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ORIGINAL ARTICLE

Investigation of Power performance of a PEM fuel cell using MATLAB simulation

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Abstract

Fuel cell based power generation systems have gained remarkable interest in this modern age, due to its high conversion efficiency and reliability. Among the different types of fuel cells, PEM fuel cells are achieving more significance due to its fast start up time and low operating temperature. This paper studies the mathematical model of proton exchange membrane fuel cell (PEMFC) using Matlab/SIMULINK software. The paper consists of the calculation of cell voltage, stack current, ohmic loss, activation loss. This model is used to research the fuel cell behavior and the characteristic of output values of different parameters. The model consists of the cathode gas channel, gas diffuser, catalyst layer, and the membrane. In order to composite shape of the gas diffuser and for its gradient in liquid water content, the gas diffuser is modeled as a series of parallel layers with different porosity. It represents in terms of the physical and thermodynamic parameters of the fuel cell. The curve of polarization is expressed parametrically as a function of the surface over potential. This paper expresses for cathode internally as well as overall effectiveness factors, active fraction of the catalyst layer resistance, catalyst layer, limiting current density, and the slope of the polarization curve.

Keywords: PEM, Fuel cell, MATLAB, Voltage, Power, Activation loss

Introduction

The price of natural resources is increasing year by year in the global market. In the meantime, it also concerns that natural resources like oil, coal and natural gas are being consumed in huge amounts by human beings thus resulting in a rapid decrease in the availability of these resources. On the contrary, this huge consumption is resulting in serious environmental pollution and causing the greenhouse effect. In recent years, the major focus of research is on renewable sources of energy. PEMFC (proton exchange membrane fuel cell) has drawn the interest of researchers as one of the most promising technology. Due to its high efficiency, high stability, low energy consumption and environmental friendly, in terms of the technology and its application the PEM fuel cells are considered as the most reliable and preferable power source among different types of the fuel cell.

The fuel cell is a medium that converts the chemical energy of a fuel directly into electrical energy by electrochemical reactions. A single fuel cell has an open circuit voltage of 0.8-1.2 V. In order to achieve a higher performance, the fuel cells are preferably organized in cascade series and parallel form (Tanrioven & Alam, 2006).

Hydrogen is used as input fuel and produces DC power at the output of the stack. Polarization effects, which displays in polarization curve have many variants based on three conditions, namely; a) activation polarization, b) ohmic polarization, and c) concentration polarization curve, which provides the relation between stack terminal voltage and load current. Fig.1 shows that the cell voltage decreases almost linearly as the load current increases. In view of this, the output voltage should be regulated for a final value. The polarization characteristic can be maintained at a constant level, however the parameters such as cell temperature, oxygen partial pressure, air pressure, and membrane humidity need to be controlled. The proton exchange membrane (PEM) fuel cells with the association of hydrogen and oxygen over a platinum catalyst for producing the electrochemical energy with heat and water as the output products. The Simulation of a PEMFC for residential use is also considered in this paper (Ratlamwala et al., 2010).

Types of fuel cell

There are different types of fuel cells, which currently under development. Each of the fuel cells has its advantages, limitations, and its potential applications as explicitly explained below:

1. Polymer electrolyte membrane fuel cells
2. Direct methanol fuel cells
3. Alkaline fuel cells
4. Phosphoric acid fuel cells
5. Molten carbonate fuel cells
6. Solid oxide fuel cells
7. Reversible fuel cells

a. ***Polymer electrolyte membrane fuel cells:*** The fuel cell of (PEM) Polymer electrolyte membrane known as proton exchange membrane fuel cells—gives high power density and offers less weight and volume compared with other fuel cells. Generally, fuel cells are a solid polymer as an electrolyte and porous carbon electrodes containing a platinum or platinum alloy catalyst. We need only hydrogen, oxygen from the air, and water to operate. Interestingly, PEM fuel cells operate at relatively low temperatures, around 80°C. The lower temperature allows them to start and less wear on system components, resulting in better durability.

b. ***Direct methanol fuel cells:*** For hydrogen power, the maximum fuel cells can be fed to the fuel cell system directly or can be produced within the fuel cell system by reforming hydrogen-rich fuels such as ethanol, methanol, and hydrocarbon fuels. The direct methanol fuel cells (DMFCs) are powered by pure methanol, mixed with water and fed directly to the fuel cell anode. Direct methanol fuel cells however, do not possess any fuel storage problems on typical fuel cell systems as the methanol has a higher energy density than hydrogen, even though lesser than gasoline or diesel fuel. The methanol in liquid forms is preferably the best option by the public for transportation.

