

#### Please cite the Published Version

Alrewq, M and Albarbar, A (10) (2016) Investigation into the characteristics of proton exchange membrane fuel cell-based power system. IET Science, Measurement and Technology, 10 (3). pp. 200-206. ISSN 1751-8822

DOI: https://doi.org/10.1049/iet-smt.2015.0046

Publisher: Institution of Engineering and Technology

Version: Accepted Version

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Based	Power System
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#### Abstract

Fuel Cells (FCs) use hydrogen as their prime fuel source, which promotes them as one of the 10 attractive options for clean energy generators. Although they have been around for some 11 time, their characteristics are not yet fully understood. This paper offers a thorough 12 investigation into the characteristics of proton exchange membrane (PEM) type of fuel cells 13 based power system. The paper firstly presents a concise explanation of the working 14 principles of the PEM electrolyser and FCs supported by novel modelling using MatLab. 15 The simulation results are then validated by a series of experiments carried out on 16 500 mW FC followed by detailed performance parameters of such type of operational 17 FCs. Parameters affect the efficiencies of each part of the system are investigated and the 18 total system's efficiency is then calculated. The efficiency of the electrolyser and PEM was 19 found to be 85% and 60 % respectively. Polarization curve has been used in order to evaluate 20 FC's performance. From the polarization curve, it is noticed the efficiency of the FC increase 21 with increasing pressure and temperature. The activation losses are reduced when the 22 temperature increased. Moreover, the mass transfer is enhanced towards reducing the 23 PEMFC's resistance. 24

Keywords: Hydrogen, Renewable Energy, Fuel Cells (FCs), Proton Exchange Membrane25FCs (PEMFC), Reliability and Sustainability, Performance Evaluation, Modelling and26Simulation.27

# **1-Introduction:**

The rising of fossil fuel prices and the growing concerns about the greenhouse gas emissions 29 prompt scientists and researchers to search for other sources of energy that are sustainable 30

with low cost, high efficient energy conversion and minimal environmental impact. 31 Hydrogen and bio-fuels can be used as an alternative clean energy source in the near future. 32 Fuel Cells (FCs) have promising features as they have high efficiency and low emissions 33 (Cultura 2014). There are numerous types of FCs that operate in a similar way, but they 34 differ in operating conditions and the type of their materials. Proton exchange membrane fuel 35 cells (PEMFCs), among the different types of FCs, have attracted the research interest 36 especially for automobile applications. They have high-power density at low operating 37 temperatures(less than 1000C), quick start-up and zero emissions. However, PEMFC 38 systems still present certain drawbacks and improvements must be made in order to enhance 39 their reliability for industrial applications. Cost reduction, durability, performance evaluation 40 reliability thus remain strong research issues. Mathematical modelling and and 41 simulation are needed to examine the behaviour and characteristics of FCs. These techniques 42 can help in predicting and improving FCs' performance and reliability. There are several 43 studies that have focused on the study and modelling of FC, among these studies, Guang 44 (Guang et al., 2013), which presented the fundamental electrochemical and it also 45 demonstrated the underlying electrochemical and transport mechanisms essential for PEMFC 46 modelling. Chanpeng(Chanpeng 2011) used experimental and developed MatLab Simulink 47 module to study the operation performance of 1.2KW PEMFC. (Tian 2009) proposed 48 PEMFC mechanism modelling based on artificial intelligent to investigate PEMFC 49 mechanism and faults. Tanrioven (Tanrioven and Alam 2006) presented a methodology for 50 modelling and determining PEM characteristic mechanism to enhance its reliability. The 51 Models play vital role to ensure the optimum design of FCs. This paper offers 52 comprehensive study on the modelling and Simulink the operation mechanism of PEMFCs 53

in order to investigate the reliability and performance of PEMFC under differ operating				
condition. Mathematical equations and modelling are used to define operating conditions and				
the performance of PEMFC.				
The aim of this research is to develop a model for investigating the performance of a PEM	57			
fuel cell at different operation variables using semi-empirical equations. Model validation				
against the experimental data.	59			
2. Fuel Cell System:	60			
The basic structure of a PEMFC system as depicted in Figure (1) is composed of the	61			
following parts:	62			
i- Electrolyser: device that uses to separate the distilled water to hydrogen and oxygen	63			
which are used as fuel of FC.	64			
ii-Fuel Cell: the main part of this system. FC is an electrochemical device which uses the	65			
chemical energy to produce electrical energy.	66			
iii- DC/DC converter: device that works to control the output voltage (buck or boost	67			
converter).	68			
iv- DC/AC inverter: the main task of this device is to convert the output voltage from				
D.C signal into A.C signal.	70			



