Faculty of Electrical Engineering

PROTON EXCHANGE MEMBRANE FUEL CELL MODEL VALIDATION USING EQUIVALENT ELECTRICAL CIRCUIT

Ayu Nurfatika binti Abdul Mubin

Master of Science in Electrical Engineering

2018

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AYU NURFATIKA BINTI ABDUL MUBIN

A thesis submitted
in fulfillment of the requirements for the degree of Master of Science
in Electrical Engineering

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2018

DECLARATION

I declare that this thesis entitled "Proton Exchange Membrane Fuel Cell Model Validation Using Equivalent Electrical Circuit" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ....

Name : AYU NURFATIKA BINTI ABDUL MUBIN ....

Date : ....

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Electrical Engineering.

Signature	:………………………………………..
Supervisor Name	: DR. MAASPALIZA BINTI AZRI
Date	:………………………………………..

DEDICATION

To my beloved family

ABSTRACT

Fuel cell is one of the most preferable renewable energy power sources nowadays due to its simplicity, capability, high efficiency, quick start-up, is environmentally friendly and has no geographical limitations. PEMFC is effective in the transformation of input energy into electrical energy and has been seen as being a great potential power source for the future. Because of its potential, there have been many experiments and empirical studies which have been carried out in both the academic and industrial fields. The focus of most research has been on the steady-state analysis of PEMFC. It is important to consider PEMFC reactions within this research as well. The processes of the PEMFC were implemented by modelling mathematical and electrical models using Matlab/Simulink simulation software. Both of the models were developed as two types of models which were steady-state and dynamic model to provide a comparison of the consideration of charge-double layer capacitance (CDL) and thermodynamic effect. Apart from that, to develop a more accurate model, both of the models were modelled by following the real-stack specification of the 500-W PEMFC system which was manufactured by Horizon Pte. Ltd. Both models showed a different output response and the parameter of the losses was dependent on the duration of the simulation, temperature and the hydrogen pressure. The output of both models which differed in the stack output voltage, rated power, efficiency and time response of the model, were discussed. The parameters used were verified by testing the model with different values of reference temperature and the input hydrogen pressure. From that, the PEMFC emulator was also designed and built to verify the use of the parameter values in the modelling. The output obtained was analysed and discussed. The model produced an output with an efficiency higher than 30% compared with the H-500 PEMFC specification efficiency of 40% which makes the model eligible for further development purposes. The parameters of reference temperature and input hydrogen pressure were suitable for the model and were verified.

ABSTRAK

Sel bahan api adalah salah satu tenaga yang paling baik berbanding dengan sumber-sumber yang boleh diperbaharui lain yang wujud pada masa kini disebabkan oleh kesederhanaannya, keupayaannya, kecekapan yang tinggi, permulaan yang cepat, mesra alam dan tiada batasan geografi. PEMFC adalah efektif dalam mentransformasi sumber kuasa masukan kepada tenaga elektrik dan dilihat mempunyai potensi yang baik dalam sumber tenaga pada masa akan datang. Atas sebab potensinya, telah banyak eksperimen dan pembelajaran empirikal dilakukan di dalam bidang akademik dan industri. Proses PEMFC telah dilaksanakan dengan memodelkan model matematik dan elektrik menggunakan perisian simulasi Matlab/Simulink. Kedua-dua model dimodelkan dengan dua kategori model iaitu model keadaan mantap dan juga model berkeadan dinamik untuk mempelajari perbezaan dalam melibatkan efek caj lapisan kapasitor berganda (CDL) dan juga kesan termodinamik. Disamping itu, bagi membangunkan model yang lebih tepat, kedua-dua model ini dimodelkan mengikuti spesifikasi sebenar bagi sistem 500-W PEMFC yang dihasilkan oleh Horizon Pte. Ltd.. Kedua-dua model menunjukkan tindak balas pengeluaran yang berbeza dan parameter kerugian bergantung pada tempoh masa simulasi, suhu dan tekanan hidrogen adalah diperhatikan. Keluaran kedua-dua model akan berbeza dalam voltan keluaran stak, kuasa undian, kecekapan dan tindak balas masa model adalah dibincangkan dalam penyelidikan ini. Justeru itu, parameter yang digunakan disahkan dengan menguji model dengan nilai suhu rujukan yang berbeza dan tekanan kemasukan hidrogen. Dari situ, emulator PEMFC direka dan dicipta untuk mengesahkan penggunaan parameter dalam permodelan ini. Keluaran yang diperolehi dianalisis dan dibincangkan. Model ini menghasilkan pengeluaran dengan kecekapan lebih tinggi daripada 30% jika dibandingkan dengan spesifikasi kecekapan H-500 PEMFC iaitu 40% dimana ia membuatkan model ini layak untuk digunakan bagi tujuan pembangunan selanjutnya. Parameter rujukan suhu dan tekanan hidrogen adalah sesuai untuk model dan ianya telah disahkan.

ACKNOWLEDGEMENTS

The completion of this undertaking could not have been possible without the participation and assistance of so many people. Their contributions are sincerely appreciated and gratefully acknowledged. I would like to express my deep appreciation and gratitude particularly to the following:

Dr. Maaspaliza bini Azri, my supervisor from the Faculty of Electrical Engineering Universiti Teknikal Malaysia Melaka (UTeM) for her attentive supervision, kind support and continuous encouragement towards the completion of this thesis.

Prof. Dr. Zulkifilie bin Ibrahim, my co-supervisor also from the Faculty of Electrical Engineering UTeM for his advice and suggestions.

Special thanks to UTeM grant funding, titled Power Control Technology for Fuel Cell Vehicles, for the financial support throughout this project, LRGS/2014/FKE/TK01/02/R0000.