c. ***Alkaline fuel cells:*** The alkaline fuel cell was the first technologies discovered in the world and the first type of fuel cell used in the U.S. space program for generating the electrical energy as well as the water on-board spacecraft. These type of fuel cells utilize potassium hydroxide in solution form, which water acts as the electrolyte use a different type of non-precious metals as a catalyst at the anode and cathode. Currently, novel AFCs have been developed as a polymer membrane as the electrolyte. Moreover, the high performance of AFCs is achievable when the electrochemical reactions rate in the cell increased.

d. ***Phosphoric acid fuel cells***: The fuel cells of phosphoric acid use liquid phosphoric acid act as an electrolyte. The acid embedded the Teflon-bonded silicon carbide matrix—and porous carbon electrodes bearing a platinum catalyst. When the PAFCs achieved more than 85% efficiency for the co-generation of electricity and heat, but it unlikely has potential for generating the electricity itself (37%–42%). The potential of PAFC slightly more than the combustion-based power plants (basically operates at around 33% efficiency).

e. ***Molten carbonate fuel cells***: Molten carbonate fuel cells (MCFCs) are being modified to suit with its application for natural gas and coal-based power plants, industrial, and military. The fuel cells of MCFCs possess a high-temperature that uses an electrolyte, composed of a molten carbonate salt mixture suspended in a porous. For operational at high temperatures of 650°C (roughly 1,200°F), low quality of metals used as catalysts at the anode and cathode. Disadvantage of the MCFC technology is its stability as it operates at high temperature and the corrosive electrolyte used to accelerate component breakdown and corrosion, decreasing cell life.

f. ***Solid oxide fuel cells:*** The fuel cell of solid oxide (SOFCs) uses harden and non-porous compound as the electrolyte. It is noticeable that SOFCs has potential of nearly 60% for converting fuel cells to the electricity. It utilizes the system's waste heat (co-generation of 0°C (1,830°F). For the high-temperature operational, the fact is that it enables the requirement of high quality of metal catalysts, thereby it provides a cost reduction. Further, it allows the usage of variety of fuels in association with adding the reformer to the system is desirable. To develop the lower-temperature SOFCs, durability and less quality are the major problems. The SOFCs lower-temperature unlikely to give the best performance regardless of stacks material. To produce low-temperature fuel cells systems are still under development.

g. ***Reversible fuel cells:*** Generally, the reversible fuel cells produce the electricity from hydrogen and oxygen. This fuel cells are available in generating heat and water. Moreover, reversible fuel cell systems utilize electricity from wind power, solar power or other sources to split water into oxygen and hydrogen fuel through the electrolysis process. The reversible fuel cells are able to supply power during in needs, higher power production from other technologies (such as when high winds lead to an excess of available wind power), reversible fuel cells can store the excessive energy form the hydrogen. This type of energy storage capacity is the alternative for renewable energy technologies.

Basic elements of a PEM Fuel Cell

A fuel cell is combining of an anode, a cathode, and an electrolyte membrane. A fuel cell works by passing hydrogen through the negative portion of the fuel cell that means anode and oxygen through the positive portion that is cathode. At the anode site, the hydrogen molecules emits the electrons and protons. The semi reactions take places at both electrodes are as follow:

$$H_2 \rightarrow 2\,H+ + 2\,e^- \quad \text{anode} \tag{1}$$

$$O_2 + 4\,e^- \rightarrow 2\,O^{-2} \quad \text{cathode} \tag{2}$$

When the protons pass into the electrolyte membrane, then the electrons are forced through a circuit, generating an electric current and excess heat. At the cathode, the electrons, protons, and oxygen combine to produce water molecules. And finally, Hydrogen PEM fuel cells transform chemical energy into electrical and thermal energy via a simple chemical reaction (Garche & Jorissen, 2003).

