Faculty of Engineering

PREDICTIVE MAXIMUM POWER POINT TRACKING (MPPT) ALGORITHM FOR PERMANENT EXCHANGE MEMBRANE FUEL CELL (PEMFC)

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Bachelor of Engineering

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UNIVERSITI MALAYSIA SARAWAK

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Final Year Project Report √

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PREDICTIVE MAXIMUM POWER POINT TRACKING (MPPT) ALGORITHM FOR PERMANENT EXCHANGE MEMBRANE FUEL CELL (PEMFC)

MOHD RIZZWAN BIN MINGGU

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ABSTRACT

Renewable energy is increasingly being used as a backup energy source by a wide range of sectors due to concerns about negative impacts of continuous consumption of fossil fuel. Fuel cell power generation technology is gaining importance in its own right in the current global landscape of electricity generation, distribution, and satisfying consumer demand since it has numerous advantages such as environmentally friendly, high efficiency, noise-free, and safe operation. In this project, a PEMFC has been chosen due to its striking features that is suitable for stationary applications like residential and transportation uses. Generally, the output characteristics of fuel cells are non-linear and influenced by parameters such as the cell temperature, oxygen partial pressure, hydrogen partial pressure, and membrane water content. In each particular condition, there is only one unique operating point for a fuel cell system with the maximum output. Therefore, it is important to find the optimal operating voltage or current of fuel cell systems in order to increase the efficiency of fuel cells. This maximum output can be determined by using MPPT method such as P&O, INC, FLC, PSO, MPC and more. The milestone of this project is to develop a fully functional PEMFC system based on the mathematical modelling presented in the literature with predictive MPPT control. This algorithm is said to be able to enhance the performance of the PEMFC system due to high in stability and low in complexity. This project introduces a PEMFC system with model predictive control (MPC). In this project, a DC-DC boost converter is used to regulate the output voltage of the fuel cell in order to extract the maximum output power where the switch of this boost converter is controlled by the MPC. The focus of this project is to show the power characteristics extracted from the PEMFC system by using predictive control. A comparison of PEMFC performances based on the proposed technique with other existing MPPT algorithms will be done to validate the algorithm performance. As a result, model predictive control (MPC) exhibits the fast tracking of MPP locus, outstanding accuracy, and robustness with respect to environmental changes.

ABSTRAK

Tenaga boleh diperbaharui semakin digunakan sebagai sumber tenaga alternatif oleh pelbagai sektor kerana kebimbangan mengenai impak negatif akibat penggunaan bahan api fosil yang berterusan. Kini teknologi penjanaan kuasa sel bahan api menjadi semakin penting dalam landskap global semasa penjanaan, pengedaran, dan memuaskan permintaan pengguna kerana ia mempunyai banyak kelebihan seperti mesra alam, kecekapan tinggi, bebas bunyi dan operasi yang selamat. Dalam projek ini, PEMFC telah dipilih kerana ciri menariknya yang sesuai untuk aplikasi pegun seperti kegunaan kediaman dan pengangkutan. Secara amnya, ciri keluaran sel bahan api adalah tidak linear dan dipengaruhi oleh parameter seperti suhu sel, tekanan separa oksigen, tekanan separa hidrogen dan kandungan air membran. Dalam setiap keadaan tertentu, hanya terdapat satu titik operasi unik untuk sistem sel bahan api dengan keluaran yang maksimum. Oleh itu, adalah penting untuk mencari voltan atau arus operasi optimum bagi sistem sel bahan api untuk meningkatkan kecekapan sel bahan api. Keluaran maksimum ini boleh ditentukan dengan menggunakan kaedah MPPT seperti P&O, INC, FLC, PSO, MPC dan banyak lagi. Pencapaian projek ini adalah untuk membangunkan sistem PEMFC berfungsi sepenuhnya berdasarkan pemodelan matematik yang dibentangkan dalam literatur dengan kawalan MPPT secara ramalan. Algoritma ini dikatakan mampu untuk meningkatkan prestasi sistem PEMFC kerana kestabilan yang tinggi dan ciri kompleksiti yang rendah. Projek ini memperkenalkan sistem PEMFC dengan model ramalan kawalan (MPC). Dalam projek ini, penukar DC-DC lif digunakan untuk mengawal voltan keluaran sel bahan api untuk mengekstrak keluaran kuasa maksimum di mana suis penukar lif ini dikawal oleh MPC. Fokus projek ini adalah untuk menunjukkan ciri kuasa yang diekstrak daripada sistem PEMFC dengan menggunakan kawalan ramalan. Perbandingan prestasi PEMFC berdasarkan teknik yang dicadangkan dengan algoritma MPPT sedia ada yang lain akan dilakukan untuk mengesahkan prestasi algoritma. Hasilnya, model ramalan kawalan (MPC) menghasilkan penjejakan lokus MPP yang pantas, ketepatan yang cemerlang dan keteguhan pada perubahan persekitaran.

