Modeling and Simulation of Solid Oxide Fuel Cell Based Distributed Generation System

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Abstract— **Due to ever increasing energy consumption, rising public awareness of environmental protection and steady progress in power deregulation alternative (i.e. renewable and fuel cell based) DG system has attracted increased interest. Fuel cell systems show great potential especially in the area of DG due to their fast technological development and merits, such as, high efficiency, zero or low emission (of pollutant gases) and flexible modular structure. This paper describes dynamic modeling and simulation results of SOFC based Distributed generation system. The SOFC is modeled individually and latterly integrated to the grid. Dynamic model of SOFC is developed with the help of MATLAB / SIMULINK software. Simulation studies have been carried out to verify the system performance under fault condition.**

Keywords- Fuel cell, Distributed generation, inverter,Solid oxide fuel cell (SOFC)

1. INTRODUCTION

Distributed generation is referred in general to small generators, starting from a few kW up to 10 MW, whether connected to the utility grid or used as stand-alone at an isolated site. Normally small DGs, in the 5-250 kW range serve households to large buildings [2]. DG technologies can be categorized to renewable and nonrenewable DG. Fuel cells based DG system is considered an alternative to centralized power plants due to their nonpolluting nature, high efficiency, flexible modular structure, safety and reliability. At present, they are under extensive research investigation as the power source of the future, due to their characteristics. A fuel cell converts chemical energy directly to electrical energy through an electrochemical process. As opposed to a conventional storage cell, it can work as long as the fuel is supplied to it. There are many motivations in developing this method of energy generation and it needs further development to have a realistic system analysis combining various subsystems and components [1].

The integration of the fuel cell system is to provide the continuous power supply to the load as per the demand. In the fuel cell energy system which is used for the distributed generation applications, the source is integrated with the DC – DC boost converter to stabilize the voltage from the fuel cell. The output of the boost converter is then fed to the three phase PWM inverter to get the three phase ac voltage for the grid connected applications. The overall block diagram of the fuel cell energy system is shown in figure 1.[2]
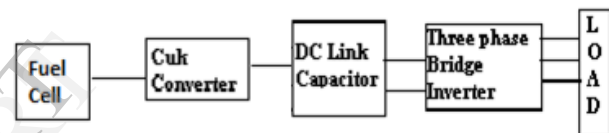

Fig. 1: Block Diagram of Fuel cell energy System

II. SOFC

Solid oxide fuel cell is based on the concept of oxide ion migration through an oxygen ion conducting electrolyte from the oxidant electrode (cathode) to fuel electrode (anode) side. It operates at temperatures in the range of 600 – 1000ºC, which makes them highly efficient as well as fuel flexible. In case of SOFC the electrolyte is a dense solid that involves ceramic materials like Yttrium-stabilized zircon dioxide whose function is to prevent electrons from crossing over while allowing passage to the charged oxygen ions [6].
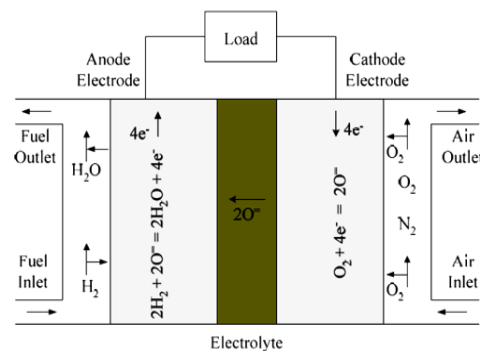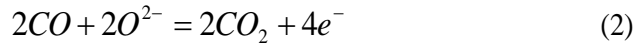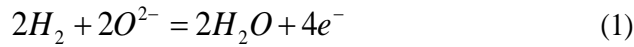

Fig. 1: Schematic diagram of a SOFC.

