

Thermal and Electrical Model of Fuel Cell in Connected to Grid/Isolated Mode

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Abstract-- The fuel cell based distributed generation (DG) system are gaining more attention due to stationary operation, reliable power and less maintenance. Among the different types of fuel cell, one of the high temperatures operating promising Solid Oxide Fuel Cell (SOFC) is preferred due to reliable operation and co-generation purpose. This paper presents the thermal and electrical model of SOFC in connected to the grid and isolated model of operation through power electronics interfacing circuit. The developed model SOFC includes the mathematical expression for thermal and electrical parameter variation inside the fuel cell. The developed model for this study is implemented using Matlab/Simulink environment and the simulation results reported in this paper validated the load following performance of SOFC based DG system.

Keywords: Distributed Generation, Solid Oxide Fuel Cell, Power Electronics Interface.

I. INTRODUCTION

Distributed generation (DG) technologies can provide energy solutions to some customers that are more cost-effective, more environmentally friendly, or provide higher quality power or reliability than conventional solutions. Various DG technologies are available including gas turbines generators, internal combustion engine and photovoltaic's [1]. The application of fuel cell technology to advance power generation systems portends the most significant advancement in energy efficiency, conservation and environmental protection for next decade [2]. The application of fuel cell technologies to DG portends the most significant advancement in energy efficiency, conservation, and environmental protection. SOFC are rapidly developed as the primary power source in movable power supplies and DG. The voltage of SOFC stack decreases largely as the load current increase, and the voltage increases as the temperature increase at the same current [1].

The modelling, control design and simulation study of a fuel cell as a DG system has been explained and reported in [3]. The report [3], also explains the dynamic modelling of PEMFC and power electronics interface are briefly explained and methodologies are explained using Matlab/Simulink

environment. The power quality requirement for demanding load and the economic impacts associated with power quality are characterized using lead acid batteries and diesel engines are presented in [5]. A dynamic model of an anode supported tubular counter flow SOFC is validates with an experimental data in [6]. In the process of validation, it is observed that, the mass transfer resistances inside the electrode play a key role in determining the transient response of the system. A load following strategy using either ultra capacitor or fuel utilization with an SOFC is able to reduce or eliminate the effect of a dynamic load perturbation on the utility grid is presented in [7]. Along with active power filter proper design of SOFC interconnection can produce model behaviour by improving power quality and eliminating erratic power demands is also coated in [7]. The dynamic modelling and analysis of SOFC system response to grid connection using PSCAD/EMTDC simulation software is presented in [8]. The capability of exploring various fuels and the advantage of SOFC on stationary power application and promising solution for coal through the integrated gasification fuel cell application are presented in [9]. An overview of the recent works on dynamic modelling and control design for stationary fuel cell systems including the research developed at ITC-Irst. Are also presented the studies developed in different areas connected with fuel cells systems ranging from power management to freeze start-up in [10]. The non-linear comprehensive dynamic model of SOFC that can be used to transient behaviour studies based on electrochemical and thermal equation is presented in [12].

This paper presents the thermal and electrical model of SOFC in connected to the grid and isolated load through power interfacing circuit. The model is developed using mathematical expression and implement in Matlab/simulink environment. The DC output voltage of SOFC is inverted to AC using power electronics interfacing with DC link capacitor and line filters. The simulation result of the developed model shows the load following performance of SOFC with fuel utilization factor.

II. SOLID OXIDE FUEL CELL (SOFC)

A fuel cell is an electrochemical device, which converts a chemical energy to electrical energy directly by chemical reaction releasing water and gases. On the other hand, there are no moving parts in the device, hence noiseless and power density of is between 200 and 300Wh/L which is approximately ten times of battery. Hence fuel cell are received a good attention for a DG source [2]. The Table.1 gives the performance of different DG sources.

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There are different type of fuel cell currently being investigated for use in industry, they are Proton exchange membrane fuel cell(PEMFC), Molten carbonate fuel cell(MCFC), Phosphoric acid fuel cell(PAFC), Aqueous alkaline fuel cell(AAFC) and solid oxide fuel cell(SOFC) are being rapidly developed as the primary source in movable power supply.

