MODELING AND SIMULATION OF FUEL CELL BASED POWER SYSTEM

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Abstract: This article presents the reduced emission of carbon to develop pollution free environment in fuel cells. The need of electrical energy is raised to meet the requirement of the fuel cell technology has become as a power source for future. This paper presents the mathematical modelling of proton exchange membrane fuel cell and its output range is designed for residential application. The fuel cell based power system comprises of DC/DC converter and inverter is simulated by MATLAB Simulink . By this power source the pollution due to fossil fuels will reduce and prevent the environment.

Index Terms – PEM Fuel cell, Mathematical modelling, Boost converter, Inverter, MATLAB

I. Introduction

Now a days the carbon-di-oxide produced in large amount due to usage of vehicles, fossil fuel based power plants which will aggravate the green house effect and speed up global climate change. This leads to the negative effect in environment. The petroleum reservoir availability is limited, so alternate energy source has become an important one. Micro grid technology has become as one of the solution to attain the demand problem.

The renewable energy sources such as solar energy, wind energy, storage system and fuel cell are combined in micro grid. They are connected with grid in the site where they connected with low voltage distribution network with the help of power electronic[1-2]. Thus the storage of energy in batteries has less life time compare to hydrogen storage technology. The hydrogen storage is emission free and long term storage system which is used to store the intermittent energy of solar and wind energy system. Thus for the conversion of hydrogen energy to electrical energy the fuel cell is used.

The fuel cell is electrochemical device which convert chemical energy to dc electrical energy and heat. The major features of fuel cell are high energy efficiency, low emission and noise free environment, so this technology has become an excellent power source. There are various types of fuel cells available for use in industry such as Proton exchange membrane fuel cell (PEMFC), Solid oxide fuel cell (SOFC), Molten carbonate fuel cell (MCFC), Phosphoric acid fuel cell (PAFC), Aqueous Alkaline fuel cell (AAFC). Compared to all the types of fuel cell, PEMFC has high energy density; temperature level is low and simple in structure. The requirements of fuel cells are hydrogen and oxygen. At the end of conversion it produces dc electrical energy and heat in addition that the water is produced as a residue. They have high efficiency compared to thermal generation and the concern related due to construction, transportation, safety is reduced due the presence of solid polymer as an electrolyte. The literature [2&6] represents the mathematical model of fuel cells and its performance for residential application the fuel cell with power electronic devices and integration with grid[5] are effectively illustrated.

This paper proposes the fuel cell based power system (150V) for residential application. The detailed mathematical model of fuel cell is developed. Power conditioning unit i.e. Power electronic interfacing circuit is necessary for FC based power systems to condition its output dc voltage and converts the dc voltage to ac voltage is connected to the load via inverter.

II. The Fuel Cell

A. The Description of Fuel cell

The fuel cell produces electricity by an electrochemical reaction. It has two electrodes, one positive anode and one negative cathode. The electricity produced by the reactions takes place at the electrodes. In the PEMFC[1] shown in fig.1, a polymer electrolyte in the form of a thin, permeable sheet which carries electrically charged particles from one electrode to the other, and a catalyst, which speeds the reactions at the electrodes. The basic fuel is hydrogen, but oxygen also required. Thus fuel cells generate electricity with very less pollution and form a harmless by product, namely water.

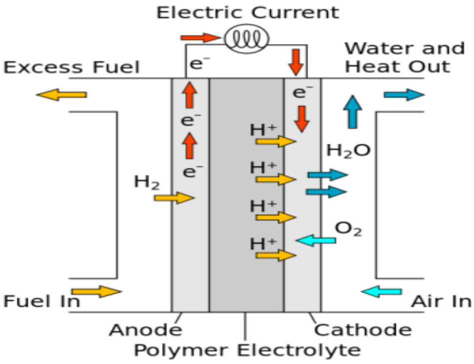

Fig.1 Schematic representation of PEMFC

The hydrogen is oxidized at the anode and yields electron and hydrogen ions.

$$2H_2 \rightarrow 4H^+ + 4e^- \quad (1)$$

The yielded electrons flow from anode to cathode via the external circuit. The hydrogen ions travel through the electrolyte and reaches cathode. At the cathode, oxygen reacts with the incoming electrons and hydrogen ions produce water as a by product.

$$2H_2 + O_2 \rightarrow 2H_2O + Heat \quad (2)$$

The flow of electrons provide power to the load. The number of cells connected in series to make a stack and produce dc voltage.

