Faculty of Engineering

PROTON EXCHANGE MEMBRANE FUEL CELL MAXIMUM POWER POINT TRACKING FEATURING PREDICTIVE VOLTAGE CONTROL

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PROTON EXCHANGE MEMBRANE FUEL CELL MAXIMUM POWER POINT TRACKING FEATURING PREDICTIVE VOLTAGE CONTROL

MOHD. AKHIMULLAH BIN KASIM SELAMAT

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ABSTRACT

Concerns about climate change and the finite supply of fossil fuels have increased interest in renewable energy during the last few years. Renewable energy has the potential to offer a stable, cost-effective source of power for homes and businesses, in addition to being environmentally friendly. Fuel cells have lately gained interest as a potential renewable energy source due to their low environmental impact. Fuel cells provide various benefits over conventional combustion-based systems, including high efficiency, minimal emissions, and silent operation. In this project, a PEMFC was chosen because it has interesting features and very efficient since it can operate at low temperatures, which makes them good for a wide range of uses, such as in portable devices, vehicles, and stationary power systems. In general, the output characteristics of fuel cells are nonlinear and influenced by parameters such as the cell temperature, oxygen partial pressure, hydrogen partial pressure, and membrane water content. Thus, there are several techniques to determine the maximum power of the fuel cell by using MPPT method such as P&O, INC, FLC and PSO. This project involves research on the general concept of PEMFC and the fundamentals of model predictive control. A PEMFC system with model predictive control is introduced in this research. In this project, a DC-DC boost converter is utilised to manage the output voltage of the fuel cell in order to extract the maximum output power. Then, a DC-AC converter is utilised to transform the output voltage from the boost converter into an AC waveform by using voltage source inverter. Both of the power converter system will be controlled by using the MPC whereby the switching state for the boost converter and voltage source inverter is based on the predictive approach. Hence, this project's goal is to demonstrate the power characteristics retrieved from the PEMFC system utilising predictive control and to regulate the voltage based on the standard of electrical appliances to ensure safety and reliable operation.

Keyword: DC-AC Inverter, DC-DC Boost Converter, MPPT, PEMFC, Predictive Voltage Control

ABSTRAK

Kebimbangan mengenai perubahan iklim dan bekalan bahan api fosil yang terhad telah meningkatkan minat terhadap tenaga boleh diperbaharui dalam beberapa tahun kebelakangan ini. Tenaga boleh diperbaharui berpotensi menawarkan sumber kuasa yang stabil dan menjimatkan kos untuk kediaman dan perniagaan, selain mesra alam. Sel bahan api baru-baru ini mendapat minat sebagai sumber tenaga boleh diperbaharui yang berpotensi kerana impak alam sekitar yang rendah. Sel bahan api memberikan pelbagai faedah berbanding sistem berasaskan pembakaran konvensional, termasuk kecekapan tinggi, pelepasan minimum dan operasi senyap. Dalam projek ini, PEMFC telah dipilih kerana ia mempunyai ciri yang menarik dan sangat cekap kerana ia boleh beroperasi pada suhu rendah, yang menjadikannya baik untuk pelbagai kegunaan, seperti dalam peranti mudah alih, kenderaan dan sistem kuasa pegun. 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. Oleh itu, terdapat beberapa teknik untuk menentukan kuasa maksimum sel bahan api dengan menggunakan kaedah MPPT seperti P&O, INC, FLC dan PSO. Projek ini melibatkan penyelidikan tentang konsep umum PEMFC dan asas kawalan ramalan model. Sistem PEMFC dengan kawalan ramalan model diperkenalkan dalam penyelidikan ini. Dalam projek ini, penukar rangsangan DC-DC digunakan untuk menguruskan voltan keluaran sel bahan api untuk mengekstrak kuasa keluaran maksimum. Kemudian, penukar DC-AC digunakan untuk mengubah voltan keluaran daripada penukar rangsangan kepada bentuk gelombang AC dengan menggunakan penyongsang sumber voltan. Kedua-dua sistem penukar kuasa akan dikawal dengan menggunakan MPC di mana keadaan pensuisan untuk penukar rangsangan dan penyongsang punca voltan adalah berdasarkan pendekatan ramalan. Oleh itu, matlamat projek ini adalah untuk menunjukkan ciri kuasa yang diperoleh daripada sistem PEMFC menggunakan kawalan ramalan dan mengawal voltan berdasarkan piawaian peralatan elektrik untuk memastikan keselamatan dan operasi yang boleh dipercayai.

Kata Kunci: Kawalan Voltan Ramalan, MPPT, PEMFC, Penukar Rangsangan DC-DC, Rangsangan DC-AC.