Fig.1 The schematic diagram of Fuel cell system

#### 3. Electrolyser:

Hydrogen is one of the most promising alternative sources of energy for the future due to it
has the capability of storing energy at high quality. For that, the hydrogen has been presented
to become the cornerstone of future energy systems based on other renewable energy
sources. Some of the researchers have been studied the uses of hydrogen as an energy carrier
in storage and transport of energy.

Electrolyser is electrochemical device that uses electricity to decompose water into hydrogen 80 and oxygen. When the voltage across the two electrodes (anode and cathode) exceeds the 81 decomposition voltage of water (which is 1.23 V), the pure water will be separated into 82 hydrogen and oxygen a. Equation (1) demonstrates the chemical reactions in electrolyser at 83 both anode and cathode side: 84

at Anode side : 
$$2H_2O \rightarrow 4H^+ + 4e^- + O_2$$
 85

at Cathode side : 
$$4H^+ + 4e^- \rightarrow 2H_2$$
 86

Total reaction : 
$$2H_2O \rightarrow 2H_2 + O_2$$
Eq. (1) 87



Fig .2 the functionality of the electrolyser (HTE 2012)

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Electrical energy is need to achieving the previous equation. In addition to the electrolyser 90 device, hydrogen may extract from natural gas as depicted in figure 3. 91



Fig.3 The natural energy hydrogen cycle

There are many methods used to conversion the hydrogen energy to electrical energy. Fuel 94 cell has many advantages such as high conversion efficiencies that make it best way for 95 hydrogen conversion. 96

### 4. The Operation Principle of the FC:

The operation mechanism of PEMFC will be investigated in order to illustrate the operation 98 principle of FCs. The idea of operation depends on the presence of a Membrane separator 99 (the Electrolyte) and the catalyst which is usually made of platinum powder and coating the 100 carbon paper or cloth with a very thin layer (Dokkar 2011). The side of the plate is coated by 101 the platinum is placed next to proton exchange membrane. Upon entering the hydrogen  $H_2$  to 102 the cell, the platinum works on separating it into proton and an electron. The membrane 103 separator allows protons to pass and does not allow electrons. Therefore, electrons have to 104 pass only through the current collectors, and this produces DC electrical current. In the 105 opposite side of the membrane (i.e., at the cathode side) the electron binds with the proton 106

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in the presence of a catalyst again and with the presence of oxygen, the water  $H_2O$  is 107 produced and heat spreads as shown in Figure 4.



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112

# Fig .4 the functionality of the PEMFC (HTE 2012) 110

Table.Error! Reference source not found. Types of FCs and their characteristics and	111
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#### usages

Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Efficiency	Applications
Proton Exchange Membrane (PEM)	Perfluoro sulfonic acid.	50 - 100°C Typically 80°C	< 1kW– 100kW	60% transportation 35% stationary	<ul> <li>Backup power</li> <li>Portable power</li> <li>Distributed generation</li> <li>Highway transportation</li> <li>Specialty vehicles</li> </ul>
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix.	25 - 75°C	10 – 100 kW	60%	<ul> <li>Military</li> <li>Space</li> <li>Supermarkets</li> <li>Hospitals</li> <li>Hotels</li> </ul>
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a matrix	150 - 200°C	400 kW 100 kW module	40%	• Distributed generation
Molten Carbonate (MCFC)	Solution of lithium, sodium, and/or potassium carbonates, soaked in a matrix	600 - 700°C	300 kW-3 MW 300 kW module	50%	<ul><li>Electric utility</li><li>Distributed generation</li></ul>
Solid Oxide (SOFC)	Yttria stabilized zirconia	700 - 1000°C	1 kW – 2 MW	60%	<ul> <li>Auxiliary power</li> <li>Electric utility</li> <li>Distributed generation</li> </ul>