III. TABLE I
IV. PERFORMANCE OF DIFFERENT DG SOURCES

Technology	Diesel engine	Microturbine	Mini turbine	Fuel cell
Size (MW)	0.03-10	0.03-10	0.5-10	-0.1-3
OEM(\$/kWh)	0.005-0.015	0.004-0.010	0.003-0.008	0.002-0.015
% of Electric Efficiency(LHV)	36-43	18-32	21-40	40-57
Usable CHP Temp(Degree F)	180-190	400-650	500-1100	140-700
Overall efficiency2 (%)	80-85	80-85	80-90	80-85
Availability	90-97%	90-98%	90-98%	>95%
Footprint (Sq ft/kW)	0.25	0.25	0.30	0.90

In this work, the model of SOFC assumed that, hydrogen is obtained from the internal reformer. A SOFC can produce the DC voltage by the reaction of hydrogen with oxygen. The hydrogen and air is passed into the anode of fuel cell. The hydrogen ion moves towards the electrolyte and electrons moves through the external circuit. Fig.1 shows the basic schematic model for the fuel cell used in this work.

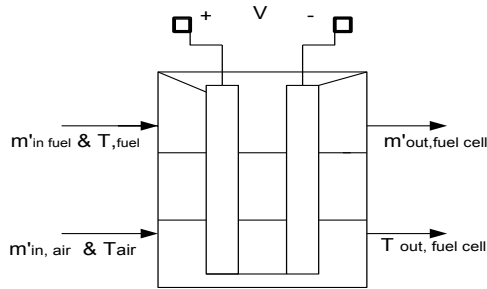


Fig.1 Schematic model of fuel cell

To describe the mathematical model of SOFC, two parts of cell model are considered. One is electrical model and another is electrical model.

A. Electrical model

The output voltage of stack can be expressed by the following equation [11, 12],

$$V_{stack} = NE_0 - V_{act} - V_{con} - V_{ohm} \quad (1)$$

As it can be observed from the equation the voltage loss in the fuel cell is caused by the activation polarization (V_{act}), the ohmic polarization (V_{ohm}) and the mass transportation loss or concentration polarization (V_{con}) which is the results of

electrochemical reactions. The voltage-current characteristic of SOFC can be divided into three regions, the voltage change has logarithmic relation with the current. In the medium current density region, the voltage changes approximately linearly with the change in current. The third part of the V-I curve of a fuel cell is related to the concentration loss for high current operation shown in Fig.2 and typical P-I curve is shown in Fig.3.

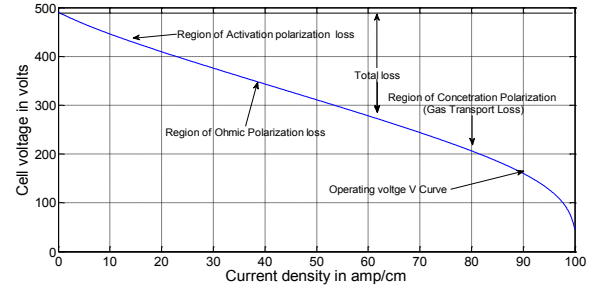


Fig.2 Typical V/I curve of fuel cell

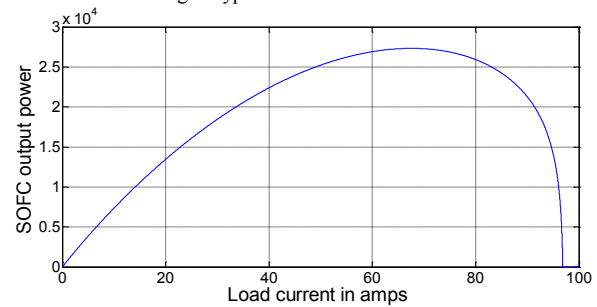


Fig.3 Typical P-I curve of fuel cell

The activation polarization loss can be calculated by equation explained in [11, 12] and it is given by,

$$V_{act} = \begin{cases} \frac{RT}{4F} \frac{I_{stack}}{AJ_0} & \frac{I_{stack}}{A} \leq J_0 \\ \frac{RT}{2F} \ln\left(\frac{I_{stack}}{AJ_0}\right) + \frac{RT}{4F} \frac{I_{stack}}{AJ_0} & \frac{I_{stack}}{A} < J_0 \end{cases} \quad (2)$$

Where, T is the fuel cell temperature in Kelvin (K), I_{stack} is the cell current in amperes (A).

