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Numerical Simulation based Modeling and Analysis of Fuel Cell System

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Abstract: ***Fuel cells are considered as the potential for future clean energy in both electrical energy transmission and mobile applications. The biggest challenge in the operating fuel cell system is how to obtain the highest efficiency of fuel cell output voltage in the presence of many variables that affect the work of the cell such as the fuel pressure, temperature, humidity, load current as well as the non-linear dynamical behavior for fuel cell system. This paper presents the modeling of fuel cell system based on the nonlinear mathematical model and analysis it. In this work, it analyzed and studied the stability and the dynamic behavior response of fuel cell output voltage model by using MATLAB/m.files simulation to illustrate the effectiveness performance of the fuel cellsystem when changing the hydrogen partial pressure and temperature variation of the fuel cell as well as the characteristic of the fuel cell "voltage against load current" variation.***

Keywords: Fuel Cell, Hydrogen Partial Pressure, Temperature, MATLAB Simulation

1. Introduction

Recently, the world towards alternative energy sources or renewable energy due to the pollution in our planet and climate change, as well as the diversity of sources that are sought by major energy companies in order to control the price of fuel [1]. Therefore, renewable energy refers to energy from natural resources "wind, water, and the sun" that it is fundamentally different from fossil fuels used in petroleum, coal and natural gas or nuclear fuel used in nuclear reactors. Renewable energy generally does not produce carbon dioxide (CO2) or harmful gases, nor does it exacerbate global warming as it does when burning fossil fuels or harmful atomic waste in nuclear reactors [1]. However, these alternative sources of power generation rely on complex and expensive technologies because they are not suitable for all applications as "alternative" fuels. Therefore, many researchers are focusing for fuel cell because of their advantages as they operate as the battery or internal combustion engines, but with high efficiency up to two or three times [2, 3].Although discovered in the 18th century, it began to highlight on fuel cells in the 1960s when NASA was used in spacecraft launched into space as in **Figure (1)**[4, 5].

Fuel cells are considered as the potential for future clean energy in both electrical energy transmission and mobile applications, but the biggest challenge is how to obtain the highest efficiency of fuel cells in the presence of many variables that affect the work of the cell such as the fuel pressure, temperature, humidity and current applied are factors affecting the fuel cell and making the fuel cell system generation non-linear dynamical behavior [6]. The sensitivity of fuel cell system is very high because of its high current and low output voltage with respect to the hydrogen and oxygen inputs flow rate, so it needs a controller that can minify this sensation by making the external voltage constant. Therefore, to obtain greatest energy generation and more efficiency, many researchers resorted to use different types of linear and nonlinear controllers for tracking output voltage of fuel cells [7].

Figure 1: NASA produced fuel cell [5]

2. Description of the Fuel Cell

The principle of mechanism working for the fuel cell is simply the production of electrical energy because of the chemical reaction. There are many ways in which fuel cells are classified, the most important of which is by electrolyte and the most important types are Alkaline Fuel Cell (AFC), Phosphoric Acid Fuel Cell (PAFC), Molten Carbonate Fuel Cell (MCFC), Solid Oxide Fuel Cell (SOFC) and Proton Exchange Membrane Fuel Cell (PEMFC)[8, 9]. The mostly used fuel is hydrogen as in PEMFC or carbon monoxide and natural gas. The anode is supplied with hydrogen and the cathode with oxygen in the fuel cells, the catalyst separates the hydrogen atoms in anode into protons and an electron, the membrane allows only the hydrogen protons Cross to the cathode. The hydrogen electrons moving from outside the cell to the cathode. The chemical reaction occurs in the cathode between hydrogen atoms and oxygen with the help of the catalyst and produces water and heat. The electrical energy produced as the resulting of the hydrogen electrons through the electrical circuit, which generates a DC voltage. A single fuel cell produces approximately 1.23 volt, when the load is applied 0.6 to 0.7 volt [10]. The fuel cells can produce an electric energy that may reach MW by forming it in a serial or parallel manner for obtaining the necessary energy. Grouping of cells is called a stack. In this research, it will focus on the PEMFC because its great advantages and the most important is that it can work in room temperature with low pressure and fast response quiet, does not have moving parts, and can be applied in portable applications, the domestic power or power stations [3][7][10].

