# EVALUATION OF OPERATING PARAMETERS TO IMPROVE THE EFFICIENCY OF A PROTON EXCHANGE MEMBRANE FUEL CELL

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*Abstract*— This paper presents the modelling and simulation of a proton exchange membrane fuel cell (PEMFC) for the improvement of its efficiency. Short life span and low efficiency is a general issue of fuel cell systems. Therefore, designing and simulating a system capable of measuring crucial parameters of a PEMFC is essential for achieving an improved system performance. A polarization curve is utilised to evaluate the performance of a fuel cell, so this paper is focused on a variety of critical parameters and their output is traced specifically on a polarization curve. The system design was simulated in Matlab-Simulink and the data agreed well with the published data. The output of this study has the potential to contribute in renewable energy sectors, and industry.

Keywords—Efficiency, polarization curve, PEMFC, Matlab-Simulink

#### I. INTRODUCTION

The use of fossil power has caused environmental pollution. There is large energy consumption due to the rapid development of society and economy. One of the methods to relieve the contradiction between energy consumption and environmental pollution is by using fuel cell (FC) for electricity generation [23]. FC system is an advanced future power system that is sustainable, clean and environmentally friendly; the system has none of the pollutants produced by boilers and furnaces [18]. FC is a device that converts chemical potential energy into electricity. A cell uses hydrogen gas (H<sub>2</sub>) and oxygen gas (O<sub>2</sub>) as fuel. Water, electricity and heat are the products of the reaction in the cell. The use of FC serves as a huge improvement over coal burning, internal combustion engines (ICE) and nuclear power plants, all of which result in environmental pollution.

Technical challenges for hydrogen FC systems include cost, durability and hydrogen storage capacity [4]. Some disadvantages include low efficiency, overall lifetime of the FC and membrane dehydration due to high operating temperature. A better understanding of FC mechanism could lead to better improvement and further increase efficiency, reliability and life span. Major obstacles to FC commercialization include insufficient longevity, reliability and in many cases, unacceptably high cost [1].

The challenge of making reliable, efficient FC is rooted in the complexities of how they operate, which involves multiple chemical and physical interactions at the atomic level [1]. Reducing repair and maintenance activities require a strategy based on seeking quality and cost leadership in order to improve reliability [21].

FC technologies have long been recognized as one of the most promising future energy solutions. Nevertheless, some major technological barriers delay the potential realization of this clean energy source [10]. Technological barriers such as difficulty with gas pressure, ambient oxygen measurement to ensure a safe operating environment for the user have a great negative impact on FC performance. Therefore, it is clear that reliability and durability are the most important factors that need attention for reducing the whole system cost and increasing acceptance of the system.

A slight change in any parameter of a FC has an effect on it. It has been identified that many physical and chemical factors can affect the FC's performance; factors include the operating pressure, operating temperature, the type of electrolyte in use, the efficiency of the FC, the catalyst used, reactant flow rates, reactant humidity, FC mass balance (inlet and outlet flow rates), FC energy balance among others [16].

The performance of a FC reduces after a period of time, this is due to decrease in durability often as a result of flooding and loading cycle [16]. The degradation rates of a FC could increase in size when conditions include some of the following, namely load cycling, start-stop cycles and low starvation [7]. For the improvement of FC durability, the individual components need to be well characterised to determine and measure the quantity of degradation mechanisms that occur [3].

There are two causes of failure in a FC, which are long time operation (natural ageing) or operation incidents, such as membrane electrode assembly (MEA) contamination or reactant starvation [19]. Durability and efficiency are also affected by losses experienced during the operation of a FC. Losses such as activation losses, fuel crossover and internal currents, ohmic losses, and mass transport or concentration losses have an impact on FC performance. A reduction of the concentration oxygen around the electrodes when the oxygen used by the cell is supplied in the form of air will be experienced, as well as a reduction of hydrogen pressure as more hydrogen is consumed as a result of high currents being drawn from the cell [8]

FC parameter evaluation is a key for the maintenance actions to be taken in order to maximise the reliability of operation and useful lifespan of the cells when accurate health monitoring is performed [20]. The key factors that lead to FC maintenance improvement when assessed correctly include cell stack temperature, hydrogen pressure, hydrogen leak concentrations, oxygen quality and level.

