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Dynamic Performance Analysis of SOFC

Shruti Yadav[1], Mukund Kumar Singh[2], K. Sudhakar[3] and Ruchi Yadav[4]

[1,2,3]Energy Centre, MANIT Bhopal
[4]K.R. Mangalam University
E-mail: [1]shruti.yadav2009@gmail.com, [2]mukundsingh89@gmail.com,
[3]nittsudhakar@gmail.com, [4]yadav.ruchi1990@gmail.com

Abstract—*The depletion in the conventional energy sources has created a need to explore various nonconventional energy sources such as wind energy, solar energy, hydro energy, fuel cell energy systems etc. Apart from the fact that they are readily available, they are also least harmful to the environment as compared to the conventional energy sources. Consistency and portability of fuel cell makes it the best contender of renewable energy system. This paper deals with the study of dynamic performance of solid oxide fuel cell (SOFC) based on transfer function. Various losses are considered in the model and its performance is tested for constant utilization mode and constant fuel flow mode of operations for both high and lower power. The effect of varying power, operating temperature and fuel flow on the performance of SOFC has been analyzed for two modes of operation.*

Keywords: *Distributed generation, dynamic modeling, solid oxide fuel cell.*

1. INTRODUCTION

Distributed generation (DG) technologies can deliver energy elucidations to some customers that are more economical, more environmentally approachable, or deliver higher quality power or consistency and 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 presages the most noteworthy development in energy efficiency, management, conservation and environmental protection for next decade [2]. SOFC are briskly industrialized 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].

Research in solid oxide fuel cell SOFC is attaining impulse because of its distinct advantages over other energy conversion methods. It has the diverse benefits of high energy conversion efficiency, low environmental impact, and flexibility of usable fuel type. Due to high operating temperature 800°C it allows the direct reformation of the natural gas. The hydrogen is electrochemically converted producing electrical power and high quality by-product heat for cogeneration or other cycle. So far, a 47% net SOFC electrical efficiency has been accomplished as demonstrated in reference [4]. Furthermore, the incorporation of a pressurized SOFC stack provides itself to the possibility of hybrid power generation, where the stack gases can be used to drive a gas turbine. One such power system is in operation today in Siemens-Westinghouse Power Corporation and it achieves an efficiency of 55% [5]. It is ostensible that the SOFC has the potential to play a substantial role in the electric utility.

Simulation and mathematical models are positively helpful for expansion of various power generation technologies; however, they are perhaps more important for fuel cell expansion. This is due to complexity of fuel cells and systems based on them, and the difficulty in experimentally personifying their internal operation. This intricacy can be explained based on the statistic that within the fuel cell, tightly coupled electrochemical reactions, electrical conduction, ionic conduction, and heat transfer takes place concurrently. That is why a complete study of fuel cells needs a multidisciplinary methodology. Modeling can help to understand what is actually happening within the fuel cells [6]. Understanding the inside physics and chemistry of fuel cells are often difficult. This is because of countless number of physical and chemical processes in the fuel cells, difficulty in independent controlling of the fuel cells parameters, and access limitations to inside of the fuel cells [7].

Fuel cells simulation, in addition can help to concentrate on untried researches and to expand accuracy of interpolations and extrapolations of the results. Furthermore, mathematical models can serve as treasured tools to design and optimize fuel cell systems. On the other hand, dynamic models can be used to design and test fuel cell systems. Finally, models can be established to assess whether characteristics of specific type of fuel cell can encounter the requirements of an application and its cost-effectiveness [6].

In this paper a study on modeling and simulation of fuel cell which includes partial pressures of respective species (hydrogen, oxygen and water) and different losses (ohmic, activation and concentration loss) are considered under constant fuel flow and constant utilization mode and responses are drawn for different temperatures and for different power levels.