Ohmic polarization occurs because of the resistance related to the electron transfer from the anode to the cathode and proton movement through the electrolyte. The ohmic resistance of the cell is approximately by an equation.

$$V_{ohm} = r_{ohm} I_{stack} \quad (3)$$

Concentration polarization occurs in all current densities, but in more evident in large current densities and can be calculated using an equation (4).

$$V_{con} = \frac{RT}{2F} \ln\left(1 - \frac{I_{stack}}{AJ}\right) \quad (4)$$

The current of SOFC is depends on the fuel flow rate and it can be calculated by the equation (5).

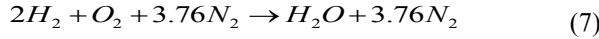
$$I_{stack} = \frac{2Fm_{fuel}}{N.M_{H_2}} \quad (5)$$

The output power of fuel cell stack can be obtained by the equation (6).

$$P_{e,f} = V_{stack} \cdot I_{stack} \quad (6)$$

B. Thermal model

The ambient air consists of 21% of oxygen and 79% nitrogen is been considered and the chemical reaction in the fuel cell can be explained as follows



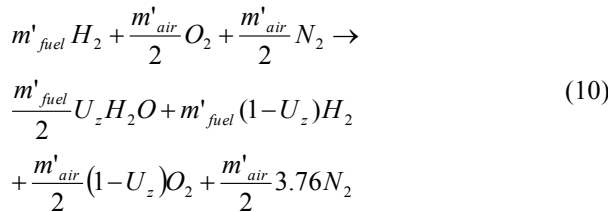
From equation (7), every 2 moles of hydrogen (fuel) are required one mole of oxygen and 3.76 moles of nitrogen. Based on this, the relation between the fuel and air flow rate is given as,

$$m'_{air} = Km'_{fuel} \quad (8)$$

Where, K is a constant. But in reality not all the hydrogen fuel is consumed in the fuel cell. Whereas, the rate of reaction depends on the fuel utilization factor. The fuel utilization factor is ratio of reacting fuel and input fuel and it can be defined as,

$$U_z = \left[\left(\frac{I_{stack} N}{2F} \right) * \left(\frac{M_{H_2}}{m'_{fuel}} \right) \right] \quad (9)$$

Considering the utilization factor and neglecting the mass loss the chemical reaction would be written as,



Thus, considering that the water has been condensed, the exhaust of fuel cell can be calculate by an equation [12],

$$m'_{fuelcell} = \frac{m'_{fuel}}{M_{H_2}} \left[(1-U_z)(2M_{H_2} + M_{O_2}) + 3.76M_{N_2} \right] \quad (11)$$

During the condensing process there is a slight decrease in the temperature of exhaust, which is neglected in this work. The thermal power generated inside the fuel cell can be written as,

$$W'_{th} = W'_{ch} - P_{e,f} \quad (12)$$

Where, W'_{ch} is the heat generation rate by the chemical reaction. Considering the enthalpy change of the consumed fuel only and neglecting other species. It is possible to obtain.

$$W'_{ch} = U_z \left(\frac{m'_{fuel}}{M_{H_2}} \right) \Delta H_f \quad (13)$$

Where, ΔH_f is the heat combustion of the hydrogen(J/mol). A portion of the thermal power generated in the fuel cell stack is consumed to consequently increase the input and air temperature. The energy used to increase the fuel temperature in neglected. The reaming power is released to environment by the radiation. This thermal energy flow can be described as,

$$W'_{th} = C_{fc} m_{fc} \frac{dT}{dt} W'_{amb} + W'_{air} \quad (14)$$

Where, W'_{amb} is the transferred power to the ambient[11,12] and can be denoted as,

$$W'_{amb} = A_{ex} h_{ex} (T - T_{amb}) \quad (15)$$

The thermal power that increases the inlet air temperature, W'_{air} , can be expressed by an equation,

$$W'_{air} = m'_{out} C_p (T - T_{air}) \quad (16)$$

Where, C_p is the specific heat ratio of air.

