SUPERCAPACITOR CONTROL FOR ELECTRIC VEHICLE POWERED BY HYBRID ENERGY STORAGE SYSTEM

by

Ntokozo Musawenkosi Khanyile

Submitted in partial fulfilment of the requirements for the degree

Master of Engineering (Electrical Engineering)

in the

Department of Electrical, Electronic and Computer Engineering

Faculty of Engineering, Built Environment, and Information Technology

UNIVERSITY OF PRETORIA

January 2024

SUMMARY

SUPERCAPACITOR CONTROL FOR ELECTRIC VEHICLE POWERED BY HYBRID ENERGY STORAGE SYSTEM

by

Ntokozo Musawenkosi Khanyile

Supervisor:	Dr Mwana Wa Kalaga Mbukani
Department:	Electrical, Electronic and Computer Engineering
University:	University of Pretoria
Degree:	Master of Engineering (Electrical Engineering)

Keywords: Electric vehicle (EV), energy management system (EMS), hybrid energy storage system (HESS), supercapacitor (SC) energy control.

Governments worldwide are encouraging the phasing out of vehicles that use internal combustion engines in favour of electric vehicles (EV) to reduce emissions. Electric vehicles that are currently on the market use a battery only energy storage system (ESS). The main disadvantage of this ESS is that when the EV requires more that rated power from the battery on a frequent basis, the battery's lifespan is greatly reduced. Although the battery output power may be electronically limited, reducing the battery output power reduces the performance of the EV. To compensate for the battery's inadequacies, a supercapacitor (SC) is introduced to the ESS to form a battery-SC hybrid energy storage system (HESS).

An energy management system (EMS) play an important role as it manages the power slit between the battery and the SC. There are three types of EMSs namely, rule-based, optimization based and intelligent based systems each with their own advantages and disadvantages. A rule-based EMS was proposed that utilizes the vehicle's parameters, that

is, mass, drag coefficient, the vehicle's frontal area, and the vehicle's rolling resistance. The EMS also considers external factors such as terrain elevation, and traffic information.

The proposed EMS was modelled in MATLAB Simulink using the EV reference model. The implementation and design of the proposed EMS was guided by knowledge gained throughout the study. Unlike in previous studies where the SC was used only as a peak power shaving solution, in the proposed EMS the SC is used throughout the operation of the EV. The simulation results of the proposed EMS showed that for city driving conditions, the battery current was reduced by 19% when compared to a battery only ESS of the same size. For traffic conditions, the battery current for was reduced to 0 A while with highway driving the battery current was reduced by 50% when compared to a battery only ESS of the same size. Furthermore, the proposed EMS ensured that the battery current is only in one direction, discharge only. These factors ensure the longevity of the battery.

LIST OF ABBREVIATIONS

AC	Alternating Current
CBD	Central Business District
DC	Direct Current
EMS	Energy management system
EV	Electric vehicle
HESS	Hybrid energy storage system
SA	South Africa
SC	Supercapacitor
SOC	State Of Charge

LIST OF SYMBOLS

A_f	EV frontal cross section
α	road slope
C_d	air drag coefficient
f_a	aerodynamic drag force
f_r	rolling resistance force
f_t	traction force
g	gravitational acceleration
m	mass of the EV
η_{bat}	discharging efficiency of the battery dc-dc converter
η_d	combined mechanical transmission efficiency and the efficiency of the electric motor
η_{sc}	supercapacitor discharging and dc–dc converter efficiencies
p_a	air density
p_{ev}	power required by the EV
p_{bat}	battery charge/discharge power
$P_{bat,limit}$	battery power limit
p_{sc}	supercapacitor charge/discharge power
$P_{sc,limit}$	Supercapacitor power limit
µ	rolling resistance coefficient
v	velocity of the EV

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 INTRODUCTION

1.1 PROBLEM STATEMENT

1.1.1 Context of the problem

According to available data from 2010, fossil fuel combustion contributed to 65% of the world's CO_2 emissions [1]. In South Africa, the transportation sector contributed 15% to CO_2 emissions [2]. In the USA, the transportation sector contributed 29% to CO_2 emissions [3]. It can be observed that the transport sector is one of the significant contributors to CO_2 emissions [1]. Governments around the world have provided tax incentives for EVs and some have resorted to ban internal combustion (IC). The UK government announced that the sale of all petrol and diesel vehicles will be banned in the UK in 2040 [4]. Therefore, EVs and their ESSs have been investigated by researchers.

Currently, EVs use battery only ESS as it is the most common ESS, easily available, and it does not have high-cost implications. The main drawback with batteries is that when they are exposed to frequent charge and discharge cycles, or if they are exposed to high frequency currents, their life cycle is greatly reduced. For this reason, a SC is added to the ESS to form a battery-SC HESS. The SC is in place to protect the battery from high frequency currents and to assistant the battery when the EV demands more than rated power from the battery.

A battery-SC HESS has two energy sources and therefore an EMS is required to manage the power slit between the battery and the SC [5]. The objective of the EMS is to increase the HESS efficiency, power quality and system stability [6]. The EMS is also responsible for increasing the life span of the battery and the SC as well as protecting each storage element. The EMS control techniques can be summarized into three categories namely rule-based EMS, optimization-based EMS, and intelligent EMS. The rule-based control method uses experiences and mathematical models to derive rules that determine the power exchange of the HESS [7]. The rule-based control approach is effective in real-time energy management applications. Optimization control techniques use optimization algorithms such as dynamic programming (DP), particle swarm optimization (PSO), linear programming etc. to find the global minimum/maximum of a cost function. The cost function being the energy slit between the battery and the SC to support the EV power demand. Intelligent/data driven control methods use intelligent algorithms such as neural networks (NN), supervised learning etc. to obtain the best power slit solution [8].

The are two main challenges that arise with respect to EMSs. The first challenge is regarding designing an algorithm that is real-time implementable and provides the most optimal [9]. The rule-based algorithm may be the most real-time implementable strategy, it does not provide the most optimal power slit solution. While optimization techniques provide the optimal power slit solution, they are computational expensive, and they require the drive cycle to be known beforehand. Intelligent/data driven methods observe the behaviour of the ESS over time to provide the most optimal power slit [10]. The problem with this approach is that extensive training data is required and computational expensive. The second challenge is ensuring that the EMS effectively utilizes the energy stored in the SC. In the EMSs presented in literature so far, the SC is only used to assist the battery during peak power demand situations and to absorb high frequency currents. While this is the function of the SC, this approach does not effectively utilize the energy stored in the SC.

1.1.2 Research gap

It became apparent from study literature that there are no EMSs that utilize the SC to support the EV load demand during normal driving. In [11], an ANN based strategy embedded in a rule-based control scheme to control the SOC of the SC to ensure that the energy stored in the SC is available for more than one drive cycle is presented. But this system required a large amount of training data. In studies [6] – [10], the authors attempted to use the energy stored in the SC such that the SC is available for more than one drive cycle.

The research gap lies in the fact that researchers thus far have not used the SC in their EMSs to support the load during normal driving operations. In this study, a rule-based EMS was developed with the following control objectives:

1. Utilize the energy stored in the SC during normal driving scenarios. This is done to alleviate stress on the battery.
2. Increase the battery lifespan by ensuring that the battery does not deliver more than rated current to the EV. This is because if the battery deliveries more than its rated current to the EV on a frequent basis,
3. Increase the accuracy of the power slit between the battery and the SC of the rule-based algorithm by using multiple parameters such as the EV mass, aerodynamic coefficient, and the vehicle frontal area. Road parameters such as traffic information and terrain information.

1.2 RESEARCH OBJECTIVE AND QUESTIONS

- What is the state of the art for the proposed study on rule-based EMSs for EVs?
- What is the appropriate rule-based EMSs and how to increase EVs' performance?
- Will the modelling of the EVs system and the implementation of the rule-based EMSs for EVs equipped with both the battery result in the performance validation?

1.3 APPROACH

A simulation (MATLAB/Simulink) software had been chosen which had the capability to simulate an EV as well as power electronic components. The EV reference application model was best suited for this design. The electric vehicle (EV) reference application represents a full electric vehicle model with a motor-generator, battery, direct-drive transmission, and associated powertrain control algorithms. The simscape electrical toolbox was used to simulate DC-DC converters.

The model used a Li-ion battery model found under the simscape electrical toolbox. Instead of using the default parameters, the model was made to resemble the specifications of a first-generation BMW ix3. The drive cycles that were chosen were UDDS cycle which represents city driving, the CBD drive cycle which represents stop/start traffic and the Artemis motorway 130 driving cycle which represents highway driving with a maximum speed of 130 km/h. The reference model with the battery only configuration will be compared to the battery-SC HESS equipped with the proposed EMS. The battery only ESS was also used to size the battery-SC HESS.

It was decided that the HESS topology to be used would be a fully active HESS topology, that is, the battery and the SC was buffered by a DC/DC converter. This was done so that the flow of energy from and to each storage element may be controlled efficiently. The advantages, disadvantages, and the cost implications of having a fully active HESS were documented.

1.4 RESEARCH CONTRIBUTION

- The proposed EMS uses a multitude of information, that is, traffic information, road slope information, temperature, wind speed as well as vehicle dynamics. Previous studies only used one of these parameters while this study uses all the above-mentioned parameters to attempt to increase the accuracy of the rule-based EMS. The advantage of using a multitude of information is that the EMS can slit the EV power demand between the battery and SC more optimally without using optimization techniques.
- It was determined that having the SC fully contributing to the EV's load reduced the stress on the battery and the battery size could be reduce as well to save costs.

- The study proved that the fully active HESS topology must be the topology of choice when implementing a HESS to gain full control of the energy flow from the energy storage elements.
- The study slits the driving scenarios between, city driving, stop/start traffic and highway driving. The EV power demand is split between the battery and the SC according to the driving scenario encountered by the EV.

1.5 RESEARCH OUTPUTS

Two conference papers were submitted to the PEMD (power electronics, machines, and drives) 2023 conference.

Authors: Ntokozo Khanyile and Dr. Mwana Wa Kalaga Mbukani

Title: Supercapacitor Control for Electric Vehicle Powered by Hybrid Energy Storage System: A Review Paper

Abstract: The energy storage system (ESS) of an electric vehicle determines the electric vehicle's power, range, and efficiency. The electric vehicles that are available in the market currently use battery-based ESS. ESS of electric vehicles experiences a high number of charge and discharge currents which degrade the battery life span. The introduction of supercapacitors has led to the development of battery-supercapacitor hybrid energy storage systems (HESS) which takes advantage of the high energy density of batteries for drive range and the high-power density of supercapacitors to protect the battery of high charge and discharge currents. To manage the energy slit between the battery and the supercapacitor an energy management system is required. This paper reviews the different energy management strategies that have been proposed in literature.

The paper was accepted and published.

Authors: Ntokozo Khanyile and Dr. Mwana Wa Kalaga Mbukani

Title: Supercapacitor Control for Electric Vehicle Powered by Hybrid Energy Storage System

Abstract: Pure electric vehicles and hybrid electric vehicles have gained attention in recent years due to concerns about the carbon footprint of internal combustion engines. In recent years, the focus in the electric vehicle research space has been to establish systems that will ensure the maximum life span of the battery. Therefore, research has coupled the battery with a supercapacitor to become a battery-supercapacitor hybrid energy storage system (HESS). The supercapacitor can absorb the high frequency power surges of the EV while the battery supplies the average power of the EV. In this paper, a novel rule-based energy management system (EMS) is proposed. The proposed EMS uses the physical parameters of the EV to limit the battery power rate and amplitude. The simulation results show that the control objectives of the controller were reached with the use of the urban dynamometer driving schedule (UDDS).

The paper was accepted and published.

A Journal article was compiled using the knowledge gained from this study and was submitted to the IEEE Transactions on Transportation Electrification.

Authors: Ntokozo Khanyile and Dr. Mwana Wa Kalaga Mbukani

Title: A New Rule-Based Energy Management System for Battery-Supercapacitor Hybrid Energy Storage System for Supercapacitor Energy Effective Usage

Abstract: The battery life span in electric vehicles (EVs) that utilize a battery only energy storage system (ESS), is affected by its frequent utilization, high current surges, accumulated heat, and overall energy output. The inclusion of a supercapacitor (SC) to form a battery-SC hybrid energy storage system (HESS) has ensured that the battery is protected from high current surges, and it has allowed researchers to utilize the battery more effectively. As the battery-SC HESS uses two ESSs, an energy management system (EMS) plays a significant role in determining the overall efficiency of the system. It was noted that the EMSs proposed in literature mainly used the SC to absorb high frequency currents and to absorb high current surges. This strategy does not allow the energy stored in the SC to be used effectively because in instances where the EV does not experience high frequency current, the SC is not utilized. In this paper, a new

rule-based EMS is proposed that considers the traffic information, terrain information, wind speed and ambient temperature. The proposed battery-SC HESS utilizes a fully active HESS topology. The proposed EMS is compared with a battery ESS system with the same specifications as that of a first-generation BMW ix3. The systems were tested under three drive cycles i.e. UDDS, Artemis motorway 130 and the CBD drive cycle. It is shown that the proposed EMS effectively uses the energy stored in the SC and the battery lifespan is improved. MATLAB Simulink was used as the simulation software and the EV reference model was used as a template.

1.6 OVERVIEW OF STUDY

- **Chapter 2** provides background and context to the study documented in this dissertation.
- **Chapter 3** introduces the theoretical calculations for the proposed EMS. The reader will also be introduced to the EV reference model in MATLAB SIMULINK and how it was used to simulate the EMS. This chapter also includes the sizing of the battery-SC HESS.
- **Chapter 4** presents the simulation results. Waveforms are provided to compare the battery-SC HESS results with the reference and the proposed. The system was simulated on three different drive cycles namely UDDS, Artemis motorway 130 and the CBD drive cycle.
- **Chapter 5** discuss the results. The benefits as well as the disadvantages of the proposed EMS in terms of battery life and total system cost.
- **Chapter 6** concludes the study and provides the reader with a complete summary of all the work done and a subjective outcome of the study followed by work that can possibly be done in the future.
- **Addendum A** is the final part of the document in which some more information is provided about the simulation models used in this study.

CHAPTER 2 LITERATURE STUDY

2.1 CHAPTER OVERVIEW

This chapter presents the literature study for this dissertation. Section 2.2 introduces the development of the battery-SC HESS and the different topologies that are available. Sections 2.3 discusses the different EMS strategies.

2.2 HYBRID ENERGY STORAGE SYSTEM

Battery only EV's suffer from a decreased battery lifespan over time as discussed in section 1.1.1. Therefore, to extend the battery lifespan, a supercapacitor is added to the ESS to ensure that battery is protected from high frequency currents. There are four battery-SC HESS topologies namely, passive, semi-active, and fully active.

2.2.1 Passive HESS topology

The passive battery-SC consists of the battery and the SC are connected in parallel as shown in Figure 2.1. In the passive topology, the SC is purely used as a low pass filter. This connection directly links the HESS to the DC bus without the need for any DC-DC converters. Consequently, there is no control over the active power flow through the storage devices. The amount of current drawn from the battery and SC depends on their internal resistances [13],[12]. As a result, the SC's transient power handling capability is not fully utilized. The battery primarily provides the ramp up (and down) power in response to a frequency nadir (zenith). Furthermore, due to the small voltage variation at the battery terminal, the SC does not operate within its full SoC range, leading to poor volumetric efficiency [14],[13]. The passive HESS offers advantages such as simplicity and low implementation cost since it does not require power electronics and control circuits [15],[14].

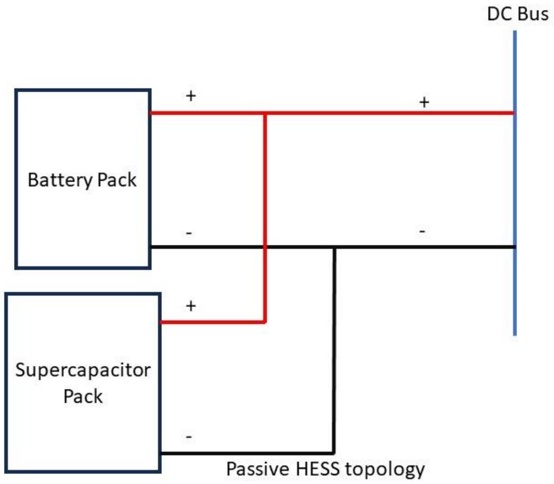

Figure 2.1. Passive battery-SC HESS.

The advantages of the passive battery-SC HESS topology are summarised below [16],[17]:

1) As there are not DC/DC converters used, the cost of the system is decreased.
2) The system is easy to implement.
3) Easily serviceable.

The disadvantage of the passive battery-SC HESS topology are as follows [18]-[20]:

1) The battery may be still exposed to high frequency currents.
2) The energy stored in the SC is not effectively used. According to [21], the passive HESS topology utilizes 25% of the energy stored in the SC.
3) As there are no DC/DC converters, the flow of energy from the battery and the SC cannot be controlled.

2.2.2 Semi-Active HESS topology

There are two types of semi-active HESS topologies as shown in Figure 2.2 and Figure 2.3. The SC semi-active HESS consists of the SC that’s connected to the DC through a DC/DC converter while the battery is connected directly onto the DC bus.

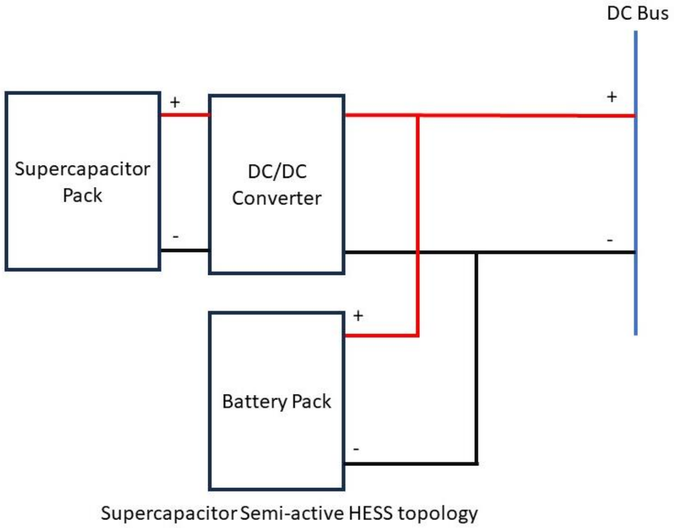

Figure 2.2. SC Semi-active battery-SC HESS.

The advantages of the SC semi-active battery-SC HESS, shown in Figure 2.2, are as follows [22]-[24]:

1) The DC/DC converter allows for the energy stored in the SC to be controlled.
2) As there is one DC/DC converter used, the cost of the system is moderate.
3) The inclusion of the DC/DC converter allows for a supervisory controller/EMS to be added onto the system.

The disadvantage of the SC semi-active battery-SC HESS are as follows [3],[25],[26]:

1) The battery may still be exposed to high frequency currents. This is dependent on the response time of the DC/DC converter.
2) The inclusion of a DC/DC converter increases the cost of the system. This is dependent on the type of DC/DC converter that is selected as its power rating.
3) The battery must be sized according to the DC bus voltage.

