

MATHEMATICAL MODELING AND SIMULATION OF SOLID OXIDE FUEL CELL POWER SYSTEM FOR DISTRIBUTED GENERATION

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Abstract:-Renewable energy systems have developed wide interest to supply electricity in remote areas as well as for distributed power generation. Due to intermittent nature of renewable sources such as wind and solar, the energy storage systems (ESS) are required in renewable power generating systems particularly during peak hours. Fuel-cell based power generation is also gaining popularity in residential applications as well as distributed power generation due to its cleanliness, portability, high efficiency, zero or low emission (of pollutant gases), flexible modular structure and suitability for electricity and heat generation. Solid oxide fuel cells are shows potential for distributed energy stationary power generation that offers efficiencies up to 55% in stand-alone applications, 75% in hybrid gas turbine applications and 90% in cogeneration. In this paper, we developed model which describes and simulates the dynamic behavior of a Solid Oxide Fuel Cell (SOFC) and this model can test the dynamic response for the power demand change from 0% to 115% of the rated value. Results prove the effectiveness of the proposed developed model and this model can be used to describe the behavior of the Micro Grid (MG) under different disturbance conditions like load following, load shedding, unbalanced loads, failure of one micro source and so on. By using the micro sources a complete model can be built for the description of the overall dynamic performance of the Micro Grid (MG). The viability of the proposed power control mode is simulated by MATLAB/SIMULINK.

Index Terms: DistributionGenerator (DG); DER; Unit Power Control (UPC); micro grid, Solid Oxide Fuel Cell (SOFC); Dynamic response

I. INTRODUCTION

Increased energy consumption and global pollution awareness have made green/renewable power more and more important for stand-alone as well as distributed generation. Wind turbines, photovoltaic cell, and fuel cells (FCs) are different types of green power technologies. Wind and photovoltaic technologies have a serious drawback, i.e., these technologies can deliver power only when wind blows or sun shines and thus can only be recommended as secondary power supply in the grid. FC systems have attracted a viable interest in distributed power generation, particularly during peak load. It can also be used in low and medium power residential applications, as an uninterruptible power supply particularly for houses, industries, and remote places, and for the hybrid vehicles [1].

Fuel cell FC systems are divided into two types according to the source of its fuel. Accordingly, if the fuel comes from techniques depend on fossil fuel, like natural gas steam reforming or coal gasification, then the system is considered a greenhouse gases GHGs emitter such like traditional sources, while if the fuel is produced without GHGs, like using renewable sources to electrolyze water, then it is considered as a renewable fuel cell system. However, FC system is an energy provider system, which combines between giving energy as long as there is fuel, and the quiet operation as it does not have basically any moving parts. This renewable system is analyzed into four subsystems: fuel cells, electrolyzers, PV system, and finally H₂ storage tank.

Distributed generation (DG) is system is gaining more and more attention world wide as an alternative generation Source. Among the several DG source, the fuel cell is most suitable hybrid system with renewable and non-renewable power sources. Distribution networks play a key role in the electrical market as it is on the consumer side. Customer satisfaction is based on the reliability and the quality of the electricity supplied. To improve the voltage profile and to reduce the active power losses, researchers all across the globe have put in all their efforts to overcome this problem. Time and again, the integration of compensators into the distribution network or the reconfiguration of the network has proved to be successful. However, in the 21st century, with the electricity market getting deregulated, an endless opportunity was available to play with the distribution networks. And this era began with the incorporation of distributed generations (DGs) in the distribution network. DGs have changed the way distribution networks looked like.

Most of the new DG technologies include power electronic devices to provide usable output power. These DGs are often referred to as power electronically interfaced DGs. Enormously improved power control of these generation sources has become possible by controlling their power electronic interfacing units. In a common approach the output voltage of these generation devices whether dc or ac is converted to a controlled output voltage [4].

The realities require that the transmission and distribution system must [4-5]:

- Provide for load growth with enhanced stability and with minimal growth of the transmission system.
- Make greater use of renewable energies, such as wind and photovoltaic systems.
- Increase energy efficiency and reduce pollution and greenhouse gas emissions.
- Increase the availability of high power quality for sensitive loads.

