Dynamic Modeling and Simulation of Solid Oxide Fuel Cell System

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Abstract— **This paper deals with the modeling and analysis of dynamic model of Solid Oxide Fuel Cell (SOFC) system in response to the grid connection using PSCAD/EMTDC simulation software. Fuel cells are known for their reliability, power quality, eco-friendly nature and fuel efficiency. Its promising technology and extremely significant in the near future. A voltage source inverter controller is developed for conversion of SOFC generation into ac grid system. The designed controller is also implemented to analyzed the output response of the developed fuel cell that can be used in distributed generation applications.**

Keywords—**Dynamic model; solid oxide fuel cell; inverter**

I. INTRODUCTION

Distributed Generation powered by microsources such as fuel cells, photovoltaic cells and microturbines, have been gaining popularity among the industry and utilities due to their higher operating efficiencies, improved reliabilities, and lower emission levels. The introduction of distributed generation to the distribution system has a significant impact on the flow of power and voltage conditions at the customers and utility equipment [1]-[2]. Among the microsource, fuel cells are attractive due to their modular, efficient, and environmentally friendly performance [3]. Fuel cells are capable of operating at efficiencies greater than traditional energy production methods. Moreover, the scalability of fuel cells has allowed for applications in almost every field. Fuel cell systems can be easily placed at any site in a power system for grid reinforcement, thereby deferring or eliminating the need for system upgrades and improving system integrity, reliability, and efficiency. Therefore, proper controllers need to be designed for a fuel cell system to make its performance characteristics as desired [4]-[5]. Development of a standalone, reduced-order, dynamic model of fuel cell power plant connected to a distribution grid via dc/ac converter [6]. The proposed model includes the electrochemical and thermal aspects of chemical reactions inside the fuel-cell stack but the dynamics model of DC/DC and DC/AC Converters are not considered [7]. A novel hierarchical control architecture for a hybrid distributed generation system that consists of dynamic models of a battery bank, a solid oxide fuel cell and power electronic converters has been presented [8]. The fuel cell power plant is interfaced with the utility grid via boost dc/dc converters and a three-phase pulse width modulation (PWM) inverter. A validated SOFC dynamic model used in this paper are reported in [9].

The voltage source inverter (VSI) modeling and the associated control methodologies are discussed in this paper. The VSI plays a vital role in interfacing the fuel cell system with the utility grid. Figure.1 depicts a one-line diagram of the fuel cell system connected to the utility grid.

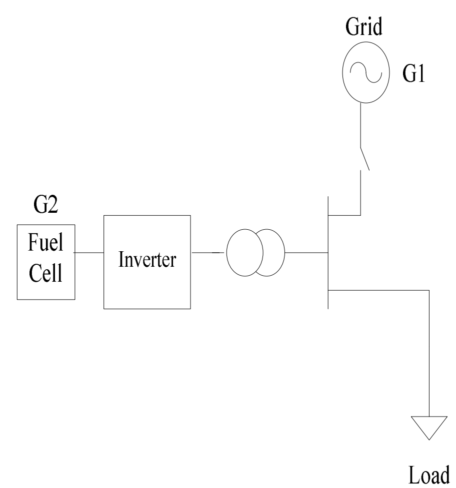

Figure 1. Single line diagram of grid connected fuel cell

The main objective of the inverter system is to convert DC power from the fuel cell converter to AC feeding to grid. Additional requirement for a power distribution system is to exchange the power between the source and load. Section II deals with a brief description of the SOFC technology, operation and modeling will associated with equations and subsystems. The inverter modeling has been discussed in section III. Section IV contains the simulation results and section V concludes the paper.

II. FUEL CELL TECHNOLOGY

The general classifications of fuel cells are based on the type of electrolyte used. There are many types of fuel cell such as alkaline fuel cells (AFCs), phosphoric acid fuel cells (PAFCs), proton exchange membrane fuel cells (PEMFCs), molten carbonate fuel cells (MCFCs) and solid oxide fuel cells (SOFCs). Fuel cells can further be classified based on operating temperature. Details on fuel cells based on type of electrolyte, operating temperature and fuel are shown in Table I.