The battery semi-active HESS consists of the battery that's connected to the DC bus through a DC/DC converter while the SC is connected directly onto the DC bus. This arrangement separates the battery from the SC through a DC-DC converter. While this setup ensures a smooth operation for the battery with the converter's assistance, the SC's full potential cannot be realized due to its linear discharge characteristic. The optimal ramping capability of the SC ought to be exponential, but this is not feasible economically as it would necessitate an exceptionally high SC rating.

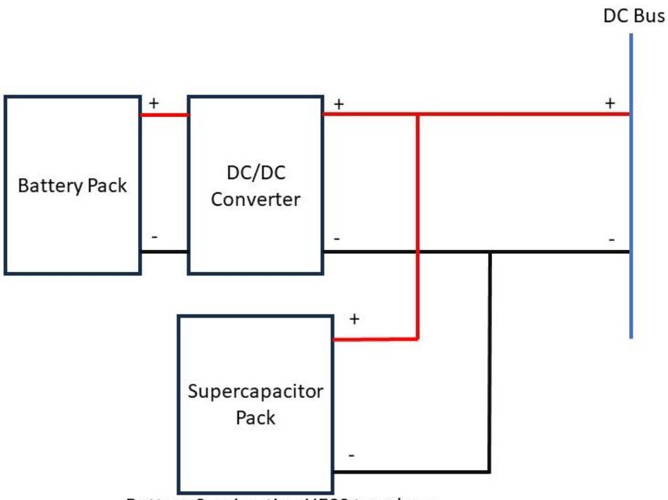

Figure 2.3. Battery Semi-active battery-SC HESS.

The advantages of the battery semi-active battery-SC HESS, shown in Figure 2.3, are as follows [27]-[29]:

1) The DC/DC converter allows for the energy stored in the battery to be controlled.
2) The battery is full protected from high frequency currents as it is buffered by a DC/DC converter.
3) The size of the battery may be reduced to reduce the cost of the system.

The disadvantage of the battery semi-active battery-SC HESS are as follows [30]-[32]:

1) As the SC is connect directly to the DC bus, the energy stored in the SC is not efficiently used.
2) The battery DC/DC converter can only be operated in voltage control mode to keep the DC bus voltage stable.
3) The SC must be sized according to the DC bus voltage which will drastically increase the cost of the system.

2.2.3 Fully Active Battery-SC HESS

The fully active battery-SC HESS consists of the battery and the SC both connected to the DC bus through a DC/DC converter as illustrated by Figure 2.4.

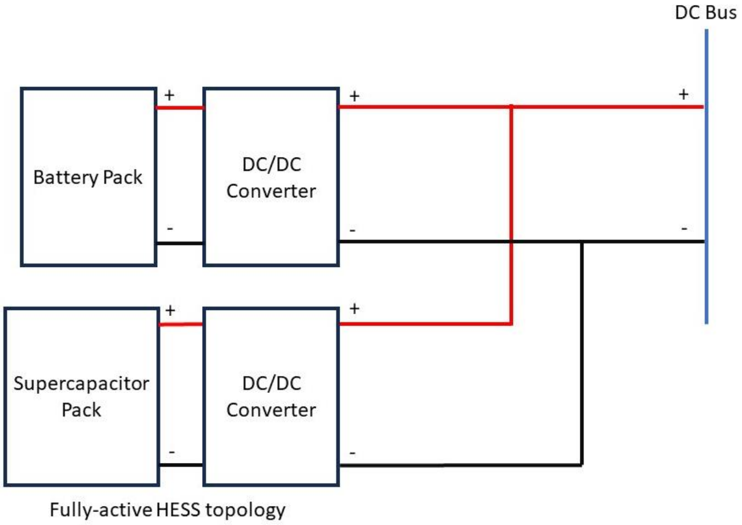

Figure 2.4: Fully active battery-SC HESS.

The advantages of the battery semi-active battery-SC HESS, shown in Figure 2.4, are as follows [33]-[35]:

1) The DC/DC converter connected to the battery grants the battery full protection from the high frequency currents.
2) The energy flow from both the battery and the SC are controlled.
3) The energy stored in the SC and the battery may be efficiently used.

The disadvantage of the battery semi-active battery-SC HESS are as follows [36]-[38]:

1) Due to the use of two DC/DC converters, the cost of the system may increase.
2) The complexity of the system is increased due to the control of two DC/DC converters.
3) The weight of the system is increased.

2.3 ENERGY MANAGEMENT SYSTEM

An energy management system (EMS) is essential for the optimal functioning of the battery-supercapacitor HESS [39]. The primary goal of the EMS is to enhance the efficiency, power quality, and stability of the HESS system. By carefully regulating the power distribution between the battery and supercapacitor, the EMS maximizes the utilization of their complementary characteristics, thereby improving the overall efficiency of the HESS [40],[41]. Additionally, the EMS monitors the State of Charge (SOC) and State of Health (SOH) of the system, adjusting the charging and discharging rates to ensure safe operation within the prescribed limits [42],[43]. Through the implementation of advanced control algorithms, the EMS also mitigates voltage and current fluctuations, promoting system stability. Furthermore, the EMS plays a crucial role in extending the lifespan of both the battery and supercapacitor, safeguarding them against excessive power, temperature, and energy usage [44]. The battery is protected from high-frequency discharge cycles to prolong its lifespan, while the supercapacitor is shielded from overcharging and over-discharging. Moreover, the EMS is responsible for optimizing the utilization of both the battery and supercapacitor, ensuring their effective and efficient operation [45],[46]. The control objectives of the EMS are summarized in Figure 2.5.

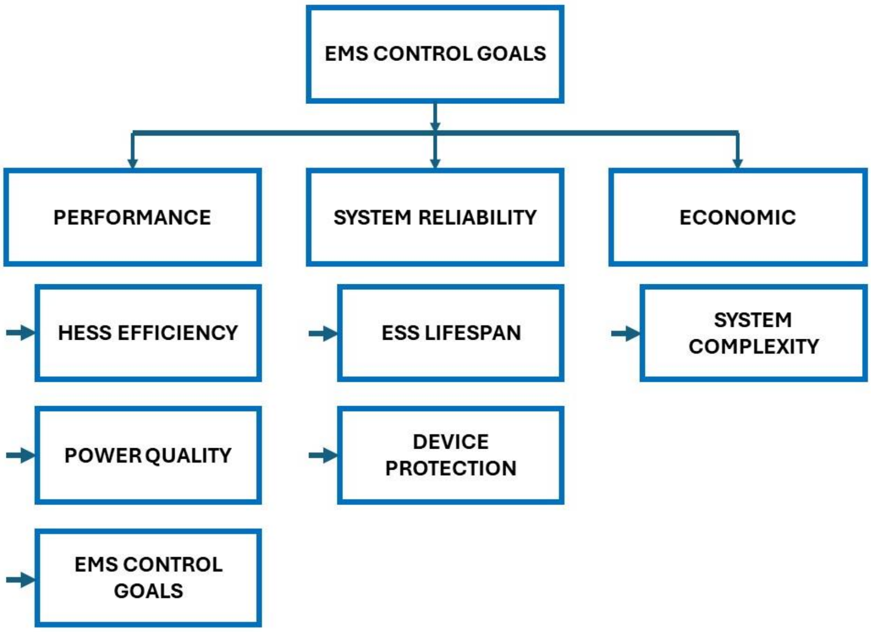

Figure 2.5. EMS control goals adapted from [22]**, © 2011 IEEE.**

EMS control techniques can be categorized into two main types: rule-based EMS and optimization-based EMS. Rule-based EMS utilizes a flow diagram with instructions to determine the system's behaviour in different scenarios [47]. These methods are derived from heuristics and intuition, where the control law is based on rules extracted from human experience, without prior knowledge of a predefined driving cycle [48]. On the other hand, optimization-based EMS employs techniques like Dynamic Programming (DP), Particle Swarm Optimization (PSO), and others to optimize the power distribution between the battery and the supercapacitor [49].

Rule-based EMS control techniques have the advantage of being easier to implement compared to optimization-based methods and they impose less computational burden [16]. This makes them an ideal choice for real-time implementation. However, the drawback of rule-based EMS control is that it does not offer an optimal power slit solution when compared to optimization-based control techniques [12]. On the other hand, optimization control techniques provide an optimal power slit solution but come with a high computational cost [17]. When dealing with the battery-supercapacitor HESS EMS problem, it is challenging to design a real-time supervisory controller that can achieve an optimal solution [50]. To address this challenge, researchers have developed supervisory controllers that combine both rule-based and optimization-based control techniques [18]-[20]. In [21], an EMS was developed that utilized a combination of an intelligent online Neural Network (NN) controller and an offline Dynamic Programming (DP) to provide an optimal online EMS. Another approach proposed in [22] is an online EMS that utilizes a NN (Neural Network) based methodology and a Particle Swarm Optimization (PSO) to generate a real-time predictive power management control strategy.

2.3.1 Rule-based control strategy

2.3.1.1 Deterministic

The power exchange of the HESS is determined by rules derived from experiences and mathematical models in the rule-based control method [8],[21]. In real-time energy management applications, the rule-based control approach proves to be highly effective [51]. The rule-based approach can be divided into two main categories: deterministic and fuzzy logic [52]. The deterministic rule-based strategy employs a predetermined set of rules to determine the power distribution between the battery and the SC [53]. On the other hand, fuzzy logic control utilizes prior knowledge of the system's functionality to establish the rules that govern its operation [54].

Deterministic rule-based algorithms are further sub-divided four categories namely thermostat on/off, power follower, state machine control and frequency-decoupling [55]. In the thermostat control strategy, the battery's optimal power efficiency point is identified and maintained by operating the battery at a constant power level [56]. The battery's operation is regulated by turning it on and off based on the current upper and lower limits of the battery's state of charge (SOC) [57].

On the other hand, in the power follower control strategy, the energy management system (EMS) assigns the power demand of the electric vehicle to the battery, while the supercapacitor supplies the difference between the power demand of the electric vehicle and the battery's response [58]. This difference is calculated by subtracting the maximum allowable battery supply power from the power demand of the electric vehicle [59]. The power follower approach involves the independent control of the battery and supercapacitor to meet the electric vehicle's demand while optimizing the efficiency of the HESS [24]. The battery supplies consistent power for steady-state operation, while the supercapacitor delivers high-power bursts during acceleration and regenerative braking. There are two versions to implement the power follower control strategy, such as [25],[7]:

- Version 1: In the direct control approach, the battery and supercapacitor are managed directly to meet the necessary power output. When there is a surge in power demand, the supercapacitor discharges to supply extra power, and when the power demand decreases, the supercapacitor is recharged.
- Version 2: In the indirect control approach, the estimation of power demand is carried out through a model, and subsequently, the battery and supercapacitor are regulated according to this estimated power demand. The estimation of power demand relies on various factors such as vehicle speed, acceleration, and road grade.

The benefits and disadvantages of the power follower methods are listed in Table 2.1 below.

Table 2.1. Advantages and disadvantages of the power follower method [15],[60]-[62].

Advantages	Disadvantages
The supercapacitor enhances the vehicle's acceleration and braking performance by delivering high power bursts, resulting in improved overall performance.	The implementation of the power follower control strategy can pose greater complexity compared to other control strategies, especially when dealing with larger-scale systems.
The battery's cycle life can be extended by reducing the load on the battery during periods of high-power demand, resulting in an extended battery life.	The implementation of the power follower HESS control strategy may result in increased expenses due to the need for additional control hardware and software, thereby impacting the overall cost of the system.
By utilizing the supercapacitor to deliver high-power surges, the battery can	The power follower, may have limited flexibility compared to other control

operate at an ideal power level, thereby enhancing its efficiency and prolonging its lifespan.	strategies, especially when it comes to accommodating systems with fluctuating power demands or evolving energy storage needs.

In the state machine control approach, multiple rules are employed to govern the flow of power flow of HESS. These rules are determined based on factors such as the maximum charge/discharge rates of the battery and supercapacitor, the upper and lower limits of their SOC, and the maximum power that can be drawn from each storage element. The algorithm used in this approach determines the appropriate power distribution between the battery and the supercapacitor based on the power demanded from the HESS [63][64]. The state machine has the capability to be programmed for transitioning between various modes of operation, including [28],[65]:

- State 1: In the charge mode, the battery and supercapacitor receive energy from an external power source to replenish their charge.
- State 2: In the discharge mode, the HESS provides power to the electric motor to propel the vehicle.
- State 3: During regenerative braking, the HESS is utilized to store the energy produced while braking. This stored energy can later be employed to propel the vehicle forward during acceleration.

The advantages and disadvantages of state machine control are listed in Table 2.2 below:

Table 2.2. Advantages and Disadvantages of state machine control [15],[66].

Advantages	**Disadvantages**
The state machine control ensures a rapid response time by promptly adapting the energy flow between the battery and supercapacitor in real-time to meet any	The state machine alternates between the charge and discharge states, without computing the most efficient power distribution solution for the electric

changes in power demand.	vehicle.
Enhanced system dependability: Through the implementation of state machine control, the HESS can be engineered to function within secure parameters, thereby minimizing the possibility of system malfunction.	The control algorithm's limited flexibility restricts its ability to adapt to various operating conditions or system configurations.

2.3.1.2 Fuzzy Logic

The implementation of the deterministic rule-based control concept is straightforward and dependable [6],[67]. Nevertheless, the rules are established according to the initial states of the battery and the supercapacitor. Consequently, the accuracy of the EMS diminishes over time. To address this issue, the fuzzy logic control strategy is introduced, which utilizes membership functions and fuzzy rules to determine the transition between different rules. Fuzzy logic is a methodology for handling variables that enables the processing of multiple potential truth values using a single variable [68]. By incorporating an open and imprecise range of data and heuristics, fuzzy logic aims to address problems and derive a diverse set of precise conclusions [69]. As a result, the operation becomes smoother, more logical, and more adaptable. Fuzzy rule-based control algorithms can be integrated with other control strategies to create a hybrid control algorithm that enhances the performance of HESS.

Different researchers have developed multiple versions of fuzzy control systems. [6] developed a supervisory controller based on fuzzy logic to effectively regulate the voltage of the supercapacitor within an appropriate range. To enhance the performance of the controller, particle swarm optimization is employed to optimize the membership function curves. In [34], a fuzzy rule-based energy management system was devised to optimize the state of charge (SOC) of both the supercapacitor and the battery.

Additionally, the real-time vehicle speed is utilized as an input to the controller, enabling further optimization of the power allocation in the energy management system. Authors in references [34], [27], and [28] have devised fuzzy logic rule-based EMSs for fuel cell-supercapacitor systems. The focus of these EMSs was to enable the supercapacitor to handle the transient power demands of the electric vehicle. The fuzzy-logic control system developed by reference [34] is passively based and builds upon the controller created by reference [28], with the distinction that the EMS utilized the supercapacitor to supply power to the electric vehicle in both steady-state and transient conditions, depending on the supercapacitor's state of charge. EMSs based on fuzzy logic have also been employed in stationary battery-supercapacitor hybrid energy storage systems (HESS) for transit rail applications [29]. The HESS comprises a fully active battery-supercapacitor system. PI controllers are employed for voltage and current regulation, while the energy management system (EMS) utilizes a fuzzy-logic rule set for power distribution control. The primary aim of this research was to guarantee voltage stability and enhance energy efficiency by reducing reliance on grid power.

2.3.2 Optimization technique

The energy management Optimization approach entails determining the optimal energy distribution between the battery and the supercapacitor through the utilization of mathematical [20]. Optimization techniques can be classified into two categories: offline optimization and online optimization techniques. This section will provide a concise overview of various optimization techniques.

2.3.2.1 Offline optimization approach

Offline optimization methods entail resolving the energy management issue beforehand by utilizing a predetermined driving cycle or usage pattern [59]. The optimization dilemma can be expressed as a mathematical program, aiming to minimize a cost function that considers elements like energy loss and battery deterioration [66]. The resolution to the optimization issue offers a series of control inputs, like the power requirement on the battery and supercapacitor, which can be integrated into the vehicle's control system.

Offline optimization techniques offer several benefits. Firstly, they are computationally efficient as they solve the optimization problem in advance and pre-determine the control inputs [23]. This results in a reduced computational burden on the vehicle's control system and enhances real-time responsiveness. Additionally, offline optimization techniques enable the exploration of optimal trade-offs between various performance objectives, such as maximizing fuel economy or minimizing emissions [25].

Nevertheless, offline optimization methods do have certain constraints. They are usually tailored to cater to driving cycles or usage patterns and may not be suitable for more erratic or changeable driving situations. Furthermore, offline optimization techniques necessitate precise understanding of a vehicle's operational surroundings, encompassing elements like road incline, traffic congestion, and weather conditions [21],[25].

2.3.2.2 Online optimization approach

Online optimization is a distinctive methodology that has gained popularity in the field of computer science. Its objective is to evaluate the effectiveness of a strategy that operates without any prior knowledge of future events (online) in comparison to an optimal strategy that possesses complete knowledge of the future (offline) [27]. Implementing optimization-based control techniques can be challenging due to their complexity and high computational resource requirements [41]. Additionally, offline global optimization methods rely on a predetermined driving cycle, making them unsuitable for real-time applications. Despite these drawbacks, global optimization techniques offer precise results. Hence, a blend of global optimization techniques and rule-based control techniques is preferred.

The most control online optimization control method is Model predictive control (MPC). MPC has gain attention amongst researchers in developing an EMS for battery-SC HESS based EVs. MPC is a control strategy that involves determining the optimal control actions to minimize a cost function for a constrained dynamical system within a finite, receding horizon [9]. At every time step, the MPC controller obtains the current state of the plant either through direct measurement or estimation. Subsequently, it computes a sequence of control actions that minimize the cost over the horizon by solving a constrained optimization problem [25]. This optimization process is based on an internal plant model and is influenced by the current system state. The controller then implements only the first calculated control action on the plant, disregarding the remaining actions. This cycle repeats in the subsequent time steps. Figure illustrates a basic MPC control loop.

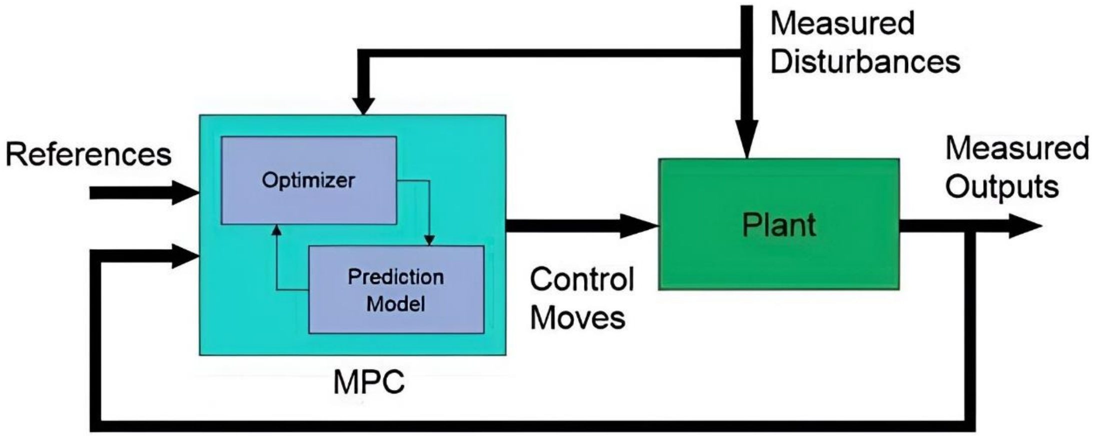

Figure 2.6. Basic MPC control loop, taken from [70] **with permission.**

P. García introduced an energy management system utilizing model predictive control (MPC). The primary goal of the controller was to maintain the state of charge (SOC) of the battery and supercapacitor close to their set reference values to achieve optimal charging efficiency. The main purpose of the MPC controller is to forecast the upcoming control actions by analysing the current system output. According to P. García et al., the implementation of the predictive controller was challenging due to its complexity and extensive computational requirements. Nevertheless, the controller delivered precise outcomes [24].