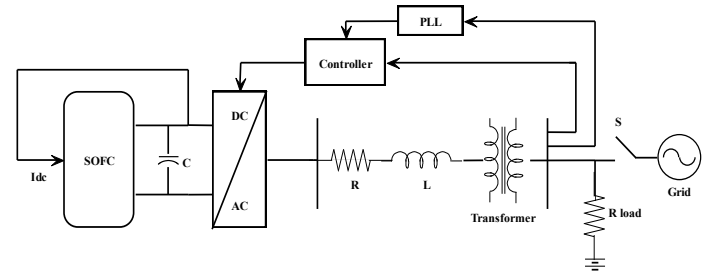


Fig.4 Fuel cell connected to the grid and isolated load

The fuel cell connected to the grid and load through the power interfacing circuit is shown in Fig 4. The proposed model is divided into three major parts namely SOFC model, voltage source inverter (VSI) controller and grid connected fuel cell system, respectively.

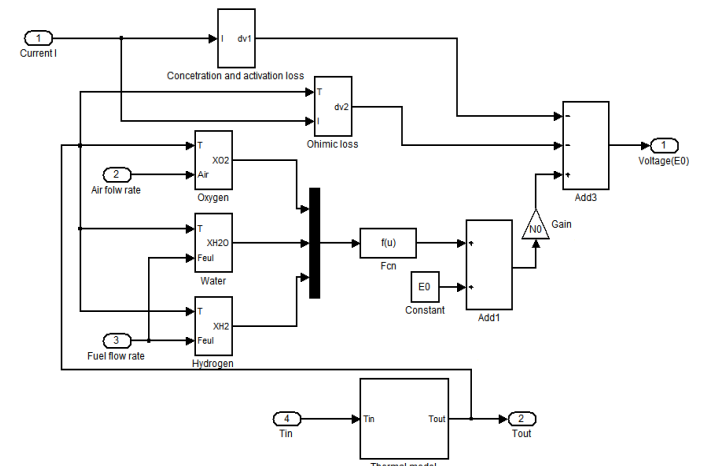


Fig.5 Schematic of SOFC model using Matlab/Simulink

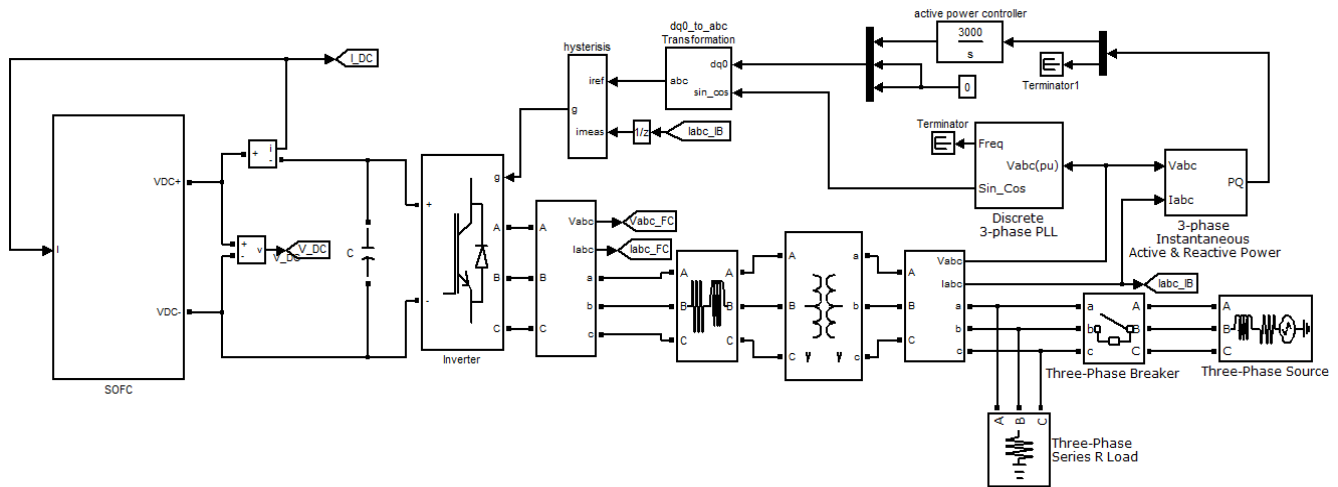


Fig.6 Matlab/Simulink schematic of SOFC connected to grid

V. POWER ELECTRONICS INTERFACE

A. Isolated mode

The developed model of SOFC using Matlab/simulink is connected to the grid using power electronics interface is shown in Fig.6. The power electronics VSI controller is used to supply the AC power from the SOFC DC power. The VSI and SPWM switches are developed in Matlab/simulink and are used as basic controller design. In the voltage control loop, the measured three phase voltages are fed to the phase locked loop (PLL) in order to detect the phase angle and angular position of the voltages. The PLL is responsible for providing the basic voltage synchronizing signal with angle. The measured value of voltage is in per unit and a constant are fed in a maximum block to calculate the maximum voltage signal. Output signal of the maximum block is then passed through the filter to attenuate the voltage transients and signals are compared with a reference voltage. An error is observed and fed to the voltage lag-lead functional block.