TABLE I.
TYPE OF ELECTROLYTE, OPERATING TEMPERATURE AND FUEL FOR DIFFERENT FUEL CELLS

Type	Electrolyte	Fuel	Operating Temp. ^{0}C
AFC	KOH	H_2	50-200
PAFC	Phosphoric acid	H_2	~220
PEMFC	Solid polymer	pure H_2	50-100
MCFC	Lithium and potassium carbonate	H_2, CO, CH_4 other hydro-carbons	~650
SOFC	Solid oxide electrolyte	H_2, CO, CH_4 other hydro-carbons	500-1000

Different types of fuel cells have been developed using the same operating principle, each one with advantages and disadvantages respect to the others. The alkaline fuel cell (AFC) achieves a performance of 60 % operating at temperatures between 90 and 100 ºC and it can supply 100 kW. The fuel cell with polymer membrane (PEM) works at 80 ºC and produces 250 kW. Meanwhile, a performance of 85 % operating at 650 ºC, and a 2 MW supply can be obtained using fuel cell of fused carbon (MCFC).

Among different types of fuel cells classified by the type of electrolyte material, the SOFC is considered in this paper for distributed generation performance analysis under normal operating conditions. The features of SOFC in [11] can tolerate relatively impure fuel such as obtained from gasification of coal, operate at extremely high temperatures of 500 to 1000^O C. The reformer system of SOFC is less complex due to its using carbon monoxide as fuel along with hydrogen. The operating temperature of the reformer and the stacks are compatible. The SOFC system has relatively simple and response to load changes makes them suitable for large stationary power generations.

A. Fuel cell operation

Fuel cells are electro-chemical devices which are used to convert the chemical energy of a gaseous fuel directly into electricity. In fuel cells, a chemical reaction takes place to convert hydrogen and oxygen into water, releasing electrons in the process. In other words, that hydrogen fuel is burnt in a simple reaction to produce electric current and water. A fuel cell consists of two electrodes, known as anode and cathode that are separated by an electrolyte is shown in Fig. 2. Oxygen is passed over the cathode and hydrogen over the anode. Hydrogen ions are formed together with electrons at the anode. Hydrogen ions migrate to the cathode through the electrolyte and electrons produced at the anode flow through an external circuit to the cathode. At the cathode, they are combining with oxygen to form water. The flow of electrons through the external circuit provides the current cell. In order to storage energy, Hydrogen and Oxygen are obtained from water by passing a direct current in a process known as electrolysis. The chemical reactions that take place inside the SOFC and directly involved in the production of electricity are as follows.

At anode (fuel electrode)

$$2H_2 + 2O^{2-} \rightarrow 2H_2O + 4e^- \tag{1}$$

and

$$2CO + 2O^{2-} \rightarrow 2CO_2 + 4e^- \tag{2}$$

At cathode (air electrode)

$$O_2 + 4e^- \rightarrow 2O^{2-} \tag{3}$$

Overall cell reaction can be expressed as

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{4}$$

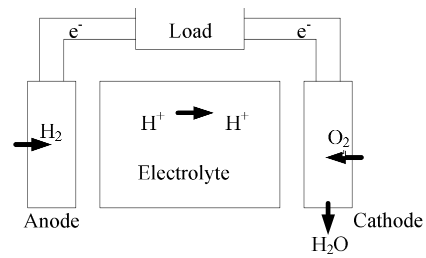

Figure 2. Schematic diagram of a fuel cell

B. Solid Oxide fuel cell model

A simulation model is developed for the SOFC in PSCAD based on the dynamic SOFC stack. The model developed parameters and validated in [9]. Considering ohmic losses of the stack, the expression of total stack voltage can be written as

$$V_{fc} = N_0\left(E_0 + \frac{RT}{2F}\left(\ln\frac{P_{H_2}P_{O_2}^{\;0.5}}{P_{H_2O}}\right)\right) - rI_{fc} \tag{5}$$

where V is the total stack voltage and rI is ohmic loss of the stack.

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 and to the resistance of the flow of oxygen ions through the electrolyte. Partial pressure of hydrogen, oxygen and water are given in Equations (6), (7) and (8). The slow dynamics of the fuel cell current is represented by Equation (9).

$$P_{H_2} = \left(\frac{\frac{1}{KH_2}}{1+\tau_{H_2} S} \right) \left(qH_2 - 2K_r I \right) \tag{6}$$

$$P_{O_2} = \left(\frac{\frac{1}{KO_2}}{1+\tau_{O_2} S} \right) \left(qO_2 - 2K_r I \right). \tag{7}$$

$$P_{H_2O} = \left(\frac{\frac{1}{KH_2O}}{1+\tau_{H_2} OS} \right) \left(2K_r I \right) \tag{8}$$

$$I = \left(\frac{I_{ref}}{1+\tau_e S} \right) \tag{9}$$

I_{ref} is the reference current which is given by Equation (10). Fuel and oxygen flow are given by Equations (11) and (12).

$$I_{ref} = \left(\frac{P_{ref}}{V_{fc}} \right) \tag{10}$$

$$qH_2^r = 2K_r I \tag{11}$$

$$qO_2^r = \frac{qH_2}{rHO} \tag{12}$$

The power output of the fuel cell system is the product of stack current and voltage. The block diagram represents SOFC dynamic model is shown in the Figure 3.

