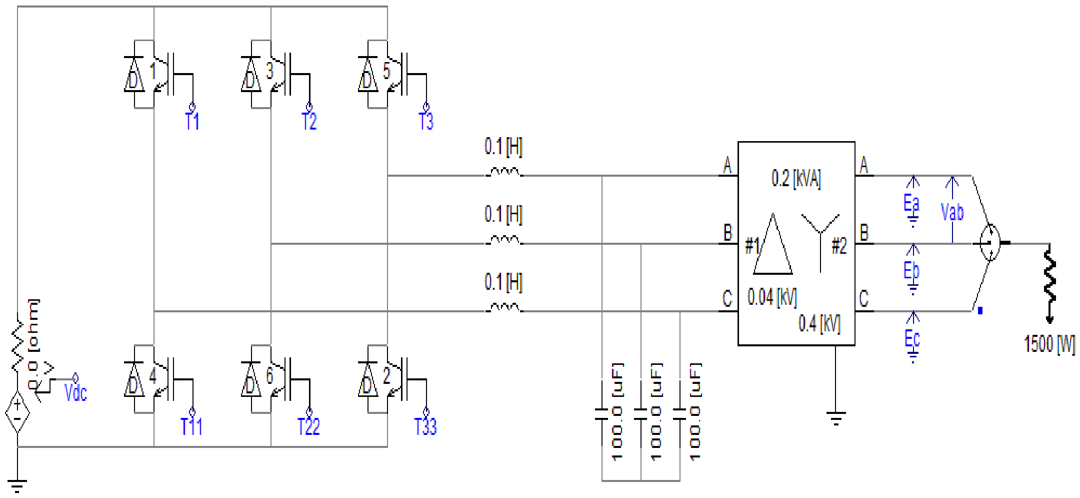


Figure 5.5 : DC–AC Inverter Model and Three Phase Transformer

Figure 5.5 shows three – phase voltage source inverter (VSI) and three phase transformer model using PSCAD software. VSI has three paralel legs which consist of two forced commutated IGBTs and anti paralel diodes. SPWM (Sinusoidal Pulse Width Modulation) technique is used in DC–AC inverter model. SPWM is generated by comparing sinusoidal referance signals with the triangular carrier wave and this comparison is shown in figure 5.6. Figure 5.7 shows a module of the DC–AC inverter modulation index.

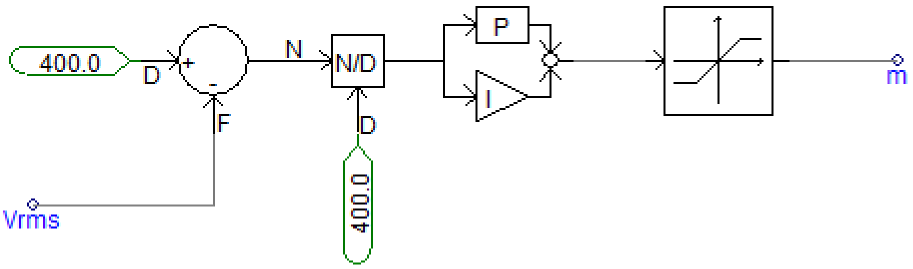


Figure 5.6 : DC–AC inverter modulation index

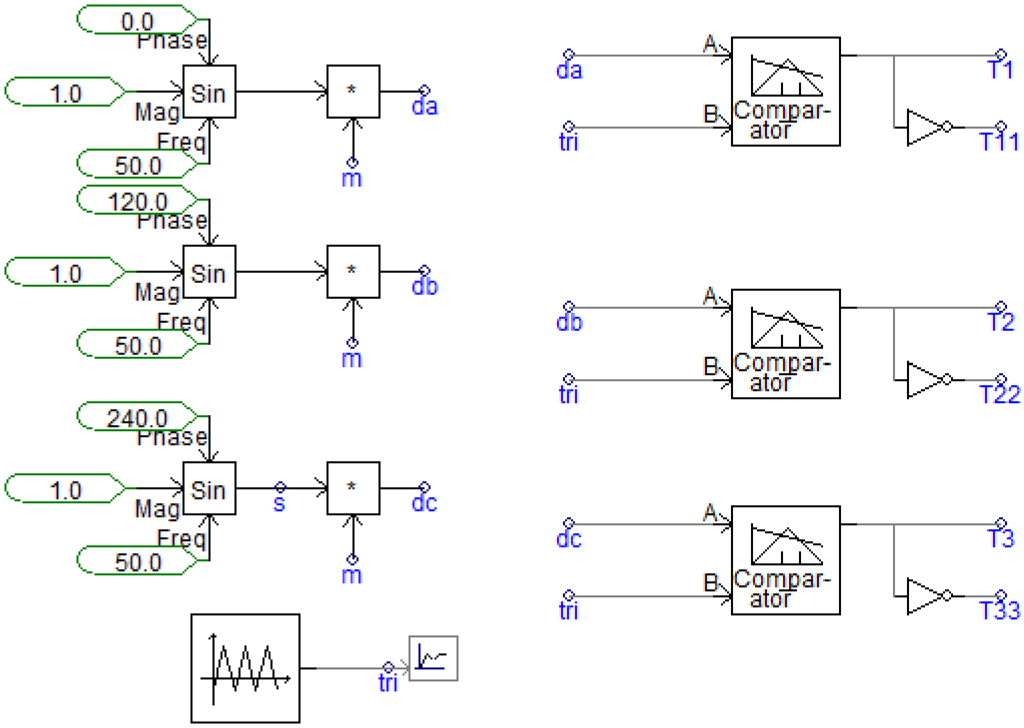


Figure 5.7 : DC–AC Inverter Switching Signals

5.5 The Transmission Line Connection

The inverter has an impotant function in interfacing the fuel cell with the utility grid. The main function of the inverter is to convert DC voltage from the fuel cell into AC voltage. Using PSCAD, the fuel cell system is connected with a transmission line shown in figure 5.8.

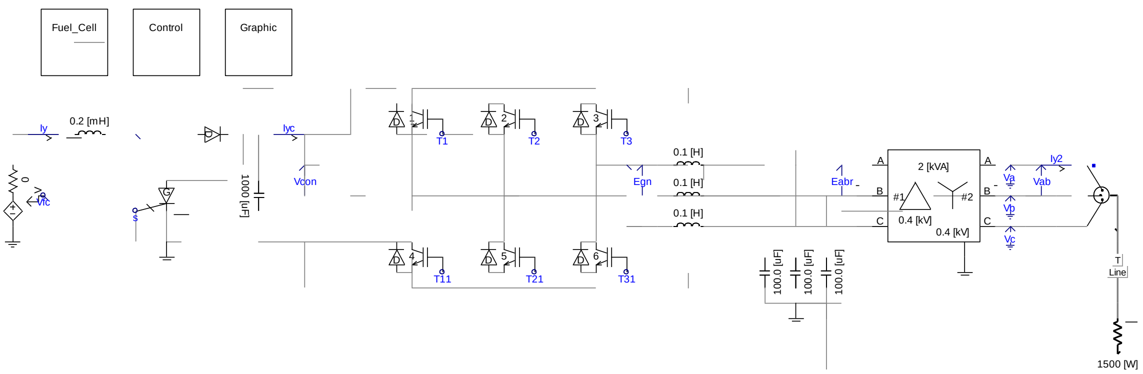


Figure 5.8 : Fuel Cell System Connected Transmission Line

5.6 Grid Connected Fuel Cell System

In this section, grid connected fuel cell model is achieved using PSCAD software. The figure 5.9 shows the grid connected fuel cell system consist of a fuel cell model, a DC–DC converter model, a DC–AC inverter and transformer.

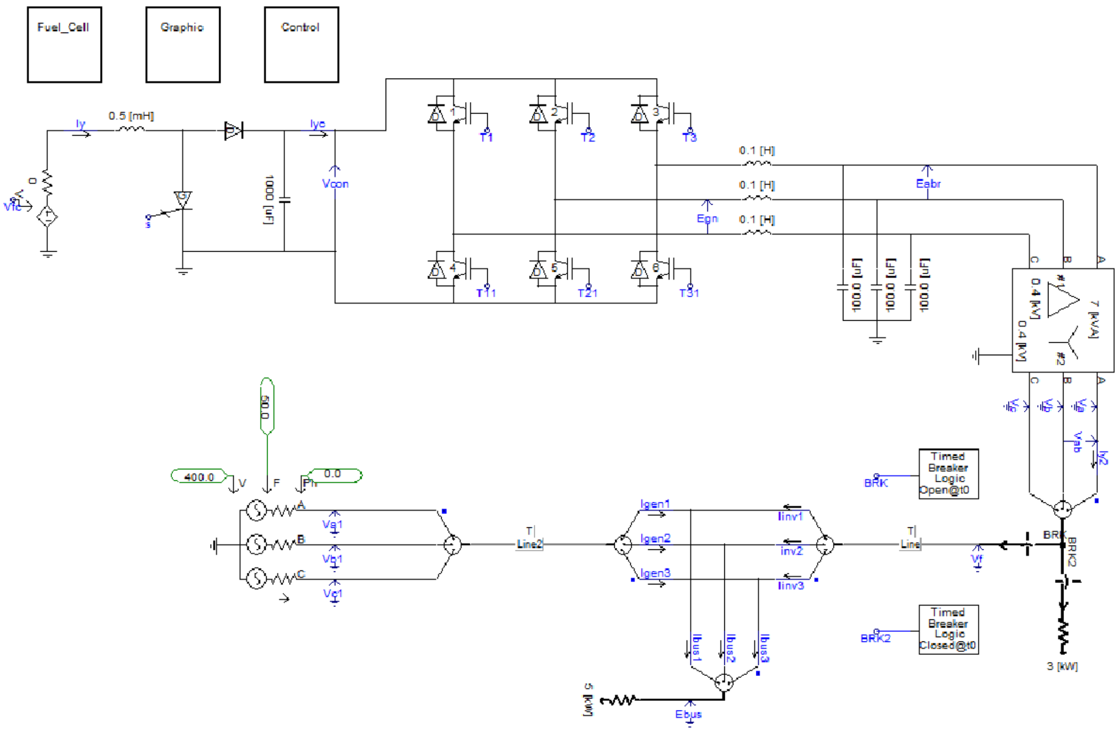


Figure 5.9 : Grid Connected Fuel Cell System

The transformer is used for electrical isolation in this system model. The fuel cell system has three bus including infinite bus, load bus and fuel cell bus. The fuel cell system is connected to the infinite bus through a transmission line. The PLL (Phase Locked Loop) structure and breaker are used for grid synchronization between fuel cell and infinite bus.

CHAPTER 6

SIMULATION RESULTS

6.1 Introduction

This chapter consists of simulation results obtained using PSCAD software for the solid oxide fuel cell (SOFC) system. The first simulation result is about the dynamic behavior of the SOFC. The second simulation result shows the behaviour of the fuel cell system with DC–DC converter and DC–AC inverter. The last simulation result shows the behavior of grid connected fuel cell system.

6.2 SOFC Characteristics

In this section, the behaviours of the SOFC are analyzed for constant and variable DC load. 5 cells for fuel cell system are used in this simulation studies. The parameters are shown Table 5.1 for SOFC simulation studies.

Table 6.1 Solid Oxide Fuel Cell Parameters [33]

Parameters	**Representation**	**Units**	**Values**
T	Absolute Temprature	[K]	1273
F	Faraday's Constant	[C/mol]	96487
R	Universal Gas Constant	[J/(kmol×K]	8314
E_0	Open Circuit Voltage	[V]	1.18
N_0	Number of Cells in Stack		384
K_r	Constant: K_r=N_0/4F	[kmol/(s×A)]	9.94x10^{-7}
K_{H_2O}	Valve Molar Constant for Water	[kmol/(s×atm)]	2.52 x 10^{-3}

K_{H_2}	Valve Molar Constant for Hydrogen	[kmol/(s×atm)]	8.43 x 10^{-4}
K_{O_2}	Valve Molar Constant for Oxygen	[kmol/(s×atm)]	2.81 x10^{-3}
τ_{H_2O}	Response Time for Water Flow	[s]	78.3
τ_{H_2}	Response Time for Hydrogen Flow	[s]	26.1
τ_{O_2}	Response Time for Oxygen Flow	[s]	2.91
r_{HO}	Ratio of Hydrogen to Oxygen		1.168
R_{ohm}	Ohmic Loss	[Ω]	0.126

6.2.1 SOFC Constant DC Load Characteristic

Figure 6.1 shows the fuel cell stack voltage. Fuel cell voltage increases to 4 V in 2 seconds then it reaches a steady state value of 3.8 V. The voltage drop is observed because of the ohmic losses.

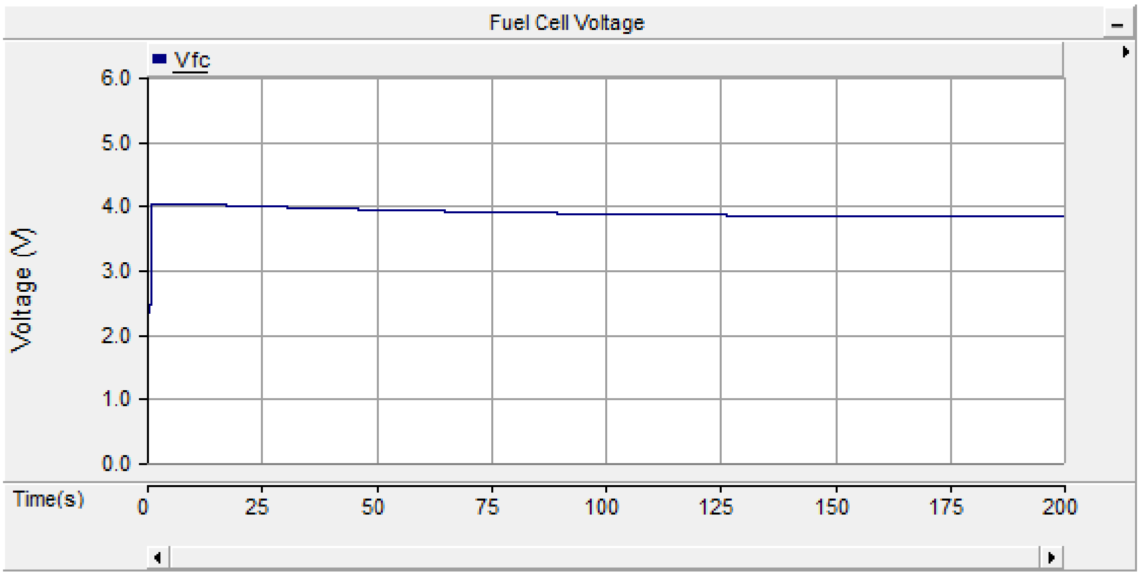


Figure 6.1 : Fuel Cell Stack Voltage

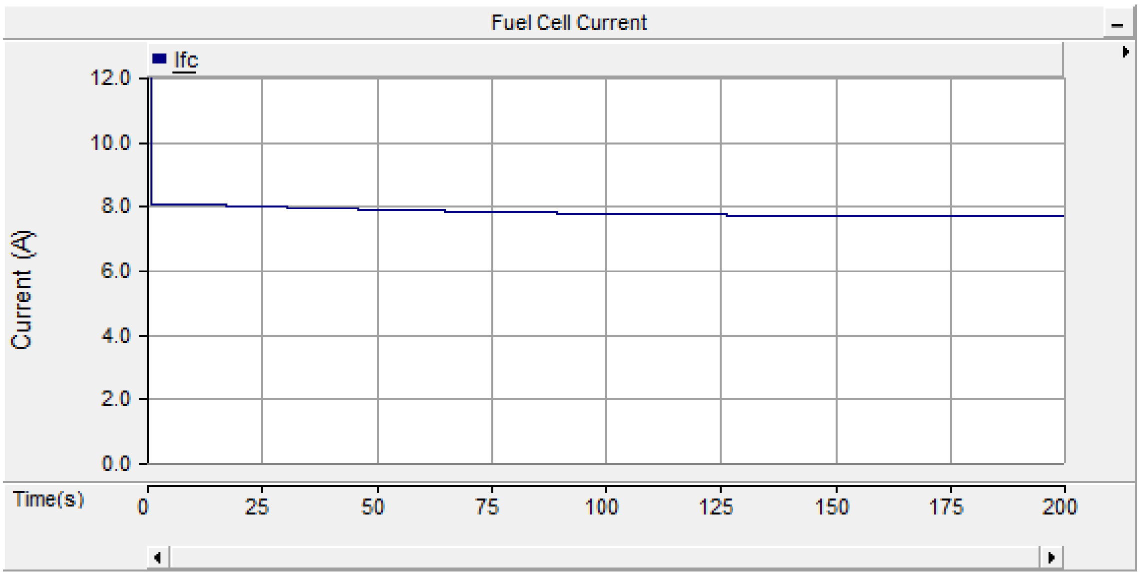


Figure 6.2 : Fuel Cell Stack Current

Figure 6.2 shows the stack current of the fuel cell which takes 125 seconds to reach a steady state value of 7.8 A. The response of the fuel cell is slow because of the electrochemical reactions in the cell. Figure 6.3 shows the fuel cell stack power which reaches a steady state value of 30 W. Fuel cell power can vary based on load value but it cannot exceed the maximum power capacity of fuel cell.

