www.thericjournal.ait.ac.th

Modeling and Performance Analysis of Solid Oxide Fuel Cell Based Distributed Generation System

Birendra Kumar Singh*, Dattataraya N. Gaonkar+1, Radhakrishna S. Aithal#, and Govind Sharma@

Abstract – *Fuel cells are widely recognized as one of the most promising technologies to meet the future power generation requirements. The accurate modeling and performance study is crucial to the success of their deployment in the power system. This paper presents the dynamic model of solid oxide fuel cell (SOFC) based distributed generation system for isolated application. The model is implemented and its performance has been studied in MATLAB/SIMULINK software. The developed model reflects the electrochemical reaction dynamics and major voltage losses in SOFC. A constant utilization mode has been adopted for operation of fuel cell using current feedback to adjust the hydrogen input flow rate. The proposed scheme has been used to study the dynamic performance of the SOFC based DG system for step change in three phase isolated load. A DC/DC power electronic converter and PWM based three phase inverter topology is considered to regulated the fuel cell voltage and interface the three phase AC load respectively along with the control schemes. The simulation results reported in the paper shows that the developed model is able to maintain load voltage constant and also the follow load changes accurately.*

Keywords – dynamic modeling, fuel cells, isolated load, and PWM inverter.

1. INTRODUCTION

The continuous increasing demand of energy has created the need of alternative energy sources to supplement the conventional existing generation amenities. But growing in tandem with energy demands are the concerns about sustainable development and environmental issues, such as the movement to reduce greenhouse gas emissions. The result of fulfilling energy needs and meeting environmental, social concerns is the growing interest in reliable distributed energy sources. Distributed generation encompasses a wide range of prime mover technologies such as wind, photovoltaic, microturbines and fuel cell. Among DG systems, much attention is focused on environmental friendly fuel cell. Fuel cell (FC), being a nonconventional source of energy, is considered as an alternative to fossil energy mainly due to its clean and non-polluting nature, high efficiency, safety, and reliability. Hence, FC is set to become the power source of the future. Fuel cells DGs can be connected to a utility grid or an isolated load applications.

There are many types of fuel cells are available. Among them, the solid oxide fuel cells are considered as a promising type of fuel cell technology for distributed generation (DG) and stationary applications, where there is a demand for both heat and power. SOFC converts chemical energy into electrical energy at higher temperature (500 ^{0}C – 1000 ^{0}C) compared other types of fuel cells such as PEM fuel cell [1].Since the SOFCs operate at a high temperature, they do not have any complex problems with electrolyte management. A number of literatures have been reported on the works of solid oxide fuel cell (SOFC). The dynamic modeling of SOFC, are presented in [2], [3], [4]. Different voltage losses have been considered in finding the stack voltage of SOFC [5]. In [2], only ohmic voltage loss has been taken into account to find SOFC stack voltage. The control of SOFC for standalone mode with DC/DC boost converter and grid connected mode with DC/DC converter, along with a DC/AC inverter were proposed using fuzzy logic [6]. Although the modeling of SOFCs were attempted in many literatures, yet a very few of them are reported about the power electronic converter interface control schemes. In this model, a PWM based inverter, along with active and reactive power control scheme to keep the voltage constant at the load terminals.

In this work the mathematical modeling of SOFC, along with its configuration has been given. The dynamic model of SOFC is implemented in the Matlab/ Simulink. The power electronic converter control scheme using active and reactive power PI controller is developed. The simulation results of the performance study of the developed model using isolated three phase load is presented.

2. DYNAMIC MODELING OF SOFC

Fuel cell is an electrochemical device that converts chemical energy into electrical energy through performance of chemical reaction. In Figure 1 a single

---

*Department of Electrical and Electronics Engineering, Manipal Institute of Technology, Manipal-576104, Karnataka, India.

+Department of Electrical and Electronics Engineering, National Institute of Technology Karnataka Surathkal, Mangalore-575025, Karnataka, India.

#Department of Electrical and Electronics Engineering, Manipal Institute of Technology, Manipal-576104, Karnataka, India.

@Department of Computer Science and Automation, Indian Institute of Science, Bangalore, India.

[1] Corresponding author;
Tel: + 918242474000 ext 3457, Fax: + 91824247093
E-mail: dngaonkar@gmail.com.

cell configuration of SOFC is shown [7]. A typical fuel cell consists of two electrodes, viz. anode, and cathode that are separated by an electrolyte. At cathode, reduction of oxygen occurs and at anode, the oxidation of fuel (hydrogen) takes place and thus the chemical reaction of reactants releases electrons with water and heat as by-products which make them suitable for CHP (Combined Heat and Power) application [8], [9]. The electrons flow from anode to cathode through external circuit. Electrolyte does not allow the electrons through it but allows the conduction of ionic charge between the electrodes.SOFC is considered in this paper due to the following significant features:

- It is suitable for stationary power applications with step load changes.
- It provides higher system efficiency, higher power density, and a design simpler than a fuel cell based on liquid electrolytes.
- The exhaust heat in case of SOFC is utilized for co-generation application in industries.
- Internal reforming of natural gas may reduce 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.
- SOFCs are flexible in the choice of fuel such as carbon-based fuels, like natural gas.
- SOFCs technology is suited for distributed generation application because of its high conversion efficiency.
- It has an ability to integrate with other power generating systems, such as automotive engines or various size gas turbines.