*B. **The mathematical model of Fuel cell***

The fuel cell depends on number of factors such as current density, cell temperature, membrane humidity, and partial pressure of reactants. The potential of a single cell V_{cell}, is found using Eq. (3).

$$V_{cell} = E - V_{act} - V_{ohm} - V_{conc} \quad (3)$$

E – Nernst equation (Eq.(4)) is a open circuit cell potential as a function of cell temperature and partial pressures.

$$E = E_o - 0.85 \times 10^{-3}(T - 298.15) + \frac{RT}{2F}\ln\left(\frac{P_{H_2O}}{P_{H_2} \times P_{O_2}{}^{1/2}}\right) \quad (4)$$

Where E_o represents the reference potential at unity, R is the universal gas constant, and F is the Faraday constant. P_{H2}, P_{O2}, and P_{H2O} are vapour pressure of hydrogen, oxygen and water.

V_{act} - Activation loss are take places due to the slowness of reaction on the surface of electrodes. It is analysed by Tafel's equation and model is outlined.

$$E_{act} = \xi_1 + \xi_2 T + \xi_3 T(\ln(CO_2)) + \xi_4 T(\ln(i)) \quad (5)$$

Where ξ_1 to ξ_4 represent constant parametric coefficients, i is current density and CO_2 is the oxygen concentration and is given as a function of stack temperature in Eq.(6).

$$CO_2 = \frac{P_{O2}}{5.08\times10^6 e^{(-498/T)}} \quad (6)$$

Since, the activation overvoltage appears as a voltage drop in Eq.(3) and Eq.(5) is negative throughout the whole range, Eq.(7) is used to avoid a double negation for this term.

$$V_{act} = -E_{act} \quad (7)$$

There exist a charge double layer in the PEMFC, an electrical capacitor can be considered as the layer of charge on or near the electrode– electrolyte interface, which is a store of electrical charge and energy.

The electrochemical equivalent circuit model of fuel cell is shown in fig.2.

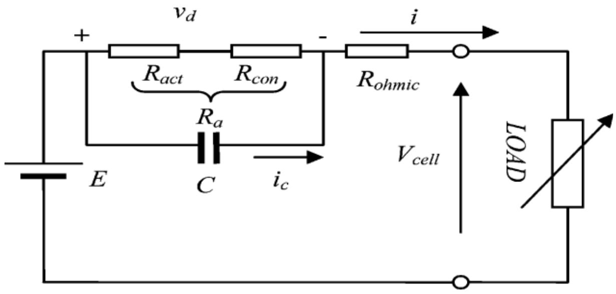

Fig. 2 Equivalent circuit model of the PEMFC

In fig. 2, E is the open circuit voltage, R_a is the equivalent resistance that includes the activation equivalent resistance R_{act} and the concentration equivalent resistance R_{conc}; the equivalent capacitance C can effectively smooth the voltage drop across R_a. Thus it is easier to analyse serial/parallel combination of fuel cell.

The effects of double layer capacitance charging at electrode-electrolyte interfaces can be expressed by Eq.(8)

$$\frac{dV_{act}}{dt} = \frac{i}{C_{dl}} - \frac{V_{act}}{R_{act}C_{dl}} \tag{8}$$

Where, C_{dl} is the double layer capacitance and R_{act} is the activation resistance, found by dividing the activation voltage, V_{act} with the cell current density i.

$$R_{act} = \frac{V_{act}}{I} \tag{9}$$

Here R_{act} is standard effective resistance for a given cell current I.

