

**ENHANCED POWER CONTROL MANAGEMENT
FOR DIRECT METHANOL FUEL CELL/BATTERY
HYBRID SYSTEM VIA DUAL THRESHOLD CASCADE**

BY

MAJED ABDULBASIT ALJESHI

A Thesis Presented to the
COLLEGE OF GRADUATE AND INTERDISCIPLINARY STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

**CHEMICAL ENGINEERING
JULY 2024**

Enhanced Power Control Management for Direct Methanol
Fuel Cell/Battery Hybrid System via Dual Threshold
Cascade

By

MAJED ABDULBASIT ALJESHI

A DISSERTATION PRESENTED TO THE DEPARTMENT OF CHEMICAL ENGINEERING
AT KING FAHD UNIVERSITY OF PETROLEUM & MINERALS IN FULFILLMENT OF
REQUIREMENT FOR MASTER OF SCIENCE DEGREE

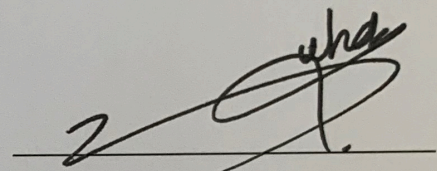
July 2024

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

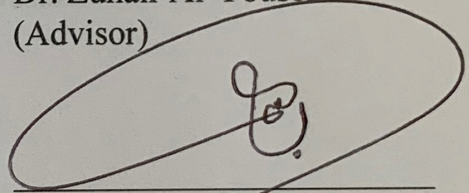
DHAHRAN- 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

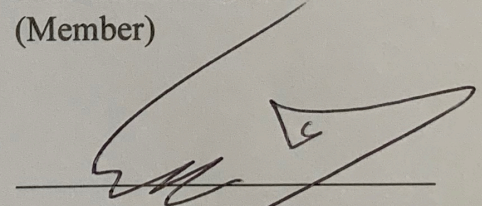
This thesis, written by Majed Abdulbasit Aljeshi under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of Master of Science in Chemical Engineering



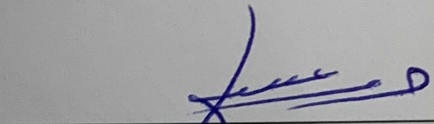
Dr. Zuhair Al-Yousef
(Advisor)



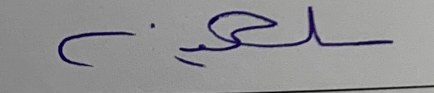
Dr. Basim Abussaud
(Member)



Dr. Abdallah Al-Shammari
(Member)



Dr. Hassan Baqeel
Department Chairman



Dr. Suliman Al-Homidan
Dean of Graduate Studies

Date



© Majed Abdulbasit Al-Jeshi

2024

To My family and friends who supported me through this journey

ACKNOWLEDGMENTS

I would like to express a sincere thanks to my academic advisor and mentor Dr. Zuhair Al-Yousef who supported me through this research journey with his wealth of knowledge and experience in the fuel cell field along with providing his valuable guidance in identifying area of improvements to further strengthen the proposed work part of this dissertation. During my time at KFUPM, Dr. Zuhair Al-Yousef was extremely supportive in dedicating part of his time to monitor the progress of my research activities and having continuous two ways dialogues that further enriched the objective of this research and made it more challenging and interesting. In addition, I would like to express my gratitude to the review committee represented by Dr. Basim Abussaud and Dr. Abdallah Al-Shammari for their valuable time to review and provide feedback on my dissertation.

In addition, a word of appreciation goes to my sponsor, Saudi Aramco, for giving me an outstanding self-development opportunity by joining a high prestigious university such as KFUPM where I have learned and gained an advanced knowledge in the field of chemical engineering.

Reflecting on my time at KFUPM, I believe that I had the most productive years of my life by accomplishing major milestones on my academic and personal levels. I'm eager to apply what I have learned at KFUPM into practical applications at Saudi Aramco

TABLE OF CONTENTS

ACKNOWLEDGMENTS	V
TABLE OF CONTENTS.....	VI
LIST OF TABLES	VIII
LIST OF FIGURES	IX
LIST OF ABBREVIATIONS.....	X
ABSTRACT.....	XI
ملخص الرسالة.....	XIII
CHAPTER 1 INTRODUCTION	14
CHAPTER 2 LITERATURE RESEARCH.....	18
2.1 Operation Principle and Design Architecture of Direct Methanol Fuel Cells	18
2.1.1 Electrochemistry of DMFCs	18
2.1.2 Open Cathode Architecture of DMFC	20
2.1 Control Architectures in DMFC System and the Effect on Power Response.....	21
2.2.1 Standard Cascade Control Structure for Liquid-Level Management	21
2.2.2 Improved Dual Threshold Cascade Control for Liquid Management	24
2.3 Battery Operation Principle and Qualitative Behavior	26
CHAPTER 3 PROPOSED POWER	28
3.1. Common Configurations of Hybrid Systems.....	28

3.2. Generic Concept of Proposed Configuration	30
3.3. Detailed Power Management System Configuration.....	31
3.4. Impact of Proposed Hybrid Configuration on Battery Life	36
3.5 Hybrid System Model and Methodology of Testing	38
CHAPTER 4 RESULTS & DISCUSSION	42
4.1. Dynamic Response of DMFC Under Standard Cascade and Dual Threshold Cascade Controllers	42
4.2. Dynamic Response of DMFC/Battery Hybrid System Using PMS with Various Scenarios.....	46
4.3. Economic Analysis	51
CHAPTER 5 CONCLUSION & RECOMMENDATIONS.....	54
REFERENCES	55
VITAE.....	62

LIST OF TABLES

Table 1: Case studies for integrating DTC in PMS of DMFC/battery hybrid system	35
Table 2: Some parameters of DMFC for simulation study	40
Table 3: Important parameters of Li-ion battery for simulation study	41
Table 4: DMFC/battery hybrid system response using PMS integrated with DTC	51
Table 5: DMFC/battery hybrid assumptions for economic evaluation.....	53

LIST OF FIGURES

Figure 1: Graphical representations of DMFC	20
Figure 2: Graphical diagram of DMFC system and the cascade control.....	22
Figure 3: Typical Li-ion battery polarization curve	27
Figure 4: Structure of DMFC/ battery hybrid system in series configuration	29
Figure 5: Structure of DMFC/ battery hybrid system in parallel configuration	30
Figure 6: DMFC/battery hybrid system power signal flow diagram.....	31
Figure 7: Logical configuration of DMFC/battery hybrid PMS.....	33
Figure 8: Li-ion battery and DMFC operation time versus capacity retention	37
Figure 9 : Matlab combined integrated model combining DMFC & Battery.....	40
Figure 10: Dynamic Responses of liquid-level, temperature and power.....	45
Figure 11: Case 1: dynamic response of DMFC/battery system for load change of 47 W to 50 W with DTC on manual mode ($f(t)=0$).....	47
Figure 12: Case 2: dynamic response of DMFC/battery system for load change of 47 W to 52 W with DTC on manual mode ($f(t)=0$)	48
Figure 13: Case 3&4: Dynamic response of DMFC/battery system for load change of 47 W to 50 W with DTC on auto mode ($f(t)=1$)	49
Figure 14: Cost of operating battery versus DMFC/Battery Hybrid system	52

LIST OF ABBREVIATIONS

DMFC	:	Direct Methanol Fuel Cell
PMS	:	Power Management System
DTC	:	Dual Threshold Cascade
LBL	:	Liquid Barrier Layer
PI	:	Proportional Integral
LC	:	Level Controller
LT	:	Level Transmitter
TC	:	Temperature Controller
TT	:	Temperature Transmitter
SC	:	Standard Cascade

ABSTRACT

Full Name : Majed Abdulbasit Aljeshi
Thesis Title : Enhanced Power Control Management for Direct Methanol Fuel Cell/Battery Hybrid System via Dual Threshold Cascade
Major Field : Chemical Engineer
Date of Degree : July 2024

An enhanced high-level power management control system for direct methanol fuel cell (DMFC)/battery hybrid device is proposed in this work. Integrated with parallel configuration of hybrid device, the power management system (PMS) aims to extend battery lifetime by making the fuel cell as the main source for supplying energy to external loads, while invoking battery whenever necessary. For satisfying this objective, a novel dual threshold cascade (DTC) controller is incorporated with PMS. The controller function is to properly adjust the level of liquid inside the methanol solution tank of the fuel cell but has a direct effect on thermal state and output power. Installing this controller in DMFC improves power performance of the cell by enabling it to change the power and satisfying load requirement in some periods of operation, at which case master level and slave temperature controllers are de-coupled. In such periods where the controller is at manual mode, the battery stays uncalled. Whenever DMFC is unable to deliver the required power to the load, battery is used to compensate for the balance of power. The study has tested the system by utilizing MATLAB Simulink software capability, combining a comprehensive dynamic modeling of DMFC system, a reliable model of Li-ion battery and the improved PMS being proposed. Simulation results demonstrate that using dual threshold controller in PMS makes the DMFC/battery hybrid system to operate and satisfy

the requested signal of load in various case scenarios being studied. In some cases, DMFC by itself is sufficient to feed the load while the battery is incorporated in other occasions. An example is the case when the load requests 47 W of power while DTC is on manual mode, at which case DMFC sends the entire wattage to the load while battery is not used. Utilizing improved PMS can lengthen the lifespan of the battery and make compact hybrid system.

Keywords: Hybrid system, Power management system, Battery life

ملخص الرسالة

الاسم الكامل: ماجد عبدالباسط عبدالحميد الجشي

عنوان الرسالة: تطوير كفاءة عمل خلية الميثانول DMFC مع البطارية عن طريق خاصية DTC

التخصص: الهندسة الكيميائية

تاريخ الدرجة العلمية: يوليو ٢٠٢٤

المقترح في هذه الرسالة هو اقتراح نظام عمل محسن للتحكم في إدارة الطاقة الى عمل (DMFC) مع البطارية. يهدف نظام إدارة الطاقة (PMS) المتكامل إلى إطالة عمر البطارية من خلال جعل خلية الميثانول هي المصدر الرئيسي لتزويد الطاقة للأحمال الخارجية مع استدعاء البطارية عند الضرورة فقط. ولتحقيق هذا الهدف تم وضع وحدة تحكم ذكية (DTC) مع نظام PMS. تتمثل وظيفة جهاز التحكم الذكي في ضبط مستوى السائل داخل خزان الميثانول في نطاق معين يعبر عنه بحد علوي وحد سفلي بخلاف وضع مستوى ثابت داخل الخزان والمتعارف عليه. هذه الخاصية تمنح DMFC القدرة على تغيير الحرارة بهدف تلبية الأحمال الخارجية في بعض فترات التشغيل حيث انه خلال هذه الفترة يتم فصل وتعطيل اقتران التحكم في مستوى الخزان عن أجهزة التحكم في درجة الحرارة. عندما يكون DMFC غير قادر على استيعاب الطاقة المطلوبة للحمل، يتم استخدام البطارية للتعويض في حالة الضرورة فقط. تم اختبار هذا النظام الذكي من خلال برنامج MATLAB Simulink بهدف توضيح نتائج المحاكاة من خلال سيناريوهات عمل مختلفة.