The chemical reactions that take place at anode and cathode in SOFC to produce electricity are given as follows: [7], [8], [9].

i. Anode:

$$H_2 + \frac{1}{2}O^{2-} \rightarrow H_2O + 2e^- \quad (1)$$

ii. Cathode:

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

The overall cell reaction that takes place is:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \quad (3)$$

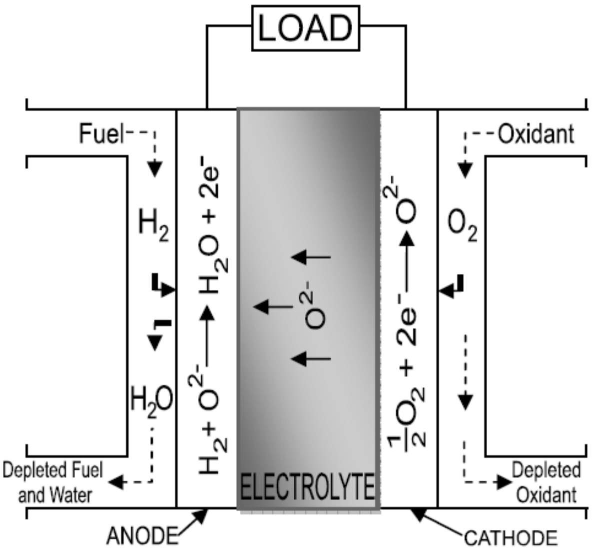

Fig.1. Basic structure of a fuel cell [7].

The electrolyte in SOFC is typically made from zirconium doped with yttrium. On cathode side, oxygen catalytically reacts with electrons supplied to produce oxygen ions. These ions travel through the electrolyte to anode wherein they react with hydrogen fuel on anode side and produces electrons and water. The flow of electrons through external circuit is the production of electric current. The following assumptions are made in the development of SOFC model: [2], [3].

- FC is fed with hydrogen and oxygen.
- The used gases are ideal (the chemical and physical properties of the materials are not co-related with pressure).
- Nernst equation is applicable.
- FC temperature is stable at all times.
- The channels have a fixed volume to transport gases along the electrodes and their lengths are so small that only a single pressure value is required to be defined in their interior.
- The ratio of pressure between inside and outside of the channels is sufficient to consider choked flow.
- Ohmic, activation, and concentration losses are considered.

The change in Gibbs free energy of formation is given as follows: [8]

$$\Delta G_f = \Delta G_f^{product} - \Delta G_f^{reactant} \quad (4)$$

The Gibbs energy of formation per mole is given by:

$$\Delta \bar{g}_f = \left(\bar{g}_f\right)_{H_2O} - \left(\bar{g}_f\right)_{H_2} - \frac{1}{2}\left(\bar{g}_f\right)_{O_2} \tag{5}$$

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

$$V_{cell_{rev}} = -\frac{\Delta \bar{g}_f}{2F} \tag{6}$$

Where, F is the Faraday's constant (96487 C/mol).

The change in Gibbs free energy varies with different pressure and temperature of the fuel cell, which in turn changes the voltage of fuel cell. The equation shows how $\Delta \bar{g}_f$ varies from its standard value which is stated at STP [8].

$$\Delta \bar{g}_f = \Delta g_f^{\,0} - RT\ln\left(\frac{p_{H_2O} - p_{O_2}^{\,0.5}}{p_{H_2O}}\right) \tag{7}$$

Where, T is the operating temperature of fuel cell in K, R is the universal gas constant (8.31 J/mol/K) and $\Delta \bar{g}_f^{\,0}$ is the change in Gibbs free energy of formation per mole at standard pressure. Using $E_0 = -\frac{\Delta \bar{g}_f^{\,0}}{2F}$ and substituting the value of $\Delta \bar{g}_f^{\,0}$ from Equation 7 in Equation 6 gives the following equation, which shows the effect of pressure on Nernst equation at standard temperature [8].

$$V_{nernst} = E_0 + \frac{RT}{2F}\ln\left(\frac{p_{H_2}p_{O_2}^{\,0.5}}{p_{H_2O}}\right) \tag{8}$$

The above equation gives reversible voltage (open circuit voltage) of each cell, also known as Nernst voltage at standard temperature and varying pressure. By taking into consideration that the molar flow of any gas through any valve is proportional to its partial pressure inside the channel, the following equations are obtained: [2]

$$\frac{q_{H_2}}{p_{H_2}} = \frac{K_{an}}{\sqrt{M_{H_2}}} = K_{H_2} \tag{9}$$

$$\frac{q_{H_2O}}{p_{H_2O}} = \frac{K_{an}}{\sqrt{M_{H_2O}}} = K_{H_2O} \tag{10}$$

where q_{H_2} and q_{H_2O} are the molar flows of hydrogen and water through the anode valve respectively; p_{H_2} and p_{H_2O} are the partial pressures of hydrogen and water in atm respectively; K_{an} is the anode valve constant; M_{H_2} and M_{H_2O} are the molecular masses of hydrogen and water respectively; K_{H_2} and K_{H_2O} are the valve molar constant for hydrogen and water, respectively.

i. Calculation of Partial Pressures

Using the ideal gas law, the partial pressure of the gases is calculated as follows [2]. For hydrogen,

$$p_{H_2}V_{an} = n_{H_2}RT \tag{11}$$

where, V_{an} is the volume of anode-channel and n_{H_2} is the hydrogen moles in the channel. R and T are the universal gas constant and the operating temperature respectively, of the fuel cell stack.