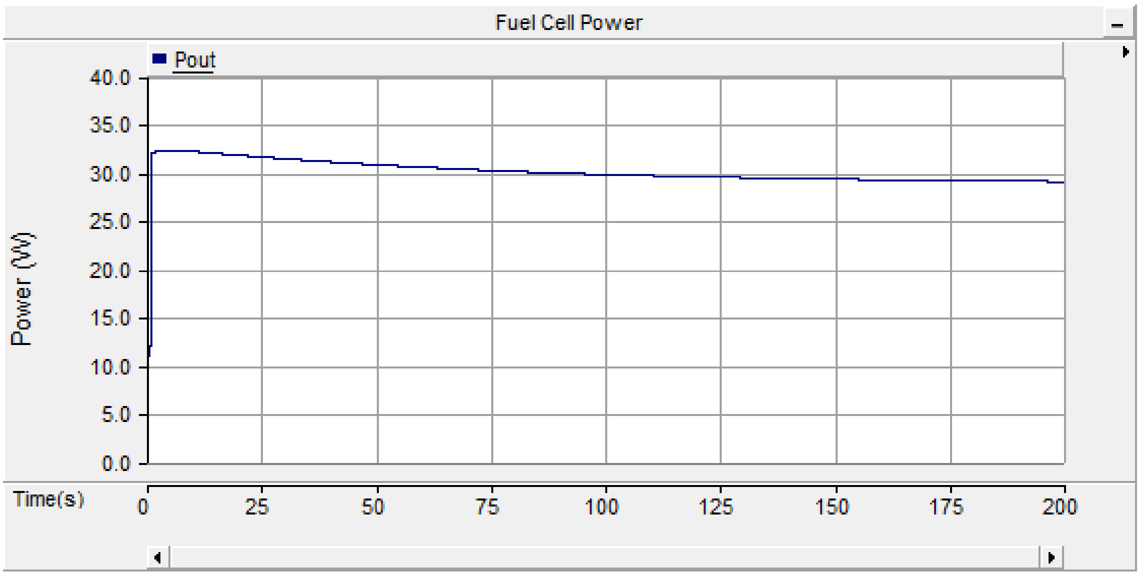


Figure 6.3 : Fuel Cell Stack Power

6.2.2 Variable DC Load Characteristics

Figure 6.4 shows the fuel cell stack current under variable DC loads. The fuel cell stacks current increases and decreases based on the DC load change. The value of the fuel cell stack current reaches its lowest value between 130 and 140 secconds.

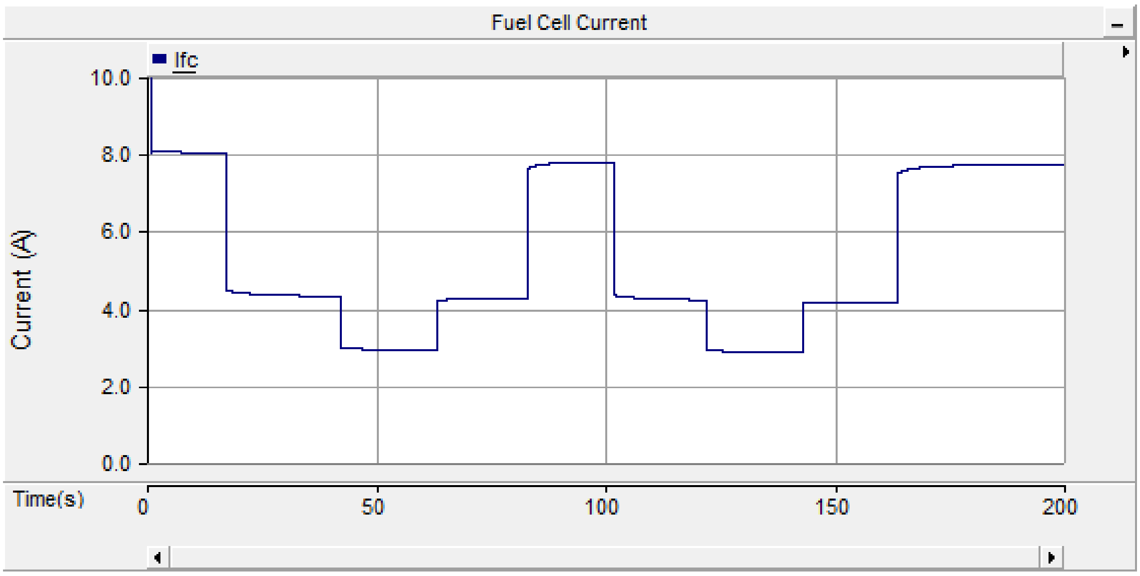


Figure 6.4 : Fuel Cell Stack Current Under Variable DC Loads

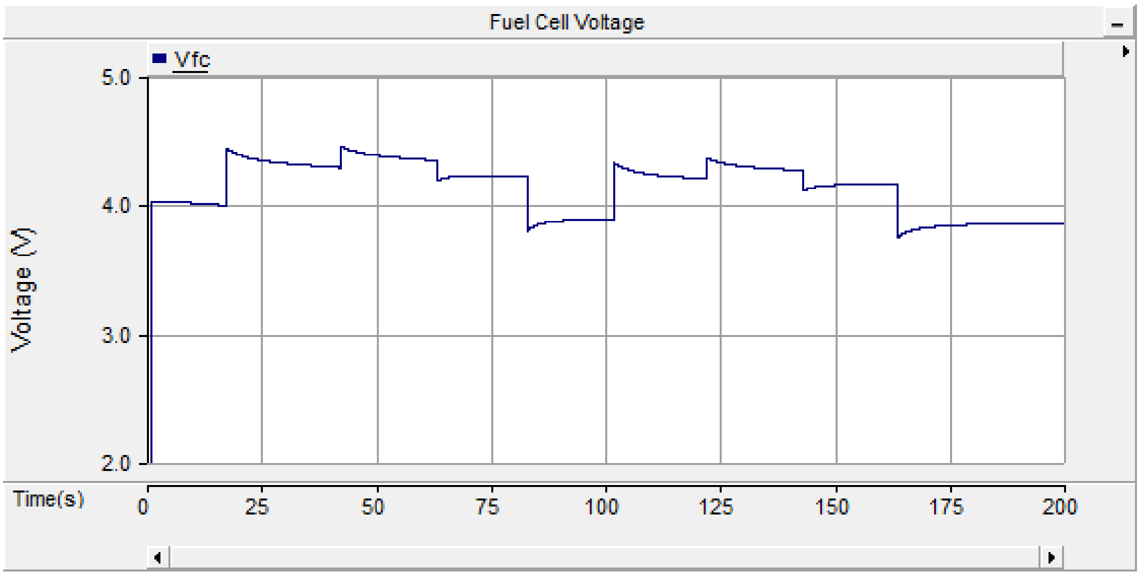


Figure 6.5 : Fuel Cell Stack Voltage Under Variable DC Loads

Figure 6.5 shows fuel cell stack voltage under variable loads. Because of slow response time, fuel cell stack voltage transient is not linear. The fuel cell stack voltage is changing between 4.5 V and 3.5 V depending on the load values.

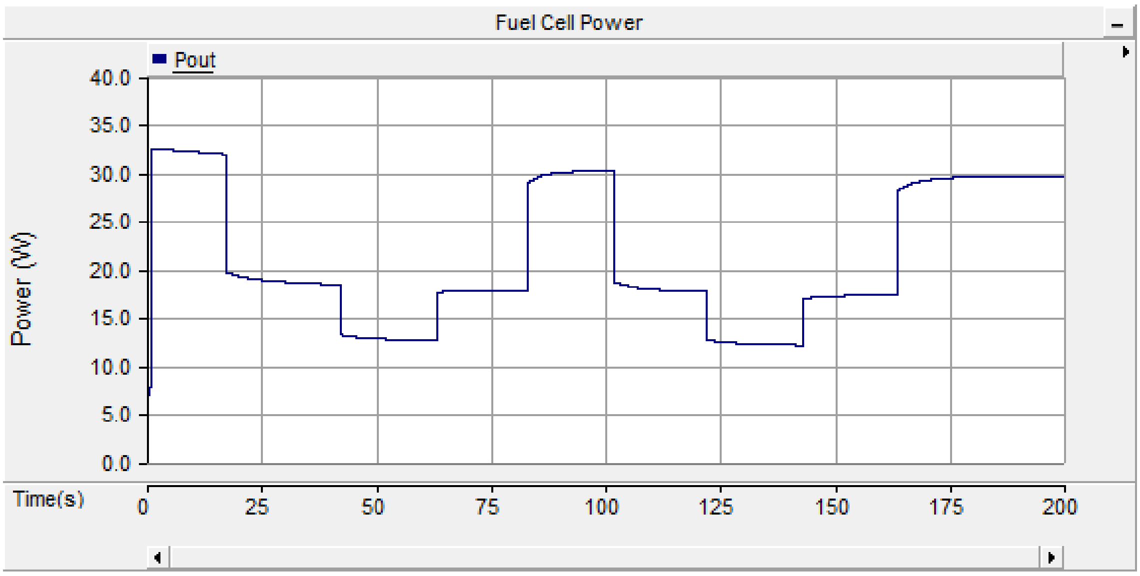


Figure 6.6 : Fuel Cell Stack Power Under Variable DC Loads

Figure 6.6 shows fuel cell stack power under variable DC load. Fuel cell stack power increses and decreases between 30 W and 12 W value.

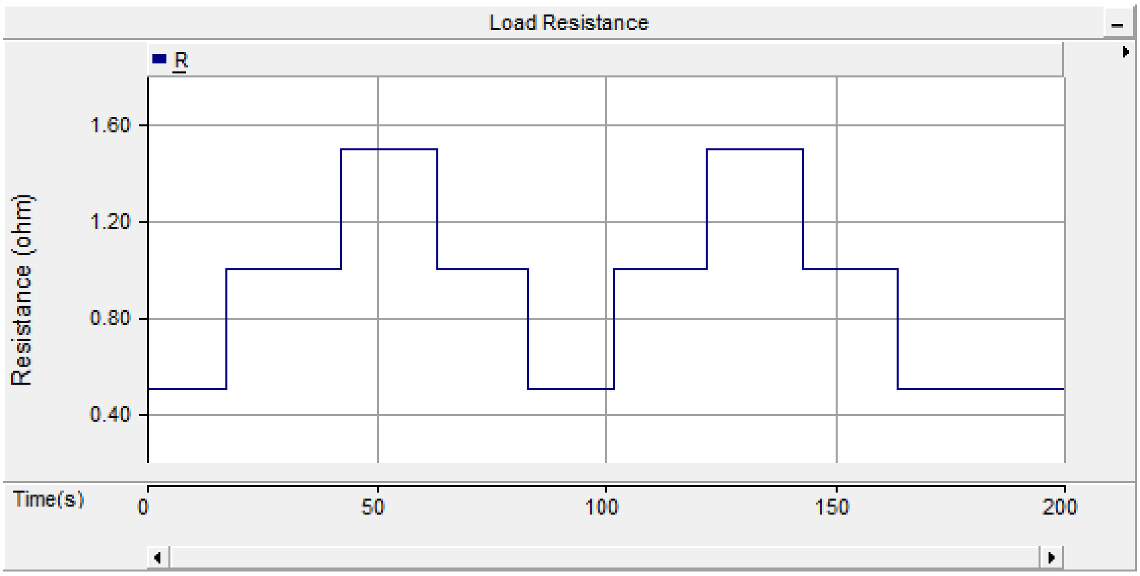


Figure 6.7 : Variable Load Resistance

Figure 6.7 shows the variable load resistance in fuel cell system. The load resistance values vary between 1.5 and 0.5 ohms.

6.3 DC–DC Converter Behaviour

In this section, the behaviour of DC–DC converter will be analyzed under variable loads. The fuel cell provides the necessary power to the load through the DC–DC converter as shown in figure 6.8.

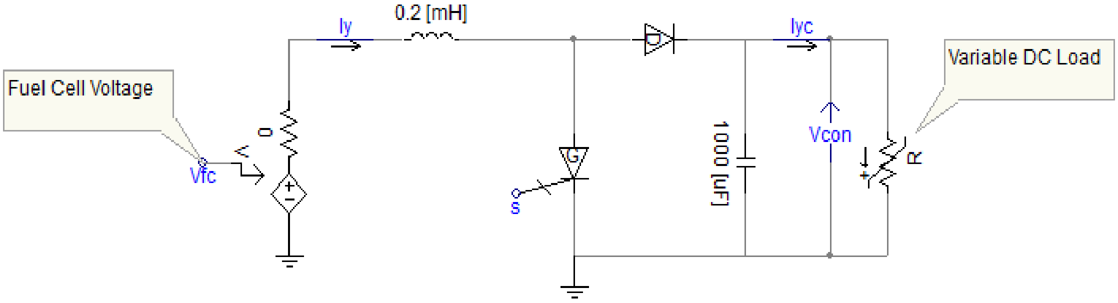


Figure 6.8 : DC–DC Converter Model

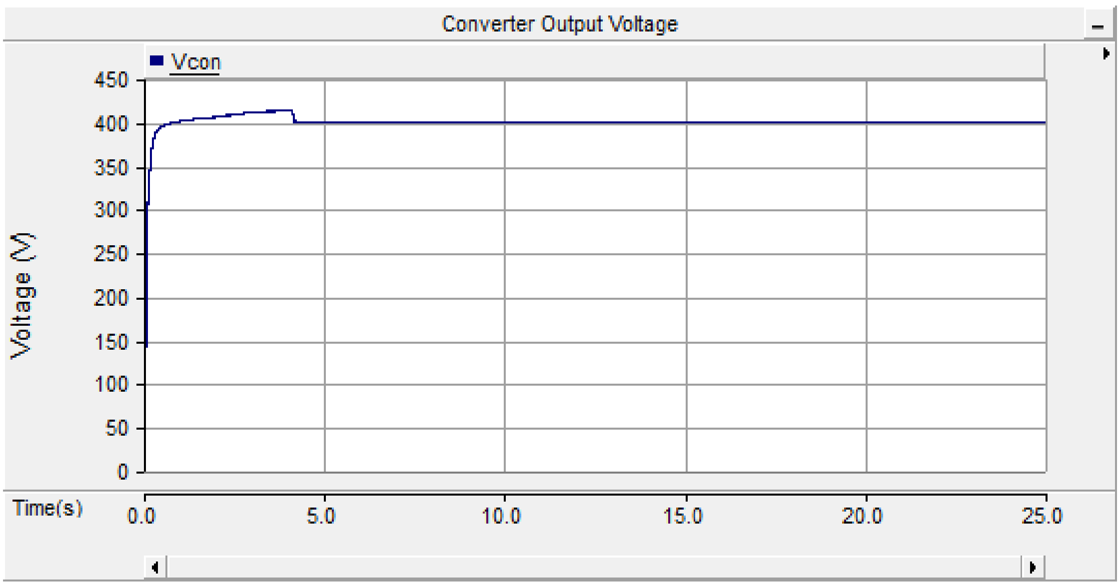


Figure 6.9 : DC–DC Converter Output Voltage

Figure 6.9 shows DC–DC converter output voltage. The DC–DC converter output voltage reaches steady state value of 400 V after 4 seconds in this simulation result.

Although DC load is variable, the control structure of DC–DC converter model provides the converter output voltage to remain constant. Figure 6.10 shows DC–DC converter output current change under variable load conditions. The output current is changing between 1.5 and 2 A.