The chemical reactions that take place inside the SOFC which are directly involved in the production of electricity are as follows [2]

At anode

$$2H_2 + 2O^{2-} = 2H_2O + 4e^- \qquad (1)$$

$$2CO + 2O^{2-} = 2CO_2 + 4e^- \qquad (2)$$

At cathode

$$O_2 + 4e^- = 2O_2^- \qquad (3)$$

Overall cell reaction:

$$2H_2 + O_2 = 2H_2O \qquad (4)$$

III. MODELING OF SOFC

The following assumptions are made in developing the mathematical model of fuel cell stack. The gases considered are ideal, that is, their chemical and physical properties are not co-related to the pressure. Nernst equation is applicable and fuel cell temperature is constant at all times. The ideal gas law is used to calculate the partial pressure of all the gases. For hydrogen is given by.

$$p_{H_2} V_{an} = n_{H_2} RT \qquad (5)$$

Taking the derivative of the equation (5) w.r.t. time

$$\frac{d}{dt}\left(p_{H_2}\right) = \frac{d}{dt}\left(\frac{n_{H_2} RT}{V_{an}}\right) \qquad (6)$$

The hydrogen molar flow is further divided into three parts and their relationship can be expressed as follows

$$\frac{d}{dt}\left(p_{H_2}\right) = \frac{RT}{V_{an}}\left(q_{H_2}^{in} - q_{H_2}^{out} - q_{H_2}^{r}\right) \qquad (7)$$

According to the electrochemical relationship, the quantity of hydrogen that react is given by.

$$q_{H_2}^{r} = \frac{N_0 I_{fc}}{2F} = 2k_r I_{fc} \qquad (8)$$

Substituting (8) in (7), the time derivative of hydrogen partial pressure can be expressed as

$$\frac{d}{dt}\left(p_{H_2}\right) = \frac{RT}{V_{an}}\left(q_{H_2}^{in} - q_{H_2}^{out} - 2k_r I_{fc}\right) \qquad (9)$$

Taking the Laplace transforms both side and gives the expression for partial pressure of hydrogen

$$p_{H_2} = \frac{1/k_{H_2}}{1 + \tau_{H_2} s}\left(q_{H_2}^{in} - 2k_r I_{fc}\right) \qquad (10)$$

In similar way, the partial pressure of oxygen and water is given by

$$p_{O_2} = \frac{1/k_{O_2}}{1 + \tau_{O_2} s}\left(q_{H_2}^{in} - k_r I_{fc}\right) \qquad (11)$$

$$p_{H_2O} = \frac{1/k_{H_2O}}{1 + \tau_{H_2O} s}\left(2k_r I_{fc}\right) \qquad (12)$$

Calculation of Stack Voltage

The expression for stack output voltage V_{fc} of a fuel cell can be obtained applying Nernst's equation and also taking into account the voltage losses such as the Ohmic, Activation and mass transportation (concentration) losses as:

$$V_{fc} = E_{fc} - V_{act} - V_{conc} - V_{ohmic} \qquad (13)$$

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

$$E_{fc} = N_0\left\{E^0 + \frac{RT}{2F}\ln\left(\frac{p_{H_2} p_{O_2}^{0.5}}{p_{H_2O}}\right)\right\} \qquad (14)$$

IV. Calculation of Voltage Losses

1. Activation voltage losses

The reason for this loss in SOFC is the sluggishness of chemical reaction that takes place on the surface of electrodes. A certain amount of voltage produced by fuel cell is lost in carrying the reaction forward that transfers the electrons to or from the electrode. Activation losses are estimated using Tafel equation [2].

$$V_{act} = B \ln(i) \qquad (15)$$

2. Concentration voltage losses

These losses are also known as mass transport losses and are caused due to the reduction in concentration of reactants in the region of electrode as the fuel is consumed. The consumption of reactants at respective electrodes, i.e. hydrogen at the anode and oxygen at the cathode leads to a slight reduction in concentrations of the reactants. Due to the reduction in concentrations, there is a drop in partial pressure of

gases which will result in a reduction of voltage that portion of the electrode can produce [2].