From Equation (8)

$$p_{H_2} = \frac{n_{H_2}RT}{V_{an}} \tag{12}$$

Taking the first derivative of Equation 12:

$$\frac{d}{dt}\left(p_{H_2}\right) = \frac{d}{dt}\left(\frac{n_{H_2}RT}{V_{an}}\right) \tag{13}$$

$$= \frac{q_{H_2}RT}{V_{an}} \tag{14}$$

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 in to three parts and their relationships can be expressed as follows [2], [10].

$$\frac{d}{dt}\left(p_{H_2}\right) = \frac{RT}{V_{an}}\left(q_{H_2}^{in} - q_{H_2}^{out} - q_{H_2}^{r}\right) \tag{15}$$

where $q_{H_2}^{in}$ and $q_{H_2}^{out}$ are the molar flow rates of hydrogen in and out of the channel respectively and $q_{H_2}^{r}$ is the molar flow rate reacting in the channel.

The quantity of hydrogen flow that reacts is given as follows: [2], [3]

$$q_{H_2}^{r} = \frac{N_0 I_{fc}}{2F} = 2K_r I_{fc} \tag{16}$$

where, N_0 is the number of cells connected in series in the stack, I_{fc} is the stack current and K_r is modeling constant given as follows:

$$K_r = \frac{N_0}{2F} \tag{17}$$

From Equations 15 and 16, the time derivative of the hydrogen partial pressure is expressed as follows [2], [10].

$$\frac{d}{dt}\left(p_{H_2}\right) = \frac{RT}{V_{an}}\left(q_{H_2}^{in} - q_{H_2}^{out} - 2K_r I_{fc}\right) \tag{18}$$

The equation for hydrogen partial pressure can be obtained by substituting the molar output flow of hydrogen from Equation 9 in Equation 18 and taking the Laplace transform, as follows:

$$p_{H_2} = \frac{1/K_{H_2}}{1 + \tau_{H_2} s}\left(q^{in}_{H_2} - 2K_r I_{fc}\right) \qquad (19)$$

where, τ_{H_2} is the value of system pole associated with the hydrogen flow, expressed in seconds and is given as follows:

$$\tau_{H_2} = \frac{V_{an}}{K_{H_2} RT} \qquad (20)$$

Similarly, the partial pressure for the reactant, oxygen and product, water can be expressed as follows:

$$p_{O_2} = \frac{1/K_{O_2}}{1 + \tau_{O_2} s}\left(q^{in}_{O_2} - K_r I_{fc}\right) \qquad (21)$$

$$p_{H_2O} = \frac{1/K_{H_2O}}{1 + \tau_{H_2O} s}\left(2K_r I_{fc}\right) \qquad (22)$$

ii. Stack Voltage

The stack output voltage, V_{stack} 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: [10], [11]

$$V_{fc} = E - V_{act} - V_{conc} - V_{ohmic} \qquad (23)$$

where, V is the open circuit voltage, given by:

$$E = N_0 V_{nernst} = N_0 \left\{ E_{0_{cell}} + \frac{RT}{2F}\left(\ln \frac{p_{H_2} p_{O_2}^{0.5}}{p_{H_2O}} \right) \right\} \qquad (24)$$

$$V_{stack} = E - A\log\left(\frac{i}{i_0}\right) - m\exp\left(ni\right) - rI_{fc} \qquad (25)$$

where V_{stack} is the total output voltage of a stack, A is Tafel line constant, m , n are constants, i is the current density and $E_{0_{cell}}$, a function of temperature, can be expressed as [10]:

$$E_{0_{cell}} = E_0 - K_E\left(T - 298\right) \qquad (26)$$

where $E_{0_{cell}}$ is the ideal standard voltage at standard state 298 K and 1-atm pressure.

iii. Calculation of Voltage Losses

a. Activation Losses

The reason for this loss in SOFC is the sluggishness of the chemical reaction that takes place on the surface of the electrodes. A certain amount of voltage produced by fuel cell is lost in carrying forward the reaction that transfers the electrons to or from the electrode. Activation losses are estimated using Tafel equation [7], [8], [11], [12], [13].

$$V_{act} = B \ln\left(\frac{i}{i_0}\right) \qquad (27)$$

Where B is the Tafel line constant, given by:

$$B = \frac{RT}{2F\alpha} \qquad (28)$$

The constant, α is the charge transfer coefficient and is proportionate to the electrical energy applied that is harnessed in changing the rate of an electrochemical reaction. The value of α depends on the reaction involved as well as on the materials used for electrode. Its value ranges from 0.0 to 1.0.

b. Concentration Losses

These losses are caused due to the reduction in the concentration of the 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 this reduction in concentrations, there is a drop in partial pressure of gases, which will result in a reduction in voltage. It is given as the follows: [8].

$$V_{conc} = \frac{RT}{2F}\left(1 - \frac{i}{i_L}\right) \qquad (29)$$

The value of i is always is always smaller than i_L . Nevertheless, in this paper, another equation has been used to estimate the concentration loss, which gives very good results if the constant are chosen properly, which is: [7].

$$V_{conc} = m\exp(ni) \qquad (30)$$

c. Ohmic Losses

These losses in SOFCs are caused due to the resistance both to flow of electrons through the electrode and to the migration of ions through the electrolyte. In addition, the fuel cell interconnects or bipolar plates also contribute to the ohmic losses [7], [8]. Ohmic loss is given as

$$V_{ohmic} = rI_{fc} \qquad (31)$$

Where, r is an internal resistance.