$H_2 + 1/2\ O_2 \rightarrow H_2O$ + heat + electrical energy (3)

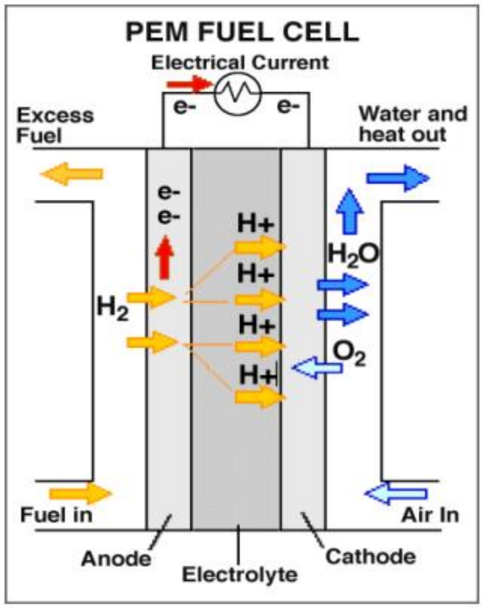

Figure 1: Working principle of PEM fuel cell (Garche & Jorissen, 2003)

The output voltage of a single cell can be written by the following expression (Science application Corporation, 2000; Baschuck & LI, 2000).

$V_{FC}=E_{Nernst}-V_{act}-V_{ohm}-V_{conc}$ (4)

Where,
V_{nernst} = it is thermodynamic potential of the individual cell.
V_{act} = it is the voltage loss due to activation of cathode and anode.
V_{ohmic} = Ohmic Voltage drop
V_{con} = it is the voltage glass due to concentration reduction of the reactants

Cell Reversible Voltage
The reversible voltage of the cell is calculated starting from a modified version of the equation of Nernst, with the consideration of an extra change of temperature in accordance with the standard reference temperature 30 ◦C (Baschuck & LI, 2000).

$E_{Nernst} = \Delta G/2F + \Delta S/2F\ (T - T_{ref}) + RT/\ 2F\ [\ \ln(PH_2) + 1/2\ \ln(PO_2)\ ]$ (5)

Where:
ΔG denotes as the changes in free Gibbs energy (J/mol),
F represents the constant of Faraday (96.487 ◦C),
ΔS denotes as the changes of the entropy (J/mol),
R is the universal constant of the gases (8.314 J/K mol),

pH_2 and pO_2 are the partial pressures of hydrogen and oxygen (bar)
T signifies the cell operation temperature (K) and T_{ref} the reference temperature.
Using the standard pressure and temperature (SPT) values for ΔG and ΔS can be simplified to (Baschuck & LI, 2000).

$$E_{Nernst} = 1.229 - 0.85 \times 10^{-3} (T - 298.15) + 4.31 \times 10^{-5} T [\ln(PH_2) + 1/2 \ln(PO_2)] \quad (6)$$

Activation voltage drop
As shown in [5], the activation over potential, including anode and cathode can be calculated by

$$Vact = - [\xi1 + \xi2T + \xi3T \ln(CO2) + \xi4 \ln(Istack)] \quad (7)$$

Here Istack is the cell operating current (A) and CO_2 is the concentration of oxygen at the catalytic interface of the cathode mol/cm, determined by:

$$CO2=PO2/5.08\times106e-498/T \quad (8)$$
$$=8.40\ 10\text{-}7$$

Ohmic Voltage Drop
In this model, a general expression for resistance is defined to include all the important parameters of the membrane.

$$Vohmic=Istack(Rm+Rc) \quad (9)$$

Here Rc represents the resistance to the transfer of protons through the membrane, usually considered constant and

$$Rm=\rho m^*l/A \quad (10)$$

ρm is the specific resistivity of the membrane (Ωcm),
A is the cell active area (cm^2)
and l is the thickness of the membrane (cm),
The density of current, Stack =Istack/A and the relative temperature = (T(k))/(303 k)

$$\rho=(181.6\ +[1+ 0.03Jstack + 0.062\theta2J\ 3.5\ stack\ )/([\psi - 0.634 - 3Jstack]\ e\ 4.18(1\text{-}\theta)\ ) \quad (11)$$
$$= 14.10$$

Concentration Voltage Drop
The voltage drops as a result of the mass transport can be determined by

$$Vcon= -B\ln(1-J/Jmax) \quad (12)$$
$$= 1.28^*10\text{-}5$$

Where,
B (in volts) is a parametric coefficient which depends on the cell and its operation state, and J represents the actual current density of the cell (A/cm^2).