V_{ohm} – At the intermediate current density the voltage drop is almost linear and ohmic in nature. The memebrane resistance, R_{mem} is found by dividing the thickness, t_m by the conductivity, σ in Eq.(10) & Eq.(11).

$$V_{ohm} = IR_{mem} \tag{10}$$

$$R_{mem} = \frac{t_m}{\sigma} \tag{11}$$

The factors such as water drag from anode to the cathode due to moving protons, external water content of the reactants, water removal by the circulating reactants and back diffusion of water from the cathode to the anode are taken in to consideration for the membrane water content. The effect water drag is a significant factor, it could be hypothesized that the membrane proton concentration is a function of cell current density only. Thus the membrane conductivity σ is estimated by determining the proton concentration C_{H+} is given in Eq.(12) & Eq.(13).

$$\frac{dC_{H+}}{dt} + \frac{C_{H+}}{\tau_{H+}} = \frac{1+\alpha_{H+}i^3}{\tau_{H+}} \tag{12}$$

$$\alpha = \frac{F^2}{RT} D_{H+}C_{H+} \tag{13}$$

Sym	Parameters	Values	Unit
E_o	Reference Potential	1.229	V
R	Universal gas constant	8.314	$Jmol^{-1}K^{-1}$
F	Faraday constant	96485	$Cmol^{-1}$
T	Stack temperature	353	K
t_m	Memebrane thickness	175×10^{-4}	cm
C_{dl}	Double layer capacitance	0.035×232	F
τ_{H+}	Time constant	12.78	s
α_{H+}	Relational parameter	5.78	cm^6A^{-3}
D_{H+}	Ddiffusion coefficient	0.85×10^{-6}	$cm\ s^{-1}$

Table 1. Fuel Cell Model Parameters

V_{conc} – At higher current density the cell potential decreases rapidly due to mass transport limitation. This nonlinearity is termed as concentration over potential is given in Eq.(14).

$$V_{conc} = ae^{(bi)} \tag{14}$$

Here, the coefficients a (V) and b (cm^2mA^{-1}) vary with temperature and are given as

$$a = 1.1 \times 10^{-4} - 1.2 \times 10^{-6}(T - 273) \quad (15)$$

$$b = 8 \times 10^{-3} \quad (16)$$

Thus from the Eqs.(3)-(16), the cell potential V_{cell} can be solved. To obtain the stack output, product of cell potential and number of cells (40).

$$V_{stack} = V_{cell} \times 40 \quad (17)$$

The output power of PEMFC stack is

$$P_{stack} = V_{stack} I \quad (18)$$

III. Power Conditioning Unit

The fuel cell is connected to the utility load/grid through power converters. The block diagram of fuel cell power system is shown in fig.3

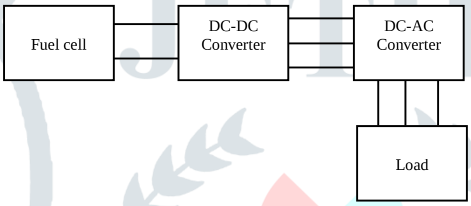

Fig.3 Block diagram of Fuel cell power system

A. DC-DC Boost converter

In the boost converter in fig.4, when switch S is open inductor current increases linearly and at that time the diode D is off. When switch S is closed, the stored energy in the inductor is released through the diode to the output RC circuit.

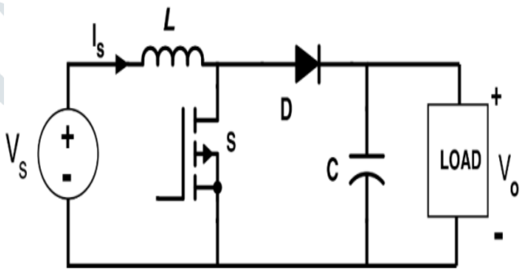

Fig.4.Circuit diagram of Boost converter

Where V_s is the DC input voltage, L is the boost inverter, S is the controlled switch, D is a diode, C is a capacitor and R is the load resistance.