2.3.3 Data Driven Approach

2.3.3.1 Machine Learning

Data driven control methods involve the use of intelligent algorithms that learn the behaviour of the system and then optimize its operation. Machine learning is a rapidly developing method that has been employed to tackle energy management in battery-supercapacitor HESSs for electric vehicles. By utilizing machine learning algorithms, it becomes possible to acquire knowledge from data and utilize it to make predictions or carry out actions. This makes machine learning particularly suitable for energy management applications, where timely decisions need to be made based on intricate and ever-changing data [12].

Machine learning has found a valuable application in energy management through predictive control. In this context, the control algorithm utilizes past patterns to forecast future energy demand and adjusts the energy flow accordingly. An illustrative example is the use of machine learning algorithms to analyse previous driving patterns and anticipate power demand based on factors like road grade, traffic conditions, and weather conditions [29]. By doing so, the algorithm optimizes performance and efficiency by effectively regulating the energy flow between the battery and supercapacitor.

Reinforcement learning is also utilized in energy management for optimizing the energy flow between the battery and supercapacitor by adapting to the vehicle's real-time performance. In this approach, the control algorithm learns through trial and error by interacting with the environment, leading to more efficient energy utilization [20].

Machine learning has the capability to enhance the design of battery-supercapacitor HESSs. For instance, machine learning algorithms can forecast the deterioration and lifespan of the battery and supercapacitor by considering variables like temperature, voltage, and current. This data can then be utilized to refine the energy storage system's design, ultimately enhancing its efficiency and durability.

Nevertheless, there exist certain constraints when employing machine learning in the realm of energy management for electric vehicles. The efficacy of machine learning algorithms heavily relies on the availability of substantial data for learning purposes, thus rendering them less effective in scenarios where data is scarce [17]. Furthermore, the computational demands of machine learning algorithms can be quite burdensome, necessitating considerable processing capabilities and memory, which can pose a challenge within the constrained computing resources of vehicles [22].

2.3.3.2 Deep Learning

Deep learning has demonstrated significant promise in tackling energy management in battery-supercapacitor hybrid energy storage systems (HESSs) for electric vehicles (EVs). By leveraging deep learning techniques, it is possible to create predictive models that can effectively forecast the energy requirements of EVs and optimize the utilization of HESSs. These models can learn from historical data, real-time sensor data, and other pertinent factors, enabling them to make precise predictions and enhance the overall performance of the system.

An essential use of deep learning in energy management involves creating predictive models for battery SOC and SOH estimation. Precise estimation of these parameters is crucial for maintaining the safe and effective functioning of the battery in the HESS. By training deep learning algorithms on extensive datasets of battery performance data, accurate and reliable models for SOC and SOH estimation can be developed.
Deep learning in energy management has found another application in the form of control algorithms that aim to optimize the utilization of the battery-supercapacitor HESS. These algorithms can learn from both historical and real-time data, enabling them to make informed decisions regarding the charging and discharging of the system, as well as determining the appropriate amount of energy to be utilized from each storage component [21]. By implementing such algorithms, the lifespan of the battery can be prolonged, while simultaneously enhancing the overall efficiency of the HESS.

2.4 SUMMERY

It has been observed in the literature that the control objectives of the EMS should encompass at least one of the following:

1) Maximizing the driving range.
2) Minimizing component stress.
3) Maximizing battery lifespan.

4) Satisfying instantaneous load demand.
5) Managing power flow optimally for future demand.

In most scenarios, a controller would have multiple control objectives, and the selection of a control approach would be based on the primary control objective. It has been acknowledged that rule-based EMSs are easier to implement, have a quicker reaction time, and are less computationally intensive, making them ideal for real-time implementation. However, rule-based EMSs do not provide the most accurate power distribution information, resulting in suboptimal utilization of energy stored in the battery and supercapacitor.

On the other hand, optimization-based EMSs are much more precise in determining the optimal power distribution between the battery and supercapacitor. However, optimization-based EMSs are computationally more demanding, and some require prior knowledge of the drive cycle. Therefore, a hybrid controller is necessary to mitigate the drawbacks of these control approaches and leverage their advantages.

CHAPTER 3 IMPLEMENTATION AND SIMULATION

3.1 CHAPTER OVERVIEW

In this study, Chapter 3 delves into the comprehensive coverage of the modelling and simulations. The chosen topology for the battery-SC HESS is the fully active one, and the rationale behind this selection is elucidated. Furthermore, the selection and design calculations of the DC/DC converters for both the battery and the SC are expounded upon. The setup and design of the EMS are also outlined, along with the demonstration of how the MATLAB EV reference model was utilized to simulate the proposed EMS. Section 3.2 discusses the control design of the EMS. Section 3.3 illustrates the HESS topology selection. Section 3.4 shows the EV simulation model while section 3.5 discusses the sizing of the complete battery-SC HESS. The chapter concludes with a chapter summary in section 3.6.

3.2 CONTROL DESIGN

The aim of this study is to develop a real-time EMS that considers various factors influencing the power demand of EV. These factors include:

1) The real-time power needs of the vehicle
2) Gravitational resistance
3) Wind resistance.
4) Road incline.
5) Traffic conditions.

The proposed EMS categories driving into three types, that is, stop/start traffic, highway driving and city driving. During start/start traffic only the SC contributes to the load, during highway and city driving both the battery and the SC actively contribute to the EV load. The advantages of the proposed EMS are as follows:

1) The proposed rule-based EMS operates in real-time.
2) The proposed EMS does not require the user to upload the drive cycle beforehand.
3) The vehicle's physical parameters are used to in determining the power limit on the battery and the SC.
4) The SC is sized according to the amount of regenerative energy produce by the UDDS drive cycle, the Artemis motorway 130 drive cycle and the CBD drive cycle.

3.2.1 EV Modelling

Newton's second law of motion states that:

$$m\dot{v} = f_t - f_a - f_r, \tag{3.1}$$

where the mass of the electric vehicle is denoted by m in kilograms and the speed of the electric vehicle is represented by v in meters per second. The traction force is labelled as f_t, the aerodynamic drag force as f_a, and the rolling resistance force as f_r. The equations that govern the aerodynamic drag force and rolling resistance force are as follows:

$$f_a = \frac{1}{2} p_a C_d A_f v^2 \tag{3.2}$$

and

$$f_r = mg\mu cos\ (\alpha)\ + mgsin(\alpha). \tag{3.3}$$

The parameters in the formula consist of p_a for air density, C_d for air drag coefficient, A_f for EV frontal cross section, μ for rolling resistance coefficient, g for gravitational acceleration, and α for road slope.

The power needed for an EV moving at a speed v can be represented as:

$$p_{ev} = \ f_t v = \ (f_a + f_r + m\dot{v})v, \tag{3.4}$$

p_{ev} is the power needed by the EV.

The vehicle needs power from the HESS to operate. In the development of the proposed EMS, it is considered that the HESS DC/DC converters, battery, and supercapacitor have a consistent energy transmission efficiency. As a result, according to (3.5), the power required by the electric vehicle can be calculated as:

$$p_{ev} = \eta_d(p_{bat}\eta_{bat} + p_{sc}\eta_{sc}), \tag{3.5}$$

η_d symbolizes the overall mechanical transmission efficiency and the efficiency of the electric motor. p_{bat} stands for the power used for charging and discharging the battery. p_{sc} refers to the power for charging and discharging the supercapacitor. η_{sc} denotes the efficiencies of supercapacitor dc-dc converter, and η_{bat} indicates the discharging efficiency of the battery dc-dc converter.

3.2.2 Control Objectives

The primary goal of the controller is outlined below:

1) Efficient energy management: The EMS is designed to prevent the battery from experiencing high frequency charge/discharge currents, thus prolonging the battery's lifespan.

2) Utilization of supercapacitor energy: The controller prioritizes the involvement of the SC in meeting the power needs of the electric vehicle.

The control laws outlined in reference [16] utilize a Lyapunov-based nonlinear controller and are presented as follows:

$$P_{bat,limit} = \frac{mv}{\eta_d \eta_{bat}} \left(\frac{p_a C_d A_f}{2m} {v_r}^2 + g\mu cos\,(\alpha) \right) \tag{3.6}$$

and

$$P_{bat,limit} = \frac{mv}{\eta_d \eta_{bat}} \left(\frac{p_a C_d A_f}{2m} {v_r}^2 + g\mu cos\,(\alpha) \right). \tag{3.7}$$

$P_{bat,limit}$ signifies the battery power and $P_{bat,limit}$ indicates the power of the supercapacitor. A key enhancement in control design from [16] is that the control laws outlined in Eq. 6 and 7 serve as power constraints rather than determining factors for power distribution.

Figure 3.1 depicts the initial verifications conducted by the EMS. Initially, the system requests the driver to input the desired destination. The system is already aware of the current location of the electric vehicle (EV). Subsequently, the system utilizes Google maps to assess the level of traffic congestion along the most efficient route. The road gradient along the chosen route is determined by employing Google Earth. Following this, the system calculates the amount of energy necessary for the journey. The EMS operates in three distinct modes: city driving, traffic conditions, and highway driving. Whenever necessary, the system seamlessly transitions between city driving, traffic driving, and highway driving. The loop marked red is the “driving loop” which the system stays in until the destination is reached.

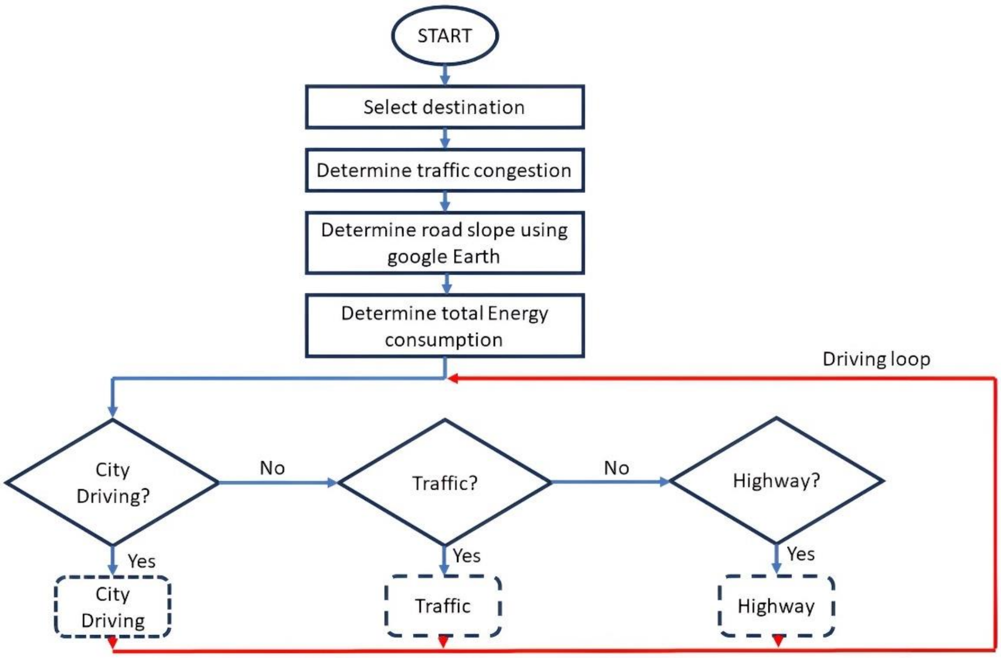

Figure 3.1: EMS initial setup.

Figure 3.2 illustrates the rules for driving in the city. In the case where the electric vehicle (EV) requires power for forward motion, the system checks the State of Charge (SOC) of the Supercapacitor (SC) to determine if it is above or below 50%. This check is done to ensure that the supercapacitor can last for more than one drive cycle.

If the SOC of the supercapacitor is greater than 50%, the system will calculate the power limit for the supercapacitor using (3.7). This calculated power limit will be used as the upper limit for the SC, and the SC will solely supply the power required by the EV.

On the other hand, if the SOC of the SC is below 50%, the system will calculate the upper power limit for both the battery and the SC using (3.6) and (3.7). In this case, the SC will still supply the power requirement of the EV, while the battery is used to charge the SC, ensuring that the SOC of the battery remains above 50% and its current is stable. During regenerative braking, all the power is absorbed by the SC.

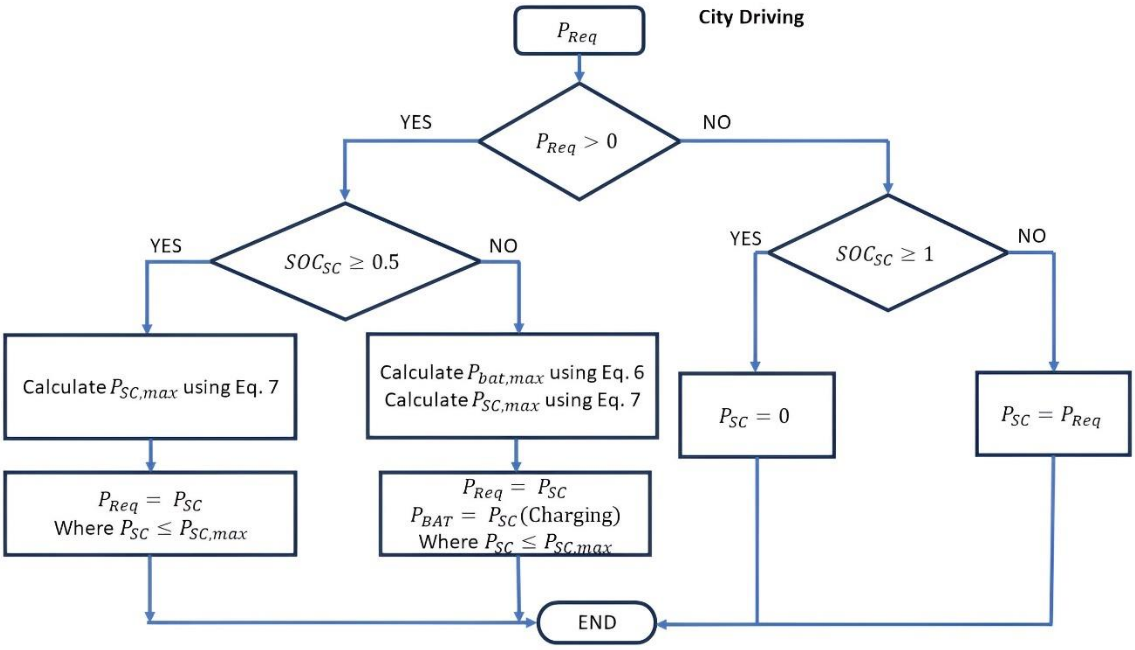

Figure 3.2: City driving flow diagram.

Figure 3.3 depicts the rule set governing traffic conditions. The rule set for traffic driving conditions closely resembles that of city driving. However, the key distinction lies in the scenario where the state of charge (SOC) of the SC falls below 50%. In such cases, both the SC and the battery contribute to supporting the load, with their upper power limits determined by (3.6) and (3.7). This adjustment is made specifically during traffic driving conditions, where regenerative braking is minimal, resulting in limited opportunities to recharge the SC. If the battery is utilized for recharging purposes, it will inevitably reduce the driving range of the electric vehicle (EV).

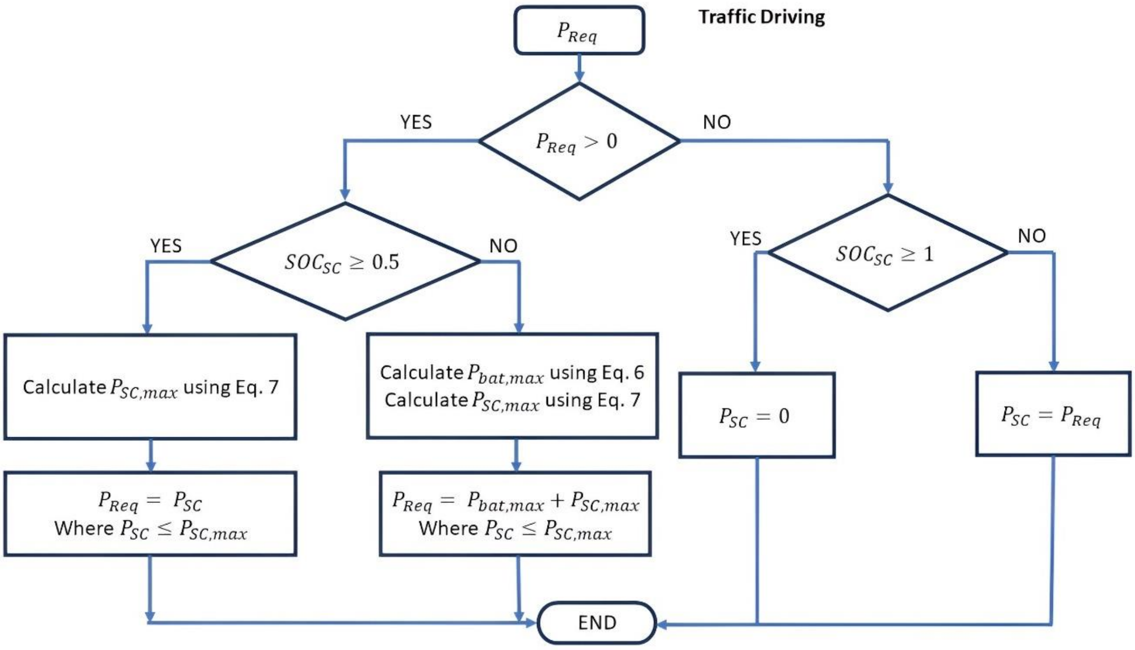

Figure 3.3: Traffic conditions flow diagram.

Figure 3.4 depicts the rule set for highway driving. When driving on the highway, the power demand of the electric vehicle (EV) is divided between the battery and the supercharger (SC), with the SC only providing power during peak periods. This approach is adopted due to the high energy consumption during highway driving, necessitating the battery to bear a significant portion of the EV's load.