Equivalent circuit Model
The electric circuit Dicks-Larminie model is shown in Figure 3.2. This model defines the activation polarization, the concentration polarization, the ohmic polarization and the Nerst voltage. The activation losses (Ra) and concentration in fuel cells are related to double layer capacitance. Any

changes in current resulting an immediate change in the voltage drop across this resistor. The double layer charge is the capacitor(C), which delays the waste of electronic charges near electrolyte/electrode interface (Andrea et al., 2009).

In common, the effect of this capacitance as resulted from the double layer charges corresponding to a 'good' dynamic performance. In the sense of good dynamic performance, the voltage moves gently and smoothly to a new value in response to any changes of the current demand. It also indicates that a simple and effective way to distinguish between the main types of voltage drop, and how to analyze the performance of a fuel cell. The ohmic losses are defined by the resistor (Rr), which explains the internal resistance of the PEMFC, such as the resistances of electrodes, conductive plates and proton transmitting through membranes. Among these losses, the activation losses are represented by a parallel connection of a resistor (Ra) with a capacitor (Ca) that models the double layer charge capacitances at the interface of membrane and the electrodes. The DC voltage source (E0) is the theoretical open circuit voltage of the PEMFC. The DC voltage source (E_0) is the theoretical open circuit voltage of the PEMFC (Andrea et al., 2009).

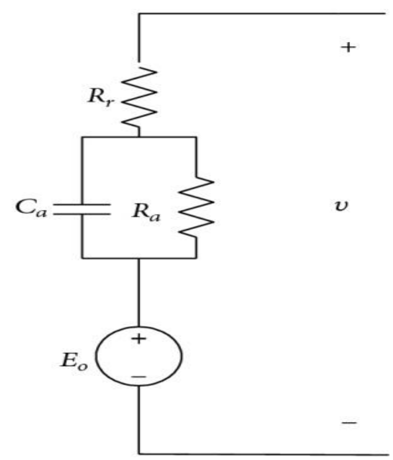

Figure 2: The simplified equivalent circuit model of PEMFC (Ahmad Fuad & Ahmad Saudi, 2007)

Model parameters

T 343 K
A 333 cm^2
L 178µm
B 0.016 V
R_C 0.3 mΩ
ζ_1 -0.948
ζ_2 0.00286+0.0002lnA + 4.3 × 10−5 ln(C_{H_2})
ζ_3 7.6×10^{-5}
ζ_4 -1.93×10^{-4}
Ψ 23
J_{max} 1500 mA/cm^2
J_n 1.2 mA/cm^2

Simulation and Result

Simulation was carried out using MATLAB-SIMULINK environment and the complete simulation model is shown in Figure 3. It shows the voltage of each cell of the stack with different load conditions. All the cells inside the stack highlights the necessity of controlling because due to its individual behavior serves the function of the current density (Lazarou et al., 2016).

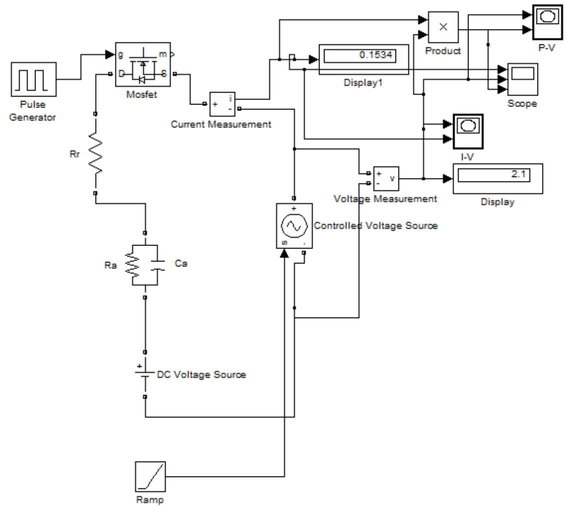

Figure 3: Simulation Diagram of PEM fuel cell

Figure 4 shows the P-V curve of PEM fuel cell. The x-axis denotes output power and y-axis denotes current density. By using the Matlab Simulink the maximum output power of 0.6W was achieved. After obtaining the accurate value, it was observed that the power has significantly declined (from 0.6W to 0.3W) at the current density of 2.25V.

