Generic Model Control Design for Hybrid Energy Storage System in Electric Vehicle

Submitted to the School of Engineering and Information Technology, Murdoch University in partial fulfilment of the requirements for the ENG470 Engineering Thesis

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Author’s declaration

I declare that this thesis is my own account of research and contains, as its main content, work which has not previously been submitted for a degree at any tertiary education institute.

______________________
Mahmood Al Kharusi
Abstract:

The use of hybrid energy systems has gone wide in the transportation industry, and especially with electrical vehicle, which has caused a lot of studies and researches to be conducted on this area. This system requires an appropriate controller design to maintain the variation of the voltages and currents in an electrical system that affect the overall output of the system, which results in an overall controlled performance of the vehicle. This makes controlling these variables an essential need in order to obtain an efficient and high quality system, because vehicles can accelerate and decelerate instantly and they require instant high power supply sources. This demand of high power cannot be provided by a single power source, therefore, an auxiliary power source to overcome the high and instantaneous demand of power is required. The proposed control method in this research is called Generic Model control (GMC), which is a nonlinear control method that is widely used in the industry to control nonlinear systems. GMC maintains the output of the process variables at a desired rate in a process by manipulating certain effective variables.

The project discusses the proposal design of two dc-dc converters to boost and buck voltages as required by the load to ensure a stable closed-loop energy supply system. The main electronic components that are required in order to design a HESS in Electric Vehicle (EV) will also be explained and discussed separately in details along with their functionality and effects on the vehicle. This research also discusses the modelling of the overall systems and implementing the derived binary equations into GMC and implement the overall closed loop control system into Simulink. The tuning methodology of GMC parameters $K1$ and $K2$ is also discussed in this report. The results of this simulation is illustrated in graphs that show the behaviour of the voltages and currents of different components in the system and the effectiveness of the control system on the performance of the vehicle.
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Acknowledgment

I would like to start by thanking Professor Parisa Bahri for guiding me through selecting a thesis topic that interests my ideas and encouraging me to work on this very topic. She guided me through the beginning of this project and offered me many valuable advices that helped settle on power electronics and control system design. I also must thank my supervisor Doctor Farhad Shahnia for his unlimited support and guidance throughout the last year of research and work on this project. He has always been there when I needed him and helped me figure out some complicated stuff that I could not have done on my own.

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<th>Description</th>
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<td>HESS</td>
<td>Hybrid Energy Storage System</td>
</tr>
<tr>
<td>EV</td>
<td>Electric Vehicle</td>
</tr>
<tr>
<td>GMC</td>
<td>Generic Model Control</td>
</tr>
<tr>
<td>SC</td>
<td>supercapacitor</td>
</tr>
<tr>
<td>TSBB</td>
<td>Two Switches Buck Boost Converter</td>
</tr>
<tr>
<td>PEMFC</td>
<td>Proton Exchange Membrane Fuel Cell</td>
</tr>
<tr>
<td>PEM</td>
<td>Proton Exchange Membrane</td>
</tr>
<tr>
<td>FC</td>
<td>Fuel Cell</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>AC</td>
<td>Alternate Current</td>
</tr>
<tr>
<td>DC-DC</td>
<td>Conversion between DC and DC</td>
</tr>
<tr>
<td>IGBT</td>
<td>Insulated-Gate Bipolar Transistor</td>
</tr>
<tr>
<td>MOSFET</td>
<td>Metal-Oxide-Semiconductor Field-Effect Transistor</td>
</tr>
<tr>
<td>EMF</td>
<td>Electromagnetic Force</td>
</tr>
<tr>
<td>PLC</td>
<td>Programmable Logic Controller</td>
</tr>
<tr>
<td>VSC</td>
<td>Vehicle Stability Control</td>
</tr>
<tr>
<td>HRES</td>
<td>Hybrid Renewable Energy System</td>
</tr>
<tr>
<td>BWSC</td>
<td>Battery without Supercapacitor</td>
</tr>
<tr>
<td>PI</td>
<td>Proportional Integral</td>
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<tr>
<td>$C_F$</td>
<td>Capacitor of the Fuel Cell</td>
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<td>$U_{dc}$</td>
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<tr>
<td>$i_S$</td>
<td>Current of the Supercapacitor</td>
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<td>$i_{fc}$</td>
<td>Output Current of the Fuel Cell Circuit</td>
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</table>
\( i_{fcc} \)  
Current of the Fuel Cell

\( I_o \)  
Load Current

\( i_{sc} \)  
Current of the Supercapacitor

\( I_{scref} \)  
Supercapacitor Reference Current

\( U_{dcref} \)  
DC Bus Reference Voltage
Chapter 1 – Introduction

1.1 Background:

The use of energy for different purposes has rapidly increased in the past few decades. The Energy Information Administration (EIA) has recently released data showing that the transportation of people is the main consumer of the energy. As the environmental issues energy consumption and oil crisis arise, new technologies have been developed all around the world to find an alternative and efficient energy source for vehicles. Among all these developments, hybrid electric vehicles have attracted researchers’ and engineers’ attention as an efficient and promising technology for the future. A stand-alone fuel cell system cannot provide an Electric Vehicle (EV) with the required power during sudden changes of load demand; therefore, a supercapacitor (SC) is required to provide the vehicle with the desired peak power during start-up, acceleration, deceleration or sudden external disturbance [1]. This combination of two energy sources, which has been identified as the hybrid energy system, should supply the EV with enough energy to run for larger distances, which eventually results in an increase in the overall efficiency of the vehicle. The energy that is provided by both the fuel cell and SC needs two DC-DC converters to travel through the system.

The energy that is provided by the fuel cell travels in one direction through the system, whereas, the SC has energy flowing in and out to maintain the sudden change in the peak power of the vehicle. Based on that, a boost converter can be installed to drive the energy from the fuel cell, and a buck-boost converter can be installed in the system to drive the energy from and to the SC. The system also has a DC bus that communicates between the DC power lines of the converters and AC power lines of the inverter. The DC bus also filters the AC power that produces by both electrical circuits and delivers a DC power with less variations and noise to ensure the high performance of the power Inverter and eventually the asynchronous motor’s
output. The inverter then converts the DC power into an AC power, send it through a DC traction motor, which regulates the front wheels of the vehicle, and makes the vehicle starts moving. Figure 1 below shows the structure of the overall proposed system that is connected to a control system.

Figure 1: Overall Power Structure of the Controlled HESS

1.2 Project Objectives:

This thesis project aims to fulfil the following objectives:

1. Design Control system to
   a. Control the voltage of a DC Bus that is connected to two DC-DC converters.
   b. Control the Current of a SC that is connected to a bidirectional DC-DC Converter.
2. Ensure the overall stability of the overall closed-loop system
3. Simulate the controller design and the overall power structure of the circuit in Simulink
The proposed theory is to design a generic model control system to control the signals of the Insulated-Gate Bipolar Transistors (IGBTs) in both DC-DC converters to maintain the energy supply to the EV as needed. These signals are basically being modelled through the proposed control system GMC and fed back to the switches in the circuits. It is hypothesised that, if the system and the are designed as proposed, the GMC control system will maintain the current and voltage of the SC and DC bus, respectively, as desired with a minimum response error.

1.3 Project Structure

This project is divided into nine chapters, where each chapter is entitled with a heading of the overview discussion that a chapter is trying to deliver. This report starts with some background information of the proposed system design in the first chapter, while the second chapter goes through literature review research that was conducted at an early stage of this project. The literal review also goes through some specific details about electronics and electrical components that are proposed to be used in the project, the overall process and some relevant case studies. Chapter 3 investigates the electric circuit structure and the components that were selected on the design, while chapter 4 outlines the modelling steps that were followed to derive the required binary equations in order to design the control system. Chapter 5 shows the design of the control system using those equations and the implementation of the derived equations into the control system. The 6th chapter explains the simulation of the overall electrical and control system in Simulink and the way that the proposed design was implemented in the software. The illustration of the results of the simulation are shown in chapter 7 and compared with hypothetic results. Lastly, the report is concluded in the 8th chapter and some recommendation and future work are discussed in the same chapter. The references that were used to back-up the statements that were used in the project are listed at the end of the report and an appendix section is included for further explanation and illustrations.
Chapter 2 – Literature Review

2.1 Energy Supply

As was mentioned earlier in this project, the EV is supplied by two combined power sources. The first main power source is the fuel cell, which is the main energy supplier to the overall system. The second energy source is a supercapacitor, which stores the energy supplied by the fuel cell and adjust the energy flow into the vehicle through a bidirectional DC-DC converter. These two energy suppliers will be explained and discussed separately in the next two sub-sections.

