Faculty of Electrical Engineering

PROTON EXCHANGE MEMBRANE FUEL CELL (PEMFC) PARAMETERS ESTIMATION USING TIME-FREQUENCY ANALYSIS TECHNIQUE

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DECLARATION

I declare that this thesis entitle “Proton Exchange Membrane Fuel Cell (PEMFC) Parameters Estimation Using Time-Frequency Analysis Technique” 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 : .....

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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 award of Master of Science in Electrical Engineering.

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Date	:.....

DEDICATION

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ABSTRACT

Proton Exchange Membrane Fuel cell (PEMFC) is a device that converts chemical energy into electrical energy. The performance characteristics of the PEMFC are affected by many factors either from PEMFC design specification or from the operating conditions. Improper handling the operating condition of the PEMFC will cause failure and damage to the entire system. Thus, the system needs the accurate information about the performance characteristics of PEMFC at various operating conditions with changing load demand to prevent the PEMFC from damage. In this research, periodogram and spectrogram techniques are proposed in order to determine the hydrogen (H_2) inlet pressures and stack temperature performance characteristics of PEMFC. Firstly, the signal voltages of various PEMFC operating conditions are captured by using oscilloscope. The raw signals from oscilloscope are then transformed into periodogram and time-frequency distribution (TFD) which is spectrogram. The signal parameter that desired to be extracted from spectrogram are instantaneous voltage of direct current (V_{DC}), voltage of root mean square (V_{RMS}), and voltage of alternating current (V_{AC}) parameters. From the parameter estimation curves and the three-dimensional maps of H_2 inlet pressures result, the highest values of instantaneous V_{RMS} and V_{DC} are obtained at a pressure of 0.5 bars, whereby the lowest values are obtained at a pressure of 0.1 bars. These parameters are highest in open voltage conditions but decrease gradually with increasing load demand up to 35 A. The highest values of parameter estimation curves and the three-dimensional maps of stack temperatures are obtained at 40 °C whereas the lowest values are obtained at 20 °C. These parameters are highest at open voltage conditions but decrease gradually with an increase in the load demand up to 18 A. The absolute percentage error (APE) and mean absolute percentage error (MAPE) are used to justify the performance analysis of the spectrogram parameters. The highest APE is attained at a load demand of 15 A, with a value of 0.76% whereas the highest MAPE is obtained for a stack temperature of 25 °C with a value of 0.334%. Based on the results, the estimation of the V_{DC} parameter from TFD technique for both H_2 inlet pressure test and stack temperature test are acceptable since the APE and MAPE values are less than 1%. The outcome of this research verifies that the TFD technique clearly gives the information of the performance characteristics of PEMFC at various operating conditions with changing load demand.

ABSTRAK

Membrane Penukar Proton Sel Fuel (PEMFC) adalah satu alatan yang mengubah tenaga kimia kepada tenaga elektrik. Ciri-ciri prestasi PEMFC dipengaruhi oleh pebagai faktor samaada daripada spesifikasi reka bentuk PEMFC atau daripada kondisi operasi. Pengendalian yang tidak betul daripada PEMFC akan menyebabkan kegagalan dan kerosakkan kepada sistem PEMFC. Oleh itu, sistem PEMFC memerlukan maklumat yang tepat mengenai parameter PEMFC di pelbagai kondisi operasi serta pelbagai perubahan permintaan beban untuk menggelakkan PEMFC daripada kerosakkan. Di dalam kajian ini, teknik periodogram dan spectrogram adalah di cadangkan untuk mengenal pasti cirri prestasi tekanan hydrogen (H_2) dan suhu stak oleh PEMFC. Pertama sekali, isyarat voltan pada pelbagai keadaan PEMFC diambil dengan menggunakan osiloskop. Isyarat asas daripada osiloskop kemudiannya di ubah menjadi periodogram dan taburan masa-frekuansi (TFD) iaitu spectrogram. Parameter isyarat yang dikehendaki untuk diekstrak daripada spectrogram adalah parameter voltan arus terus (V_{DC}), voltan punca min persegi (V_{RMS}), dan voltan arus ulang-alik (V_{AC}). Daripada lengkungan parameter anggaran dan peta tiga-dimensi oleh keputusan tekanan H_2, nilai yang tertinggi oleh V_{RMS} dan V_{DC} didapati pada tekanan 0.5 bar, sementara nilai terrendah adalah pada tekanan 0.1 bar. Parameter ini adalah tertinggi pada keadaan voltan bukaan tetapi semakin menurun apabila peningkatan beban meningkat kepada 35 A. Nilai tertinggi lengkungan parameter anggaran dan peta tiga-dimensi oleh keputusan suhu stak didapati pada suhu 40 °C sementara nilai terrendah adalah pada suhu 20 °C. Parameter ini adalah tertinggi pada keadaan voltan bukaan tetapi semakin menurun apabila peningkatan beban meningkat kepada 18 A. Peratusan kesalahan mutlak (APE) dan min peratusan kesalahan mutlak (MAPE) digunakan untuk mengesahkan keputusan analisis prestasi parameter spectrogram. Hasil kajian mendapati APE tertinggi dicapai pada permintaan beban 15 A, dengan nilai sebanyak 0.76% manakala MAPE tertinggi diperolehi untuk suhu stak 25 °C dengan nilai sebanyak 0.334%. Berdasarkan keputusan, nilai APE dan MAPE untuk ujian kemasukkan tekanan H_2 dan suhu stak adalah diterima, kerana nilainya adalah kurang daripada 1%. Hasil dapatan kajian mengesahkan bahawa anggaran parameter daripada teknik TFD memberikan makumat yang paling tepat berkenaan parameter PEMFC pada pelbagai kondisi operasi dan pada setiap perubahan bebanan.