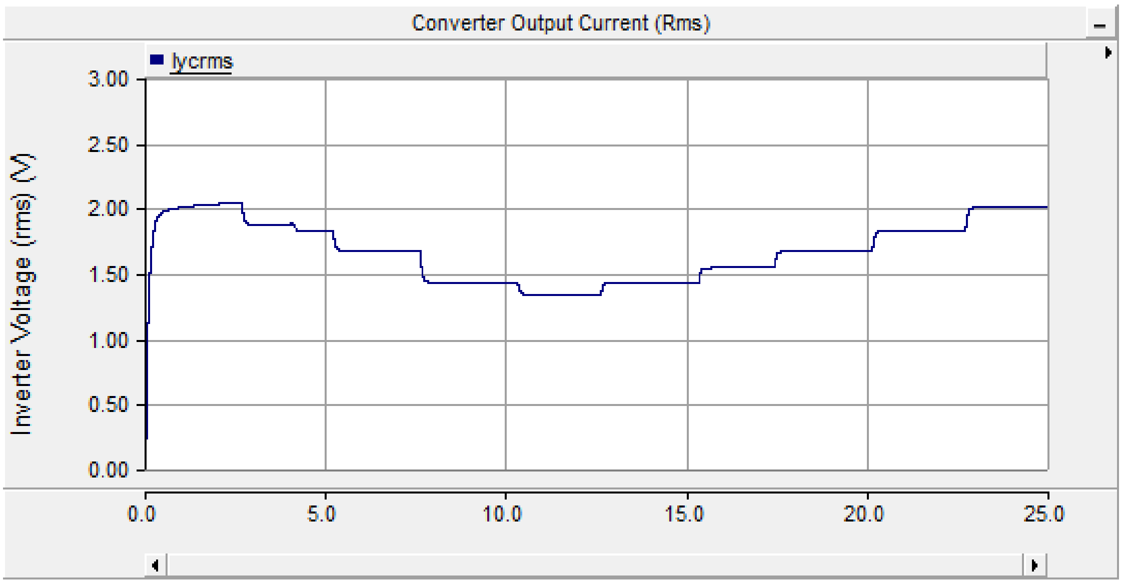


Figure 6.10 : DC–DC Converter Output Current

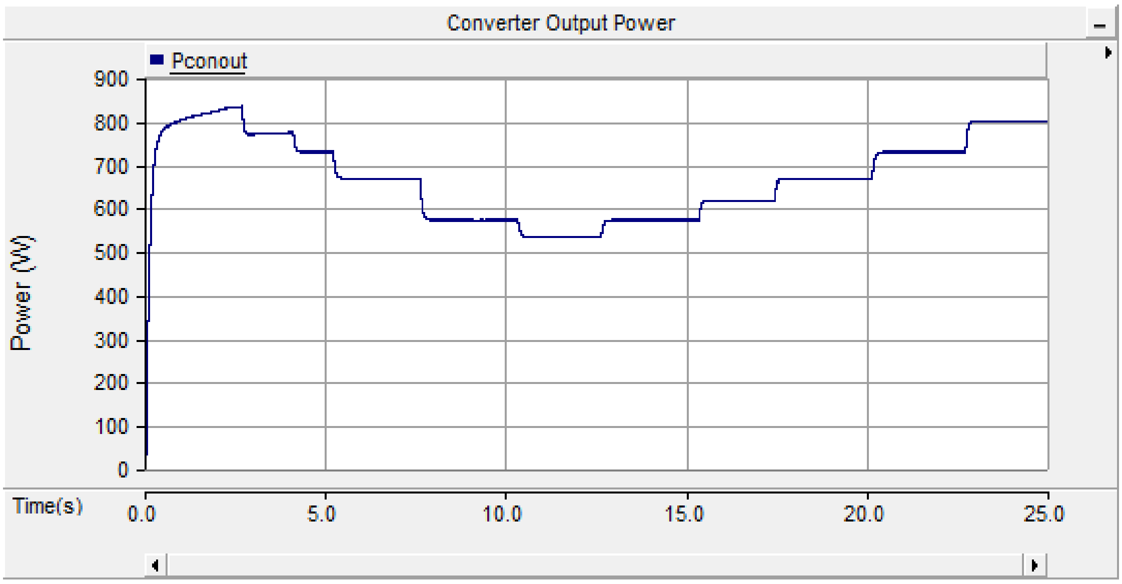


Figure 6.11 : DC–DC Converter Output Power

The converter output current decreases with increasing the load resistance step by step. Figure 6.11 shows DC – DC converter output power changes between 800 and 550 W under variable DC load conditions. The converter output voltage reaches its lowest value at the 12th seconds because of the load resistance.

6.4 AC Performance of SOFC

In this section, the behaviour of solid oxide fuel cell system which includes DC–DC converter and DC–AC inverter for constant load is examined. The load of 1.5 kW is selected for this simulation study.

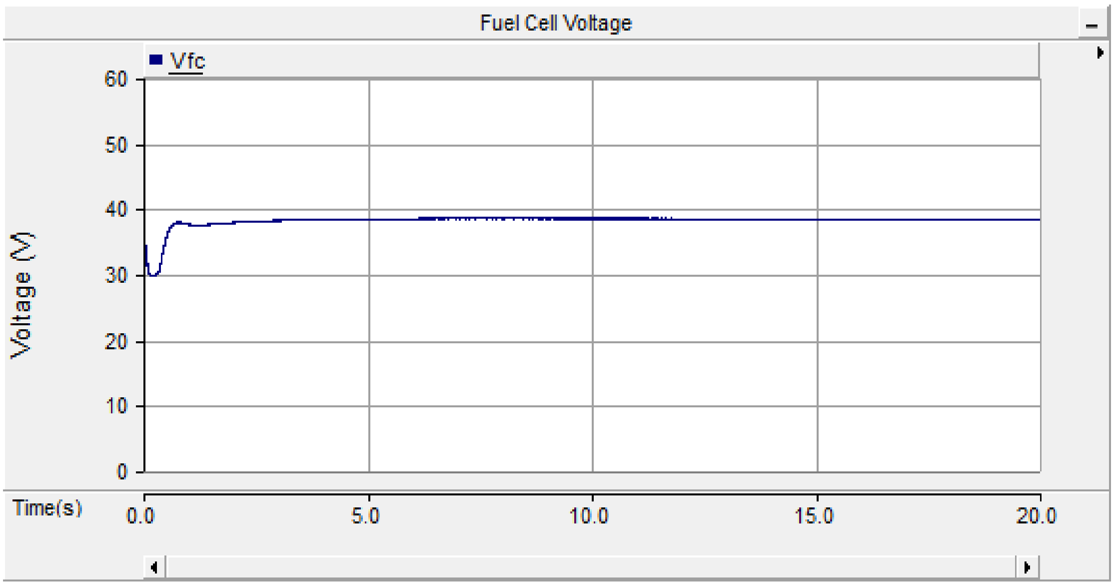


Figure 6.12 : Fuel Cell Stack Voltage

Figure 6.12 shows fuel cell stack voltage. There are 45 cells in fuel cell system. Fuel cell stack voltage reaches steady state value of 38 V.

Figure 6.13 shows fuel cell stack current. Fuel cell current is suddenly increasing to 120 A values then it is constant to 76 A because of the constant load. Figure 6.14 shows fuel cell stack power. The value of fuel cell stack power starts in 2.9 kW, and then it reaches steady state value of 2.8 kW.

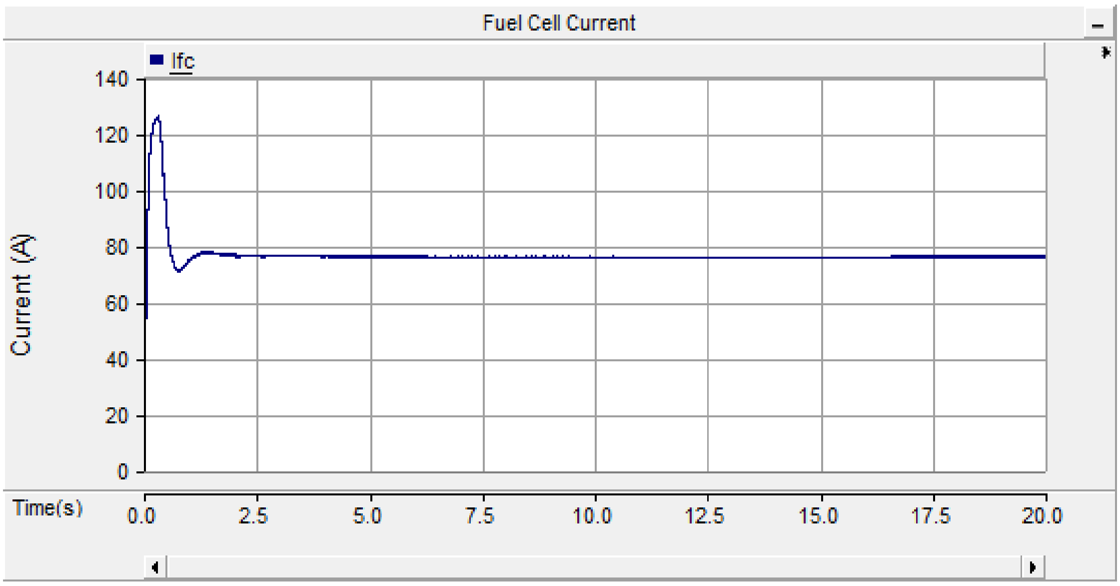


Figure 6.13 : Fuel Cell Stack Current

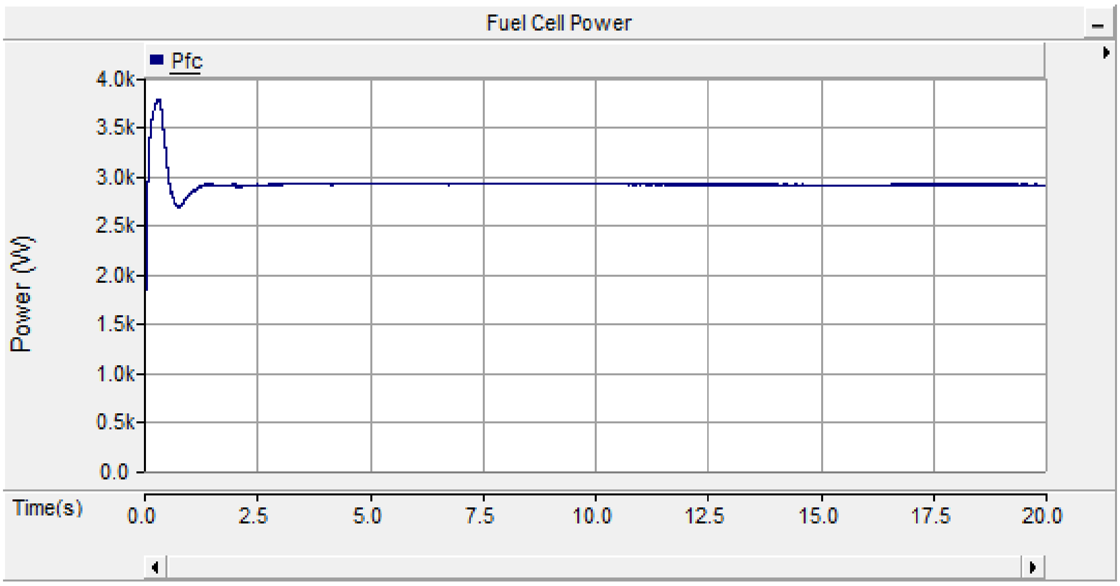


Figure 6.14 : Fuel Cell Stack Power

Figure 6.15 shows converter output voltage. In this study, DC–DC converter boost the fuel cell voltage depends on duty cycle.

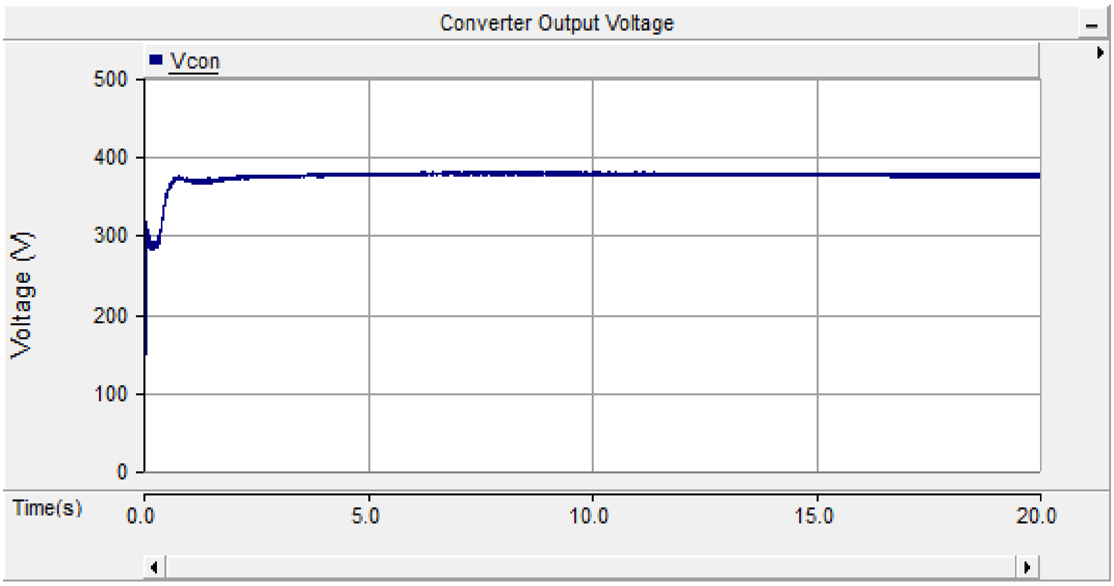


Figure 6.15 : DC–DC Converter Output Voltage

The converter output voltage reaches steady state value of 380 V. Figure 6.16 shows phase to phase voltage of inverter. The peak amplitude of the inverter output voltage is 565 V value. Figure 6.17 shows phase to phase rms voltage of inverter. Inverter voltage reaches steady state value of 400 V.

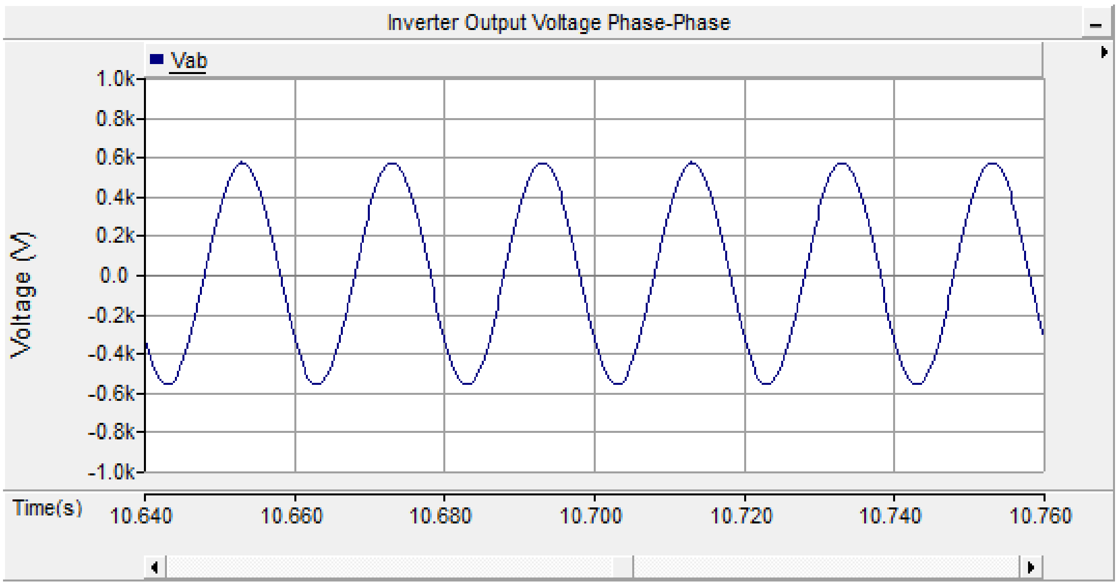


Figure 6.16 : DC–AC Inverter Output Voltage

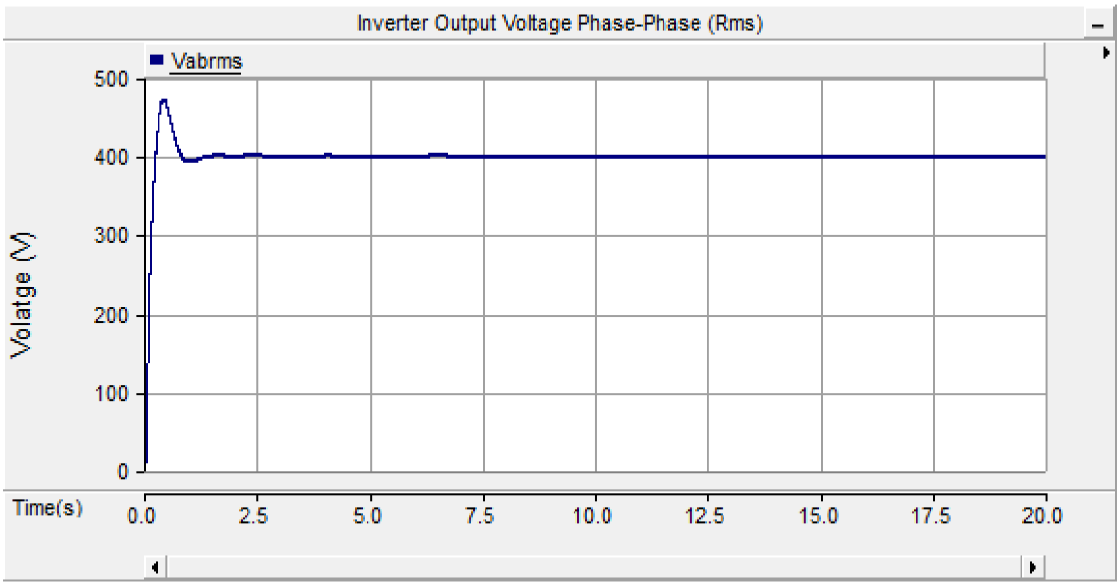


Figure 6.17 : DC–AC Inverter Output Voltage Rms Value

Figure 6.18 shows inverter output voltage phase to ground. Inverter output voltage is regular sinusoidal signal, and its peak value is 320V.