2.1.1 Fuel Cell

A fuel cell is basically a device that generates electricity by performing a chemical reaction through two electrodes, which are the anode and the cathode [3]. A fuel cell also consists of electrolyte that carries the electrical particles between the anode and cathode as well as a catalyst that speeds up the reaction that occurs at the fuel cell’s electrodes. The figure below shows the chemical reaction in a general fuel cell.

![Figure 2: General Structure of a Fuel Cell](image)
There are many types of fuel cell each distinguished based on the fuel that it uses. For instance, Alkali fuel cell operates using a highly compressed hydrogen and oxygen, which generates an output power ranges between 300 watts (W) to 5 kilowatts (KW) [3]. This type of fuel cells has several applications such as providing electricity and drinking water in space crafts as it was used in Apollo space craft for those purposes [3]. The second type of fuel cells is the Molten Carbonate Fuel Cell (MCFC). The MCFC uses the combination of salt and carbonates at a very high temperature as the electrolyte. This FC operates under a temperature of 650 degrees and generates an output power varies from 2 to 100 megawatts (MW) [3]. The fuel cells that work with a polymer electrolyte in the form of a thin and permeable sheet are called Proton Exchange Membrane Fuel Cells (PEMFC). Those FCs generate an output power between 50 to 250 KW and operate under a temperature of 80 degrees [3].

Although many FCs have been discussed and all have an output power that is enough to operate a vehicle, the PEMFC will be purposed in this project due to its suitable operating conditions for cars. The figure below illustrates the operation mechanism of a PEMFC. Moreover, PEMFC can also tailor electrical output to meet dynamic power requirement.

![Figure 3: Proton Exchange Membrane Fuel Cell (PEMFC) [5]](image_url)
2.1.2 Supercapacitor

In this project, the super capacitor is an auxiliary power source that supports the fuel cell. As mentioned earlier in this project, the supercapacitor supplies the system with the required power during the quick power demand changes through a bidirectional DC-DC converter. Supercapacitor, also known as an ultra-capacitor, is a type of capacitor that has the ability to store an amount of energy 10 to 100 times per unit volume or mass more than the electrolytic capacitors [6]. The feature that distinguishes supercapacitors from other energy storing technology is its ability of fast recharge and delivering the energy, which makes it an ideal auxiliary power source in a vehicle. A supercapacitor has high capacity but low voltage to bridge the gap between electrolytes. The figure below shows the internal structure of a supercapacitor.

![Figure 4: Structure of a Supercapacitor [7]](image)

Supercapacitors have electrical double layers and a very high capacitance. It also has high energy density, which makes it an ideal power sources in applications that require a high durability of power unit [8].
2.4 Power Conversion

A DC-DC converter is a type of electronic circuit that takes the DC source and then converts it from a current voltage to another [9]. The amount of power required for an electronic device varies depending on the device’s type. For example, if too much power is fed into a DVD player in a car, the DVD player will blow up. Similarly, if a small amount of power is supplied into a device where a larger amount of power is needed, the device will not run. There are different types of DC-DC converters that are used for different applications and the user must know the specifications of the converter before installing. Based on that, DC-DC boost power converters are required for both the fuel cell and the supercapacitor to step up the power in this project.

2.4.1 Boost Converter

The EV runs on very high voltage and using banks of batteries too much the required voltage and power will require a large space and weight, which will result on a very unpractical vehicle. Therefore, the use of a boost converter to overcome this an issue is necessary. As discussed earlier in this project, the boost converter will match the demand of voltage and power that the vehicle needs in order to run efficiently. In this case, the available output voltage will increase, which will result in a decrease in the available output current. Figure 5 shows the basic structure of a boost converter. The initial period of the boost converter circuit contains high-frequency square waves applied to the MOSFET gate at the start-up. Meanwhile, the MOSFET places a circuit between the right hand side of the inductor L1 to the negative terminal of the supply voltage $V_{IN}$, which results in L1 storing energy in its magnetic field [10]. When the MOSFET is witched off, L1 produces a counter Electromagnetic Force (EMF) to keep the current flowing and therefore the current flows through the diode D1, charges up the capacitor C1 and also supplies the load [1]. It also important to mention that the diode is witched off when the MOSFET goes back on again due to the difference of the positive charge between the anode
and cathode of D1, however, the load will still be supplied by C1 and C1 is instantly charged up whoever the MOSFET is switched OFF [1].

![Boost Converter Continuous Conduction Mode](image)

**Figure 5: Boost Converter Continuous Conduction Mode [10]**

### 2.4.2 Buck-boost Converter

The same as the boost converter, the main purpose of a buck-boost converter is to boost up the supply voltage to a desired level. The buck-boost converter combines the buck converter and boost converter principles which helps in regulating the output DC voltage in the system [11]. The structure of the buck-boost converter is shown in figure 6. During the boost operation of the converter, the first transmitter (Tr1) is switched on and the second transmitter (Tr2) is switched off due to the high frequency square waves applied by the control unit. The current flows through the inductor L and charges its magnetic field along with the capacitor C and the load while the diode D1 is off due to the difference between the positive charge of the anode and the cathode [10]. On the other hand, during the buck operation of the converter, both transmitters are switched off by the control unit and the current is supplied to the circuit by the inductor [10]. The magnetic field of the inductor collapses and reverses the polarity of the voltage across the L, and therefore, D1 is turned on and the current flows through D2. As L keeps supplying the circuit, it discharges while the capacitor C supplies the load using the
accumulated charge that was obtained when Tr1 was on [10]. This process keeps the ripple amplitude of the output voltage $V_{out}$ minimum and the voltage constant and close to the value of $V_s$ [10].

![Buck-Boost Converter Discontinuous Conduction Mode](image)

**Figure 6:** Buck-Boost Converter Discontinuous Conduction Mode [2]

### 2.7 Power Line Communication

The transfer of data and signals from power sources through existing cables in a system is known as Power Line Communication (PLC) technology [13]. PLC can be divided into two main sections, the narrowband PLC and the wideband PLC. Narrowband PLC works at a frequency of (3-500 kHz) and a low data capacity that gets only up to 100s of kbps, however, it has a wide range in terms of reachability with the ability to reach several kilometres [13]. On the other hand, wideband PLC has a higher frequency and data capacity with ranges of (1.8-250 MHz) and 100s Mbps respectively, however, it is only used for short range applications [13]. The figure below shows the difference in frequency and noise containing between wideband and narrowband signals. Power lines can be communicated over either AC or DC lines, however, this report will focus on the PLC over DC lines.
DC-bus is a power line technology that was developed by Yamar Electronics Ltd for economical multiplex power line communication network over noisy DC or AC power lines [13]. It basically helps in transferring the data of the power provided by the battery and the supercapacitor through the system to the inverter. The use of PLC via DC-bus reduces wiring complexity, a lower weight of the vehicle and significantly lower the cost, which makes it an ideal technology for an electric vehicle [12]. The figure below shows the power line communication system via a DC-bus.

Figure 7: wideband and narrowband signals [14]

Figure 8: Power Line Communication via a DC-Bus [15]
2.8 Power Inverter

The primary job of a power inverter is to convert the DC current from the power source to AC current that is suitable for appliances [16]. As the power that is produced from the energy source in the proposed system is DC, the use of a power inverter to convert this power into AC power is necessary to be able to use appliances in the car. The power inverter also supplies the 3 phase electric traction motor by AC power. The next figure below shows the basic circuit of a 3 phase power inverter connected to a motor.