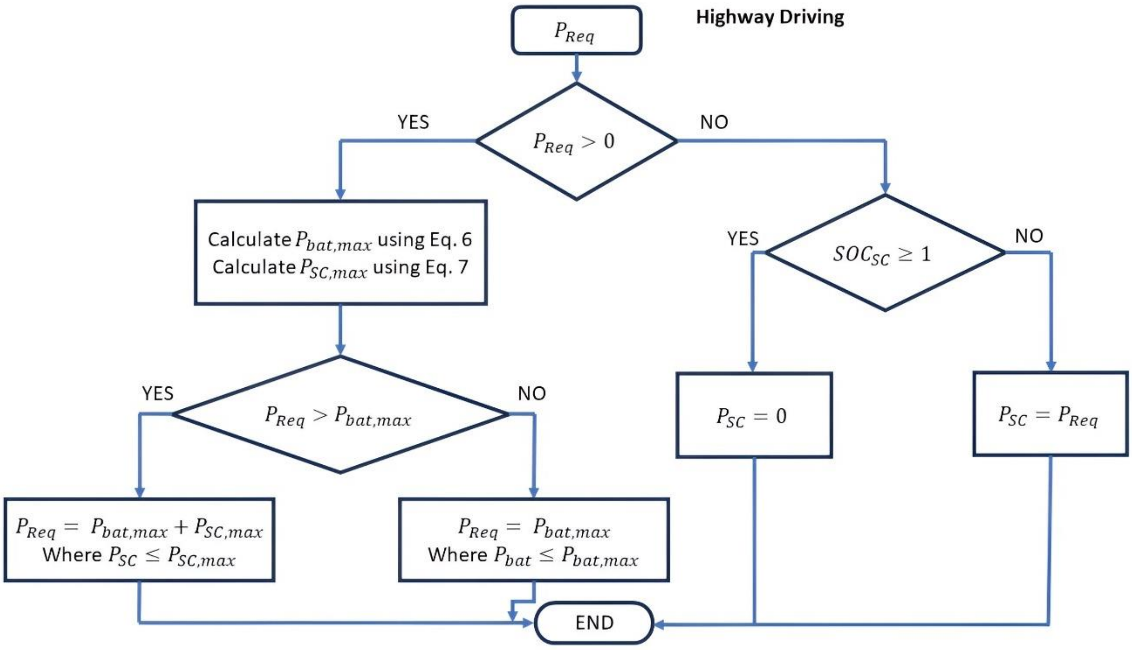

Figure 3.4: Highway driving flow diagram.

3.3 HESS TOPOLOGY

The SC semi-active topology, as depicted in Figure 2.2, is the most utilized battery-SC configuration. This topology involves a single DC/DC converter linking the SC to the DC bus, potentially leading to cost savings for the system. The SC DC/DC converter plays a crucial role in managing the energy of the SC.

On the other hand, the SC semi-active topology faces limitations as the battery is directly connected to the DC bus, resulting in inefficient control and protection of battery energy. To address this issue, the fully active HESS is employed, featuring two DC/DC converters to regulate energy flow for both the SC and the battery. The fully active battery-SC HESS topology can be observed in Figure 2.4. The proposed system utilizes a fully active battery-SC HESS topology.

The proposed system intends to discharge the battery in one direction (forward direction) while the SC is to be discharged and charged through regenerative braking. Therefore, a single directional boost converter will be used for the battery while a bi-directional buck/boost converter will be used for the SC. The full system diagram is illustrated by Figure 3.5 and Figure 3.6 shows the system diagram legend.

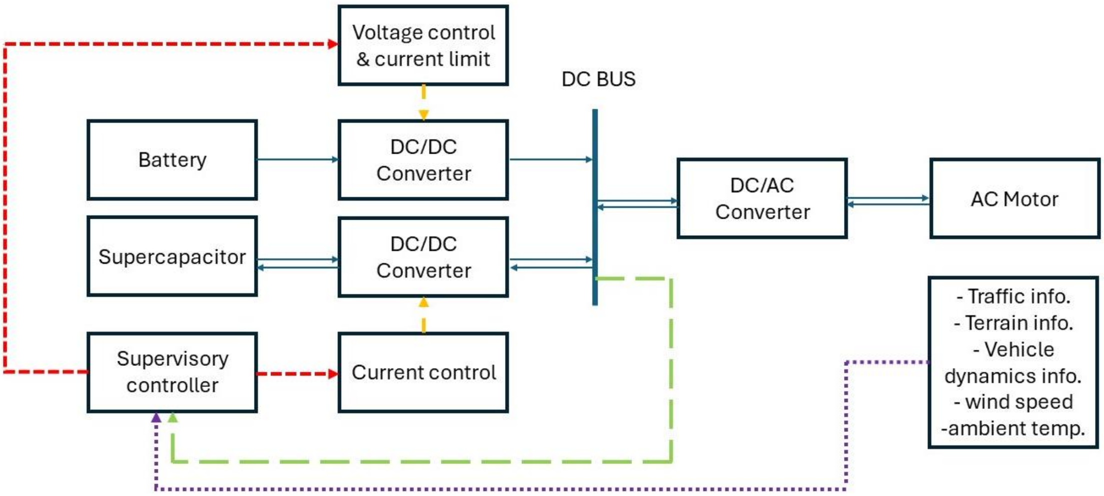

Figure 3.5: Proposed Full system diagram.

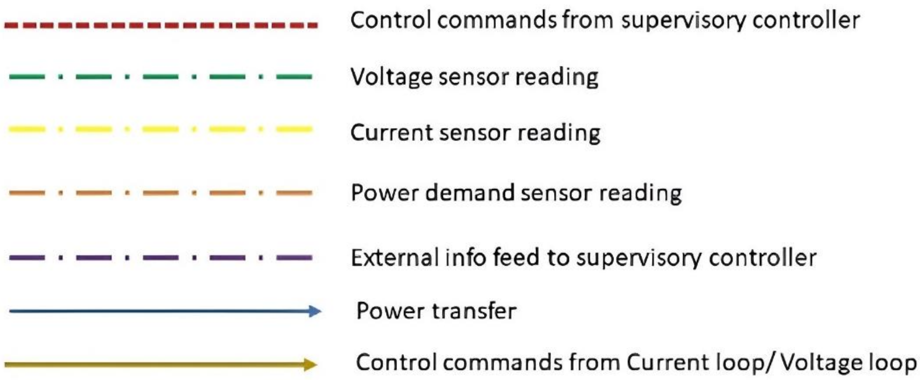

Figure 3.6: System diagram legend.

3.4 EV SIMULATION MODEL

The MATLAB EV reference application is a comprehensive model that includes a motor-generator, battery, direct-drive transmission, and powertrain control algorithms. It serves as a valuable tool for conducting powertrain matching analysis, selecting components, designing control and diagnostic algorithms, and performing hardware-in-the-loop (HIL) testing. Figure 3.7 illustrates the MATLAB EV reference model.

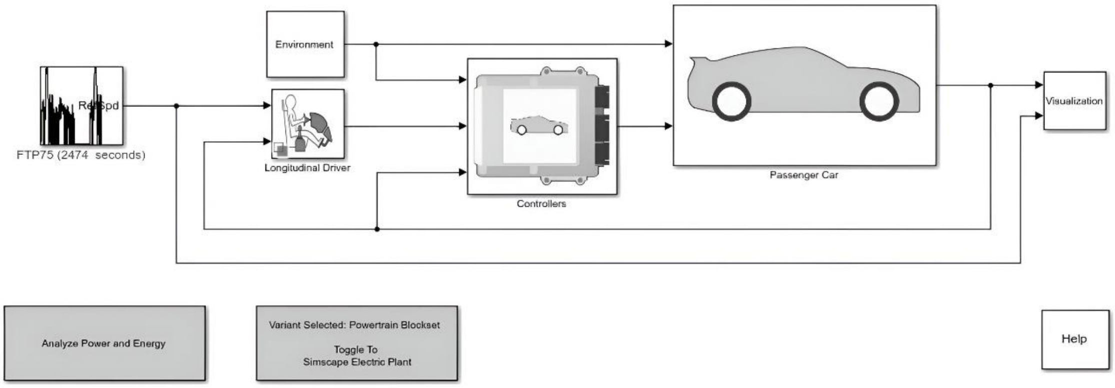

Figure 3.7: MATLAB EV reference model, taken from [16] with permission.

Table 3.1 specifies the different subsystems that are present in the EV reference model. Each subsystem is customizable according to the user specifications.

Table 3.1: EV reference model subsystem descriptions

Reference Application Element	**Description**
Analyse Power and Energy	This is a live script of the power and energy consumption of the EV on the component level as well as on the system level.
Drive Cycle Source block	This block provides a list of standard drive cycles to choose from.
Environment subsystem	This subsystem enables the user to input environmental variables such as road slope, wind speed, atmospheric temperature, and pressure.
Longitudinal Driver subsystem	This subsystem simulates a driver and outputs acceleration and braking commands such that the specified drive

	cycle velocity is followed.
Controllers' subsystem	This subsystem implements a powertrain control module (PCM) that incorporates regenerative braking, motor torque arbitration, and power management.
Passenger Car subsystem	This subsystem mimics a passenger vehicle with an electric system and drivetrain subsystems.
Visualization subsystem	Provides vehicle-level performance data, battery state of charge (SOC), and equivalent fuel economy outcomes that are valuable for powertrain matching and component selection analysis.

In this work, the MATLAB EV reference model was customized to match the specifications of the proposed system.

3.5 HESS SIZING

The proposed system is directly compared with the first-generation BMW ix3 to gain a real-world comparison of how the proposed system performs in simulation. The BMW ix3 has an 80kWh battery only ESS. Therefore, the total energy of the proposed system will be designed such that it is equivalent to 80kWh.

Table 3.2: BMW G08 ix3 parameters.

Parameter	Value
Vehicle weight	2270 kg (full loaded = 2740 kg)
Electric motor power	210 kW
Battery Capacity	80 kWh

Battery nominal voltage	400 V
Vehicle frontal area	2,65
Transmission efficiency	0.98
Gravitational acceleration	9,8 m/s^2
Air drag coefficient	0,29
Rolling resistance coefficient	0.05

3.5.1 Total Regenerative braking energy

Another factor that was considered when sizing the battery-SC HESS was the regenerative braking energy that the SC would need to absorb. As the proposed EMS takes into consideration three types of drive conditions i.e. city driving, traffic driving and highway driving. To represent city driving the UDDS is used, the traffic driving is represented by the CBD cycle, the highway driving is represented by Artemis motorway 130 drive cycle. To obtain the total regenerative braking energy, the EV reference model was tuned with the parameters shown in Table 3.2. Then each of the drive cycles (i.e. UDDS, CBD, and Artemis motorway 130) are ran and the battery power is measured. Figure 3.8 to Figure 3.12 illustrates the battery power for each drive cycle. This was done to get an indication of the of how much power the SC would need to absorb during regenerative braking.

Figure 3.8 illustrates the power demand on the battery during the UDDS drive cycle. Figure 3.9 illustrates the negative power demand during the UDDS driving cycle. The average regenerative braking power is 3.605kW.

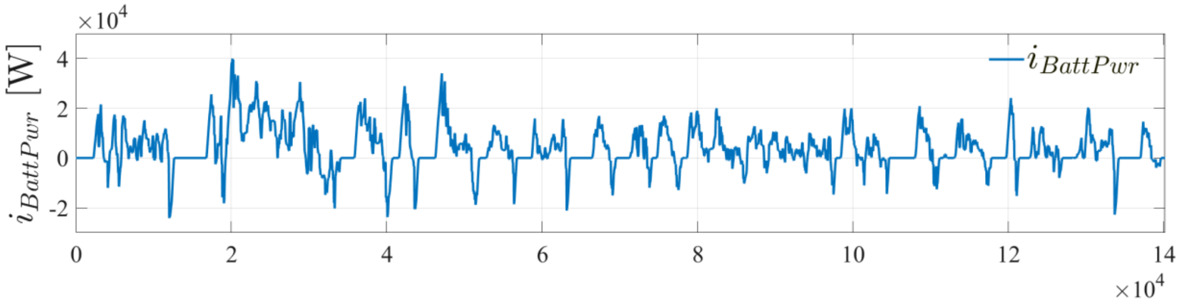

Figure 3.8: UDDS city driving battery power.

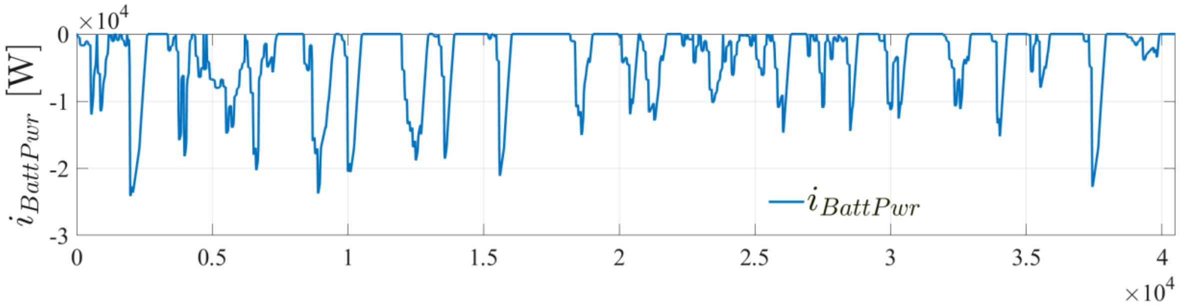

Figure 3.9: UDDS city driving negative battery power.

Figure 3.10 depicts the battery power waveform for the CBD. The CBD cycle showcases a driving pattern resembling a "sawtooth" shape, consisting of 14 iterations of a fundamental cycle comprising idle, acceleration, cruise, and deceleration modes. This driving cycle accurately represents a vehicle navigating through stop-start traffic. On the other hand, Figure 3.11 showcases the regeneration power waveform for the CBD drive cycle. The average power obtained from regenerative braking amounts to 4.036kW.

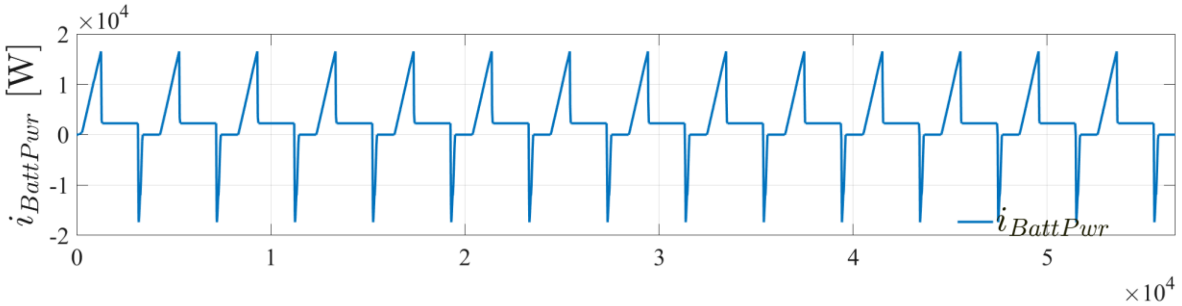

Figure 3.10: CBD traffic driving battery power.

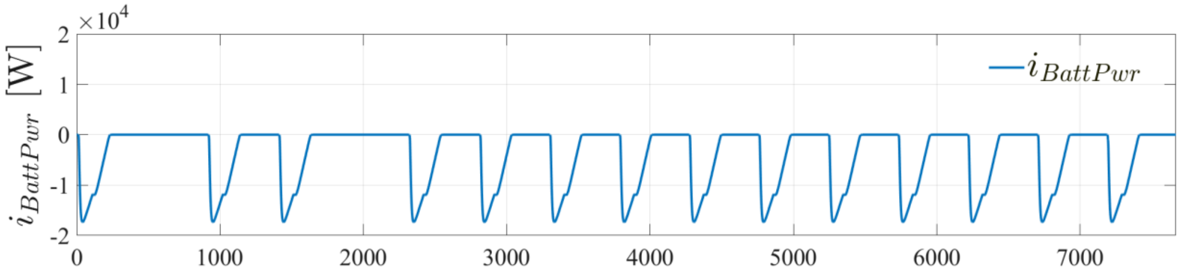

Figure 3.11: CBD traffic driving negative battery power.

Figure 3.12 depicts the power requirements of the battery throughout the Artemis motorway 130 driving cycle, which simulates motorway driving conditions. Meanwhile, Figure 3.13 showcases the negative power demand that occurs during motorway driving. The average regenerative braking power is measured at 14.297kW.

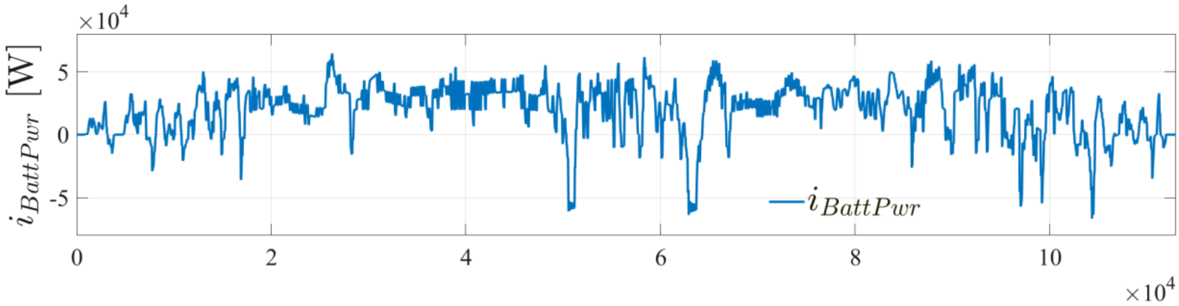

Figure 3.12: Artemis motorway 130 highway driving battery power.

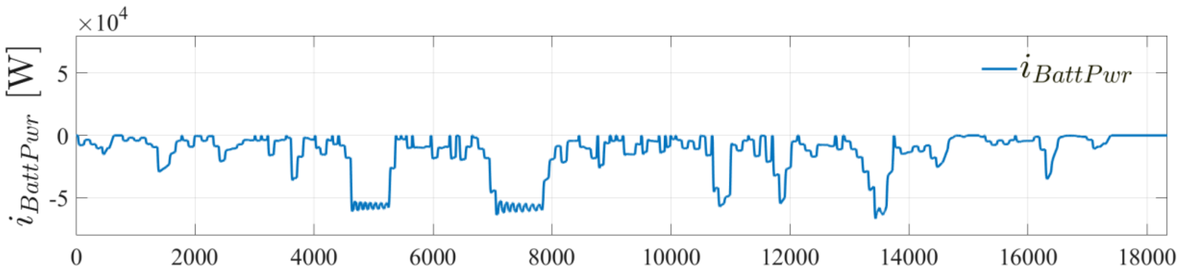

Figure 3.13: Artemis motorway 130 highway driving negative battery power.

Hence, the SC should have the capability to absorb a minimum regenerative power of 21.938 kW.

3.5.2 Battery Degradation Model

Numerous battery degradation models have been studied, with the most pertinent model for lithium-ion batteries being introduced by [10]. This model is widely utilized to assess the decrease in battery capacity over time in electric vehicles (EVs). The battery capacity loss is specifically defined as:

$$Q_{loss} = Be^{-\frac{E_a}{RT}} A_h^{\rho}. \tag{3.8}$$

The battery's percentage capacity loss, denoted as Q_{loss}, can be calculated using the following variables: B (preexponential factor), E_a (activation energy from Arrhenius law in J mol-1), A_h (ampere-hour throughput of the battery in Ah), T (absolute temperature in K), R (gas constant of 8.314 J mol-1K-1), and ρ (power law factor of 0.5).