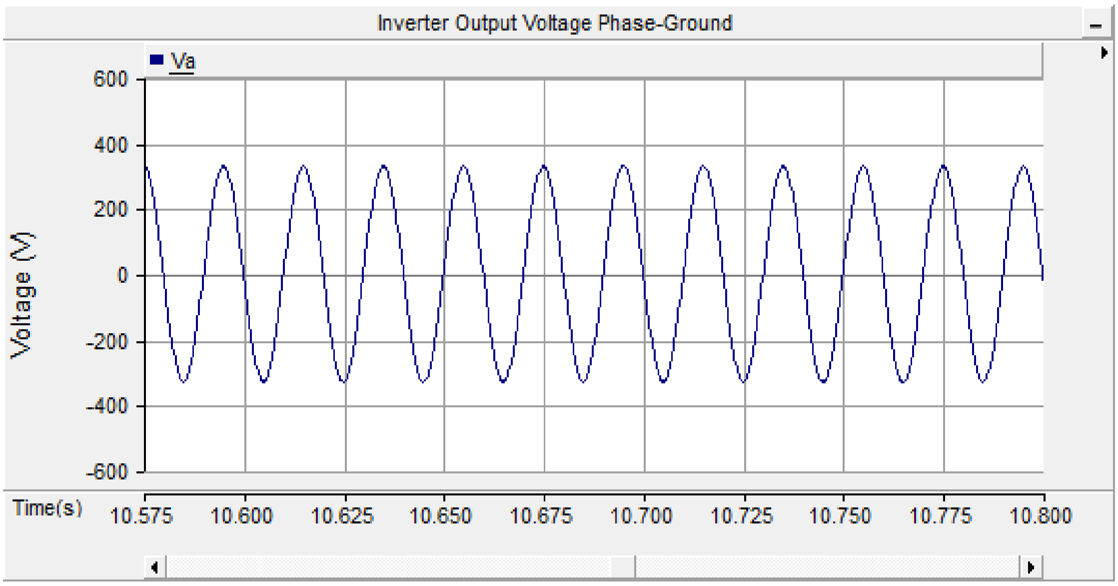


Figure 6.18 : Phase to Ground Voltage of Inverter

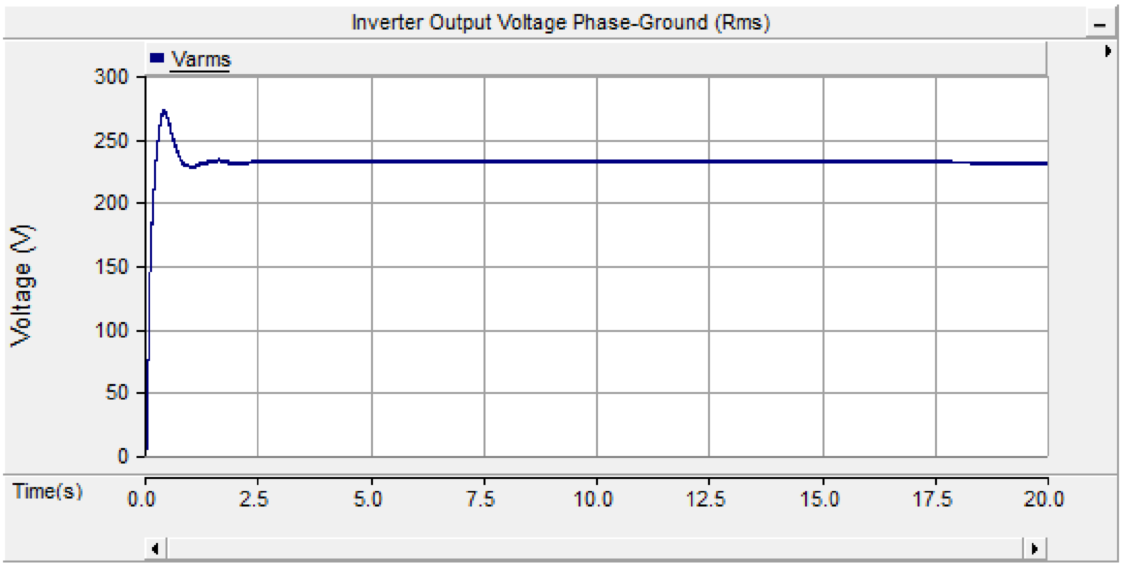


Figure 6.19 : Phase to Ground Rms Voltage of Inverter

Figure 6.19 shows phase to ground rms voltage of inverter. It reaches steady state value of 230 V in 2 seconds.

Figure 6.20 shows converter output power. It reaches steady state value of 2.4 kW in 400 seconds. The converter efficiency is 82%.

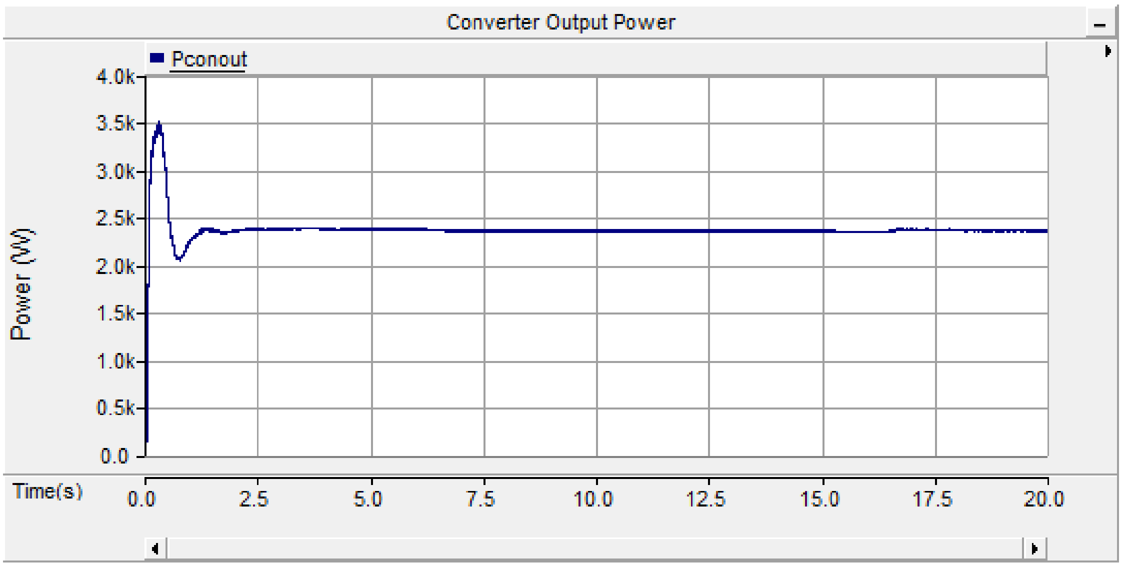


Figure 6.20 : DC–DC Converter Output Power

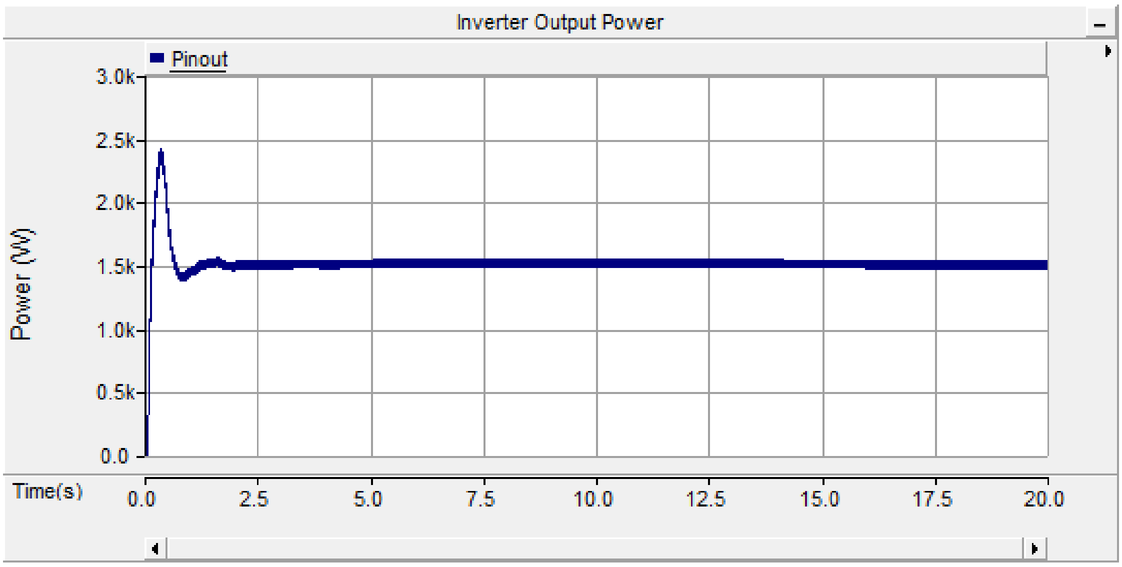


Figure 6.21 : DC–AC Inverter Output Power

Figure 6.21 shows inverter output power. The inverter output power becomes 1.5 kW. Figure 6.22 shows repeating triangular and control signals. Sinusoidal signal's magnitude is less than triangular signal magnitude. Gating signals are produced according to control signals.

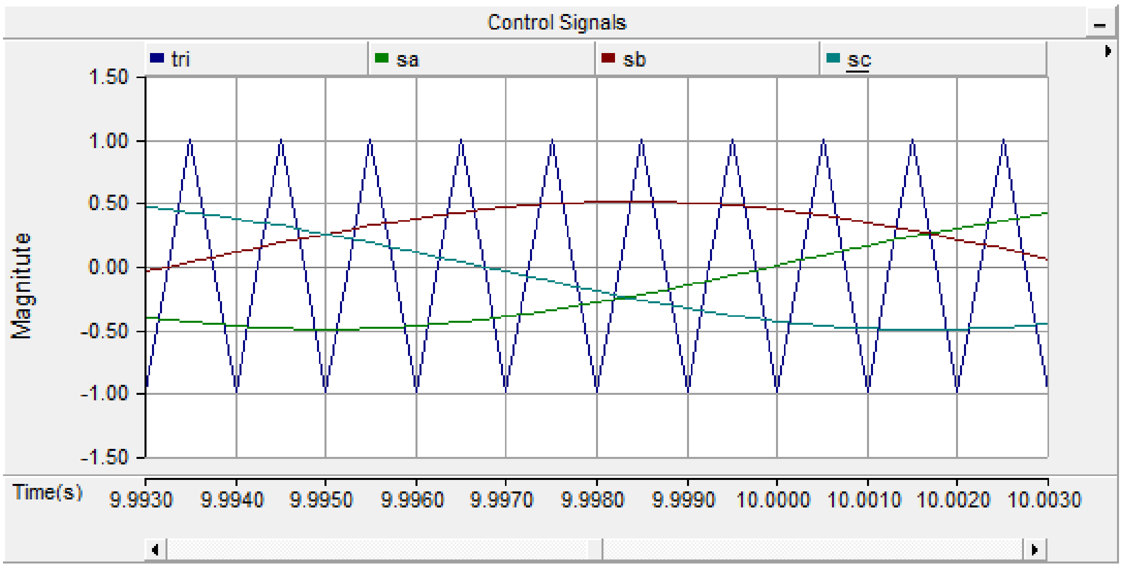


Figure 6.22 : DC–AC Inverter Control Signals

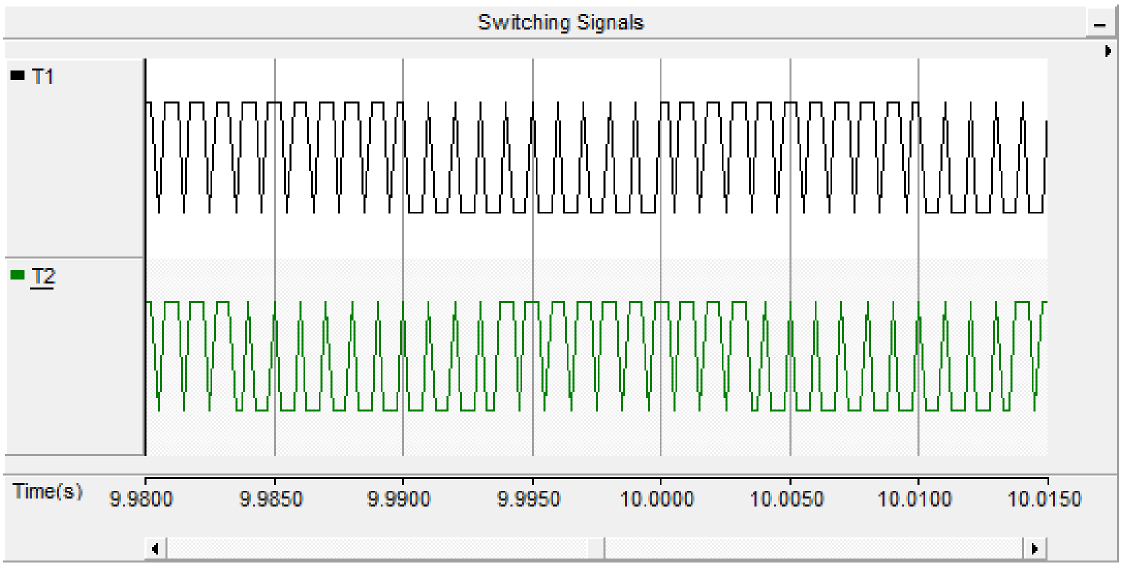


Figure 6.23 : Transistor Signal for Phase A and B

Figure 6.23 shows switching signal for phase A and phase B. Switching signals are obtained from comparing the phase A and B control signal and the triangular signal.

Figure 6.24 shows inverter voltage before filter. Figure 6.25 shows inverter output voltage after filter.