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LIST OF ABBREVIATIONS

A	-	Amp
AC	-	Alternating Current
ADSP		Advanced Digital Signal Processing
AERC	-	Alternative Energy Research Centre
AFC	-	Alkaline Fuel Cells
APE	-	Absolute Percentage Error
CI	-	Current Interruption
DC	-	Direct Current
DMFC	-	Direct Methanol Fuel Cells
EIS	-	Electrochemical Impedance Spectroscopic
FCV	-	Fuel Cell Vehicles
FFT	-	Fast Fourier Transform
FRA	-	Frequency Response Analyser
GDL	-	Gas Diffusion Layer
HFR	-	High Frequency Resistance
HV	-	High Voltage
Hz	-	Frequency unit, Hertz
IEEE	-	Institute of Electrical and Electronics Engineers
MAPE	-	Mean Absolute Percentage Error

MCFC	-	Molten Carbonate Fuel Cells
MEA	-	Membrane Electrode Assembly
MOHE	-	Ministry of Higher Education
PAFC	-	Phosphoric Acid Fuel Cells
PEMFC	-	Proton Exchange Membrane Fuel cell
RMS	-	Root Mean Square
SOFC	-	Solid Oxide Fuel Cells
TFD	-	Time-Frequency Distribution
TFR	-	Time-Frequency Representation
UTeM	-	Universiti Teknikal Malaysia Melaka
W	-	Watt
A	-	Amp

LIST OF SYMBOLS

H_2	-	Hydrogen Gas
O_2	-	Oxygen Gas
V_{DC}	-	Direct Current
V_{RMS}	-	Root Mean Square
V_{AC}	-	Alternating Current
H^+	-	Hydrogen Ions
e^-	-	Electrons
H_2O	-	Water
E_{nernst}(V)	-	Nernst Voltage
T_{nernst} (K),	-	Temperature of Stack
P_{O_2}(Pa)	-	Oxygen Pressure of the Cell
T	-	Temperature
I	-	Current
C_{O_2}	-	Oxygen Concentration
V_{act}	-	Activation Polarization Losses
V_{ohmic}	-	Ohmic Polarization Losses
I_{stack}	-	Stack Current
R_m	-	Membrane Resistance
R_c	-	Proton Transfer Resistance
V_{conc}	-	Concentration Polarization Losses
I_{lim}	-	Limit or Maximum Current Density
Hz	-	Hertz
ms	-	Millisecond
$S_v(f)$	-	Periodogram

F_s		Sampling Frequency
F_{res}	-	Frequency Resolution
T_s	-	Time Sampling
T_{res}	-	Time Resolution
$E_{xx}(k)$	-	Energy Voltage
$X(k)$	-	Analysis Function
$S_x(t,f)$	-	Spectrogram
$x(\tau)$	-	Input Signal
$w(\tau - t)$	-	Observation Window
A	-	Amplitude of Actual Voltage
f_{max}	-	Maximum Frequency
f_1	-	Fundamental Frequency
Δf	-	Bandwidth
$\%e_r$	-	Percentage Error
A_t	-	Actual Value
F_t	-	Measured Value
n	-	Number of Data
ΔV	-	Voltage Drop

LIST OF PUBLICATION

A. Journal

1) Mohd Shahril Bin Ahmad Khiar, Muhammad Zuhaili Bin Razali, Sharin Bin Ab Ghani, and Imran Bin Sutan Chairul,. 2015 Automated Calculation of Thermodynamic Potential Applied for Proton Exchange Membrane (PEM) Fuel Cell *Applied Mechanics and Materials* Vols. 754-755 (2015) pp 649-653