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LIST OF SYMBOLS

ΔG	–	Specific entropy
$\Delta G°$	–	Gibbs free energy
ΔI_{FC}	–	Change/ripple in fuel cell current
Δi_L	–	Change in inductor current
ΔP_{FC}	–	Change/ripple in fuel cell power
ΔS	–	Change in entropy
ΔV_{FC}	–	Change/ripple in fuel cell voltage
τ_{H_2}	–	Hydrogen time constant
τ_{O_2}	–	Oxygen time constant
ξ_{1-4}	–	Parametric coefficients
A	–	Cell active area
C	–	Step of perturbation
D	–	Duty cycle
E_{Nernst}	–	Thermodynamic potential
F	–	Faraday’s constant
I_{FC}	–	Fuel cell current
k	–	Number of discrete sampling steps
k_{H_2}	–	Hydrogen valve molar constant
k_{O_2}	–	The oxygen valve molar constant
k_r	–	Modeling constant
n	–	Number of electrons
P_{H_2}	–	Partial pressure of hydrogen
P_{O_2}	–	Partial pressure of hydrogen

P_{FC}	–	Fuel cell power
q_{H_2}	–	Molar flow of hydrogen
q_{O_2}	–	Molar flow of oxygen
R	–	Universal gas constant
r_m	–	Membrane specific resistivity
T	–	Operational temperature
t	–	Time
T_{ref}	–	Standard temperature
T_s	–	Sampling time
t_m	–	Membrane thickness
V_{FC}	–	Fuel cell voltage
V_{act}	–	Activation voltage
V_{cell}	–	Cell voltage
V_{con}	–	Concentration voltage
V_{ohm}	–	Ohmic voltage
V_{peak}	–	Peak voltage
V_{rms}	–	Root mean square voltage
v_L	–	Voltage across inductor

LIST OF ABBREVIATIONS

AFC	–	Alkaline Fuel Cell
DC	–	Direct Current
IGBT	–	Insulated Gate Bipolar Transistor
INC	–	Incremental Conductance
KCL	–	Kirchhoff's Current Law
KVL	–	Kirchhoff's Voltage Law
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
PSO	–	Particle Swamp Optimisation
P-I	–	Power-Current
PV	–	Photovoltaic
PVC	–	Predictive Voltage Control
PWM	–	Pulse Width Modulation
SMC	–	Sliding Mode Control
SOFC	–	Solid Oxide Fuel Cell
THD	–	Total Harmonic Distortion
V-I	–	Voltage-Current

CHAPTER 1

INTRODUCTION

1.1 Background

Massive use of traditional fossil fuels in the modern society has not only made the energy crisis worse, but it has also caused global warming and pollution of the environment, which have major consequences for human life and health. This is causing an increase in carbon emissions, the predominant greenhouse gas in the atmosphere. Reducing the carbon intensity of electricity is essential for preventing climate change in the future. Thus, it is important to use renewable and sustainable fuels in place of fossil fuels by utilising resource-saving and ecologically beneficial approaches. In response to the massive rise in energy consumption, a variety of low-cost technologies based on renewable energy have been made to replace machinery that runs on fossil fuels.

Increasing amounts of research and development are being carried out in the field of technologies for generating electrical energy from renewable sources. Furthermore, obtaining solutions to the environmental problems today require actions with a long-term perspective for sustainable development. One of the most efficient and effective methods seems to be renewable energy sources. This is the reason why renewable energy and sustainable development are intimately connected. The use of renewable energy is a suitable strategy for meeting energy needs without harming the environment. Alternative forms of energy such as hydroelectric power, wind, and solar have been developed as substitutes for traditional forms of energy generation.

Fuel cells have recently acquired interest as a possible renewable energy source because of its minimal environmental effect and high energy efficiency [1]. A fuel cell is an electrochemical device source that generate electricity using hydrogen and oxygen with the by-products of water and heat through an electrochemical process [2]. It is an extremely efficient and clean process which more efficient than fuel combustion with low pollutant gas emissions and a flexible modular structure. Fuel cells are at the top of the list of preferred technologies for numerous power production applications. Common fuel cells that have been researched are Proton Exchange Membrane Fuel Cell (PEMFC), Phosphoric Acid Fuel Cell (PAFC), Alkaline Fuel Cell (AFC), Solid Oxide Fuel Cell (SOFC), and [1]. As stated in Table 1.1 [3], there are five categories of fuel cell.

Table 1.1: Categorization of fuel cells[3]

Characteristic	Types of Fuel Cells				
	Polymer electrolyte membrane (PEMFC)	**Alkaline (AFC)**	**Phosphoric acid (PAFC)**	**Molten carbonate (MCFC)**	**Solid oxide (SOFC)**
Operating temperature (°C)	40-80	65–220	205	650	600–1000
Electrolyte	Hydrated polymeric ion exchange membrane	Mobilized or immobilized potassium hydroxide in asbestos matrix	Immobilized liquid phosphoric acid in SiC	Immobilized liquid molten carbonate in $LiAlO_2$	Perovskites (ceramics)
Electrodes	Carbon	Platinum	Carbon	Nickel and nickel oxide	Perovskite and perovskite/metal cermet
Catalyst	Platinum	Platinum	Platinum	Electrode material	Electrode material
Interconnect	Carmon or metal	Metal	Graphite	Stainless steel or nickel	Nickel, ceramic, or steel
Charge carrier	H^+	OH^-	H^+	CO_3^+	O^-

Proton Exchange Membrane Fuel Cell (PEMFC) has drawn significant interest among various fuel cell technologies due to its attractive characteristics, such as efficiency, rapid startup, high power density, and operation at relatively low temperatures [4]. Polymer electrolyte membranes are used in PEMFC to transport protons and separate gaseous reactants on the anode and cathode sides [5]. Also, it has an extensive variety of uses including automotive, stationary and portable power supplies [6].

