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Designing Size and Stack Number of Fuel Cell Urban Vehicle

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ABSTRACT

A fuel cell converts the energy in the chemical reaction of a continuously supplied fuel and its oxidizing agent into electrical energy. Fuel cells are used in various industries, including the automotive industry. In this context, fuel cell electric vehicles (FCEVs) have emerged as a promising alternative that offers zero emissions and competitive performance. This work was conducted to obtain a fuel cell design and determine the fuel cell modeling that suits the needs of FCEVs. The Pahl and Beitz method with QFD is used. It was found that the type of fuel cell used is PEMFC (Proton Exchange Membrane Fuel Cell) with platinum electrode material, and the fuel used is hydrogen on a small scale. Overall, fuel cell dimensions were 175 x 259 x 175 mm, and the number of fuel cell stacks that can be arranged is 35. With this geometry, the factor of safety value obtained at the stack fuel cell is 26, and at the end plate fuel cell 2.4, this value indicates that the PEMFC design is safe. Then, the output voltage is 50.55 V, and the output current is 25.27 A, so the power generated is 1.277 kW.

Kata Kunci: *Fuel cell, Proton Exchange Membrane Fuel Cell, Safety Factor*

1. INTRODUCTION

Fuel cell electric vehicles (FCEVs) are becoming increasingly popular as an environmentally friendly transportation solution. FCEVs offer zero emissions and competitive performance, working on the principle of converting hydrogen and oxygen into electricity, generating water and heat. This makes renewable fuels in fuel cells a key solution to emissions and dependence on fossil fuels.

Hydrogen fuel cell technology in electric vehicles requires a deep understanding of fuel cell design and modeling. Design analysis and modeling of fuel cell performance is essential for the design of efficient and reliable FCEVs. SOLIDWORKS was used in the design process to select the best variant for the specifications of the FCEVs. MATLAB Simulink does electrochemical calculations using the Nernst equation for fuel cell voltage influenced by pressure and temperature. The design and modeling results become simulation parameters, providing an in-depth understanding of the working system of FCEVs and improving the overall efficiency and performance of electric vehicles. This research contributes to developing environmentally friendly and efficient technologies in electric vehicles.

A fuel cell is a galvanic cell that converts the energy in the chemical reaction of a continuously supplied fuel and its oxidizing agent into electrical energy. The fuel cell is not an energy storage device but a converter where the energy supplied is chemically bonded to the fuel. Although fuel cells are often referred to as hydrogen-oxygen fuel cells, many other fuels can be used besides hydrogen (H_2), including methanol, butane, and other natural gases. There are several technology options that can be used depending on the type of electrolyte used, resulting in different operating temperatures and pressures (Lindorfer, Rosenfeld, & Böhm, 2020).

Polymer Electrolyte Membrane Fuel cell (PEMFC), also known as a proton exchange membrane fuel cell, the electrolyte in this fuel cell is a polymer electrolyte membrane (fluorinated sulfonic acid polymer or other similar polymers) which is very good as a proton conductor. The physical structure of PEMFC consists of seven components, including feeding channels on the anode side, diffusion layer, catalyst layer at the anode, membrane, catalyst layer at the cathode, diffusion layer, and feeding channel at the cathode. The physical structure of PEMFC consists of seven components, including feeding channels on the anode side, diffusion layer, catalyst layer at the anode, membrane, catalyst layer at the cathode, diffusion layer, and feeding channel at the cathode (Malasari, Onggo, & Rokhmat, 2015).

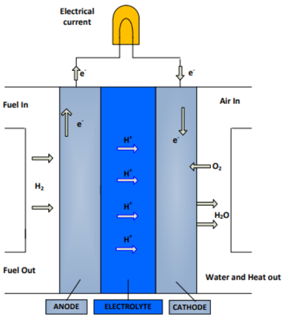


Figure 1.1 *Polymer Electrolyte Membrane Fuel Cell*

Proton Exchange Membrane Fuel Cell (PEM FC) works at low temperatures (60° - 80°C) with pure hydrogen as fuel. Hydrogen is delivered to the anode at constant pressure, where a platinum catalyst releases electrons to the external circuit and proton ions to the cathode. The protons (H+) are transferred to the cathode through a proton-conducting membrane that only allows proton ions to pass and filter out electrons. Because if there are electrons passing through the electrolyte (proton conducting membrane) there will be damage due to a short circuit. That is often the case with previous fuel cell technology.