$$V_{conc} = m \exp(ni) \tag{16}$$

3. Ohmic voltage losses

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

$$V_{ohmic} = r I_{fc} \tag{17}$$

V. Implementation of SOFC Model in Simulink /MATLAB

The SOFC model is based on the expression for partial pressures of hydrogen, oxygen, water, Nernst's voltage, Ohmic loss, activation loss and mass transportation loss. A comprehensive dynamic model of a SOFC has been developed and simulated in the MATLAB / Simulink as shown in Fig. 3 and V- I characteristic of SOFC in fig.4.
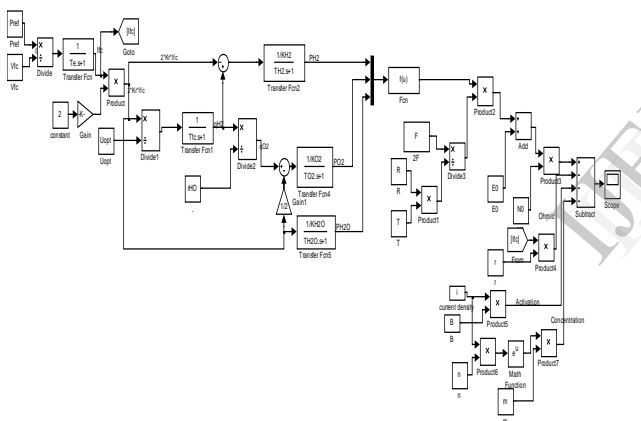

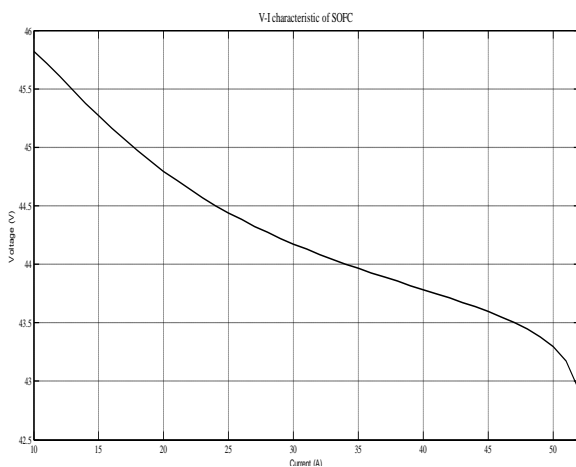
Fig. 3: Simulink diagram of a dynamic model of SOFC

Fig. 4: V –I characteristic of SOFC

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 and is expressed as:

$$U_f = \frac{q_{H_2}^r}{q_{H_2}^{in}} \tag{18}$$

The fuel utilization ranging from 0.8 to 0.9 yields better performance and prevent overused and underused fuel conditions. The optimum utilization factor assumed for this model is 0.85.

VI. 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 [8].

The complete model of SOFC based DG system with power electronics three–phase resistive load is shown in Fig. 5. The individual component modeling of SOFC is given in this paper. The three phase inverter, pulse generator, PWM and AC filter available in Simpower System of the MATLAB has been used.
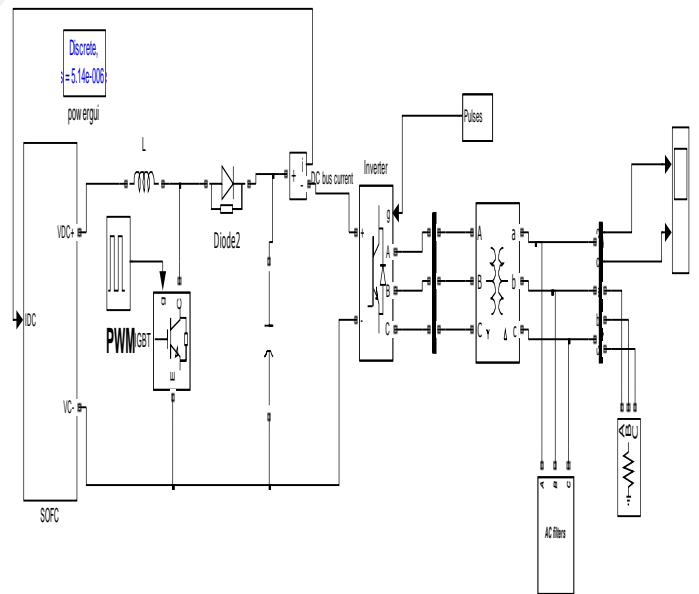