To study the dynamic response of each one of the Distributed Energy Resources (DERs), the theory of operation of SOFC must be studied. Mathematical models that describe the dynamics of converters, wind energy conversion systems, photovoltaic systems, fuel cells, micro turbines, battery energy storage systems and super capacitors are mainly addressed in [6]. The main objective of work is developing a complete model that

can simulate MG components more accurately. In this paper, I developed Matlab® Simulink® models to simulate a solid oxide fuel cell. The developed Simulink model of fuel cell system is then connected to 11Kv grid through an AC bus. Simulation studies have been carried out to verify the system performance under faulty condition.

II. DYNAMIC EQUATION OF SOLID OXIDE FUEL CELL

The structure and the functioning of a fuel cell are similar to that of a battery except that the fuel can be continuously fed into the cell. The physical structure of a fuel cell consists of two porous electrodes (anode and cathode) and an electrolyte layer in the middle. The Schematic of individual fuel cell is shown in figure 1 and Figure 2 shows the basic workings of a fuel cell with positive ion flow through the electrolyte, which is based on electrochemical principles. Hydrogen and oxygen molecules combine to form water. The process is caused by the fact that charged particles migrate toward regions of lower electrochemical energy.

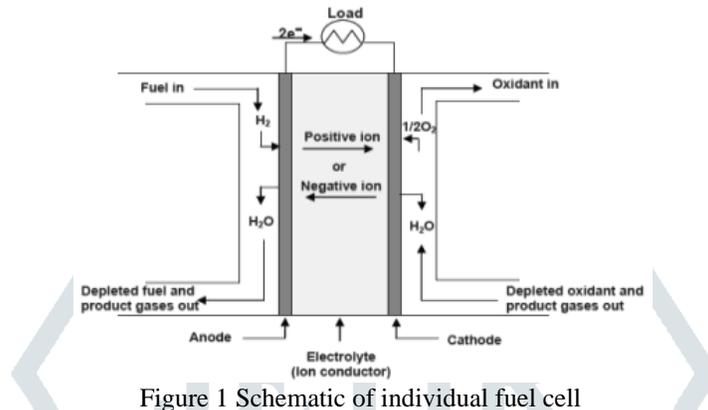


Figure 1 Schematic of individual fuel cell

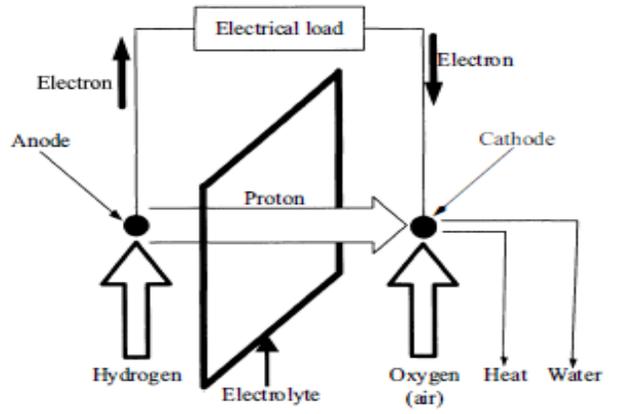
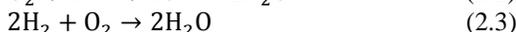
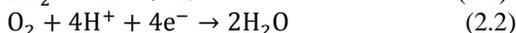


Figure 2 Working of individual fuel cell

The charged hydrogen and oxygen particles move toward each other and bond to one another because the final product of this reaction has a lower overall electrochemical energy. Electrical energy is generated as a result of the movement of the charged hydrogen and oxygen particles, which is essentially the controlled movement of electrons. By breaking the hydrogen molecules to electrons and positive ions (protons), with the help of a catalyst to facilitate faster reaction, the protons move from the cathode to anode through the membrane (electrolyte), but the electrons cannot. The electrons travel through an external electrical circuit (load) to recombine with the hydrogen protons and oxygen molecules at the cathode (again, with the help of the catalyst) to produce water. The actual chemical reaction inside a hydrogen fuel cell can be broken down into two half reactions, the oxidation half reaction and the reduction half reaction. The oxidation half reaction, represented by eq. (2.1), shows the dissociation of hydrogen molecules to protons and electrons at the anode. After the dissociation, the protons are free and pass through the electrolyte, and recombine with the electrons (which move through the external circuit) at the cathode. In this process, which is often called the reduction half reaction, the electrons and hydrogen protons combine with the oxygen molecules from the surrounding air, according to eq. (2.3), to form water.