أشارت النتائج أن النظام الذكي الى خلية الميثانول مع البطارية يعمل ويلبي إشارة الحمل المطلوبة في سيناريوهات الحالات المختلفة بكفاءة عالية في بحيث تكون كافية لتغذية الأحمال الكهربائية الخارجية بينما يتم استعمال البطارية في سيناريوهات قليلة فقط. النظام المقترح يؤدي الى تعزيز كفاءة نظام إدارة الأداء والطاقة مما يترتب عليه من إطالة عمر البطارية

CHAPTER 1

INTRODUCTION

Power generation and its environmental consequences have become a controversial subject worldwide especially with the grow in population and the need to meet future energy demands. Currently, energy sources are mainly based on fossil fuels which contribute to air pollution through gas emissions (Hoseintabar-Marzebali, 2019). With the strong need of alternative clean energy in the future, the scientist and industrial communities are turning their attention to various options that effectively and rigorously reduce the negative impacts of traditional energy sources. Among promising technologies which are an integral part of clean energy vision are fuel cells that have various traits making them a long-term sustainable clean energy choice with high efficiencies. The principle of fuel cells operation is to directly transform the stored chemical energy in the fuel to electrical energy without burning, and their applications vary from small portable power devices to medium electrical applications such as electric vehicles, all the way to high power supply such as residential and commercial buildings (Dohle, 2002).

One key challenge facing fuel cells commercialization and preventing large scale deployment is the high cost associated with their manufacturing, compared with competitive market prices for products based on fossil fuels (Wang et al., 2018). For example, fuel cells still have technical challenges associated with membrane material design properties, catalyst selection and synthesis which are highly related to fuel cell

robust operation and economic feasibility (Blum et al., 2003). However, advances in fuel cell technologies are continuously evolving over the years to address these obstacles and eventually to make future investment commercially viable.

Fuel cells usually do not work as standalone devices due to their relatively slow dynamics in some occasions such as startup and rapid magnitude changes of load requirements (Gurau & Smotkin, 2002). Thus, it is imperative to integrate them in hybrid systems with other storage devices such as batteries and supercapacitors to satisfy the load signal in real-time basis (Franzoni et al., 2005). There are two main configurations of the hybrid systems, namely series and parallel structures. The explanation of each system is detailed in chapter 3 of this dissertation.

There are several works that have been reported in the literature about hybrid systems. The authors in (Boukhniifer et al., 2016) conducted a comparison study between different energy management systems of a fuel cell/battery parallel configuration with more emphasis being put on optimizing fuel consumption without discussing the impact on battery health. Vichard et al., 2021 presented different degradation mechanisms for fuel cell/battery hybrid system components and their work reveal that battery performance and health tend to drop over time with the increase in battery operating cycles.

While there are several works reported in the literature treating fuel cell/battery hybrid systems to feed external loads, there are not enough studies investigating the effect of using the fuel cell as the primary source in such systems. Specifically, the effect of operation on the hybrid system life does not have a good attention from the researchers when proposing certain power management strategy. This study introduces a power management

architecture for a fuel cell/battery hybrid system with the objective of extending battery lifetime through the dependence on fuel cell as primary energy source. This goal is achieved via the utilization of a control algorithm that we call Dual Threshold Cascade (DTC) integrated in fuel cell system for improving the thermal state and power output of the cell. The signature of this work lies in designing fuel cell/battery parallel hybrid configuration, where DTC algorithm is integrated in the power management system to maximize the dependence on the fuel cell for power delivery to the connected load while the battery remains on sleep mode and is operated once needed only.

This dissertation is organized as follows: Chapter 2 (literature review) has many subsections to provide the reader with important information; Section 2.1 (Operation Principle and Design Architecture of Direct Methanol Fuel Cells) presents DMFC operating principle, and the adopted architectural design of the system, Section 2.2 (Control Architectures in DMFC System and the Effect on Power Response) presents the original cascade control and the modified cascade control structure alongside with the effect of each design on electrical outputs of DMFC, Section 2.3 (Battery Operation Principle and Qualitative Behavior) shows how the behavior of battery voltage changes with respect to capacity on qualitative basis, Chapter 3 (Proposed Power Configuration of DMFC and Battery Hybrid System) presents detailed explanation of the proposed power management system and the role of dual threshold algorithm for the DMFC/battery hybrid configuration along with the impact of integrating this system on life of the battery, Section 3.2 (Hybrid System Model and Methodology of Testing) presents the main information of the simulation parameters for both DMFC and Li-ion battery that are used in this study as well

as the methodology of testing power management system. Chapter 4 (Results & Discussion) discusses dynamic simulations results using MATLAB & Simulink under different scenarios of user power load demand. In addition, it will provide a summary of an economic analysis between battery and DMFC/battery over a function of time. Chapter 5 (Conclusion & Recommendation) will summarize the dissertation findings and proposed future work and outlooks in terms of energy optimization opportunities

CHAPTER 2

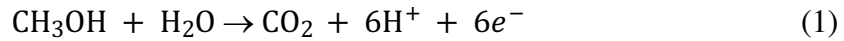
Literature Research

2.1 Operation Principle and Design Architecture of Direct Methanol Fuel Cells

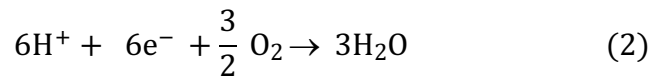
Direct methanol fuel cells operate based on the principles of electrochemistry. In addition, there are various architectural design schemes available for DMFC systems. This section presents a brief discussion about the principle of operation and the design structure adopted for DMFC system utilized in this study.

2.1.1 Electrochemistry of DMFCs

DMFC consists of anode and cathode electrodes which are spatially separated by a thin membrane as the electrolyte. Methanol solution is oxidized at anode side following the oxidation reaction (Junoh et al., 2020)



where the liberated electrons travel through an outer circuit while the generated protons diffuse to the other side of the cell through the membrane. At the cathode side, oxygen gas which is typically provided thorough air flow joins the diffused protons and returning electrons where all together undergo the reduction reaction described by



resulting in the water production (O’Hyre et al., 2016). In parallel, a considerable amount of methanol molecules diffuses to the cathode side through the membrane yielding the undesirable phenomenon of methanol crossover, where methanol is consumed via a side reaction resulting in its loss and further water production without generating electricity(Gurau & Smotkin, 2002)

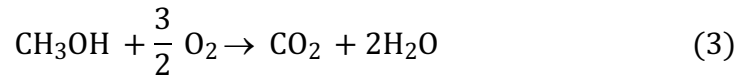


Figure 1 shows a typical DMFC structure with anode inlet receiving methanol solution while cathode side receiving oxygen. Carbon dioxide can be discharged at both anode and cathode chambers where it is produced from methanol oxidation at anode while is generated via methanol crossover reaction at cathode. The water exhaust from the anode side is typically in liquid form that is part of the returned water from cathode side through back convection flux while the outlet from cathode side state depends on the DMFC architectural design as discussed in the ensuing subsection.

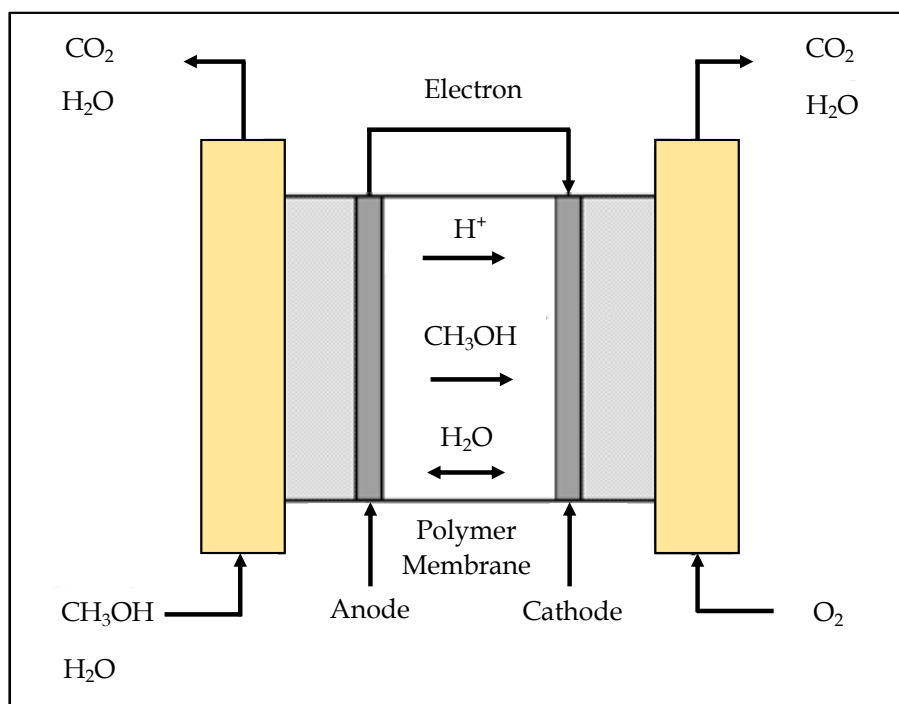


Figure 1: Graphical representations of DMFC. (García et al., 2004)

2.1.2 Open Cathode Architecture of DMFC

The architectural design of DMFC system adopted in this study is the open-cathode structure. The compact size of this design makes it advantageous over the classical closed cathode via eliminating the need of excessive equipment such as condensers and tanks for water recirculation and recovery. Rather, the open cathode features a liquid barrier layer (LBL) with hydrophobic properties allowing water produced at the cathode to be back transported to the anode side to participate in the oxidation reaction (1) while simultaneously provides further hydration to the membrane (Mudiraj, 2015). In addition, the open-cathode, in contrast to the closed-cathode design, is not constrained by the requirement to maintain a low air flow rate as it does not have a condenser. Accordingly, providing high rates of air allows for the removal of significant amounts

of heat from the cathode side without the need to install a cooling subsystem. Furthermore, the design makes it feasible for the water to be partially discharged from cathode chamber to the ambient via evaporation mechanism. Further discussion and elaboration about this novel design and its detailed properties can be found in (Mudiraj et al., 2015).

2.2 Control Architectures in DMFC System and the Effect on Power Response

As demonstrated in Section 2.1.2, the DMFC system in this work adopts the open-cathode architectural design. One key process unit in the system is the tank supplying methanol solution to support anodic oxidation reaction (1). The control structure utilized to manage the tank level is the standard cascade (SC) control. The reason behind this adoption is detailed in (Mudiraj, 2015) and (Al-Yousef et al., 2019). This section discusses both the original cascade control and the improved cascade control or Dual Threshold Cascade (DTC) for the purpose of demonstrating the effect of both control algorithms on thermal and power responses in DMFC system.

2.2.1 Standard Cascade Control Structure for Liquid-Level Management

Figure 2 shows a simple diagram of the DMFC system. As demonstrated in the figure, main parts of the system are (i) mixing tank, (ii) DMFC stack, (iii) air expander (fan) and (iv) associated control loops, from which only one is shown (cascade control loop). The mixing tank provides the solution to support the oxidation reaction at anode, whereas the fan has the dual purpose of oxygen supply to cathodic reduction reaction

(2) and simultaneously manipulating the temperature of the system. The stack is the venue for the reaction occurrence and generation of electricity.