The volt – ampere characteristic of one cell of SOFC is shown in Figure 2. The dynamic model of SOFC fuel cell is shown in Figure 3.

The SOFC model is based on the expression for partial pressures of reactants (hydrogen and oxygen) and water, Nernst equation, various voltage losses as discussed in this section and the different parameters pertaining to SOFC model such as electrical response time, fuel system response time, maximum and minimum fuel utilization and many others as listed in Table 1.

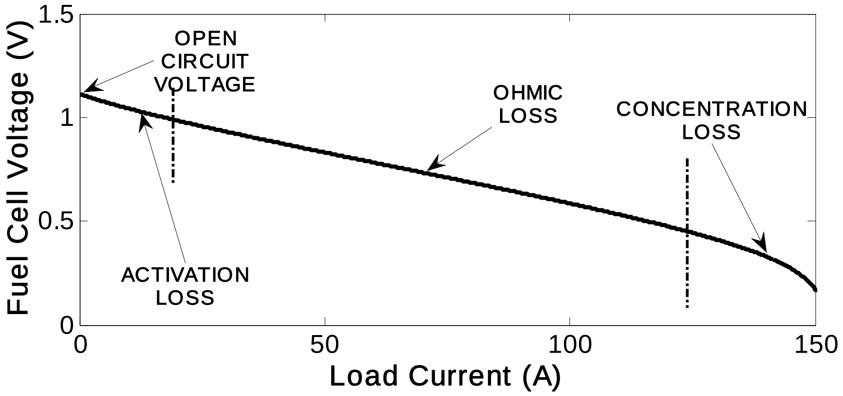

Fig. 2.Volt - Ampere characteristics of SOFC.

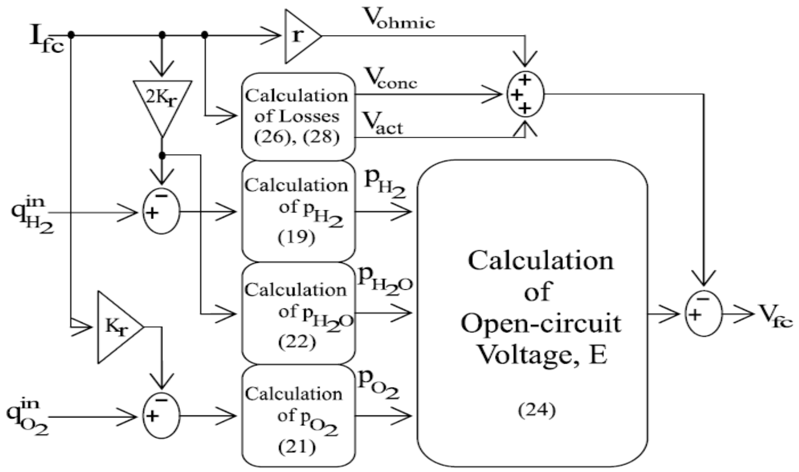

Fig. 3. SOFC system dynamic model.

Table 1. Parameters of the SOFC Model.

Symbol	Parameter representation	Value
P_{rated}	Rated power	100 kW
P_{ref}	Reference power	100 kW
T	Operating temperature	1273 K
F	Faraday's constant	96487 C/mol
R	Universal gas constant	8.431 J/(mol K)
E_0	Ideal standard potential	1.18 V
N_0	Number of Cells	800
U_{max}	Maximum fuel utilization	0.9
K_{H_2}	Valve molar constant for hydrogen	8.43×10^{-4} kmol (s atm)
K_{H_2O}	Valve molar constant for water	2.81×10^{-4} kmol (s atm)
K_{O_2}	Valve molar constant for Oxygen	2.52×10^{-4} mol (s atm)
τ_{H_2}	Response time for hydrogen	26.1 sec
τ_{H_2O}	Response time for water	78.3 sec
τ_{O_2}	Response time for oxygen	2.91 sec
r	Ohmic resistance	0.126 Ω
m	Mass transportation constant	1×10^{-3}
n	Mass transportation constant	8×10^{-3}
A	Electrode area	0.5 m^2
B	Tafel line constant	0.002

Fuel cells can be operated in two basic modes, one is constant input mode and another one is 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 [2] and is expressed as:

$$U_f = \frac{q^r_{H_2}}{q^{in}_{H_2}} \tag{32}$$

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 [2],[3]. 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 [14]. For definite hydrogen input flow, the demand current of fuel cell system can be limited in the range given as: [2]

$$\frac{0.8 q^{in}_{H_2}}{2K_r} \le I_{fc} \le \frac{0.9 q^{in}_{H_2}}{2K_r} \tag{33}$$

Where, $K_r = \frac{N_0}{4F}$ is a constant.

The optimum utilization factor assumed for this model is 0.85 [3]. 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. With reference to Equation 3, the stoichiometric ratio of hydrogen to oxygen is 2:1. Excess oxygen is continuously taken in order that hydrogen can react with oxygen completely [3]. 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 . Therefore, the value of fuel input flow, depending on fuel cell output current is given as

$$q^{in}_{H_2} = \frac{2K_r I_{fc}}{0.85} \tag{34}$$

3. POWER ELECTRONIC INTERFACE

The DC voltage obtained from the fuel cell is converted to AC using a DC/AC coupling inverter, which is required to connect the DG unit to a local or grid network. In case the fuel cell voltage is small, a DC-DC converter is used to boost it to a higher level, before conversion. In this paper, it is shown that the power-conditioning unit not only transforms DC voltage to AC, but also maintains a constant voltage across the load. In order to achieve this, the FC is connected to a PWM inverter, followed by an LC filter, as shown in Figure 4. A PI controller is used to obtain a fast dynamic response and a better harmonic rejection.