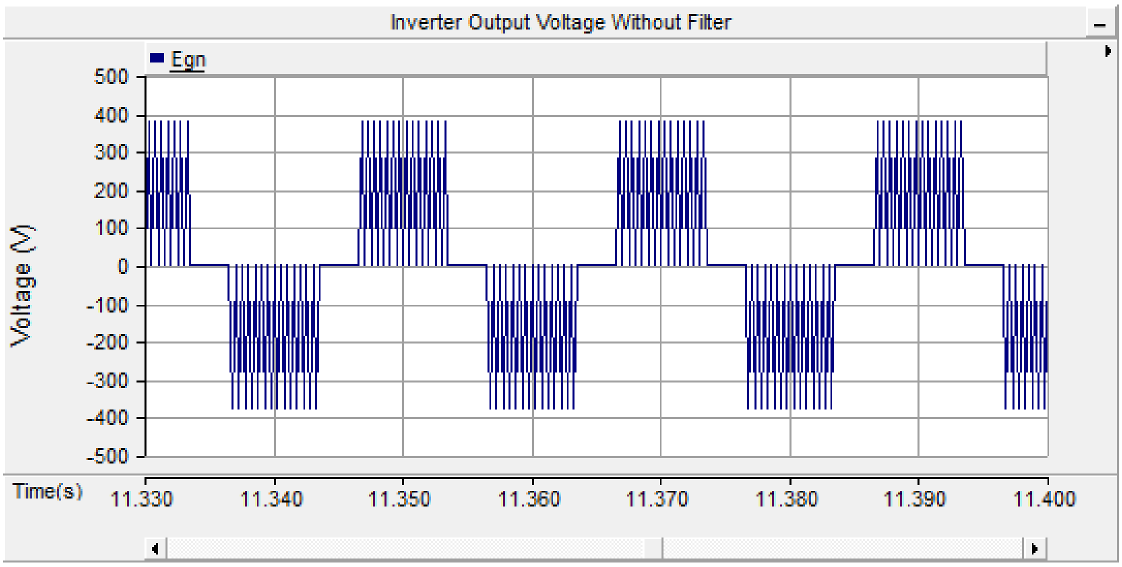


Figure 6.24 : Inverter Line to Line Voltage Before Filter

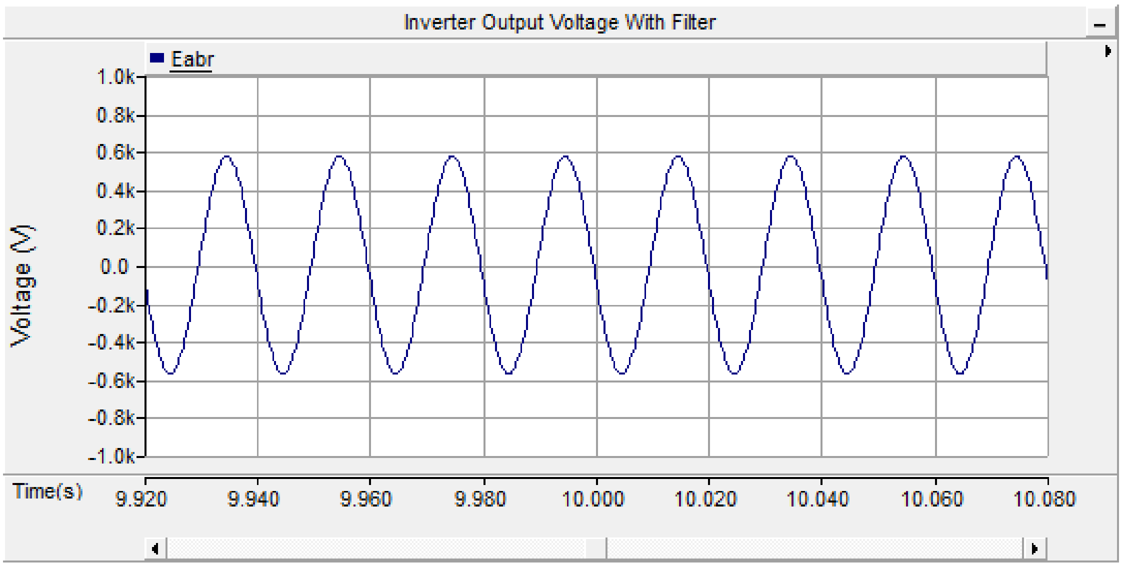


Figure 6.25 : Inverter Line to Line Voltage After Filter

6.5 Fuel Cell System Different Load Characteristics

In this section, solid oxide fuel cell system model is simulated under different AC load conditions. The fuel cell system model is shown figure 5.9. AC loads are used for 1kW, 1.5kW, 2kW and 4kW values. In this study, output power and output voltage of inverter are analyzed under different AC load conditions. The aim of this simulation is to observe the variation of power and voltage under 3 different loads.

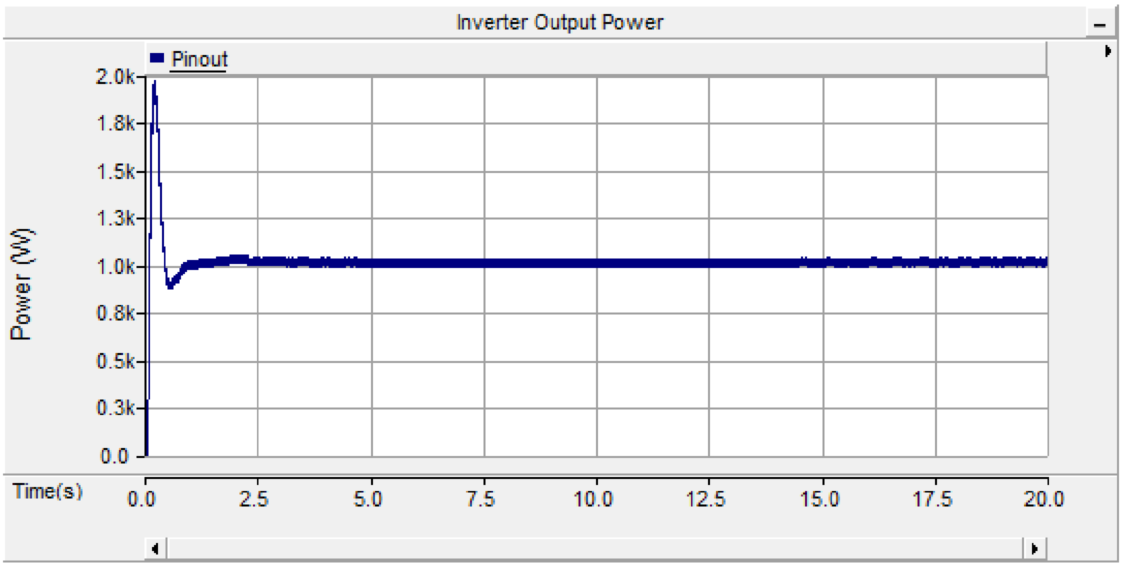


Figure 6.26 : Inverter Output Power for 1 kW Load

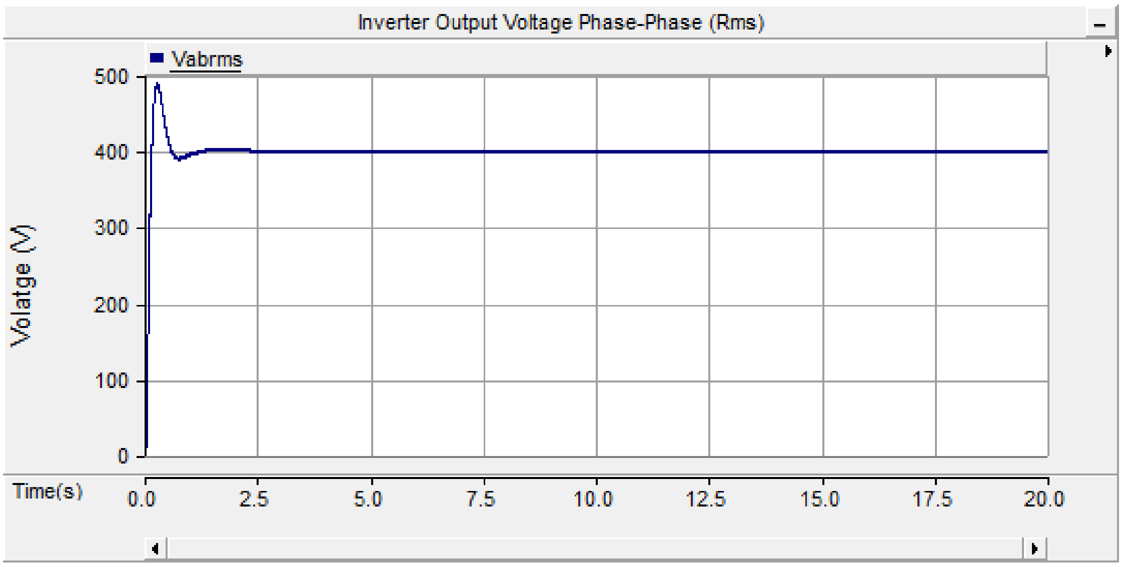


Figure 6.27 : Inverter Output Voltage for 1 kW Load

Figure 6.26 shows inverter output power under 1 kW load. The inverter output power reaches steady state value of 1 kW. The fuel cell feeds 1 kW AC load. Figure 6.27 shows inverter output voltage under 1 kW load and it reaches steady state value of 400 V. Gains of PI controller of the converter are $K_p = 0.5$, $K_i = 0.02$ respectively. The response rate of the PI controller of the inverter is reasonable for this study.

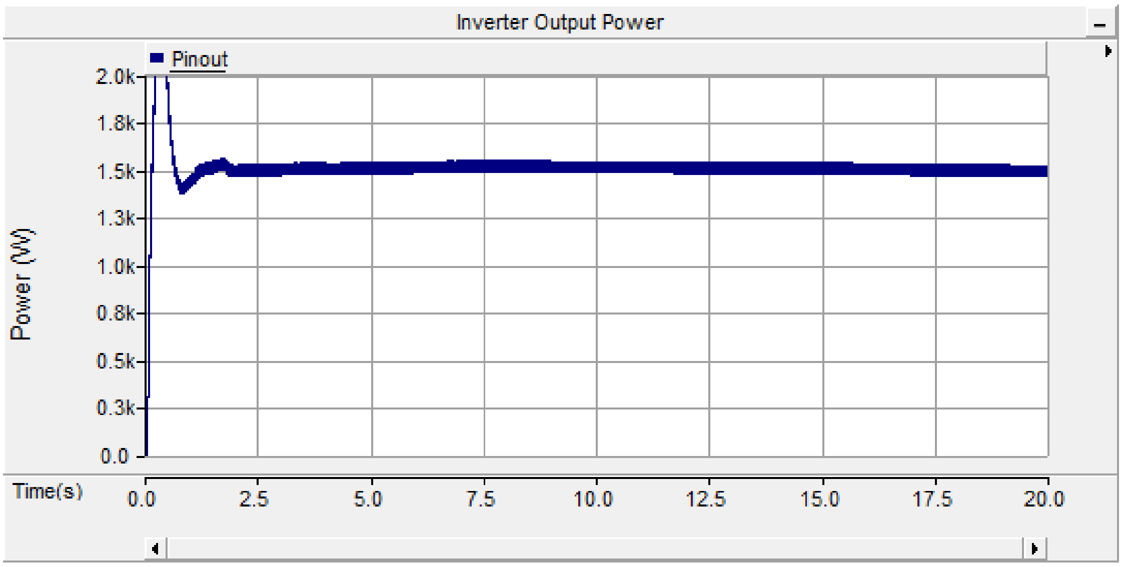


Figure 6.28 : Inverter Output Power for 1.5 kW Load

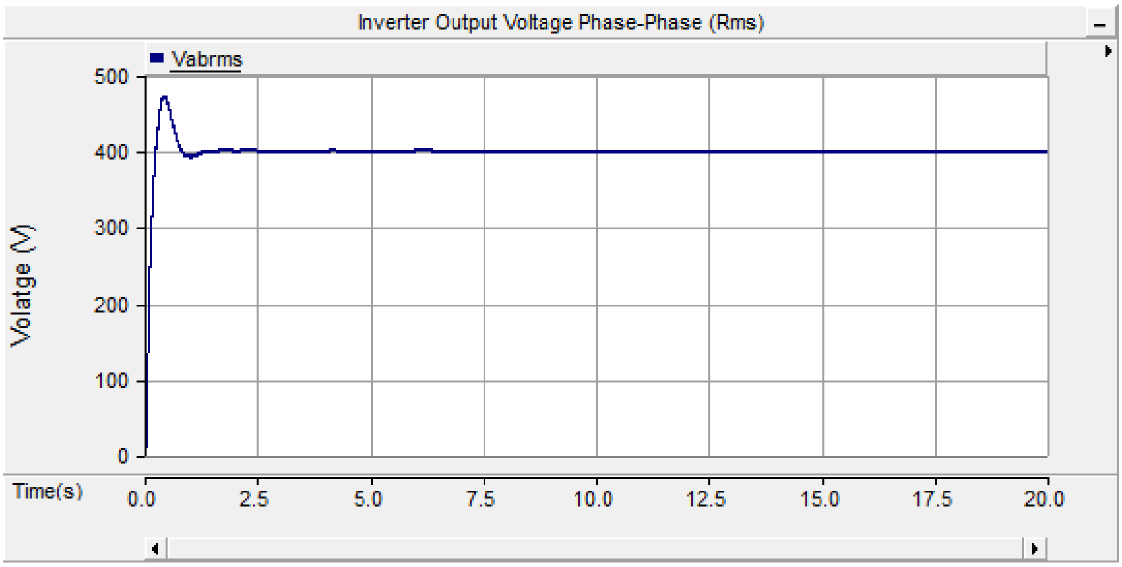


Figure 6.29 : Inverter Output Voltage for 1.5 kW Load

Figure 6.28 shows inverter output power for 1.5 kW load. Inverter feeds AC load regularly and its value reaches steady state value of 1.5 kW. Figure 6.29 shows inverter output voltage phase to phase rms value. In this study, its reaches steady state value of 400 V after 1 second. Figure 6.30 shows inverter output power under 2kW load. Its value reaches steady state value of 2 kW around 1s.

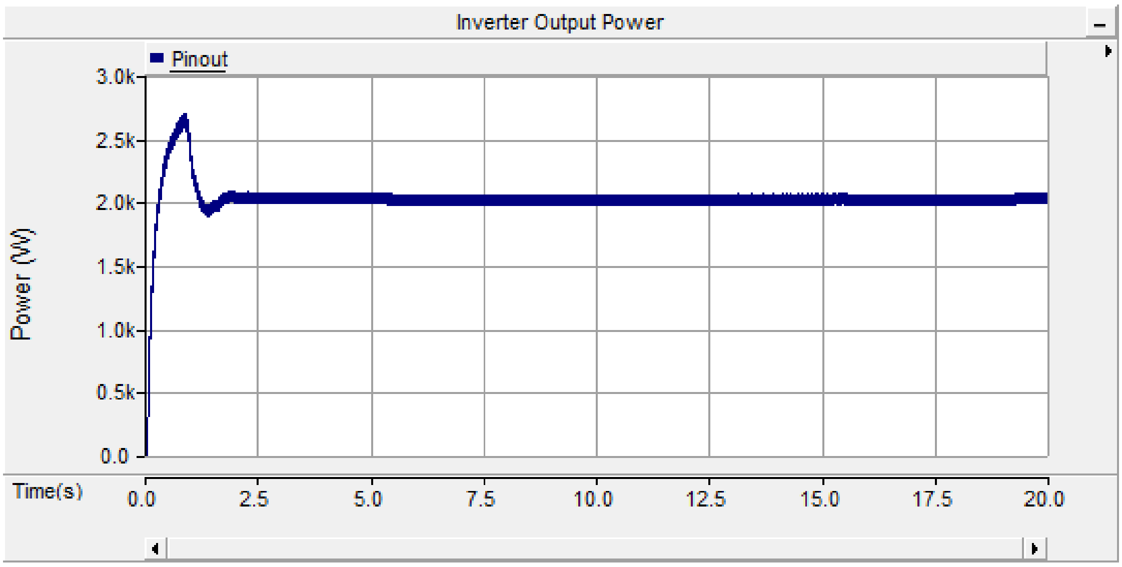


Figure 6.30 : Inverter Output Power for 2 kW Load

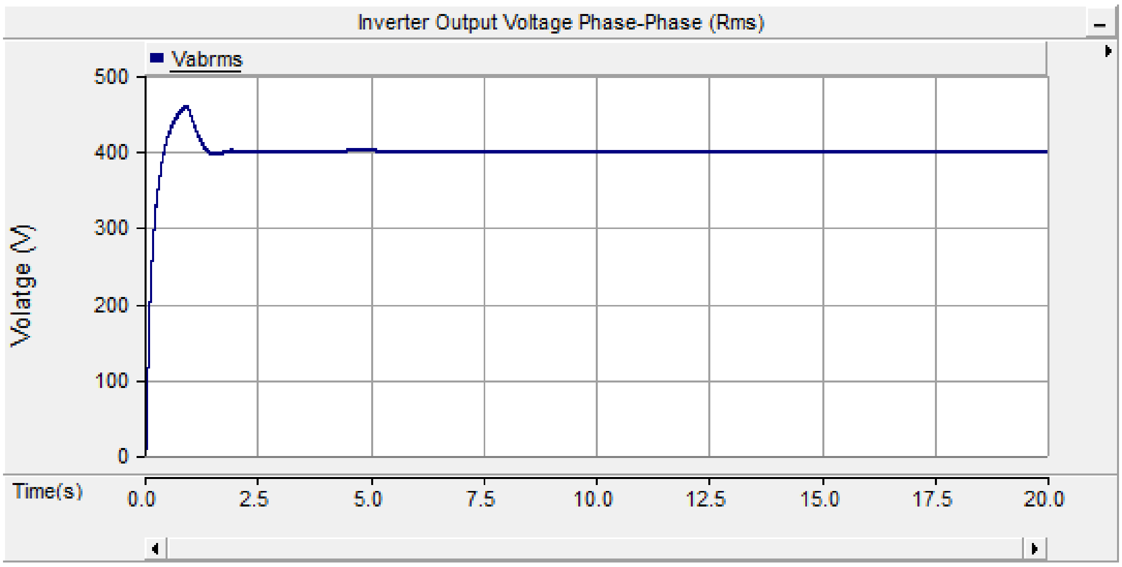


Figure 6.31 : Inverter Output Voltage for 2 kW Load

Figure 6.31 shows inverter output voltage for 2 kW load, and it reaches steady state value of 400 V. Figure 6.32 shows inverter output power for 4 kW load, and it reaches steady state value of 1.8 kW. Figure 6.35 shows inverter output voltage for 2 kW load. It reaches steady state value of 280 V.