The input-output voltage and duty cycle associated by the Eq. (19)

$$\frac{V_O}{V_S} = \frac{1}{1-D} \quad (19)$$

The inductance L is calculated in Eq. (20), such that inductor current flows continuously and never falls to zero.

$$L = \frac{(1-D)^2 DR}{2f} \quad (20)$$

Where, f is switching frequency

Similarly the output capacitance C is calculated by Eq. (21), to produce the desired output voltage ripple.

$$C = \frac{D}{Rf\Delta V} \tag{21}$$

Where, ΔV is output voltage ripple factor.

B. Inverter

The output voltage of DC/DC converter is fed to DC side of the inverter. The generated output voltage of three phase inverter is connected to load.

IV.Results and Discussions

In order to verify the proposed method, fuel cell based power system comprises of DC/DC converter and inverter is used in MATLAB simulink. The simulink diagrams of fuel cell are shown in the following figures (5)-(8).

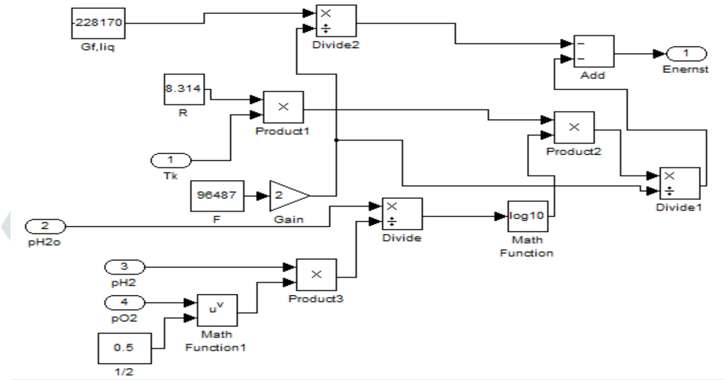