The PEMFC model is used in my work because it has small size and weight as laboratory device which it operates at normal temperatures ranging from 25-35 °C and the fuel cell efficiency ranges from (75 to 95)% as well as it used hydrogen and oxygen gases inlet and produced DC voltage with high load current and water output.

3. Literature Survey

In general, many researchers have been investigated the problem statement of the fuel cell that related for obtaining the maximum power point PEMFC operating as well as stabilizing the output voltage of the fuel cell during load current variation as follows: In 2011, Mehdi, et al. [11], the proposed model has been built based on a backpropagation neural network model with a PID controller to remove the harmful effects of fast pulse currents that effect on parts of the fuel cell stack (Membrane Electrode Assembly (MEA)) through control of the input air pressure signal. In 2012, Ren, et al., [12], the proposed fuzzy controller model based particle swarm optimization (PSO) has been studied to minimize cost and maximize the efficiency of generation systems to the (PEMFC).In 2014, Belmokhtar, et al. [13], the proposed feedforward neural network modeling based on off-line learning via empirical data for prediction the PEM fuel cell voltage without using any analytical relationships used and tested successfully with a good accuracy a stack voltage and validate with experimental data of existing model.In 2016, Abbaspour, et al. [14], the authors were studied to prolong the life of fuel cells PEM through stabilization of the partial pressure in PEMFCs in there anode and cathode by using an adaptive neural network control with on-line learning feedback linearization and from the results, the proposed controller has the ability to boost the output performance and refuse the disturbances which could prevent membrane damage.In 2017, Kumar, et al.[15], the authors were presented to enhance the performance of (PEM) fuel cells by reducing the temperatures generated via added Nano coolants and used the genetic algorithm method for obtaining an optimization of the PEM model parameter during adding suitable thermal conductivity to PEM fuel cells.In 2017, Derbeli, et al.[16], the proposed adaptive sliding mode controller was used to increase power efficiency and made the output voltage system more stable. The proposed controller algorithm modeled and simulated using Matlab /Simulink and found it more advantageous when compared it with the classical sliding mode control.In 2018, Dagher, K, [10], the author was built model of the PEMFC by using identification based on NARMA-L2 neural model with combined of optimization algorithms (Hybrid Firefly and Chaotic Particle Swarm Optimization) to learn the neural network and used direct inverse controller to obtain the desired output voltage of the fuel cell. In 2019, Chahkandi, et al. [17], were presented a lead-lag control system with genetic algorithm to study one of the fuel cell voltage problems that represented in both high-speed voltage fluctuations and low-speed dynamic response by obtaining a possible for optimum PEMFC control parameters. The proposed algorithm could reduce voltage deviation and improve dynamic response of the fuel cell system. In 2019, Dhanya, et al.[18], the authors were examined the efficiency of the neural network-intelligent controller for organizing the parameters of the PEMFC system under dynamic load conditions by using genetic algorithm. The proposed control algorithm was maintained the cathode inlet pressure and achieved the desired value of relative humidity. In 2019, Al-Araji, et al.[3], the authors were proposed a robust feedback predictive voltage-tracking control algorithm for fuel cell model by using a neural network technique based on-line auto-tuning intelligent Chaotic Particle Swarm Optimization (CPSO) algorithm to find the optimal control action (hydrogen partial pressure) for N-step ahead prediction. The proposed controller had abilities in terms of strong adaption algorithm, fast and smooth learning also high robustness behavior. In 2019, Deng, et al. [19], the authors were studied the effect of oxygen ratio in the air regulation of the proton exchange membrane (PEM) cathode in the nonlinear dynamic system modeled reducer a sixth-order model using cascade adaptive sliding mode controller and implemented on a real-time emulator with the regulation of the model parameters on-line that improved the PEMFC performance. In 2020, Fathy, et al. [20], the authors were presented a novel methodology in identifying the optimal parameters of PEM fuel cells by using the hybrid optimization approach (vortex search algorithm (VSA) and differential evolution (DE). The result of the model is compared to other approaches and confirmed the superiority and reliability of the proposed VSDE in identifying the optimal parameters of PEMFC operated under different conditions.In 2020, Miao, et al. [21], presented the optimization technique to valuation the parameters of the PEMFC model by using the hybrid grey wolf optimizer algorithm to enhancement power efficiency of the fuel cell. Based on four cases PEM fuel cell models Statistical and experimental data, the researcher showed the effectiveness of the proposed algorithm to determining the model parameter with high accuracy.In 2020, Cao, et al. [22], proposed to increase the lifetime of the fuel cell by using (linear quadratic regulator) LQR with chaotic-whale optimization algorithm based on designed feedback control that improved the efficiency regulating the PEMFC and overcame the parameters sensitivity when they are changing during the operation of fuel cell. Simulation results showed that the proposed control algorithm was more efficient in terms of very low current ripple and very small overshoot in the output of the fuel cell.