The model was expanded by [16][21] to assess the capacity degradation of a battery under non-uniform current profiles. This involved generating a histogram of the battery current rates, followed by determining the depth-of-discharge (DoD) of the battery based on k (DoD(k)). Here, k represents the specific current rate being analysed. The battery capacity loss is determined by (3.9) and (3.10).

$$Q_{loss} = \sum_k Q(k). \tag{3.9}$$

$$Q(k) = B\left(C_{rate}(k)\right)e^{-\frac{E_a\left(C_{rate}(k)\right)}{RT}} A_h\left(DoD(k)\right)^{\rho}. \tag{3.10}$$

3.5.3 Optimal Sizing

An ideal sizing model was developed to achieve the following objectives:

1) The supercapacitor (SC) should have the capacity to absorb 21.938 kW from regenerative braking.
2) The combined power of the battery and the SC should be 80kW, ensuring that the hybrid energy storage system (HESS) is equivalent to an 80kW battery-only energy storage system (ESS).
3) The battery's capacity should not decrease by more than 20% over a span of 10 years.

The objective function for the optimal sizing problem is formulated as follows:

$$f({n_{sc}}^{s},{n_{sc}}^{p},{n_{bat}}^{s},{n_{bat}}^{p}) = {n_{sc}}^{s}{n_{sc}}^{p}{m_{sc}}^{cell} + {n_{bat}}^{s}{n_{bat}}^{p}{m_{bat}}^{cell} \quad (3.11)$$

subject to the following constraints:

$${n_{sc}}^{s}{v_{sc}}^{cell} \geq V_{l1,min} \quad (3.12)$$

$${n_{sc}}^{s}{v_{sc}}^{cell} \leq V_{l1,max} \quad (3.13)$$

$${n_{bat}}^{s}{v_{bat}}^{cell} \geq V_{l2,min} \quad (3.14)$$

$${n_{bat}}^{s}{v_{bat}}^{cell} \leq V_{l2,max} \quad (3.15)$$

$${n_{sc}}^{s}{n_{sc}}^{p}{p_{sc}}^{cell} \geq 21.938\ kW \quad (3.16)$$

$${n_{sc}}^{s}{n_{sc}}^{p}{p_{sc}}^{cell} + {n_{bat}}^{s}{n_{bat}}^{p}{p_{bat}}^{cell} = 80\ kW \quad (3.17)$$

$$Q_{loss,10} \leq 0.2 \quad (3.18)$$

In the (3.12) to (3.18), n denotes the total number of cells, while the superscript "s" indicates the number of cells in series, and the superscript "p" signifies the number of cells in parallel. $V_{l1,min}$ and $V_{l1,max}$ refer to the minimum and maximum input voltage for the SC dc/dc converter, respectively. On the other hand, $V_{l2,min}$ and $V_{l2,max}$ represent the minimum and maximum input voltage for the battery dc/dc converter. The subscript "bat" is used for the battery, and P denotes power in Watts.

A PSO algorithm was used to determine the optimal size of the battery and the SC given the about cost function and constraints. The PSO algorithm was chosen because of its ease of implementation, it is not computational expensive, and its code resource is widely available. The MATLAB PSO solver was used to determine the battery size as well as the SC size. It was calculated that the battery size must be 41.34 kW and the SC 38.66 kW. It was decided that the sizes of the battery and the SC would be made equal to 40 kW.

3.6 CHAPTER SUMMERY

In this section, the design of the controller was done. The EV modelling equations were formulated, the control objectives as well as the rules that govern the rule-based EMS were defined. The fully active HESS topology was selected as it allows the battery energy and the SC energy to be fully controlled. The EV model that was used was the MATLAB EV reference. The driving condition were split into three categories namely city driving, stop/start traffic and highway driving. The drive cycles that represent these conditions are the UDDS, CBD, and the Artemis motorway 130 drive cycles respectively. To size the battery-SC HESS, the following was considered: the total average regenerative breaking energy required by each drive cycle, the battery degradation, and the total ESS size of the BMW ix3. An optimization cost function with constraints was formulated and solved using PSO.

CHAPTER 4 RESULTS

4.1 CHAPTER OVERVIEW

This section provides the simulation results for the EV with a battery only ESS and they are compared with a battery-SC HESS (with the proposed EMS) of the same size. The aspects that were considered are the battery current, SC current, battery and SC SOC after each drive cycle. All these factors were considered for the UDDS, CBD, and Artemis motorway 130 drive cycles. Section 4.2 defines the UDDS drive cycle and illustrates the simulation results for the battery-only system and for the battery-SC HESS under the UDDS drive cycle. Section 4.3 defines the CBD drive cycle and illustrates the simulation results for the battery-only system and for the battery-SC HESS under the CBD drive cycle. Section 4.4 defines the Artemis Motorway 130 drive cycle and illustrates the simulation results for the battery-only system and for the battery-SC HESS under the Artemis Motorway 130 drive cycle. The chapter concludes with a summary in section 4.5.

4.2 UDDS DRIVE CYCLE

UDDS, an acronym for Urban Dynamometer Driving Schedule, is a dynamometer test required by the United States Environmental Protection Agency. This test accurately simulates city driving conditions and is specifically designed for evaluating the fuel economy of light duty vehicles. Figure 4.1 shows the velocity (km/h) versus time (seconds). The cycle replicates an urban course spanning 12.07 km with numerous stops. It reaches a top speed of 91.25 km/h and maintains an average speed of 31.5 km/h. In the context of South Africa, specifically Gauteng, the UDDS cycle can be likened to travelling from Turffontein (Johannesburg South) to Dunkeld West (Rosebank, Johannesburg North) through Johannesburg CBD. Figure 4.2 shows the path on the map while Figure 4.3 shows the elevation profile of the path.

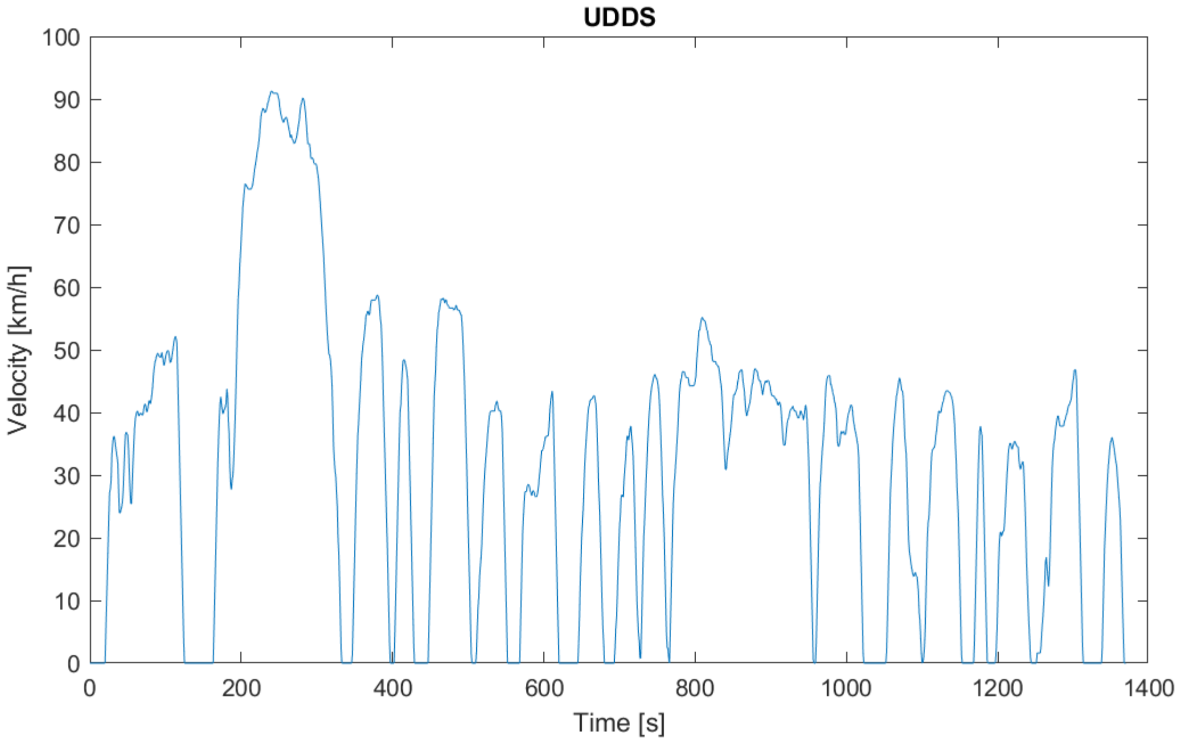

Figure 4.1: UDDS Velocity versus time graph.

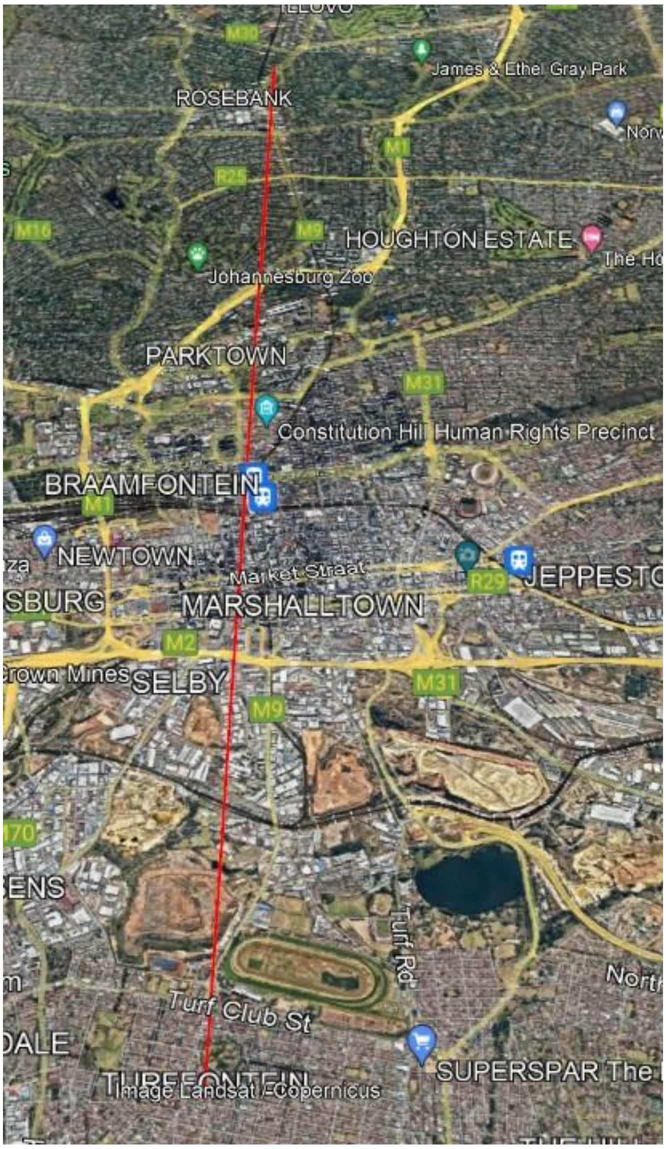

Figure 4.2: Turffontein to Dunkeld West path.

Figure 4.3: UDDS elevation profile.

4.2.1 Battery Only Simulation Results

Figure 4.4 and Figure 4.5 below show the battery current and the battery SOC for the battery only system when put through the UDDS cycle under the above stated conditions. It can be observed that the battery current is frequently charging and discharging. The battery SOC remains steady at 80% with a slight drop to 79%.

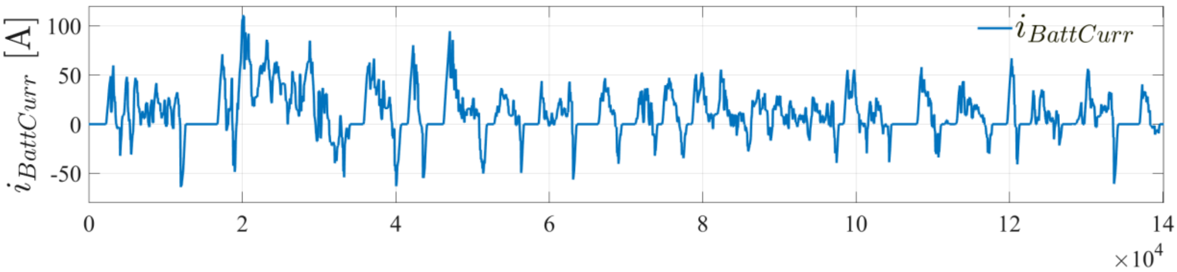

Figure 4.4: Battery-only ESS current (UDDS).

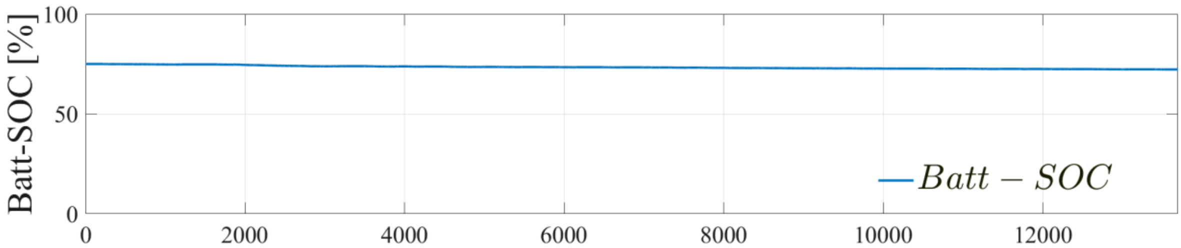

Figure 4.5: Battery-only ESS battery SOC (UDDS).

4.2.2 Battery-SC HESS Results

Figure 4.6 shows the traffic information between Turffontein and Dunkeld west. It can be observed that the traffic conditions are moderate.

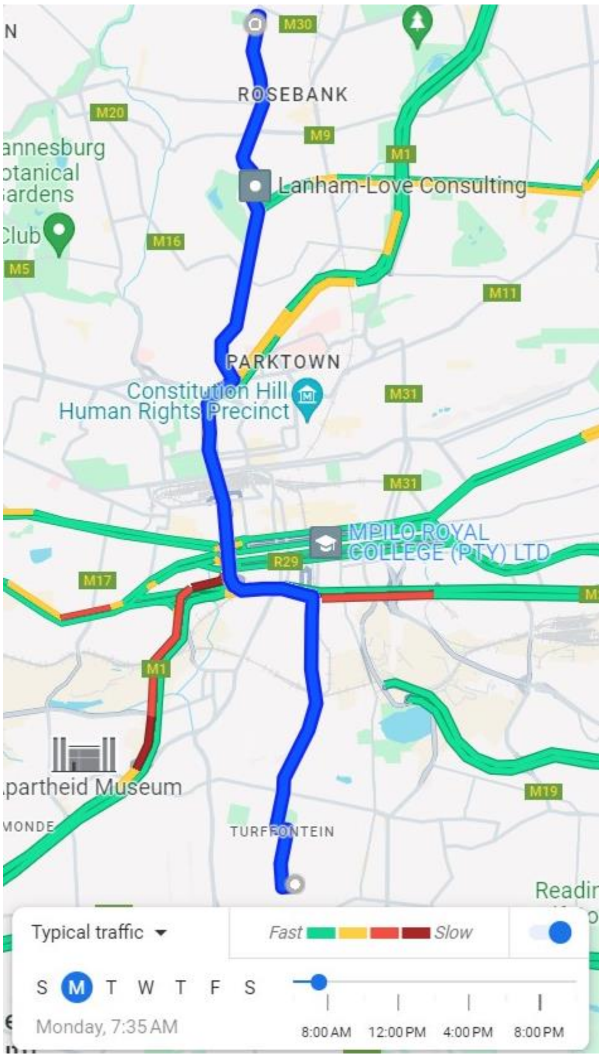

Figure 4.6: UDDS traffic conditions.

The average discharge power required to complete the trip is 6.987 kW. Considering that the UDDS drive cycle runs for 1369 seconds, the energy required to complete the trip is 2.657 kWh.

Figure 4.7 illustrates the battery HESS current, Figure 4.8 illustrates the battery HESS SOC. The proposed EMS ensures that the battery average battery current is equal to the average current required for the total trip. Another observation is that the battery current is only in the forward direction to ensure that the battery is not exposed to frequent charge and discharge cycles. As the energy used for the trip is much lower than the capacity of the battery, the battery SOC remain constant at 80% for the duration of the UDDS cycle.

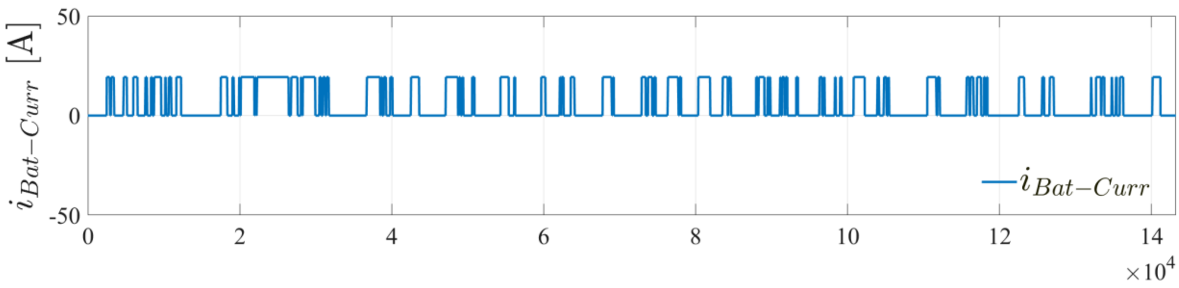

Figure 4.7: Battery HESS current (UDDS).

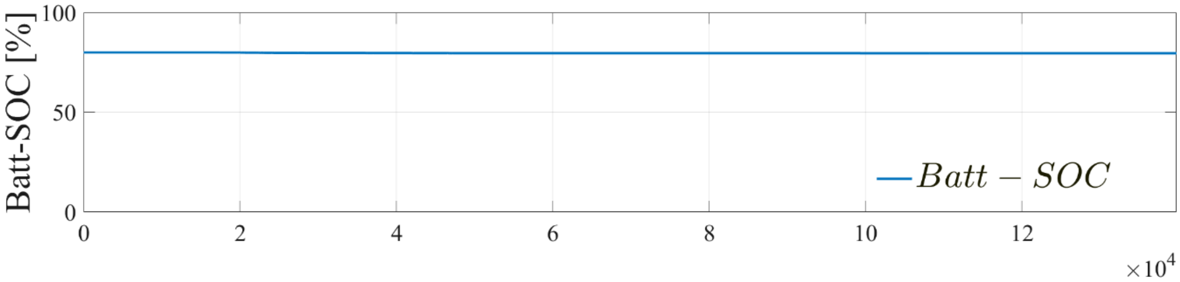

Figure 4.8: Battery HESS SOC (UDDS).

Figure 4.9 illustrates that SC current, and Figure 4.10 illustrate the SC SOC. It can be observed that the SC absorbs a large portion of the current required by the EV is supplied by the SC. the SC also absorbs the regenerative braking energy during the drive cycle. the SC SOC drop from 100% to approximately 60%.