![3 Phase Power Inverter](image)

There are two types of power inverters, the modified sine waves and the pure sine waves. The modified sine inverter produces and AC output adequate for powering simple devices such as mobile phones, heaters, and air conditioners, whereas, pure sine inverters are more advanced and complex technology that is used for powering sensitive appliances such as laptop, fridges and microwaves [17]. The pure sin inverter is more expensive than the modified sine inverters, however, the advance in technology has recently resulted in lowering the price of the pure sine
inverter, which makes a better option in most cases [18]. The figure below shows the difference between the output waveform of the two inverters.

![Figure 10: Modified and Pure Sine Wave Inverters [18]](image)

2.9 Traction Motor

Generally, the motors are used to convert electrical power into mechanical power to provide a propulsion force. The traction motors are also classified based on the type of the input power they receive. The DC motors are constructed with a commutator and either brushes or without brushes. The brushed DC motor generates a swinging current in the armature using a split ring communicator, whereas, the brushless DC motor uses a mechanical rotating switch to perform the same process [22]. The figure below illustrates a brushed DC motor.

![Figure 11: DC Motor [21]](image)
On the other hand, the AC motor is classified as synchronous as AC motors and induction AC motor. The synchronous type rotates when a supply frequency kicks into the motor, where the rotor magnetic field is a result of slip ring current or some permeant magnet [22]. The induction type turns a little bit slower than the frequency being supplied which results in the need of induced current to make the magnetic field on the rotor works [20]. The following figure shows the structure of a synchronous AC motor.

![Figure 12: Synchronous AC Motor](image)

The induction AC motor has two pairs of electromagnet coils, which are energized by an AC supply (the inverter in this case). The electromagnetic coils then produce a magnetic field, which induces an electric current in the rotor. The current that was produced on the rotor produces its own magnetic field and therefore, the interaction between the magnetic field causes the rotor to turn at almost the same speed as the supplied frequency [24]. The figure below shows the rotation process in the induction motor, which is the main concern in this project.
Based on that, the AC motor is much less complicated than the DC motor in term of structure, which makes it a low-cost. Moreover, the AC and has the ability to last longer and does not need much maintenance compared to the DC motor [21]. The AC motor depends entirely on the frequency supplied and rotates at a constant speed unless a variable-frequency drive is used, whereas, the DC motor can be easily controlled by changing the supply voltage.

2.10 Control System

Generic Model control is an advanced control technique that was developed by Lee and Sullivan in 1988 to find the values of manipulated inputs that force a model of the system to follow a desired reference system, which is referred to as the trajectory [25]. This control technique has been developed to handle the nonlinearity in most chemical systems that cannot be controlled by other linear control techniques. The GMC is used to control different parameters in chemical reactors such as temperature and volume, however, this project will
analyse the possibility of using this control technique maintain the performance of the Hybrid Energy Storage System (HESS) and therefore, the overall performance of the EV. Due to the nonlinearity of the power electronic converters and the fuel cell that are used in the design of the HESS, a nonlinear process control technique must be used to ensure the performance of the entire system [26]. Generic Model Control (GMC) allows nonlinear process models to be directly embedded within the control structure, which provides a better possibility of a better process control because an accurate process model is controlled. Therefore, the generic model control method will be discussed to enhance the performance of the HESS. The design of this control system will require deriving differential equations for the main components of HESS such as fuel cell, DC-DC converters, and traction motor. Those differential equations will then be used to design the control system.

The design of a generic model control system can be explained by analysing the following basic nonlinear model:

\[ \dot{y} = f(y, u, d, t, \theta) \]  \hspace{1cm} \text{(2.1)}

where \( y \) is a vector of process output of dimension \( m \), \( u \) is a vector of process input of dimension \( m \), \( d \) is a vector of process disturbances of dimension \( l \), \( t \) is time and \( \theta \) is a vector of model parameters of dimension \( q \), whereas, \( f \) is a vector that expresses the nonlinear functional relationships [25]. The reference system \( r(y) \) that expresses the generic model control can be expressed as follows:

\[ r(y) = K_1(y^* - y) + K_2 \left( \int_{0}^{t_k} (y^* - y) dt \right) \]  \hspace{1cm} \text{(2.2)}

Where \( t_k \) is the current instant of time, \( K_1 \) and \( K_2 \) are the controller parameters and \( (y^* - y) \) is the error of the system. The figure below shows the structure of the control process.
The GMC expressed in the equation 7.2 desires that the system is a long way from the set-point and must be traveling towards the set-point quickly [25]. In addition, the performance of the system should be offset-free, therefore, it must move towards set-point in case it was not. The nonlinear model 7.1 must be forced to follow the desired reference model 7.2, thus the overall control system model is expressed as follows:

\[
f(y, u, d, t, \theta) = K_1(y^* - y) + K_2 \left( \int_0^t (y^* - y) \, dt \right)
\]

Now the equation 7.3 can be rearranged for the manipulated input \( u \) of the nonlinear system that needs to be controlled. The constant parameters \( K_1 \) and \( K_2 \) can be tuned depending on the behaviour of the targeted system and the desired output.
2.10.1 Tuning of Controller’s Parameters

The parameters of the GMC controller K1 and K2 are constant values that can be selected using different tuning methods to achieve the desired output. There different ways to tune the parameters of a GMC controller. The first method involves the use of linear continuous time system models and applying the following equations:

\[ K1 = \frac{2\zeta}{\tau} \quad \text{E (2.4)} \]

\[ K2 = \frac{1}{\tau^2} \quad \text{E (2.5)} \]

Where \( \zeta \) is the damping coefficient of the system and \( \tau \) is the time constant. Considering the fact that the models of the proposed system are nonlinear and it requires a lot of time and effort to linearize them, this method is not a valid option in this case. Another method of tuning the controller’s parameters is trial and error. The values of K1 and K2 must be selected to get an output of a minimum oscillation and quicker stabilization. The more the output stays on the set-point the better the controller is. The values of K1 and K2 that are selected must be the best valid option to get the best control design. For instance, selecting random values and observe the system’s behaviour and observing the response while decreasing and increasing the values until the best-tuned values are obtained.

2.11 Case Studies on HESS with a Control System:

The controller design is necessary in this project to maximize the performance and avoid any errors that might occur during trial and run of the vehicle. For example, it keeps the stability of the voltage of the DC bus when the load changes [1]. The controller also ensures that the output current \( I_{sc} \) of the supercapacitor always follows the reference current \( I_{scref} \) that is introduced by the controller. There are quite a lot of researches and studies that have been conducted on the design of advanced control systems in EVs. Some researchers from the
University of Electronic Science of Technology in China have done a study on the control design of a nonlinear robust and optimal controller in 2010. The figure below shows the robustness test results of a controller designed for light-weighted EV compared with a regular response of a PID controller with some specified parameters.

![Figure 15: Robustness Test 1 for Nonlinear Robust Controller](image)

As appears on the previous figure, a sudden change on the nonlinear robustness controller is applied at $t=20$ and at $t=50$ s on the double loop PID controller. On the same study, the robustness test was re-conducted under parameters uncertainties. The following figure shows a perfect response of the robustness test for the nonlinear robust controller.
Another study was done in designing a Vehicle Stability Control (VSC) system for hybrid energy vehicle to deliver desired output commands to each subsystem, which includes desired torque from the engine, desired torque or speed from the motor and motor control mode [27]. Open loop and dynamic control algorithm are used to determine the levels of those signals within each state [27]. The figure below illustrates the transition into and out of the boost state within the VSC. At approximately t=2s, an acceleration is initiated by depressing on the accelerating paddle rapidly, and at about t=2.15s, the power requested by the driver reaches a level that cannot be provided by the driver, thus, the VSC switches to boost mode and commands the required torque from the motor until the driver is finally backed off the paddle at t=2.95s [27].