Anode : $H_2 \rightarrow 2H^+ + 2e^-$

Cathode : $\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$

Total reaction : $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$ (air) + Heat

The electrons produced are derived from each 1 mole of hydrogen, and has an energy of 2 FE Joules this reaction will continue (continuously) produce electrical energy as long as the hydrogen supply exists. The fuel used is pure hydrogen. Therefore, a tool is needed that can convert gasoline, diesel, natural gas or methanol into hydrogen used in the fuel cell stack, this tool is commonly called a reformer.

2. METHODOLOGY

2.1. Flow Chart

The following is a flow chart of the analysis of fuel cell Design and Performance Modeling for Fuel Cell Electric Vehicles (FCEVs) Applications.

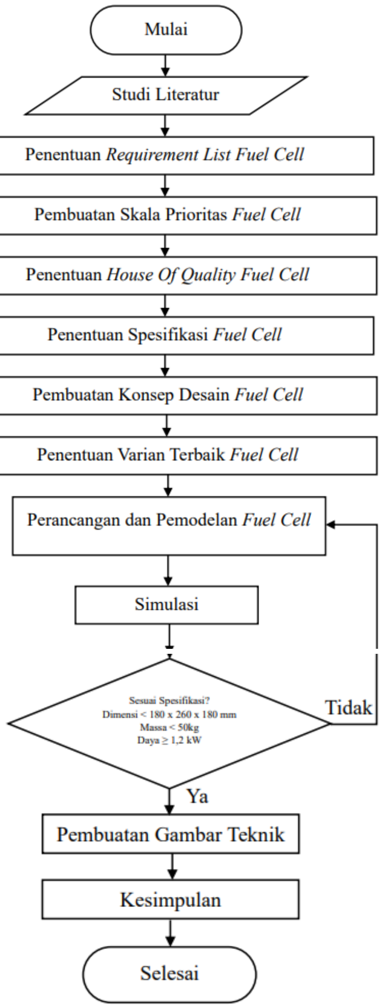


Figure 2.1 Flow Chart

2.2 Requirement List

The requirement list needs to be compiled in more detail and explained in more depth about the things that become requirements in the manufacture of fuel cells. One of the main requirements is the amount of power generated; the power generated must reach 1.2 kW so that the electrical energy needs of the FCEV are met. This power is influenced by the amount of fuel cell surface area and the number of cells arranged. In addition, the dimensions of the fuel cell are limited to the size that has been provided in the FCEVs car. Therefore, careful design is required to ensure the requirements are met. The exact specifications for this body will be organized in a table called the requirement list. In this table, each feature or advantage to be incorporated into the body will be grouped into demands and wishes aspects.

Table 2.1 *Requirement List*

Requirement List	**Description**	***Demands* (D) / *Wishes* (W)**
Function	Fuel cells meet the electricity needs of FCEVs	D
Geometry	Able to hold flowing gas for as long as possible	D
	Dimensions adapt to FCEVs	D
Material	Good electrical conducting	D
	Light	D
	Cheap	W
Manufacture	Bentuk *fuel cell* mudah dibuat	D
	Fuel cell shape is easy to make	D
Maintenance	Easy maintenance	D
	Low-cost maintenance	W
Operational	Accesible fuel cell	D
K3	Safety under pressure	D
Biaya	Low cost	W

The results of the requirement list obtained are a reference for making the House of Quality. Thus, the required specifications are obtained. Then, determine the best variant for the best body model.

3. RESULTS AND DISCUSSION

3.1. Design of Proton Exchange Membrane Fuel Cell

The design begins with determining the material and dimensions that will be used in each PEMFC component. The fuel cell that will be made will be applied to an electric car is a type of PEMFC, the dimensions of the PEMFC are determined based on the place that has been designed in the car. Based on the design of the car, PEMFC is placed in a position with a size of 180 mm x 260 mm x 180 mm. Then the dimensions of the PEMFC stack must be less than these dimensions; the following is an explanation of the PEMFC dimensions.

a. *Bipolar Plate*

The bipolar plate is an important component of PEMFC, which is used to direct hydrogen gas flow to the anode and oxygen gas flow to the cathode. The fluid flow path has a width and height of 1 mm x 1 mm, respectively (Wilberforce, 2022). In this study, 6 serpentines type flows were made which were used for homogeneous gas distribution on the cathode and anode sides, shown in the following figure.