2. PRINCIPLE AND OPERATION OF SOLID OXIDE FUEL CELL

Fuel Cell comprises of two electrodes known as anode and cathode which are separated by electrolytes (made up of ceramic). In fuel cell through anode Hydrogen is passed and through cathode oxygen is passed. Hydrogen ions are molded together with electrons at the cathode. Over the electrolytes hydrogen ions moves to the cathode and at the anode produced electrons flow over an external circuit to the cathode. Hydrogen ions and electrons associate with oxygen to form water at the cathode. The cell current is delivers over the flow of electrons through the external circuit. The overall reaction gives water as its by-product, so it accomplishes that fuel cells are environmental friendly. The chemical reaction equation of anode and cathode is given as

At Anode:

$H_2 + O_2^{-} - > H_2O + 2e^-$

And

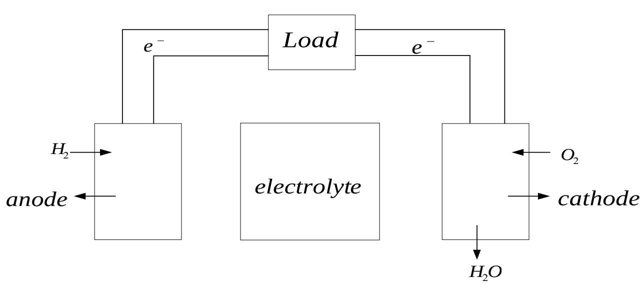
At Cathode:

$1/2O_2 + 2e - > O_2^{-}$

Overall:

$H_2 + 1/2O_2 - > H_2O$

The anode is classically porous nickel-zirconium cermets that serve as the electro catalyst, which can be electronically conductive. It allows fuel gas to reach the electrolyte interface, and catalyzes the fuel oxidation reaction.



3. MODELING OF SOLID OXIDE FUEL CELL

The proposed dynamic model is based on the following chemical and physical principles:

1) Electrochemical model: Effect of partial pressure on SOFC output voltage;

2) Thermal model: Effect of temperature on SOFC output voltage;

3) Voltage activation, concentration, and ohmic losses: Nernst voltage equation.

These components are described below.

Fuel Cell Voltage

The output voltage Vfc of the SOFC is given by [1]–[10]

Vfc=E−Vact−Vcon−Vohmic Where E is the Nernst reversible voltage, Vact is the activation loss, Vcon is the concentration loss, and Vohmic is the ohmic loss.

Nernst Reversible Voltage:
The Nernst reversible voltage is the open-circuit voltage of the Solid oxide fuel cell when the current density Ifc is zero

$$E = E_0 + \frac{RT}{2F}\ln\left(\frac{P_{H_2}P_{O_2}^{1/2}}{P_{H_2O}}\right)$$

(5)Where E0 = 1.1 V is the standard potential, R = 8.314 kJ/kmol· K is the universal gas constant, T is the operating temperature of the fuel cell in Kelvin's, F = 96 486 C/mol is the Faraday constant, and PH2 is the hydrogen partial pressure, PH2O is the water partial pressure, and PO2 is the oxygen partial pressure.

Partial Pressure Calculation
For calculation of the output voltage of the fuel cell the effective partial pressure of reactant gasses must be known. The formula of the partial pressure of hydrogen is following the procedure discussed in [10] which is given as-

$$p_{H_2} = \left(\frac{1/k_{H_2}}{1+\tau_{H_2}s}\right)(q_{H_2} - 2K_r I)$$

Where Kr is a constant defined for calculating partial and s is the Laplace variable. Similarly partial pressure of oxygen and water is given below-

$$p_{O_2} = \left(\frac{1/k_{O_2}}{1+\tau_{O_2}s}\right)(q_{O_2} - K_r I)$$

$$p_{H_2O} = \left(\frac{1/k_{H_2O}}{1+\tau_{H_2O}s}\right)(2K_r I)$$

2) Effect of temperature
SOFC is high temperature fuel cell. From Nernst equation it can we analyzed fuel cell voltage directly depends on operating temperature. Its efficiency depends on temperature because fuel cell output voltage depends on the operating temperature. Both Change in Gibbs free energy (J mol-1) and Enthalpy of formation (J mol-1) both depends on the operating temperature of fuel cell.

$$\eta_{\max} = \frac{\Delta\overline{g}_f}{\Delta\overline{h}_f} \times 100\%$$

4. FUEL CELL LOSSES

There is three types of losses befalls in fuel cell and each of them are listed below-

4.1) Activation Losses

Chemical reactions, together with electrochemical reactions, must overcome energy barricades, called "activation energy," this is essential for the reaction to proceed. This leads to activation polarization. The activation loss is given by the Butler–Volmer equation [6], [8], [17], [18]

$$i = i_o \left\{ exp\left(\beta \frac{nF\eta_{act}}{RT}\right) - exp\left[-(1-\beta)\frac{nF\eta_{act}}{RT}\right]\right\}$$