#### **5. PEMFC Proton Exchange Membrane**

#### 5.1 Proton Exchange Membrane Fuel celles (PEMFCs):

The two scientists L. Niedrach and T. Grubb invented proton exchange membrane in 1960 in 116 General Electric Company. PEMFC is the most common used fuel cell type; it is used in 117 various fields due to its small size and its low temperature operation. PEMFC uses a polymer 118 as membrane (Nafion), which plays the role of mediator in the electrochemical cell, in a 119 solid state and thus it reduces the reaction temperature and increases the efficiency (speed of 120 interaction in the start-up and responding when loading). The polymer separation membrane 121 positioned between two electrodes of perforated platinum and it causes no risk of pollution 122 due to the solid nature. Interaction takes place under the temperature of 80°C and when the 123 membrane exposed to water, it becomes conductive material for ions(Yan, Fan et al. 2012). 124 The electrodes are made of platinum. The efficiency of such cells is up to 45-50% and their 125 power density is high compared with other types of cells where up to 350-600 mW/cm<sup>2</sup> and 126 the reactions are defined in Equation 2. 127

at Anode: 
$$2H_2 \rightarrow 2H^+ + 4e^-$$
 Eq. 2a 128

at Cathode : 
$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$$
 Eq. 2 b 129

at Cell: 
$$2H_2 + O_2 \rightarrow 2H_2O + electricity + heat Eq. 2c$$
 130

131

Another type of polymeric cells runs on methane gas directly, and it differs from the first 132 type in terms of the electrode's materials. These cells have a device for the preparation of 133 fuel, where it works on the saturation of methane with hydrogen. The problem in this type is 134 the crossing of methane from the membrane and there is currently a lot of research to address 135 this issue. 136

114

#### 6. Polarization phenomenon:

When the FC is loaded, the voltage goes down by 60% or 70% of the open circuit voltage 138 (because of the phenomenon of polarization as shown in figure.5). Both the output voltage 139 and current density determine the characteristic of V-I curve. The output voltage of PEMFC 140 is closely related with thermodynamically predicted in FCs and three major losses that are 141 Activation losses, Ohmic losses, and Concentration losses. Activation losses occur due to 142 electrochemical reaction. Ohmic losses occur due to ionic electronic condition. 143 Concentration losses are produced due to mass transport.(Chanpeng 2011, Zheng 2013). 144



Fig.5 The schematic diagram of the FC through the production cycle and three losses. 146

# 6.1.1Activation polarization η<sub>act</sub>:

When the cell is loaded, the voltage drops suddenly by ( $\eta_{act} > 50-100 \text{ mv}$ ) and then remains 148 constant; because of the energy needed to trigger the interaction between gases and oxygen 149 in particular. This drop is linked to the amount of catalysts and density of hydrogen and 150

147

oxygen on the surface of the catalyst. The polarization equation is given by the following 151 expression: 152

$$\eta_{act} = -0.9514 + T * 0.00312 + T * 7.4 * 10^{-5} [\ln(c * o_2) - 0.000187 * \ln(i) Eq.3$$
 153

$$C * O_2 = \frac{P_{O2}}{5.08 * 10^6 EXP\left(\frac{-498}{T}\right)} Eq.4$$
 154

Where i is the density of current and  $C^*O_2$  is the density of the hydrogen on the catalyst. 155

# 6.1.2 Ohmic polarization:

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The ohmic polarization ( $\eta ohm$ ) is positively proportional to the current. Since the cell's 157 resistance almost constant, the ohmic polarization changes linearly and this is because of the 158 emergence of resistance while crossing of ions in the electrolyte and ohmic resistance 159 electrodes (Dihrab, Sopian et al. 2009). The reduction of these resistances by using the 160 appropriate electrolyte and metals in the electrodes can be adopted to overcome this problem, 161 and the equation can be written as follows: 162

$$\eta ohm = iR^{internal} \quad Eq. 5 \tag{163}$$

Where i represent the current of the cell and  $R_{internal}$  is the internal resistance of the 164 cell, and is given in the data sheet of the cell or calculated from the following relationship: 165

$$R^{internal} = 0.01605 - 3.5 * 10^{-5} \cdot T + 8.0 * 10^{-5} * i \qquad \text{Eq. 6}$$

#### **6.2.3Concentration Polarization:**

This polarization occurs at high current densities due to lack of gases required for the 168 reaction at the electrodes and that causes drop in the cell's voltage, which is calculated from 169 the following relationship: 170

$$\eta_{con} = -\beta * \ln\left(1 - \frac{I}{I_{max}}\right) \quad Eq.7$$
171

$$\beta = 0.016$$
 172

$$I_{max} = 1.5A/Cm^2$$
173

Where  $\beta$  is the cell's constant and (I) is the current density of the cell,  $I_{max}$  is the maximum 175 current density and its value between 1 and 1.5 per centimetre square, and the equation of 176 the final voltage of the cell becomes: 177