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LIST OF SYMBOLS

ΔI_{FC}	–	Change/ripple in fuel cell current
ΔP_{FC}	–	Change/ripple in fuel cell power
ΔV_{FC}	–	Change/ripple in fuel cell voltage
E_{Nernst}	–	Thermodynamic potential
I_{FC}	–	Fuel cell current
P_{H_2}	–	Partial pressure of hydrogen
P_{O_2}	–	Partial pressure of hydrogen
P_{FC}	–	Fuel cell power
T_{ref}	–	Standard temperature
T_s	–	Sampling time
V_{FC}	–	Fuel cell voltage
V_{act}	–	Activation voltage
V_{cell}	–	Cell voltage
V_{con}	–	Concentration voltage
V_{ohm}	–	Ohmic voltage
k_{H_2}	–	Hydrogen valve molar constant
k_{O_2}	–	The oxygen valve molar constant
k_r	–	Modeling constant
q_{H_2}	–	Molar flow of hydrogen
q_{O_2}	–	Molar flow of oxygen
r_m	–	Membrane specific resistivity
t_m	–	Membrane thickness
v_L	–	Voltage across inductor
ξ_{1-4}	–	Parametric coefficients
τ_{H_2}	–	Hydrogen time constant
τ_{O_2}	–	Oxygen time constant
Δi_L	–	Change in inductor current
ΔG	–	Specific entropy
$\Delta G°$	–	Gibbs free energy

A	–	Cell active area
C	–	Step of perturbation
D	–	Duty cycle
F	–	Faraday's constant
R	–	Universal gas constant
T	–	Operational temperature
k	–	Number of discrete sampling steps
n	–	Number of electrons
t	–	Time

LIST OF ABBREVIATIONS

AFC	–	Alkaline Fuel Cell
DC	–	Direct Current
FLC	–	Fuzzy Logic Controller
IGBT	–	Insulated Gate Bipolar Transistor
INC	–	Incremental Conductance
MATLAB	–	Matrix Laboratory
MCFC	–	Molten Carbonate Fuel Cell
MPC	–	Model Predictive Control
MPP	–	Maximum Power Point
MPPT	–	Maximum Power Point Tracking
P&O	–	Perturb and Observe
PAFC	–	Phosphoric Acid Fuel Cell
PEMFC	–	Proton Exchange Membrane Fuel Cell
PID	–	Proportional Integral Derivative
PSO	–	Particle Swamp Optimisation
P-I	–	Power-Current
PV	–	Photovoltaic
PWM	–	Pulse Width Modulation
SOFC	–	Solid Oxide Fuel Cell
V-I	–	Voltage-Current

CHAPTER 1

INTRODUCTION

1.1 Background

The continuous consumption of non-renewable energy sources such as oil, coal, and gas upon the dependency of people's lives in this era of globalization has resulted in depletion of its sources. Apart from that, this action also resulted in serious environmental pollution and greenhouse effect. The enormous growth in energy consumption has forced the development of cost-effective renewable energy-based technologies to replace fossil-fuel-powered machinery in a numerous application. This is due to the fact that fossil fuels still meet a significant part of the energy demand [1]. Hence, the rise in energy demand has led to the increase in usage of fossil fuels which resulting in dwindling fossil fuel resources and higher fossil fuel prices. Furthermore, the negative environmental impact of fossil fuel combustion such as global warming has exacerbated the problem.

Nowadays, renewable energy has grown in popularity remarkably over the last century, and it continues to expand at a much faster pace than traditional energy sources like oil and coal [2]. Therefore, there is a pressing need to look for abundant and sustainable energy sources. Among all renewable energy sources, solar energy is described as one of the best alternatives that can be utilized. Recently, fuel cells have gained popularity as a potential renewable energy source due to their low environmental impact [3]. A fuel cell is a electrochemical device that generates electricity by combining hydrogen and oxygen with water and heat as a byproduct [4]. According to Karami et. al [5], fuel cells provide a number of advantages such as high in efficiency and reliability, noise-free, and environment friendly since the energy conversion undergo electrochemical process without combustion. In fuel cell system, unit cell is a core component that executes the electrochemical energy conversion. It consists of an electrolyte that is in contact with negative and positive electrodes namely anode and cathode respectively [6]. Fuel cells can be categorized into five major types in accordance with the electrolyte type used as shown in Table 1.1 [7].