4.2) concentration losses

As the reactant is consumed at the electrode by electrochemical reaction, there is a loss of potential due to the inability of the surrounding material to maintain the initial concentration of the bulk fluid. Concentration loss equation is as follows [3], [6], [7], [10]–[12]:

$$\eta_{\text{con}} = \frac{RT}{n_a F} \ln\left(1 - \frac{i}{i_L}\right)$$

4.3) Ohmic Losses

Ohmic losses arise because of resistance to the flow of ions in the electrolyte and resistance to flow of electrons over the electrode materials. This resistance is reliant on on the cell temperature and is obtained by [7] and [12]

$$r = \alpha \exp\left[\beta\left(\frac{1}{T_o} - \frac{1}{T}\right)\right]$$

5. SIMULATION RESULTS OF SOFC

1) Constant fuel flow mode-for low power (3kw)

The simulation block for the constant fuel flow mode is given below in Fig. 1. In constant fuel flow mode we keep the temperature (T=958k) constant and vary the applied fuel input. In this we vary the input fuel from qH21=.2130mol/sec to qH22=.3130mol/sec and obtain the graph for output voltage and current. From the graph we can see that as we increase the fuel input it took less time to voltage to reach steady state. Variation of load current, output power and voltage with time is presented in Fig. 2 (a), (b) and (c), respectively for two different Fuel inputs.

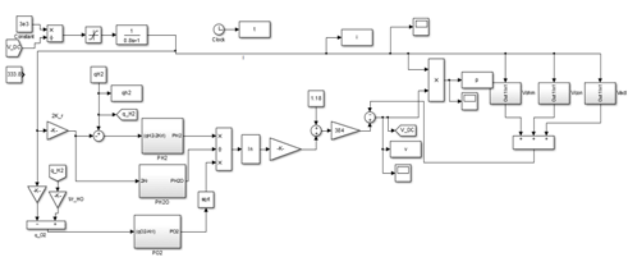


Fig. 1: SOFC model for constant fuel flow operation

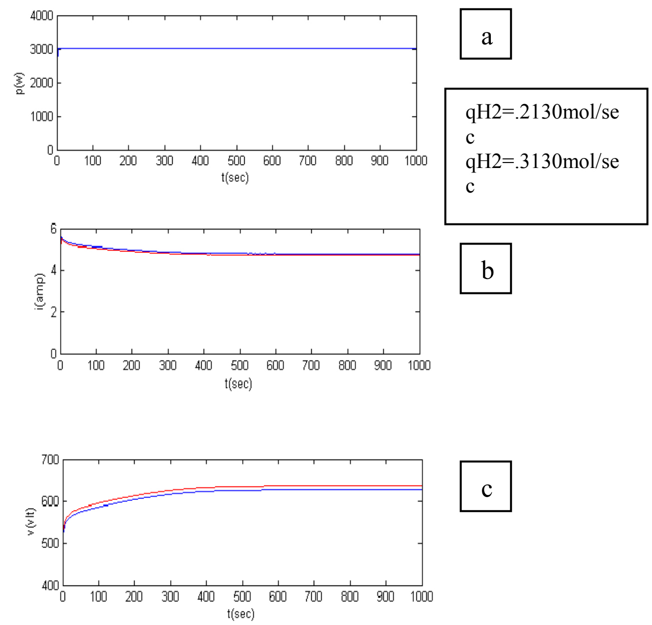


Fig. 2: (a) output power (b) Stack current and (c) output voltage under different fuel input for a constant temperature.

2) Constant utilization mode for low power (3kw)

SOFC can also be operated in constant fuel utilization mode, where fuel utilization (Uf) is the ratio between the fuel flow that reacts and the input fuel flow [2], is given as equation (17):

