DESIGN OF A 2x2 LINEAR MPC SCHEME FOR A SOLID OXIDE FUEL CELL

By

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Chemical Engineering Pogramme
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Approved by,

____

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

LEONG WAI CHUN

ABSTRACT

Fuel cell is one of the promising energy sources that produce electrical energy with almost zero pollutant. Although fuel cell had been invented for quite some time, it is only recently that fuel cell garners the attention in the energy industry for their clean electricity generation. Among all the available fuel cell, solid oxide fuel cell (SOFC) is one of the most interesting fuel cells types due to high energy efficiency, low emission from the chemical reaction, long-term stability, flexibility in options for fuel and low cost. Since the SOFC is to be used as an electrical source, there is a need to keep the fuel cell in a state of constant power output. Hence, maintaining a fuel cell system in correct operating conditions and a good control system is required. Model Predictive Control (MPC) proves to be an effective control strategy to control the power output of the SOFC.

In this paper, the problem statement is defined and an objective is developed. In literature review, the more in depth review will be done on SOFC and MPC. Other than that, literature review also discusses the application of MPC to fuel cell in general, not limiting to Solid Oxide fuel cell. A detailed methodology on how the project will be simulated is included in Chapter 3.. In Chapter 4, the results of the simulation of scenarios will be discussed. Conclusion for the overall activities which have been carried out for this project will be in Chapter 5.

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CHAPTER 1

INTRODUCTION

1.1. Background Study

The need for pollutant free and energy efficient energy source has brought many researchers to fuel cell technology. Fuel cell proves to be one of the promising energy technologies for the sustainable future with its high energy efficiency and environmentally friendly. A fuel cell is similar yet different from a battery. The similarity between them is such that they use chemical reaction to produce electrical energy. The difference is that a battery stores the reactant internally while a fuel cell reactant is stored externally. The application of fuel cell is very versatile as it can be used in either stationary or mobile applications. It can even be used to replace combustion engine in vehicles. Among the many types of fuel cells, the two most common and promising fuel cell is the proton electrolyte membrane fuel cell (PEMFC) and the solid oxide fuel cell (SOFC).

Control theory is an interdisciplinary branch of engineering and mathematics dealing with the behavior of a dynamic system. A control system consists of a detector, transducer, transmitter, controller and a final control element. These units in a control system are used to perform measurement, comparison, computation and correction in a dynamic system. Today, there is a variety of control systems employed in the industry. Among them is a control system called Model Predictive Control which have been used in process industries such as chemical plants and oil refineries.

Model predictive control (MPC) is an advanced method of process control. The models generally used in MPC are intended to represent the behavior of complex dynamical systems. This control approach is capable of performing multivariable system identification, performance monitoring and diagnostics, non-linear state estimation and batch system control.

1.2. Problem Statement

A fuel cell requires a continuous supply of fuel to continuously produce electrical energy. For the fuel cell be used in real life application, the fuel cell needed to have control system to ensure the fuel cell can provide a constant output when any disturbance is introduced to the system.

A fuel cell in real life application is a dynamic system. Hence there is a need for a control system to deal with any disturbance in the input variable or when a need to change the output variable of a system. Hence, there is a need to designing a control system for the fuel cell, such that any disturbance can be corrected to the set point value or changed to a different set point.

Solid oxide fuel cell is known to operate at high temperature. Therefore, there is a need to regulate the temperature of the fuel cell to prevent overheating while providing a constant voltage output by controlling the flow rate of reactants to the fuel cell.

1.3. Objective

The objective of this project is to design a Model Predictive Control for the dynamic model of a Solid Oxide fuel cell.

1.4. Scope of Study

The scope of study for this project is to design a Model Predictive Control for a 5 kW SOFC MATLAB/SIMULINK-based model developed at the Electrical and Computer Engineering Department at Montana State University by Caisheng Wang and M. Hashem Nehrir.

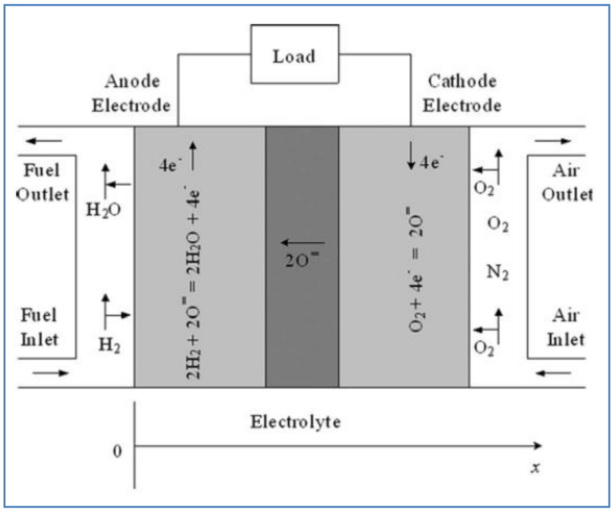
CHAPTER 2

LITERATURE REVIEW

2.1. Solid Oxide Fuel Cell (SOFC)

Among the types of fuel cell available, SOFC is considered to hold the greatest potential. A solid oxide fuel cell (SOFC) is an all-solid-state fuel cell based on a solid oxide electrolyte. The advantage of this fuel cell is high energy efficiency, low emission from the chemical reaction, long-term stability, flexibility in options for fuel and low cost. However, the operating temperature of a SOFC is rather high. The fuel cell usually operates at a temperature range of 600°C to 1000°C. This high temperature is the fuel cell disadvantages which results in the fuel cell longer start up time and compatibility issues (Zuo, Liu, & Liu, 2012).

Figure 1: Schematic representation of the operating principle of a SOFC



The electrochemically active component of a solid oxide fuel cell is the fuel cell itself. The fuel cell consists of 3 main parts namely; the anode, a solid oxide electrolyte and the cathode. In general, the oxygen at the cathode side are adsorbed, dissociated and reduced on the cathode surface into oxygen ion which is then moved through the electrolyte to the anode side of the fuel cell. Reaching the anode side of the fuel cell, the oxygen ions will then react with the fuel supplied at the anode of the fuel cell. Depending on the fuel, water, carbon dioxide or carbon monoxide will be formed as a product. In this case, hydrogen is used as the fuel which from water as product from the electrochemical reaction. In tangent to the reduction of the fuel at the anode, electrons will be travel along an external load circuit from anode to cathode of the fuel cell, converting chemical energy of the fuel to electrical energy.

The oxidation and reduction reaction on both anode and cathode side of the fuel cell can be represented by the reaction below:

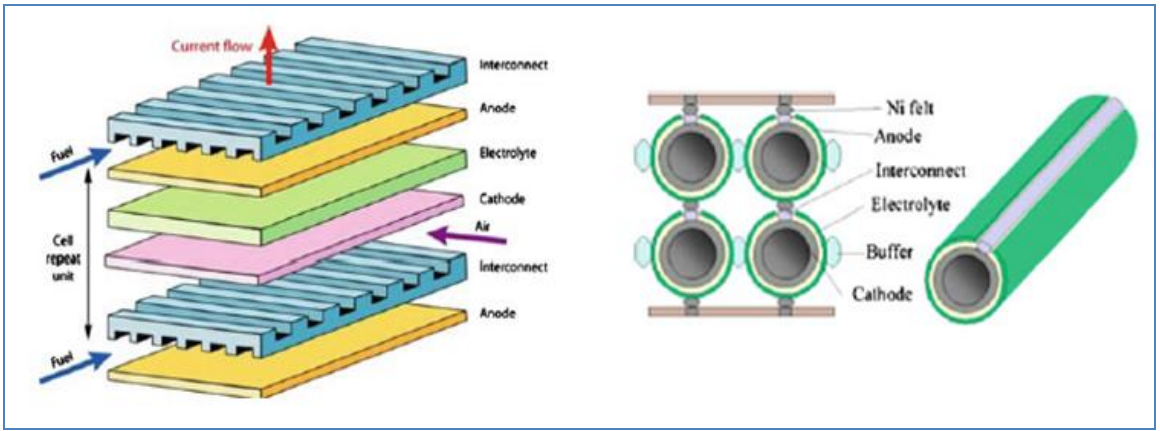
$$H_2 \rightarrow 2H^+ + 2e^-$$

$$\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$$

By combining the two half reaction above, the overall reaction for the fuel cell is as following:

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$$

Figure 2: Schematic for a planar (left) and tubular (right) SOFC design



There are two types of SOFCs in terms of cell structure as shown in the figure above. The left one is a SOFC with planar cell structure while the other one is a SOFC with a tubular cell structure. A comparison between a planar SOFC and a tubular SOFC is given in the table below (Zuo, Liu, & Liu, 2012):

Table 1: Comparison between planar SOFC and tubular SOFC

	Planar SOFC	Tubular SOFC
Power per unit area	Higher	Lower
Power per unit volume	Higher	Lower
Ease of fabrication	Easier	Difficult
Cost of fabrication	Higher	Lower
Ease of sealing	Difficult	Easy
Long term stability	Fair	Excellent
Thermo-cycling stability	Fair	Good

Earlier studies in SOFC were more focused on high temperature tubular SOFC systems. However, later on with the reduction of electrolyte thickness in the planar SOFC technology coupled with the higher power density compared to tubular SOFC and easier fabrication of the fuel cell, more interest are shown towards planar SOFC. It is not to say the tubular SOFC have lost in favor to planar SOFC as tubular SOFC is still favorable for portable application where rapid start up and cool down are required (Zuo, Liu, & Liu, 2012).

This paper will focus on a physically based dynamic model for tubular solid oxide fuel cell based on the electrochemical and thermodynamic characteristic inside a SOFC.

2.2. Model Predictive Control

Model predictive control (MPC) is an advanced method of process control. The models generally used in MPC are intended to represent the behavior of complex dynamical systems. This control has already been in the industry for more than 15 years serving as an effective means to deal with multivariable constrained control problem. This control approach is capable of performing multivariable system identification, performance monitoring and diagnostics, non-linear state estimation and batch system control. Problems like control objective prioritization and system aided diagnostic can be integrated systematically and effectively into the MPC framework by expanding the problem formulation to include variables yielding a mixed-integer quadratic of linear program (Monrari & Lee, 1999).

MPC offers several advantages compare to other control systems. One such advantage is that the process model captures the dynamic and static interactions between input and, output and disturbance variables. Another advantage is that constraints on inputs and outputs are considered in a systematic manner. Control calculation too can be coordinated with the calculation of optimum set point. An accurate model prediction by this control system can provide early warning of potential problems (Seaborg, Edgar, & Mellichamp, 2003).

2.3 MPC Application in Fuel Cell

It is only recently that fuel cell is seen as potential alternative energy resources. Hence there is little effort in research regarding the control study of fuel cell. The reason a control system is needed in a fuel cell system is because it is important for the fuel cell to achieve high efficiency while operating at condition where it won’t damage the fuel cell (Sanandaji, Vincent, Colclasure, & Kee, 2011). These are the several papers that apply Model Predictive Control strategy on a fuel cell.