2) Muhammad Zuhaili Bin Razali, Mohd Shahril Ahmad Khiar Irnie Azlin Zakaria, Wan Ahmad Najmi Wan Mohamed,. 2014 Effect of Temperature towards Electrical Conductivities of Low Concentration of AL_2O_3 Nanofluid in Electrically Active Cooling System *2014 IEEE International Conference on Control System, Computing and Engineering*

3) Muhammad Zuhaili Bin Razali, Abdul Rahim Bin Abdullah, Wan Ahmad Najmi Wan Mohamed, Mohd Shahril Ahmad Khiar,. 2015 Effect of Hydrogen Inlet Pressure Analysis on open Voltage of Proton Exchange Membrane (PEM) Fuel cell by using Periodogram *Australian Journal of Basic and Applied Sciences,* 9 (12) Special 2015, Pages: 86-92

4) Muhammad Zuhaili Bin Razali, Abdul Rahim Bin Abdullah, Wan Ahmad Najmi Wan Mohamed and Mohd Shahril Ahmad Khiar,. 2016 Hydrogen Inlet Pressures Parameter Analysisof Proton Exchange Membrane Fuel Cell (PEMFC) Using Spectrogram *ARPN Journal of Engineering and Applied Sciences* vol. 11, no. 6, pp 3875-3882

5) Muhammad Zuhaili Bin Razali, Abdul Rahim Bin Abdullah, Wan Ahmad Najmi Wan Mohamed, Mohd Shahril Ahmad Khiar, Muhammad Sufyan Safwan, 2016 Stack Temperature Parameter Analysis of Proton Exchange Membrane Fuel Cell (PEMFC) Using Spectrogram *Journal of Scientific Research and Development,* 3 (5) Pages: 63-68

CHAPTER 1

INTRODUCTION

1.1 Introduction

Present developments of green technology give a big impact to the world as its performance efficiency could compete with the existing fossil fuel sources. Therefore, Proton Exchange Membrane Fuel cell (PEMFC) green energy is introduced to overcome pollutions, greenhouse effect along with other global problems. This is due to the PEMFC generates electricity through the electrochemical reaction of hydrogen gas (H_2) from anode inlet and oxygen gas (O_2) from cathode inlet without any internal combustion process take place (Wan et al., 2014) (Ortiz-Rivera et al., 2007). PEMFC provides higher energy density, lower life cycle cost and a longer lasting system compared to a battery system (Dudek et al., 2013) (Ryan et al., 2006).

Currently, the researches on PEMFC are spread across various engineering disciplines such as chemical, electrical, mechanical, biotech and many others. Rapid development has been seen in PEMFC technology due to the advances research and development made in these areas that allows the technology to be ready for commercialization.

The performance characteristics of the PEMFC are mainly influenced by design specification and operating conditions of PEMFC. The cell flooding, cell drying, membrane humidity, stack temperature, reactant pressures, internal resistances and

assembly quality, concentration losses, activation losses, ohmic losses and mass transport losses of PEMFC are some factors which cause the damage of PEMFC stack. These factors will make the performance characteristics of PEMFC in uncertain condition.

Research on performance analysis of PEMFC by using signal processing technique is not been widely establish. Signal processing technique cost is much cheaper rather than present technique such as electrochemical impedance spectroscopic (EIS) and current interruption (CI) technique. Apart from that, signal processing techniques are able to analysing in micro monitoring of the PEMFC. Magnitude, frequency and time are very important information in signal processing.

1.2 Problem Statement

Output terminal voltages from a PEMFC stack were found to be unstable (Strahl et al. 2014) (Chen & Zhou 2008). Stable and efficient operation of PEMFC will be reached when the reaction electrochemistry reaches steady-state with respect to change in time and operating conditions (Rabbani & Rokni 2013) (Argyropoulos et al., 2000). Further load demand changes leads to periodic voltage instability as a new stated is require to be analyse (Kunusch et al., 2012). PEMFC requires substantial time for about 2 to 60 minute by fixed current load to warm-up before it achieve the stable voltage condition (Tzamalis et al., 2011) (Han et al. 2014) (Ryan et al., 2006). However, this unstable voltage occurs for every load variation (Zhang et al., 2012).

The electrically unstable response may damage the entire system and even put the operators life at risk and decreased its life time (Tang et al. 2010) (Onwubolu 2005). Therefore, the further analysis on effect of load variation towards the voltage characteristics is required.