The PLL also provides the voltage synchronization signal in which it is multiplied by SPWM switching frequency of 1.6 kHz, which is 33 times of the system operating frequency in order to convert the carrier ramp signal into the carried signal of whose amplitude is between -1 and +1. In the SPWM technique, by comparing the triangular carrier signal with voltage modulating signal, the firing signal operated the switches with anti parallel diode combination to get AC output from the DC voltage.

B. Grid connected mode

The Matlab/Simulink model of grid connected fuel cell and its power interface circuits are shown in Fig.6. The SOFC system connected to the grid includes a fuel cell, power interfacing circuit with resistive, inductive RL filter and step up transformer. The fuel cell output power depends upon the DC link current. The v_q control for the inverter will match with SOFC output power and phase sequence. The transformer is used to increase the voltage level over a boost converter.

VI. RESULTS AND DISCUSSION

A. Grid connected

The SOFC power is connected to the grid through the power interfacing circuit. The demand power varies at $t=0.4$ sec. The variation of fuel cell power and the fuel utilization factor are shown in Figs 7 and 8 respectively. From the reported Fig.7 and 8 it is observed that, the fuel demand increases with increase in demand power. The DC link current depends upon the load, the variation of DC link current and load voltage are shown in Figs 9 and 10 respectively. The SOFC developed for only providing an active power where as the reactive power supplied by the fuel cell is zero, thus the variation of active and reactive power is shown in Fig.11. From the reported Fig.11 it is observed that, only there is a variation in active power where as the reactive power is almost zero. The variation of load current is shown in Fig.12.