2.3.1. Improved Model Predictive Control for a Proton Exchange Membrane Fuel Cell

In this paper (Fan, Zhang, Liu, & Shi, 2012), two improved model predictive controllers which use Laguerre function and exponential data weighting are proposed for the proton exchange membrane fuel cell to realize constant power output.

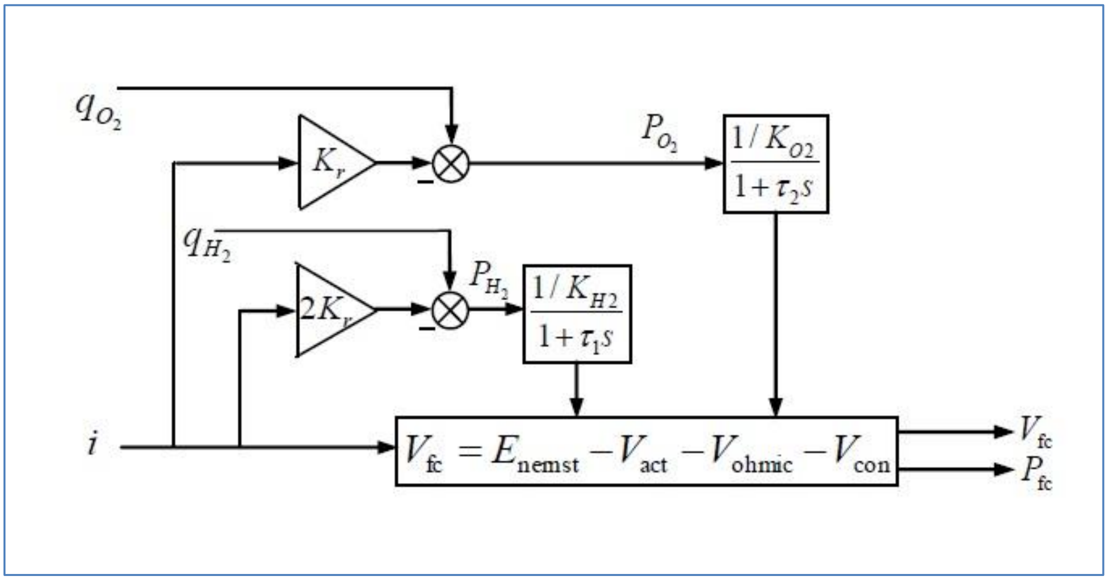


Figure 3: PEMFC dynamic model used in "Improved Model Predictive Control for a Proton Exchange Membrane Fuel Cell"

The figure above shows a generally accepted dynamic model of the PEM fuel cell, in which is used to develop the improved model predictive control. From the diagram, q_{O_2} is the input molar flow of hydrogen, q_{H_2} is the input molar flow of oxygen, K_{H2} is the hydrogen valve molar constant, and K_{O2} is oxygen valve molar constant. Based on the above described mathematical model, a Matlab/Simulink simulation model of the PEMFC can be set up.

In this paper, three control strategies are designed and compared which includes traditional MPC with reduced horizon control, improved MPC with Laguerre functions and improved MPC with exponential data weighting. These controllers are design for two control schemes. One is to control the output power by adjusting the hydrogen flow; the other is to control the output power by adjusting the oxygen flow.

The results of the control strategies are as shown below:

Figure 4: MPC and Laguerre based MPC with oxygen flow as the control variable

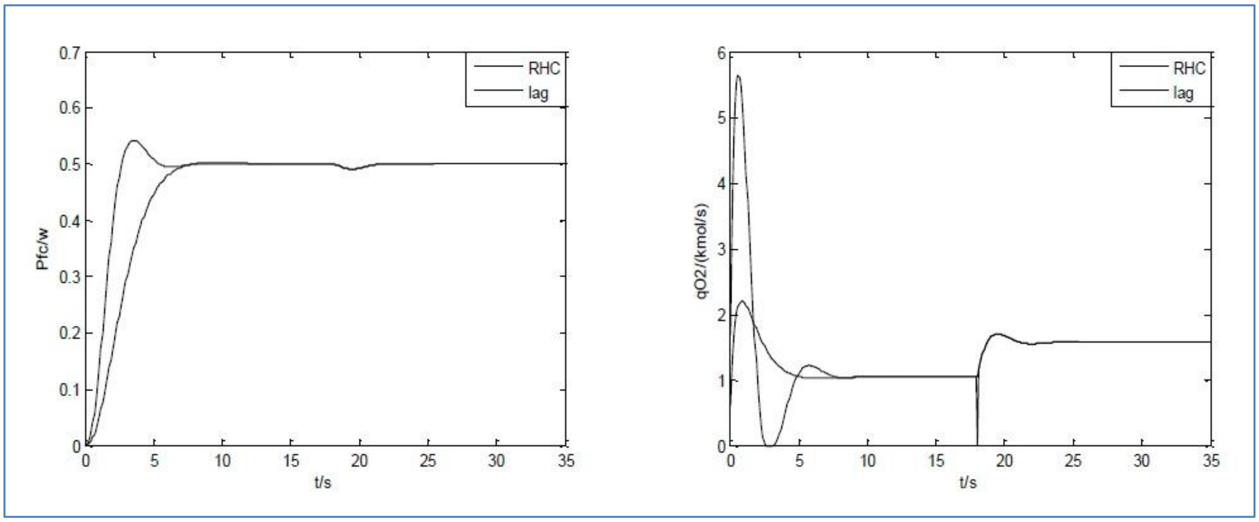
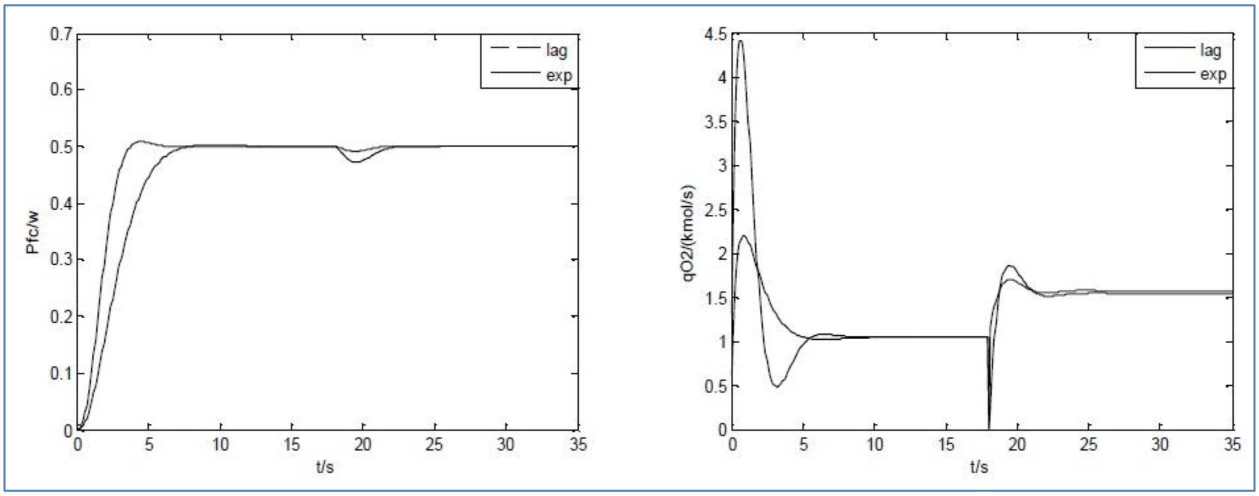


Figure 5: Improved MPC based on Laguerre function and exponential data weighting adjusting oxygen flow



From both Figure 4 and 5, it can be noted that the traditional MPC can make the system reach an elementary control objective roughly, but it cause big overshoot and long regulating time. The improved MPC with Laguerre functions or exponential data weighting can give better control effects.

Figure 6: Traditional MPC and Laguerre based MPC with hydrogen flow as the control variable

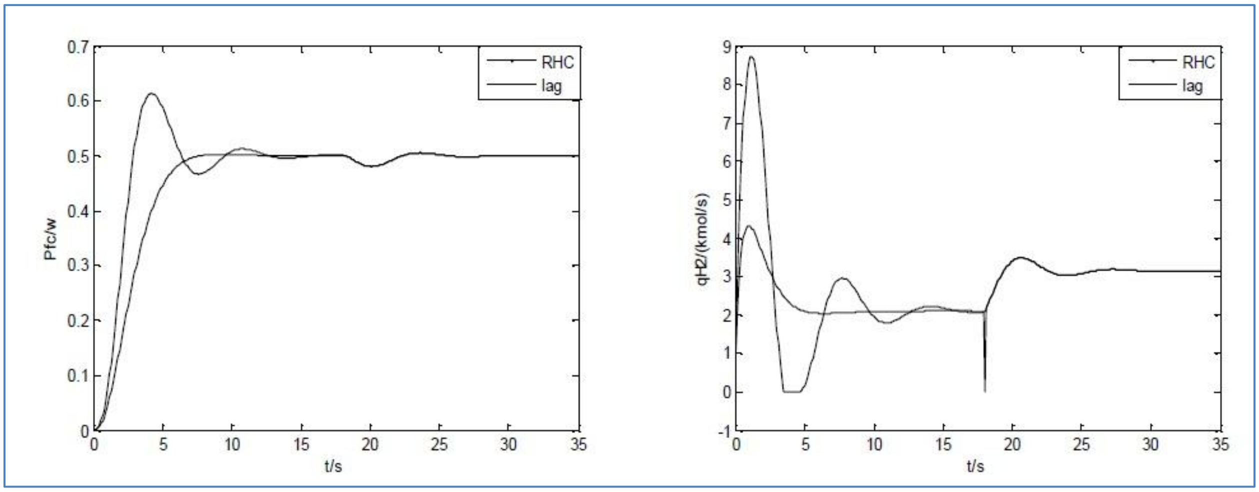
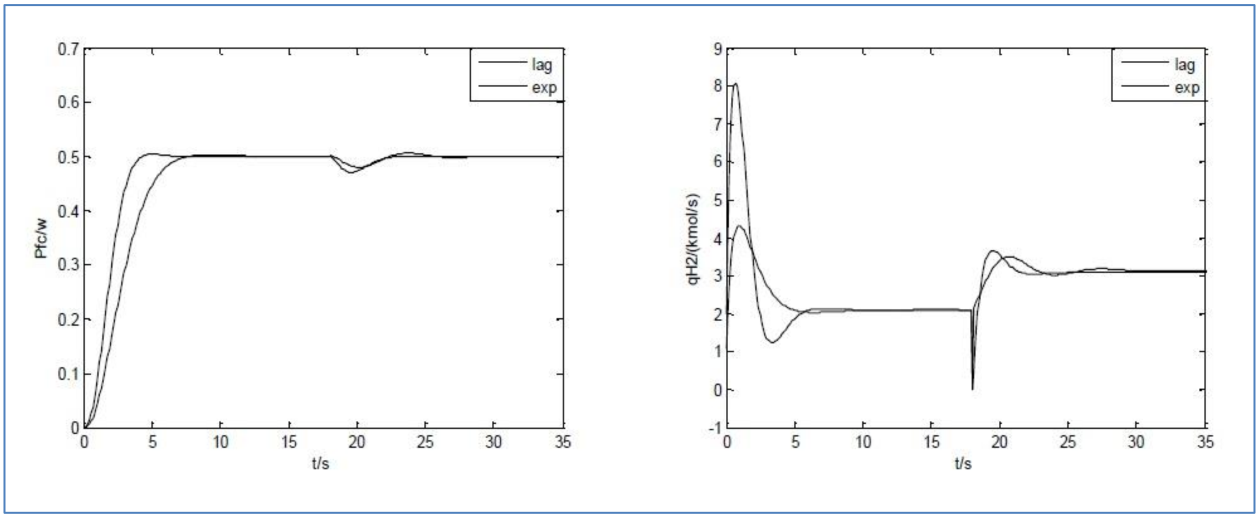


Figure 7: Improved MPC based on Laguerre function and exponential data weighting adjusting hydrogen flow



Other than adjusting the oxygen flow, hydrogen flow can be used as an operating variable as well as shown in Figure 6 and 7. By using the same control strategy as used in controlling the oxygen flow, a similar control effect is obtained. It should be noted that the tracking time caused by adjusting oxygen flow is a bit shorter than that of adjusting hydrogen flow. When a load disturbance is introduced to the system, the improved MPC can make the system return to the given steady state rapidly after a short fluctuation.