*Figure 16: Robustness Test 2 for Nonlinear Robust Controller*
On the same case study, the process was re-tested on a more complicated algorithm as shown in figure 18. The vehicle is initially at a rest state where an unspecified event occurs that forces the VSC to transition to the engine start state and commands the motor to achieve the requested speed, which is about 700 rpm [28]. Once the motor reaches this speed, the clutch closes causing the engine speed to start increasing as appears in the following figure.
2.12 Case Studies on HESS with a PI Controller System:

Another case study that was conducted on the design of hybrid energy source management system is as shown in figure 19 [37]. This proposed model consists of one IGBT switch in the boost DC-DC converter circuit while two IGBTs switches in the buck-boost circuit. The two switches operate based on the required mode of the circuit, either buck or boost conversion. The DC-DC converters also help in adapting the voltage levels between the two sources and the DC bus [37].

The IGBT switches in the buck-boost circuit are connected to an antiparallel diode to ensure the flow of the reverse current during the all the operation mode of the circuit. A control system is applied on this process to control the opening and closing of the switches called a Proportional Integral (PI) which manipulates the state of 0 and 1 while both circuits are connected in parallel. The PI controller ensures the stability of the super-capacitor voltage and the overall system. Applying control method on the switches results on a high efficiency response of the motor, where the energy source is controlled to supply the power needed at
certain required time while the inverter operates inverting the power to AC then supply it to an AC motor.

Figure 20 shows the voltages of the fuel cell, hybrid energy source and the super-capacitor [37]. The figure also illustrates that the voltage of the DC bus keeps tracking the reference voltage which is 300V. This controlled voltage is caused due to the effect of the PI controller on the IGBTs’ signals, where the controller maintains a stabilize process variable by manipulating a certain parameter in the system. The MV in this case is the signal of the IGBT and the process variable is the SC voltage.

![Figure 20: Output Voltage of the Hybrid Energy Source](image)

The power that is produced by the energy source management is illustrated in figure 21 [37]. During the time from about 4s to 8s the fuel cell provides the required power where the voltage of the DC bus is kept at 300V. After 8s, the fuel cell does not provide any power for two seconds while the SC provides the required power then it collapses back to zero while the fuel cell kicks in. When the power of the SC drops to negative during the period from 14s to 15s,
the motor works as a generator and supplies the fuel cell and the SC by the regenerated power where it is stored in the SC to be later supplied when required.

![Figure 21: Output Power by the Hybrid Energy Source](image)

2.13 Case Studies on Hybrid Renewable Energy System (HRES):

The hybrid energy systems are widely used with renewable energy technologies to overcome the short in energy supply during the short availability of renewable energy sources and the high demand in power. The advantage behind using hybrid renewable energy storage systems in renewable technologies is that 100% of the energy that is being provided is renewable energy for off-grid systems. In most of the renewable system, batteries have been used as storage elements due to their energy storage capacity; however, there has always been some issues to deal with when batteries get involved in a system. For instance, the high load demand in a short duration affects the lifetime of the battery, because batteries are high in energy density but are not favourable for the high power density applications [39]. Therefore, some studies started investigating the possibility of involving SCs in HRES to maximize the energy storage capacity
and minimize the cost. Combining batteries and SCs helps in reducing current load on the batteries and the need of large batteries. It also helps in improving the lifetime of the batteries and decrease the depth of charge and discharge, which therefore, reduces the need of buying large and expensive batteries and maintenance cost. The figure below illustrates an overall design of renewable system with batteries and SC storage system [39].

As mentioned earlier in this report, the SC helps reducing the current stress of a battery by reducing the load intensity and discharge and re-charge of the battery. Figure 23 shows that the current of the battery fluctuates much more with the absence of the SC support while it seems more stable in the case of battery with supercapacitor (BWSC) [39]. The negative magnitude
of the SC identifies the periods when the SC is being charged while the positive magnitude refers to the discharging periods.

![Figure 23: Current Comparison between Battery with and without SC](image)

The results of this system clearly indicates the benefits of combining a SC with a battery. The SC helps in overcoming the stability issues and increasing the reliability of the battery. The fluctuations of the battery current have dramatically decreased when SC supplies the load along with the battery, therefore, this proves the operability of the SCs and their ability of meeting sufficient peak energy supply requirements in short period of time. The tremendous amount of benefits that impact the overall system is clearly observed when the SC was combined with the battery, which makes the it an ideal option in designing hybrid energy systems in electric vehicles.
2.12 Summary

The orientation to the use of Electric Vehicle EV has become more intense in the past decade, which has resulted in a more technologies development in that segment. The need of having more reliable and efficient EVs has led researchers and engineers to develop much better and reliable environmentally friendly vehicles. Many challenges come with designing an efficient vehicle that depends purely on electrical power to serve humans needs, such as designing a control system that enhances the performance of the EV. This chapter of the report has discussed a literal review study on the design of a hybrid energy storage system (HESS) in an EV. The main components that are required to design this system have been explained and discussed in details. In addition, this chapter has explained the functionality of some electronics components that are proposed in HESS designs and their effects on the EV’s system. The design of the advanced control technique called Generic Model Control has also been explained in depth on this paper and the way that it can be used to control the HESS. Some different researches and studies that have been conducted on the same topic were referred to and discussed at the end of this literature review along with some obtained results illustrated on graphs. The possibility of using different control method such as Proportional Integral (PI) controller on hybrid energy system has been investigated. The use of supercapacitor in renewable energy systems has a great benefit of stabilizing the current stress on the battery as was discussed in one of the case studies in this chapter. SCs help in maintaining the performance of the batteries and reducing the discharge and re-charge states, which results in a better lifetime and higher performance of the overall system. In short, this literal review has analysed the possibility of designing a control system for a fuel cell and supercapacitor hybrid energy system design, which supports the proposal idea of this thesis research. Some knowledge and clarification on the needed components to achieve the proposal design have been gained from this chapter of the report.
Chapter 3 – Electric Circuit Structure

3.1 DC-DC Boost Converter

The idea behind a hybrid energy system is to have two power suppliers, which work simultaneously to provide an efficient power supply to the overall system. The main energy supply in the proposed circuit structure is a Proton Exchange Membrane Fuel Cell (PEMFC), which is connected to a boost converter to step up the voltage as required. The fuel cell circuit consists of a capacitor that is connected in parallel with the battery, which plays a great role in protecting the fuel cell in case of an overvoltage. The circuit also composes of an inductor that is connected in series with a resistance considering non-ideal situation, because the inductors have to have some resistance due to a metal coil formation around it. An IGBT switch is also needed in this circuit to control the boosting mechanism of the circuit. An output capacitor filter is connected at the end of the circuit to ensure the clarity of the DC signal that is being produced. Figure 24 below shows the circuit design in Simulink. The signal that is being sent to the switch is generated by a GMC control design.

![Figure 24: Circuit Structure of the Fuel Cell DC-DC Boost Converter](image-url)
3.2 DC-DC Buck Boost Converter

The design of the SC is basically a connection of equivalent resistance and capacitance in series to form a large capacitor that could supply enough energy to the system. This energy supplier is connected to an inductor and resistor in series, and two IGBTs switches which are switched ON and OFF based on the charging and discharging mode in the circuit. Both signals of the IGBTs are being controlled by the GMC control design, however, the signals of those switches are being generated using a further control design, which will be discussed in the next chapter, to prevent them from being opened or closed at the same time. Figure 25 shows the proposed design of the TSBB converter for the SC.

![Figure 25: Circuit Structure of the SC DC-DC Buck-Boost Converter](image)
3.3 Electrical Components Selection and Sizing

The electrical components that are used in this project must be selected based on the many factors to ensure the best possible performance of the system. Therefore, this section will discuss the calculation of selecting the proper size for each component in the HESS design.