4. PEM Fuel Cell Mathematical Model

In general, PEM fuel cells consists of three main components: anode, cathode, and electrolyte [23]. Anode typically displays a catalyst containing platinum or platinum, and cathode a platinum catalyst. The electrolyte is a thin, solid polymeric sheet. The reactions of a PEMFC shows in in **Figure (2)**, when hydrogen feeds to an anode side the catalyst causes hydrogen atoms to become (H^+) ions (protons) and releases their electrons as in Eq. (1).

$$2H \rightarrow 4H^+ + 4e^- \quad \text{anode} \qquad (1)$$

The electrolyte membrane will only allow hydrogen protons to pass throws from the anode side to the cathode side as shown in **Figure (2)**. The reaction in the cathode occurs as a result of the reaction of hydrogen ions entering from the electrolyte to the cathode side with electrons from the outer circuit and oxygen supply from air the cell and produces water as in Eq. (2)

$$4H^+ + 4e^- + 4O^+ \rightarrow 2H_2O + \text{heat} \qquad (2)$$

Under normal operation conditions, a single cell produces from 0.5 to 0.9 volts since a higher power is needed and a number of cells are connected serially and as needed called a stack and a stack arrangement can be up to hundreds of kilowatts. Generally, the polarization curve is used to express the performance of the whole cell and shows highly non-linear properties between voltages and current [3],[10].The output voltage of a single cell can be defined as follows:

$$V_{cell} = E_N - V_{ohm} - V_{act} - V_{con} \qquad (3)$$

Where, E_N is the thermodynamic potential of the cell and its represents reversible voltage in volt. V_{ohm} is the ohmic voltage drop in volt, a measure of the ohmic voltage drop associated with the conduction of the protons through the solid electrolyte and electrons through the internal electronic resistances [24]. V_{act} represents the voltage drop due to the activation of the anode and of the cathode in volt. V_{con} represents the voltage drop resulting from the concentration or mass transportation of the reacting gases in volt [24].

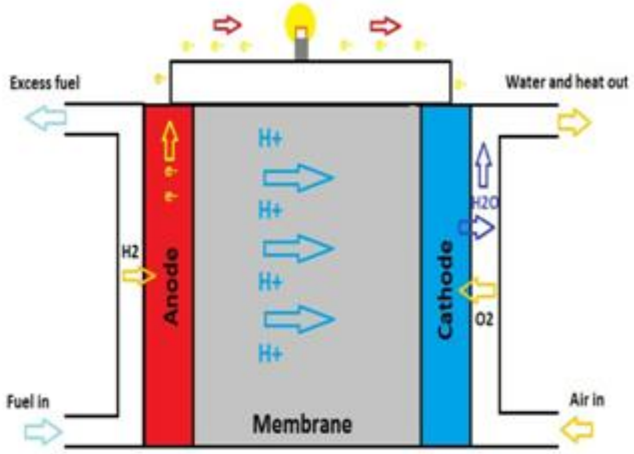

Figure (2): The PEMFCS operating [3]

Table 1 shows the physical parameters of PEMFC that are taken from[3] , [10]

Table 1: Physical Parameters of PEMFC Model [10].