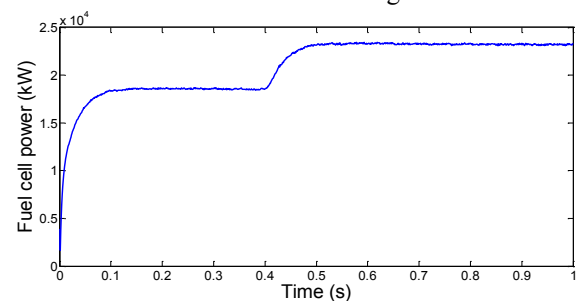


Fig.7 Fuel cell power

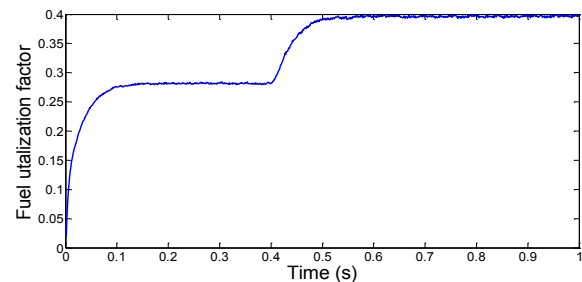


Fig.8 Fuel utilization factor

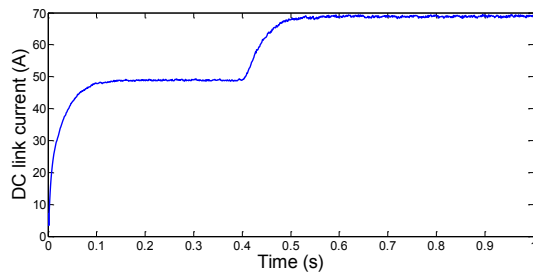


Fig.9 DC link current

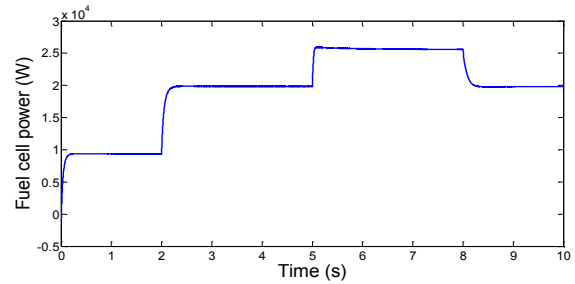


Fig.13 Fuel cell power

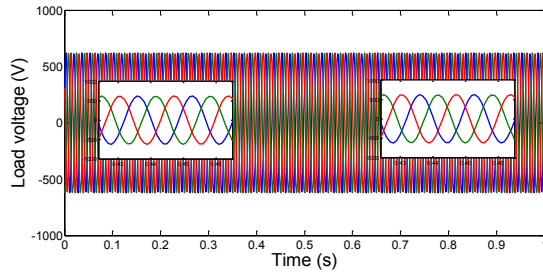


Fig.10 Load voltage

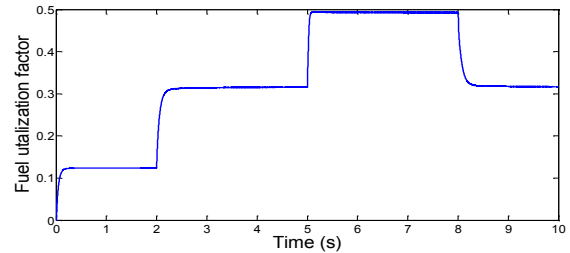


Fig.14 Fuel utilization factor

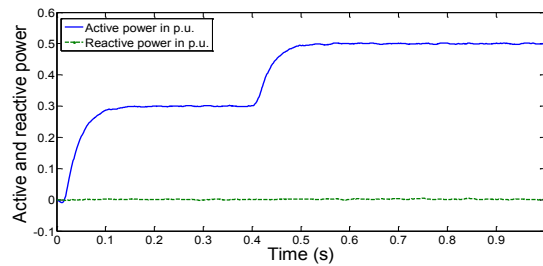


Fig.11 Active and reactive power

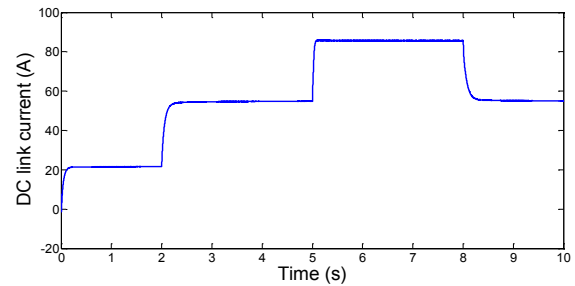


Fig.15 Load current

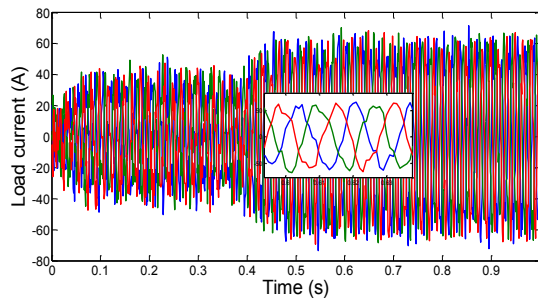


Fig.12 Load current

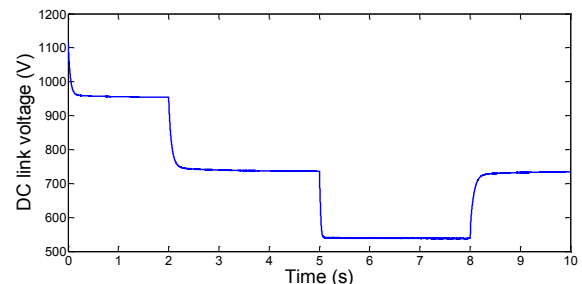


Fig.16 DC link voltage

B. Isolated mode

In this mode of operation, the SOFC is connected to an isolated load through the power interfacing circuit. The variations of fuel cell power and fuel utilization factor are shown in Fig(s). 13 and 14 respectively. The variation of DC link voltage and current are shown in Fig(s) 15 and 16. The load current and voltage are shown in Fig(s) 17 and 18. The active and reactive powers are shown in Fig.18. From all the reported results Fig(s) 13 to 19 shows the load flowing performance, within their parametric value variation. From the Fig. 19 it is observed that, fuel cell can supply only active power where as the reactive power supplied by the fuel cell zero.