2.3.2. Multilinear-Model Predictive Control of a Tubular Solid Oxide Fuel Cell System

In this paper (Hajimolana, Hussain, Soroush, Daud, & Chakrabarti, 2012), the researcher uses an approach that involves the development of multiple linear models that account for the anticipated operating range, design a controller based on each model and then develop a criterion which the control system switches from one controller to another. A multilinear model predictive controller (MMPC) is implemented to control the outlet voltage of the Solid Oxide fuel cell (SOFC) by manipulating the fuel flow rate. Comparison is done between MMPC, single model predictive controller (SMPC) and a conventional proportional-integral (PI) controller.

Figure 8: Responses under the MMPC, SMPC, and PI controller to a series of small set-point changes in Vout: (a) controlled variable; (b) manipulated variable profiles corresponding to panel (a)

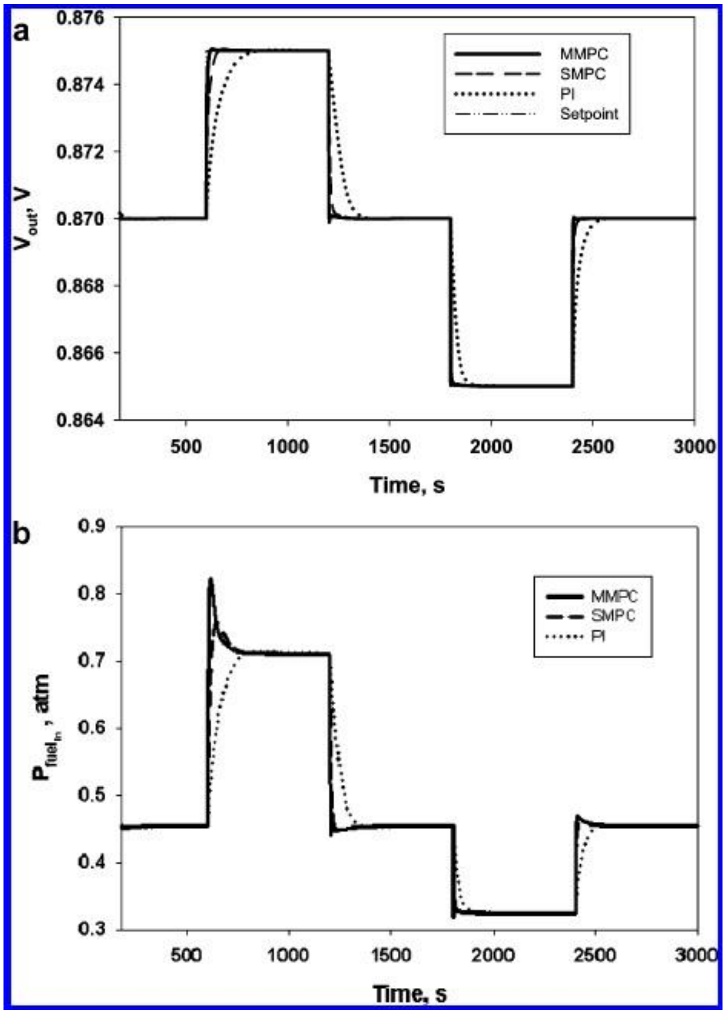
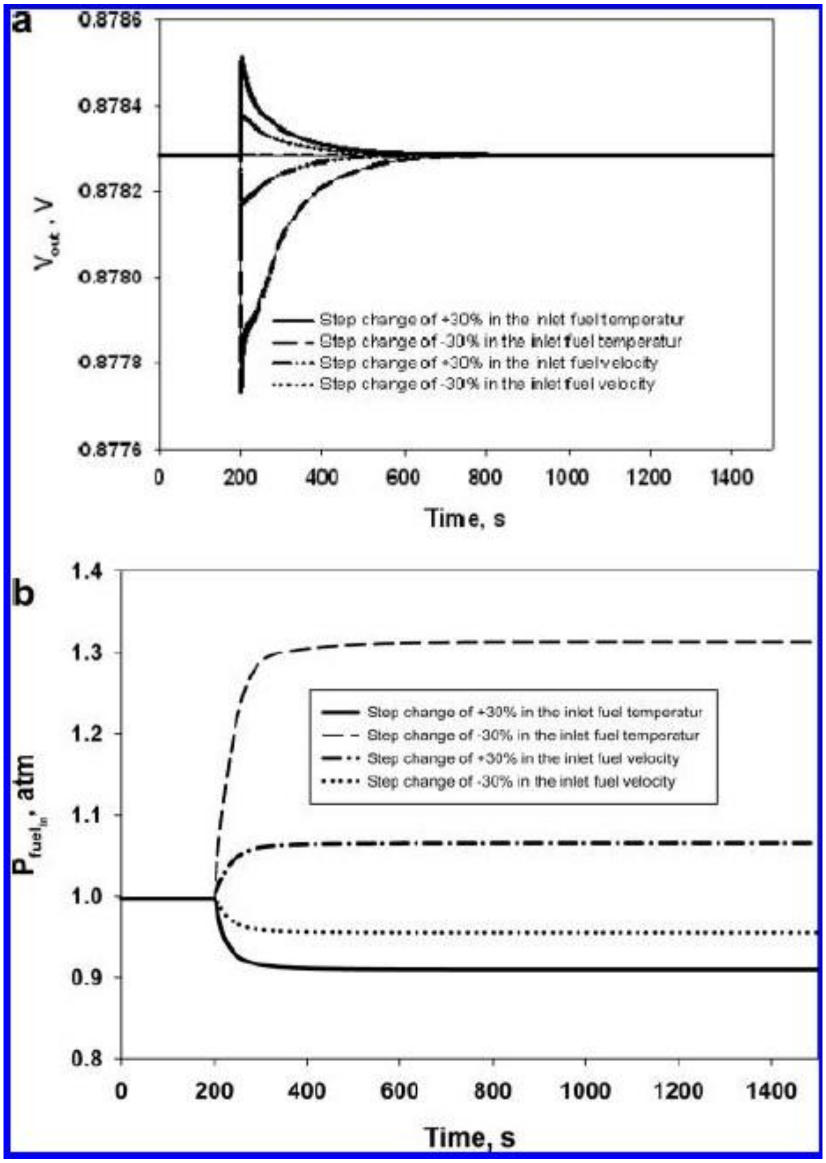


Figure 9: (a) Closed looped response of the SOFC under MMPC to step changes of ±30% in the inlet fuel temperature and velocity. (b) Manipulated variable profile corresponding to panel (a)



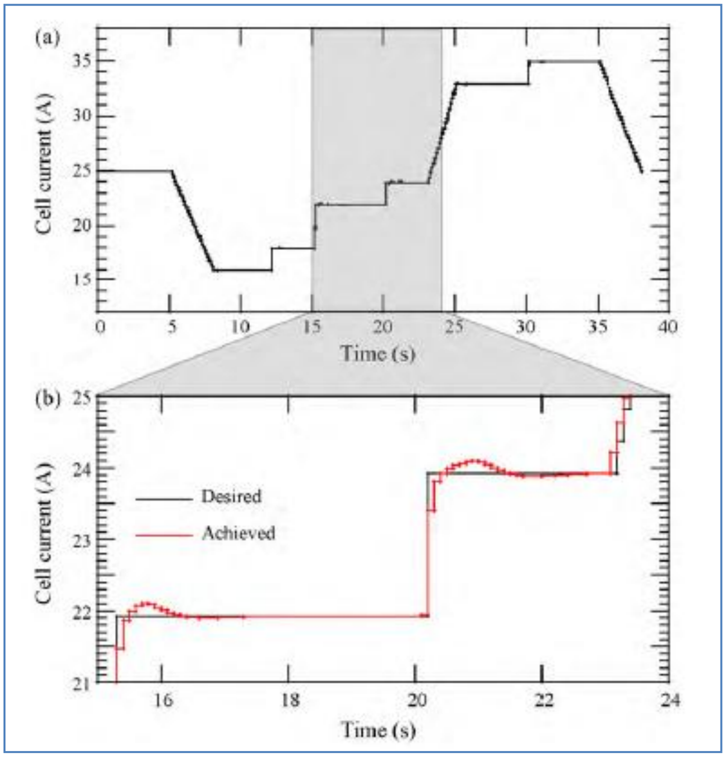
It is concluded that the SMPC provides a better control than the classical PI controller. At a higher load changes, the SMPC and PI controller failed to control the voltage while the MMPC performs satisfactorily. Also, the MMPC can regulate the process when subjected to greater load disturbances that does not surpass the design capacity of the fuel cell.

2.3.3. Modeling and control of tubular solid-oxide fuel cell systems: II. Nonlinear model reduction and model predictive control

In this paper (Sanandaji, Vincent, Colclasure, & Kee, 2011), a control strategy is design to enhance the system efficiency and to avoid possible damage to the system by controlling the system to operating within a range of specific operating conditions. MPC is used as the control strategy. To implement the MPC, a linear parameter varying (LPV) model structure is developed and used to obtain a control-oriented dynamic model of the SOFC stack. Using the reduced-order model, an MPC controller is designed that can respond to the load requirement over a wide range of operation changes while maintaining input–output variables within specified constraints.

An MPC controller is used to control the physical SOFC model through a specified transient trajectory of desired output current, while also satisfying constraints. The controller uses the low-order LPV-based model for state estimation and actuation sequences.