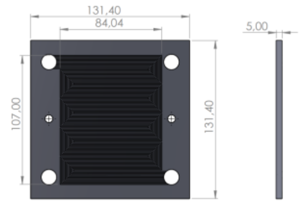
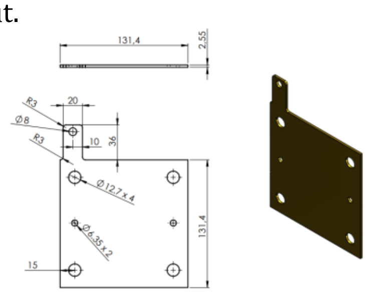


Figure 3.1 *Bipolar Plate* Anode

P = 131,40 mm
L = 131,40 mm
T = 5 mm
Material = carbon graphite

b. *Current Collector*

Current collector on PEMFC is a component that serves to collect electric current from the electrodes in the fuel cell and then drain the current out.



Gambar 3.2 Dimensi *Current Collector*

P = 131,40 mm
L = 131,40 mm
T = 2,55 mm
Material = Brass

c. Membrane Electrode Assembly (MEA)

The core of a Proton Exchange Membrane Fuel Cell (PEMFC) is the Membrane Electrode Assembly (MEA), which consists of a proton exchange membrane (PEM) and a catalyst. As a membrane material, polymers such as Nafion are used, and the catalyst uses carbon platinum.

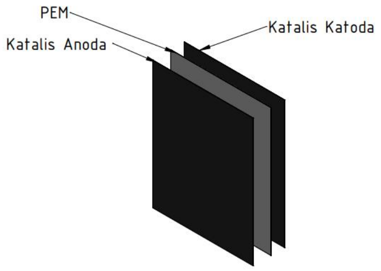
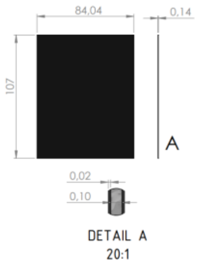


Figure 3.3 *Membrane Electrode Assembly* (MEA)

Based on the dimensions of the fluid flow, which is 84.04 mm x 107 mm or has an area of 89.92 cm2, the dimensions used in MEA follow the dimensions of the fluid flow. The anode and cathode on the catalyst are 0.02 mm thick, and the PEM is 0.1 mm thick. (Guo, Chen, & Ismail, 2022).



Fifure 3.4 Geometry MEA

d. *Gas Diffusion Layer* (GDL)

The gas diffusion layer (GDL) serves as a gas diffusion pathway provider, drainage and also an electrical connection between the catalyst and the bipolar plate which also supports the MEA mechanically.

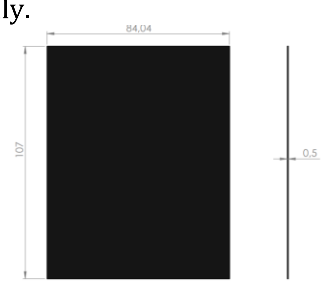


Figure 3.5 Geometry *Gas Diffusion Layer* (GDL)

P = 84,04 mm
L = 107 mm
T = 0,5 mm
Material = Carbon nanotube

e. Gaskets

The gasket is one of the important complementary components in PEMFC, which is used as a seal to ensure that the hydrogen gas, oxygen gas, and water produced during the chemical reaction inside the PEMFC do not leak out of the system.