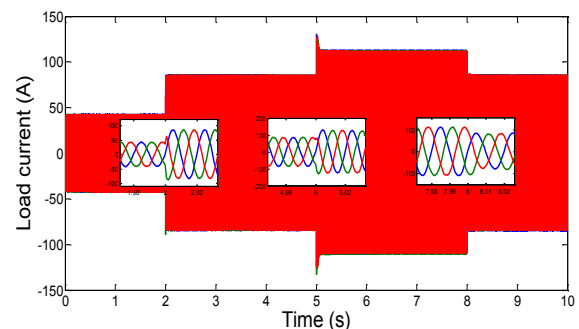


Fig.17 Load current

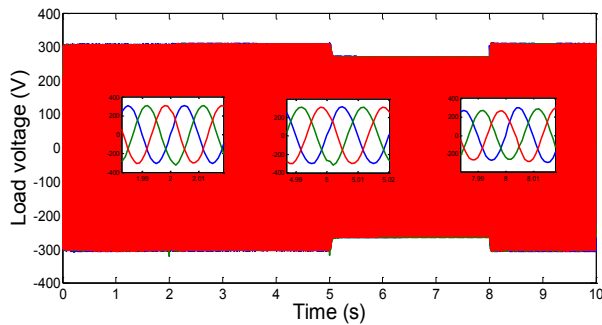


Fig.18 Load current

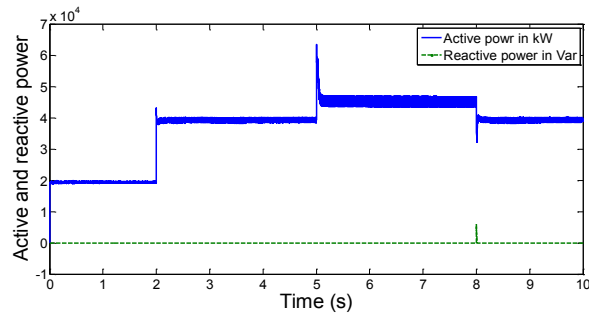


Fig.19 Load current

VII. CONCLUSION

The thermal and electrical model of SOFC system in grid connected and isolated mode of operation is performed and presented. The developed SOFC is categorized into thermal and electrical model based on the mathematical expression and it is implemented using Matlab/Simulink. From the simulation results, it is observed that, the SOFC output power is following the load by varying the output power, fuel utilization factor. The DC power of fuel cell is been integrated to the grid using power electronics interfacing circuit. The DC link capacitor and RL series filter are used to improve the power quality. The developed model of SOFC system can be used for studying and performance analysis of electrical phenomena that occurs when a fuel cell is connected to the grid and isolated load. This work can accelerate the thermal model with other(gas turbine or microturbine) combined DG system strongly contributing clean, reliable and cost effective energy in the future.

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IX. BIOGRAPHIES

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