178

$$V = E - \eta_{act} - \eta_{ohm} - \eta_{con} \text{ Eq.8}$$
 179

$$V = \left(1.23 - 0.9 * 10^{-3}(T - 298) + \frac{RT}{4F}(\ln(P^2H_2 * PO_2))\right)$$
180

$$-\left[-0.9514 + T * 0.00312 + T * 7.4 * 10^{-5} [\ln(C * O_2)] - 0.000187 * \ln(i)\right]$$
 181

+ 
$$(-i * (0.01605 * 10^{-5}) * -3.5 * T + 8.0 * 10^{-5} * i))$$
 182

$$-\left(-\beta * \ln\left(1 - \frac{I}{I_{max}}\right)\right) = \text{Eq. 9}$$
183

184

185

#### 6.3 Heat and Temperature Management:

When modelling or designing FCs stake, the heat management must be taken into account to ensure that the FC will work at the desired temperature. The management of heat is significantly related to FC's performance. The amount of waste heat in FC equivalent almost its electric power produced leads to reduce the efficiency around 50%.

#### **6.4 Output Power of the FC :**

The capacity of the FC can be obtained from the following equation where I is the current 191 density per centimetre squared in the pole of the cell. A is the electrode surface, and V is the 192 voltage of the cell and these values are given in the datasheet of the cell. 193

$$P = V * I * A$$
 Eq. 10 194

# 7. FC's Modelling:

To improve the system's performance, design optimisation and analysis of FC systems are 196 important. Modelling and simulation are needed as tools for design optimization of FCs, 197 stacks and FCs power systems. The performance of FC during operation depending on the 198 final equation 9, obtained by the integration of the equations 5 to 8. The advantage of the 199 final equation is that it is less influenced by the determinants of mechanical and physical 200 components of the cell and this equation relies on constants, temperature, operating, and 201 pressure of the gases involved and the current density and voltage FC. The final equation has 202 been represented in the environment MatLab to show the electrical performance of the cell 203 and the impact of gases' pressure and temperature on the cell. 204

# 7.1 Voltage / Power Relationship Curve:

Figure 6 shows the relationship between the output voltage of the cell, power density with 206 current density under the operation conditions given in the cell's data sheet such as 207 temperature and pressure (346 K & 3 bar), and the results are similar to the curves in the 208 scientific literature for FCs .This curve is the true measure of the performance of the cell and 209 the conclusion of voltage and current work and the maximum power that can be produced 210

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without damaging the cell during the investigation of the effect of pressure and temperature, 211 which will be addressed in the subsequent paragraphs in detail. 212



Fig.6 Relationship between voltage, power density and current density

7.2 Power Density Curve:

Figure 7 shows the power density against the current density. When the power density 217 increased, the current density rises and then the power density it go down because of the 218 increasing polarization affecting the cell's voltage. Usually the highest point of the curve is 219 not the point of the operation for the cell (i.e., the cell cannot operate at the maximum power 220 because of that cell outcome becomes low). At this point, the water increase and the 221 temperature rises; making it difficult for the driving/ controlling the cell and shorten its 222 useful life.

216

215

213



Fig.7 Relationship between power and current density

# 7.3 The Effect of Pressure and Temperature on the Polarization Curve and Power 226 Density: 227

Figure 8 shows the polarization curve of the FC for two cases of operation: 228

The first case of works under the conditions of the cell such as temperature and pressure 229 (353 K &3 bar). The second case of operation is within the statutory requirement (323K 230 &1.5 bar), which shows the decline in output cell. polymeric FCs typically operate at a 231 temperature of  $70-90^{\circ}$  C and atmospheric pressure (1.5-3.5 bar) as the cell then gives its 232 highest outcome. Therefore, Figure 6 shows at low temperature and pressure, the voltage 233 declines 0.1 V, and it causes the decline in the outcome by 10 % of its nominal output. 234