Parameters	Values	Units
Ncell	32	--
T	298	Kelvin degree
A	64	cm2
L	178 *10-6	cm
P_{H_2}	1-5	bar
P_{O_2}	0.2	bar
Rc	0.0003	Ω
Β	0.0169	V
J	0.0073	mA/cm2
Jmax	0.469	mA/cm2
Φ	23	--
α1	0.948	V
α2	-0.00312	V/ Kelvin
α3	-706*10-5	V. cm2 / Kelvin. mol
α4	1.93*10-4	V / Kelvin. Amp

E_N also called the reversible voltage of the cell and can be found out[3], [10],[24] .

$$E_N = 1.229 - 0.85 * 10^{-3} * (T - 298) + 4.3085 * 10^{-5} * \left(T\left(\ln(P_{H_2}) + 0.5\ln(P_{O_2})\right)\right) \qquad (4)$$

Where, P_{H_2} and P_{O_2} is the partial pressure of hydrogen and oxygen in atom respectably. Moreover, T is fuel cell temperature in Kelvin.

The voltage of the ohmic loss can be determined by using the Eq. (5) [10], [24], [25].

$$V_{ohmic} = I.(R_c + R_m) \qquad (5)$$

Where, I represents cell loaded current. Rc denotes proton resistance (Ω) constant value[3] ,[10].

R_m : is the electron flow equivalent resistance (Ω) and can represent as in (2.6) [10],[23],[24].

$$R_m = \frac{L * \rho_m}{A} \qquad (6)$$

Where, L is thickness of the polymer membrane (cm).
A: is active cell area (cm^2).
ρ_m denotes membrane specific resistivity (Ω.cm) which computed as following expression:

$$\rho_m = \frac{181.6\left[1 + 0.03\left(\frac{L}{A}\right) + 0.062\left(\frac{T}{303}\right)^2\left(\frac{L}{A}\right)^{2.5}\right]}{\left[\emptyset - 0.634 - 3\left(\frac{L}{A}\right)e^{\frac{4.18(T-303)}{T}}\right]} \qquad (7)$$

∅ is the ratio of the number of water moles for each sulfonic group in the membrane.

V_{con} can be expressed as follows:

$$V_{con} = -\beta \ln\left[1 - \frac{J}{J_{max}}\right] \qquad (8)$$

β is parametric coefficient. J is the current density that passes through the cell (amp/cm2). J_{max} is the maximum current density that passes through the cell (amp/cm2), can be expressed as follows:

$$J_{max} = \frac{I_{max}}{A} \qquad (9)$$

V_{act} is the voltage drop (V) due to the activation of the anode and can be expressed as follows:

$$V_{act} = \alpha_1 + \alpha_2.T + \alpha_3.T.\ln(C_{O2}) + \alpha_4.T.\ln(I) \qquad (10)$$

Where, α_i are parametric coefficients. C_{O2} is effective concentration of oxygen (mol/cm3) and can be calculated as follows:

$$C_{O2} = \frac{P_{O_2}}{5.08 * 10^6 * \left(e^{\frac{-498}{T}}\right)} \qquad (11)$$

The total output voltage of the stack can be determined by the (12) [3] , [10].

$$V_{FC} = N_{cell} V_{cell} \quad (12)$$

Where, Ncell symbolizes the number of stack.

The Eq. (13) is used to determine the overall output power (in watt) from the stack:

$$Power_{FC} = I\, V_{FC} \quad (13)$$

5. Simulation Results

To study the characteristic of the fuel cell "voltage against load current" at temperature 25 C° and partial pressure of hydrogen and oxygen are (1 and 0.2) bar respectively is shown in **Figure (3)** that seen the output voltage of the fuel cell against a variable load current.