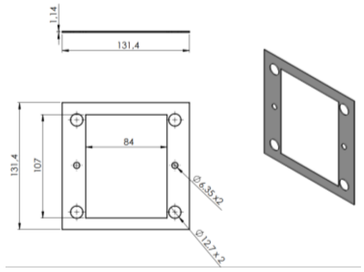
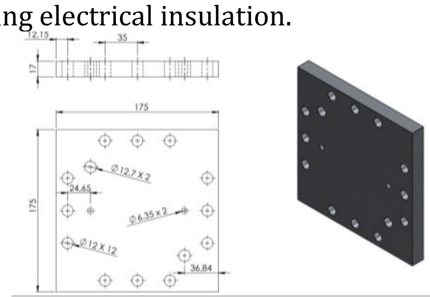


Figure 3.6 Gasket Geometry

P = 131,40 mm
L = 131,40 mm
T = 1,14 mm
Material = *Silicone Rubber*

f. *End Plate*

The End Plate of a PEMFC circuit is used to reinforce the inner stack, reduce contact pressure, and provide a seal between Membrane-Electrode Assemblies (MEA). Therefore, they require sufficient mechanical strength to withstand tightening stresses, light weight to obtain high energy density, and stable chemical/electrochemical properties, as well as providing electrical insulation.



Gambar 3.7 End Plate Geometry

P = 175 mm
L = 175 mm
T = 17 mm
Material = *Aluminum Alloy 6061*

g. *Overall Dimensions*

From the specifications made, the fuel cell is arranged as many as 35 cells to meet the dimensions available on FCEVs. The following is the arrangement of the PEMFC, along with the dimensions.

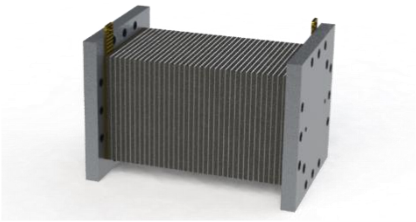


Figure 3.8 *Proton Exchange Membrane Fuel Cell Assembly*

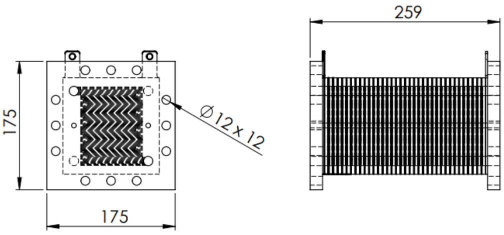


Figure 3.9 PEMFC *Assembly*

After being combined and arranged based on the PEMFC arrangement, the dimensions of 175 x 259 x 175 mm were obtained.

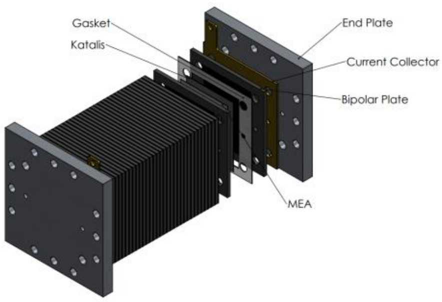


Figure 3.10 PEMFC Arrangement

3.2 Simulation

3.2.1 *Stack Fuel Cell* PEMFC

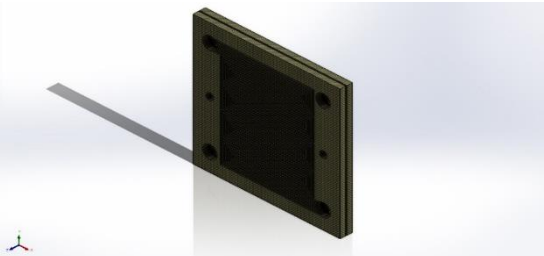


Figure 3.11 *Stack Fuel Cell* PEMFC

Based on the literature obtained on fuel cells with an electrode surface area of 350 cm², the pressure obtained from the process is 1 - 4.4 atm. (U.S Departement of energy, 2000). Based on this, the area on the electrode designed in the PEMFC design research here is 3.8 times smaller than the literature. The material used by some components on the PEMFC stack is a non-linear material, so the simulation used is a nonlinear simulation. This simulation is done with Solidworks 2022 software. After the drawing is successfully made, the part that becomes the fixed support is determined, and the loading is determined. After that, the meshing process is carried out and then followed by the solving process to get the values of stress, displacement, strain, and safety factors.

The simulation used a loading of 1 atm (14.69 psi), 2.7 atm (39.68 psi), and 4.4 atm (64.66 psi). The following is a recap of the results of displacement simulation, strain simulation, stress simulation and safety of factor.