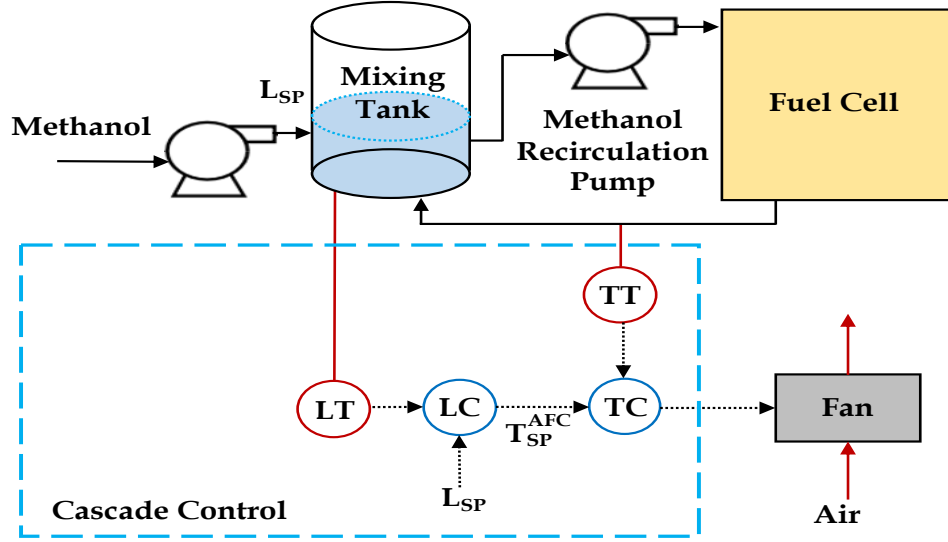


Figure 2: Graphical diagram of DMFC system and the cascade control loop of liquid-level control.

One of the key challenges in DMFC operation is the proper design of control strategies leading to efficient operation while simultaneously achieving water, thermal and power management in the system under different set of operating conditions (Al-Yousef et al., 2019). For example, water content has to be regulated in both mixing tank and fuel cell stack as it is consumed in the anode and produced at the cathode. Another crucial aspect is the DMFC temperature management as the thermal state of the system affects many critical variables such as electrochemical reaction kinetics, proton transfer, methanol crossover, water balance within the system, among other variables. More importantly, the power generated from DMFC is directly influenced by the temperature as reported in the references covering the electrochemical principles of fuel cells (O’Hyre et al.,

2016). Consequently, the temperature must be considered as a pivotal variable in the phase of proposing a control structure for the system.

One way of achieving water management in the system is through the level control in the mixing tank. The detailed discussion of this can be found in (Mudiraj et al., 2015). Figure 2 demonstrates the cascade control, proposed originally to control the level of liquid inside the tank. In this structure, there are two controllers in series, namely the primary level controller defined as (LC) and the secondary temperature controller defined as (TC). Both temperature and level are monitored through transmitter instrumentation known as (LT) and (TT). The output of primary controller (LC) will adjust the set point for secondary controller (TC) where the objective is to dictate and manage the level inside the tank to be continuously at one set point. The adopted output of primary controller is used as Proportional-Integral (PI) as per below

$$T_{SP}^{AFC}(t) = \bar{T} + K_p e(t) + K_i \int_0^t e(\tau) d\tau \quad (4)$$

which involves the level feedback error

$$e(t) = L_{SP} - L^{Tank}(t) \quad (5)$$

where T_{SP}^{AFC} is the temperature set point, $\bar{T}$ is the bias temperature value, K_p is the proportional gain constant, K_i is the integral gain constant, L_{SP} is the mixing tank level set point, and $L^{Tank}(t)$ is the measured actual tank level.

It can be seen from the PI law in Equation (4) that master LC always employs secondary TC for the sole purpose of manipulating tank level to a certain value. Thus, the

temperature of the cell always satisfies the need of the level controller and cannot be specified or optimized for any other purpose. In other words, the temperature is not a free variable that can be selected or altered by the user for a certain objective other than level control.

2.2.2 Improved Dual Threshold Cascade Control Structure

Despite the standard cascade controller being effective in managing tank level, that comes with a drawback of continuously manipulating the temperature of the system for the single objective of tracking the set point L_{SP} . Consequently, the output power of the cell cannot be altered or shifted from one state to another since the temperature is not free for change. In view of this effect, the fuel cell cannot respond to load changes in the applications with frequent fluctuations of power requirement.

A novel modified cascade control structure is proposed in (Al-Yousef et al., 2019) & (Alyousef, 2020) to improve thermal management and hence the electrical performance of the cell. The Dual Threshold Cascade (DTC) algorithm enables intermittent decoupling of LC and TC, making the temperature to be a free variable in the disconnection periods between the two controllers. In other words, temperature can be a free controlled variable on many occasions, allowing DMFC to switch its power and therefore to deliver the targeted power output while simultaneously maintaining the liquid level between the two threshold boundaries to avoid flooding and dry out scenarios

The control law of DTC is constructed by modifying the PI law of standard cascade via introducing a switching function $f(t)$ such that the output of the controller becomes

$$T_{SP}^{AFC}(t) = \bar{T}_{dt} + f(t) \left[K_P e_{dt}(t) + K_i \int_0^t e_{dt}(\tau) d\tau \right] \quad (6)$$

where the switching function $f(t)$ adopts a binary value of 0, indicating that PI master controller is in manual mode, or 1 which leads to the automatic mode activation of master controller LC. DTC feedback error e_{dt} of level controller is defined as

$$e_{dt}(t) = f(t) [L_{SP} - L^{Tank}(t)] \quad (7)$$

The working mechanism of DTC algorithm is centered about the status of switching function $f(t)$. In case $f(t) = 0$ (manual), the level in the tank is between the upper and lower thresholds leading to operating the system at the selected temperature $\bar{T}_{dt}$ that can determine the desired output power. If either one of the thresholds is reached, $f(t)$ status is converted to a value of 1 (automatic) forcing the primary level controller in the tank to be activated where the system operation is returned to the standard cascade control mode and the temperature is no longer a free variable of choice. Hence, the output power cannot be altered as well. However, DTC is advantageous over standard cascade due to the periods of decoupling between the primary LC and secondary TC such that the temperature is no longer directed by the primary controller. In future studies, there will be some demonstration to optimize the conditions of the system to lengthen the periods of decoupling as much as possible while shortening the periods of coupling between primary and secondary controllers.

2.3 Battery Operation Principle and Qualitative Behavior

Batteries are considered efficient, high energy density storage devices. They provide sustainable power harvested from different energy sources such as wind or solar and they are used in wide applications including, but not limited to portable devices and electric vehicles (Kebede et al., 2022). Batteries resemble fuel cells operational principle, where they have an anode, a cathode compartment, and an electrolyte as constituents of the cell to carry out the electrochemical reaction and generate electricity (Bandyopadhyay & Nandan, 2023). They are considered as closed thermodynamic systems with a quantified fuel storage while fuel cells are open thermodynamic systems with continuous fuel supply, crossing the system boundary (Winkler & Williams, 2014).

For the purpose of illustration, lithium-ion battery is chosen as a storage device for the fuel cell/battery hybrid system considered in this work. One reason behind this selection is the widespread use of such type of battery in vast number of applications. Furthermore, there is a plethora of models available to simulate the performance of those batteries (Jongerden & Haverkort, 2008). For example, MATLAB and Simulink software provides a simulation suit for Li-ion battery which is integrated with the power management system proposed in this study. The reader should observe, however, that the design of power management system is irrespective of the battery type, i.e. it is valid for any type of battery or storage device.

Figure 3, reported by (Raszmman et al., 2017) shows a typical battery polarization curve for Li-ion battery. The vertical axis represents the voltage of the battery in units of volts while the horizontal axis shows the capacity in units of Ampere-hour (Ah). The battery in this curve is in discharge mode. The plot demonstrates that the battery is initially has a full cell voltage V_{full} and it experiences a sudden drop once the current is withdrawn; that zone is characterized by the exponential behavior. As more current is withdrawn, the battery enters the nominal zone where the voltage of the battery remains essentially constant at V_{nom} . With more current being withdrawn, the battery reaches the final stage of discharge, characterized by fast voltage drop which indicates that battery needs re-charging for another cycle. There are explanations from electrochemistry point of view for the phenomenon observed in this curve but further details are out of this study's goals and can be found in relevant references.

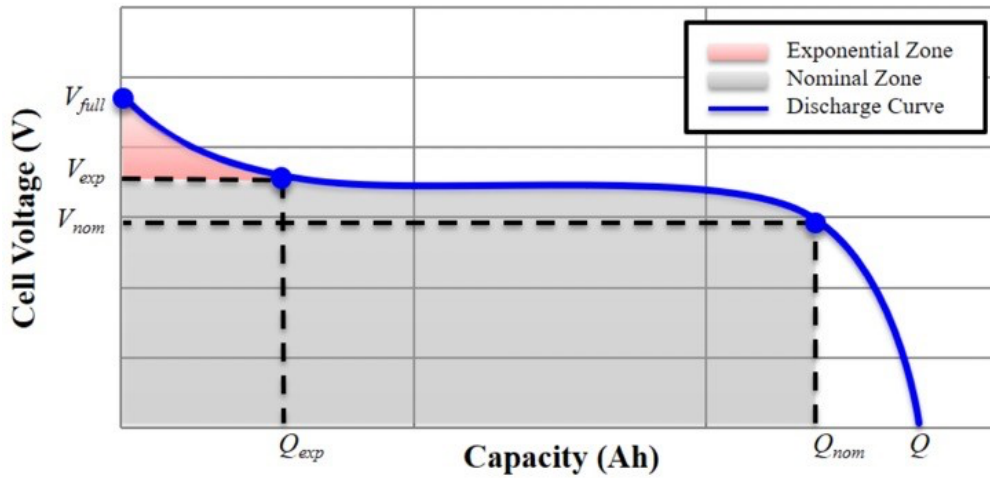


Figure 3: Typical Li-ion battery polarization curve in discharge mode (Raszmman et al., 2017)

CHAPTER 3

Proposed Power Configuration of Hybrid System

Several works in the literature report that the fuel cell as a standalone device is usually unable to fulfill the power requirements of the connected load. For example, it is mentioned in the Introduction that relatively slow dynamic response in some occasions hinder the fuel cell from delivering the needed power to the external load. Thus, it is critical to integrate the fuel cell with another storage device in a hybrid system to overcome such shortcomings, especially in the applications with frequent load changes (Pourrahmani et al., 2022),(Jiang & Dougal, 2006).

This chapter is devoted for detailed discussion about the proposed power management system of DMFC/battery hybrid system. The discussion covers (i) the explanation of available common hybrid configurations, (ii) the logic of the proposed system including the role of DTC algorithm, and (iii) the impact of the hybrid system on battery life.

3.1. Common Configurations of Hybrid Systems

There are two main configurations of the fuel cell/battery hybrid systems: the series and parallel structures. The series form is designed in a fashion of connecting the fuel cell to a battery and/or supercapacitor which in turn feeds an external load as shown in Figure 4. Thus, the fuel cell in this configuration supplies the energy as needed to the battery only and does not have any connection to the load (Ma et al., 2021). While it is

simple, this form of hybrid structure is not optimized or efficient in energy usage of both fuel cell and battery. Furthermore, the configuration may lead to a large system size due to high number of battery packs needed, especially in the applications of high-power loads (Hoogendoorn, 2018)

The parallel configuration, on the other hand, is designed to simultaneously make both fuel cell and battery as the supplying energy sources to the load with different power split according to a certain energy management strategy (Azib et al., 2014). Figure 5 shows a simple demonstration of the parallel structure of hybrid system with both fuel cell and battery connected to the load through a governing energy management system. However, the degree of power supply from each device depends on several factors and design considerations. Thus, this configuration is more flexible in the design and has a wide room for making a compact system size with high efficiency in power utilization.