Solid Oxide Fuel Cells (SOFCs) are high temperature (600-1000°C) direct energy conversion devices, which transport the chemical energy of a fuel to electrical energy. Due to their high-temperature operation, they allow internal reforming of gaseous fuel inside the fuel cell, which gives them multi fuel capability. Their energy conversion efficiency is higher than that of the traditional combustion methods and can reach up to 65%. In addition, SOFCs can be used in combined heat and power (CHP) applications. They take advantage of their high-temperature exhaust gas streams for uses in such applications as residential or commercial heating or for further electricity production. Their disadvantage is their relatively slow start up and thermal stresses due to the high operating temperature. High operating temperature requires stringent materials to be used which further drives up the cost. Intermediate-temperature SOFCs cannot be used for all applications. Higher temperature is required for fuel cell micro-turbine hybrid systems. However, for smaller systems intermediate temperature SOFCs would be ideal [3].

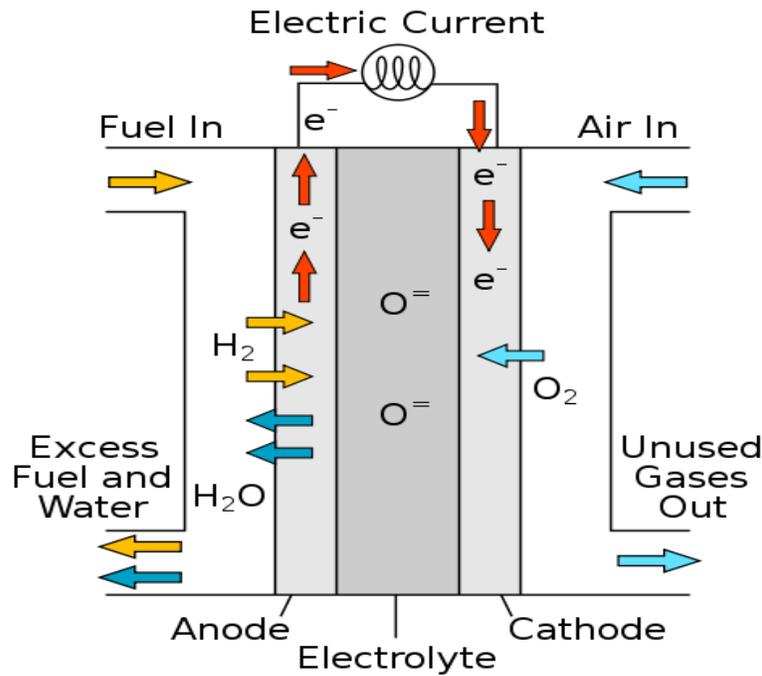


Figure 3 Schematic of solid oxide fuel cell

The modeling of SOFC is carried out based on the assumptions made that the fuel cell temperature is made to be constant; the fuel cell gasses are ideal and the Nernst's equation applicable to the cell. By Nernst's equation output fuel cell dc voltage V_{nernst} across stack of the fuel cell at current I is given by the

$$V_{\text{nernst}} = N_0 \left(E_0 + \frac{RT}{2F} \ln \left(\frac{p_{\text{H}_2} p_{\text{O}_2}^{0.5}}{p_{\text{H}_2\text{O}}} \right) \right) \quad (2.4)$$

Where,

- V_{nernst} – Operating dc voltage (V),
- E_0 – Standard reversible cell potential (V),
- P_i – Partial pressure of species i (Pa),
- N_0 – Number of cells in stack,
- R – Universal gas constant (J/ mol K),
- T – Stack temperature (K),
- F – Faraday's constant (C/mol).