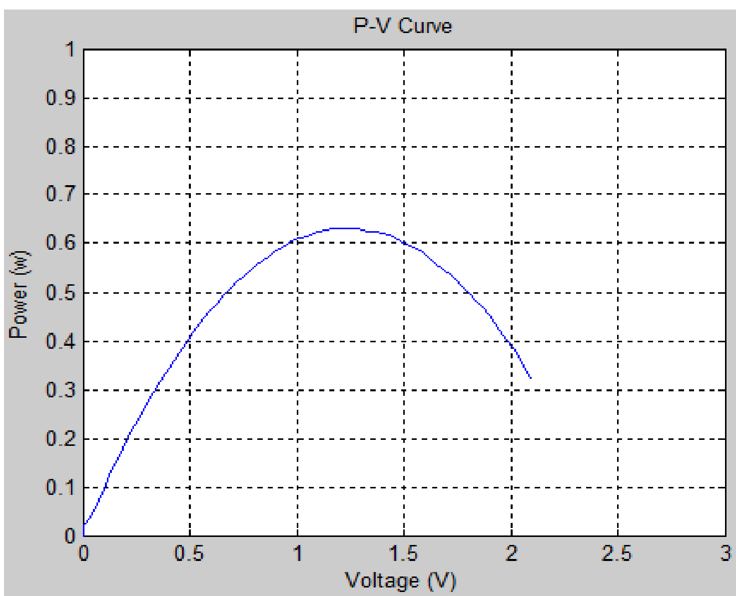

Figure 4: P-V Curve of PEM fuel cell

Figure 5 shows that I-V curve of PEM fuel cell. The x-axis denotes current and y-axis denotes voltage. Using the Matlab Simulink the maximum output current of 1A was achieved after reaching the true value at the voltage of 2.2V.

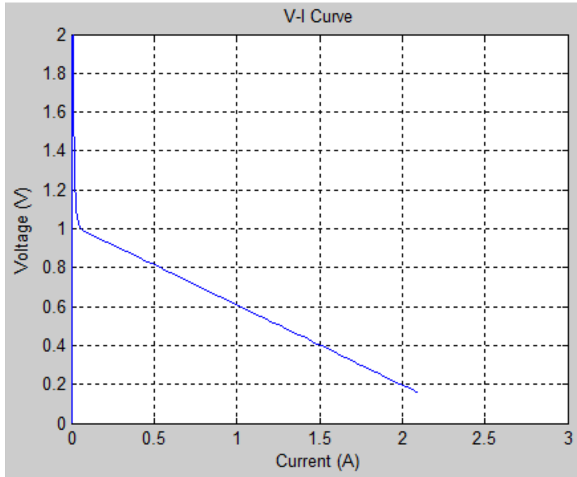

Figure 5: I-V Curve of PEM fuel cell

Table 1 and Figure 6 depicts that Ohmic losses occurred due to ionic, electronic, and contact resistances, which occurs in the electrodes and electrolyte, current collectors, contact resistance, and interconnect because every material has instinct resistance to charge flow. It denotes the losses of FC performance. With the highest achievement of power (0.79W) and resistance (0.01 (Ω)), the voltage, I_{stack} and ohmic losses the true value was observed at 1.26A. On contrary, when the resistance value (R_r) of 0.4833 (Ω), the lower power value obtained was 0.6288W. The maximum power was achieved correspond with the lower resistance value.

Table 1: Ohmic loss of the resistor (R_r)

R_r(Ω)	P_{max}(watt)	V_m(volt)	I_{sc}(A)	V_{oc}(volt)
0.01	.7839	1.26	1.26	2.5
0.10	.7484	1.26	1.22	2.48
0.15	.7269	1.26	1.2	2.46
0.20	0.7163	1.26	1.18	2.45
0.25	0.7006	1.26	1.17	2.49
0.30	0.6798	1.26	1.15	2.49
0.35	0.6651	1.26	1.1	2.49
0.4	0.6506	1.26	1	2.49
0.45	0.6873	1.26	1	2.49
0.4833	0.6288	1.26	1	2.49
0.50	0.6246	1.26	1.00	2.49
0.55	0.6124	1.26	.95	2.49
0.60	0.6007	1.26	.95	2.49
0.65	0.5894	1.254	.95	2.49
0.70	0.5785	1.254	.9	2.49
0.75	0.5680	1.254	.88	2.49
0.8	0.5578	1.254	.88	2.49
0.85	0.548	1.254	.88	2.49
0.90	0.5386	1.254	.85	2.49
0.95	0.5295	1.254	.85	2.49
1.0	0.5207	1.254	.8	2.49