3.3.1 Energy Supply Sources

3.3.1.1 Fuel Cell Sizing and Selection

Electrical car industry has gone wide in the last decade, and different variety of energy supply systems have been applied and investigated, however, a PEM fuel cell was selected in this design. The reason behind selecting this type of fuel cell is the operational behaviour of the FC where it uses hydrogen as fuel and reacts with oxygen to produce energy, which does not emit any harmful gases to the environment [32]. Nevertheless, the need of an auxiliary power source is essential in this design, therefore, a supercapacitor is needed to overcome the short in power supply during start-up and sudden acceleration as discussed in the next section of this chapter. The capability of discharging and recharging of the capacitor makes it an ideal choice in this proposal design of the HESS [33]. They are different sizes that could be chosen to design a HESS based on the power required by the vehicle and the practical size of a hydrogen fuel cell is usually over 20KW. However, and since the mean concern of this project is to design a stable and controlled close loop system, a PEM fuel cell of 5000W power rating has been selected due to lack of availability of other fuel cells on the market which made it a little difficult to get the required specifications. Table (1) down below shows the specifications that were used to design the PEM fuel cell in the project [34].
Table 1: PEM Fuel Cell Specifications

<table>
<thead>
<tr>
<th>Horizon 5000W PEM Fuel Cell Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of cells</strong></td>
</tr>
<tr>
<td><strong>Rated Power</strong></td>
</tr>
<tr>
<td><strong>Rated Performance</strong></td>
</tr>
<tr>
<td><strong>Efficiency of the System</strong></td>
</tr>
<tr>
<td><strong>Low voltage Protection</strong></td>
</tr>
<tr>
<td><strong>Over Current Protection</strong></td>
</tr>
<tr>
<td><strong>Over Temperature Protection</strong></td>
</tr>
</tbody>
</table>

3.3.1.2 Supercapacitor Sizing

There are many factors that should be taken into account while selecting a supercapacitor. One of the factors that affect a supercapacitor is the resistivity that the supercapacitor experiences during discharging and charging considering a non-ideal situation [7]. This is why a supercapacitor is connected in series with a resistance in the circuit series in figure 24. Some of the main factors that affect the choice of a supercapacitor are peak capacitor voltage and current, allowable maximum percentage discharge, cell voltage and number of cells needed [7]. The time constant and time of discharge of the SC also play a big role on selecting a suitable capacitance size of the SC. The following equation expresses the capacitance calculation of the auxiliary power source in the HESS design:

\[ C = \frac{I}{V_{max} - V_{min}}(t + \tau) \]

Equation 1: Capacitor Sizing Calculation

Where \( \tau \) is the time constant of the SC, \( t \) is the discharge time, \( V_{max} \) is the peak capacitor voltage and \( V_{min} \) is the lowest voltage the capacitor gets after discharging.
3.3.2 Capacitors

Capacitors are basically electrical components that charge and discharge energy in a certain amount of time. The larger the capacitor is, the greater the energy storage and supply are. Therefore, the size of the capacitor depends on the job that the capacitor is assigned to. For instance, the protection capacitor (\(C_P\)) that is connected in parallel with the fuel cell is used to protect the fuel cell in case of an overvoltage or reversed current with does not require a large capacitance to do that, and that is the reason behind selecting a 1.6 mF capacitor for that purpose. Similarly, the output filter of the DC-DC boost converter circuit is used to minimize the noise and disturbance in the dc voltage, which requires the very same capacitance as \(C_F\).

3.3.3 Inductors

The key of boosting the voltage is the inductors, where the build-up and collapse of the magnetic field that is formed in the coil around the inductors releases a greater voltage that the one that is being supplied. Similar to the capacitors, the larger the inductance is, the higher the step-up voltage is. Selecting the best size of an inductor in a DC-DC converter circuits depends on the inductor current ripple which can be calculated using the following formula [36]:

\[
I_{L(\text{DC MAX})} = \frac{V_{\text{OUT}} - I_{\text{out(MAX)}}}{V_{\text{IN}} \eta} \quad \text{E (3.2)}
\]

Where \(V_{\text{OUT}}\) is the output voltage of the DC-DC converter, \(I_{\text{out(MAX)}}\) is the maximum output current, \(V_{\text{IN}}\) is the typical input voltage and \(\eta\) is the efficiency of the boost converter. Using the obtained value of from the previous equation the final inductance value is calculated as follows:

\[
L = \frac{V_{\text{IN}} (V_{\text{OUT}} + V_D - V_{\text{IN}})}{I_L f_{\text{SW}} (V_{\text{OUT}} - V_D)} \quad \text{E (3.3)}
\]

*Equation 2: Inductor Sizing Calculation*
Where $f_{SW}$ is the switching frequency of the DC-DC converter, $V_D$ is the voltage of the rectify diode.

3.3.4 Switches

The possible valid options when it comes to switches design in DC-DC converters are mostly MOSFETs and IGBTs as mentioned earlier in the literal review section of this research. However, the switch that was selected for this proposal design is the IGBT, due to its advantage on turning off and on rapidly [35]. IGBTs also have a reasonably high communication speed and greater efficiency during higher voltages operations, such as electric vehicles [35]. Furthermore, IGBTs have freewheeling diodes placed in parallel of the switch, which is needed for the opposite current flow situations.

3.4 DC Bus Filter

The purpose of using the DC bus in this design is to create a communication channel between the DC-DC converters and the power inverter. It also helps in delivering a clearer power during both generation and regeneration modes of the system. Some of the factors that need to be considered while selecting a DC bus capacitor filter are the operating temperature and peak current [36]. The following equation is used to determine the suitable size of the DC link capacitor:

$$C = \frac{I \cdot t}{V}$$

*Equation 3: DC Bus Capacitor Size Calculation*

Where $I$ the input current that is being supplied, $t$ is the capacitor charging cycle, which depends on the switching frequency, and $V$ the reference voltage that the capacitor is controlled to follow.
3.5 Power Inverter

The output power that is delivered to the motor must be in AC mode, which requires an inverter to do that job. The power inverter is a three phase inverter being supplied by a power from both the fuel cell and the SC. The inverter that is designed in this project is a bidirectional inverter that converts the DC power that is being supplied from the DC converters and rectifies the generated power from the motor to DC mode to be stored back in the SC. The design of the inverter involves the use of six IGBTs connected to a sine wave and saw-tooth signals as shown in figure 26 below. A discrete time PID controller is also used to control the conversion process of the power inverter, which will be further discussed in the next sub-section of this chapter.

![Figure 26: Power Inverter Design in Simulink](image-url)
3.6 Asynchronous Motor

Asynchronous motor is an electric motor that operates on an AC power to produce the required torque for the load. There are different types of asynchronous motor but the one that is used in this design is 67KW Dual Siemens Azure AC Induction 3-Phase Motor. The table down below shows the main specifications of the asynchronous motor [31].

Table 2: AC Induction Motor Specifications

<table>
<thead>
<tr>
<th>TYPE</th>
<th>AC INDUCTION MOTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>RATED TORQUE</td>
<td>160 Nm</td>
</tr>
<tr>
<td>RATED POWER</td>
<td>67 KW</td>
</tr>
<tr>
<td>MAXIMUM SPEED</td>
<td>10,000 rpm</td>
</tr>
<tr>
<td>RATED VOLTAGE</td>
<td>300 V</td>
</tr>
</tbody>
</table>

This type of motors consists of stator and rotor where the frequency of the rotating field in the air gap does depends on the motor feed’s frequency and number of poles and not on the change of the motor’s load. However, the load does affect the rotation frequency of the rotor where it varies based on the load [28]. The rotation speed of the rotating field in rotation per minute (rpm) is calculated as follows:

\[
N = \frac{120f}{p} \quad \text{(E3.5)}
\]

Where f is the feed frequency and P is the number of the poles of the stator winding. The motor that is used in this project is a three phase and 3-pole asynchronous motor and with fixed feed.
frequency of 50 Hz, the rotation speed will be 2000 rpm. The torque that feeds the motor can be calculated using the following equation [30]:

\[
Torque (N.m) = \frac{Power (KW)}{Speed (RPM)} \times 9.5488
\]  
(E3.6)
In order to design the proposed control system, the binary equations of the overall system must be derived and implemented with the control trajectory, which will be discussed in the next chapter. The binary equations is derived as follows:

4.1 Model of the Boost Converter

4.1.1 Inductor Voltage Balance

The model of the boost converter can be found based on the state of the switch. When the IGBT switch is ON, and by applying Kirchhoff’s voltage law, the following equation is obtained from the circuit:

\[ V_L = U_F - i_{FCC}R_{FCC} \]  \hspace{1cm} (E4.1)

Whereas, when the switch is OFF, the following equation is obtained:

\[ V_L = U_F - i_{FCC}R_{FCC} - U_{dc} \]  \hspace{1cm} (E4.2)

Where

\[ V_L = L \frac{di}{dt} \]  \hspace{1cm} (E4.3)

Knowing that the inductor voltage over one cycle at steady state = 0

\[ V_L \big|_{ON} + V_L \big|_{OFF} = 0 \]  \hspace{1cm} (E4.4)

By substituting equation (3) into (1) and (2), and substituting (1) and (2) into (4) we obtain the following final equation

\[ [U_F - i_{FCC}R_{FCC}]DT_S + [U_F - i_{FCC}R_{FCC} - U_{dc}] (1 - q_1)T_S = i_{FCC}L \]  \hspace{1cm} (E4.5)

Rearrange for \( i_{FCC} \)

\[ i_{FCC} = -(1 - q_1) \frac{U_{dc}}{L_{FC}} - \frac{R_{FC}}{L_{FC}} i_{FC} + \frac{U_F}{L_{FC}} \]  \hspace{1cm} (E4.6)
4.1.2 Capacitor Charge Balance

When the switch is ON, and by applying Kirchhoff’s current law, we obtain the following current equation around the output capacitor

\[ i_C = -i_{f_C} \]  \hspace{1cm} (E4.7)

While the following equation is derived when the switch is OFF

\[ i_C = i_{f_{CC}} + i_{f_C} \]  \hspace{1cm} (E4.8)

Combining the two equations leads to the following overall equation of capacitor charge balance

\[-i_{f_C} DT_S + [i_{f_{CC}} + i_{f_C}](1 - q_1)T_s = C U_{dc} \]  \hspace{1cm} (E4.9)

Rearrange the equation for the voltage of the DC bus filter

\[ U_{dc} = (1 - q_1) \frac{i_{f_{CC}}}{C} - \frac{i_{f_C}}{C} \]  \hspace{1cm} (E4.10)

*Equation 5: Voltage of the DC Bus Overall Equation Using KCL*

4.2 Model of the Buck-Boost Converter

The Buck-Boost converter circuit consists of two switches to maintain the boosting and bucking operations efficiently. The modelling of this circuit is divided into two main modes, the first mode is when the SC is discharging, IGBT2 is ON, IGBT3 is OFF, the second mode is when the SC is charging, IGBT2 is OFF, and IGBT3 is ON.

4.2.1 Discharging Mode

4.2.1.1 Inductor Charge Balance

\[ V_L = U_S - i_s R_{SC} \]  \hspace{1cm} (E4.11)

\[ V_L = U_S - i_s R_{SC} - U_{dc} \]  \hspace{1cm} (E4.12)
Combining both equations, the following is obtained:

\[ [U_S - i_s R_{SC}] q_s T_s + [U_S - i_s R_{SC} - U_{dc}] (1 - q_s) T_s = i_s L_{SC} \]  \hspace{1cm} (E4.13)

Rearranging for SC current \( i_s \):

\[ i_s = -(1 - q_s) \frac{U_{dc}}{L_{SC}} - \frac{R_{SC}}{L_{SC}} i_s + \frac{U_S}{L_{SC}} \]  \hspace{1cm} (E4.14)

Equation 6: SC Circuit Output Current - Inductor Charge Balance (Discharging Mode)

4.2.1.2 Capacitor Charge Balance

Charge balance of the SC while IGBT2 is ON:

\[ i_s = -i_{SC} \]  \hspace{1cm} (E4.15)

Charge balance of the SC while IGBT2 is OFF:

\[ i_s = i_s + i_{SC} \]  \hspace{1cm} (E4.16)

Combining both equations, the following is obtained:

\[-i_{SC} DT_s + i_s (1 - q_s) T_s + i_{SC} (1 - q_s) T_s = 0\]  \hspace{1cm} (E4.17)

Rearrange for SC current \( i_{SC} \):

\[ i_{SC} = (1 - q_s) i_s \]  \hspace{1cm} (E4.18)

Equation 7: SC Current - Inductor Charge Balance (Discharging Mode)

4.2.2 Charging Mode

4.2.2.1 Inductor Charge Balance

IGBT3 ON

\[ V_L = U_S - i_s R_{SC} - U_{dc} \]  \hspace{1cm} (E4.19)

IGBT3 OFF

\[ V_L = U_S - i_s R_{SC} \]  \hspace{1cm} (E4.20)
Combining both equations we obtain the following:

\[ [U_s - i_s R_{SC}]q_3 T_s + [U_s - i_s R_{SC} - U_{dc}](1 - q_3)T_s = i_s L_{SC} \]  

(E4.21)

Rearranging for SC current \( i_s \):

\[ i_s = -q_3 \frac{U_{dc}}{L_{SC}} \frac{R_{SC}}{L_{SC}} i_s + \frac{U_s}{L_{SC}} \]

(E4.22)

*Equation 8: SC Circuit Output Current - Inductor Charge Balance (Charging Mode)*

4.2.2.2 Capacitor Charge Balance

Charge balance of the SC while IGBT3 is ON:

\[ i_s = -i_s + i_{SC} \]  

(E4.23)

Charge balance of the SC while IGBT3 is OFF:

\[ i_s = i_{SC} \]  

(E4.24)

Combining both equations, we obtain the following:

\[ [-i_s + i_{SC}] D T_s + i_{SC} (1 - q_3) T_s = 0 \]  

(E4.25)

Rearrange for SC current \( i_{SC} \):

\[ i_{SC} = q_3 i_s \]  

(E4.25)

*Equation 9: SC Current - Capacitor Charge Balance (Charging Mode)*

4.3 Model of the Global System:

Combining the SC current \( i_s \):

\[ i_s = -[m(1 - q_2) + (1 - m)q_3] \frac{U_{dc}}{L_{SC}} \frac{R_{SC}}{L_{SC}} i_s + \frac{U_s}{L_{SC}} \]

(E4.26)
Where \( m \) is a variable of switch operating state. The Buck-Boost circuit output current \( i_{sc} \) is given by the following equation:

\[
    i_{sc} = [m (1 - q_2) + (1 - m)q_3]i_s
\]  

(E4.27)

Applying KCL, the overall current around the two DC-DC converters expressed as follows:

\[
    i_{fc} + i_{sc} = i_o
\]

(E4.28)

We substitute \( E_? \) into \( E_? \)

\[
    i_{fc} = -[m(1 - q_2) + (1 - m)q_3]i_s + i_o
\]

(E4.29)

Substitute \( E_? \) into \( E_? \) and rearrange for \( U_{dc} \)

\[
    U_{dc} = (1 - q_1)\frac{i_{fCC}}{C} - \frac{1}{C}i_o + \frac{i_s}{C}q_{23}
\]

(E4.30)

Equation 10: DC Bus Global Voltage

Where \( q_{23} \) is the signal of both is switches in the Buck-Boost converter and expressed in the following equation:

\[
    q_{23} = [m(1 - q_2) + (1 - m)q_3]
\]

(E4.31)

Based on \( E_? \), rewriting \( E_? \) gives the final equation for \( i_s \)

\[
    i_s = -q_{23}\frac{U_{dc}}{L_{sc}} - \frac{R_{sc}}{L_{sc}}i_s + \frac{U_s}{L_{sc}}
\]

(E4.32)