Figure 4: Structure of DMFC/ battery hybrid system in series configuration

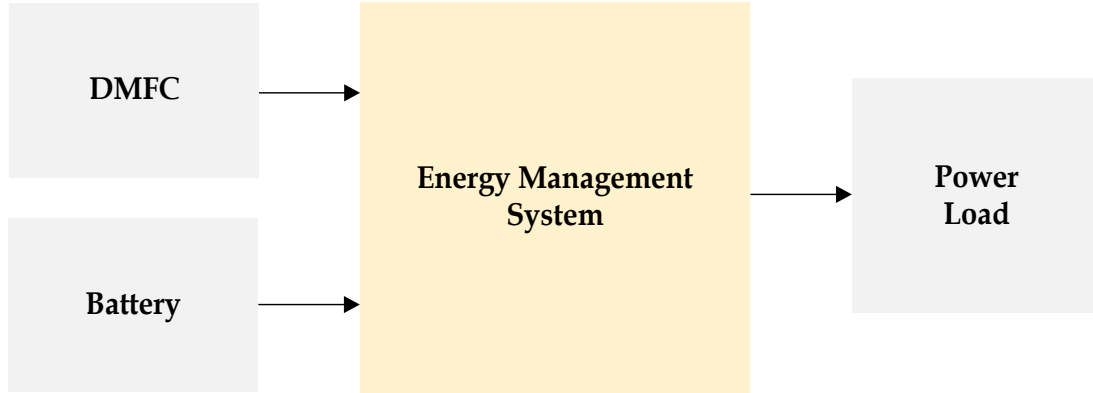


Figure 5: Structure of DMFC/ battery hybrid system in parallel configuration

3.2. Generic Concept of Proposed Configuration

The goal of the proposed hybrid system in this work is to enable an efficient power distribution between the DMFC and the battery to satisfy the load demand on real time basis without any lag or interruption. Specifically, the design of the power management system (PMS) is sought to depend mostly on the fuel cell while minimizing the usage of the battery. Indeed, there are advantages associated with implementing this strategy and that discussion is left for Section 3.4. In view of the objective being targeted, the following points are considered in the design of PMS:

- The hybrid system follows the parallel configuration demonstrated by Figure 5 so that the power can be split between DMFC and battery accordingly
- Whenever possible, the battery stays on sleep mode (not used) such that it is invoked only when the fuel cell fails to satisfy the load requirement

- The design assumes that the combined fuel cell and battery rated power is greater than or equal to the maximum load requirement

3.3. Detailed Power Management System Configuration

Figure 6 presents the signal flow diagram of the DMFC/battery parallel hybrid structure, including power management system (PMS). The diagram consists of main parts in the system including switches, DMFC with its associated power controller, and battery alongside with its controller. The PMS can be considered as a supervisory controller for all power sources of the hybrid system, where it governs the signal flow from and to the connected load as demonstrated in the ensuing paragraphs.

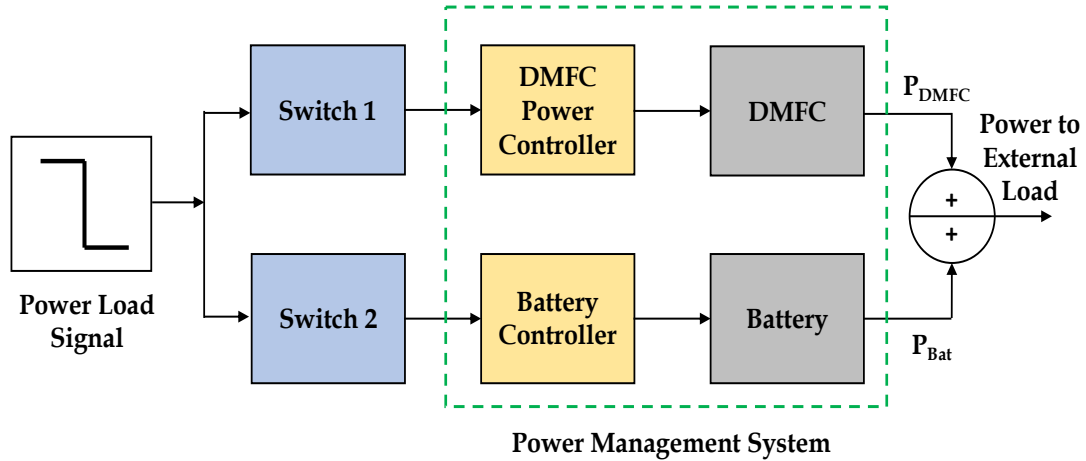


Figure 6: DMFC/battery hybrid system power signal flow diagram

As shown in Figure 6 , the process is initialized by sending the signal of the external load to PMS, which makes a decision based on a logical configuration whether to pass that signal to DMFC only or to combine the battery in the loop. As such, the power set

point is defined by the load signal (P_L) which has to be satisfied by either DMFC only or the combination of both devices (DMFC and battery). Once that power is calculated properly by PMS, the loop is closed by sending the power signal to the load to satisfy its requirement. Since the objective of this study is to depend mainly on DMFC with minimizing the use of battery, Switch 1 is always kept open unless there is a shutdown of the DMFC for any reason such as a safety concern or a fault of the device which necessitates to isolate it from the process. On the other hand, Switch 2 is open in the states where battery is needed while it is kept closed in other occasions. It should be noted that the power of the battery is assumed to be zero at the initialization state.

Figure 7 demonstrates the logical configuration of the proposed PMS with the integration of DTC controller. The diagram explains the possible cases encountered during the operation of the hybrid system, wherein the logic makes the selection of the device to be used at a specific case scenario along with the calculated amount of power delivered to the external load. The reader should observe the following points to follow the logic presented in Figure 7.

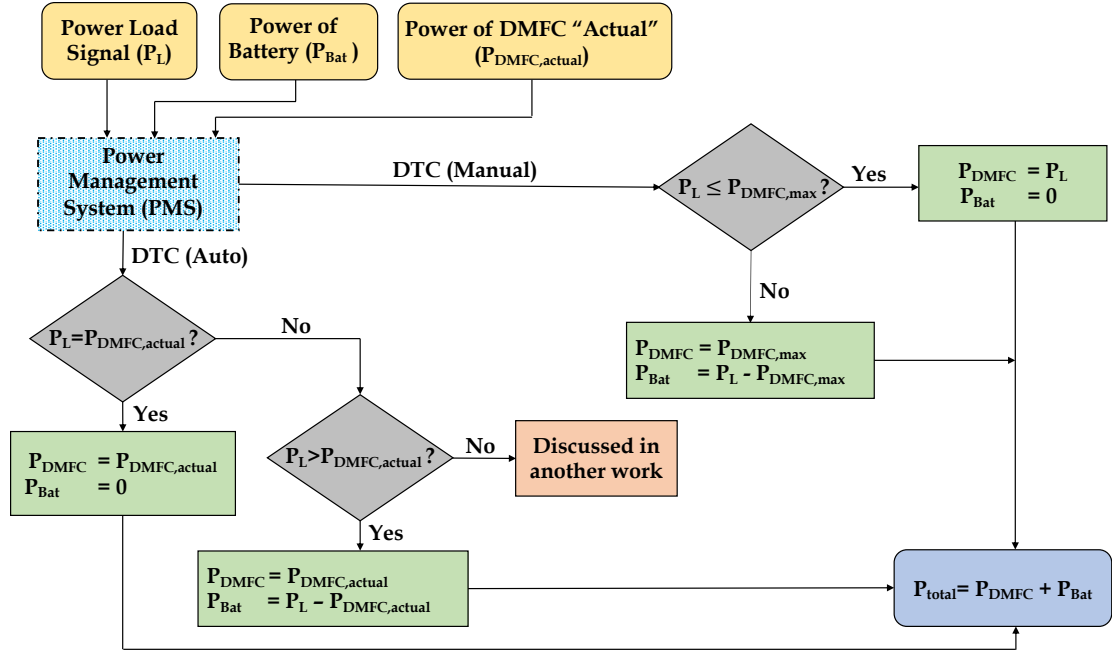


Figure 7: Logical configuration of DMFC/battery hybrid power management system (PMS)

- The symbol P_L refers to power's load which is considered as the set point received by PMS
- The symbol P_{DMFC} refers to the power that PMS assigns to DMFC such that it is delivered to the load
- The symbol P_{Bat} refers to the power of battery calculated by PMS to be delivered partially to the load
- The symbol P_{total} refers to total power calculated by PMS which is delivered to the load. Ideally, P_{total} should be equivalent to P_L . In other words, if PMS is successful, total power (DMFC + battery) delivered to the load should be the same as the set point P_L when the process is initialized.
- The symbol DTC (manual) means that the controller is in manual mode, which implies that master LC and slave TC are decoupled ($f(t) = 0$).

- The symbol DTC (auto) means that the controller is in automatic mode, which implies that master LC and slave TC are connected ($f(t) = 1$).

The logic works by starting from the load signal received by PMS. At the same time, PMS acquires the reading signals of DMFC and battery power on real time basis. The first task of PMS is to check whether DTC (the same controller shown in Figure 2 but with the improvement discussed in Section 3.2) is operating at manual mode ($f(t) = 0$) or automatic mode ($f(t) = 1$). In case that DTC is at state of manual, where the temperature can be selected freely and hence the power of DMFC can be changed from one state to another, then the possible cases are:

- 1) Power of load is less than or equal to the maximum possible power obtained by DMFC ($P_{DMFC, max}$) in which case the delivery of power to the load can be implemented solely by DMFC due to the ease of transition from one value to another
- 2) Power of load is greater than $P_{DMFC, max}$ in which case DMFC cannot generate more than its maximum limit and hence the excess power is provided by the battery to the load

On the other hand, the cases at which the controller is at auto state are slightly more complicated. To reinstate, if the DMFC is initiated at a certain temperature while at automatic mode, there is no room of changing the thermal state of DMFC and hence the power generated cannot be altered from one value to another. For the sake of

demonstration, let us say that DMFC is initially operating at 40 W (we call it $P_{DMFC, actual}$) then the possible cases are:

- 3) Power of load is exactly equal to $P_{DMFC, actual}$, in which case the delivery of power is achieved by DMFC without the battery
- 4) Load requirement is greater than $P_{DMFC, actual}$. In this state the delivery to the load is done by both DMFC and battery. Notice that even if P_L is less than $P_{DMFC, max}$, nothing can be done to increase the actual DMFC power in this case due to the coupling between master LC and slave TC
- 5) Power load is less than $P_{DMFC, actual}$ in which case DMFC has excess power over the load requirement. This case is beyond the scope of this work and is treated in the upcoming extended work. The reason is that the excess power of DMFC has to be managed by its delivery to the battery (if needed) or to another part of the plant of the system. In addition, further hardware such as switches, and other parts are need for this case to be studied. Table 1 makes a good summary for all of the cases discussed.