Special thanks to my beloved family members and all colleagues for their moral support in completing this degree. Lastly, thank you to all who had in one way or another shared support, either morally, financially or physically and were associated with the crucial parts of realization of this project.

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A	-	Active area of cell
a	-	Anode
AFC	-	Alkaline Fuel Cell
B	-	Semi-empirical constant
C	-	Capacitor
c	-	Cathode
C_{H_2O}	-	Concentration of water
C_{O_2}	-	Concentration of oxygen
C_t	-	Total thermal capacitance for all the volume or mass of fuel cell
$C_t \frac{dT}{dt}$	-	Rate of change for the capacitance value
CDL	-	Charge double layer capacitance
DC	-	Direct-current
DMFC	-	Direct Methanol Fuel Cell
E	-	Thermodynamic voltage
F	-	Faraday's constant
G	-	Gibbs free energy
H	-	Total heat transfer coefficient for all the surface of fuel cell
H_2	-	Hydrogen gas
H_2O	-	Water

HHV	-	Higher heating value
i	-	Current
i_{lim}	-	Current limit
IPCC	-	Intergovernmental Panel on Climate Change
j	-	Charge flux
K	-	Intrinsic rate constant
$K_a°$	-	Anode intrinsic rate constant
$K_c°$	-	Cathode intrinsic rate constant
l	-	Length
LHV	-	Lower heating value
m	-	Gradient
MCFC	-	Molten Carbonate Fuel Cell
n	-	Number of mole
O_2	-	Oxygen gas
OCV	-	Open circuit voltage
P	-	Pressure
PAFC	-	Phosphoric Acid Fuel Cell
PEMFC	-	Proton Exchange Membrane Fuel Cell
PID	-	Proportional-Integral-Derivative
PWM	-	Pulse Width Modulation
Q	-	Electrical work done by a moving charge
R	-	Ideal gas constant
R_{act}	-	Activation resistance
R_{conc}	-	Concentration resistance

R_{ohmic}	-	Ohmic resistance
S	-	Entropy
SOFC	-	Solid Oxide Fuel Cell
T	-	Temperature
T_f	-	Reference temperature
U	-	Internal energy
V	-	Volume
V_{act}	-	Activation voltage
V_{act0}	-	Initial activation voltage
V_{cell}	-	Cell voltage
V_{conc}	-	Concentration voltage
V_{ohmic}	-	Ohmic voltage
W	-	Work
x_1	-	Initial output voltage
x_2	-	Peak output voltage
y_1	-	Initial desired current
y_2	-	Peak desired current
ξ	-	Semi-empirical coefficient
σ	-	Conductivity of material
$\Delta G°$	-	Standard-state of Gibbs free energy of activation for chemisorption
ΔH	-	Change in enthalpy of formation
η_e	-	Efficiency of fuel cell
$\eta_{e,max}$	-	Maximum efficiency for fuel cell
μ_f	-	Utilization coefficient

LIST OF PUBLICATIONS

Journal Paper

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CHAPTER 1

INTRODUCTION

1.1 Background of Research

One of the prevailing global issues nowadays is the escalating increase in energy demand and power consumption in tandem with the growth of the world population. However, most power generators are operated based on the combustion of fossil fuels, which release carbon dioxide, carbon monoxide, sulphur dioxide, nitrogen oxide and particulate matter, resulting in a host of environmental problems such as air pollution, acid rain, and the greenhouse effect. Fossil fuels such as coal and petroleum are non-renewable sources of energy. Therefore, there is growing concern about the depletion of fossil fuels over the years, which will eventually reach a stage where the availability of fossil fuels will be unable to fulfil the ever-increasing global energy demand. In addition, there is increasing awareness of the environmental impact resulting from the combustion of fossil fuels, and this is one of the primary concerns of environmental protection agencies throughout the world. This has even been highlighted in an article by the Union of Concerned Scientists, titled "The Hidden Costs of Fossil Fuels" (Union of Concerned Scientists, 2016).

For these reasons, there is a critical need to explore alternative sources of energy which are renewable and sustainable, with minimum impact on the environment. This is the one of the key areas explored by the scientific community for many years with promising results, indicating that alternative sources of energy such as biomass, geothermal sources, solar radiation, wind, and water (*i.e.* ocean waves and tides, as well as water stored in large reservoirs such as dams) have great potential to substitute fossil fuels. All of the aforementioned sources of energy are dependent on geographical location, and therefore, systems which are based on these renewable energy sources are impractical for use in the transportation sector, where portability is of utmost importance. In addition, renewable energy sources such as solar radiation and wind will vary depending on climate conditions (which are unpredictable in nature) and this will cause disruption to the performance of solar and wind energy-based systems.

In this regard, hydrogen fuel cells are a more feasible alternative particularly in the transportation sector because these systems are more efficient in converting chemical energy into electrical energy, compared with internal combustion engines. In addition, these systems are portable and independent of climate conditions (Erdinc and Uzunoglu, 2012). More importantly, hydrogen fuel cells are environmentally friendly since these systems do not release harmful pollutants into the environment. Hydrogen fuel cells have been studied extensively over the years in order to enhance power output, reduce costs, and extend the service life of these systems to suit a wide variety of applications.

Nowadays, there is growing interest in proton exchange membrane fuel cells (PEMFCs), which is a special type of hydrogen fuel cell, because of their high power density (3.8–6.5 kW/m^3) and these systems can be operated at low temperatures (50 °C – 100 °C) (Balasubramanian et al., 1999; Shah, 2007; Kunusch et al., 2012). In addition, PEMFCs are operated based on electrochemical reaction between hydrogen (H_2) and oxygen (O_2), which are both renewable and sustainable sources. It is anticipated that