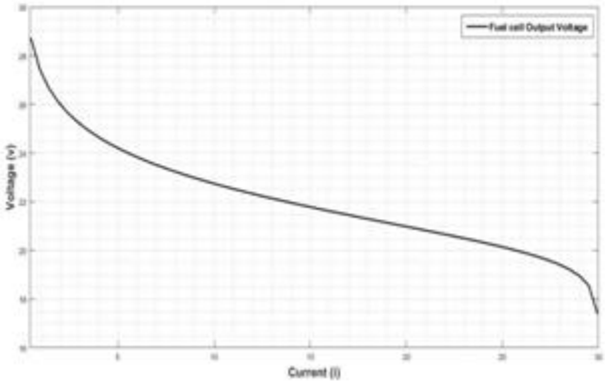

Figure 3: The output voltage of the fuel cell against load current Variable

When increasing the load current with constant each of partial pressure of hydrogen and oxygen, it notice that the fuel cell output voltage will decrease significantly. Because of the effect of the losses voltage for fuel cell will begin clearly, when increasing load current that can be shown at the polarization curve in **Figure (4).**To understand the effect of variation the hydrogen partial pressure from range 0.2 to 1 bar with constant oxygen partial pressure is 0.2 bar of the fuel cell at maximum load current is 30A is shown in **Figure (5)**. It notice that the fuel cell output voltage will increase significantly because of the increased reaction. However, the hydrogen partial pressure cannot be increased as much as possible because it will break the cell's proton membrane. To analyze the effect of temperature variation of the fuel cell with constant partial pressure of hydrogen and oxygen and with maximum load current is 30 A, as shown in **Figure (6)**. It notice that the fuel cell output voltage will slight increase but it is not possible to raise the temperature more than the operating temperature, and this will lead to the drying of the cell's proton membrane and will lead to its breakage.

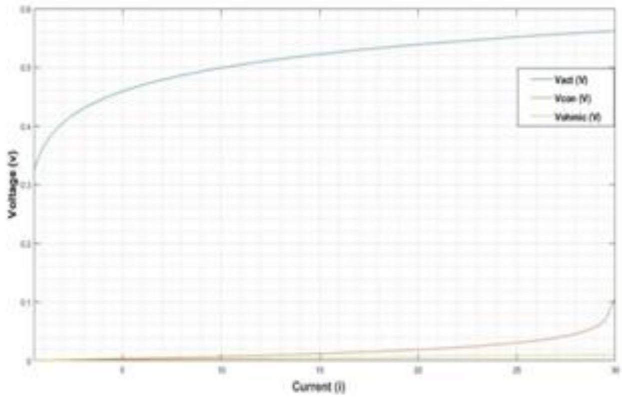

Figure 4: The drop voltage in the fuel cell system against the variable load current.

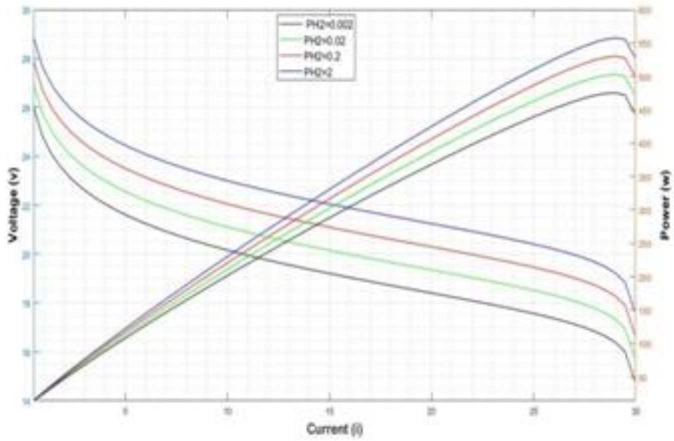

Figure 5: The effect of variation the hydrogen partial pressure for fuel cell.

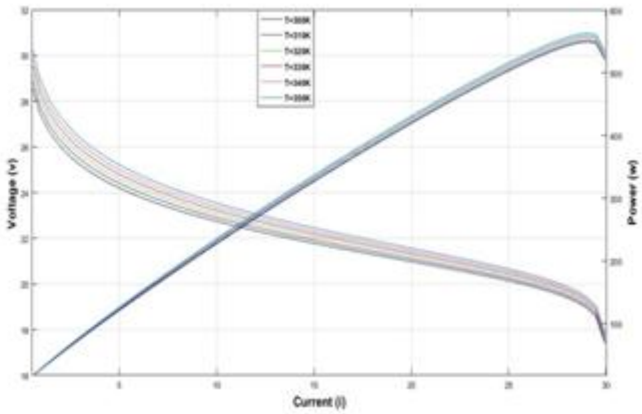

Figure 6: The Effect of Temperature Variation of the Fuel Cell.

6. Conclusion

This work presented the non-linear modeling of fuel cell and illustrated the effectiveness performance the dynamic behavior response of output voltage model as well as it analyzed and studied the stability of fuel cell output voltage model by using MATLAB simulation package and demonstrated the effects of changing the hydrogen partial pressure and temperature variation of the fuel cell as well as the characteristic of the fuel cell "voltage against load current" variation.

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