1.2 Problem Statement

Due to the complexity of design, the implementation cost of a fuel cell is high compared to other energy sources. Therefore, numerous attempts have been made to enhance its economics, either by reducing the price of the electrodes or by improving its performance [7]. The performance of the PEMFC is mainly reliant on operational conditions such as membrane water content and temperature [8]. Also, the major part contributing to fuel cell performance degradation is load change, which causes the deterioration [9]. Various mathematical models have been proposed to assess the behaviour of voltage change with discharge current in fuel cell [10]. This has been done to gain a better understanding of PEMFC systems and to improve their overall performance.

MPPT (Maximum Power Point Tracking) is a method employed to increase the output power of a fuel cell by continuously adjusting the operating point of the fuel cell, in order to maximize its power generation capability [6]. MPP stands for Maximum Power Point, which is the point on the power-voltage curve of a fuel cell at which the maximum amount of power is generated. At this point, the fuel cell is operating at its most efficient and generates the most electrical power [11]. There are several different kinds of MPPT algorithms that are used in fuel cell systems, such as Perturb and Observe (P&O), Incremental Conductance (IC) and Sliding Mode Control (SMC) [12]. These algorithms use various methods comparing the current output power of the fuel cell with the previous output power and adjust the operating point of the fuel cell accordingly. This allows the fuel cell to adjust to changes in the environment and continue to generate the most power possible.

PVC (Predictive voltage control) is a control technique that enables the regulation of the output voltage of the fuel cell. The DC-AC power converter also known as the inverter is the primary component used to converts direct current (DC) electricity into alternating current (AC) electricity. PVC regulates the output voltage by sending signals to the switch of the inverter using a predictive approach. It involves using predictive models to predict how the fuel cell's voltage output will change and adjust the system's operating point to keep the voltage stable and at the optimum level [13]. Different prediction steps affect the system in different ways when it comes to optimization [14]. Therefore, the predictive voltage control approach is implemented in this project to improve fuel cell systems' overall reliability and performance, as it allows the system to operate more consistently and predictably.

1.3 Objectives

The objectives that need to be achieved in this project are as follows:

1. To simulate a fully functional PEMFC based on the mathematical modelling in MATLAB/Simulink.
2. To implement a predictive based MPPT algorithm for the PEMFC maximizing output power and regulating output voltage.
3. To perform robustness evaluation on predictive MPPT and voltage control algorithm.

1.4 Project Scope

The goal of this project is to develop a fully operational Proton Exchange Membrane Fuel-cell (PEMFC) using mathematical modelling and to synthesize a modified Maximum Power Point Tracking algorithm (MPPT) that utilizes a predictive approach. This project involves research on the general concept of PEMFC and the fundamentals of model predictive control. The simulation model development for this project is based on the parameters obtained from the mathematical modelling of previous research. This project focuses on improving the performance of fully functional PEMFC by using a predictive MPPT algorithm. Besides maintaining the maximum power point (MPP), the output voltage is controlled by using predictive control. To assess the robustness of the suggested method, it will be tested and contrasted with existing MPPT techniques. A variety of parameter adjustments will be considered in evaluating the system's performance. MATLAB/Simulink will be used throughout this project to design the PEMFC with predictive MPPT and voltage control. The simulation will be done using MATLAB/Simulink to validate and execute the model. The results obtained from the simulation will be used to examine and analyse the performance of PEMFC with predictive control under various operating circumstances.

1.5 Thesis Outline

This project report is divided into 3 chapters, with an appendix including references and various attachments. The project is organized in the following order: introduction, literature review and methodology. The summary of each chapter is described as follows.

Chapter 1 (introduction) includes a review of the proposed project's background, which relates to renewable energy and fuel cells. This chapter contains the problem statement, objectives, and project scope.

Chapter 2 (literature review) covers the reviews and research conducted for a better understanding of the proposed project. This chapter explains the working concept and mathematical modelling of PEMFC. In addition, this chapter discusses power converter and the MPPT algorithm.

Chapter 3 (methodology) presents the proposed methodology and procedure for the project's completion. This chapter discusses more approach and technique specifics for the proposed project. This chapter also includes the project flowchart and simulation software that will be utilized during the duration of the project.

Chapter 4 (result and discussion) focuses on presenting a detailed and in-depth review of the simulation findings and project outcomes. This chapter also includes representations of simulation graphs created using the MATLAB/Simulink software.

Chapter 5 (conclusion) summarises the entire project and develops conclusions based on the findings. This chapter also discusses the project limitation and provides recommendations for future improvements to increase the efficiency and performance of the Proton Exchange Membrane Fuel Cell (PEMFC) system.