Figure 10: Comparison between the desired cell current and the cell current delivered by the MPC controller



The figure above shows that the desired current spans a significantly wide range, over which the physical behavior is strongly nonlinear. Although near step-changes in the desired current trajectory, some small overshoots are present, the MPC controller is delivering excellent performance.

Figure 11: MPC controlled input commands and model-predicted responses

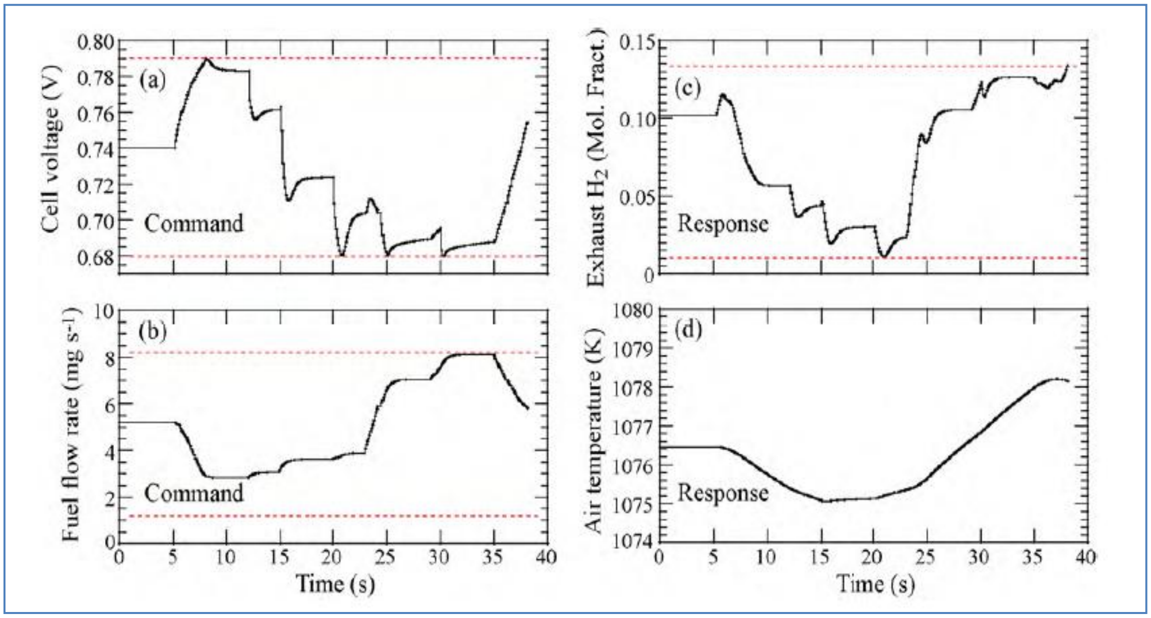


Figure 11a and 11b shows the controlled input variables. The controller maintains the commanded cell voltage and fuel flow rate within the defined bounds which is represented by the red dotted line. Figure 11c and 11d represents the output variables. It is noted that the exhaust hydrogen mode fraction remains within the specified bounds and the air temperature only have minute changes within the 40 seconds time interval.

These results show that the MPC controller provides an excellent performance for this fuel cell. The controller is able to meet the load demands while keeping the operating conditions within a specified range.

CHAPTER 3

METHODOLOGY

3.1. Research Methodology

The methodology to conduct this project is by doing simulation work. The project will be conducted in MATLAB/SIMULINK environment. A 5 kW SOFC MATLAB/SIMULINK-based model developed at Electrical & Computer Engineering Department in Montana State University will be used as a case study to develop a MPC control as the next step to be done in continuation to the study of solid oxide fuel cell.

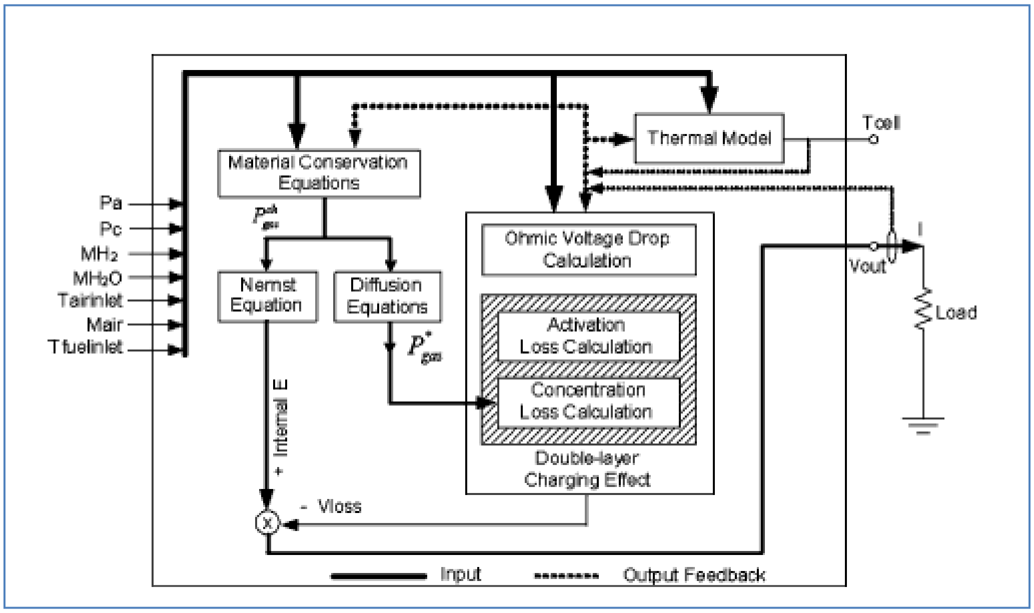
The model (Wang & Nehrir, A Physically Based Dynamic Model for Solid Oxide Fuel Cells, 2007) is composed mainly of an electrochemical part and a thermal dynamic part. A SIMULINK model for the SOFC is attached in the Appendix. It has 8 input quantities and two main outputs. The list of input and outputs is given the next page:

Table 2: List of Inputs and Outputs for SOFC model

Input Quantities	
I	Fuel cell load current [A]. Maximum current is 160A.
P_a	Pressure of the anode channel [atm]
M_{H2}	Mole flow rate of H_2 input at the anode [mol/s]
M_{H2O}	Mole flow rate of H_2O input at the anode [mol/s]
P_c	Pressure of the cathode channel [atm]
$T_{airinlet}$	The temperature of air at air inlet [°K]
M_{air}	The mole flow rate of air input at the cathode [mol/s]
$T_{fuelinlet}$	The temperature of fuel at fuel inlet [°K]
Output Quantities	
V_{out}	The output voltage of the SOFC model [V]
T_{out}	The temperature of the SOFC model [°K]

The model for the SOFC is represented by the model below:

Figure 12: Diagram of building a dynamic SOFC in SIMULINK



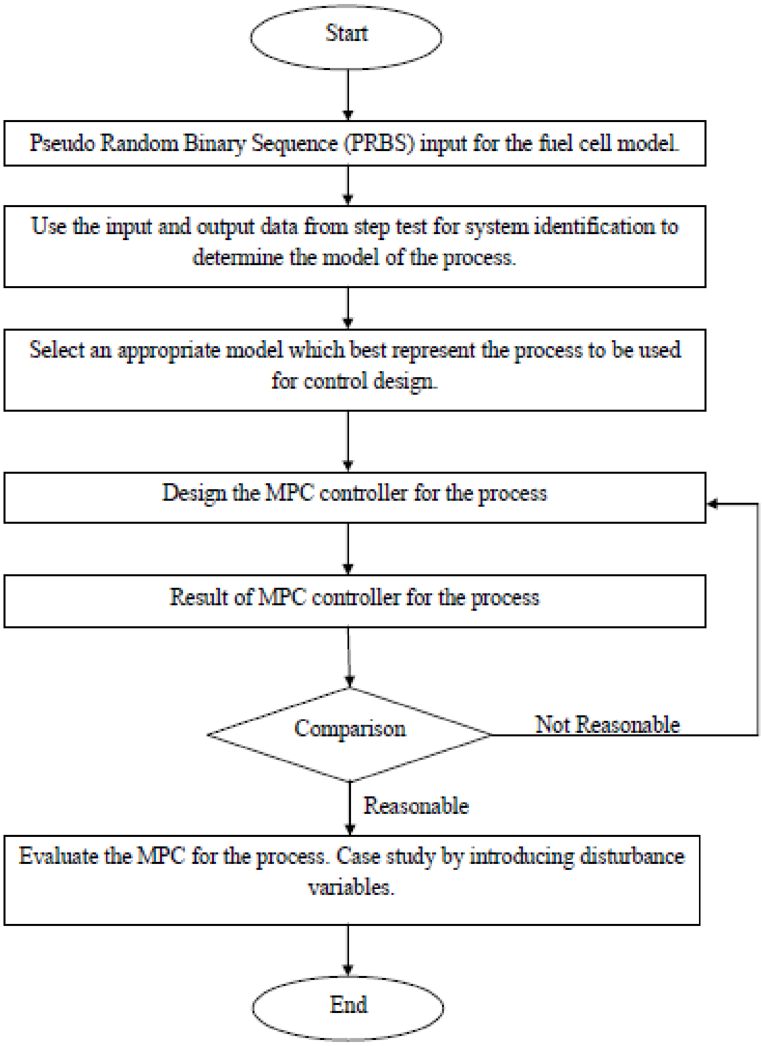
From the model, it is interested to study how the effect of air and fuel will affect the voltage output and temperature of the fuel cell.