$$U_f = \frac{q_{H2}^r}{q_{H2}^{in}}$$

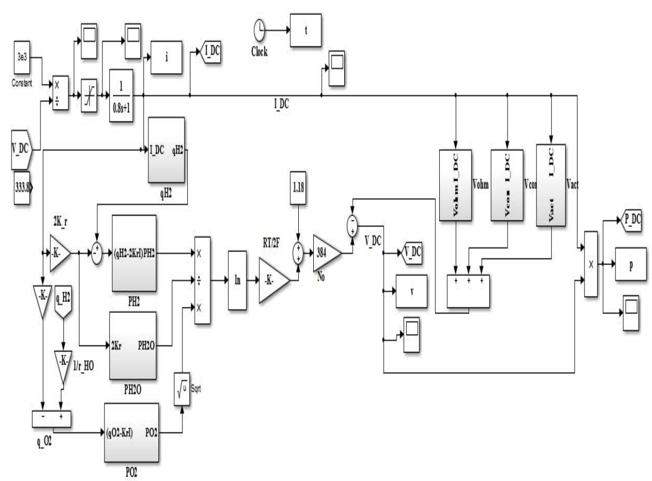


Fig. 3: Simulation model for constant utilization mode

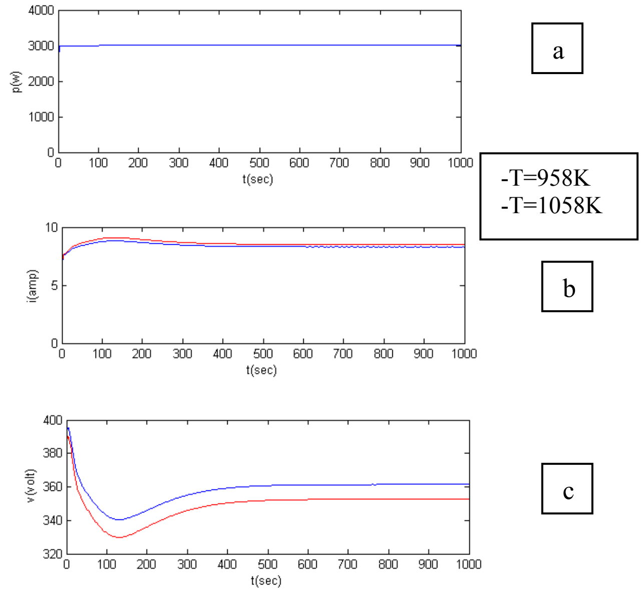


Fig. 4: (a) output power (b) Stack current and (c) output voltage under different temperatures for a constant fuel utilization.

In constant utilization mode we vary temperature of the model from T=958K to T=1058K keeping the utilization factor constant. From the obtained graphs we can analyze that as we increase the temperature current increases slightly and the output voltage decreases. And the output voltage take less time to reach steady state compare to low temperature. Initial voltage drop is due to an activation energy barrier that must be overcome before chemical reaction starts inside SOFC and this drop is called activation voltage drop. SOFC stack current vs time, output power vs time and output voltage vs time plots for constant Uf are presented as Fig. 2.1 (a), (b) and (c), respectively for two different operating temperatures (i.e. for T=958 K and T=1058 K).

3) Constant fuel flow mode for high power-

The simulation block for the constant fuel flow mode is given below in Fig.5. In constant fuel flow mode we keep the temperature (T=958k) constant and vary the applied fuel input. In this we vary the input fuel from qH21=.2130mol/sec to qH22=.3130mol/sec and obtain the graph for output voltage and current. From the graph we can see that as we increase the fuel input it took less time to voltage to reach steady state. Ohmic and activation losses are temperature dependent but here temperature is constant hence less variation in voltage is clearly visible in the obtained graph.

SOFC model for constant fuel flow operation and graph which represents Variation of load current, output power and voltage with time is presented in Fig.6 (a), (b) and (c), respectively for two different Fuel inputs.