Table 1: Case studies for integrating DTC algorithm in PMS of DMFC/battery hybrid system

<i>Case</i>	<i>DTC Mode</i>	<i>Power Load Signal (P_L)</i>	<i>Power Delivery Device</i>
1	Manual ($f(t) = 0$)	$P_L \leq P_{DMFC, max}$	DMFC only
2	Manual ($f(t) = 0$)	$P_L > P_{DMFC, max}$	DMFC + Battery
3	Auto ($f(t) = 1$)	$P_L = P_{DMFC, actual}$	DMFC only
4	Auto ($f(t) = 1$)	$P_L > P_{DMFC, actual}$	DMFC + Batter
5	Auto ($f(t) = 1$)	$P_L < P_{DMFC, actual}$	Beyond the scope of the study

As stated earlier, the novelty of this work lies in the dependence mainly on DMFC while minimizing the use of battery in the hybrid system. It should be noted that this goal can be achieved by making DMFC to operate most of the time at manual mode of DTC ($f(t) = 0$). In this case, there is a great flexibility of manipulating and changing the power. based on results referenced in (Alyousef, 2020) ,the simulation results demonstrate that DMFC can operate for a very long time in manual mode. However, this work is not devoted for that topic and the reader is advised to consult the given reference for more insights. Furthermore, choosing a system where the maximum power of DMFC is very large minimizes the case scenario 2. Thus, in principle the system can be operated most of the time to depend on DMFC.

3.4. Impact of Proposed Hybrid Configuration on Battery Life

The proposed hybrid system configuration has several advantages that can be realized. First, the main dependence on DMFC while minimizing the use of battery extends its lifetime. This can be explained from the viewpoint of battery life cycles since less utilization results in decreasing the number of battery operating cycles and ultimately slowing the aging process (Broussely et al., 2005). The aging in batteries is mainly related to the formation of surface electrode interface (SEI) with every cycle resulting in increasing resistance and reducing the capacity of batteries (Hellwig, 2013). According to (Vetter et al., 2005), SEI occurs at the start of each cycle, and it is accompanied with the corrosion of lithium in the active carbon impacting battery capacity due to low concentration of active lithium ion (Nitta et al., 2015) (Lin et al.,

2013). Figure 8 illustrates how the discharged capacity for Li-ion battery decreases as the number of cycles increases in comparison to DMFC (Klett, 2014) (Xie et al., 2020). Second, less use of battery implicates that this device can be considered as a backup for the hybrid system. Consequently, the hybrid system size can be significantly reduced to a good extent which ultimately cuts the capital cost and that is considered a plus from economic point of view. Finally, the efficiency of the hybrid system can be improved since there is a great flexibility for the power optimization in the hybrid system. However, further studies and investigation should be performed for this aspect to be evident.

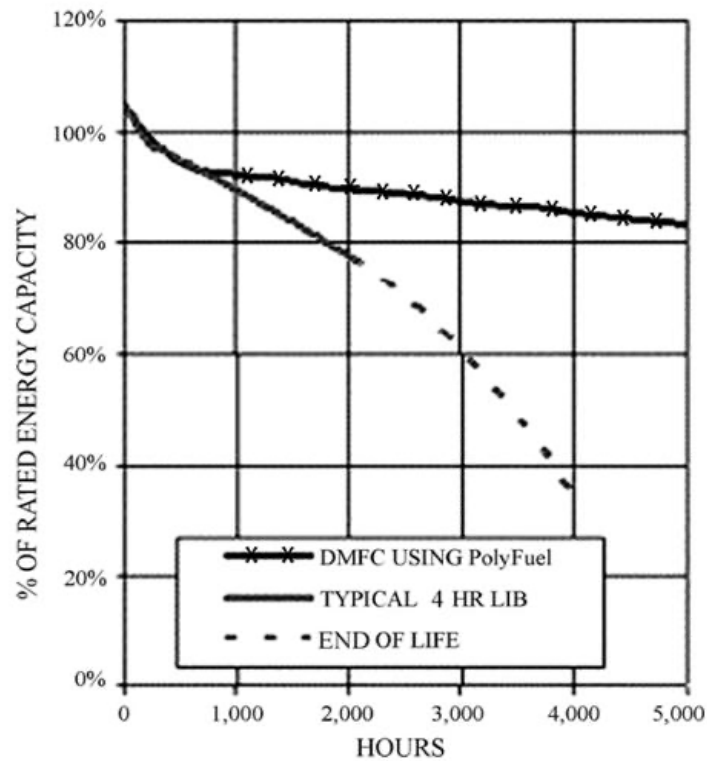


Figure 8 Capacity degradation of Lithium-ion battery and DMFC as a function of operation time (Horuz et.al. 2008)

3.5 Hybrid System Model and Methodology of Testing

The hybrid system used in this study is thoroughly modeled and tested in simulation environment. For DMFC, a comprehensive mathematical model that is based on first principles of material and energy balances as well as thermodynamics and transport phenomena is developed by (Mudiraj et al., 2015). Indeed, both steady state and dynamic modeling are constructed and simulated in MATLAB and Simulink environment. It should be noted that the model is also validated experimentally and thus the simulation produces reliable results that can be used for control and optimization studies or analysis. The Li-ion battery, on the other hand, is simulated using an existing software suite in MATLAB Simulink and is coupled with the software of DMFC dynamic model in the same environment. The last step is to develop a combined integrated model combining the DMFC and battery. Part of this model, input signals will be defined such as power of the load and power of the DMFC. Also, governance will be defined such as the maximum power of DMFC. Furthermore, PMS will be constructed to govern the power distribution between DMFC and battery. A representation of this integrated model is in Figure 9

The PMS logic is developed using MATLAB code and is embedded in the same simulation environment of both DMFC and Li-ion battery for testing the software. As mentioned earlier, PMS can be considered as a high-level controller governing the power that goes from and to both DMFC and battery. The reader should observe that further studies about control strategies for DMFC system are conducted by (Mudiraj, 2015) but their focus is beyond the scope of this work and therefore are mentioned

whenever needed in this manuscript for the sake of clarifying some concepts or points. Table 2 and Table 3 list the main parameters and information that may interest the reader for both DMFC and Li-ion battery.

The testing of the new logic is presented in two stages: (i) DTC in DMFC only and (ii) PMS in the hybrid system. DTC is detailed in (Alyousef, 2020) but the relevant results are presented in the ensuing section. The algorithm of DTC is tested by introducing a step change in the requested power of the load and the response of controlled variables in DMFC (liquid-level, temperature and output power) are shown. Furthermore, DTC is compared to standard cascade such that the reader can observe the effect of the improvement. In the second stage, PMS is integrated within the whole hybrid system (DMFC and Li-ion battery) such that it is tested by introducing step changes in the requested power of load, as well. The response of both DMFC and battery output powers are shown and hence the success of PMS can be observed by satisfying the required load signal in various case scenarios as shown in Section 4.2. The reader should observe that this work is not intended to give further details about satisfying voltage or current requirements of the load; it is merely focused on the power in whole (product of current and voltage). Such details are treated in the extended version to this work.

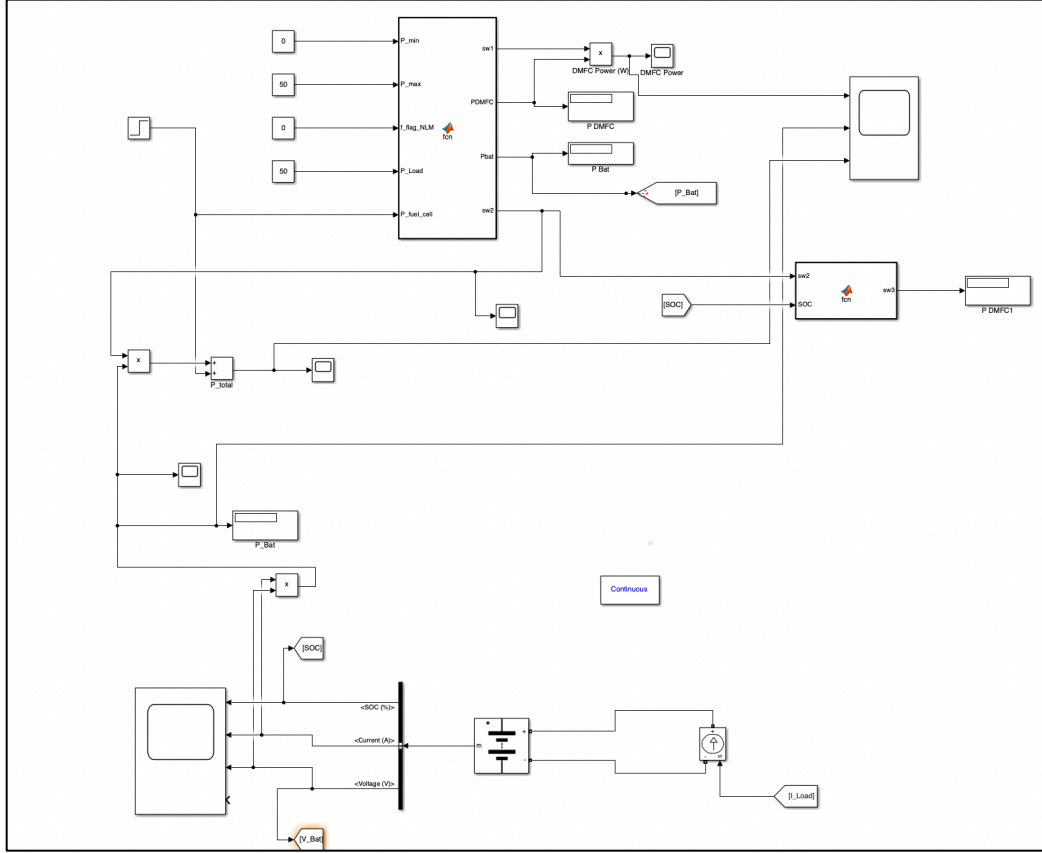


Figure 9 : Matlab combined integrated model combining DMFC & Battery

Table 2: Some parameters of DMFC for simulation study (Al-Yousef et al., 2019)

<i>Parameter</i>	<i>Value</i>	<i>Unit</i>
Ambient air temperature	30	°C
Anode fuel-mixture flow rate per cell (methanol solution)	1.3	mL min ⁻¹
Number of cells in the stack	40	[-]
Faraday's constant	96,485	C mol ⁻¹
Methanol concentration set point in the tank	0.8	M (mol L ⁻¹)
Liquid level set point (L_{SP})	70	%
Maximum power of DMFC (assumed for simulation study)	50	W

Table 3: Important parameters of Li-ion battery for simulation study

<i>Parameter</i>	<i>Value</i>	<i>Unit</i>
Nominal voltage	4	Volts
Fully charged voltage	4.66	Volts
Rated capacity	10	Ampere-hour
Nominal discharge current	4.35	Ampere
Internal resistance	0.007	Ω (Ohms)