The Hydrogen flow (fuel flow) is given by the below equation

$$\frac{dq_{\text{H}_2}}{dt} = \frac{1}{\tau_f} \left[-q_{\text{H}_2} + \frac{2K_r}{U_{\text{opt}}} I_{\text{DC}} \right] \quad (2.5)$$

The Oxygen flow is given below equation

$$q_{\text{O}_2} = \frac{1}{r_{\text{HO}}} q_{\text{H}_2} - K_r I_{\text{DC}} \quad (2.6)$$

The pressure equation of hydrogen, oxygen and water is given by the equations

$$\frac{dp_{\text{H}_2}}{dt} = \frac{1}{\tau_{\text{H}_2}} \left[-p_{\text{H}_2} + \frac{1}{K_{\text{H}_2}} (q_{\text{H}_2} - 2K_r I_{\text{DC}}) \right] \quad (2.7)$$

$$\frac{dp_{\text{O}_2}}{dt} = \frac{1}{\tau_{\text{O}_2}} \left[-p_{\text{O}_2} + \frac{1}{K_{\text{O}_2}} \left(\frac{1}{r_{\text{HO}}} q_{\text{H}_2} - K_r I_{\text{DC}} \right) \right] \quad (2.8)$$

$$\frac{dp_{\text{H}_2\text{O}}}{dt} = \frac{1}{\tau_{\text{H}_2\text{O}}} \left(-p_{\text{H}_2\text{O}} + \frac{2K_r I_{\text{DC}}}{K_{\text{H}_2\text{O}}} \right) \quad (2.9)$$

- q_{H_2} – Fuel flow (mol/s),
- q_{O_2} – Oxygen flow (mol/s),
- K_{H_2} – Valve molar constant for hydrogen (kmol/s atm),
- K_{O_2} – Valve molar constant for oxygen (kmol/s atm),
- $K_{\text{H}_2\text{O}}$ – Valve molar constant for water (kmol/s atm),
- τ_{H_2} – Response time for hydrogen (s),
- τ_{O_2} – Response time for oxygen (s),
- $\tau_{\text{H}_2\text{O}}$ – Response time for water (s),
- τ_f – Fuel response time (s),
- U_{opt} – Optimum fuel utilization,
- r_{HO} – Ratio of hydrogen to oxygen,
- K_r – Constant (kmol/s A).

The parameters used for the modeling of SOFC is given below in table 1.

Table 1 Parameters are used for the modeling of SOFC

Representation	Variable	Value
Absolute temperature	T	1273K
Faraday's constant	F	96.487 e6C/K mol
Universal gas constant	R	8314J/(K mol K)
Ideal standard cell potential	E_o	1.18V
Maximum fuel utilization	U_{max}	0.9
Minimum fuel utilization	U_{min}	0.8
Optimal fuel utilization	U_{opt}	0.85
Valve molar constant for hydrogen	KH_2	8.43 e-4 K mol/(s atm)
Valve molar constant for oxygen	KO_2	2.52 e-4 K mol/(s atm)
Valve molar constant for water	KH_2O	2.81 e-4 K mol/(s atm)
Response time for hydrogen flow	T_{H_2}	26.1s
Response time for water flow	T_{H_2O}	78.3s
Response time for oxygen flow	T_{O_2}	29.1s
Ohmic loss per cell	R_0	3.2813e-004 Ω
Electric response time	T_e	0.8s
Fuel processor response time	T_f	5s
Ratio of hydrogen to oxygen	rHO	1.145
Initial current	I	100A
Load resistance	R	10 Ω

II. MODELING OF SOLID OXIDE FUEL CELL

Mathematical model of Solid oxide fuel cell is shown in figure 4.

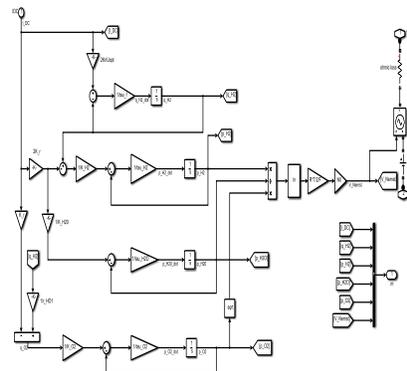


Figure 4 Mathematical model of the SOFC

The simulation of the SOFC module is shown in figure 5. It gives the output of the pressure of hydrogen, oxygen and water. Also it gives the output voltage and current of the solid oxide fuel cell.