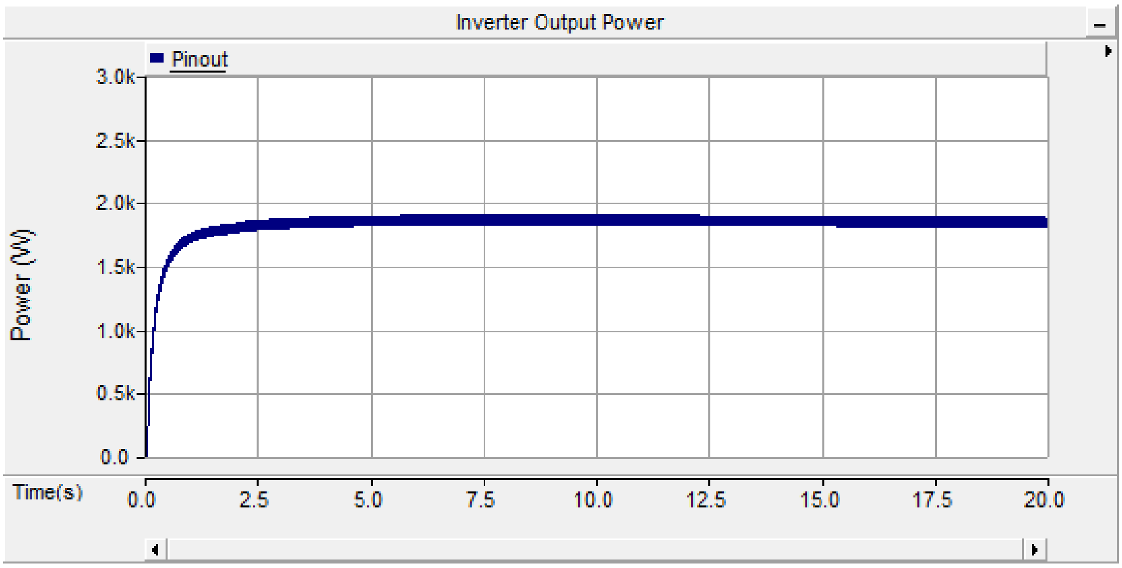


Figure 6.32 : Inverter Output Power for 4 kW Load

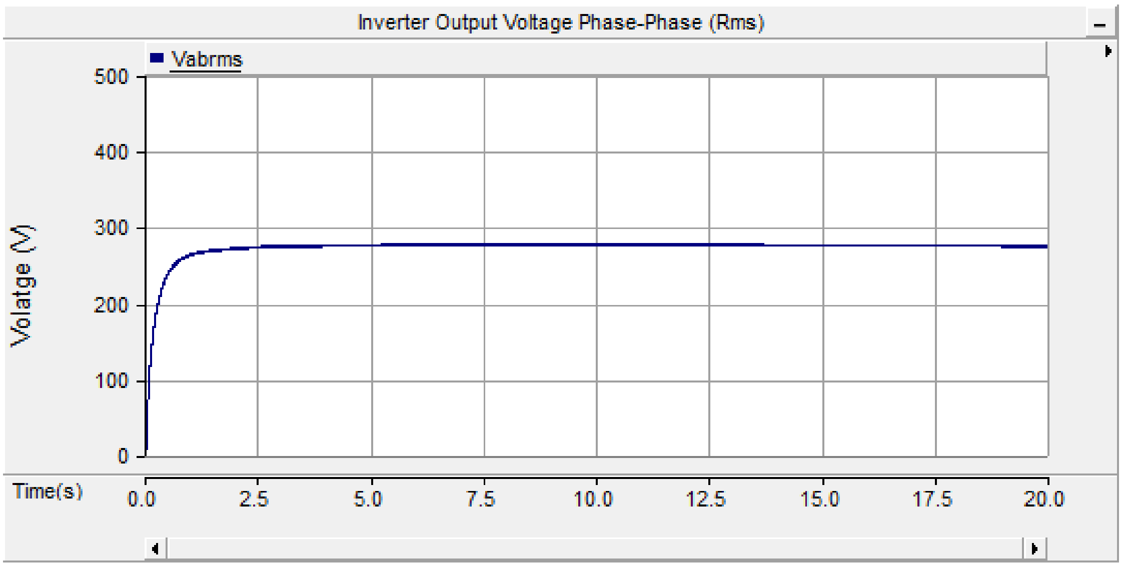


Figure 6.33 : Inverter Output Voltage for 2 kW Load

Fuel cell system can not feed the load because the fuel cell load capability and inverter's capability is 2.5 kW level. In addition, inverter output voltage is 280 V and it is shown figure 6.33 Inverter output voltage decreases due to overload.

6.6 Grid and Transmission Line Connected Fuel Cell

In this section, grid and transmission line connected to fuel cell will be examined. Grid connected fuel cell system using PSCAD software is shown in figure 6.34. The fuel cell system has three bus including infinite bus, load bus and fuel cell bus. The fuel cell system is connected to the infinite bus through a transmission line. The AC load is connected to the load bus.

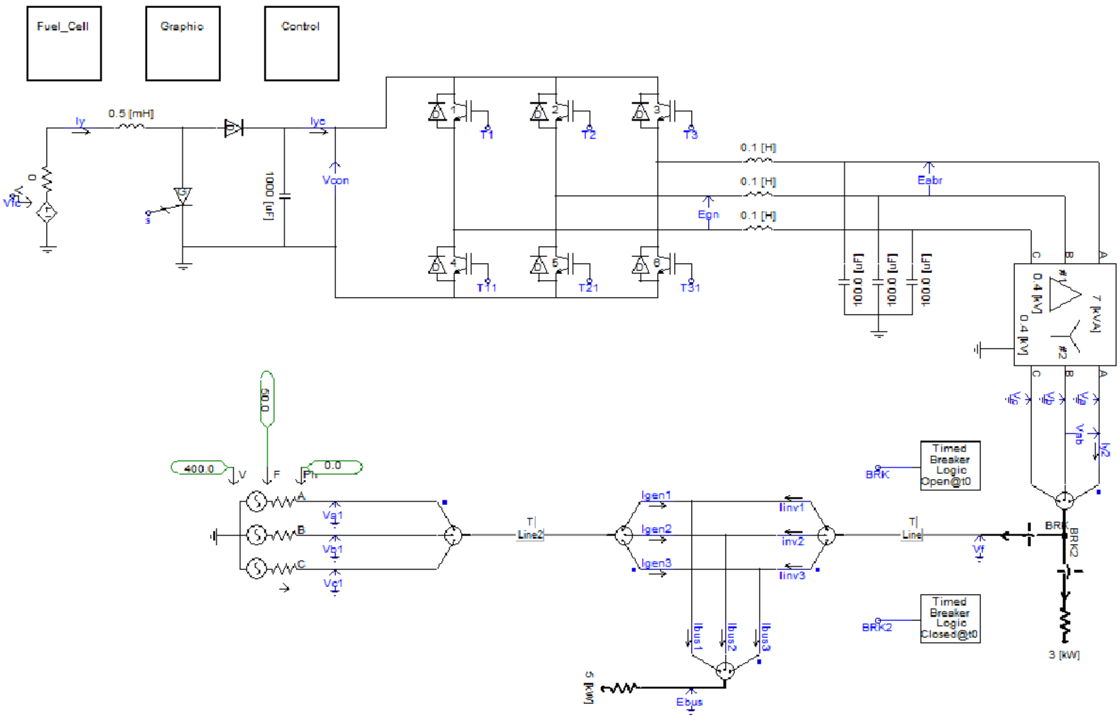


Figure 6.34 : Grid and Transmission Line Connected Fuel Cell

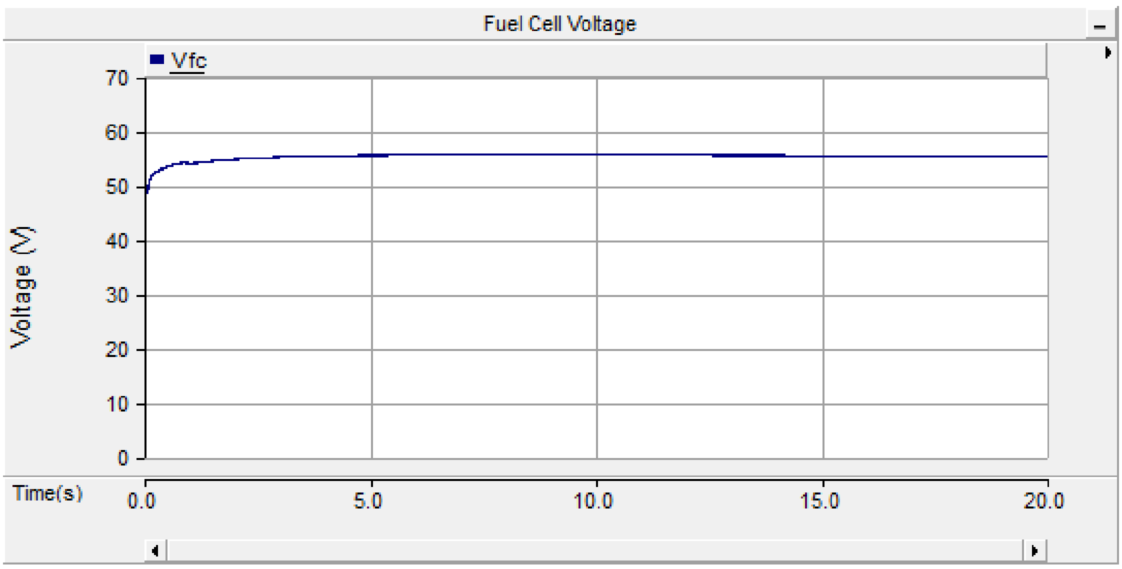


Figure 6.35 : Fuel Cell Voltage

In this grid connected model, figure 6.35 shows fuel cell voltage. Fuel cell voltage reaches steady state value of 56 V. It will be boosted 400 V with DC–DC converter. Figure 6.36 shows fuel cell power. It reaches steady state value of 3.6 kW in 3 seconds.

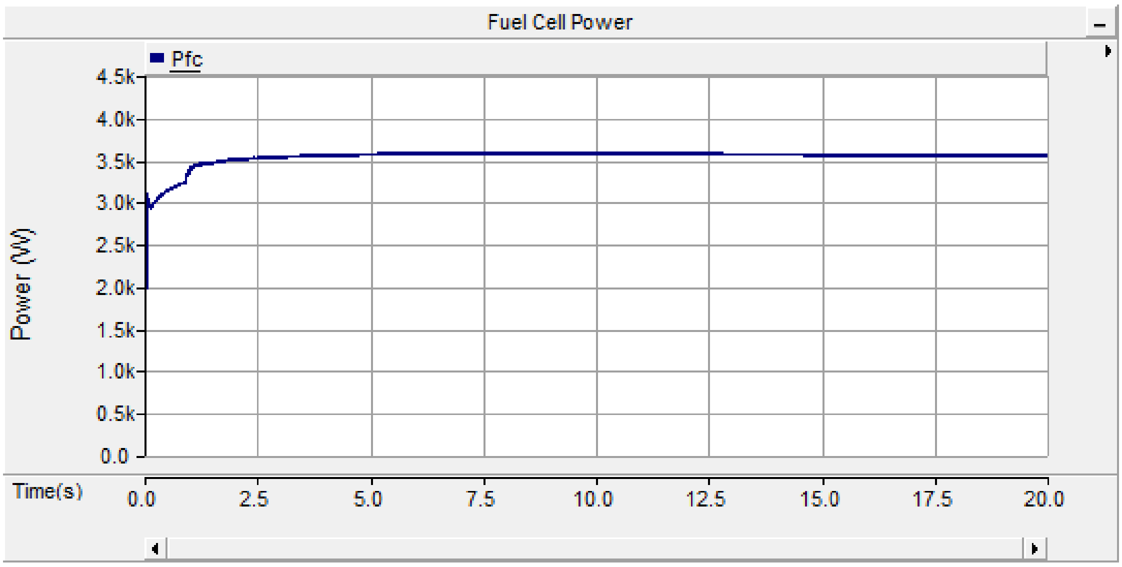


Figure 6.36 : Fuel Cell Power

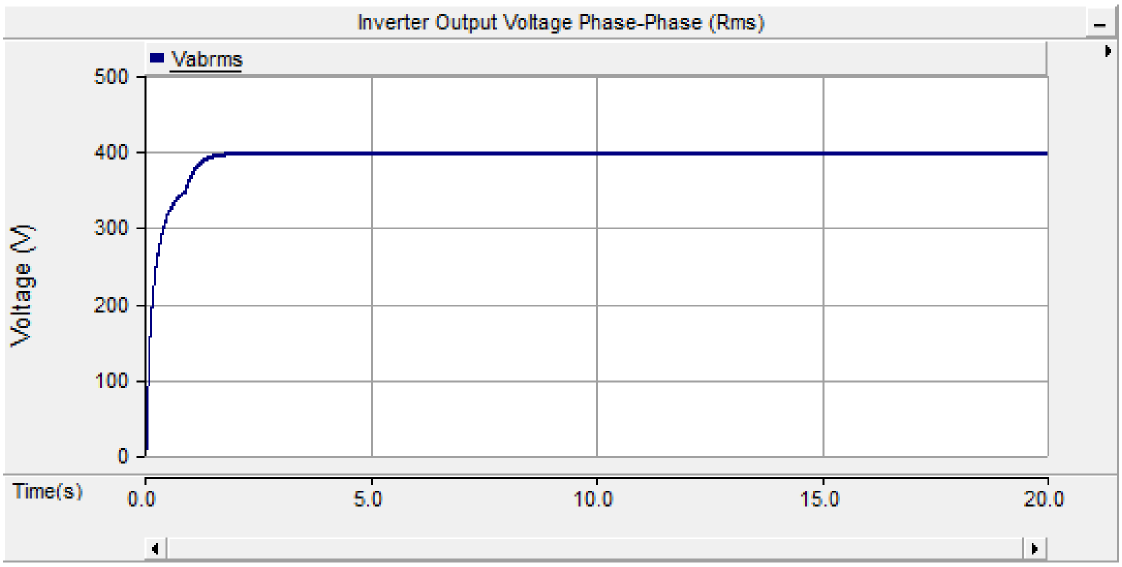


Figure 6.37 : Inverter Output Voltage Phase to Phase

Figure 6.37 shows inverter output voltage phase to phase rms value. The output voltage of inverter is averagely 400 V rms on average.