## II. EQUIVALENT ELECTRICAL CIRCUIT OF PEMFC

A simplified equivalent model of the PEMFC is illustrated in Figure 1, in which an electrical capacitor can be considered as the charge layer on or near the electrode-electrolyte interface, which is a store of electrical charge.  $R_a$  is the equivalent resistance that includes the activation equivalent resistance ( $R_{act}$ ) and the concentration equivalent resistance ( $R_{con}$ ). I<sub>FC</sub> is current produced by the flow of hydrogen (H<sub>2</sub>) electrons during a chemical reaction at the anode of an FC. The charge layer effect has no influence on the ohmic overpotential because it is directly tied to the current represented by the resistance Rm.



Figure 1: FC equivalent circuit (Outerio et al., 2007)

#### III. MATHEMATICAL MODEL OF PEMFC VOLTAGE DROPS

This section describes an electrochemical model that is used to predict the dynamic behaviour of PEMFC stacks. The mathematical model in this section employs a set of parameters, the specification of which is critical for achieving the best simulation results. The output voltage of a single cell  $V_{FC}$  is defined as:

$$V_{FC} = E_{NERNST} - V_{ACT} - V_{OHMIC} - V_{CON}$$
(1)

Each voltage drop from (1) has its own definition and is discussed individually.

#### A. The Nernst voltage drop

The Nernst equation presented in (2), is commonly used to determine the relationship between the standard potential created by the FC and the actual potential at various temperatures and pressures of reactants and products. The Nernst voltage drop is described by the following equation [12].

ENERNST 
$$\frac{1}{2F} \left[ \Delta G - \Delta S(T - Tref) + RT \left( \ln P_{-}H_2 + \frac{\ln P_{-}O_2}{2} \right) \right] (2)$$

Under standard state conditions (25 °C and 1 atm), the ideal E<sub>NERNST</sub> potential of a hydrogen/oxygen FC with liquid water as by-product is 1.229 V [12]. The energy change that happens as a result of the chemical reaction at the anode and cathode is the change in Gibbs free energy  $\Delta G$ . The voltage produced by a fuel cell at a given temperature and pressure is determined by the Gibbs free energy change and the number of moles of electrons delivered when one mol of supplied hydrogen reacts [5]. A Standard mole entropy change ( $\Delta S$ ) as a measure of the available energy in a closed thermodynamic system, and it is commonly used to assess the system's disorder [14]. Because entropy reflects the available energy in the system, a system with zero entropy optimizes the system's work output. The entropy of H<sub>2</sub> and O<sub>2</sub> will vanish, while new entropy of H<sub>2</sub>O and heat production will arise. E<sub>NERNST</sub> is hugely affected by the partial pressures of hydrogen and oxygen  $(P_{H2} \text{ and } P_{O2}).$ 

# *B.* Voltage generated from the activation of anode and cathode

To initiate the chemical reaction, a certain amount of energy is required. The activation loss of a PEMFC is caused by the slow kinetics of the processes occurring on the active surface of the electrodes. The loss occurs on both anode and cathode catalysts. Because the kinetics of the oxygen reduction process is substantially slower than those of the hydrogen oxidation reaction, the reduction reaction results in a far greater amount of activation polarization loss. The activation loss may be calculated using the following equations [12].

$$Vact = - [e1 + (e2*T) + (e3*T*\ln(C_{02})) + (e4*T*\ln(I_fc))]$$
(3)

e1, e2, e3, e4 are parametric coefficients.  $C_{02}$  represents concentration of oxygen in the catalytic interface of the cathode. All of these factors are connected to the electrochemical process required for electrode activation, and they are challenging to express with high precision. Parameters e1 and e3 are highly sensitive and affected by high current values. For high current levels, the e2 and e4 parameters have a greater impact on the stack voltage.

#### C. Voltage drops caused by proton and electron conduction

As shown in figure 3.1, the voltage drop produced by the equivalent membrane impedance  $(R_M)$ , and the voltage drop induced by the contact resistances (Rc) between the membrane and electrodes as well as the electrodes and the bipolar plates, are referred to as ohmic losses. Once the cell is built, it remains constant and the voltage drop can be represented as the following equation [11].

$$\mathbf{Vohm} = \mathbf{I}_{\mathbf{fc}} * (\mathbf{R}_{\mathbf{M}} + \mathbf{R}_{\mathbf{C}}) \tag{4}$$

 $R_M$  is the proton conduction membrane resistance equivalent.  $R_C$  represents the equivalent contact resistance to electron conduction. In (10) Ohms law can be used to express the equivalent membrane impedance [6].