Table 3: Input and Output Used for Control Study

Input Variables	Output Variables
Molar flow rate of H_2, M_{H2}	The output voltage of the SOFC model, V_{out}
Molar flow rate of air, M_{air}	The temperature of the SOFC model, T_{out}

3.2. Flowchart

Figure 13: Flowchart for Project Simulation



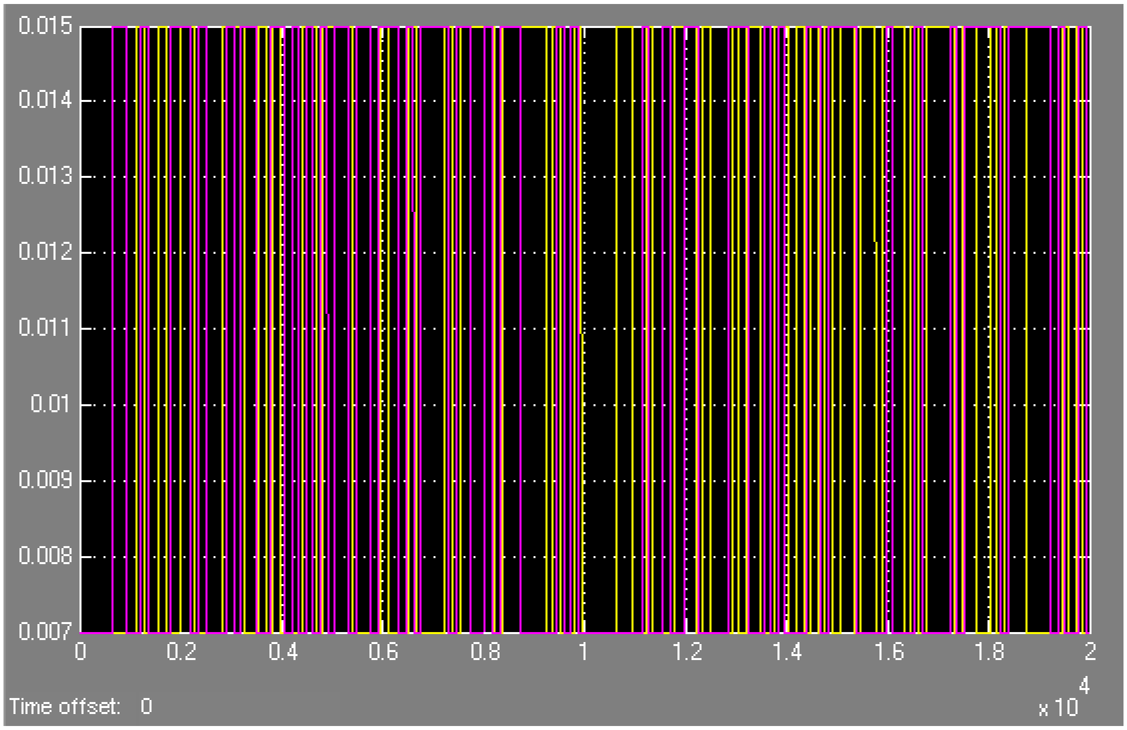
3.3. Project Activity

In FYP II, the project proceeds with designing MPC for the SOFC system. The project starts with step testing. The data from PRBS step testing phase will then be used for system identification. After performing system identification, the next step will be designing the MPC from the information obtained from system identification. Finally, an evaluation of the control will be done to compare the effectiveness of MPC for the process.

3.3.1. Step test –PRBS Signal

In this step, PRBS signal is implemented on the input variable. The PRBS signal is alternating between 0.007mol/s to 0015mol/s with a band value of 0.07. The simulation time is 20000 seconds.

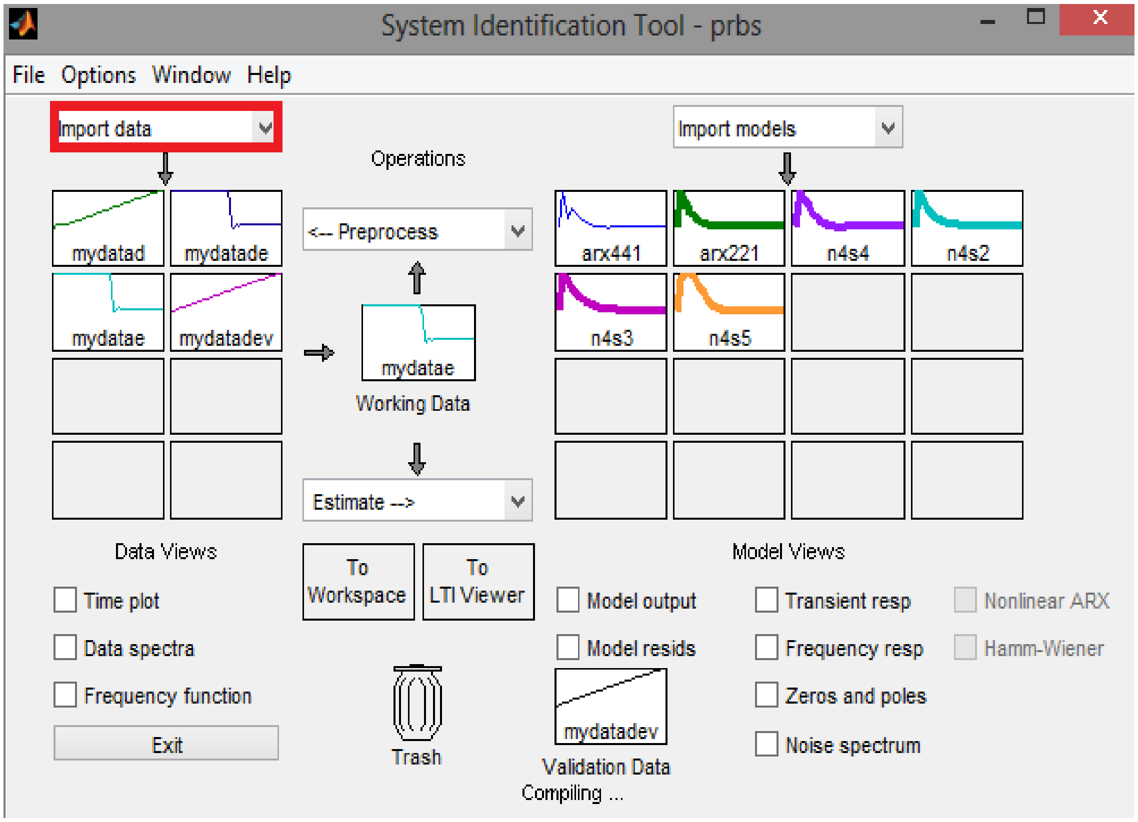
Figure 14: PRBS Signal for Input Variable



3.3.2. System Identification

In system identification, the data obtained from step test will be used to determine the model of the process. Using MATLAB, the command “`ident`” will prompt the window for system identification tool.

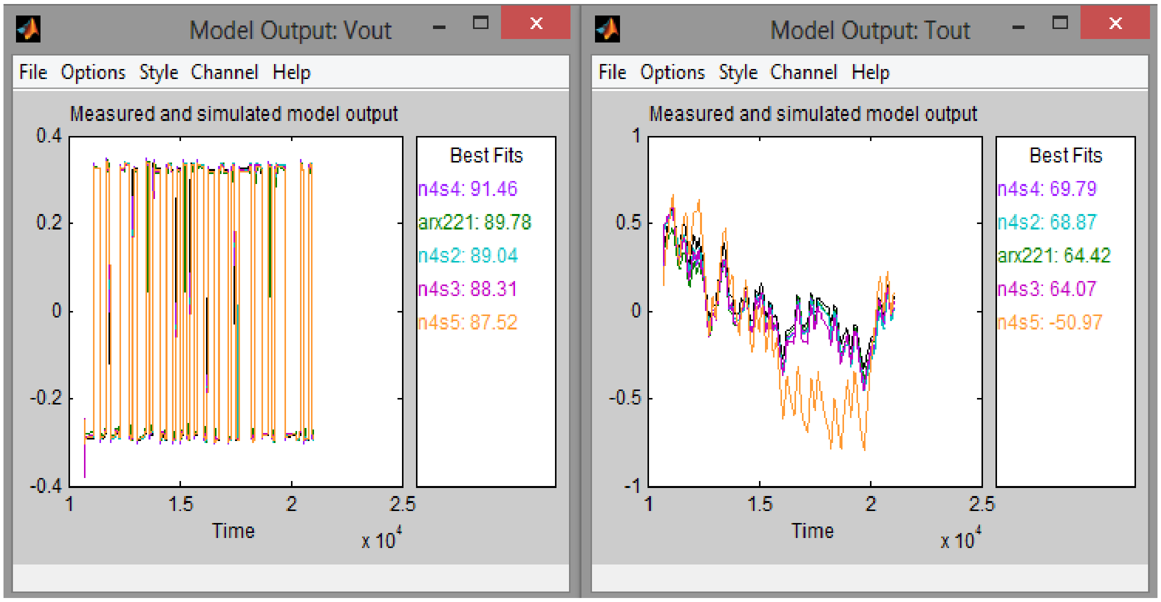
Figure 15: MATLAB System Identification GUI



Data will then be input into this tool box using the import data tab highlighted in Figure 13 by selecting “time-domain data”. The data input for the system identification process will be the 2 input variables, molar flow rate of H_2 and air while the output is the voltage and temperature of the fuel cell. The sampling interval is set to be 1 second.

Before proceeding to estimate the model, preprocess of the data are required. It is required to remove the mean of the data. After removing the mean, the data will be split into two sections. One section will be used to estimate the model while the other section will be used to validate the model.

Figure 16: Model Output - Comparison between the models

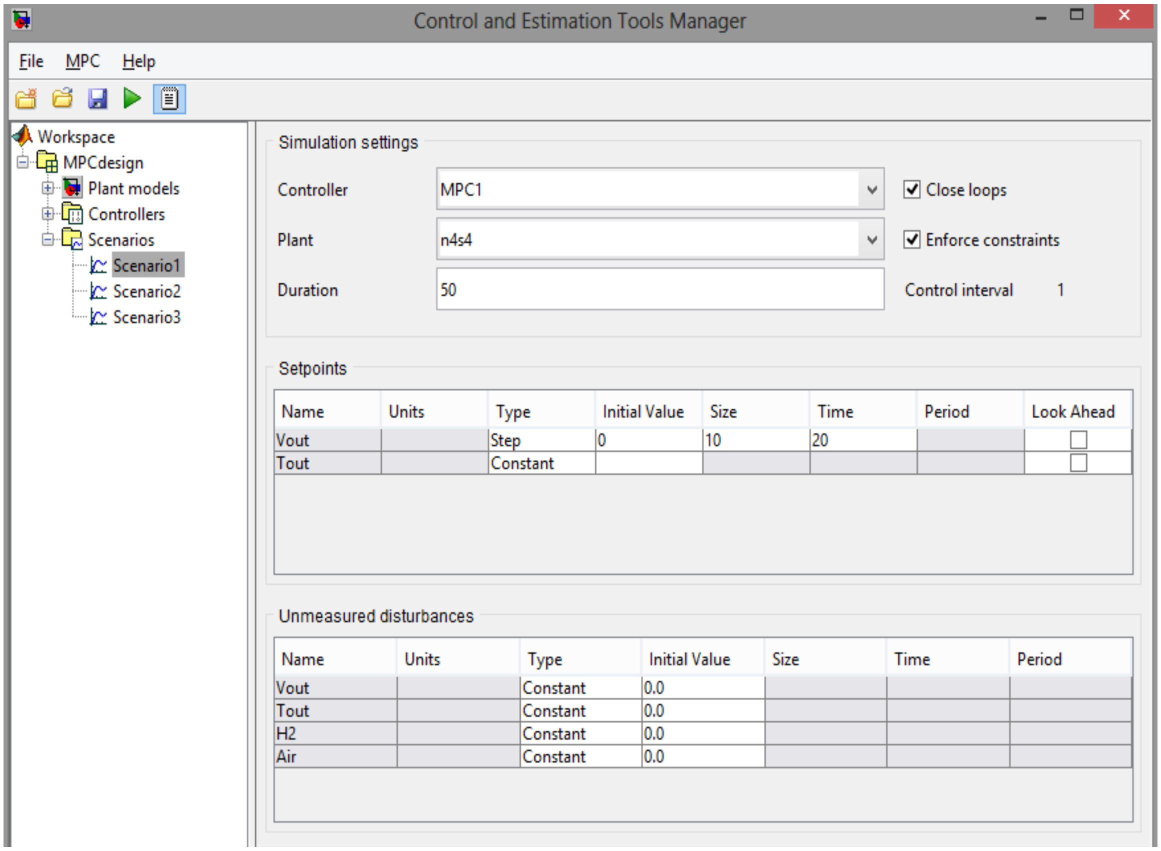


After estimating an appropriate model, each of the models will be compared with the validation set of data. From the figure above, the model “n4s4” provide the best fit among the rest.