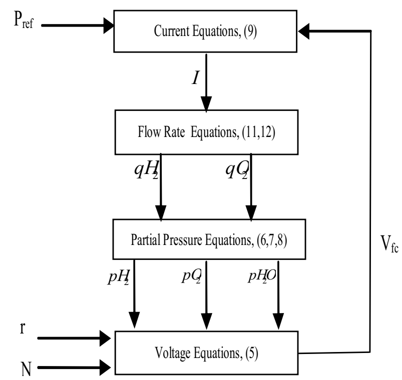

Figure 3. Block diagram for dynamic model of SOFC

III. PSCAD/EMTDC MODEL OF GRID CONNECTED FUEL CELL

PSCAD/EMTDC modeling of the proposed system is divided into three major parts,namely PSCAD/EMTDC fuel model, voltage source inverter (VSI) controller and grid connected fuel cell system, respectively, as described below. Simulation is performed by using the PSCAD/EMTDC software package.

A. *PSCAD/EMTDC Fuel Cell Model*

The Figure 4 shows the PSCAD/EMTDC model of the fuel cell system G2 of Figure 1. This dynamic model simulation is based on mathematical model of SOFC. The parameters of the system model are based on the parameters used in [11], given in the following as Table II.

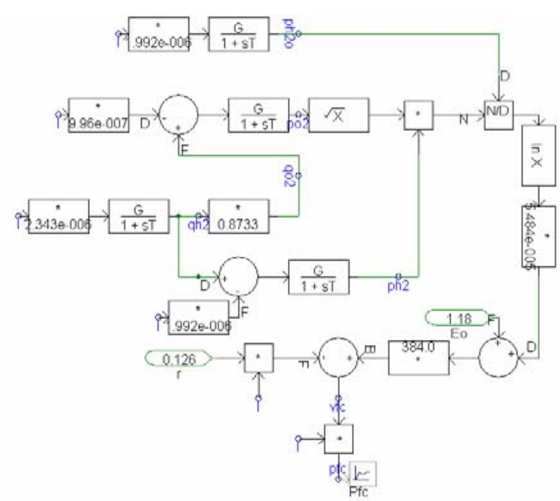

Figure 4. PSCAD model of SOFC

TABLE II.
PARAMETERS USED IN SOFC SIMULATION

Representation	Value
Operating temperature (T)	1273 K
Faraday's constant (F)	96487 C/mol
Universal gas constant (R)	8314 J/(kmol K)
Standard reversible cell potential (E)	1.18 V
Number of cells (N)	384
Constant ($K=N/4F$)	0.996 x 10^{-6} kmol/(s A)
Valve molar constant for hydrogen (KH_2)	8.43 x 10^{-4} kmol/(s atm)
Valve molar constant for oxygen (KO_2)	2.81 x 10^{-4} kmol/(s atm)
Valve molar constant for water (KH_2O)	2.52 x 10^{-3} kmol/(s atm)
Response time for hydrogen flow (T_{H2})	26.1 s
Response time for water flow (T_{H2O})	78.3 s
Response time for oxygen flow (T_{O2})	2.91 s
Ohmic loss (r)	0.126 Ω
Electrical response time (T_e)	0.8 s
Fuel processor response time (T_f)	5 s
Ratio of hydrogen to oxygen (r_{HO})	1.145
Base MVA	100

B. VSI Controller

The main function of the VSI controller is to supply the ac system voltage from the fuel cell generated dc voltage. Fig. 5 illustrates the control loops of VSI and the SPWM switching developed in PSCAD/EMTDC in which it is used as a basis in the 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 angles and angular positions of the voltages. The PLL is responsible for providing the basic voltage synchronizing signal with an angle θ. The measured voltage in per unit and a constant are fed into a maximum block to calculate the maximum voltage signal. Output signal of the maximum block is then passed through the first order low pass filter to attenuate the voltage transients and the signal is then compared with a reference voltage. A voltage error is observed and is fed to the voltage lag-lead function block, in which the output $Y(t)$ is fed to the proportional integral (PI) control block. $Y(t)$ can be expressed as,

$$Y(t) = L^{-1}\{G X_{(S)}\ (1+sT_1)/(1+sT_2)\} \tag{13}$$

where, G is the gain, T_1 is the lead time constant, T_2 is the lag time constant, s is the Laplace variable, $X_{(S)}$ is the input in the Laplace domain and L^{-1} is inverse Laplace transform.