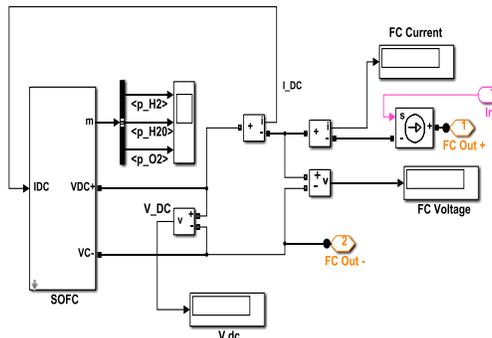


Figure 5 Simulation of the SOFC module

IV. PERFORMANCE OF SOFC IN A MICRO GRID SYSTEM

It is understood that the stand-alone SOFC system is operating with constant rated voltage, 1.0 p.u. (387.1 V), and power demand, 0.7 p.u. (70 kW). All parameters of the system are the same as in Table. At t = 100 sec, there is a step increase of the power demand from 0.7 p.u. (70 kW) to 1.0 p.u. (100 kW). Figure 6 shows the dynamic response of this system. Figure 7 shows the dynamic response of the SOFC when there is a decreasing in power demand from 0.7 p.u. (70 kW) to 0.4 p.u. (40 kW).

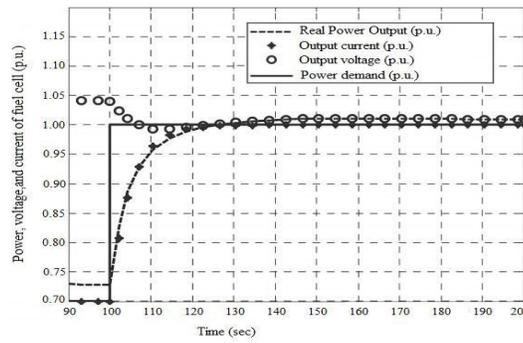


Figure 6 Response of SOFC when increasing power demand from 0.7 p.u. to 1.0 p.u

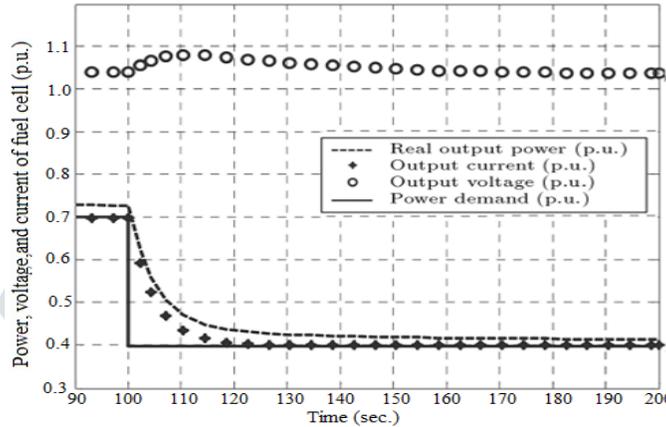


Figure 7 Response of SOFC when decreasing power demand from 0.7 p.u. to 0.4 p.u.

From simulation results, the following points can be raised:

- (i) P (output of electrical active power) increases slowly and continuously until reaching the demand power.
- (ii) From Figure 4.1, P will decrease slowly until reaching the desired value.
- (iii) In both cases, the response time of the fuel cell is about 25-30 sec.
- (iv) In the first case, the output voltage of the fuel cell suffers from some decreasing, especially during power rising; while, in the second case, the voltage has some increasing during power decreasing.
- (v) Results show that the SOFC has some slow dynamic response, so that using SOFC alone may be not suitable for systems that need a fast dynamic response.
- (vi) In this case, use of a Micro Turbine or a fly wheel type generating source can be proved profitable with the SOFC to deal with a fast system response.

V. SIMULATION MODEL OF SOFC BASED DG SYSTEM

SOFC one of the most developed fuel cells show great promise in stationary power generation applications. In isolated mode FCs based DG system can be used to supply power to remote areas or supply power during grid failure. The system may be supported by batteries or capacitors or other energy storage devices. The complete model of SOFC based DG system with power electronics 3-Ø resistive load is shown in Figure 8. The individual component modeling of SOFC is given in this paper. The three phase inverter, pulse generator, PWM and AC filter available in Sim power System of the MATLAB has been used.