$$R_{\rm M} = \frac{\rm rm.\ell}{\rm A} \tag{5}$$

Where  $\ell$  is the membrane thickness (µm), A is the membrane area (cm<sup>2</sup>), rm is the membrane resistivity for a series proton exchange membrane and can be calculated by [15].

$$r_{\rm m} = \frac{181.6 \left[1 + 0.03 * \left(\frac{l_f c}{A}\right) + 0.062 (T/303)^2 * \left(\frac{l_f c}{A}\right)^{2.5}\right]}{\left[\lambda - 0.634 - 3 * \left(\frac{l_f c}{A}\right)\right] * \exp\left[4.18 * \left\{\frac{(T-303)}{T}\right\}\right]}$$

Where,  $\lambda$  is the membrane's water content which is a variable and a function of the gas's relative humidity in the anode. At no current ( $I_{fc} = 0$ ) and at 30°C (T = 303 K), the term 181.6 / ( $\lambda - 0.634$ ) is the specific resistivity ( $\Omega$ .cm). If the cell is not at 30°C, the exponential component in the denominator is the temperature factor adjustment.

### D. Concentration losses

In this model the voltage drop is caused by a decrease in oxygen and hydrogen concentrations from the transport of mass of oxygen and hydrogen. At high current densities ( $J_{max}$ ), the concentration of hydrogen and oxygen is influenced by the mass transportation which causes concentration losses. The following equation can be used to define concentration losses [17].

Where B (V) is a constant that varies depending on the cell type and its operation state. The real cell current density, including the permanent current density, is denoted by the letter J (A/cm<sup>2</sup>) and  $J_{max}$  is the maximum current density. Equation (12) is mostly neglected in some models because it is undesirable to operate the stack in areas with large concentration loss (poor efficiency). If the stack works at a high current density, however, this term must be included [22].

#### **IV. SIMULATION**

#### A. Simulated model in MATLAB Simulink

The simulation of the system is designed in Matlab-Simulink. Equation (1) denotes the FC useful voltage under given operating conditions. Figure 3.2 represents the main Simulink model which comprises of the design's main structure. The choice of parameters used may have a major effect on the voltage, current, and efficiency characteristics of the simulated stack.



The simulation setup shown in figure 2 includes a FC subsystem and a resistor (R) which represents a load. Current measurement is used to measure the total current of a PEMFC, while voltage measurement is used to measure an output voltage. Fuel cell voltage ( $V_{FC}$ ) is an open circuit voltage (OCV) of an FC.

The FC current ( $I_{FC}$ ) of 10.72 A is taken from the output as the feedback. Because the cell voltage model only produces meaningful results when the operating voltage and current are set correctly, the range of input cell current and output cell voltage is limited [13]. The entire system is divided into subsections, each of which will be discussed individually.

## B. FC's input parameters

The first subsection is a combination of the FC's parameters as inputs, voltage drops, single cell voltage and stack voltage as seen in Figure 3.



Figure 3: FC Parameters used in MATLAB Simulink

The main inputs that affect a cell's voltage are pressure, current, cell area, and temperature. Air and fuel supply, as well as loading conditions, all influence pressure and current. Temperature is determined by the cooling subsystem as well as the thermal dynamics of the FC layers i.e., catalyst layers, and gas diffusion layers (GDLs). A mathematical simulation model of the FC output voltage is depicted in Figure 3.3. A Matlab function block portrays the Nernst voltage as the reversible voltage source, while the irreversible voltage losses are the activation loss, ohmic loss and the concentration loss. A FC stack system contains 60 single cells that produce 1.144 V connected in series to provide 68.65 V stack voltage. All voltage drops that affect the efficiency of the device can be calculated by the system in figure 3.3. The simulation proved the ideal E<sub>Nernst</sub> potential of hydrogen/oxygen FC to be 1.229 V under standard state conditions (25°C and 1 atm).

# C. FC algorithm

The second section is the FC's algorithm. As shown in Figure 4, a Simulink model of a PEMFC is created by sequentially adding the mathematical equations (1-12) in the form of a Matlab function Simulink block. The complete technique is written in Matlab and implemented as a functional block in the Simulink model. The parameters are used as initial inputs to build the experimental curve. The Matlab function block is programmed to calculate the output voltage and voltage drops



Figure 4: Matlab Function Simulink block

The mathematical model described in Section 3.3 demands the specification of numerous parameters prior to computer simulation. The designed system is presented in Matlab-Simulink by its initial configurations which will be varied during the course of the simulation. Table 1 illustrates initial state of the designed system parameters based on published data for similar stacks as well as manufacturer data [12].