Equation 11: SC Global System Current
Chapter 5 – Controller Design

5.1 Generic Model Control:
The GMC controller works similar to other control methods. It basically manipulates certain effective parameters in the system and force them to follow a certain desired output that is required by the process. In the case of the GMC, it has a trajectory equation that can be expressed as follows:

\[
\frac{dy}{dt} = K_1 (y_{SP} - y) + K_2 \int_0^{t_k} (y_{SP} - y) dt
\]  

\(E5.1\)

Equation 12: GMC Trajectory Equation

5.2 Controller Design:
This trajectory equation is equated with a manipulated variable equation, which is the parameters that will be varied to control a certain process variable. This project aims to control the current of the SC and the voltage of the DC Bus; therefore, the variables that will be manipulated in order to fulfill that purpose are the signals of the first switch of the Boost converter \(n_1\) and the signal of the switches in the buck boost converter \(n_{23}\). The following equations shows the final MVs with respect to the controller trajectory.

\[
n_1 = \frac{C}{i_{FCC}} \left[ \frac{i_{FCC}}{C} + \frac{i_s}{C} n_{23} - \frac{i_0}{C} - K_1 (y_{SP} - y) - K_2 \int_0^{t_k} (y_{SP} - y) dt \right]
\]

\(E5.2\)

Equation 13: Controlled Signal of IGBT1

\[
n_{23} = \frac{L_{SC}}{U_{dc}} \left[ - \frac{R_{SC}}{L_{SC}} i_s + \frac{U_s}{L_{SC}} - K_1 (y_{SP} - y) - K_2 \int_0^{t_k} (y_{SP} - y) dt \right]
\]

\(E5.3\)

Equation 14: Controlled Signal of IGBT2 & IGBT3

Those MVs are fed into the Pulse Width Generation (PWM) to limit the signals between 0 to 1 as it is further discussed in the next sections of this chapter.
5.3 Tuning of Controller’s Parameters

The parameters of the GMC controller K1 and K2 are constant values that can be selected using different tuning methods to achieve the desired output. However, the tuning method that was used to select the parameters of the controller was “trial and error”. The selection of K1 and K2 depends on the response of the controlled variables; therefore, the parameters that are the most appropriate for the design are the ones that keep the output’s response of the controlled variables with the least variations and the closest to the desired set-point. Different values have been tried and the ones that gave the best results were as follows:

Table 3: GMC Controller Parameters Values

<table>
<thead>
<tr>
<th>FIRST GMC $U_{dc}$</th>
<th>SECOND GMC $i_S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>3</td>
</tr>
<tr>
<td>K2</td>
<td>79</td>
</tr>
</tbody>
</table>

5.4 Generation of Pulse Width Modulation (PWM) for the HESS:

The use of Pulse Width Modulation (PWM) concept is essential to provide an ON/OFF signal to the IGBTs. The signal of the IGBT1 in the Boost converter circuit is modulated through a PWM functional block as shown in figure 27, whereas, the signal of IGBT2 and IGBT3 must be regulated to provide a Buck and Boost operation simultaneously as required. The Controlled signal of the GMC design $\eta_{23}$ is modulated through a PWM functional block and compared modelled with the reference current as shown in figure 27 below. The resultant of this PWM
generation is two separate PWM signals for both switches in the Buck-Boost converter circuit $q_2$ and $q_3$.

Figure 27: Pulse Width Modulation (PWM) Generation

5.6 Reference Current $i_{sref}$ and Voltage $U_{dc ref}$

The reference DC bus voltage that was selected as a desired value is 300V based on the required voltage of the required voltage for the motor to operate. This value was obtained from the specification Data sheet as discussed in table 2. The reference current of the capacitor is the current that the capacitor should operate on, because the current that the SC should operate on, differs depending on the changing of the load and the operation mode of the buck-boost circuit. The reference current that is used as a desired value (set point) in this project is based on the current that the AC motor requires, which is generated by the storage management system.
6.1 Electric and Power System Simulation Design

The whole system and control design were simulated in Simulink in an electrical and control design. The DC-DC converters were simulated as discussed in the proposal design then both connected to DC bus filter capacitor to minimize the noise of the DC power. This filtered power is sent to an inverter design to obtain an AC power that is required to operate the three-phase asynchronous motor as shown in figure 28.

![Simulation Diagram](image)

*Figure 28: Overall Simulation Structure Design of the HESS*

During regeneration mode of the motor, the inverter works as a rectifier and rectifies the power to DC mode, which is stored back in the SC. The generated signals of the switches in the SC capacitors close IGBT2 and open IGBT3 to allow the circuit to operate in Buck mode and charge the SC. The PEMFC that was simulated in the project is functional block in Simulink
with the parameters adjusted based on the fuel cell that was selected for the system. The currents and voltages variables were read from the electric circuits and fed back to the controller system design as will be discussed in the next section of this chapter. The figure below illustrates the Inverter and motor simulation design.

![Inverter and Motor Three-Phase Connection in Simulink](image)

*Figure 29: Inverter and Motor Three-Phase Connection in Simulink*

Based on the research and calculation that were discussed on chapter 3 of this thesis report, the following parameters of the HESS were obtained:

*Table 4: Parameters of Electrical Components of the HESS*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{HI}$</td>
<td>1.67 mF</td>
<td>Fuel Cell Capacitor</td>
</tr>
<tr>
<td>$C_s$</td>
<td>1.66 mF</td>
<td>Fuel Cell Capacitor</td>
</tr>
<tr>
<td>$R_{HI}$</td>
<td>18 mΩ</td>
<td>Fuel Cell Capacitor</td>
</tr>
<tr>
<td>$R^I_1$</td>
<td>18 mΩ</td>
<td>Fuel Cell Capacitor</td>
</tr>
<tr>
<td>$R_{SC}$</td>
<td>18 mΩ</td>
<td>Fuel Cell Capacitor</td>
</tr>
</tbody>
</table>
6.2 Control System Simulation Design

Designing the control system also involved the use of Simulink software. The binary equations that was derived for the MVs $\eta_1$ and $\eta_{23}$ were implemented in the software as functional blocks. The signal that was generated from the control system is fed back into the main model to obtain a closed-loop system and ensure the stability of the overall system. This concept is used to design two GMC control systems to control both current and voltage of the SC and DC bus respectively. The figure below shows the simulation method of the control system GMC.

![Figure 30: Generic Model Controller Design in Simulink](image_url)
The output of the GMC design changes based on the currents and voltages that are being supplied from the electrical circuit design as shown in figure 28, therefore, this controlled design is a part of the overall design of the electric system. The half of the GMC design on the right hand side in figure 30 is the derived model of the DC voltage as obtained in (E4.30).
Chapter 7 – Simulation Results

The generic model controller has shown a very acceptable performance in terms of keeping a track of the reference current and voltage. The current of the SC has shown a very stable response during steady state running load, however, it goes off the reference current by very small variations during the sudden changes as appears in the graph. Nevertheless, the GMC controller kicks in and stabilizes the response back to the reference current value. Figure 31 below shows the effect of the controller in the current of the SC.

Figure 31: Controlled Current of the SC Based on Reference Current

From the previous figure, the supercapacitor is supplying power to the load during the time from 0s to 0.4s, while it is charging from 0.4s to about 0.8s which explains the negative magnitude during that period of time. The presence of the generic model controller is clearly affecting the current of the SC. The SC is forced to charge at 0.4s and discharge at 0.8s, while it goes back to discharging mode from 0.8s to 1.0s. The SC’s current continues to discharge and charges very smoothly affected by the desired value of the controller. On the other hand,
the GMC shows a great performance in forcing the voltage of the DC bus to trace the reference voltage, which is 300V. There are a lot of ripples and variations in the response of the controlled voltage due to the fast closing and opening of the switch as appears in figure 32; however, they are very small with a difference of 0.00002, which can be neglected.