Table 3.1 *Stack Fuel Cell* PEMFC

Simulation		Pressure 1 atm	Pressure 2,7 atm	Pressure 4,4 atm
Displacement (mm)	**Max**	1,85E-02	5,01E-02	9,99E-02
	Min	0	0	0
Strain (mm/mm)	**Max**	1,47E-02	4,01E-02	9,54E-02
	Min	7,08E-08	1,97E-07	2,60E-07
Stress (N/m^2)	**Max**	2,45E+06	6,62E+06	8,37E+06
	Min	8,68E+00	3,71E+01	1,42E+02
Factor of Safety	**Max**	1,13E+07	5,40E+06	1,66E+06
	Min	90	40	26

a. Displacement

The maximum load of PEMFC based on the literature is 4.4 atm, based on the simulation in Figure 4.13 displacement on the fuel cell stack. This simulation shows the loading area where here the loading is in the form of pressure, then the red color shows the most burdened area. Then, the area that is said to be safe is the area that does not exceed the light blue color. In this simulation, there is not much change in shape where the maximum displacement is 0.099 mm and a minimum of 0 mm.

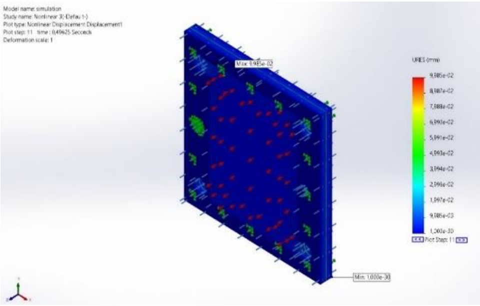
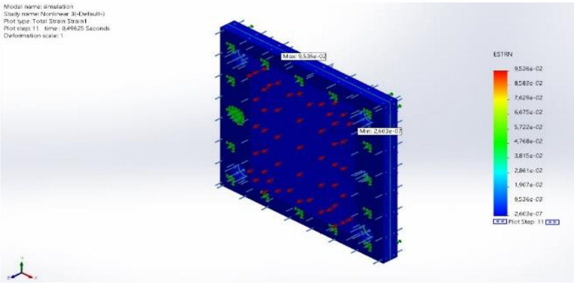


Figure 3.12 *Displacement Stack* PEMFC 4,4 atm

b. Strain

The results of the strain simulation using equivalent strain at a pressure of 4.4 atm amounted to 9.54E-02 mm/mm for the maximum value and for the minimum value of 2.6E-07 mm/mm. Equivalent strain is a concept in materials science and structural engineering that refers to a quantity that describes the deformation of a material as a whole due to an imposed load or force. Here is an illustration of the strain simulation.



Gambar 3.13 Hasil Simulasi *Strain Stack Fuel Cell* 4,4 atm

c. Stress

The stress simulation uses the von misses stress type which is used to measure the level of stress that occurs in an object when it is under load or force. With a maximum value of 8.37E+06 N/m2 and a minimum value of 1.4E+02 N/m2. The following is an illustration of the stress simulation.

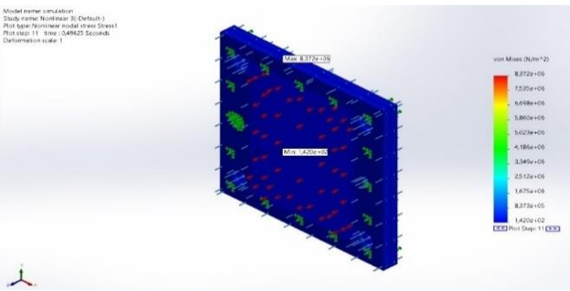
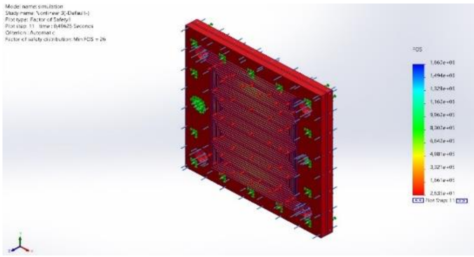


Figure 3.14 *Stress Stack Fuel Cell* 4,4 atm

d. Factor of Safety

Based on existing provisions, the range of factor of safety values for dynamic loads is 2.0 - 3.0, and the value of the factor of safety at a pressure of 4.4 atm is 26 - 1.66E6. The magnitude of the value obtained is very safe to use in the fuel cell design in this study. The following is an illustration of the factor of safety simulation on the fuel cell stack.