Table 1.1: Major types of fuel cells [6], [8]

Characteristic	Types of Fuel Cells				
	PEMFC	**AFC**	**PAFC**	**MCFC**	**SOFC**
Operating temperature (°C)	$40-80$	$65-220$	200	650	$600-1000$
Electrolyte	Polymer membrane	Immobilized KOH liquid	Immobilized H_3PO_4 liquid	Immobilized molten carbonate	Perovskites (ceramics)
Electrode	Carbon	Platinum	Carbon	Nickel and nickel oxide	Perovskite and perovskite/metal cermet
Catalyst	Platinum	Platinum	Platinum	Electrode material	Electrode material
Interconnect	Carbon or metal	Metal	Graphite	Stainless steel or nickel	Nickel, ceramic, or steel
Charge carrier	H^+	OH^-	H^+	CO_3^{2-}	O^{2-}
Cell component	Carbon based	Carbon based	Carbon based	Stainless based	Ceramic based
Fuel cell compatibility	H_2, methanol	H_2	H_2	H_2, CH_4	H_2, CH_4, CO

Among these types of fuel cells, PEMFC which on the other hand is known as polymer electrolyte membrane [9], is said to be a promising power source contender due to its striking features such as high efficiency, clean utilization, lightweight, fast start-up, low operating temperature and high power density [9 - 11] . In addition, PEMFC is also the most prominent fuel cell that is widely used various application as stated in [11].

1.2 Problem Statement

Despite the fact that fuel cell is a green energy technology invention, the implementation cost of a fuel cell system is expensive when compared to other sources [12] due to design complexity of the system [13]. Nowadays, researchers are driven to develop an accurate model of the PEMFC because of its widespread use and its distinct advantages. As a result, the modelling of PEMFC system has become significantly crucial for better comprehension and development of high efficiency PEMFC system [14]. In spite of this, the mathematical modelling of PEMFC based on empirical equations has been widely used because of the nonlinearity, multivariate, and tightly coupled properties of PEMFC. Thus, the use of optimization methods is required due to the scarcity of data, the modelling complexity, and the large number of unknown parameters [15].

Apart from that, the output power of PEMFC is highly dependent on parameters such as temperature, membrane water content, oxygen partial pressure, and hydrogen partial pressure which resulting the fuel cell to exhibits non-linear output characteristic [16]. According to [17], the fuel cell polarization curve has one unique operating point to be tracked namely maximum power point (MPP). MPP is a point where the PEMFC will generate its full power [18]. However, the location of this MPP varies depending on the operating conditions [19]. Hence, a maximum power point tracking (MPPT) algorithm is used to monitor this MPP. A robust MPPT is essential to ensure maximum power extraction and energy utilization by the fuel cell at different operating conditions [20].

When it comes to developing an MPPT with fuel cells, there have been a plethora of approaches that have been published such as Perturb and Observe (P&O) [21], Incremental Conductance (INC) [22], Fuzzy Logic Control (FLC) [23], Particle Swarm Optimization (PSO) [24] and Model Predictive Control (MPC) [25]. However, these algorithms are different in terms of complexity, accuracy, and speed. Furthermore, some of the existing MPPT algorithm suffers high oscillation and slow convergence. Omar et. al [26] stated that each routine can be classified relative to the type of control variable that it employs, such as voltage, current, and duty cycle. Therefore, the proposed MPPT algorithm in this project will be compared with other existing algorithms in order to verify the trueness of their robustness on PEMFC efficiency.

1.3 Objectives

The objectives of this project are as follows:

- To develop a fully functional PEMFC based on the mathematical modelling in MATLAB/Simulink.
- To implement a predictive MPPT algorithm for the PEMFC.
- To compare predictive MPPT algorithm with other existing MPPT techniques on PEMFC's performances.

1.4 Project Scope

The aim of this project is to develop PEMFC system with predictive MPPT algorithm. This project involves research on the general concept of PEMFC and fundamentals of model predictive control. The development of the simulation model for this project is based on the parameters obtained from mathematical modelling of previous research. This project focuses on improving the performance of fully functional PEMFC from past studies by using predictive MPPT algorithm. Throughout this project, MATLAB/Simulink will be used to design the PEMFC with predictive MPPT control. Then, a simulation will be done by using MATLAB/Simulink to validate and execute the simulation model. The results obtained from the simulation will be used to examine and analyse the performance of PEMFC with predictive control under different operating conditions.

1.5 Thesis Outline

This project report is divided into five chapters, with an appendix including references and various attachments. The project is organized in the following order: introduction, literature review, methodology, results and discussion, and conclusion. The summary of each chapter is described as follows.

Chapter 1 (introduction) entails the background study of the proposed project, which is related to renewable energy and fuel cell. This chapter also includes the problem statement, objectives, and scope of the project.

Chapter 2 (literature review) explains the reviews and studies that have been done for better comprehension of proposed project. This chapter elucidates the working principle of PEMFC and its mathematical modelling. Apart from that, types of power electronics converters and MPPT algorithm are also covered in this chapter.

Chapter 3 (methodology) outlines the proposed methodology and succinct process that involved in the project accomplishment. Further details on the method and technique used for the proposed project are discussed in this chapter. This chapter also consists of project flowchart and simulation software that will be used throughout the project completion.

Chapter 4 (results and discussion) emphasizes on the further and detailed discussion regarding the simulation results and outcomes of the proposed project. This chapter also presents simulation graphs obtained from MATLAB/Simulink.

Chapter 5 (conclusion) summarizes the entire project and conclude the obtained results. This chapter also provides few recommendations for future improvements to overcome the limitations encountered throughout the project and boost the efficiency and performance of PEMFC.