3.3.3. MPC design and Evaluation of MPC

After all the models are obtained from system identification, the model will be used to design the MPC. Using MATLAB, the command “`mpctool`” will prompt the window for MPC toolbox.

Figure 17: MATLAB MPC Toolbox GUI



Simulation settings

Controller: MPC1

Plant: n4s4

Duration: 50

☑ Close loops

☑ Enforce constraints

Control interval: 1

Setpoints

Name	Units	Type	Initial Value	Size	Time	Period	Look Ahead
Vout		Step	0	10	20		☐
Tout		Constant					☐

Unmeasured disturbances

Name	Units	Type	Initial Value	Size	Time	Period
Vout		Constant	0.0			
Tout		Constant	0.0			
H2		Constant	0.0			
Air		Constant	0.0			

After inserting the plant model, a variety of scenario can be simulated from the simulation settings. The simulated controller will be display and the efficiency of the controller can be evaluated.

3.4 Key Milestone

Due to an earlier model being incomplete, the project needs to be rescheduled. The preliminary work done using the incomplete model is rendered invalid. A new model using a tubular solid oxide fuel cell is used instead of the previous PEM fuel cell. The new key milestone is as such:

Table 4: Key Milestone schedule

Project Activities	1	2	3	4	5	6	7		8	9	10	11	12	13	14
Step Testing					●										
System Identification						●									
Control Design									●						
System Evaluation										●					

3.5. Tools and Software

This project is purely a simulation project. Hence, software is required to complete this project. The software involved is MATLAB R2009b. Within this software, there are several in-built functions that is required. The functions are:

a) SIMULINK
b) System Identification Toolbox
c) Model Predictive Controller Toolbox 3.1.1

MATLAB is a high-level language and interactive environment for numerical computation, visualization, and programming. MATLAB is currently being used in a wide range of application such as signal processing and communication, image and video processing, control system, test and measurement, computational finance, and computational biology. MATLAB also comes with an additional package called SIMULINK which will be used in this project as well and this package allows the addition of graphical multi-domain simulation and Model-Based Design for dynamic and embedded system.

SIMULINK is data flow graphical programming language tool for modeling, simulating and analyzing multi-domain dynamic system. SIMULINK uses a graphical block diagramming tool as its primary interface. It also comes with a customizable set of block libraries allowing the users more freedom is their simulation work. This software offers a tight integration with MATLAB environment allowing the software to drive MATLAB or scripted from it. SIMULINK is often used in control theory and digital signal processing for multi-domain simulation and Model-Based Design. There is a previous study of using SIMULINK for a study on PEM fuel cell and non-linear control using generic model control (GMC) approach.

System Identification Toolbox allows one to estimate linear and nonlinear mathematical models of dynamic systems from measured data. The resulting model will then be used to analyze system dynamics, simulate the output of a system for a given input, predict future outputs based on previous observations of inputs and outputs, or for control design.

The Model Predictive Control Toolbox product is a collection of software that helps to design, analyze, and implement an advanced industrial automation algorithm. A Model Predictive Control Toolbox controller automates a target system (the plant) by combining a prediction strategy and a control strategy. An approximate linear plant model provides the prediction. The control strategy compares predicted plant signals to a set of objectives, and then adjusts available actuators to achieve the objectives while respecting the plant constraints. Since SIMULINK is used to model the plant, the Model Predictive Control Toolbox also provides a SIMULINK controller block. To do so, one must first linearize a nonlinear SIMULINK model, then use the linearized model to build a Model Predictive Control Toolbox controller, and evaluate its ability to control the nonlinear model.

3.6. Gantt Chart for FYP II

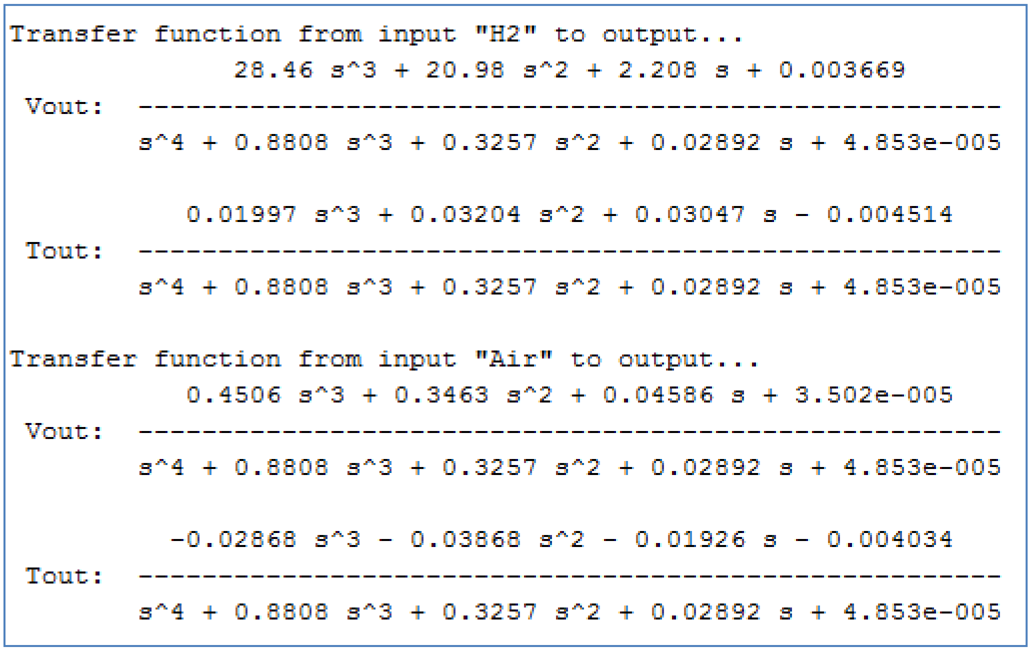
Task Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Literature Review	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦						
Step Testing		🟦	🟦	🟦	🟦									
System Identification			🟦	🟦	🟦	🟦	🟦	🟦						
MPC Design				🟦	🟦	🟦	🟦	🟦						
Submission of progress report								🟦						
Case study by introducing disturbance variables and set point change into the process								🟦	🟦	🟦				
Preparation for Pre-SEDEX										🟦	🟦			
Preparation and Submission of Softbound Dissertation											🟦	🟦	🟦	
Viva														🟦
Submission of Final Dissertation														🟦

CHAPTER 4

RESULTS AND DISCUSSION

Before the MPC can be design, an appropriate model for the SOFC must be selected. Among the many model that best represent the characteristic of the model, the 4th order state space linear parametric model labeled “n4s4” is selected as the best fit model. This is because, as shown in Figure 16, when compared to the other models and the validation data, the model performs the best. . The transfer function for the model “n4s4” is as shown in figure below:

Figure 18: Transfer Function for the Best Fit Model



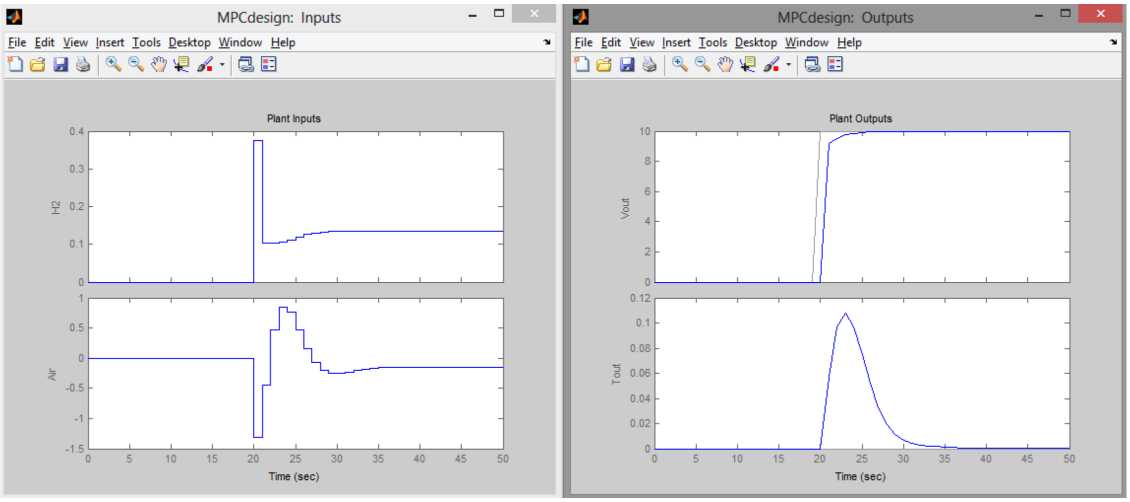
```
Transfer function from input "H2" to output...
              28.46 s^3 + 20.98 s^2 + 2.208 s + 0.003669
 Vout:  -------------------------------------------------------
        s^4 + 0.8808 s^3 + 0.3257 s^2 + 0.02892 s + 4.853e-005

           0.01997 s^3 + 0.03204 s^2 + 0.03047 s - 0.004514
 Tout:  -------------------------------------------------------
        s^4 + 0.8808 s^3 + 0.3257 s^2 + 0.02892 s + 4.853e-005

Transfer function from input "Air" to output...
           0.4506 s^3 + 0.3463 s^2 + 0.04586 s + 3.502e-005
 Vout:  -------------------------------------------------------
        s^4 + 0.8808 s^3 + 0.3257 s^2 + 0.02892 s + 4.853e-005

          -0.02868 s^3 - 0.03868 s^2 - 0.01926 s - 0.004034
 Tout:  -------------------------------------------------------
        s^4 + 0.8808 s^3 + 0.3257 s^2 + 0.02892 s + 4.853e-005
```

4.1. Case Study – Scenario

4.1.1. Set point change – Voltage output is to have an increment of 10V

In the first scenario, the set point for voltage output is changed. The fuel cell is to have an increment of 10V for it voltage output at t = 20 seconds.

Figure 19: Set Point Change for Voltage Output by an Increment of 10V



For the first 20 seconds, the process is in a steady state. When the set point change is introduced at the 20th second, the controller is seen to increase the molar flow rate of H_2 and decreases the molar flow rate of air. The molar flow rate increase by 0.374mol/s from the reference point before decreases to 0.102mol/s. From there, there is a gradual increment in the H_2 flow rate until it reaches steady state at 0.134mol/s. The sudden jump from the reference point to +0.374mol/s is to increase the voltage output from the initial set point to +10V. The drop from 0.374mol/s to 0.102mol/s is to reduce the rate of increment for the voltage output preventing overshoot. The gradual increment in the H2 flow rate show the MPC controller is gradually bringing the fuel cell voltage output to its new set point.