Figure 6.38 shows inverter current rms value. It reaches steady state value of 4 A in 2 seconds.

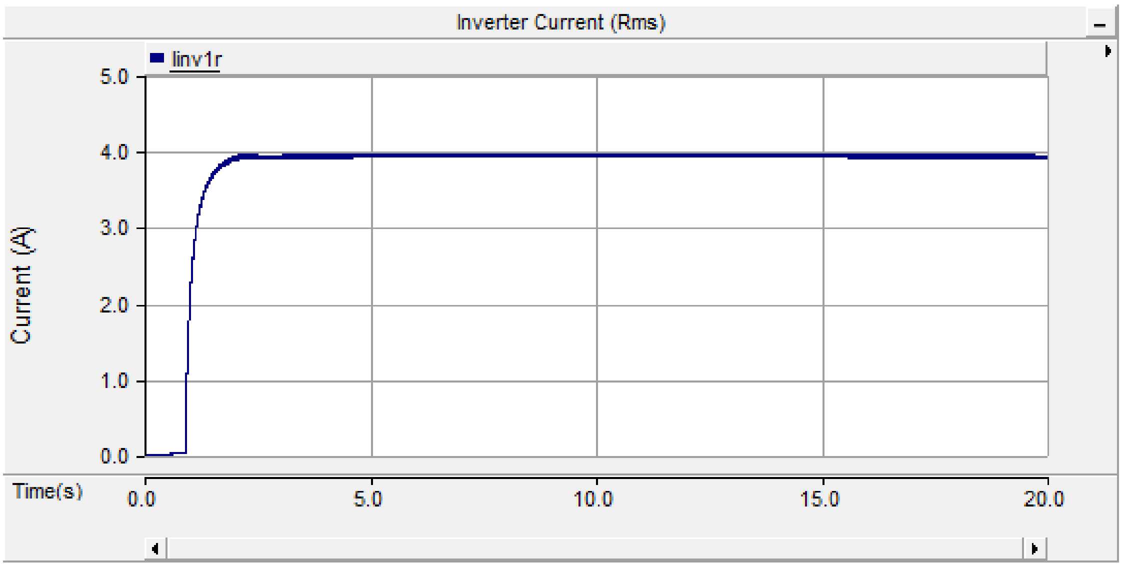


Figure 6.38 : Inverter Current Rms Value

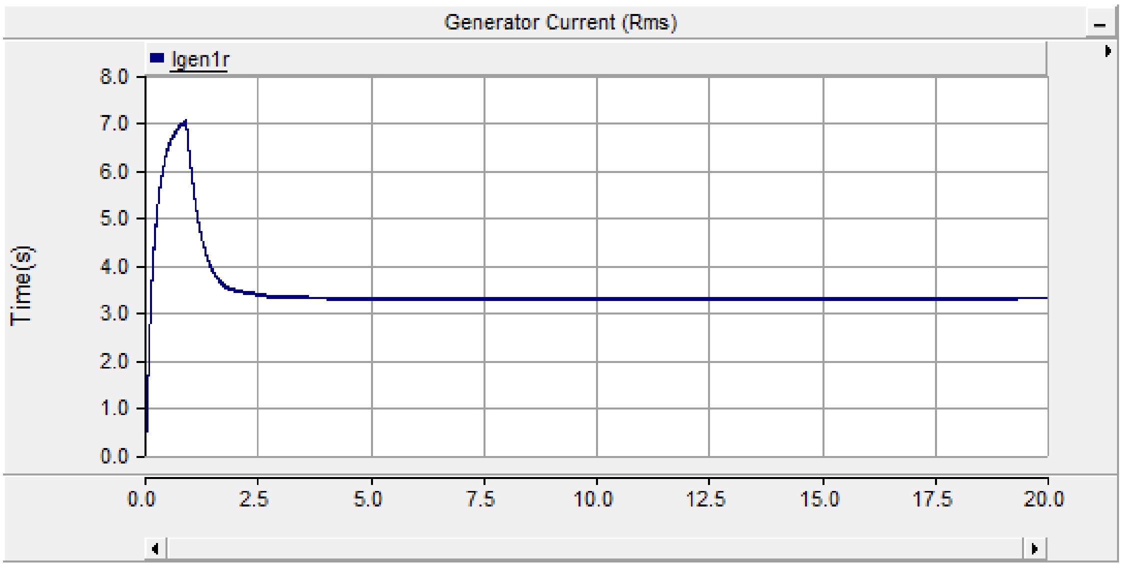


Figure 6.39 : Generator Current Rms Value

Figure 6.39 shows generator current rms value. Generator current increases suddenly in 2 seconds, then it reaches steady state value of 3.2 A.

Figure 6. 40 shows load bus current rms value. It reaches steady state value of 7.2 A in 2 seconds. In this system, the bus current equals the sum of generator current and inverter current.

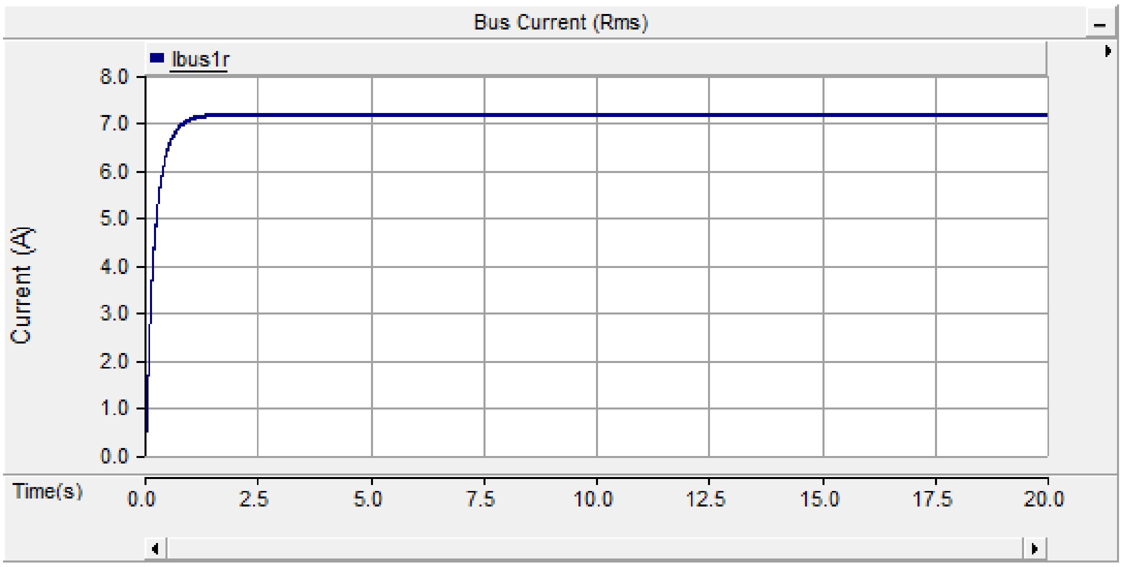


Figure 6.40 : Bus Current Rms Value

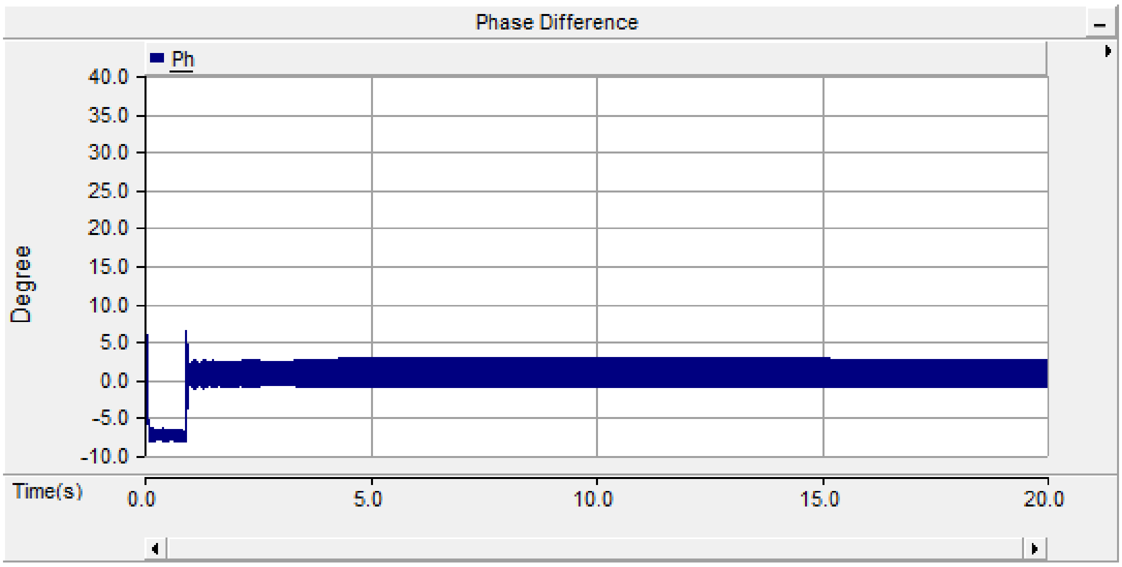


Figure 6.41 : Phase Difference Between Grid And Fuel Cell

Figure 6.41 shows phase differences between grid and fuel cell. The phase difference is almost zero degree. It reaches steady state value of 2 degrees in 2 seconds.

CHAPTER 7

THE EXPERIMENTS OF FUEL CELL AND COMPARISON WITH SIMULATION RESULTS

In this chapter, the dynamic performance of the Solid oxide fuel cell (SOFC) is tested under various load conditions. The DC power consumption of the load is measured using fuel cell test station in Niğde University Fuel Cell Research Laboratory. The fuel cell test station is shown figure 7.1. In addition, the results of experiments and simulations have been compared in terms of current, voltage and power values. Experiments and simulations have been done under various DC load. The effect of load change on fuel cell has been analyzed extensively.

Figure 7.1 : Fuel Cell Test Station

7.1 Experimental Setup

In this experiment, the SOFC stack has 5 cells, 16 cm^2 area and a nominal power capacity of 30 W and nominal open circuit voltage of 5.5 V. The SOFC cell is shown in figure 7.2. The hydrogen molar flow is 1.5 lt/min and the oxygen molar flow is 3 lt/min. The temprature of fuel cell system is 800 ^oC.

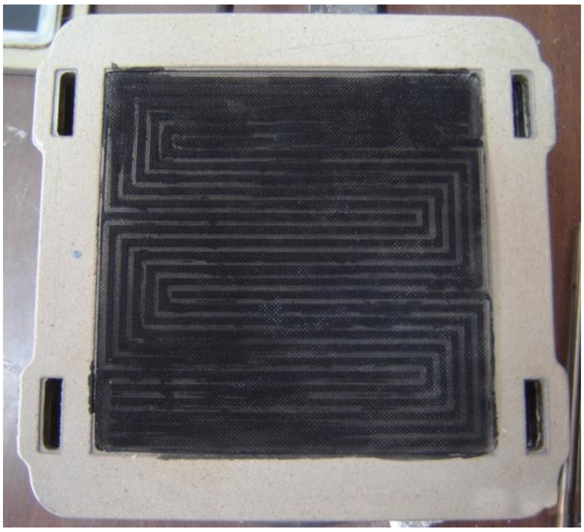


Figure 7.2 : Solid Oxide Fuel Cell

The proposed SOFC model has been tested with same load profile that has been used in the experiments. The fuel cell stack and experimental setup is shown figures 7.3 and 7.4 respectively.

Figure 7. 3 : SOFC Stack

Figure 7.4 : SOFC Experimental Setup

7.2 DC Load Experiments

In this section, the results of fuel cell experiments have been shown under variable DC load. Figure 7.5 shows a fuel cell current under variable DC load. Fuel cell current increases and decreases step by step. It reaches to maximum value of 11 A in 50 seconds, and then it drops gradually due to the load change.

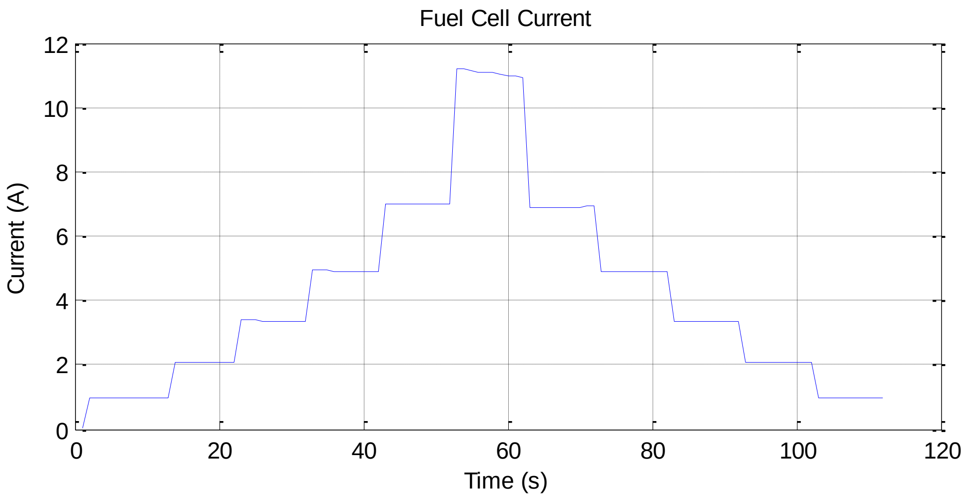


Figure 7.5 : Fuel Cell Current

Figure 7.6 shows fuel cell voltage in the range of 2.5 – 5.5 V under variable DC loads. Fuel cell voltage decreases as the load increases in 60 seconds.

Figure 7.7 shows fuel cell power in the range of 30 W under variable DC loads. Fuel cell is a good response time according to changing loads.

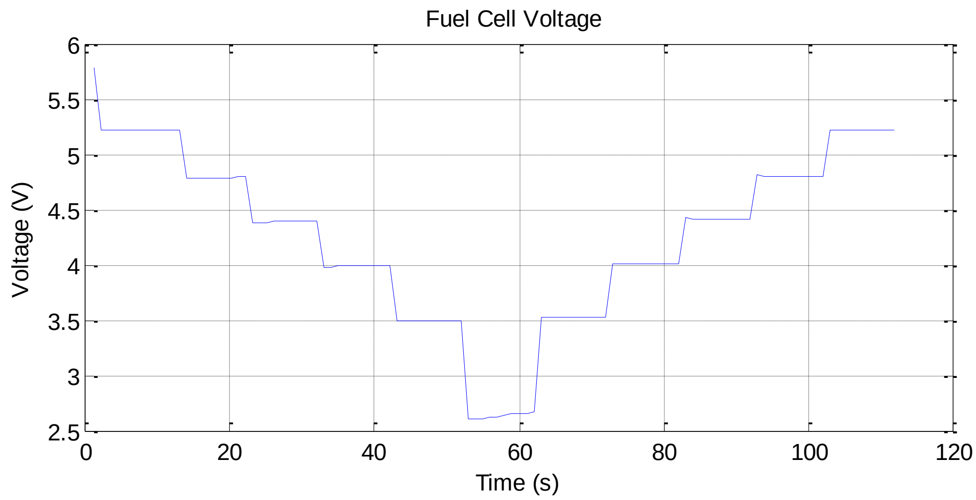


Figure 7.6 : Fuel Cell Voltage

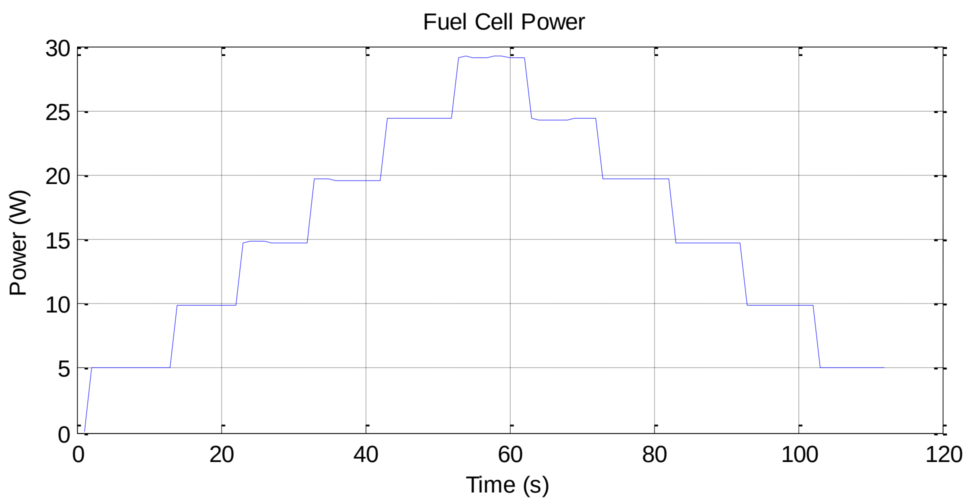


Figure 7.7 : Fuel Cell Power

7.3 The Simulation Results of Fuel Cell for Variable DC Loads

In this section, the behaviour of fuel cell has been simulated under variable DC loads. In this simulation results, 5 cells are used in fuel cell system. The parameters obtained from the SOFC experiments are used for simulatian studies and it is shown Table 7.1

Table 7.2 The Parameters Obtained From The SOFC Experiments

Parameters	**Representation**	**Units**	**Values**
T	Absolute Temprature	[K]	1273
F	Faraday's Constant	[C/mol]	96487
R	Universal Gas Constant	[J/(kmol×K)]	8314
E_0	Open Circuit Voltage	[V]	1.18
N_0	Number of Cells in Stack		5
K_r	Constant: K_r=N_0/4F	[kmol/(s×A)]	$1.29x10^{-8}$
K_{H_2O}	Valve Molar Constant for Water	[kmol/(s×atm)]	43.16 x 10^{-6}
K_{H_2}	Valve Molar Constant for Hydrogen	[kmol/(s×atm)]	4.77 x 10^{-6}
K_{O_2}	Valve Molar Constant for Oxygen	[kmol/(s×atm)]	19.13 $x10^{-6}$
τ_{H_2O}	Response Time for Water Flow	[s]	63.98
τ_{H_2}	Response Time for Hydrogen Flow	[s]	5.78
τ_{O_2}	Response Time for Oxygen Flow	[s]	14.44
r_{HO}	Ratio of Hydrogen to Oxygen		1.168
R_{ohm}	Ohmic Loss	[Ω]	0.21

In this simulation studies, the electrical characteristic of fuel cell has been analyzed in terms of voltage, current and power characteristics.