The output of the PI controller is the angle δ, which gives either a leading or lagging phase angle, which is necessary to adjust the voltage of the capacitor. The angle order represents the shift between the system voltage and the voltage generated by the D-STATCOM. The angle order also known as the displacement angle δ can be expressed as,

$$\delta = \beta - \cos^{-1}\left[\frac{V_L}{V_S}\cos\beta + \frac{Z P_L}{V_S V_L}\right] \tag{14}$$

where, Z is the impedance depending on the fault level, V_S is the system voltage, V_L is the load voltage, β is the angle of the system impedance and P_L is the power flow into the system.

The displacement angle δ combined with output signal of the voltage control loop becomes the voltage modulating signal in which its magnitude and phase are controlled.

The PLL also provide the voltage synchronizing signal in which it is multiplied by SPWM switching frequency of 1.65 kHz, which is 33 times the system operating frequency so as to convert the carrier ramp signal into the triangular carrier signal whose amplitude is fixed between –1 to +1. In the SPWM technique, by comparing the triangular carrier signal with the voltage-modulating signal, the firing signals of the GTOs can be obtained. These firing signals operate the switches with anti parallel diode combination to get ac system voltage from de voltage, which is the basic concept of voltage source inverter.

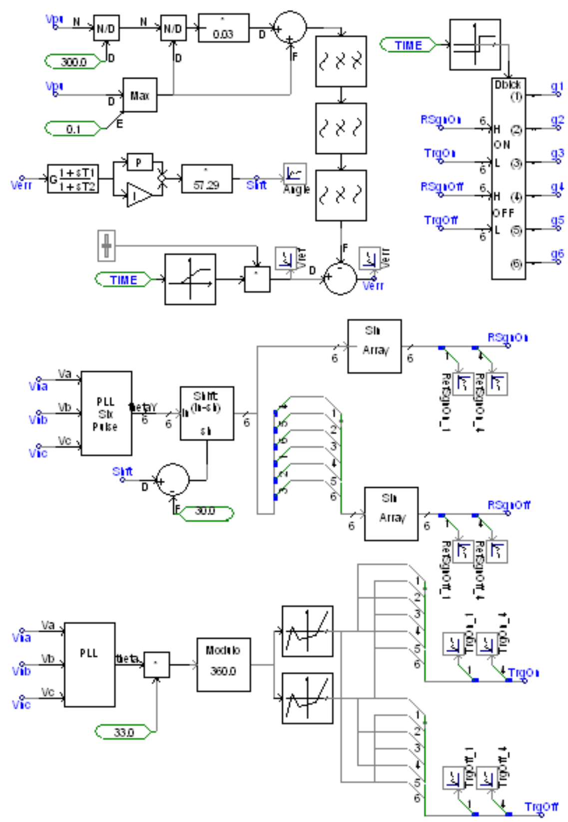

Figure 5. SPMW control of voltage source inverter

C) Grid Connected Fuel Cell System

PSCAD/EMTDC model of grid distribution system connected with fuel cell system is developed as shown in Figure 6.

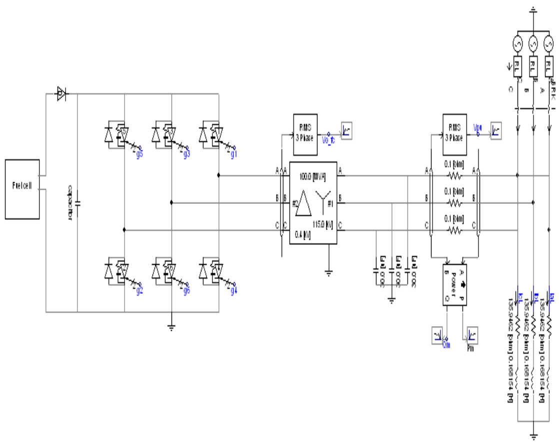

Figure 6 Grid connected fuel cell system

IV. RESULTS AND DISCUSSION

Figure 7 shows the response of the fuel cell for the power 50KW. The increase in the value of current in turn decreases the fuel cell system output voltages, which represent in Figure 8 and Figure 9.