TABLE 1 INITIAL STATE OF THE DESIGNED P	PEMFC SYSTEM
PARAMETERS	

Parameters	Value	Parameters	Value
Ν	60	e1	-0.514
Т(К)	298.15	e2	0.00312
Р <sub>н2</sub> (atm)	1	e3	0.41x10 <sup>-4</sup>
Po₂ (atm)	1	e4	-0.92x10 <sup>-4</sup>
∆G(J/mol)	237180	ℓ(µm)	129
A (cm <sup>2</sup> )	69.4	λ	27.7
ΔS (mol K)	-163.15	B (V)	0.0165
T <sub>ref</sub> (K)	298.15	C (F)	2.5
F (C/ mol)	96486.7	J <sub>max</sub> (A/cm <sup>2</sup> )	1.24
R (J/mol K)	8.314	$R_{C}(\Omega^{2})$	15x10 <sup>-4</sup>

Matlab Function Block Editor (MFBE), a programming tool, was used in this study to create the simulation's mathematical model. On MFBE a statement with two variables (input and output arguments) were declared. The statement defined five input arguments, ( $I_{FC}$ , T,  $P_{H2}$ ,  $P_{O2}$ , A) and four output arguments [ $E_{Nernst}$ ,  $V_{act}$ ,  $V_{con}$ ,  $V_{ohm}$ ]. The input and output arguments correspond to that of a Matlab function block discussed in figure 4.

The MFBE can be used to examine and create Matlab function blocks. As the Matlab code is edited on MFBE, Simulink updates the Matlab function block with input and output ports that correspond with the Matlab function's input and output arguments. FC equations are used within the function block editor to calculate optimal simulation results. This innovative way of adding algorithm codes into a Matlab-Simulink functional block model assists in a better understanding of the algorithm and the processes involved in FC modeling. The algorithm methodology is a stable approach for the optimization of FC parameters. The simulated results indicate that the method is effective, and absolute error is produced to demonstrate the algorithm's complexity.

# V. RESULTS AND DISCUSSIONS

A 60-cell stack was modelled to study the effect of factors in PEMFC analysis. Depending on the condition, an FC will behave differently. The system was simulated by varying crucial input parameters of PEMFC. The findings are essential to the system's operation. The model's input variables were load current, P<sub>H2</sub> and P<sub>O2</sub>, membrane water content, and temperature. The observed results were done to indicate an increased performance affected by a specific factor configuration. The load/electrical devices in this chapter is represented by a resistor. As the load resistance was varied, the voltage and current across the load resistor were evaluated. This was done to obtain a polarization curve. Because efficiency is frequently related to voltage, the calculation of efficiency in this study is based on simulated voltages. The simulation was done with an initial cell area of 69.4 cm<sup>2</sup>, temperature of 25°C, hydrogen and oxygen pressure of 1 atm. The model's membrane parameters were obtained from a Nafion 115 membrane.

#### A. Effect of temperature

PEMFC behavior was investigated at temperatures ranging from 25 to 80°C.



Figure 5: PEMFC polarization curve at variable temperature

There are numerous formulas for calculating an FC's efficiency. In this paper the efficiency of PEMFC stack is calculated by [12]:

$$Eff = \frac{V \text{stack}}{Enernst}$$
(8)

Figure 5 represents a polarization curve at a varying temperature. As the temperature increased, it was observed that V<sub>FC</sub> increased as well. Unlike V<sub>FC</sub>, E<sub>Nernst</sub> decrease with an increasing temperature. A decrease in E<sub>Nernst</sub> has a positive impact on stack efficiency. The graph shows a cell voltage which decrease with increased current due to internal resistance. At 25°C the voltage decreased from 1.229 to 1.207 V due to losses. As the temperature was increased to 80°C it was observed that the voltage decreased from 1.37 V to a minimum voltage of 1.301V. At lesser current and greater temperatures, the voltage falls rapidly until a particular level is achieved and then gradually decreases, whereas at lower temperature and lesser current the polarization curve shows that the voltage falls gradually with increasing current. The efficiency of PEMFC increases as the temperature rises due to a decrease in E<sub>Nernst</sub> and an increase in V<sub>FC</sub>, which automatically increases V<sub>stack</sub>. However, at higher temperature a PEMFC membrane suffer from dehydration which results in low performance and shorter lifespan of a PEMFC. At 25°C, an efficiency of 70.6% was achieved, as the temperature raises to 80°C, 77.88% efficiency was reached.