Gambar 3.15 Hasil Simulasi *Factor of Safety Stack Fuel Cell* 4,4 atm

3.2.2 *End Plate* PEMFC

In simulating the strength of the PEMFC end plate using Solidworks 2022 software. In this process, after the drawing is successfully made, the part that becomes the fixed support is determined, and the loading is determined. After that, the meshing process is carried out and then followed by the solving process to get the value of stress, displacement, strain, and safety of factor. The simulation used a loading of 1 atm (14.69 psi), 2.7 atm (39.68 psi), and 4.4 atm (64.66 psi). The following is a recapitulation of the simulation results carried out on the PEMFC end plate.

Table 3.2 *End Plate* PEMFC

Simulation		Pressure 1 atm	Pressure 2,7 atm	Pressure 4,4 atm
Displacement (mm)	Max	1,28E-03	3,46E-03	5,64E-03
	Min	0	0	0
Strain	Max	4,59E-05	1,24E-04	2,02E-04
	Min	7,82E-09	2,11E-08	3,44E-08
Stress (N/m^2)	Max	5,19E+06	1,40E+07	2,28E+07
	Min	4,34E+02	1,17E+03	1,91E+03
Factor of Safety	Max	1,27E+05	4,70E+04	2,89E+04
	Min	11	3,9	2,4

a. Displacement

The maximum load of PEMFC based on the literature is 4.4 atm, based on the simulation in Figure 4.22 displacement on the fuel cell stack. In this simulation, there is not much change in shape where the maximum displacement is 0.0056 mm and a minimum of 0 mm.

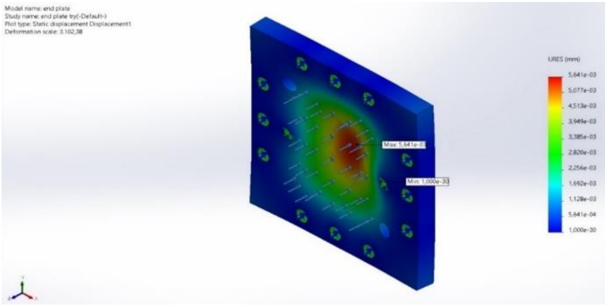


Figure 3.16 *Displacement End Plate* 4,4 atm

b. Strain

The results of the strain simulation using equivalent strain at a pressure of 4.4 atm amounted to 2.02E-04 mm/mm for the maximum value and for the minimum value of 3.44E-08 mm/mm.

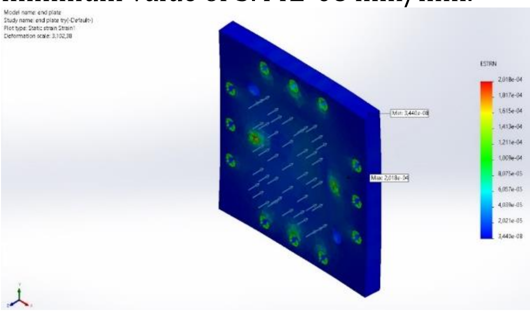


Figure 3.17 Hasil Simulasi *Strain End Plate* 4,4 atm

c. Stress

The stress simulation uses the von misses stress type which is used to measure the level of stress that occurs in an object when it is under load or force. With a maximum value of 2.28E+07 N/m2 and a minimum value of 1.91E+03 N/m2. The following is an illustration of the stress simulation.

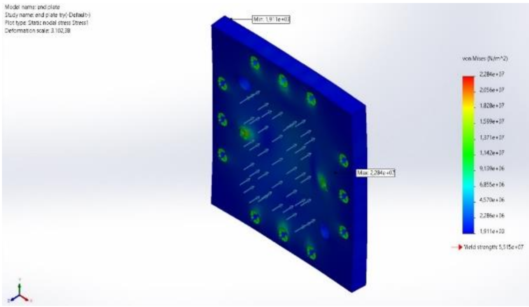


Figure 3.18 Hasil Simulasi *Stress End Plate* 4,4 atm

3.2.1 Voltage and Current

The simulation carried out is a modeling simulation of the fuel cell's electrochemical equations using MATLAB Simulink software. The parameters used come from the design that has been made. The following is a simulation of a fuel cell arranged with as many amounts, with a surface area of 89.92 cm2 and a number of cells of 35, resulting in a fuel cell width of 225 mm. The following are the results of simulations conducted from PEMFC specifications that have been determined based on the Nerst equation.