CHAPTER 4

Results & Discussion

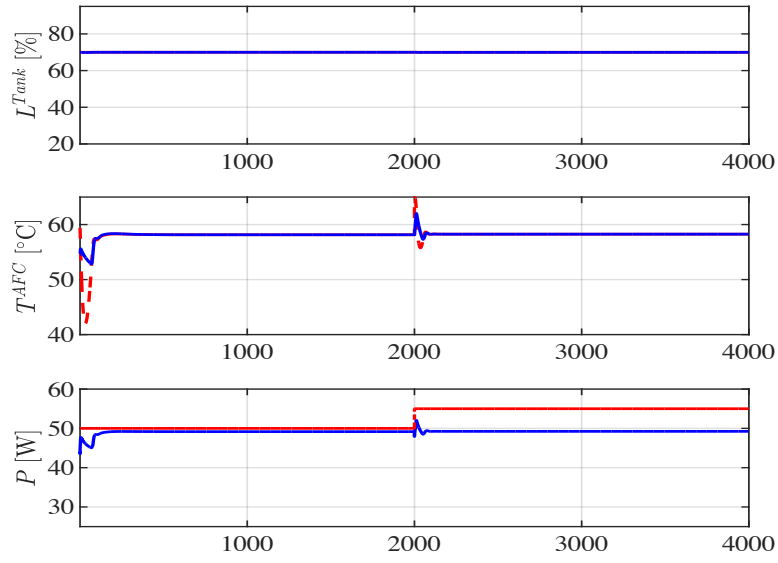
This chapter is dedicated to present the dynamic response simulations of the system under study. The first part covers a summary of DMFC simulations under the use of standard cascade (SC) and dual threshold cascade (DTC) controllers for the purpose of comparison. This gives the reader some insight about the benefits realized from using DTC algorithm. The second part is devoted for discussing the simulations of the proposed PMS of DMFC/battery hybrid configuration via utilization of DTC algorithm. The results are used to demonstrate the response of the hybrid system under the four cases (1 to 4) presented in Table 1. Ultimately, a conclusion can be drawn about the efficiency of such hybrid control structure to satisfy external load requirement in a way that achieve the objective of this dissertation

4.1. Dynamic Response of DMFC Under Standard Cascade and Dual Threshold Cascade Controllers

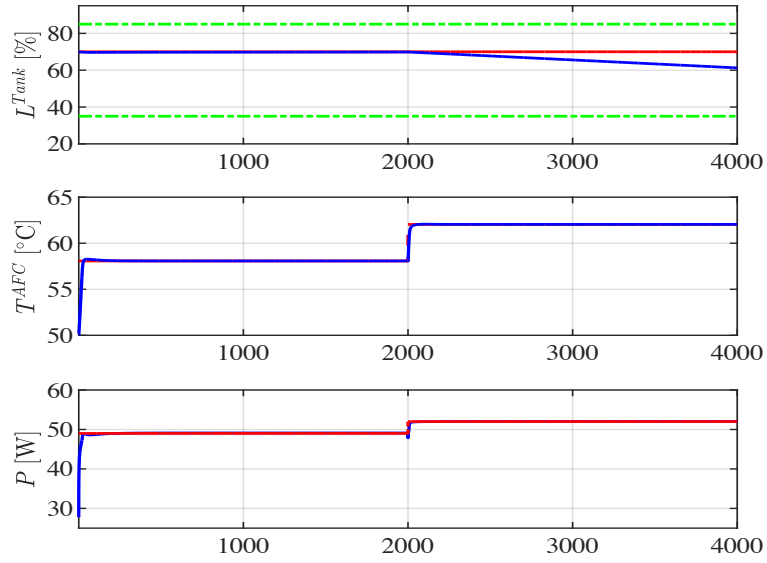
Figure 10a simulates the dynamic response of the stand-alone DMFC while operating under standard cascade (SC) control mode. The figure includes 3 subplots showing tank level L^{Tank} [%] at the top, temperature response in anode flow channel T^{AFC} [°C] in the middle, and the resulting power P [W] from DMFC at the bottom, all as a function of time in seconds. In the power subplot, the dashed-dotted line represents the requested signal of

external load while the continuous line represents the actual power produced by DMFC. Observing the power plot, the requested signal by load is initialized at 50 Watts as shown by the dashed-dotted line. This signal is sent to the power controller of DMFC. However, the actual power delivered by DMFC settles at approximately 49 W and does not change despite the requested signal of the load. During this time, it is observed that the temperature remains at approximately 58°C and the level of the tank stays at the set point of 70 % capacity. At 2000 seconds, a step change in load signal is introduced rising from 50 to 55 W. It is observed that there is a spike in power taking place at that moment and then it returns to the original value of 49 W. The temperature response also displays a spike at 2000 seconds and returns thereafter to the value of 58°C, while the tank level remains unchanged and continues at 70 % capacity. This response of DMFC is attributed to the fact that the temperature cannot be altered or changed due to the complete coupling between the master LC and slave TC in the standard control (SC) structure. As a result, the power delivered, which is affected directly by the temperature cannot be changed either and remains at the same state throughout the simulation (49 W). It is noted, therefore, that in SC controller the liquid-level is continuously monitored but that comes with failing to freely adjust or optimize other crucial variables, namely the temperature and the electrical power.

Figure 10b, on the other hand, simulates the dynamic response of stand-alone DMFC but under dual threshold cascade (DTC) algorithm. The figure contains three subplots similar in their representations to those in Figure 10a. In the tank level plot, the dashed-dotted lines represent the two thresholds. Focusing on power subplot, the requested power signal of the load is initialized at 49 W which is sent to the power controller. In response to that request, DMFC reacts successfully where the power is transitioned to 49 W, as observed from the continuous line. During this interval, DMFC temperature is also transitioned to the value of 58°C equivalent to the power of 49 W, whereas the level remains constant at the set point of 70 %. At 2000 seconds, a step change in load signal from 49 to 51 Watts takes place resulting in DMFC to shift its power from 49 to 51 W, which satisfies load requirement. Simultaneously, the temperature of operation is shifted from 58 to 62 °C, while the tank level in this time deviates from the set point (allowed by the DTC logic), but it remains within the band enclosed by the upper and lower thresholds. This success of transitioning DMFC power to meet load demand is attributed to the segregation of the primary level and secondary temperature controllers, enabling the power controller to freely change the temperature of operation and ultimately operating at the power requested by the load. The reader should be aware that the simulation results here represent part of DTC behavior wherein $f(t) = 0$ (manual mode). If the simulation continues for a long time at the temperature of 62 °C, it is anticipated that the lower threshold will be reached and the controller mode is switched to the auto mode with $f(t) = 1$. Further elaboration about those results is found in (Alyousef, 2020)



(a) DMFC Dynamic response under SC level controller



(b) DMFC Dynamic response under DTC controller

Figure 10 :Dynamic Responses of liquid-level L^{Tank} [%] , temperature in anode flow channel T^{AFC} [°C], and output P [W] of DMFC as a function of time

4.2. Dynamic Response of DMFC/Battery Hybrid System Using PMS with Various Scenarios

This subsection presents the dynamic response of DMFC/battery hybrid configuration using proposed PMS with integrated DTC algorithm in the system. The generated responses are conducted for the purpose of explaining various case scenarios of the DTC controller, i.e. whether on manual or auto mode. The reader should observe that input variables to PMS at any given time of the process are (i) the requested load signal P_L , (ii) the switching function $f(t)$ defining the status of DTC controller (whether manual or auto), (iii) the actual power of the DMFC, and (iv) the power of battery. The outputs from PMS are the calculated power of DMFC and battery which are sent to the respective controller, such that summation of those power values is equivalent to the set point P_L . As indicated in Table 2 and for demonstration purposes, the maximum attainable power delivered by DMFC is assumed to be 50 W. In all ensuing figures, upper plot represents the power requested by the load P_L , second subplot is DMFC power response regulated by PMS, third is battery power response while fourth is merely a summation of DMFC and battery power values. Ideally, the fourth plot should be equivalent to the first one (set point) if the system is successful. In all responses, DMFC is initialized at power of 47 W.

Figure 11 shows the response of PMS for the case where DTC is on manual mode corresponding to $f(t) = 0$. This case can be considered as an extension to the simulation of Figure 10b (considering DMFC operation) but with different numbers. In other words, the master LC and slave TC are decoupled. Initially, the requested load signal is 47 W.

Since the status function $f(t)$ of the DTC is at 0, DMFC has the ability to change its power easily from one state to another, as the temperature can be freely altered by the power controller. The requested load is 47 W which is less than $P_{DMFC, max}$ and therefore PMS can deliver this power solely by DMFC while the battery stays uncalled. At 2000 seconds, a higher power is requested by the load rising to 50 W. The reader has to observe that $f(t)$ is still at status of 0 (manual) in which case DMFC can shift its power. Since 50 W is exactly equivalent to $P_{DMFC, max}$, the power delivery to the load is administered again by DMFC only. It can be seen that this simulation corresponds to Case 1 presented in Table 1. To reinstate, the success of the delivery by DMFC only is attributed to the ability of power shift as DTC is on manual mode.

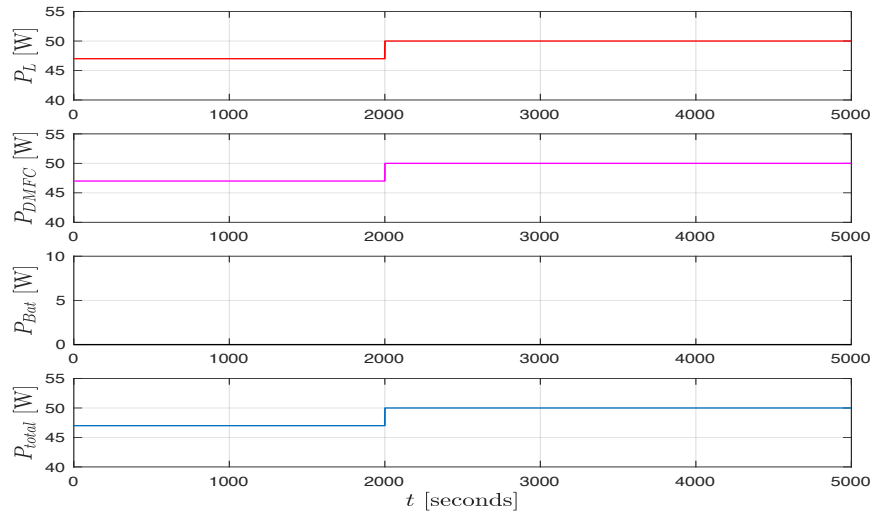


Figure 11 : Case 1: dynamic response of DMFC/battery system for load change of 47 W to 50 W with DTC on manual mode ($f(t) = 0$)

Figure 12 shows the response of PMS for the case where DTC is still on manual mode corresponding to $f(t) = 0$. The initial part of the simulation (from time 0 till before 2000 seconds) matches that of Figure 11. At 2000 seconds, the power of the load is raised from 47 to 52 W. Notice that the new requested load exceeds the maximum deliverable power by DMFC which is 50 W. It is true that DMFC can still shifts its power (DTC is on manual mode), but it cannot satisfy the load requirement solely. Thus, DMFC delivers partial power of 50 W to the load as observed in the second subplot, while the battery sends the balance of the requested power and delivers 2 W to the load as shown in third subplot. It is observed that there is a slight transient response of the battery initially, accounting for its startup mechanism. The simulation from 2000 seconds of this figure corresponds to Case 2 of Table 1