To avoid higher temperature that is capable of dehydrating the membrane it is essential to reduce voltage losses. The higher the temperature, the quicker the kinetics and a high voltage gain which generally overcomes the voltage loss caused by the negative thermodynamic link between temperature and cell voltage. Increasing current density also causes membrane dehydration, which causes membrane shrinking [9]. This lowers the efficiency of PEMFC.

# B. Effect of $P_{H2}$

The influence of hydrogen, oxygen, and water partial pressures is seen using the Nernst equation described. This section describes an effect of  $P_{H2}$  on the output cell voltage specifically. Figure 6 depicts a polarization curve for a cell voltage against current density with different  $H_2$  partial pressures.



Figure 6: Variations of hydrogen partial pressure vs stack current

The temperature was kept constant at 25 °C and the  $P_{H2}$  was varied between 1 and 4 atm to observe its effect on the cell voltage. It was observed that there was a voltage change as the pressure raised. An Increase in  $P_{H2}$  increases cell voltage. The voltage difference between 1 and 2 atm is much larger than the voltage difference between 3 and 4 atm. This implies that as  $P_{H2}$  continues to increase, there will eventually be a smaller change or no change at all. It is also observed that as more current is extracted from the cell, less voltage is given until the cell finally collapses. Thus, the graph declined.

Figure 6 shows that the current density is inversely proportional to a cell voltage. This happens when an external load is linked to an FC. It is seen that as  $P_{H2}$  is elevated from 1 to 2 atm at lower current density, cell voltage increases from 1.229 to 1.238 V and falls eventually falls as the current density raised.

Table II illustrates effects of  $P_{H2}$  and temperature on PEMFC efficiency.  $P_{H2}$  ranges from 1 to 5 atm, while temperature range is between 25 and 60°C. The measured outputs are stack voltage, Nernst voltage and the efficiency of a PEMFC. An average efficiency is calculated from 2 different temperature. At a constant temperature it is shown that an increase in  $P_{H2}$  increases Nernst voltage which is considered as a loss. Continuous increase of a loss leads to inefficient performance of a PEMFC. It is also observed that a rise in hydrogen pressure increases the stack voltage and slightly reduces efficiency.

TABLE II VARIATION OF HYDROGEN PRESSURE AND TEMPERATURE

P <sub>H2</sub> (Atm)	Voltage @ 25°C			Voltage @ 60°C		
	V <sub>STACK</sub> (V)	E <sub>Nernst</sub>	Efficiency	VSTACK	E <sub>Nernst</sub>	Efficiency
		(v)	(%)	(V)	(v)	(%)
1	81.06	1.229	65.9	84.36	1.199	70.6
2	81.54	1.238	65.8	84.90	1.209	70.2
3	81.84	1.243	65.8	85.20	1.215	70.1
4	82.02	1.247	65.7	85.44	1.219	70.1
5	82.20	1.250	65.7	85.62	1.222	70.0
Avg Efficiency (%)		65.8		7	0.2	

At a hydrogen partial pressure of 1atm and 25°C, efficiency of a PEMFC appeared to be greater than at 5atm with the same temperature. Reduction of Nernst voltage is observed on higher operating temperature than on high pressure. Because Nernst voltage is directly proportional to  $P_{H2}$ , increasing Nernst voltage causes a reduction in efficiency. At a temperature of 60°C and a  $P_{H2}$  of 1 atm, the efficiency is higher than at 25°C. Temperature has more influence than any other operating parameter of a PEMFC.

## C. Effect of Load variation

To create load current, the voltage produced by an FC is delivered to the load resistance. During the simulation time, the load resistance was varied from 0.9 to 1  $\Omega$  at a constant temperature. There is a low current at high load resistance and a higher current at low load resistance. Load is defined as either a load current or a load resistance. The load current is represented in table III by I<sub>STACK</sub> and can be defined as the current drawn from the stack by an electrical device.

Table III shows a simulated investigation of the PEMFC performance when powering various loads. This analysis assists in judging the effectiveness of their performance. Water and heat are crucial variables that influence stack performance and reliability at various loads. The efficiency is increased slowly when the stack current is decreased. Thus, at low loads the voltage efficiency is higher than that at high loads.