Fig. 5: Simulink model of SOFC based DG system

The output inverted voltage and current waveform of SOFC based distributed generation system are shown in fig. 6.
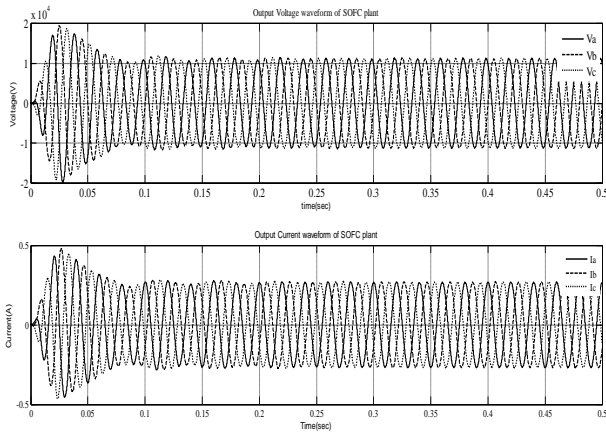
Fig. 6: Output voltage and current waveform of SOFC plant

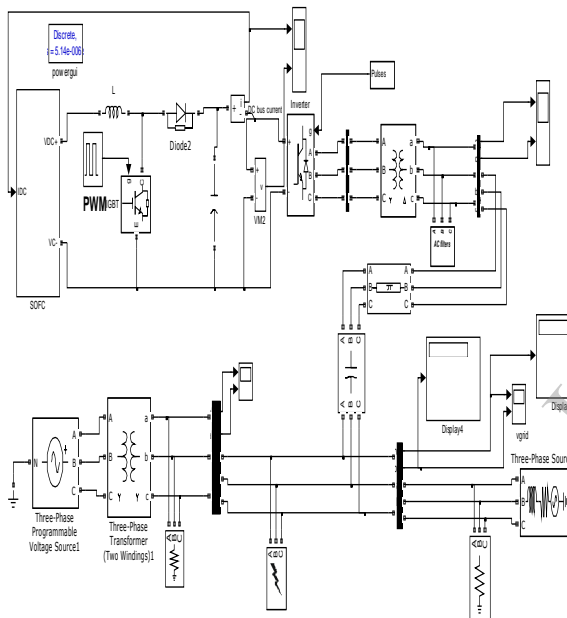## VII. Fuel cell Plant connected to the grid during L-G Fault

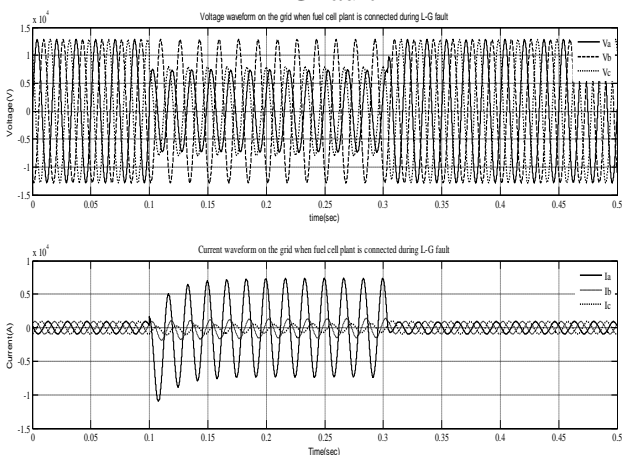Fig. 7: Simulink model with fuel cell plant during L-G fault

Fig. 8: voltage and current waveform with fuel cell plant during L-G fault

Table 1: values of voltage and current without and with fuel cell plant under normal and faulty condition

Voltage	Without fuel cell plant	With fuel cell plant
V (nom.)	11.03Kv	11.04Kv
I (nom.)	941.9A	933.1A
V (fault)	7.813Kv	7.821Kv
I (fault)	7283.33 Amp.	7250.85 Amp.

Fig.8 shows voltage and current waveforms when with fuel cell plant 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. It is clear from the above fig.8 that voltage profile is considerably improved after fuel cell plant interconnected with the grid. The various data of voltage and current are shown in table 1. After connecting the fuel cell plant system to the existing system we can say that power system stability is being improved.

VIII. CONCLUSION

This paper shows the impact of fuel cell power system on the stability of power system. The dynamic modeling and simulation results of a fuel cell based power system which consists of solid oxide fuel cell (SOFC) for power generation. The SOFC modeled 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.

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