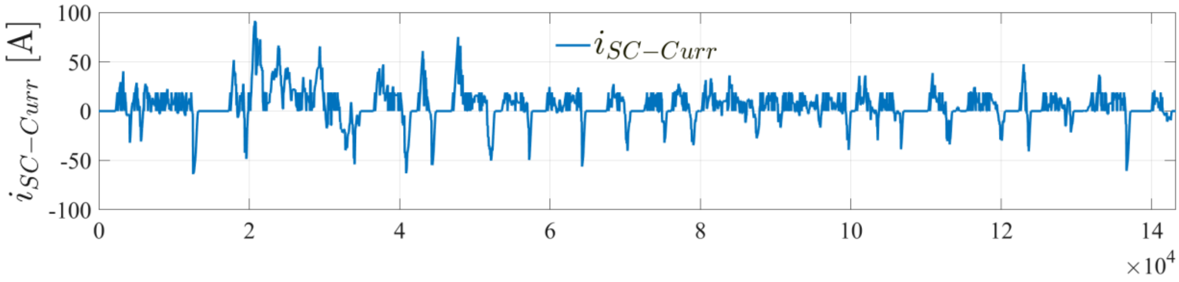

Figure 4.9: SC Current (UDDS).

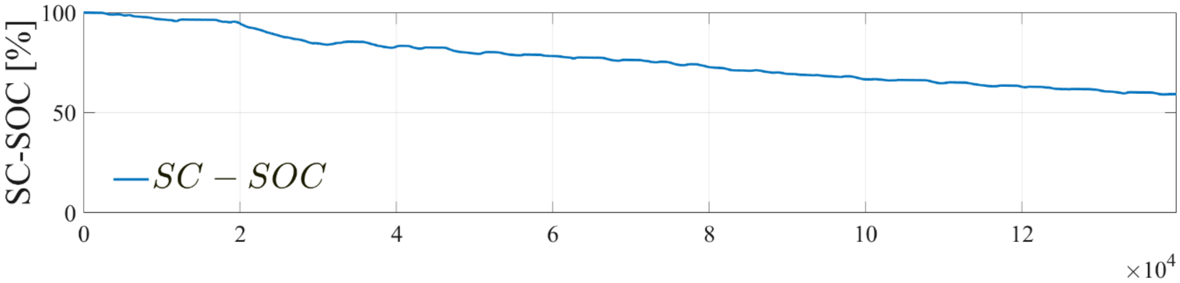

Figure 4.10: SC SOC (UDDS).

4.3 CBD DRIVE CYCLE

The CBD cycle is characterized by a "sawtooth" driving pattern, consisting of 14 iterations of a fundamental cycle that comprises idle, acceleration, cruise, and deceleration modes. Figure 4.11 illustrates the vehicle speed throughout the duration of the CBD cycle. This cycle represents stop/start traffic.

The CBD drive cycle exhibits the following characteristic parameters:

1) Duration: 560 seconds
2) Average speed: 20.23 km/h
3) Maximum speed: 32.18 km/h
4) Driving distance: 3.22 km
5) Average acceleration: 0.89 m/s^2
6) Maximum acceleration: 1.79 m/s^2

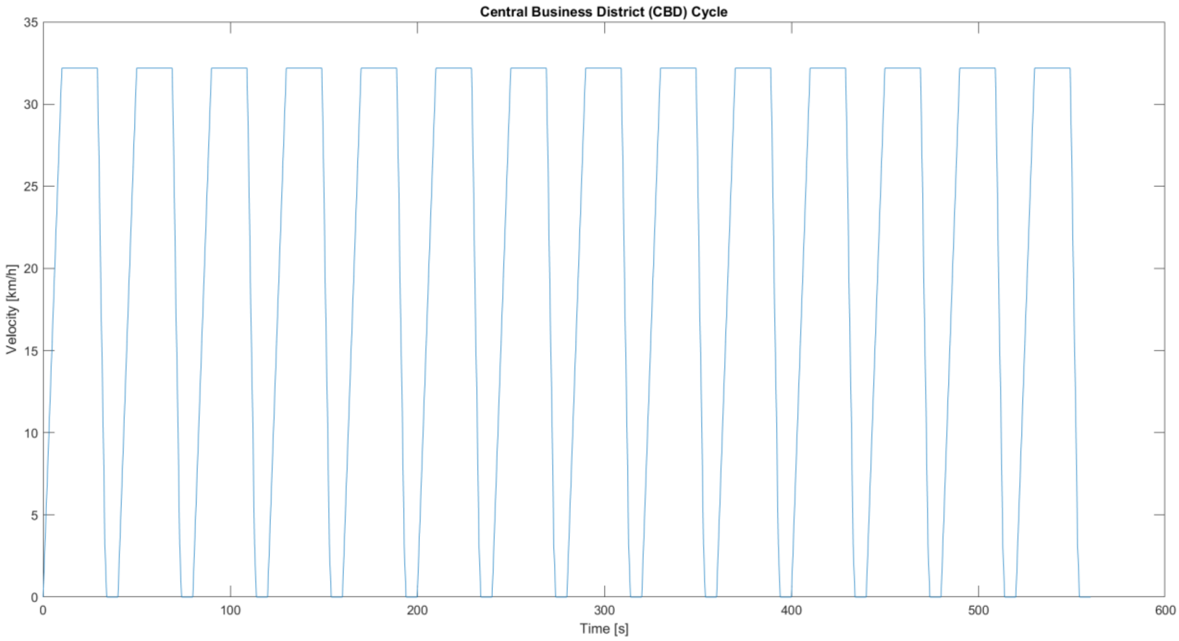

Figure 4.11: CBD drive cycle velocity versus time.

In the context of South African, stop/start traffic is normally found on the M1 highway in Johannesburg during morning peak times as shown by Figure 4.12.

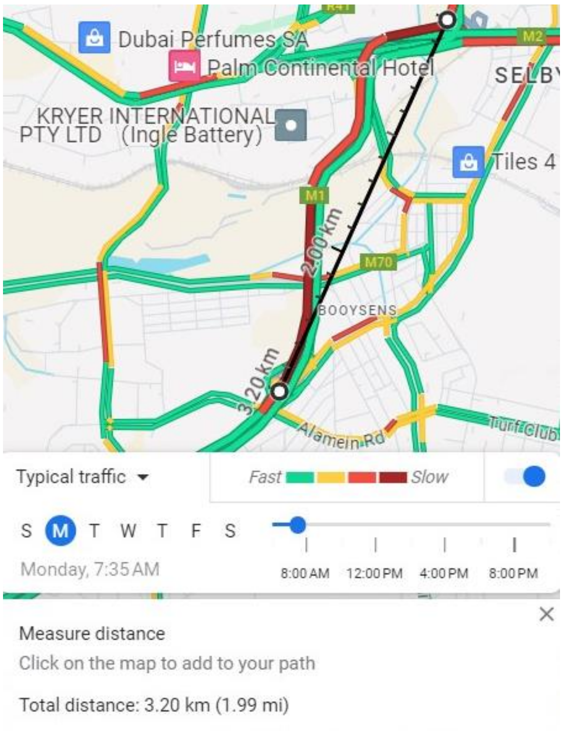

Figure 4.12: Stop/start traffic on M1 highway Johannesburg.

4.3.1 Battery Only Simulation

Figure 4.13 shows the battery current, and Figure 4.14 shows the battery SOC for the CBD drive cycle.

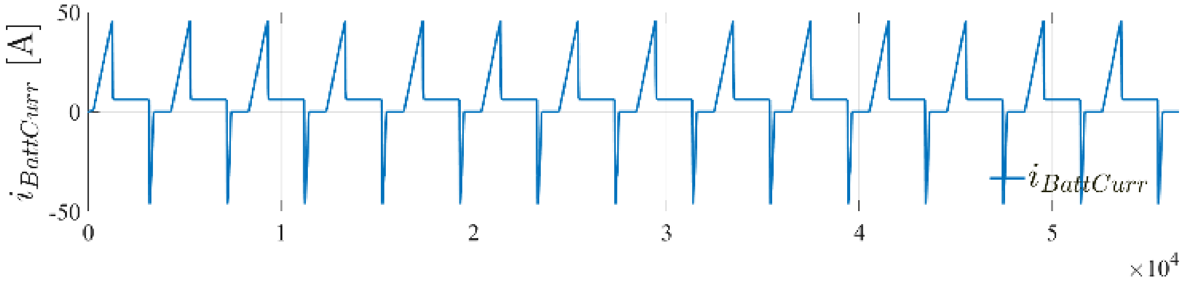

Figure 4.13: Battery only ESS current (CBD).

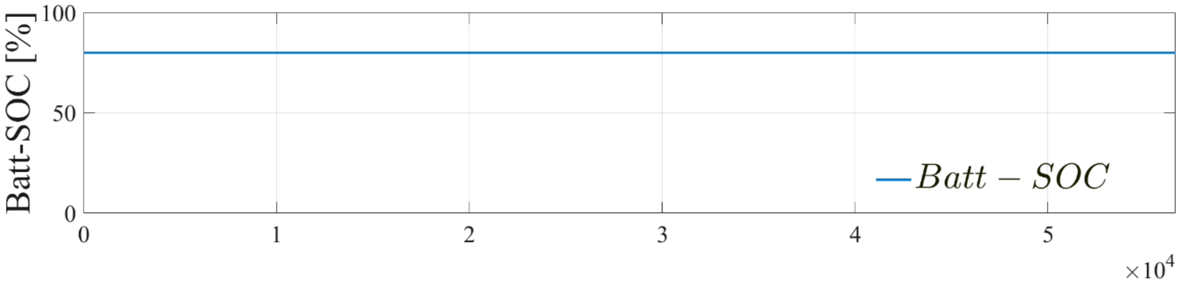

Figure 4.14: Battery only ESS SOC (CBD).

4.3.2 Battery-SC HESS Simulation

Figure 4.15 illustrates the battery current, and Figure 4.16 shows the battery SOC. The proposed EMS ensures that only the SC is used during stop/start traffic so as to ensure that the battery is not exposed to transient currents.

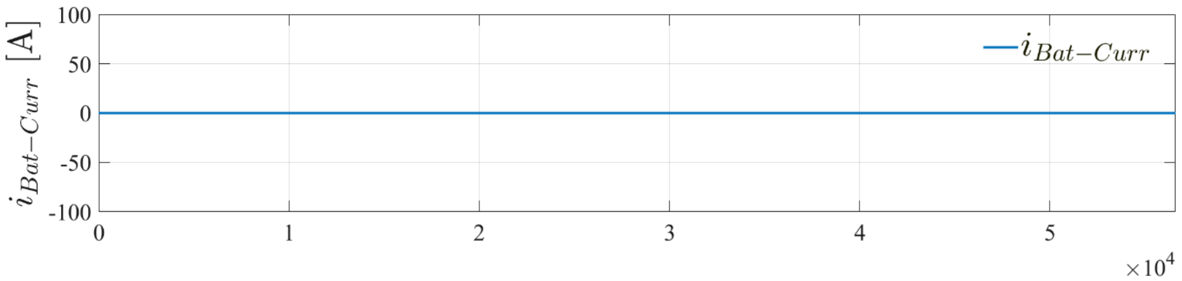

Figure 4.15: Battery-SC HESS current (CBD).

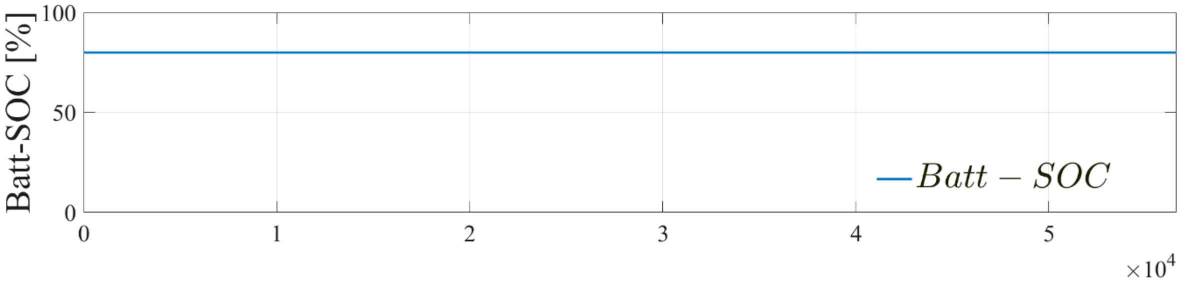

Figure 4.16: Battery-SC HESS SOC (CBD).

Figure 4.17 illustrates the SC current, and Figure 4.18 illustrates the SC SOC. It can be observed that the SC absorbs the full load of the EV.

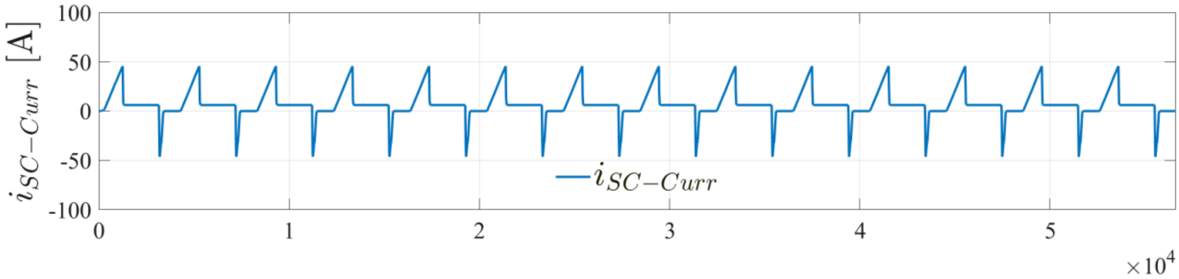

Figure 4.17: Battery-SC HESS SC SOC (CBD).

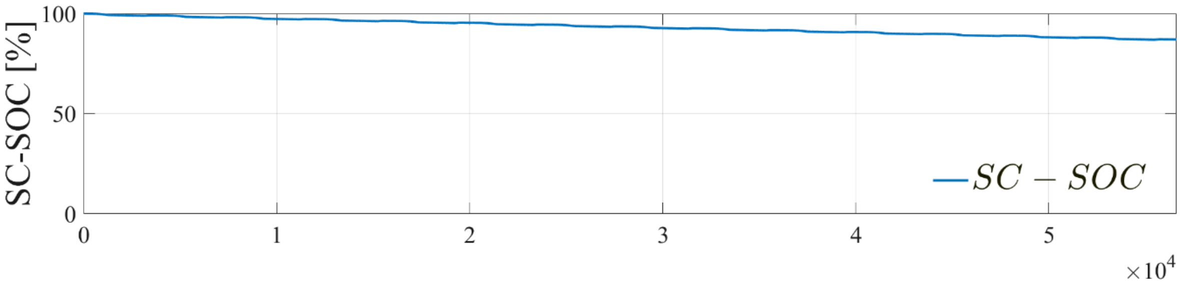

Figure 4.18: Battery-SC HESS SC SOC (CBD).

4.4 ARTEMIS MOTORWAY 130

The Common Artemis Driving Cycles (CADC) were formulated as chassis dynamometer procedures under the European Artemis project. These procedures were developed by analysing a vast database of real-world driving patterns in Europe. The CADC consists of three distinct driving schedules: Urban, Rural Road, and Motorway. The Motorway cycle offers two variations, with maximum speeds of 130 and 150 km/h respectively. For this study, the motorway 130 cycle was used. Figure 4.19 shows the velocity versus time graph for the Artemis driving cycles 130 cycles.

The Artemis motorway 130 drive cycle exhibits the following characteristic parameters:

1) Duration: 1068 seconds
2) Distance: 28 km
3) Average speed: 96.9 km/h
4) Max speed: 131.4 km/h

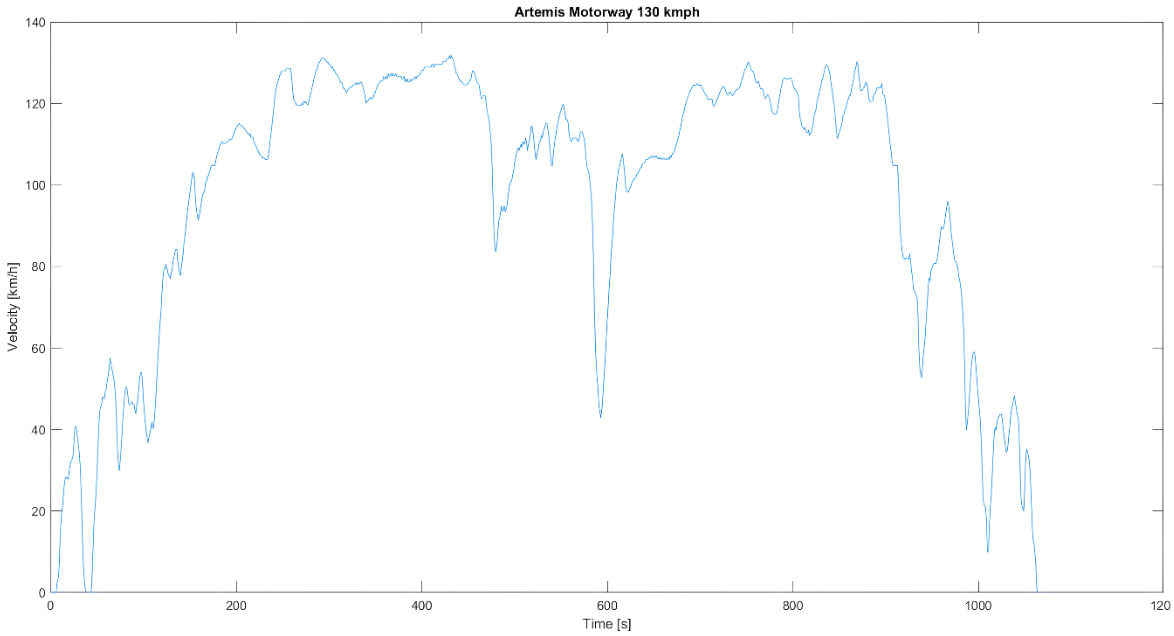

Figure 4.19: Artemis motorway 130 drive cycle.

In the context of South Africa, the Artemis motorway 130 drive cycle can be likened to travelling from gold reef city theme park to Kelvin, Santon using the M1/N1 motorway as shown by Figure 4.20. Figure 4.21 shows the elevation profile of the M1/N1 motorway from gold reef city and to Kelvin, Santon.

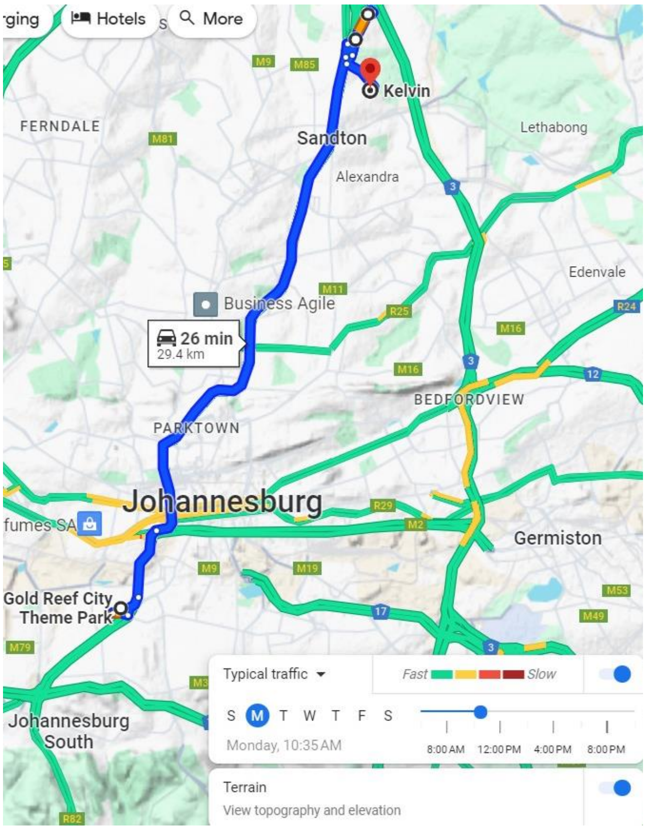

Figure 4.20: Artemis motorway 130 in SA context.