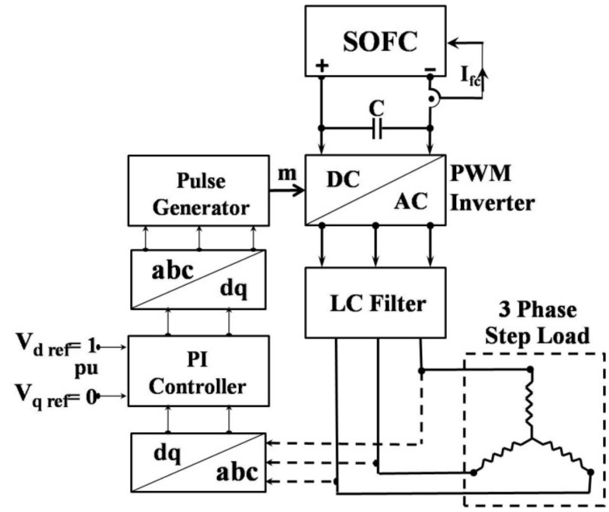

Fig. 4. Control strategy of SOFC connected to isolated load.

The stationary three-phase output voltage is transformed into two-coordinate d-q rotating DC voltage using the *abc-dqo transformation*. This transformation simplifies the calculations for the control of three phase inverters. It uses a PLL device to generate sinusoidal signals of a desired frequency (50Hz).

The transfer function of a PI controller is:

$$G(s) = K_p + \frac{K_i}{s} \tag{35}$$

$$m_a = K_p + \frac{K_i}{s}\left(V_{ref} - V_{abc}\right) \tag{36}$$

K_p and K_i are the proportional gain and integral gain of the controller and V_{ref} is the reference voltage.

The voltage derived from the PI controller is fed to the PWM generator, which compares it with a triangular wave of high frequency (called the carrier wave), to generate required PWM pulses for the inverter. Output voltage from inverter is fed to the LC filter, which suppresses the harmonics. Considering the lossless inverter power output cane be given as;

$$P_{ac} = P_{dc} = V_{fc} I_{fc} \tag{37}$$

Where, P_{dc} is the DC power.

4. RESULTS AND DISCUSSIONS

The dynamic behavior of the system is analyzed for a step change in the load from 50% to 100% at t = 0.5 sec. A capacitor is connected across the SOFC to maintain constant DC voltage. The increase in current causes a small fall in the fuel cell output voltage as shown in Figure 5. The change in stack current is shown in Figure 6. From these current responses, it is observed that a step decrease in the load resistance leads to increase in current, which attains a constant value within 0.02 seconds.

The change in the inverter output voltage with step changes in the load has been shown in Figure 7. The line-to-line output voltage, V_{ab} obtained from the PWM inverter is fed to the three phase low pass LC filter in order to obtain a pure sinusoidal waveform. It is observed that PWM technique suppresses the harmonics that are present in the line voltage.

The variation of the three phase load voltage with step changes in the load are shown in Figure 8. As the step change in the load occurs at t = 0.5 sec, small transients are observed in the output voltage, however the desired value is attained very fast. Thus, the change in the load does not affect the change in the output voltage and the voltage across the load remains unchanged. The change in the load current when the step change in the load is carried out is shown in Figure 9. The load current is observed to increase in magnitude when the load is increased, with a few transients at the time of the load change. However, these transients are smoothened out and the required value is attained rapidly.

The load voltage under *dq* reference frame is shown in Figure 10. It is observed that the d-axis voltage is about 310.27 V for the initial power demand and there is a sudden drop in this voltage at t=0.5 sec. due to decrease in load resistance, which further gets stabilized to its previous value after a few transients and remains unaffected by the change in load. Figure 11 shows that the direct axis load current is 107.4 A for the initial power demand, and increases to about 214.8 A, as the load is increased, at t = 0.5 sec.

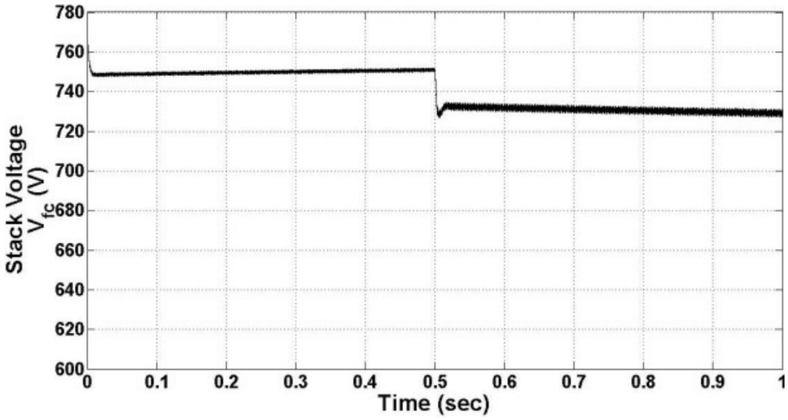

Fig. 5. Stack voltage response of SOFC for step change in load.