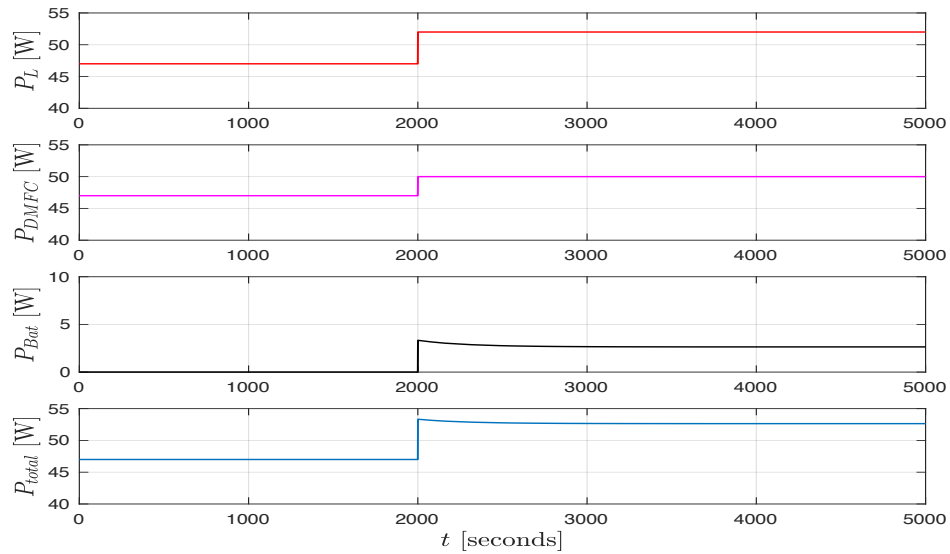


Figure 12 : Case 2: dynamic response of DMFC/battery system for load change of 47 W to 52 W with DTC on manual mode ($f(t) = 0$)

Figure 13 shows the response of PMS for the case where DTC is on auto mode corresponding to $f(t) = 1$. It should be noted that in such case the master LC and slave TC are connected, leading to the fact that the temperature is no longer a free variable of change to the power controller. Hence, the power of DMFC cannot be altered. This case could be thought of as an extension to the response in Figure 10a (considering DMFC operation) but with different values. Initially, the requested load $P_L(t)$ is 47 W which matches the initial operating and actual power of DMFC ($P_{DMFC,actual}$). Thus, the fuel cell can satisfy load requirement without invoking the battery. This part of simulation matches Case 3 given in Table 1. The reader should be cautious, however, that this case is not exactly similar to Case 1, though they seem matching at first glance. The reason lies in DTC mode, which is on manual in Case 1 while it is on auto at Case 3. The implications on power shift are evident to the reader at this stage.

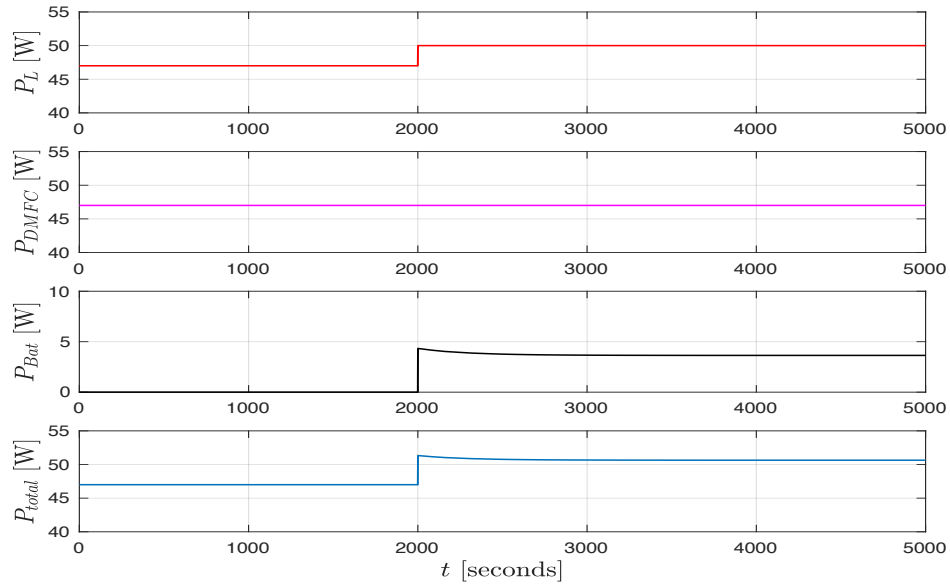


Figure 13 : Case 3&4: Dynamic response of DMFC/battery system for load change of 47 W to 50 W with DTC on auto mode ($f(t) = 1$)

At 2000 seconds, the power of the load experiences a rise to 50 W as observed in first subplot of figure 13. Again, the mode of DTC remains here is at auto state. It is evident from DMFC power subplot that it remains at the value of 47 W, though the requested load signal is exactly similar to $P_{DMFC,max}$. However, DMFC fails to change its power due to the coupling between primary LC and secondary TC. Consequently, the fuel cell delivers only 47 W to the load while the remaining 3 Watts are administered by the battery as shown in the third subplot. This part of simulation corresponds to Case 4 given in Table 1. Although this mode of operation manages to satisfy load requirement, it fails to optimize the power utilization of hybrid system. Table 4 summarizes the simulation results of Figures 11, 12 & 13.

Aside: the reader should observe that the responses of the second and third subplots in Figures 11, 12 & 13 are for DMFC and battery devices, respectively. To clarify, those are NOT the output signals of PMS. Rather, those are the simulated outputs by the dynamic model of DMFC and the model of Li-ion battery utilized from MATALB and Simulink software suits as discussed in Chapter 3. The output signal of PMS is sent to DMFC and battery controllers, which define power setpoint for each device. Accordingly, DMFC and battery make the output power displayed in the aforementioned figures as directed by the decision of PMS.

Table 4:DMFC/battery hybrid system response using PMS integrated with DTC

<i>Case</i>	<i>Figure observed</i>	<i>DTC mode</i>	<i>Initial load power (W)</i>	<i>Final load power (W)</i>	<i>Power delivery to load</i>
1	10	Manual	47	50	DMFC only
2	11	Manual	47	52	DMFC (50 W) + Battery (2 W) [after 2000 seconds]
3	12	Auto	47	50	Case 3 (0 to time before 2000 seconds): DMFC only (47 W)
4	12	Auto	47	50	Case 4 (2000 seconds to end): DMFC (47 W) + Battery (3 W)

4.3. Economic Analysis

Economic analysis was conducted to estimate the cost of satisfying a certain load requirement of 40 Watts through operating DMFC/battery hybrid system in comparison to operating a lithium-ion battery alone. The evaluation considered a short and long-term operation of both systems over 7 years period based on a set of assumptions listed in Table 5 (Rashidi et al., 2009), (Dyer, 2002)

For short-term operation, operating the battery system alone will be the attractive option from economic point of view. The long-term operation of both systems, beyond 3 years, shows the DMFC/battery hybrid system to be a cost-effective and competitive option in comparison to utilizing battery alone. In the 4th year as an example, operating battery system alone to supply the power demand requires six batteries with an estimated total cost of \$498 while operating DMFC/battery hybrid system will have a total cost of \$411. Accordingly, 17 % cost reduction could be realized in that year through the utilization of

DMFC/battery hybrid system. It's worth highlighting that cost saving of operating DMFC/battery hybrid system could be achieved while operating the system for an extended period is due to the higher capital cost of DMFC relative to the conventional Lithium-ion battery. Operating the proposed DMFC/battery hybrid system where DMFC will be the main power source and battery as a secondary source, beyond initial assumptions of equal energy split between battery and DMFC/battery, will maximize the cost reduction opportunity beyond 17% taking the 4th year as an example. Figure 14 shows the economic analysis of DMFC/battery hybrid system versus battery as a function a time, and it shows the DMFC/battery hybrid starting to be cost competitive to battery system during the second year of operation.

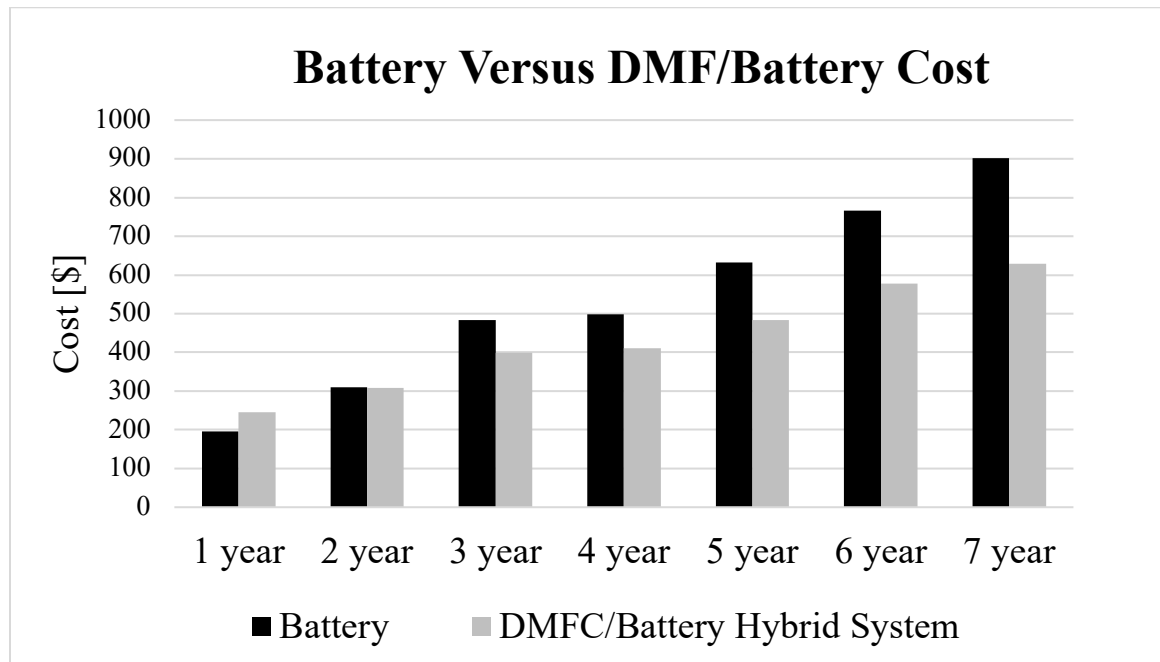


Figure 14 : Cost of operating battery system versus DMFC/Battery Hybrid system over the years

Table 5:DMFC & battery assumptions for economic evaluation (Dyer, 2002), (Rashidi et al., 2009)

System	Assumptions
Power Demand	40 W (constant load) 5 hours per day
Battery System	100 Wh rechargeable battery number of cycles = 500 Operation time per cycle = 5 hr, Manufacturing cost [$\$ \text{Wh}^{-1}$] = 0.6 Electricity for charging = \$ 0.2 per kWh, AC adapter cost = \$ 40 W
DMFC	Material cost = \$ 5 per W Methanol Fuel Cross over = $4.0 \times 10^{-8} \text{ mol cm}^{-2} \text{ s}^{-1}$ Methanol Concentration = 2 molar Power density= 80 mWcm^{-2} Fuel cell thickness = 3 cm Methanol concentration = 2 molar
DMFC/Battery Hybrid System	1:1 Power split of the 40 W between DMFC & Battery

CHAPTER 5

Conclusion & Recommendations

A hybrid device of methanol fuel cell/Li-ion battery with an improved power management system is discussed in this work. The algorithm of dual threshold cascade is embedded in PMS to enhance the power delivery, distribution to the connected load and minimizes the dependence on the battery of the hybrid system, which adopts a parallel configuration. The algorithm of DTC (installed in DMFC) works in a fashion of disconnecting the master level controller and temperature slave controller intermittently (called manual mode of operation), at which case the power of the cell can be shifted from one state to another. As such, DMFC can satisfy the load demand in those periods without the use of battery. The study is conducted in a simulation environment using a comprehensive dynamic model of DMFC and an established model of Li-ion battery using MATLAB and Simulink software. The results demonstrate that DTC when on manual mode enables DMFC to easily change its power, due to the freedom of selecting the temperature of the cell. Upon integrating DTC in PMS, the hybrid system can eliminate the use of battery on many occasions. An example is when the external load requests a power of 50 Watts, corresponding to the maximum threshold of DMFC deliverable power. The results show that PMS successfully delivers the entire power to the load using DMFC only while the battery stays on sleep mode (at the case where DTC is still on manual operation). Other case scenarios are discussed as well, and PMS shows a smooth operation of delivering the power to the load.