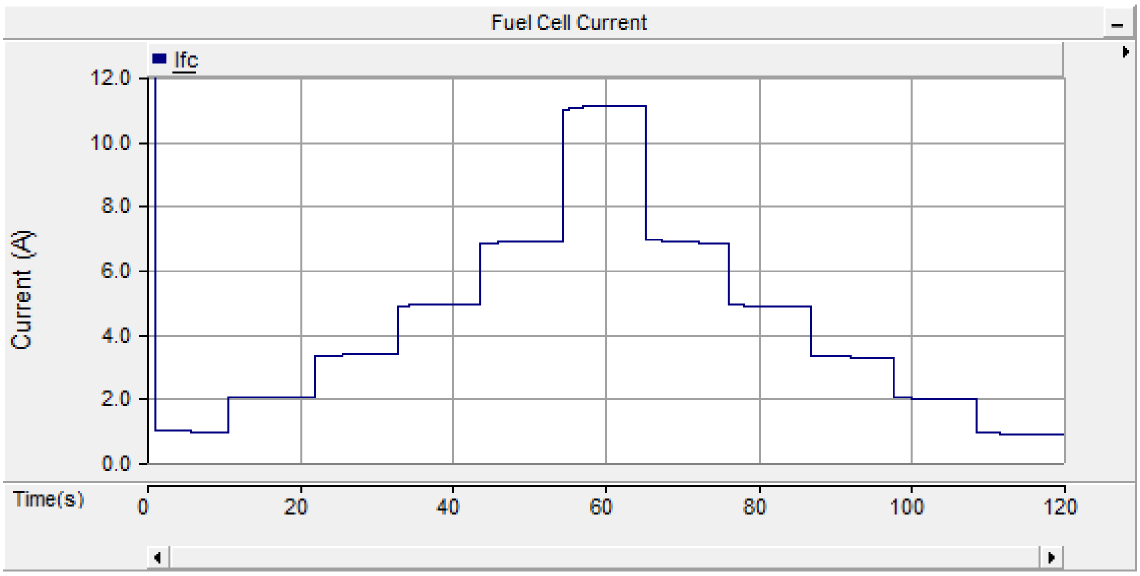


Figure 7.8 : Fuel Cell Current

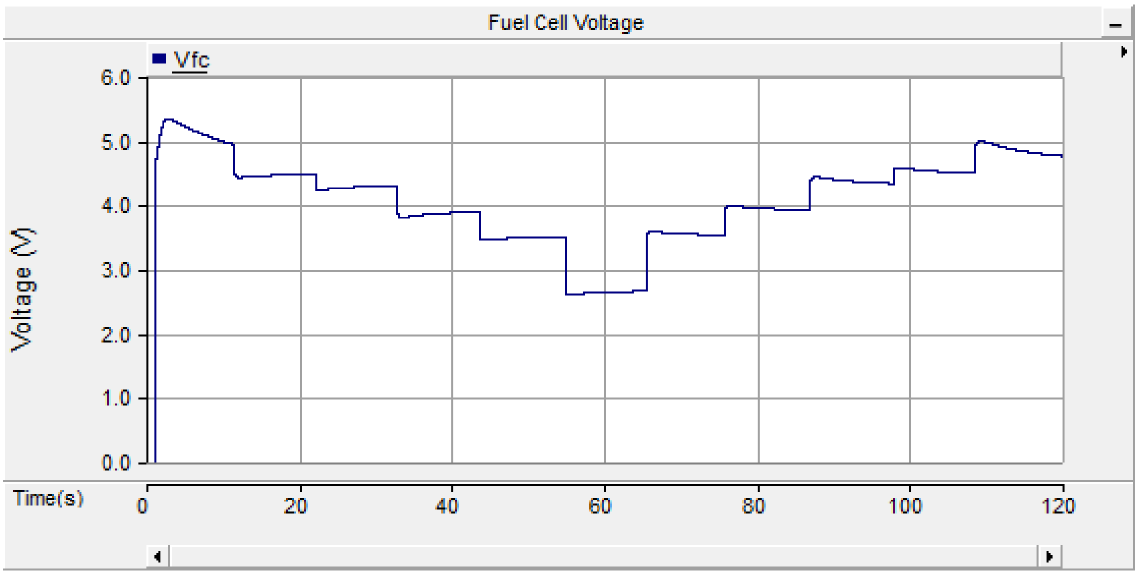


Figure 7.9 : Fuel Cell Voltage

Figure 7.8 shows fuel cell current under variable DC loads. Fuel cell current changes between 11 A and 1 A due to variable loads. Figure 7.9 shows fuel cell voltage under variable DC loads. Fuel cell voltage changes between 4 V and 2.8 V.

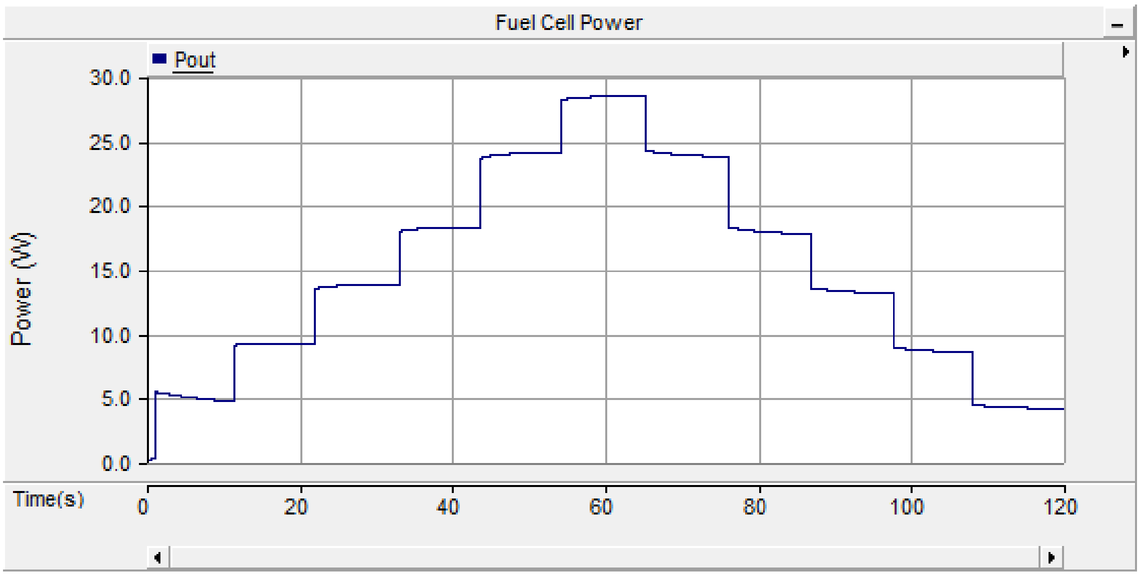


Figure 7.10 : Fuel Cell Power

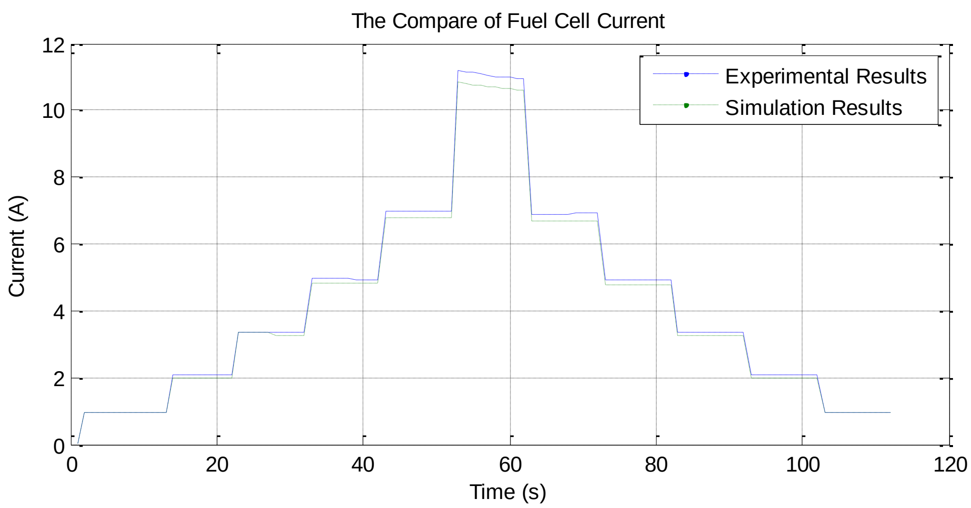


Figure 7.11 : The Comparison of Fuel Cell Current

Figure 7.10 shows fuel cell power under variable DC load. Fuel cell power increases and decreases based on variable load. The values of fuel cell power changes between 30 W and 5 W. The fuel cell experimental results and simulation results have been compared in detail. As a result of this comparison, they have been obtained similar values in terms of the comparison of fuel cell voltage, current and power. To validate the proposed model against the experimental results, the statistical indicate is used the absolute mean error. The error rate of this comparison is less than 2% level. Figure 7.11

shows the comparison of fuel cell current between experimental and simulation results under variable DC load. The values of experimental and simulation results change between 11 A and 5 A.

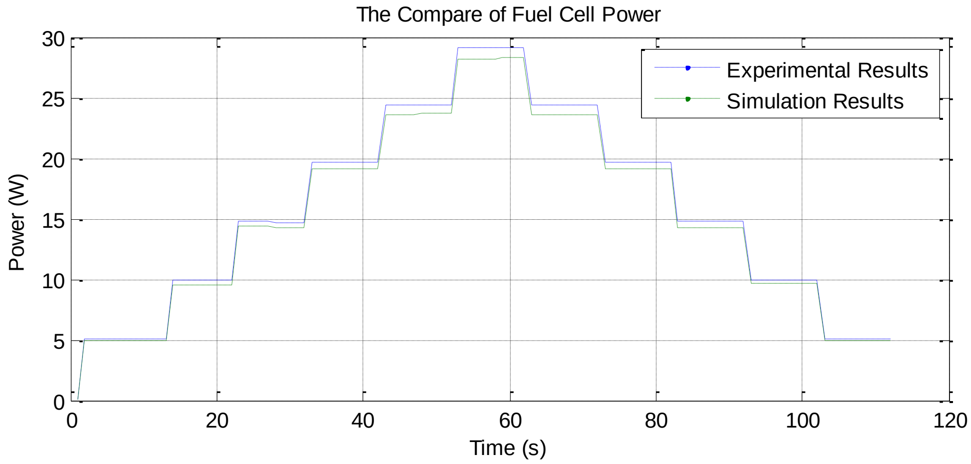


Figure 7.12 : The Comparison of Fuel Cell Power

Figure 7.12 shows the comparison of fuel cell power under varible DC loads. Figure 7.13 shows the comparison of fuel cell voltage and it changes between 4 V and 2.6 V due to variable loads.

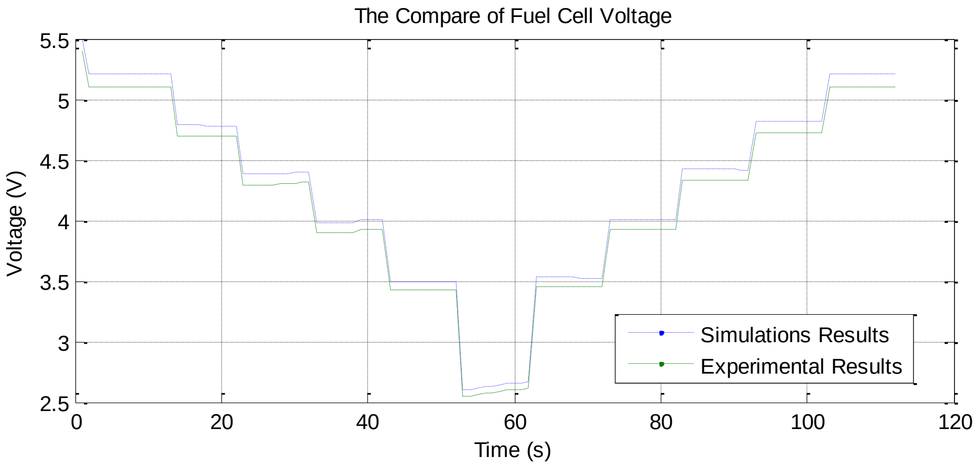


Figure 7.13 : The Cmparison of Fuel Cell Voltage

CHAPTER 8

CONCLUSION

8.1 Conclusion

The dynamic model of the solid oxide fuel cell (SOFC) is developed using PSCAD software. A DC – DC boost converter structure is modeled using PSCAD software. In addition, DC – DC converter closed loop control feedback system have been built. The three phase voltage source inverter has been modeled and connected to between SOFC model and transmission line. A control strategy for the inverter switching signals has been analyzed and modeled successfully.

The characteristics of fuel cell are obtained for constant and variable DC loads. The response of the fuel cell stack is tested under variable loads. There is a good match between experimental and simulation results. The fuel cell experimentals are done and compared to simulation results for fuel cell system. The dynamic performance of the solid oxide fuel cell is tested under various load conditions. The DC power consumption of the load is measured using fuel cell test station in Niğde University, Fuel Cell Research Center. Simulation and experimental results are very close to each other under DC load conditions. The error rate of the comparison is around 3 percent.

The characteristics of converter are obtained for constant and variable DC loads. The converter is connected to fuel cell, and fuel cell voltage is boosted for the desired value. A conventional PI control structure is used for DC–DC converter feedback system.The inverter control scheme uses a sinusoidal pulse width modulation (SPWM) and PI control strategy to control the output voltage. The power conditioning unit including DC–DC converter and DC–AC inverter implemented in PSCAD.

The fuel cell system is connected to the infinite bus through a transmission line. The phase locked loop (PLL) structure is used to control phase angle between grid and fuel cell system. The DC and AC performance of SOFC are tested for different loads using PSCAD. The solid oxide fuel cell system is connected to grid through a transmission line and, the behaviour of variable AC load is examined using PSCAD. Finally, a three bus system including infinite bus, load bus and fuel cell bus is implemented in PSCAD. In three bus system, then the load bus is fed together with infinite bus and fuel cell bus. The 5 kW AC load is connected to load bus. The fuel cell bus current is 4A, and infinite bus current is 3.2A, and also load bus current is 7.2A. If the AC load is higher than fuel cell maximum load capacity, the infinite bus feeds the AC load.

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