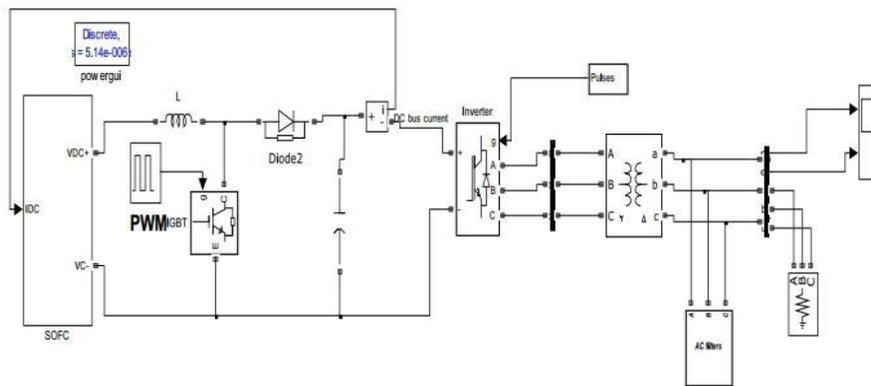


Figure 8 Simulink model of SOFC based DG system.

The output inverted voltage and current waveform of SOFC based distributed generation system are shown in figure 9.

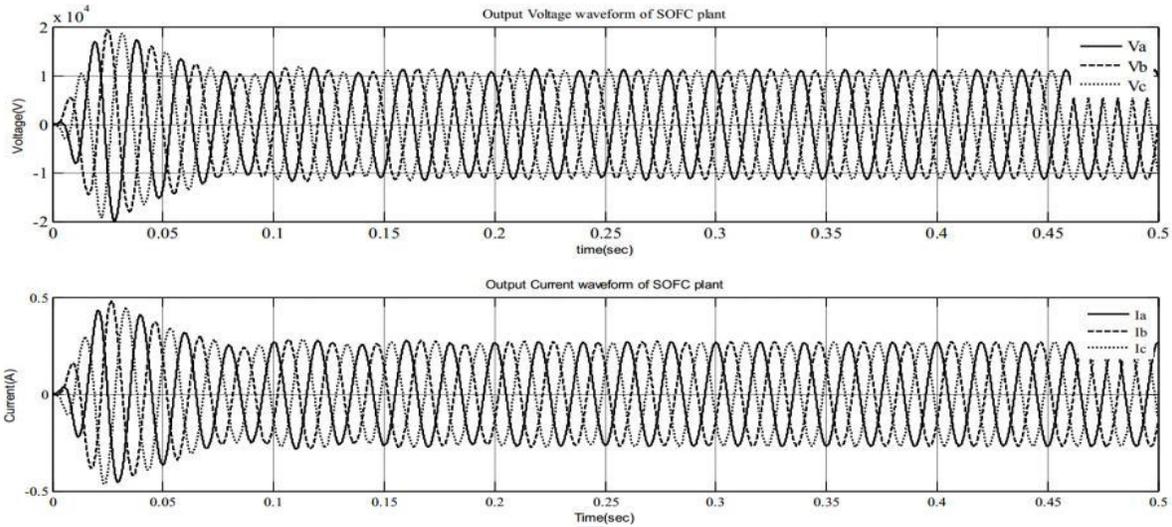


Figure 9 Output voltage and current waveform of SOFC based DG System

VI. SOFC CONNECTED TO THE GRID DURING L-G FAULT

Here the figure 10 shows the Simulink model with SOFC plant during L-G fault and Figure 11 shows voltage and current waveforms when with SOFC Connected to the grid during L-G fault, respectively. Single line to ground fault takes place on the grid during time period $t=0.1$ to 0.3 Sec. During fault we have analyzed the parameters such as voltage, current and checked the system stability.