Fig.5 Simulink model of Nernst equation

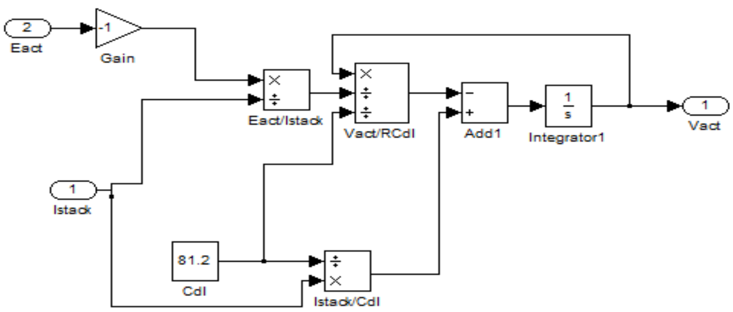

Fig.6 Simulink diagram of V_{act}

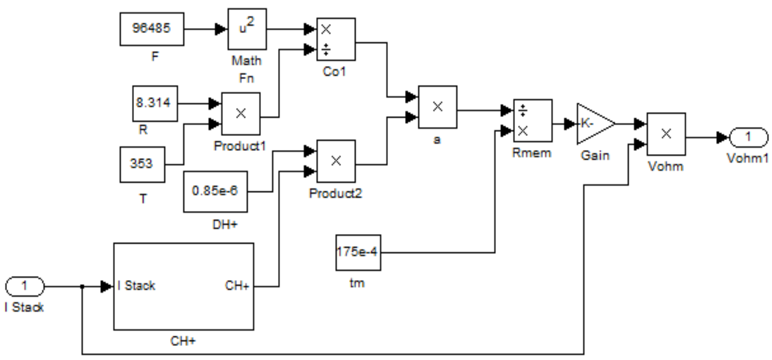

Fig.7 Simulink diagram of V_{ohm}

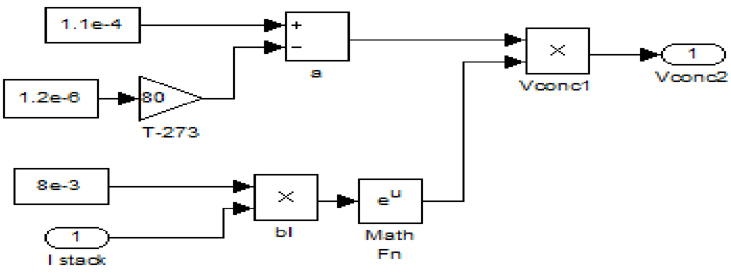

Fig.8 Simulink diagram of V_{conc}

The V-I characteristics are obtained by simulating the model using MATLAB for the following input variables: P_{H2} = 5 pascal and temperature T = 80°C. Thus the simulated V-I characteristics of a single PEMFC are shown in fig. 9.

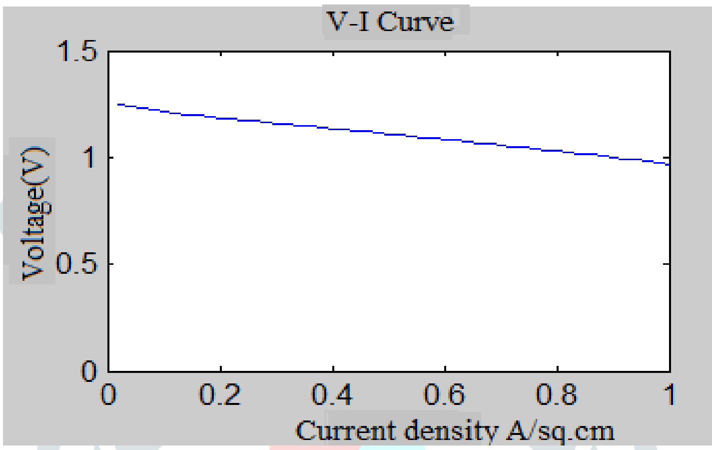

Fig.9 V-I characteristics of Fuel cell

The output stack voltage of fuel cell is obtained as 32V for the 40 cells. The corresponding graph is shown in fig.10.

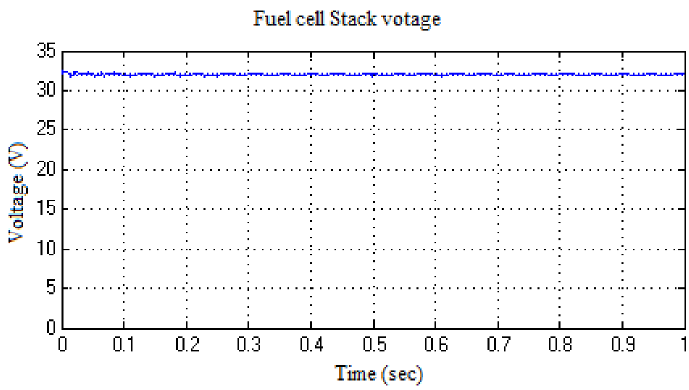

Fig.10 Fuel cell Stack Voltage waveform

In order to use the fuel cell for residential application, with the help of boost converter the voltage level is increased as 150V. The simulink model is shown in fig. 11.