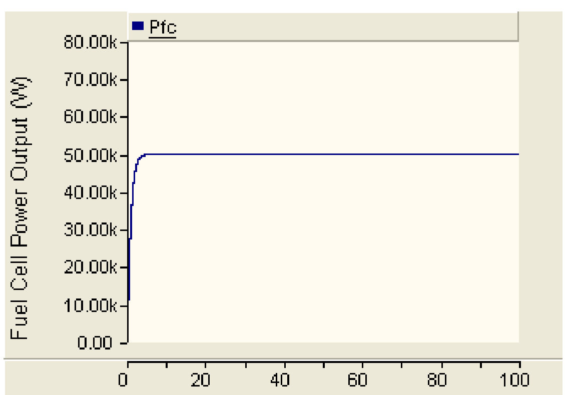

Figure 7 Fuel cell power output

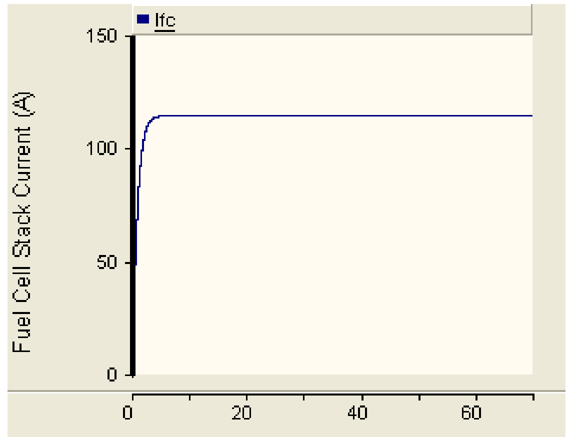

Figure 8. Response of fuel cell stack current

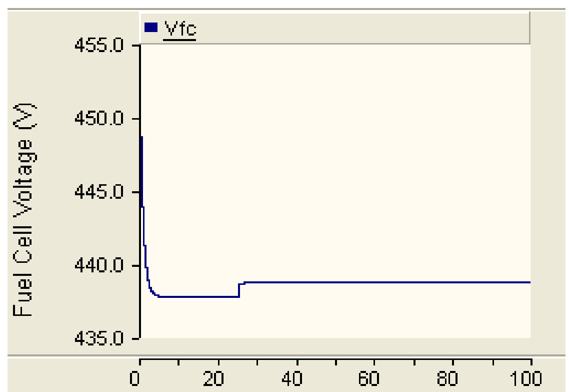

Figure 9. Response of fuel cell voltage

In the simulation, initially the circuit breaker at the bus connected to the grid is closed. When the grid is disconnected from the system, the SOFC immediately increases its power so as to compensate for the loss of grid supply at a period of 5 to 10sec. At the start of the SOFC operation, the circuit breaker opens and the load voltage is indicated by an overshoot as shown in Fig. 10. When the CB closes again, the power from the grid is then supplied to the system and a spike is indicated in the load voltage immediately following the reconnection. The simulation shows that the inverter controls respond accordingly, with the load voltage returning quickly to its pre-disturbance value.

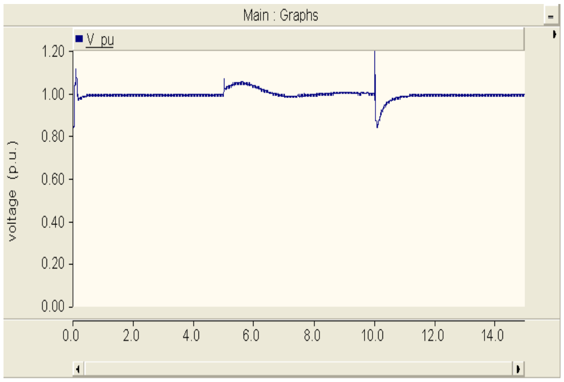

Figure 10. With fuel cell system in operation

V. CONCLUSIONS

In an industrial power generation, fuel cell is one of most important sources of distributed energy in the future. Modeling and simulation study of a SOFC power system is investigated in this paper. A validated SOFC dynamic model is used to model the fuel cell system. A three phase inverter has been modeled and connected between the SOFC power system on one side and the utility grid on the other side through an ideal transformer. A control strategy for the inverter switching signals has been discussed. In addition, the models for the three phase inverter are simulated and verified will be controllable to be 1 p.u.

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