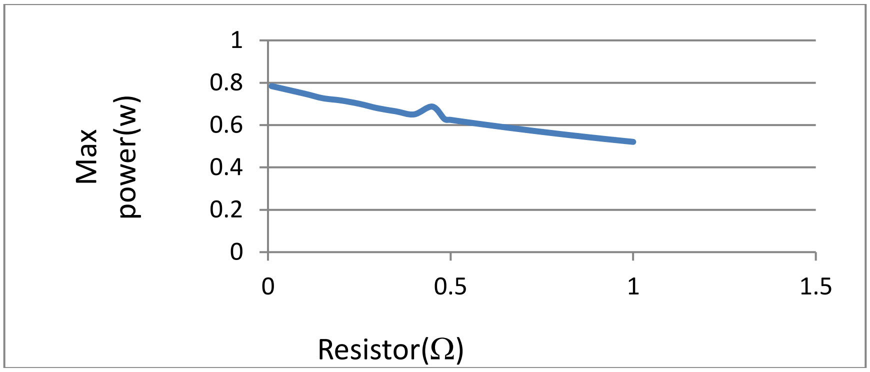

Figure 6: Ohmic loss of the resistor

Table 2 and Figure 7 indicates the activation losses occurs through the observation of the slowness of the reactions at the electrode surface. The reduction of voltage somewhat due to electrochemical reaction kinetics. While, the mass transport losses as resulted from the decreased in reactant concentration at the surface of the electrodes as fuel was used. The maximum power was achieved when I_{stack} and activation losses reached the point of 0.65 and the true value of power of 1.26W with a significant reduction of resistance value.

Table 2: Activation loss of the Resistor (Ra)

R_a(Ω)	P_{MAX}(watt)	V_m(volt)	I_{SC}(A)	V_{oc}(volt)
.65	1.26	1.26	1.92	2.49
.70	1.21	1.26	1.92	2.49
.75	1.184	1.26	1.84	2.49
.80	1.123	1.26	1.78	2.49
0.85	1.081	1.26	1.72	2.49
0.9	1.044	1.26	1.64	2.49
0.95	1.01	1.26	1.6	2.49
1.00	0.9771	1.26	1.58	2.49
1.05	0.9465	1.26	1.5	2.49
1.10	0.9177	1.26	1.46	2.49
1.15	0.8903	1.26	1.40	2.49
1.20	0.8647	1.26	1.38	2.49
1.25	0.8405	1.26	1.34	2.49
1.30	0.8176	1.26	1.30	2.49
1.35	0.7959	1.26	1.23	2.49
1.40	0.7752	1.26	1.21	2.49
1.45	0.7556	1.26	1.2	2.49
1.50	0.7369	1.26	1.18	2.49
1.55	0.7191	1.26	1.16	2.49
1.60	0.7021	1.26	1.11	2.49
1.65	0.6859	1.26	1.08	2.49
1.70	0.6703	1.26	1.06	2.49
1.75	0.6555	1.26	1.02	2.49
1.80	0.6412	1.26	1.01	2.49
1.85	0.6288	1.26	1	2.5

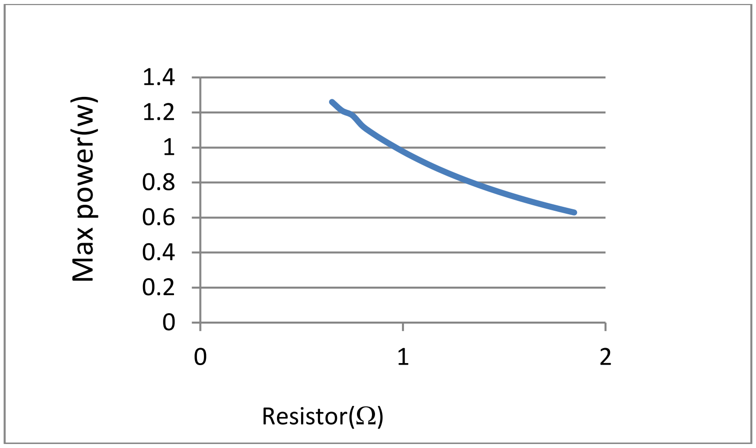

Figure 7: Activation loss of the Resistor

Table 3 and Figure 8 indicates that the dielectric loss of capacitors was the main contributor to the entire equivalent series resistance in this study. The conduction dielectric losses access to losses that are caused by the actual movement of charge across a dielectric material. These losses happened at high temperature and low frequency. At R_r of 0.06654(Ω), the maximum power was achievable, whilst the voltage, I_{stack} and capacitor losses the value of 0.6288W.