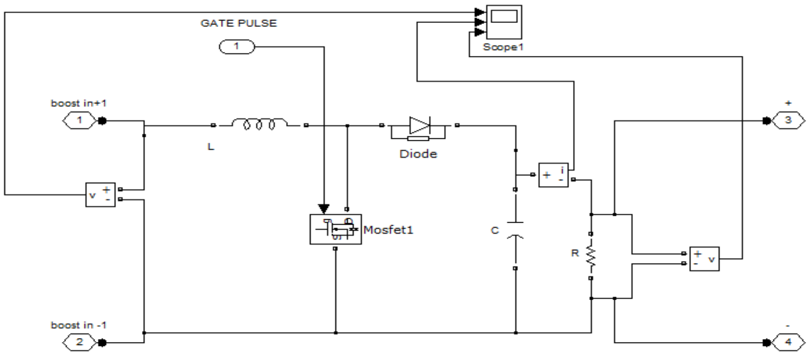

Fig.11 Simulink model of Boost Converter

The DC/DC converter output is obtained as 150V the corresponding graph is shown in fig. 12.

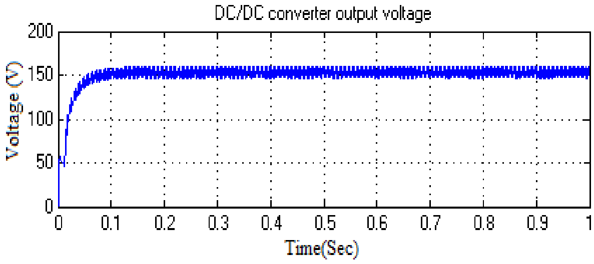

Fig.12 Converter output voltage waveform

The DC converter output is converted into AC voltage by the inverter circuit. The Simulink model of Inverter is shown in fig.13. The Inverter AC output voltage 150V is shown in fig.14.

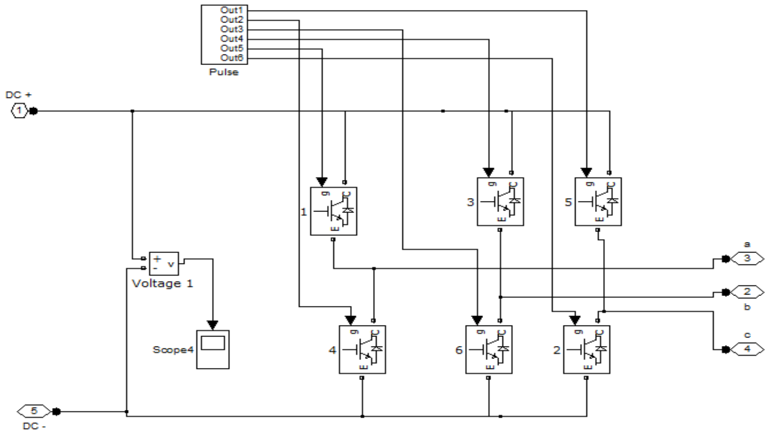

Fig.13 Simulink model of Inverter

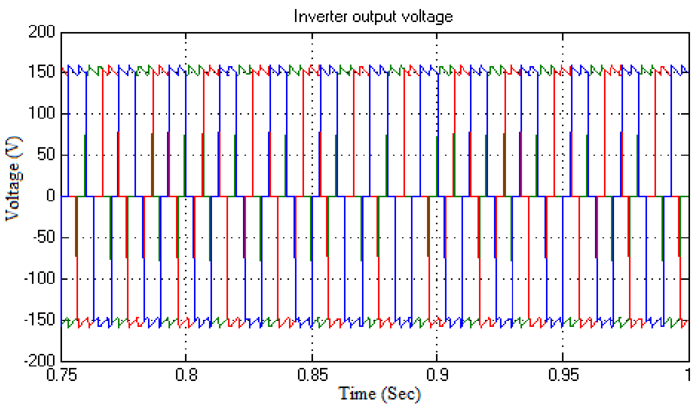

Fig.14 AC output voltage waveform

V.Conclusion

PEM Fuel cell based power system dynamic modeling is presented and simulation results are discussed. The system coupled with suitable power conditioning circuit the electrical and physical parameters are kept under desired limit. Thus this model would be useful for stand-alone applications. The analysis can be extended by designing power converter circuits and controller. With this fuel cell based power system the intermittent sources are used effectively and reduce the carbon emission and pollution free Environment.

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