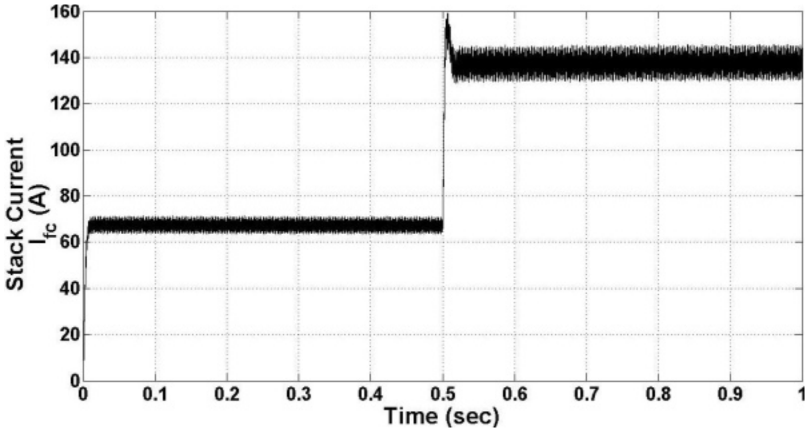

Fig. 6. Stack current response for step change in load.

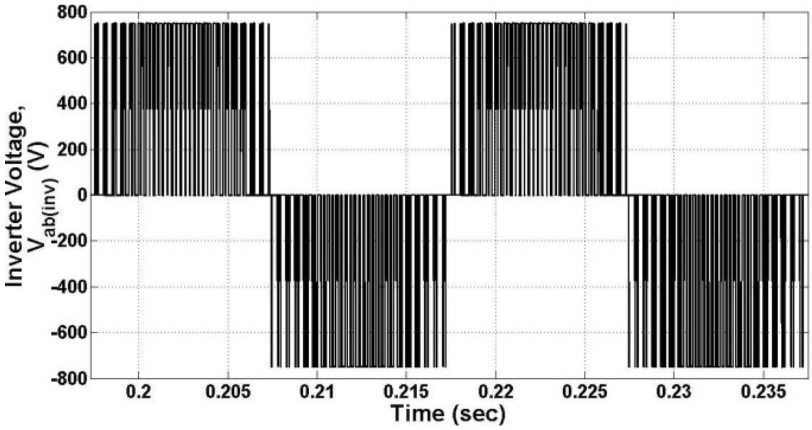

Fig. 7. PWM inverter output voltage response for step change in load.

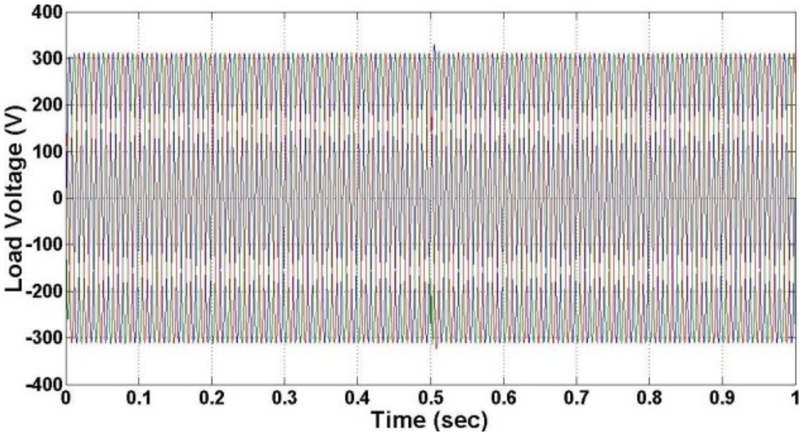

Fig.8. Load voltage response for step change in load.

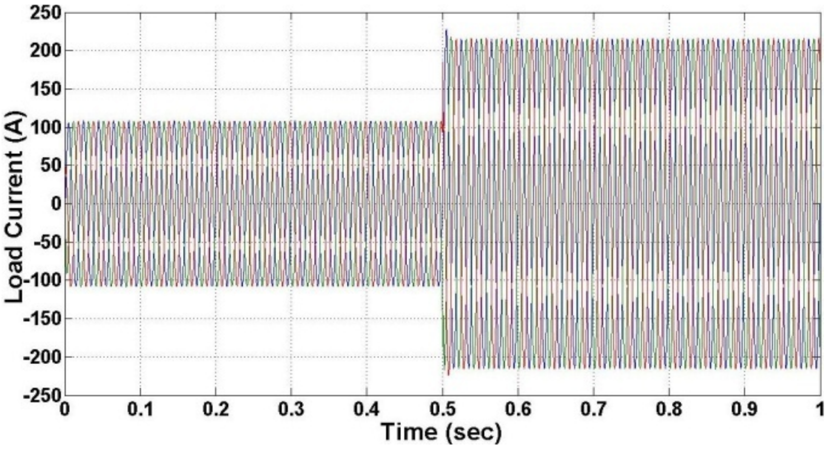

Fig. 9. Load current response for step change in load.

The variation in modulation index is shown in Figure 12. At the instant of the step change, the modulation index increases and undergoes a few transients for a very brief interval of time, but settles down to the steady state value thereafter, which is higher than the previous value. The variation of the output power of the fuel cell to the load when the step load is changed is shown in Figure 13. Although the FC power exhibits transients during the starting phases, these die out after a very brief time interval of about 0.05sec, after which the fuel cell output follows the load demand. At the instant of the change in the step-load, the transients are almost negligible and the fuel cell meets the increased power demand seamlessly.