238

# Fig. 8 Relationship between current and power density with voltage under different 236 operation conditions 237

# 7.4 Polarization Curve of the Cell

Figure 9 shows the voltage of the open circuit cell E and stages of falling the voltage in the 239 FC during operation. Owing to decline resulting from the polarization of the three (activation 240  $\eta_{act}$  and Ohmic  $\eta_{ohm}$  and focus  $\eta_{con}$ ), as the Figure 1 shows that the cell's voltage at start-up 241 lands in sudden, and due to the activation of  $\eta_{act}$  and then decline until at least this is almost 242 disappears. The second decline in the voltage is caused by the internal resistance of the cell 243  $\eta_{ohm}$  because of the of resistance of the ions while crossing in the electrolyte and resistance 244 ohmic electrodes and rise linearly with increasing load current. Third decline in voltage  $\eta_{con}$  245 happens at the high current densities and because of the non-arrival of reaction gases to the 246 electrodes sufficiently, as shown in the Figure, the activation losses and the ohmic decline at 247 low current density is the dominant and most obvious (Al-Dabbagh 2010, Dokkar 2011). 248 Note: In Figure 7, letter E is used instead of  $\eta$  to indicate polarization. 249



Fig.9 Losses in FC (activation losses, Ohmic losses and concentration losses)

#### 7.5 Impact of Pressure on FC Voltage:

Figure 10 shows the improvement of the performance of the polymeric FC when the pressure 253 increases. However, this increase must be within the allowable pressure in the datasheet of 254 the cell because the increased pressure on the nominal value of 3 bar will improves 255 performance slightly, where the values of the cell converge when voltage increased pressure 256

250

251

more, and this is illustrated by the convergence of the lines in Figure 8, but this increase 257 leads to higher temperatures and values of the three polarizations where its negative impact 258 will be more positive and this causes the decline in outcome and increase the cost of 259 production. 260



Fig. 10 Influence of gases pressure on performance of FC

261

262

263

264

### 7.6 The Impact of temperature on FC voltage:

Figure 11 shows that the increase in the temperature improves the performance of the cell, 265 causing a decline of the voltage which leads to the reduction of voltage dropping factors and 266 in particular the decline in the activation and increase the overall outcome of the cell, but 267 under the conditions of operation, in order to prevent the loss of moisture needed for the cell 268 membrane. Usually the temperature of the polymeric FC do not exceed 95°C. 269



Fig. 11 Influence of temperature on performance of FC

271 272

273

# 7.7 Operating Voltage for FC

Figure 12 shows the curve of power density vs FC voltage. it is possible to obtain higher 274 power at voltage of 0.6-0.8 V and this voltage is the operation voltage of a FC, and as noted 275 earlier, it is important to find a balance between maximum power produced by the cell and 276 the determinants such as operating pressure and heat allowed for the cell in order to not to 277 adversely affect the cell's life and performance over time. 278



Fig. 12 Relationship between power density and voltage

# 8. Experiment apparatus:

In order to determine to voltage current characteristic of PEM and to validated the modeling results, several experiments have been made in MMU labs using PEMFC system. Table 2 listed the values that have been collected form 500 mw FC unit for various load (resistance) 284 values setup. Figure .13 and figure 14 show the polarization curve and output power vs 285 current density respectively for real data gathered from experiments. 286

Load(Ω)	Voltage(V)	Current	Power
		(A)	(mw)
0	0.24	1.61	386.4
0.1	0.32	1.43	457.6
0.33	0.47	1.05	493.5
1	0.62	0.56	347.2
3.3	0.76	0.22	167.2
10	0.84	0.08	67.2
33	0.90	0.03	27
100	0.94	0.01	9.4
330	0.97	0.01	9.7
00	1.1	0	0

 Table 2 data collected form 500 mW PEMFC unite



Fig. 13 polarization curve obtained from real data



Fig. 14 output power vs current density



Fig. 15 V-I curve for simulation and experiment results

### 9. Conclusions:

This paper presented a realistic PEMFC dynamic model to allow better understanding the 301 operating parameters effects. The impact of gases' heat and pressure interaction and the 302 current density on the output voltage the cell and power density, have been analysis to 303 determine the overall performance of the PEMFC. Mathematical and simulation model has 304 been developed in order to study the behaviour of the PEMFC under various operations. 305 Where it is possible to exploit this model to analyse in detail the impact of the changes 306 on cell behaviour, such as temperature, pressure and load change. We have also modelled 307 these equations using the MatLab environment and got curves to describe the impact of 308 each case, these curves enables us to more understanding the FCs and avoiding the factors 309

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that reduce the performance and reliability of the cell. A set of lab experiments have been 310 conducted to validate the model results. 311

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