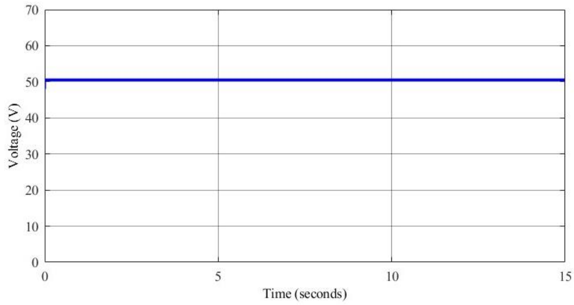


Figure 3.19 PEMFC Voltage

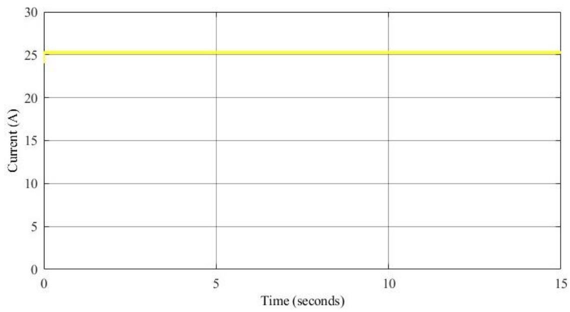


Figure 3.20 PEMFC Current

From the above simulation, it is obtained that the output voltage is 50.55 V, and the output current is 25.27 A. From the amount of voltage and current, the amount of power generated can be found with the voltage equation coupled with the amount of current, which can be seen in the following equation.

$P = V \times I$
$P = 50{,}55 \times 25{,}27$
$P = 1.277{,}3985\ Watt = 1{,}277$ kW

From the calculations obtained, the amount of power generated is in accordance with the desired amount, which is less than equal to 3 kW. This amount is expected to fulfill the supply of electrical energy in FCEV. Based on the results obtained, in accordance with the electrochemical equation in the fuel cell, where the loss of output voltage is caused by Nernst voltage, ohmic voltage, activation voltage, and concentration voltage.

4. Conclusions

From the research that has been done, the following conclusions can be drawn. Based on the needs of the vehicle, the type of fuel cell obtained is PEMFC with material on platinum (Pt) electrodes, with fuel used hydrogen. PEMFC is used because, based on the scale PEMFC is a type of fuel cell on a small scale and is able to convert hydrogen energy into electrical energy with high efficiency. Based on the available dimensions of the FCEVs, the required fuel cell is obtained 175 x 259 x 175 mm. With a power generated of 1.277 kW.

Based on simulations carried out with SolidWorks and MATLAB Simulink software, it is obtained,

a) Simulations on the PEMFC fuel cell stack with 1 atm, 2.7 atm, and 4.4 atm loading resulted in displacements of 1.85E-02 mm, 5.01E-02 mm, and 9.99E-02 mm. The strains were 1.47E-02, 4.01E-02, and 9.54E-02, with maximum stresses of 2.45e+06 N/m2, 6.62E+06 N/m2, and 8.37E+06 N/m2. All these values increase with stress. The factor of safety at each pressure is 90, 40, and 26. The safe range for dynamic loads is 2.0 - 3.0, indicating the PEMFC stack design is safe up to the maximum pressure tested.
b) Simulated loading on the PEMFC end plate resulted in displacements of 1.28E-03 mm, 3.46E-03 mm, and 5.64E-03 mm, and strains of 4.59E-05, 1.24E-04, and 2.02E-04, with stresses of 5.19E+06 N/m2, 1.40E+07 N/m2, and 2.28E+07 N/m2, respectively. All these values increase with the applied stress. The safety factor at pressures of 1 atm, 2.7 atm, and 4.4 atm is 11, 3.9, and 2.4, respectively. The safe range for dynamic load is 2.0 - 3.0, indicating the PEMFC end plate design is safe up to the maximum pressure tested.
c) Simulation of voltage and current in the fuel cell design resulted in a voltage of 50.55 V and a current of 25.27 A.

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