![Figure 32: Controlled Voltage of the DC Bus based on the Reference Voltage 300V](image)

The duty cycle of both process variables $i_S$ and $U_{dc}$ keep changing to force the output to follow the desired set point. The major changes in the response of the MVs happen during the sudden changes of the load demand during the times 0.4s, 0.8s, 1.0s and 1.4s. The figures below show the response of the duty cycles (Manipulated Variables) of both designed GMCs for the DC bus voltage and SC’s current.
Figure 33: Manipulated Variable $n1$ Response (Duty Cycle)

Figure 34: Manipulated Variable $n23$ Response (Duty Cycle)

Where the MVs change the most at 0.4s and 0.8s when the SC changes from discharge mode to charge mode based on the reference current. As Discussed in chapter 5, the PWM generation is essential before feeding the controlled signal to the IGBTS switches. The signals q2 and q3 of the SC circuit are controlled by the same GMC design but they must operate based on the
required operation mode of the system, either boost or buck conversion system, therefore, they cannot be both opened or closed at the same time. Based on that, the PWM generation method were used to ensure that operability of the Buck-Boost DC-DC converter. This process repeats during the time 1.0s to 1.4s. Figure 35 shows the response of q2 where the switch operates during the period 0.0s to 0.4 when the SC is being discharged, and it stays open when the SC is being charged during the period 0.4s to 0.8s and 1.0s to 1.4s.

![Graph](image)

*Figure 35: The response of q2*

In the next figure, the response of the signal q2 shows that the switch has operational behaviour compared to the other switch in the circuits. This proves that the PWM generation of q2 and q3 is a success and the switches do not interact during the operation. Figure 36 illustrates the response of q3.
Both IGBTs open and close rapidly which explains the fast ripples of the switches in the graphs. The IGBT switch in the fuel cell circuit behaves normally where it opens and closes intensively to supply boosted voltage to the load. When the motor decelerates, it works as a generator and it supplies reversed power to the SC through the inverter and DC link.
Chapter 8 – Conclusion and Recommendation

The research investigates the possibility of designing a control system to control the power supply mechanism in HESS in an electric vehicle. The aim of this thesis is to maintain the voltage of the DC bus filter and the current of the auxiliary power supply SC and ensure the overall stability of the system. Based on background research, the use of generic model control design was the most preferred option due to the nonlinearity behaviour of the DC-DC converters that are used in the design. The literal review research that was conducted in one of the stages of this project, has also helped in choosing the most appropriate software to implement the design, which was eventually chosen to be Simulink.

This thesis investigated the researches and case studies that were conducted in the design of HESS and the use of possible control methods to maintain the stability of the overall closed-loop system. It has detailed a proposal design of an electronic power structure of DC-DC converters, DC bus filter, and bidirectional power inverter in the system. It has also discussed the modelling and deriving of the binary equations of the system and the implementation of those equations into the controller system. The GMC control system has also investigated and the controller’s parameters that affect the system, which were tuned based on the desired output of the system. The research has also analysed the implementation of the system in simulation software and the way all circuits and components are connected together in the software.

Finally, the results obtained indicate that the designed GMC system has a high performance on affecting the overall system. It has kept both the voltage and current of the DC bus and SC respectively, tracing the reference input assigned to the controller. The response of the manipulated variables and controlled variables illustrated the opening and closing of the IGBT switches and they indicate that the controller’s performance indicates the successful selection
of this control method. Nevertheless, the behaviour of the SC’s current was not controlled as smoothly as the voltage of the DC bus was, because the current keeps changing over time unlike the voltage, which is fixed at a certain desired value. All in all, the results that were obtained were very close to the hypothesises that were set at the beginning of this project and the overall stability of the closed-loop control system was achieved. The performance of the electric vehicle under the effect of the control system makes this design a valid option to be implemented in the transportation industry.

8.1 Future Work and Recommendations

Controlling the current is definitely a valid option; however, it is wiser to control the voltage instant since the current keeps changing over time. The response of the controlled current was a success to some point; nevertheless, the voltage response has very much fewer variations than the current, because the voltage is set at a certain reference voltage. Base on that result, controlling the voltage of the SC is an area to be investigated, and the results can be compared with this project. Also, the design of a different control system, such as PID, Model Predictive Control (MPC) can be tested on the proposed HESS to examine the performance of the controllers and compare them with GMC. Using simulation software saves a lot of money and time rather than doing the real experiment, however, the design of a real mini HESS could be an option for the future work to investigate the behaviour of the system and observe the operation of the system. The big challenge might be the high cost of the electrical components that are needed for the project especially the fuel cell, SC and the asynchronous motor, therefore, designing a mini HESS for educational and observation purposes is a valid option on the table. The real design of a HESS can be tested with an asynchronous motor that can be implemented in real small vehicle design. Furthermore, the use of different simulation software such as LabVIEW and Power Factory is another field to conduct a research on.
References


Appendix

input parameters of the fuel cell stack block in Simulink

![Image of Fuel Cell Stack Block Parameters]

Figure 37: Specifications of the PEMFC

All parameters and details of the Fuel cell that was used in the design [7].

Table 5: Horizon 5000W PEM Fuel Cell Data Sheet

<table>
<thead>
<tr>
<th>Horizon 5000W PEM Fuel Cell [7]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Cells</td>
</tr>
<tr>
<td>Rated Power</td>
</tr>
<tr>
<td>Rated Performance</td>
</tr>
<tr>
<td>Hydrogen Supply Valve Voltage</td>
</tr>
<tr>
<td>Purging Valve Voltage</td>
</tr>
<tr>
<td>Specification</td>
</tr>
<tr>
<td>-----------------------------------</td>
</tr>
<tr>
<td>Blower Voltage</td>
</tr>
<tr>
<td>Reactants</td>
</tr>
<tr>
<td>Ambient Temperature</td>
</tr>
<tr>
<td>Max Stack Temperature</td>
</tr>
<tr>
<td>Hydrogen Pressure</td>
</tr>
<tr>
<td>Humidification</td>
</tr>
<tr>
<td>Cooling</td>
</tr>
<tr>
<td>Controller Weight</td>
</tr>
<tr>
<td>Stack Weight (with Fan &amp; Casing)</td>
</tr>
<tr>
<td>Hydrogen Flow Rate at Max Output</td>
</tr>
<tr>
<td>Stack Size</td>
</tr>
<tr>
<td>Hydrogen Purity Requirement</td>
</tr>
<tr>
<td>Start-up time</td>
</tr>
<tr>
<td>Efficiency of System</td>
</tr>
<tr>
<td>Low Voltage Protection</td>
</tr>
<tr>
<td>Over Current Protection</td>
</tr>
<tr>
<td>Over Temperature Protection</td>
</tr>
<tr>
<td>External Power Supply</td>
</tr>
</tbody>
</table>
Figure 38: Overall Power Structure of the HESS (Landscape)
Control Design of both $U_{dc}$ and $i_s$ in Simulink:

Figure 38: GMC Design of DC bus Voltage (Landscape)
Figure 40: GMC Design of SC Current (Landscape)
<table>
<thead>
<tr>
<th>TYPE</th>
<th>AC INDUCTION MOTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>COOLING MEDIA</td>
<td>Water-Glycol</td>
</tr>
<tr>
<td>RATED VOLTAGE DC</td>
<td>300 V</td>
</tr>
<tr>
<td>RATED POWER</td>
<td>67 KW</td>
</tr>
<tr>
<td>RATED TORQUE</td>
<td>200 Nm @ 280A</td>
</tr>
<tr>
<td>RATED CURRENT</td>
<td>248 A</td>
</tr>
<tr>
<td>MAX. SPEED</td>
<td>10,000 rpm</td>
</tr>
<tr>
<td>WEIGHT</td>
<td>90 Kg</td>
</tr>
<tr>
<td>DIMENSIONS (LXWXH)</td>
<td>425 x 245 x 245 mm</td>
</tr>
<tr>
<td>AMBIENT TEMPERATURE</td>
<td>-30º C to 70º C</td>
</tr>
<tr>
<td>DEGREE OF PROTECTION</td>
<td>IP 65 / 9K</td>
</tr>
</tbody>
</table>