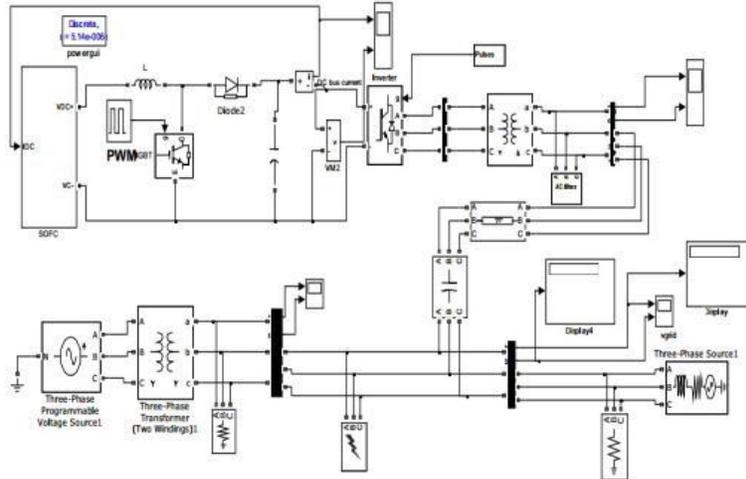


Figure 10 Simulink model with SOFC plant during L-G fault

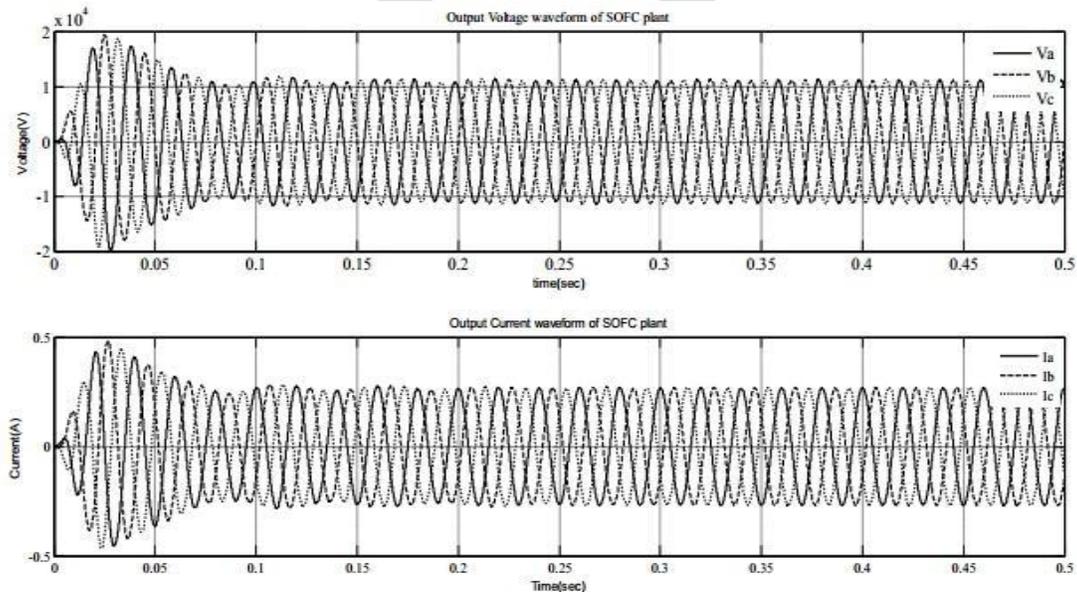


Figure 11 voltage and current waveform with fuel-cell plant during L-G fault.

It is clear from the above figure 11 that voltage profile is considerably improved after SOFC plant interconnected with the grid. The various data of voltage and current are shown in table.2. After connecting the SOFC plant system to the existing system we can say that power system stability is being improved.

Table 2 Values of voltage and current without and with fuel cell plant under normal and faulty condition

Parameters	Without SOFC	With SOFC
V_{Normal}	11.02 Kv	11.05 Kv
I_{Normal}	942 A	932.7 A
V_{Fault}	7.83 Kv	7.84 Kv
I_{Fault}	7281.33 A	7248.85 A

VII. CONCLUSION

This paper shows the impact of fuel cell power system on the stability of power system and how it is correlated with a microgrid as a dispersed generation source. The dynamic modelling and simulation results of a fuel cell based power system which consists of solid oxide fuel cell (SOFC) for power generation. The SOFC modelled individually and latterly integrate in Matlab/Simulink software. The developed Simulink model of fuel cell system is then connected to 11Kv grid through an AC bus. Simulation studies have been carried out to verify the system performance under faulty condition. Simulation results show that after combining fuel cell system the system's stability is considerably improved as compared to using just fuel cell power.

VIII. REFERENCES

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