Figure 4.21: Artemis motorway 130 in SA context elevation profile.

4.4.1 Battery Only ESS Simulation

Figure 4.22 illustrates the battery current when the battery only ESS system is put through the Artemis motorway 130 drive cycle. It can be observed that the battery current is fluctuating and the maximum current of 191 A is very close to the battery current limit of 200 A. As the duration of the drive cycle is short, 1068 seconds, the battery SOC decreased by only 10%.

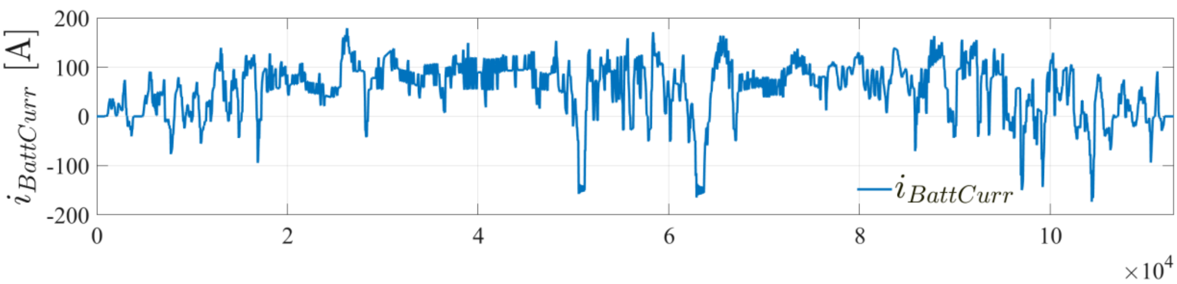

Figure 4.22: Battery only ESS current (Artemis motorway 130).

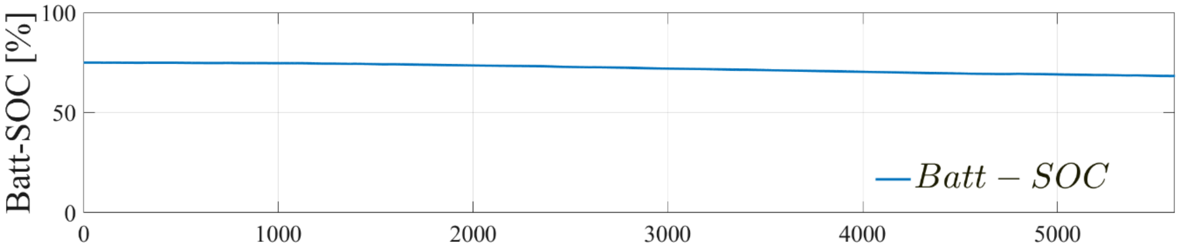

Figure 4.23: Battery only ESS SOC (Artemis motorway 130).

4.4.2 Battery-SC HESS Simulation

Figure 4.24 illustrates the battery-SC battery current and Figure 4.25 illustrates its SOC. It can be observed that the proposed EMS ensures that the battery current is only in the forward direction. The battery SOC dropped by 20%.

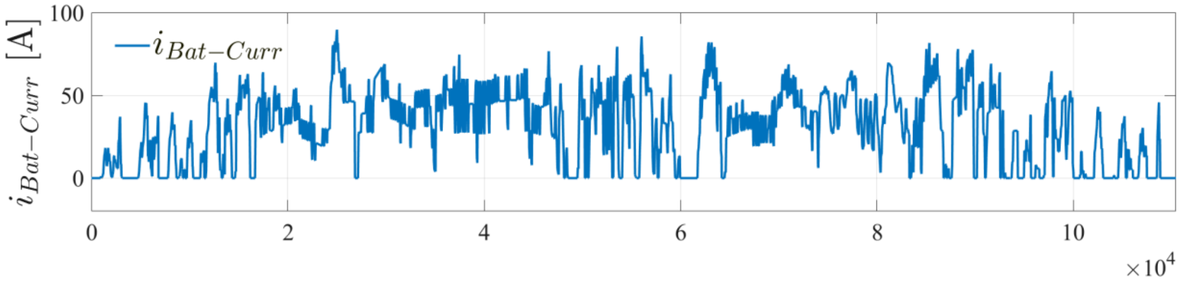

Figure 4.24: Battery-SC HESS battery current (Artemis motorway 130).

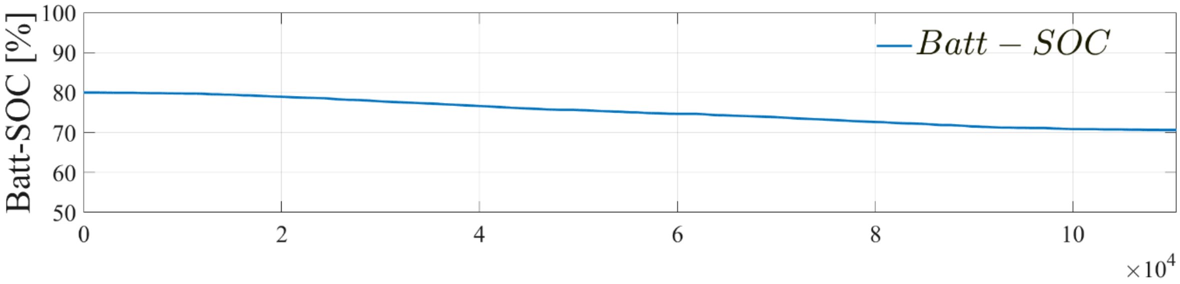

Figure 4.25: Battery-SC HESS battery SOC (Artemis motorway 130).

Figure 4.26 illustrates the SC current and Figure 4.27 illustrates the SC SOC. It was observed that the proposed EMS ensured that the SC played an active role in supporting the EV load. The SC SOC dropped significant from 100% to 20%, which indicates that the SC was over utilized.

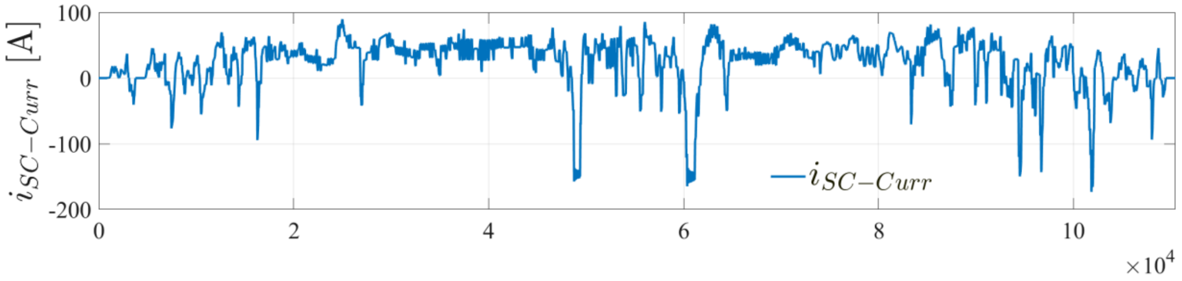

Figure 4.26: Battery-SC HESS SC current (Artemis motorway 130).

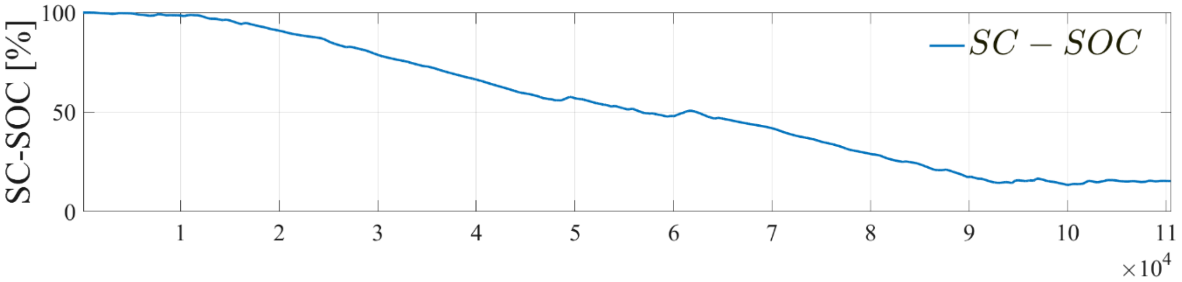

Figure 4.27: Battery-SC HESS SC SOC (Artemis motorway 130).

4.5 SUMMERY

This chapter shows the results obtained from simulations. For each drive cycle, a path was defined in the South African context, specifically Gauteng Johannesburg. The road elevation profile as well as the traffic conditions were obtained. For each drive cycle, the battery only ESS was simulated, and the proposed battery-SC HESS was simulated to compare the results of both systems.

CHAPTER 5 DISCUSSION

5.1 CHAPTER OVERVIEW

The cost, and the benefits of implementing the proposed EMS are discussed in this chapter. Section 5.2 compares the performance of the battery-only ESS and the battery-SC HESS in terms of battery life span. Section 5.3 compares the hardware cost between a battery-only ESS and a battery-SC HESS. The chapter concludes with a summary in section 5.4.

5.2 BATTERY ONLY ESS VS. BATTERY-SC HESS

There have been studies in which a rule-based EMS is designed for a battery-SC HESS. In most cases, the SC is used to supply the peak current of the EV. At the time of writing this dissertation, there have been no studies that attempt to actively use the SC in supplying the EV power demand during steady state conditions. Furthermore, there has been no study that slits the traffic conditions into three categories and address them individually.

In this study, the proposed rule-based ESS was directly compared to a battery-only ESS, i.e. both systems were simulated under the same drive cycles. The battery only system when going through the UDDS, CBD, and Artemis motorway 130 drive cycles would last 461km (sum of the city driving, stop/start traffic and highway driving). This is based on the knowledge that the lithium-ion battery has 1500 life cycles, a power consumption of 20kW/100km. the vehicle with the battery-SC HESS has a battery lifespan of approximately 800km. this is because during motion, the battery is discharge only and the SC absorbs all the regenerative braking energy and when the EV is in stop/go traffic only the SC is used to power the EV. This is done to take advantage of the 1 million duty cycles of the SC.

5.3 COST COMPARISON

Table 5.1 draws a hardware cost comparison between the battery only system and the battery-SC HESS. These are estimations if the items were purchased individually. Manufacturers may manufacture these products in house to reduce cost. It is evident from Table 5.1 that the hardware cost associated with the battery-SC HESS are high compared to the battery-only ESS. Therefore, because of the high cost associated with the battery-SC HESS, this system may be better suited to high performance luxury EV or heavy duty EVs such as trucks and construction machines to justify the cost of the total system.

Table 5.1: Cost Comparison

Parameter	**Battery only ESS**	**Battery-SC HESS**
2 x DC/DC converters	N/A	R 199 839.16
Battery	R324 938.00	R 120 834.00
SC	N/A	R 2 043 816.00
Total	R324 938.00	R 2 364 489.16

5.4 SUMMARY

This chapter shows that the results obtained are positive. The cost of the proposed system was compared to a battery only system and it was found that the cost of the proposed system is higher than that of the battery only system and therefore the proposed system maybe better suited for luxury high performance EVs. The proposed system actively utilizes the SC to supply the EV load and therefore this results in the extension of the EV battery lifespan. And compared to other studies that have been conducted, the proposed system in this dissertation is the first of its kind.

CHAPTER 6 CONCLUSION

6.1 CHAPTER OVERVIEW

Chapter 6 concludes the study. Section 6.2 provides the concluding remarks of the study. Section 6.3 provides other elements that could be focused on in future research.

6.2 CONCLUDING REMARKS

The experiment was successful. It is possible to have a rule-based EMS that actively uses the SC energy to support the EV that also considers road elevation and traffic conditions. The proposed system uses a fully active battery-SC HESS topology as shown in Figure 3.5. The battery DC/DC converter is a single direction boost converter. The SC DC/DC converter is a bi-directional to allow the SC to be discharged and to be charged by the regenerative braking energy. The factor that makes the proposed system unique is that the SC is actively used to supply the EV load, traffic and road elevation is used to inform the EMS on how to behave. Furthermore, the proposed EMS divides driving conditions into three categories namely city driving, stop/go traffic and highway driving. This is done to optimize the system for each driving condition.

The results showed that for city driving conditions in the context of SA, the battery energy was well conversed, the battery was not exposed to high frequency currents and the SC SOC dropped to just above 50%. For stop/go traffic conditions, only the SC supplied the EV to protect the battery from being exposed to continuous transient currents. The stop/go traffic condition only used 20% of the SC energy. The highway driving scenario showed to be the most energy intensive and demanded 80% of the SC energy but took only 20% of the battery energy.

The use of the proposed system was compared to an equivalent battery only system and it was found that the proposed system has the potential to increase the lifespan of the battery to 800 km compared to the 461 km.
It was also observed that the cost of the battery-SC HESS is significantly higher than that of the battery-only system. Therefore, the battery-SC HESS is better suited to high performance EV and heavy duty EVs such as SUVs and trucks.

6.3 FUTURE STUDIES

This study covered the battery-SC HESS in terms of topology and energy management. There are still a lot of other elements to be investigated. A further study could include decreasing the battery size and increasing the SC size such that they deplete at the same rate. As it was observed that battery SOC in the battery-SC HESS remained nearly the same through the different driving conditions while the SC SOC was depleted fasted in comparison.

Another study could involve the cost reduction of the battery-SC HESS such that it is equivalent to the cost of a battery-only system.

The proposed EMS could be paired with an intelligent management system such MPC, neural network or machine learning [9][7], [36]. A study could be performed in which the system learns the driving pattern of the driver, the environment, traffic condition as well as other factors affecting the EV performance to optimize the EV's performance overtime.

REFERENCES

[1] O. A. Towoju and F. A. Ishola, "A case for the internal combustion engine powered vehicle," in *The 6th International Conference on Power and Energy Systems Engineering*, Okinawa, Japan, 20-23 September 2019.

[2] Climate Transparency, "A Low-carbon transport furture for South Africa: Technical, Economic and Policy Considerations," University of Cape Town, Cape Town, 2020.

[3] United States Environmental Protection Agency , "Fast Facts: U.S. Transportation Greenhouse Gas Emissions 1990-2021," United States Environmental Protection Agency , Washington, D.C, 2023.

[4] Electric Power Research Institute, "Implications of the UK's Ban on Petrol and Diesel Vehicles by 2040," Electric Power Research Institute, Washington, D.C, 2023.

[5] S. H. Mian, M. S. Nazir, I. Ahmad, and S. A. Khan, 'Optimized nonlinear controller for fuel cell, supercapacitor, battery, hybrid photoelectrochemical and photovoltaic cells-based hybrid electric vehicles', *Energy*, vol. 4, No. 283, pp. 1-10 Nov. 2023, doi: 10.1016/j.energy.2023.129121.

[6] Y. Ye and J. Zhang, "A Fast Q-learning Energy Management Strategy for Battery/Supercapacitor Electric Vehicles Considering Energy Saving and Battery Aging," in *International Conference on Electrical, Computer and Energy Technologies*, Cape Town, South Africa, 9-10 December 2021. doi: 10.1109/ICECET52533.2021.9698682.

[7] N. D. Nguyen, C. Yoon, and Y. Il Lee, 'A Standalone Energy Management System of Battery/Supercapacitor Hybrid Energy Storage System for Electric Vehicles Using

Model Predictive Control', *IEEE Transactions on Industrial Electronics*, vol. 70, no. 5, pp. 5104–5114, May 2023, doi: 10.1109/TIE.2022.3186369.

[8] D. R. Brafianto, W. Wijono, and T. Nurwati, 'Energy Management Applications in Battery and Supercapacitor Hybrid Electric Vehicles Using Fuzzy Logic', in *Proceedings - 11th Electrical Power, Electronics, Communications, Control, and Informatics Seminar, EECCIS 2022*, Malang, Indonesia, 23-25 August 2022, pp. 76–81. doi: 10.1109/EECCIS54468.2022.9902944.

[9] C. Jia, J. Cui, W. Qiao, and L. Qu, 'Real-Time Model Predictive Control for Battery-Supercapacitor Hybrid Energy Storage Systems Using Linear Parameter-Varying Models', *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 11, no. 1, pp. 251–263, Feb. 2023, doi: 10.1109/JESTPE.2021.3130795.

[10] A. K. Podder, O. Chakraborty, S. Islam, N. Manoj Kumar, and H. H. Alhelou, 'Control Strategies of Different Hybrid Energy Storage Systems for Electric Vehicles Applications', *IEEE Access*, vol. 9, pp. 51865–51895, 2021, doi: 10.1109/ACCESS.2021.3069593.

[11] K. Alobeidli and V. Khadkikar, 'A new ultracapacitor state of charge control concept to enhance battery lifespan of dual storage electric vehicles', *IEEE Transactions on Vehicular Technology*, vol. 67, no. 11, pp. 10470–10481, Nov. 2018, doi: 10.1109/TVT.2018.2871038.

[12] A. Ostadi and M. Kazerani, 'A Comparative Analysis of Optimal Sizing of Battery-Only, Ultracapacitor-Only, and Battery-Ultracapacitor Hybrid Energy Storage Systems for a City Bus', *IEEE Transactions on Vehicular Technology*, vol. 64, no. 10, pp. 4449–4460, Oct. 2015, doi: 10.1109/TVT.2014.2371912.

[13] K. Itani, A. De Bernardinis, Z. Khatir, A. Jammal, and M. Oueidat, 'Regenerative braking modeling, control, and simulation of a hybrid energy storage system for an electric vehicle in extreme conditions', *IEEE Transactions on Transportation Electrification*, vol. 2, no. 4, pp. 465–479, Dec. 2016, doi: 10.1109/TTE.2016.2608763.

[14] J. Khazaei, 'Optimal Flow of MVDC Shipboard Microgrids with Hybrid Storage Enhanced with Capacitive and Resistive Droop Controllers', *IEEE Transactions on*

Power Systems, vol. 36, no. 4, pp. 3728–3739, Jul. 2021, doi: 10.1109/TPWRS.2021.3049343.

[15] N. M. Khanyile and M. W. K. Mbukani, “Supercapacitor control for electric vehicle using hybrid energy storage system: A review paper,” in *12th International Conference on Power Electronics, Machines and Drives (PEMD 2023)*, Brussels, Belgium, 23-24 October 2023.

[16] T. Wilberforce, A. Anser, J. A. Swamy, and R. Opoku, ‘An investigation into hybrid energy storage system control and power distribution for hybrid electric vehicles’, *Energy*, vol. 279, Sep. 2023, doi: 10.1016/j.energy.2023.127804.

[17] R. M. Reddy, M. Das, and N. Chauhan, ‘Novel Battery-Supercapacitor Hybrid Energy Storage System for Wide Ambient Temperature Electric Vehicles Operation’, *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 70, no. 7, pp. 2580–2584, Jul. 2023, doi: 10.1109/TCSII.2023.3237860.

[18] C. Beatrice, C. Capasso, S. Doulgeris, Z. Samaras, and O. Veneri, ‘Hybrid storage system management for hybrid electric vehicles under real operating conditions’, *Applied Energy*, vol. 354, Jan. 2024, doi: 10.1016/j.apenergy.2023.122170.