Load (Ω)	Istack (A)	Vstack (V)	VFC	E <sub>NERNST</sub>	Efficiency (%)
0.90	80.44	72.4	1.207	1.229	58.91
0.95	76.96	73.11	1.219	1.229	59.49
0.98	75.01	73.51	1.225	1.229	59.81
0.99	74.37	73.63	1.227	1.229	59.91
1	73.75	73.75	1.229	1.229	60

Table III shows that at a load of 80.44A, cell voltage is 1.207 V. As the load continues to reduce, the voltage is incremented. At a low load of 73.75A the cell voltage is equal to the standard Nernst voltage of 1.229 V. This implies that when the load continues to fall the cell voltage will exceed 1.229 V. The efficiency increased proportionally with the cell voltage from 58.91 to 60% when the load was reduced from 80.44A to 73.75A.

To study the characteristics of PEMFC "efficiency against cell voltage" at 25°C and partial pressure of hydrogen and oxygen are both 1 atm respectively is shown in figure 4.3.



Figure 7: Effect of load current variation on efficiency

Figure 7 depicts the impact of load current fluctuation on an FC with constant partial pressures of hydrogen and oxygen at

25°C and a maximum cell current of 1.16A. It is noticed that the efficiency slightly decreased while the cell current increase. The efficiency decreased from 60 to 58.91% due to electrical devices that consumes more operating current from an FC. Since efficiency in this research is a product of a stack voltage and Nernst voltage, it increases with an increasing cell voltage and vice versa. Cell voltage drops as current increases in a polarization curve. As a result, efficiency decreases as current increases.

## D. Effect of water content variation

Variation of water content in the membrane is presented in figure 8. The membrane resistance is determined by the amount of water in the membrane, therefore the balance between water production and the removal of water in a membrane is affected by temperature and external electrical load [2]. When the water content raises, stack current, voltage, cell voltage, and efficiency raise as well. Nernst voltage is not affected as it is a factor of temperature, and hydrogen and oxygen pressure.

Efficiency of PEMFC is directly proportional to the membrane's water content as shown at figure 8. At water content of 5 the efficiency of PEMFC was 62.39%, as the water content was elevated to 40 the efficiency of 67.06% was reached. A further increment of up to 200 water content led to the efficiency of 67.45%.



Figure 8: Effect of water content variation

Membrane resistance determines the quantity of water in a membrane. Two factors that affect the amount of water in the membrane are temperature and electrical load specifically. The ohmic resistance indicates membrane moisture and changes with a variable load current. High current density is associated with higher ohmic resistances. The proton conductivity reduces when the membrane becomes too dry due to a lack of water to solvate the proton. Because porosity channels are blocked by water when the membrane becomes too wet, the transport rate of the reactant drops [4,5]. Table IV represents the variation of a load current and its relationship to membrane's ohmic resistance which influences hydration of the membrane.

TABLE IV RELATIOSHIP BETWEEN LOAD CURRENT AND OHMIC RESISTANCE

Load (Ω)	I <sub>LOAD</sub> (A)	$V_{ohm}(\Omega)$	V <sub>STACK</sub> (V)	V <sub>FC</sub> (v)	E <sub>NERNST</sub> (V)	Efficiency (%)
0.90	76.27	0.242	68.65	1.144	1.229	55.85
0.94	73.77	0.2327	69.35	1.156	1.229	56.43
0.95	73.17	0.2305	69.51	1.159	1.229	56.56
0.96	72.58	0.2283	69.67	1.161	1.229	56.69
0.98	71.42	0.2241	69.99	1.166	1.229	56.95
0.99	70.85	0.222	70.14	1.169	1.229	57.07
1	70.29	0.220	70.29	1.172	1.229	57.19

The table showed that an increased load current lead to a higher ohmic resistance. Notice that at 70.29A load current, the membrane's moisture that is associated with ohmic resistance is  $0.220\Omega$ . As the load increased it was observed that the ohmic resistance was directly proportional to the load current. At a high load current of 76.27A, a 0.242  $\Omega$  resistance was achieved. This confirms that high current leads to high ohmic resistance which results in reduced proton conductivity due to a dry membrane.

#### VI. CONCLUSION

In this study, a Matlab-Simulink mathematical model of a PEMFC was created. The performance was evaluated by manipulating certain operational parameters such as partial pressure of hydrogen and oxygen, temperature, membrane's water content, and the load. Performance of the developed model was compared with the published PEMFC at identical working conditions. Nearly identical polarization curves of the published PEMFC studies and a constructed PEMFC model validate the proposed model.

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