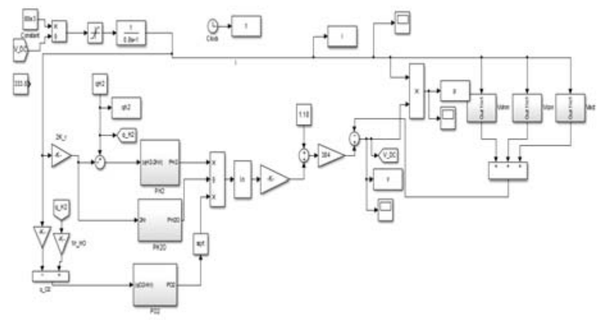


Fig. 5: Simulation model for constant fuel flow mode

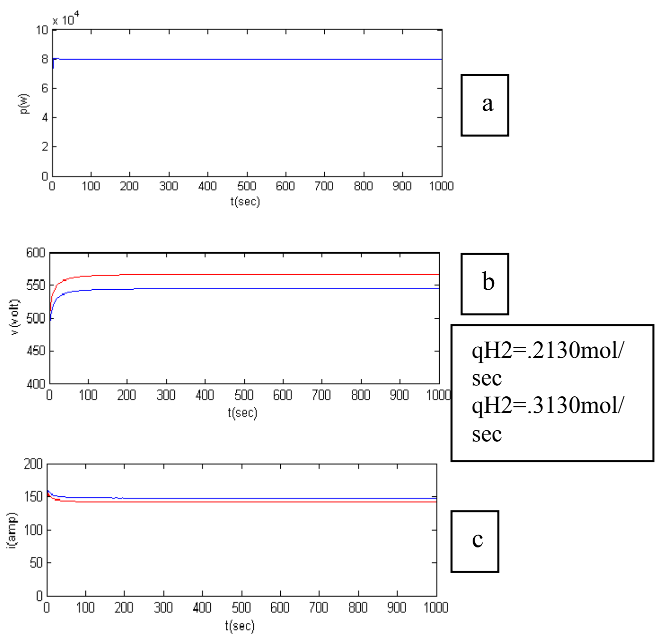


Fig. 6: (a) output power (b) output voltage and (c) Stack current under different fuel input for a constant temperature (variable fuel input)

4) Constant Fuel utilization mode for high power

SOFC can also be operated in constant fuel utilization mode, where fuel utilization (Uf) is the ratio between the fuel flow that reacts and the input fuel flow [2], is given as equation (17):

$$U_f = \frac{q_{H2}^{r}}{q_{H2}^{in}}$$

In constant utilization mode we vary temperature of the model from T=958K to T=1058K keeping the utilization factor constant. From the obtained graphs we can analyze that as we increase the temperature current increases slightly and the output voltage decreases. And the output voltage take less time to reach steady state compare to low temperature. Initial voltage drop is due to an activation energy barrier that must be overcome before chemical reaction starts inside SOFC and this drop is called activation voltage drop. SOFC stack current vs time, output power vs time and output voltage vs time plots for constant Uf are presented as Fig. 8 (a), (b) and (c), respectively for two different operating temperatures (i.e. for T=958 K and T=1058 K).

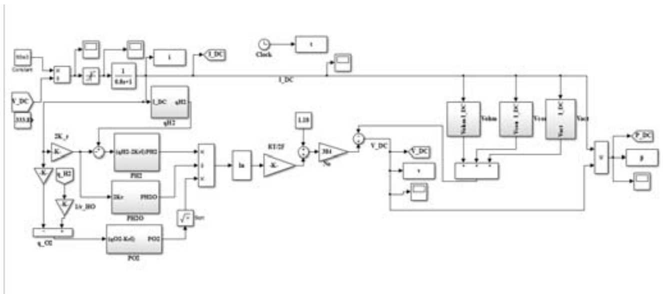


Fig. 7: Simulation model for constant utilization mode

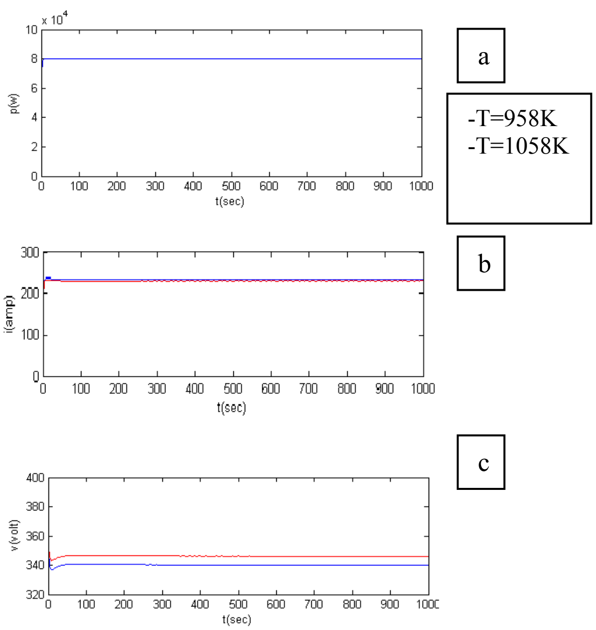


Fig. 8: (a) output power (b) stack current and (c) output voltage under different temperatures for a constant fuel utilization

6. CONCLUSION

This paper provides a dynamic modeling of SOFC from perspective of power generation to energy losses. The various performance characteristics of SOFC are studied based on constant fuel input and constant fuel utilization mode.

From the simulation study on two modes of operation of SOFC, the following conclusions are drawn.

- The constant fuel utilization mode is better than constant fuel input mode.
- In fuel utilization mode fuel input is managed automatically.
- Voltage output reached steady state rapidly in high power output mode.

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