[19] B. Wang *et al.*, ‘Consensus-Based Control of Hybrid Energy Storage System with a Cascaded Multiport Converter in DC Microgrids’, *IEEE Transactions on Sustainable Energy*, vol. 11, no. 4, pp. 2356–2366, Oct. 2020, doi: 10.1109/TSTE.2019.2956054.

[20] M. M. S. Khan, M. O. Faruque, and A. Newaz, ‘Fuzzy Logic Based Energy Storage Management System for MVDC Power System of All Electric Ship’, *IEEE Transactions on Energy Conversion*, vol. 32, no. 2, pp. 798–809, Jun. 2017, doi: 10.1109/TEC.2017.2657327.

[21] O. A. AlKawak, J. R. R. Kumar, S. S. Daniel, and C. V. K. Reddy, ‘Hybrid method-based energy management of electric vehicles using battery-super capacitor energy storage’, *Journal of Energy Storage*, vol. 77, Jan. 2024, doi: 10.1016/j.est.2023.109835.

[22] N. M. Khanyile and M. W. K. Mbukani, “Supercapacitor control for electric vehicle using hybrid energy storage system,” in *12th International Conference on Power*

Electronics, Machines and Drives (PEMD 2023), Brussels, Beligum, 23-24 October 2023.

[23] E. Naderi, K. C. Bibek, M. Ansari, and A. Asrari, 'Experimental Validation of a Hybrid Storage Framework to Cope with Fluctuating Power of Hybrid Renewable Energy-Based Systems', *IEEE Transactions on Energy Conversion*, vol. 36, no. 3, pp. 1991–2001, Sep. 2021, doi: 10.1109/TEC.2021.3058550.

[24] N. R. Tummuru, M. K. Mishra, and S. Srinivas, 'Dynamic Energy Management of Renewable Grid Integrated Hybrid Energy Storage System', *IEEE Transactions on Industrial Electronics*, vol. 62, no. 12, pp. 7728–7737, Dec. 2015, doi: 10.1109/TIE.2015.2455063.

[25] S. Rasool, K. M. Muttaqi, and D. Sutanto, 'A Multi-Filter Based Dynamic Power Sharing Control for a Hybrid Energy Storage System Integrated to a Wave Energy Converter for Output Power Smoothing', *IEEE Transactions on Sustainable Energy*, vol. 13, no. 3, pp. 1693–1706, Jul. 2022, doi: 10.1109/TSTE.2022.3170938.

[26] P. Roy, J. He, and Y. Liao, 'Cost Minimization of Battery-Supercapacitor Hybrid Energy Storage for Hourly Dispatching Wind-Solar Hybrid Power System', *IEEE Access*, vol. 8, pp. 210099–210115, 2020, doi: 10.1109/ACCESS.2020.3037149.

[27] U. R. Nair and R. Costa-Castello, 'A Model Predictive Control-Based Energy Management Scheme for Hybrid Storage System in Islanded Microgrids', *IEEE Access*, vol. 8, pp. 97809–97822, 2020, doi: 10.1109/ACCESS.2020.2996434.

[28] Z. Wang, P. Wang, W. Jiang, and P. Wang, 'A Decentralized Automatic Load Power Allocation Strategy for Hybrid Energy Storage System', *IEEE Transactions on Energy Conversion*, vol. 36, no. 3, pp. 2227–2238, Sep. 2021, doi: 10.1109/TEC.2020.3038476.

[29] D. B. W. Abeywardana, B. Hredzak, and V. G. Agelidis, 'Single-Phase Grid-Connected LiFePO4 Battery-Supercapacitor Hybrid Energy Storage System With Interleaved Boost Inverter', *IEEE Transactions on Power Electronics*, vol. 30, no. 10, pp. 5591–5604, Oct. 2015, doi: 10.1109/TPEL.2014.2372774.

[30] X. Hu, N. Murgovski, L. M. Johannesson, and B. Egardt, 'Comparison of three electrochemical energy buffers applied to a hybrid bus powertrain with simultaneous

optimal sizing and energy management', *IEEE Transactions on Intelligent Transportation Systems*, vol. 15, no. 3, pp. 1193–1205, 2014, doi: 10.1109/TITS.2013.2294675.

[31] T. Boonraksa, W. Pinthurat, P. Wongdet, P. Boonraksa, B. Marungsri, and B. Hredzak, 'Optimal Capacity and Cost Analysis of Hybrid Energy Storage System in Standalone DC Microgrid', *IEEE Access*, vol. 11, pp. 65496–65506, 2023, doi: 10.1109/ACCESS.2023.3289821.

[32] I. J. Cohen, D. A. Wetz, B. J. McRee, Q. Dong, and J. M. Heinzel, 'Fuzzy logic control of a hybrid energy storage module for use as a high-rate prime power supply', *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 24, no. 6, pp. 3887–3893, Dec. 2017, doi: 10.1109/TDEI.2017.006647.

[33] Y. Wu *et al.*, 'Spatial–temporal data-driven full driving cycle prediction for optimal energy management of battery/supercapacitor electric vehicles', *Energy Conversion and Management*, vol. 277, Feb. 2023, doi: 10.1016/j.enconman.2022.116619.

[34] O. A. AlKawak, J. R. R. Kumar, S. S. Daniel, and C. V. K. Reddy, 'Hybrid method-based energy management of electric vehicles using battery-super capacitor energy storage', *Journal of Energy Storage*, vol. 77, Jan. 2024, doi: 10.1016/j.est.2023.109835.

[35] Q. Zhang, L. Wang, G. Li, and Y. Liu, 'A real-time energy management control strategy for battery and supercapacitor hybrid energy storage systems of pure electric vehicles', *Journal of Energy Storage*, vol. 31, Oct. 2020, doi: 10.1016/j.est.2020.101721.

[36] S. C and S. J. C, 'Energy management of hybrid energy storage system in electric vehicle based on hybrid SCSO-RERNN approach', *Journal of Energy Storage*, vol. 78, Feb. 2024, doi: 10.1016/j.est.2023.109733.

[37] Y. Wu *et al.*, 'Driving style-aware energy management for battery/supercapacitor electric vehicles using deep reinforcement learning', *Journal of Energy Storage*, vol. 73, Dec. 2023, doi: 10.1016/j.est.2023.109199.

[38] L. Guo, P. Hu, and H. Wei, 'Development of supercapacitor hybrid electric vehicle', *Journal of Energy Storage*, vol. 65, Aug. 2023, doi: 10.1016/j.est.2023.107269.

[39] F. Li *et al.*, 'Incentive learning-based energy management for hybrid energy storage system in electric vehicles', *Energy Conversion and Management*, vol. 293, Oct. 2023, doi: 10.1016/j.enconman.2023.117480.

[40] S. C and S. J. C, 'Energy management of hybrid energy storage system in electric vehicle based on hybrid SCSO-RERNN approach', *Journal of Energy Storage*, vol. 78, Feb. 2024, doi: 10.1016/j.est.2023.109733.

[41] Q. Zhang, J. Han, G. Li, and Y. Liu, 'An adaptive energy management strategy for fuel cell/battery/supercapacitor hybrid energy storage systems of electric vehicles', *International Journal of Electrochemical Science*, vol. 15, pp. 3410–3433, 2020, doi: 10.20964/2020.04.50.

[42] H. Jondhle, A. B. Nandgaonkar, S. Nalbalwar, and S. Jondhle, 'An artificial intelligence and improved optimization-based energy management system of battery-fuel cell-ultracapacitor in hybrid electric vehicles', *Journal of Energy Storage*, vol. 74, Dec. 2023, doi: 10.1016/j.est.2023.109079.

[43] N. Zhao, N. Schofield, and W. Niu, 'Energy storage system for a port crane hybrid powertrain', *IEEE Transactions on Transportation Electrification*, vol. 2, no. 4, pp. 480–492, Dec. 2016, doi: 10.1109/TTE.2016.2562360.

[44] N. Vukajlović, D. Milićević, B. Dumnić, and B. Popadić, 'Comparative analysis of the supercapacitor influence on lithium battery cycle life in electric vehicle energy storage', *Journal of Energy Storage*, vol. 31, Oct. 2020, doi: 10.1016/j.est.2020.101603.

[45] S. Boumediene, A. Nasri, T. Hamza, C. Hicham, K. Kayisli, and H. Garg, 'Fuzzy logic-based Energy Management System (EMS) of hybrid power sources: Battery/Super capacitor for electric scooter supply', *Journal of Engineering Research (Kuwait)*, 2024, doi: 10.1016/j.jer.2023.07.008.

[46] J. Shi, B. Xu, Y. Shen, and J. Wu, 'Energy management strategy for battery/supercapacitor hybrid electric city bus based on driving pattern recognition', *Energy*, vol. 243, Mar. 2022, doi: 10.1016/j.energy.2021.122752.

[47] T. Zhu, R. G. A. Wills, R. Lot, H. Ruan, and Z. Jiang, 'Adaptive energy management of a battery-supercapacitor energy storage system for electric vehicles based on

flexible perception and neural network fitting', *Applied Energy*, vol. 292, Jun. 2021, doi: 10.1016/j.apenergy.2021.116932.

[48] B. Yang *et al.*, 'Applications of battery/supercapacitor hybrid energy storage systems for electric vehicles using perturbation observer based robust control', *Journal of Power Sources*, vol. 448, Feb. 2020, doi: 10.1016/j.jpowsour.2019.227444.

[49] A. K. Podder, O. Chakraborty, S. Islam, N. Manoj Kumar, and H. H. Alhelou, 'Control Strategies of Different Hybrid Energy Storage Systems for Electric Vehicles Applications', *IEEE Access*, vol. 9, pp. 51865–51895, 2021, doi: 10.1109/ACCESS.2021.3069593.

[50] H. Xiaoliang, T. Hiramatsu and H. Yoichi, "Energy Management Strategy Based on Frequency Varying Filter for the Battery Supercapacitor Hybrid System of Electric Vehicles," in *World Electric Vehicle Symposium and Exhibition*, Barcelona, Spain, 2013.

[51] T. Mesbahi, N. Rizoug, P. Bartholomeüs, R. Sadoun, F. Khenfri, and P. Le Moigne, 'Optimal energy management for a Li-ion battery/supercapacitor hybrid energy storage system based on a particle swarm optimization incorporating nelder-mead simplex approach', *IEEE Transactions on Intelligent Vehicles*, vol. 2, no. 2, pp. 99–110, Jun. 2017, doi: 10.1109/TIV.2017.2720464.

[52] J. Snoussi, S. Ben Elghali, M. Benbouzid, and M. F. Mimouni, 'Optimal sizing of energy storage systems using frequency-separation-based energy management for fuel cell hybrid electric vehicles', *IEEE Transactions on Vehicular Technology*, vol. 67, no. 10, pp. 9337–9346, Oct. 2018, doi: 10.1109/TVT.2018.2863185.

[53] R. B. Selvakumar *et al.*, 'Energy management of a dual battery energy storage system for electric vehicular application', *Computers and Electrical Engineering*, vol. 115, Apr. 2024, doi: 10.1016/j.compeleceng.2024.109099.

[54] O. C. Onar and A. Khaligh, 'A novel integrated magnetic structure-based DC/DC converter for hybrid battery/ultracapacitor energy storage systems', *IEEE Transactions on Smart Grid*, vol. 3, no. 1, pp. 296–307, Mar. 2012, doi: 10.1109/TSG.2011.2150250.

[55] S. H. Mian, M. S. Nazir, I. Ahmad, and S. A. Khan, 'Optimized nonlinear controller for fuel cell, supercapacitor, battery, hybrid photoelectrochemical and photovoltaic cells-based hybrid electric vehicles', *Energy*, vol. 283, Nov. 2023, doi: 10.1016/j.energy.2023.129121.

[56] H. Lei, K. Li, and B. Chong, 'A Review of Hybrid Energy Storage System for Heavy-Duty Electric Vehicle', in *Transportation Research Procedia*, Vol. 70, no. 1, pp. 234–240, 2023. doi: 10.1016/j.trpro.2023.11.024.

[57] A. S. Mohammed, S. M. Atnaw, A. O. Salau, and J. N. Eneh, 'Review of optimal sizing and power management strategies for fuel cell/battery/super capacitor hybrid electric vehicles', *Energy Reports*, vol. 9. Elsevier Ltd, pp. 2213–2228, Dec. 01, 2023. doi: 10.1016/j.egyr.2023.01.042.

[58] L. H. Saw *et al.*, 'Numerical modeling of hybrid supercapacitor battery energy storage system for electric vehicles', in *Energy Procedia*, Elsevier Ltd, 2019, pp. 2750–2755. doi: 10.1016/j.egypro.2019.02.033.

[59] T. Ming, W. Deng, J. Wu, and Q. Zhang, "A Hierarchical Energy Management Strategy for Battery-Supercapacitor Hybrid Energy Storage System of Electric Vehicle," in IEEE Conference and Expo Transportation Electrification Asia-Pacific, Beijing, China, 2014.

[60] S. M. Juned and D. Bhanabhagvanwala, "Simulation Analysis of Battery/Ultracapacitor Hybrid Energy Storage System for Electric Vehicle," in *International Conference on Intelligent Sustainable Systems*, Tamilnadu, India, 21-22 February 2019.

[61] S. Lu, K. A. Corzine, and M. Ferdowsi, 'A new battery/ultracapacitor energy storage system design and its motor drive integration for hybrid electric vehicles', *IEEE Transactions on Vehicular Technology*, vol. 56, no. 4 I, pp. 1516–1523, Jul. 2007, doi: 10.1109/TVT.2007.896971.

[62] Z. Shengzhe, W. Kai, and X. Wen, 'Fuzzy Logic-Based Control Strategy for a Battery/Supercapacitor Hybrid Energy Storage System in Electric Vehicles', in *Chinese Automation Congress,* Jinan, China, 20-22 October 2017.

[63] J. M. Blanes, R. Gutiérrez, A. Garrigós, J. L. Lizán, and J. M. Cuadrado, 'Electric vehicle battery life extension using ultracapacitors and an FPGA controlled interleaved buck-boost converter', *IEEE Transactions on Power Electronics*, vol. 28, no. 12, pp. 5940–5948, 2013, doi: 10.1109/TPEL.2013.2255316.

[64] M. E. Choi, J. S. Lee, and S. W. Seo, 'Real-time optimization for power management systems of a battery/supercapacitor hybrid energy storage system in electric vehicles', *IEEE Transactions on Vehicular Technology*, vol. 63, no. 8, pp. 3600–3611, Oct. 2014, doi: 10.1109/TVT.2014.2305593.

[65] Y. Kim, V. Raghunathan, and A. Raghunathan, 'Design and Management of Battery-Supercapacitor Hybrid Electrical Energy Storage Systems for Regulation Services', in *IEEE Transactions on Multi-Scale Computing Systems*, Institute of Electrical and Electronics Engineers Inc., Jan. 2017, pp. 12–24. doi: 10.1109/TMSCS.2016.2627543.

[66] W. LI, C. XU, H. YU, Y. GU, and X. HE, 'Energy management with dual droop plus frequency dividing coordinated control strategy for electric vehicle applications', *Journal of Modern Power Systems and Clean Energy*, vol. 3, no. 2, pp. 212–220, Jan. 2015, doi: 10.1007/s40565-015-0123-1.

[67] J. Moreno, M. E. Ortúzar, and J. W. Dixon, 'Energy-management system for a hybrid electric vehicle, using ultracapacitors and neural networks', *IEEE Transactions on Industrial Electronics*, vol. 53, no. 2, pp. 614–623, Apr. 2006, doi: 10.1109/TIE.2006.870880.

[68] T. Sadeq, C. K. Wai, E. Morris, Q. A. Tarboosh, and O. Aydogdu, 'Optimal Control Strategy to Maximize the Performance of Hybrid Energy Storage System for Electric Vehicle Considering Topography Information', *IEEE Access*, vol. 8, pp. 216994–217007, 2020, doi: 10.1109/ACCESS.2020.3040869.

[69] A. F. Pennington, C. R. Cornwell, K. D. Sircar and M. C. Mirabelli, "Electric vehicles and health: A scoping review," Environmental Research, vol. 251, no. 2, pp. 1-21, 2024.

[70] MathWorks, “What is Model Predictive Control?” MathWorks, 1 January 2024. [Online]. Available: https://www.mathworks.com/help/mpc/gs/what-is-mpc.html. [Accessed 31 January 2024].

ADDENDUM A EV REFERANCE MODEL PARAMETERS AND SIMULINK MODELS

The subsequent tables in this section provide an overview of the parameters utilized in all simulations. These specific values are incorporated into the graphical user interface (GUI) masks of every component displayed on the modelling page.

Table A.1. Vehicle Parameters

Parameter	**Value**
Total Vehicle Mass	2740 kg
Rotating Mass	5%
Vehicle cross section	2 m^2
Wheel diameter	0.5 m
Drag coefficient	0.29
Rolling Resistance coefficient	0.05

Table A.2. Supercapacitor model parameters

Parameter	Value
Capacity of each SC	165 F
Internal resistance of each SC	0.310 Ω
Maximum voltage of each SC	202 V
Maximum power of each SC	40 kW
Initial charge of each SC	955
Number of SC in parallel connection	1

Table A.3. Battery model parameters

Parameter	Value
Initial charge	80%
Battery voltage	200 V
Battery capacity	100 Ah

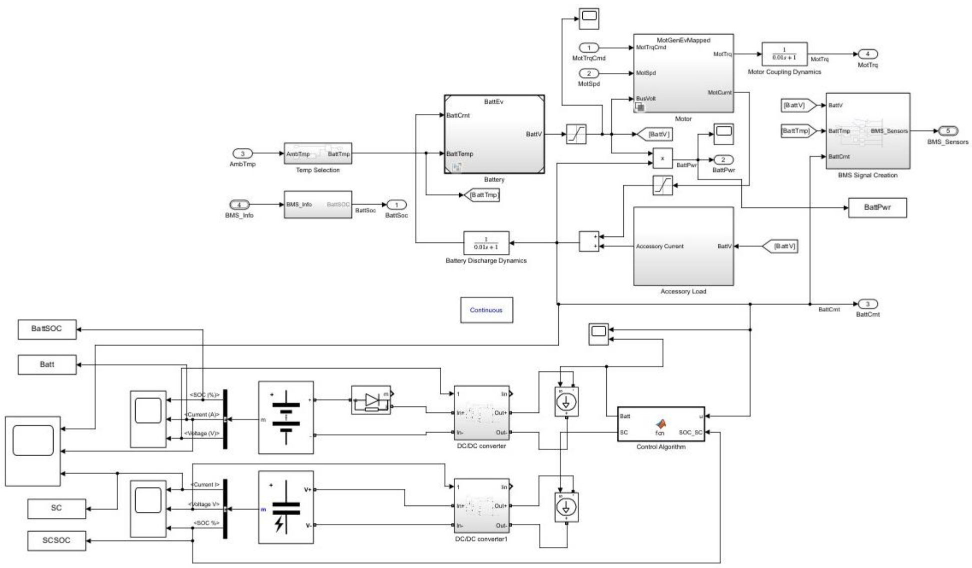

Figure A.1. Full Electric system