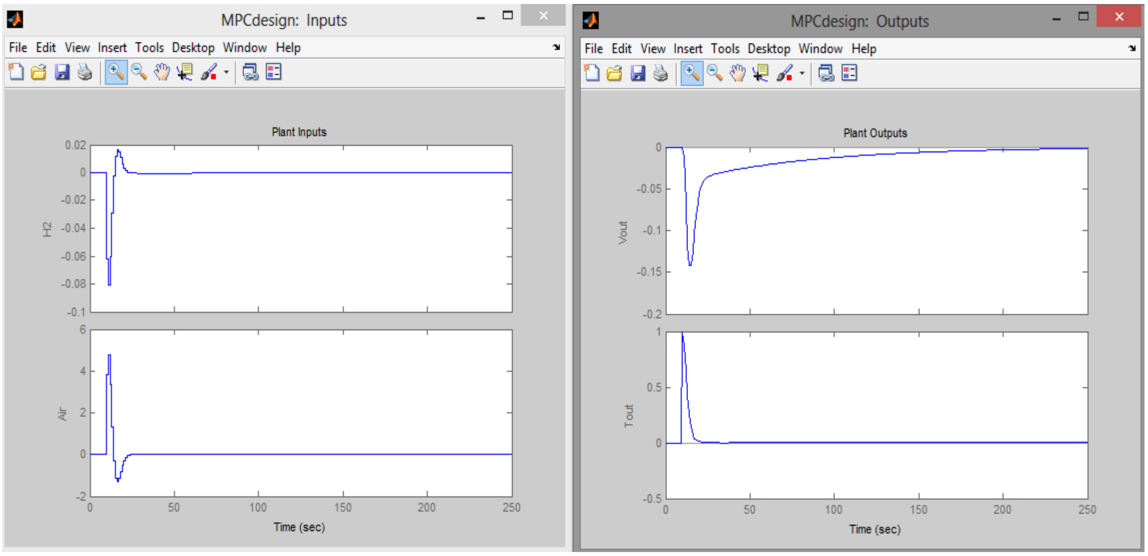
As expected, when the fuel cell set point is increased, the temperature increases as well. However, the objective of the MPC controller is to be able to keep a constant voltage output while controlling the temperature of the fuel cell. The temperature increases when the set point change is introduced to the fuel cell. The peak temperature increases up to +0.103°C from the reference temperature before the MPC controller bring down the temperature of the fuel cell to the intended temperature.

It is noted that the molar flow rate of air decreases at the time when the set point is changed to -1.31mol/s. Immediately after the drop in air flow rate, the controller then increases the air flow rate again until it reaches the peak at +0.843mol/s before it reaches steady state at -0.15mol/s from the reference point. It should be noted that when the temperature drops, the molar flow rate of air decreases as well. This likely happens because as the temperature decreases, the controller decreases the molar flow rate of air gradually to compensate the rate of decrease in the fuel cell temperature. In a sense, the function of air in this fuel cell besides as a reactant for the fuel cell, the air also acts as a coolant for the fuel cell.

4.1.2. Disturbance – The temperature of the fuel cell increase by 1°C

This scenario shows a disturbance in the temperature of the fuel cell. The SOFC experiences an increment of 1°C at t = 10 seconds.

Figure 20: Temperature Disturbance on the Fuel Cell



This scenario simulates when the temperature of the fuel cell had a sudden increment by 1°C. As shown in the figure above (a zoomed in figure is attached as Appendix 3), the controller is capable of controlling temperature of the fuel cell by bring the temperature down to the set point temperature. The MPC controller performs efficiently as the controller only takes about 20 seconds after the introduction of the disturbance to bring the temperature back to its steady state.

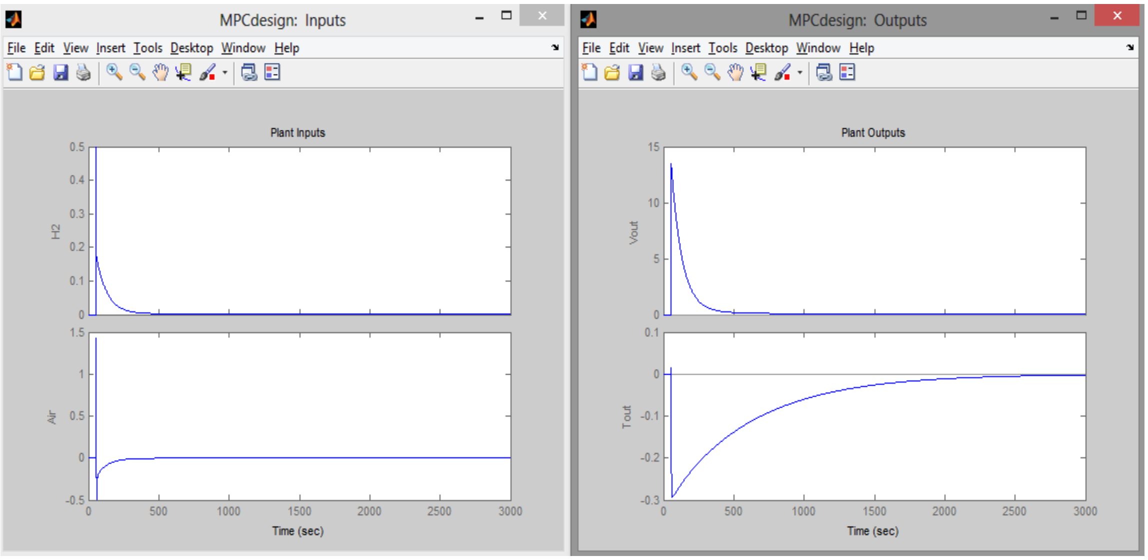
The molar flow rate of H_2 and air also stabilizes relatively fast. From the figure above (and Appendix 3), the controller manipulate the flow of the reactant by increasing the flow rate of air and reducing the flow rate of H_2 in order to control the temperature of the fuel cell. The MPC controller manages to restore the flow rate of the reactants before the disturbance happens at about 20 seconds after the disturbance is introduced into the system. However, the large increment in the air flow compared to the miniscule changes in H_2 flow is probably due to the objective of the MPC controller to bring the temperature of the fuel cell back to the initial temperature while keeping the fuel cell voltage output from deviating too much from the set point.

The voltage output of the fuel cell is also affected by the disturbance. There is a drop in voltage by 0.142V before the voltage start to stabilize. However, the time for the output voltage to reach steady state is relatively slower compared to the time for the temperature of the fuel cell to stabilize where it takes approximately 200 seconds after the introduction of disturbance for the fuel cell voltage output to reach steady state.

4.1.3. Disturbance – The flow rate of H_2 increase by 0.5mol/s

This scenario shows a disturbance in the H_2 flow rate to the fuel cell. At t = 50 seconds there is an increment of 0.5 in the molar flow rate of H_2.

Figure 21: Disturbance in H_2 Flow Rate to the Fuel Cell



In this scenario, there is a disturbance in the H_2 flow rate to the fuel cell. An addition 0.5mol/s of H_2 flow rate is introduced as a disturbance to the process. The MPC controller detecting the disturbance from the sudden voltage reading from the fuel cell, the controller corrects the disturbance by reducing the H_2 flow rate back to its initial flow rate before the disturbance occurs. The time taken for the controller to correct the disturbance in H_2 flow rate back to its initial steady state condition is approximately 500 seconds.

As a result of the disturbance, the voltage output of the fuel cell increases where it reaches its peak at 13.5V, 3 seconds after the disturbance is introduced into the process. With the MPC controller, the voltage output of the fuel cell returns to its set point value after 900 seconds. (Attached in the appendices are Appendix 4 and Appendix 5 which both is a zoomed in figure of Figure 21 for a detailed view of the figure above)

It should be noted that the temperature of the fuel cell also have a deviation resulting from the disturbance. The temperature of the fuel cell is noted to have a slight rise before the temperature drops by 0.5°C from the initial temperature. The slight rise in temperature is probably due to the sudden increase in the voltage output of the fuel cell before the MPC made the correction to the process which causes the temperature to drop below the initial temperature. Then temperature then gradually increases to its initial temperature after 2000 seconds.

As shown in the figure above and Appendix 4, when the disturbance occurs, the controller manipulated the air flow rate to increase. This is probably due to the MPC controller compensate the disturbance that occur and increases the flow of air as well to produce the increase in the fuel cell voltage output. As shown in Appendix 4 and Appendix 5, after the air flow reach its peak at +1.43mol/s from the initial flow rate, the flow rate began to decrease until the flow rate is 0.5mol/s below the initial air flow rate. From there, the air flow then gradually increases until it reaches its new steady state at 500 seconds.

4.2. Concluding Remark

The model obtained from the system identification is vital in designing the MPC controller for the process. This is because the model represents the process plant itself. An inaccurate model will cause the design of the MPC to be inaccurate as well. It should be noted that the MPC calculation is done every 1 second. This is because the process in SOFC is a very fast and a small sampling time is required to develop an accurate model of the process.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The objective to design a MPC controller for a Solid Oxide Fuel Cell (SOFC) is met. To evaluate the MPC controller, 3 case study of scenario is developed. Based on the results of the 3 case study discussed in Chapter 4, the designed MPC controller is able to achieve the intended purpose of the controller which is to control the temperature of the fuel cell while keeping a constant voltage output. From all the 3 case study given, whenever there is a set point change or disturbance is introduced to the process, the controller is capable of preventing the temperature of the fuel cell from deviating too much from its initial temperature.

5.2. Recommendation

Further study of the designed controller can be done by integrating the MPC controller designed with the SIMULINK model of the SOFC.

Although the model, gave a very good representation for the fuel cell, the model still wasn’t perfect. This can be seen while the model gives a very good fit for the model when compared to the output variable, voltage output of the fuel cell, the model does not fit well when compared with the output variable, temperature of the fuel cell. An improvement of the model can be made by using the non-linear model since this fuel cell model has a very high order.