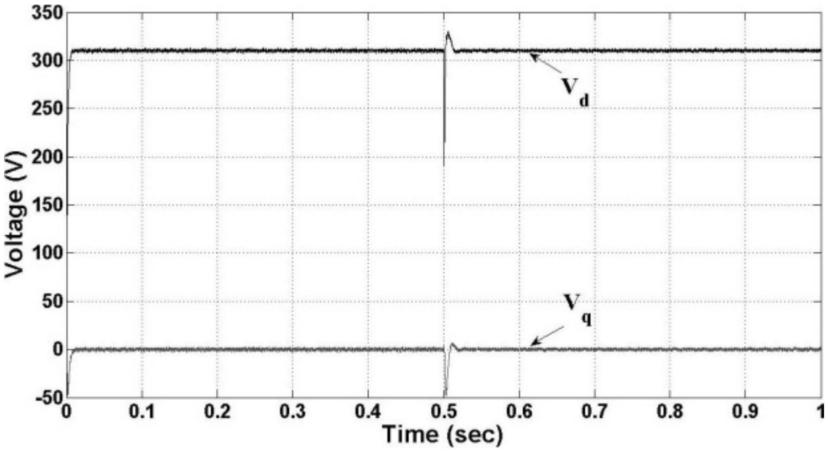

Fig. 10. Direct and quadrature axis load voltage response.

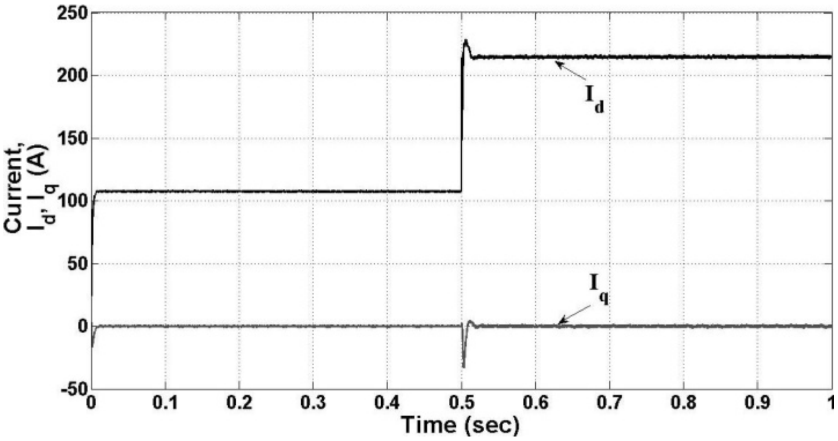

Fig. 11. Direct and quadrature axis response for step change in load.

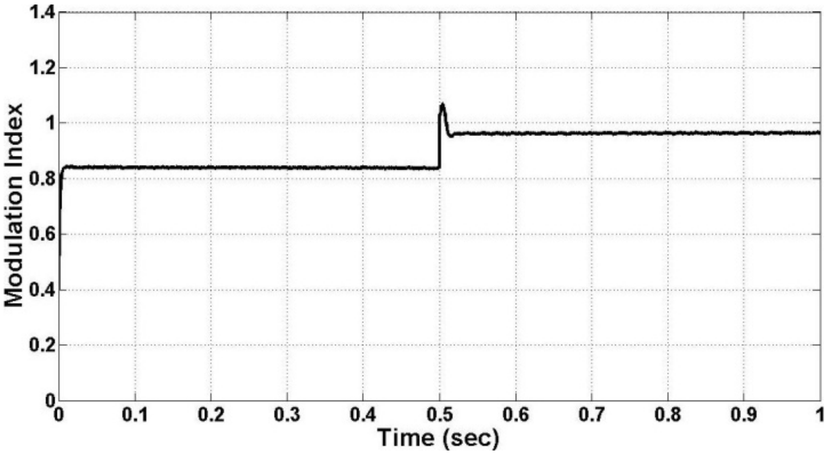

Fig. 12. Variation in modulation index for step change in load.

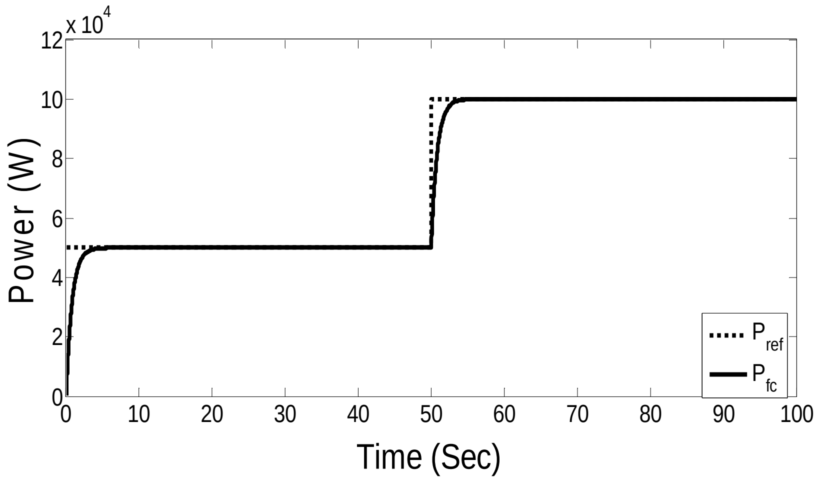

Fig. 13. Power response P_{Load} and P for step change in load.