Table 3: Activation loss of capacitor

Ca(Ω)	P_{mx}(watt)	V_m(volt)	I_{sc}(A)	V_{oc}(volt)
0.06654	0.6288	1.26	1	2.49
0.05	0.633	1.26	1	2.49
0.04	0.6351	1.26	1	2.49
0.03	0.6373	1.26	1.01	2.49
0.02	0.6396	1.26	1.02	2.49
0.01	0.6415	1.26	1.03	2.49
0.1	0.6215	1.26	0.98	2.49
0.2	0.5997	1.26	0.94	2.49
0.3	0.5778	1.26	0.94	2.49
0.4	0.556	1.26	0.9	2.49
0.5	0.5342	1.26	0.84	2.49
0.6	0.5124	1.26	0.82	2.49
0.7	0.4905	1.26	0.79	2.49
0.8	0.4687	1.26	0.75	2.49
0.9	0.447	1.26	0.7	2.49
1.0	0.4254	1.26	0.64	2.49

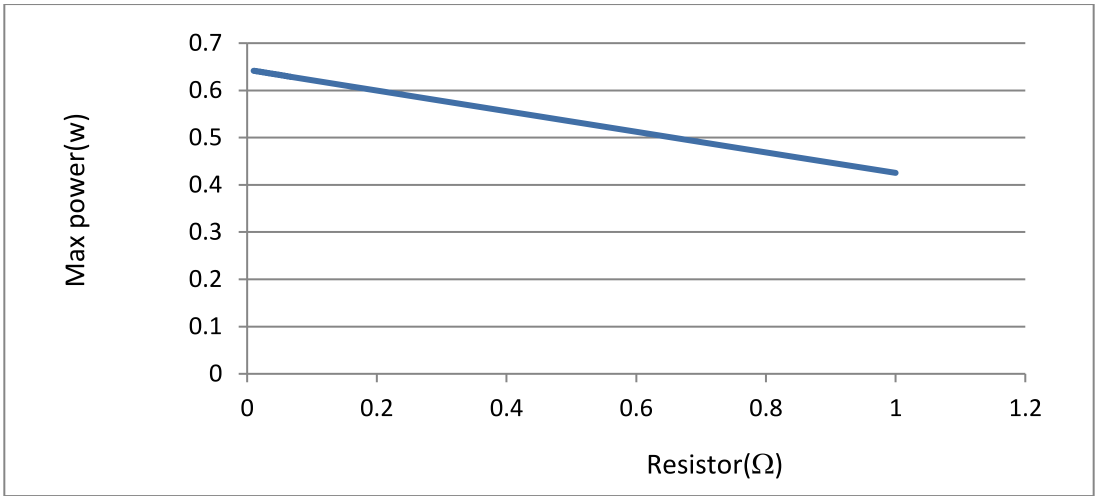

Figure 8: Activation loss of capacitor

Conclusion

The static modeling and simulation of a fuel cell based power generation system is discussed in this report. Among the different types of renewable energy sources, PEM fuel cells are widely used for residential applications due to their noise free operation and better reliability. Fuel cells can also be used in grid connected systems to supply supplemental power or as an emergency power supply system in case of critical conditions as like when national grid is a failure. Now a day, in power electronics has added more features to this power supply system.

A great deal of research has been done on fuel cells, even though it has got some disadvantages such as high cost due to expensive materials like platinum and safety concerns regarding the use of hydrogen. For higher voltage (0.8 V per cell), the current density can be developed by up to 40%, while, at a lower voltage (0.6 V per cell), the current density may be doubled. Reducing the membrane thickness by 40% and increasing photonic conductivity by 50% gives rise to a current density of up to 40% at a higher voltage and up to 100% at a medium voltage.

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