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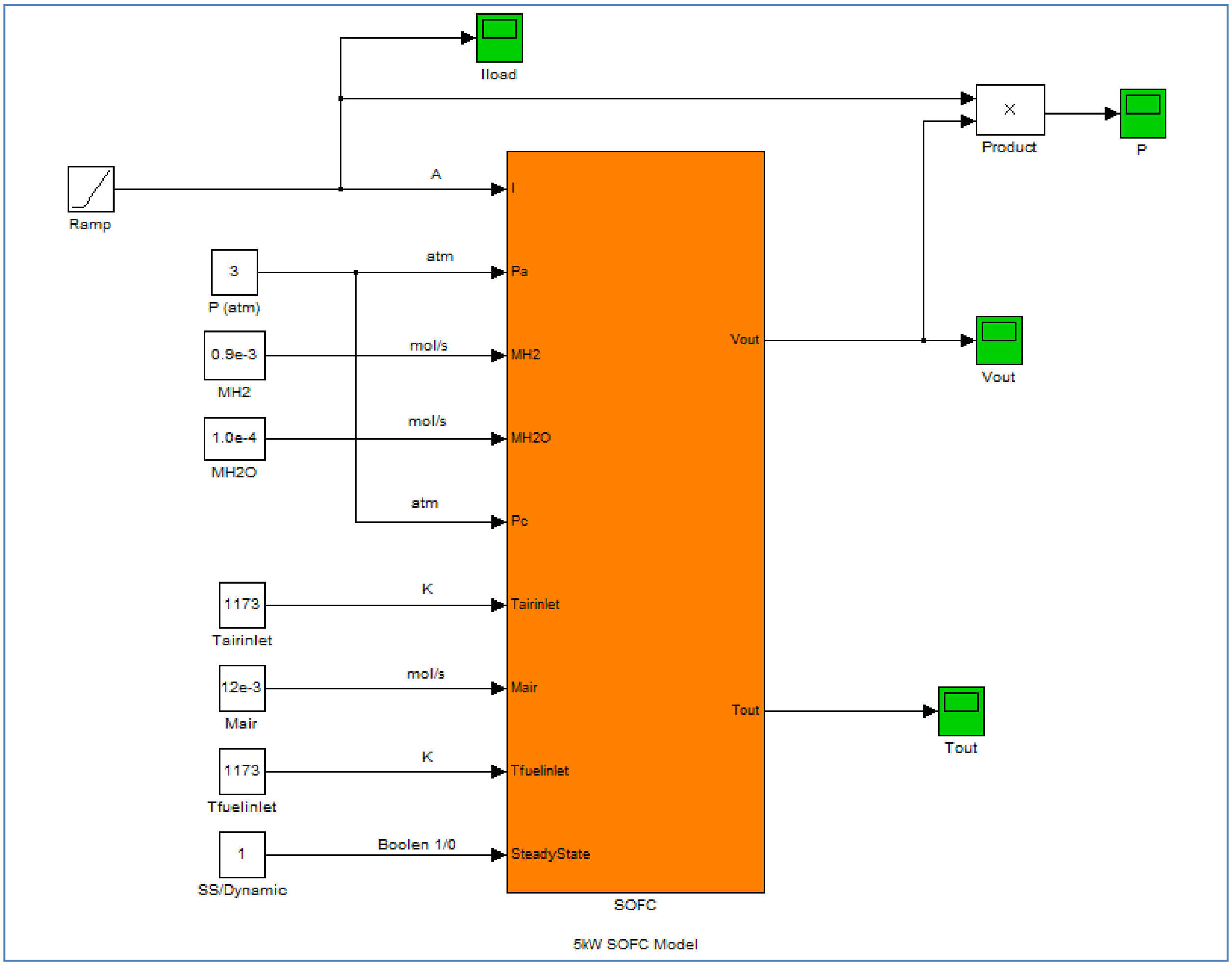
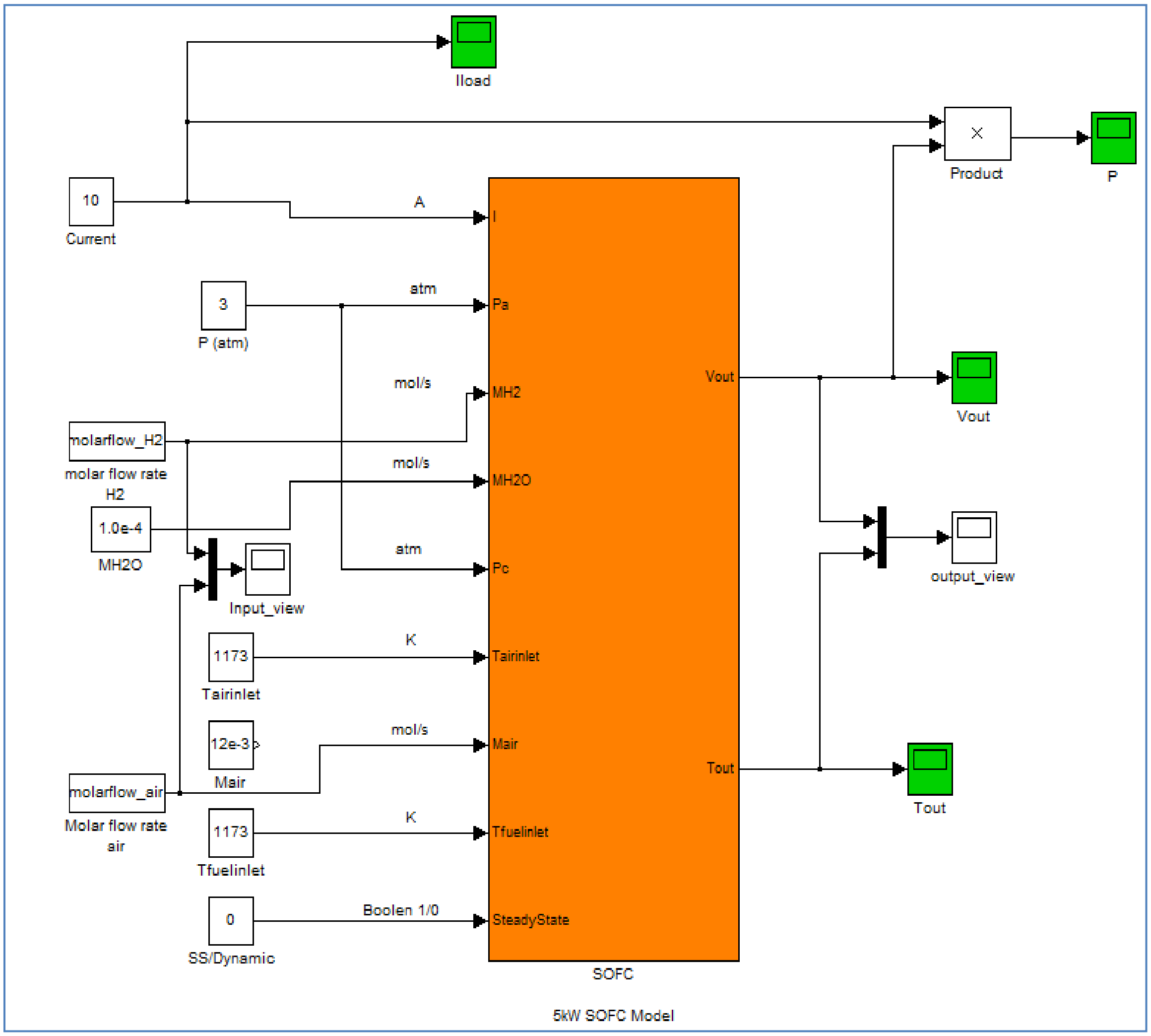
APPENDICES

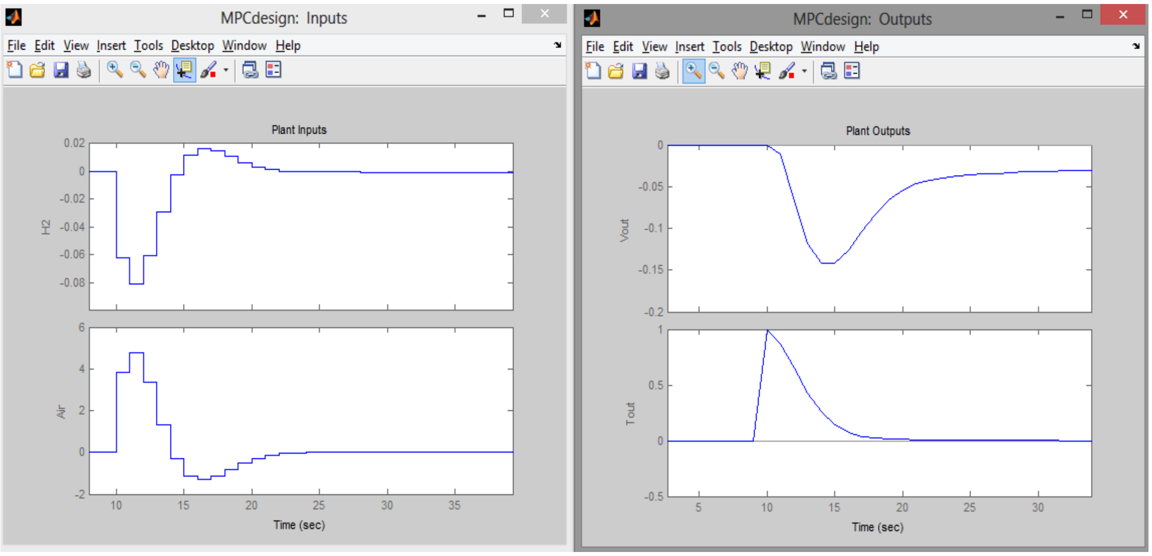
Appendix 1: SIMULINK model of SOFC



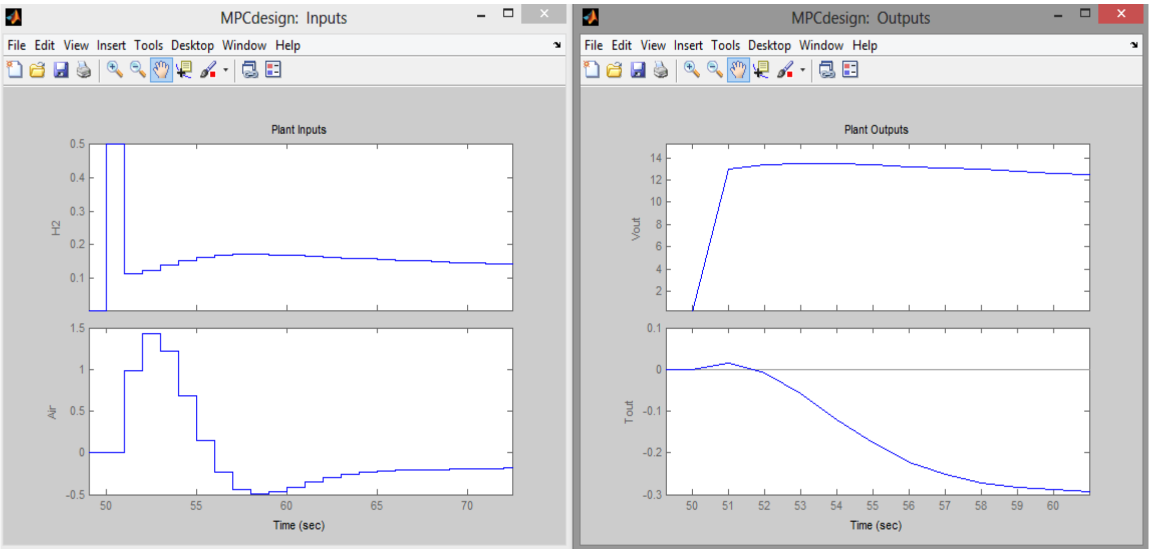
Appendix 2: Modified SIMILINK model of SOFC



Appendix 3: Zoomed in Figure 20



Appendix 4: Zoomed in Figure 21



Appendix 5: Zoomed in Figure 21