5. CONCLUSIONS

The modeling and dynamic performance analysis of a 100 kW capacity solid oxide fuel cell supplying power to an isolated load has been presented in the paper. It is observed from the simulation results that the proposed control scheme for the inverter functions accurately, even with a sudden change in the load, under isolated mode. The difference between power demand to the system and power supplied by SOFC can be supplied by energy storage device like battery or ultra-capacitor during the transient period. Such an energy device can be modeled along with necessary control strategies and implemented with developed model to obtain the enhanced system model. However, in order to improve the overall system performance, use of adaptive soft computing technique based controller can be explored in place of the traditional PI controller. Further, the presented model of SOFC can be used to study dynamic performance when connected to grid with suitable control scheme. This work is significant in respect of developing the dynamic model of SOFC and providing the control strategy that makes the complete system very much simple and comprehensive

NOMENCLATURE

Notation	**Description**
B	Slope of Tafel line
E	Reversible open circuit voltage
$E_{o_{cell}}$	Ideal standard potential
F	Faraday's constant
i	Current density
I_{fc}	Stack current
T	Stack operating temperature
R	Universal gas constant
N_0	Number of cells in stack
r	Internal resistance
V_{conc}	Concentration voltage loss
V_{act}	Activation voltage loss
V_{ohmic}	Ohmic voltage loss
m, n	Mass transportation constant
K_{an}	Anode valve constant
K_{H_2}	Valve molar constant for hydrogen
K_{H_2O}	Valve molar constant for water
K_{O_2}	Valve molar constant for oxygen
K_r	Modeling constant
m_a	Amplitude modulation.
M_{H_2}	Molecular masses of hydrogen
M_{H_2O}	Molecular masses of water
n_{H_2}	Hydrogen moles in the anode channel
P_{H_2O}	Partial pressures of water
P_{H_2}	Partial pressures of hydrogen
P_{O_2}	Partial pressure of oxygen
P_{fc}	Fuel cell stack power
P_{ref}	Reference power
$q_{H_2}^{in}$	Molar flow rates of hydrogen into the channel
$q_{H_2}^{out}$	Molar flow rate of hydrogen out of the channel
$q_{H_2}^{r}$	Molar flow rate of hydrogen reacting in the channel
q_{H_2}	Molar flow rate of hydrogen through the anode valve
q_{H_2O}	Molar flow rate of water through the anode valve
U_f	Utilization factor
r_{H_O}	Hydrogen — oxygen ratio

V_{fc}	Stack voltage of fuel cell
V_{an}	Volume of anode-channel
f_s	Switching frequency
$V_{abcinverter}$	Controlled inverter voltage
V_{d_inv}	Direct component of the inverter voltage
V_{q_inv}	Quadrature component of inverter voltage

REFERENCES

[1] Meyer, G.A., Pillay, P., Bhattacharyya, D., Rengaswemy, R., 2009. Sold Oxide Fuel Cell modeling. *IEEE Trans on Industrial Electronics* 56(1): 139-148.

[2] Padulles, J., Ault, G.W., and McDonald, J.R., 2000. An integrated SOFC plant dynamic model for power systems simulation. *Journal of Power Sources* 86: 495-500.

[3] Zhu, Y. and K. Tomsovic, 2002. Development of models for analyzing the load flowing performance of micro-turbines and fuel cells. *Electric Power Systems Research* 62: 1-11.

[4] Akkinapragada, N. and B.H. Chowdhury, 2006. SOFC-based fuel cells for load following stationary applications. *Power* Symposium 553-560.

[5] Sedghisigarchi, K. and A. Filipacchi, A., 2004. Dynamic and transient analysis of power distribution systems with fuel cells — Part I: fuel-cell dynamic model. *IEEE Transactions on Energy Conversion*, 19(2): 423-428.

[6] Sakehare, A.R., Davari, A., and Feliachi, A., 2004. Control of solid oxide fuel cell for stand-alone and grid connection using fuzzy logic technique. *IEEE Proceedings of the 36th Southeastern Symposium on System Theory* 36: 551-555.

[7] www.wisc.edu, 2000. Fuel Cells for Distributed Generation, *A Technology and Marketing Summary*, Energy Center of Wisconsin.

[8] Larminie, J. and A. Dicks. 2002. *Fuel Cell Systems Explained*, second edition, New York, John Wiley

[9] EG&G Technical Services, Inc., 2004. *Fuel cell hand book*, seventh edition, Morgantown, West Virginia.

[10] EI Sharkh, M.Y., *et al.*, 2004. A dynamic model for a stand-alone PEM fuel cell plant for residential applications, *Journal of Power* 138: 199—204.

[11] Xue, X., Tang, J., Sammes, N., and Du, Y., 2005. Dynamic modeling of singular tubular SOFC combining heat/mass transfer and electrochemical reaction effects. *Journal of Power Sources* 142 (1/2): 211—222.

[12] Noren, D.A. and M.A. Hoffman. 2005. Clarifying the Butler-Volmer equation and related approximation for calculating activation losses in solid oxide fuel cell models. *Journal of Power Sources* 152: 175-181.

[13] Chan, S.H., Khor, K.A. and Xia, Z.T., 2001. A complete polarization model of a solid oxide fuel cell and its sensitivity to the change of cell component thickness. *Journal of Power Sources* 93 (1—2): 130—140.

[14] Sedghisigarchi, K. and A. Feliachi. 2006. Impact of fuel cells on load - frequency control in power distribution systems. *IEEE Transactions on Energy Conversion* 21(1): 250 – 256.