The advantages realized from such improved PMS are several, such as extending the battery lifetime due to slowing its aging process.

In addition, economic analysis was conducted by comparing the option of utilizing battery system alone versus a hybrid system of DMFC/battery to satisfy external power load requirement over the years. The results suggest that operating the DMFC/battery hybrid system for an extended period of time beyond 3 years will be more cost-effective option in comparison to battery alone with a cost reduction opportunity of 17% and higher.

The results of this work show a promising technological advantage of proposed PMS but further work is needed to advance this study. Using this system in a practical application with actual hardware settings would further prove its feasibility. In addition, a real-time optimization work to improve the efficiency of the hybrid device and carefully select the operational parameters of the system is recommended. In addition, more factors can be considered part of the dynamic response of battery such as battery state health that will be important on the hybrid system power distribution.

References

- [1] Alyousef, Z. A. (2020). *IMPROVED CONTROL OF DIRECT METHANOL FUEL CELLS VIA MULTIVARIABLEMETHODS*. University of Florida.
- [2] Al-Yousef, Z. A., Mudiraj, S. P., & Crisalle, O. D. (2019). Improved Cascade Control Structure for Water and Thermal Management in Open-Cathode Direct Methanol Fuel Cells. *2019 American Control Conference (ACC)*, 5480–5486.
<https://doi.org/10.23919/ACC.2019.8814357>
- [3] Azib, T., Hemsas, K. E., & Larouci, C. (2014). Energy Management and Control Strategy of Hybrid Energy Storage System for Fuel Cell Power Sources. *International Review on Modelling and Simulations (IREMOS)*, 7(6), 935. <https://doi.org/10.15866/iremos.v7i6.4620>
- [4] Bandyopadhyay, S., & Nandan, B. (2023). A review on design of cathode, anode and solid electrolyte for true all-solid-state lithium sulfur batteries. *Materials Today Energy*, 31, 101201.
<https://doi.org/10.1016/j.mtener.2022.101201>
- [5] Blum, A., Duvdevani, T., Philosoph, M., Rudoy, N., & Peled, E. (2003). Water-neutral micro direct-methanol fuel cell (DMFC) for portable applications. *Journal of Power Sources*, 117(1–2), 22–25.
[https://doi.org/10.1016/S0378-7753\(03\)00310-0](https://doi.org/10.1016/S0378-7753(03)00310-0)
- [6] Boukhniher, M., Ouddah, N., Azib, T., & Chaibet, A. (2016). Intelligent energy management for hybrid fuel cell/battery system. *COMPEL - The International*

Journal for Computation and Mathematics in Electrical and Electronic Engineering, 35(5), 1850–1864. <https://doi.org/10.1108/COMPEL-08-2015-0309>

- [7] Broussely, M., Biensan, P., Bonhomme, F., Blanchard, P., Herreyre, S., Nechev, K., & Staniewicz, R. J. (2005). Main aging mechanisms in Li ion batteries. *Journal of Power Sources*, 146(1–2), 90–96. <https://doi.org/10.1016/j.jpowsour.2005.03.172>
- [8] Dohle, H. (2002). Heat and power management of a direct-methanol-fuel-cell (DMFC) system. *Journal of Power Sources*, 111(2), 268–282. [https://doi.org/10.1016/S0378-7753\(02\)00339-7](https://doi.org/10.1016/S0378-7753(02)00339-7)
- [9] Dyer, C. K. (2002). Fuel cells for portable applications. *Journal of Power Sources*, 106(1–2), 31–34. [https://doi.org/10.1016/S0378-7753\(01\)01069-2](https://doi.org/10.1016/S0378-7753(01)01069-2)
- [10] Franzoni, D., Santi, E., Monti, A., Ponci, F., Patterson, D., & Barry, N. (n.d.). An Active Filter for Fuel Cell Applications. *IEEE 36th Conference on Power Electronics Specialists*, 2005., 1607–1613. <https://doi.org/10.1109/PESC.2005.1581845>
- [11] García, B. L., Sethuraman, V. A., Weidner, J. W., White, R. E., & Dougal, R. (2004). Mathematical Model of a Direct Methanol Fuel Cell. *Journal of Fuel Cell Science and Technology*, 1(1), 43–48. <https://doi.org/10.1115/1.1782927>
- [12] Gurau, B., & Smotkin, E. S. (2002). Methanol crossover in direct methanol fuel cells: a link between power and energy density. *Journal of Power Sources*, 112(2), 339–352. [https://doi.org/10.1016/S0378-7753\(02\)00445-7](https://doi.org/10.1016/S0378-7753(02)00445-7)

- [13] Hellwig, C. (2013). *Modeling, simulation and experimental investigation of the thermal and electrochemical behavior of a LiFePO₄-based lithium-ion battery.*
- [14] Hoogendoorn, J. (2018). *Fuel Cell and Battery Hybrid System Optimization Increased Range and Endurance.*
- [15] Jiang, Z., & Dougal, R. A. (n.d.). A Hybrid Fuel Cell Power Supply with Rapid Dynamic Response and High Peak-Power Capacity. *Twenty-First Annual IEEE Applied Power Electronics Conference and Exposition, 2006. APEC '06.*, 1250–1255. <https://doi.org/10.1109/APEC.2006.1620699>
- [16] Jongerden, M. R., & Haverkort, B. R. (2008). *Battery Modeling.* <https://www.researchgate.net/publication/239851603>
- [17] Junoh, H., Jaafar, J., Nordin, N., Ismail, A., Othman, M., Rahman, M., Aziz, F., & Yusof, N. (2020). Performance of Polymer Electrolyte Membrane for Direct Methanol Fuel Cell Application: Perspective on Morphological Structure. *Membranes*, 10(3), 34. <https://doi.org/10.3390/membranes10030034>
- [18] Kebede, A. A., Kalogiannis, T., Van Mierlo, J., & Bercibar, M. (2022). A comprehensive review of stationary energy storage devices for large scale renewable energy sources grid integration. *Renewable and Sustainable Energy Reviews*, 159, 112213. <https://doi.org/10.1016/j.rser.2022.112213>
- [19] Klett, M. (2014). *Electrochemical studies of aging in lithium-ion batteries.* Chemical Science and Engineering, Royal Institute of Technology.
- [20] Lin, X., Park, J., Liu, L., Lee, Y., Sastry, A. M., & Lu, W. (2013). A Comprehensive Capacity Fade Model and Analysis for Li-Ion Batteries.

Journal of The Electrochemical Society, 160(10), A1701–A1710.

<https://doi.org/10.1149/2.040310jes>

- [21] Ma, S., Lin, M., Lin, T.-E., Lan, T., Liao, X., Maréchal, F., Van herle, J., Yang, Y., Dong, C., & Wang, L. (2021). Fuel cell-battery hybrid systems for mobility and off-grid applications: A review. *Renewable and Sustainable Energy Reviews*, 135, 110119. <https://doi.org/10.1016/j.rser.2020.110119>
- [22] Mudiraj, S. P. (2015). *Advanced model-based control design for direct methanol fuel cell systems*. University of Florida.
- [23] Mudiraj, S. P., Biswas, M. A. R., Lear, W. E., & Crisalle, O. D. (2015). Comprehensive mass transport modeling technique for the cathode side of an open-cathode direct methanol fuel cell. *International Journal of Hydrogen Energy*, 40(25), 8137–8159. <https://doi.org/10.1016/j.ijhydene.2015.04.049>
- [24] Nitta, N., Wu, F., Lee, J. T., & Yushin, G. (2015). Li-ion battery materials: Present and future. In *Materials Today* (Vol. 18, Issue 5, pp. 252–264). Elsevier B.V. <https://doi.org/10.1016/j.mattod.2014.10.040>
- [25] O’Hyre, R., Cha, S.-W., Colella, W., & Prinz, F. B. (2016). *Fuel Cell Fundamentals*. Wiley Sons, Limited, John.
- [26] Pourrahmani, H., Gay, M., Yavarinasab, A., & Van herle, J. (2022). Optimization and dynamic responses of an integrated fuel cell and battery system for an 800 kW ferry: A case study. *Energy Reports*, 8, 9757–9776. <https://doi.org/10.1016/j.egyr.2022.07.144>

- [27] Rashidi, R., Dincer, I., Naterer, G. F., & Berg, P. (2009). Performance evaluation of direct methanol fuel cells for portable applications. *Journal of Power Sources*, 187(2), 509–516.
<https://doi.org/10.1016/j.jpowsour.2008.11.044>
- [28] Raszmann, E., Baker, K., Shi, Y., & Christensen, D. (2017). Modeling stationary lithium-ion batteries for optimization and predictive control. 2017 *IEEE Power and Energy Conference at Illinois (PECI)*, 1–7.
<https://doi.org/10.1109/PECI.2017.7935755>
- [29] Vetter, J., Novák, P., Wagner, M. R., Veit, C., Möller, K.-C., Besenhard, J. O., Winter, M., Wohlfahrt-Mehrens, M., Vogler, C., & Hammouche, A. (2005). Ageing mechanisms in lithium-ion batteries. *Journal of Power Sources*, 147(1–2), 269–281. <https://doi.org/10.1016/j.jpowsour.2005.01.006>
- [30] Vichard, L., Steiner, N. Y., Zerhouni, N., & Hissel, D. (2021). Hybrid fuel cell system degradation modeling methods: A comprehensive review. *Journal of Power Sources*, 506, 230071. <https://doi.org/10.1016/j.jpowsour.2021.230071>
- [31] Wang, J., Wang, H., & Fan, Y. (2018). Techno-Economic Challenges of Fuel Cell Commercialization. In *Engineering* (Vol. 4, Issue 3, pp. 352–360). Elsevier Ltd. <https://doi.org/10.1016/j.eng.2018.05.007>
- [32] Winkler, W., & Williams, M. C. (2014). Fuel Cells and Flow Batteries: A Comparative Process and Design Analysis. *ECS Transactions*, 56(1), 49–60.
<https://doi.org/10.1149/05601.0049ecst>

- [33] Xie, S., Hu, X., Zhang, Q., Lin, X., Mu, B., & Ji, H. (2020). Aging-aware co-optimization of battery size, depth of discharge, and energy management for plug-in hybrid electric vehicles. *Journal of Power Sources*, 450.
<https://doi.org/10.1016/j.jpowsour.2019.227638>

Vitae

Name : Majed Abdulbasit Aljeshi

Nationality : Saudi

Date of Birth : 7/10/1990

Email : maaljeshi@gmail.com

Address : 20082 Almidra Tower, Dhahran, Saudi Arabia

Academic Background: Majed A. Al-Jeshi is a Process Engineer specialized in the crude oil processing facilities and working with the process and control systems department in Saudi Aramco. His responsibilities include providing technical support to a corporate crude quality program, capital projects, technology evaluation & deployment, and facilitating the fourth industrial revolution for crude oil facilities. He holds a Bachelor of Science in chemical engineering from Colorado State University (Fort Collins, CO, USA).