Design of an Improved Hybrid Lithium-Ion-Ultracapacitor Energy Storage System for Transport Vehicles

By

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DECLARATION

I, ***Buasa Andy Mayingi (student number: 214432420),*** hereby declare that this dissertation submitted for the degree of Master of Engineering: Electrical Engineering at the Tshwane University of Technology is my own original work and has not been previously submitted to any other institution of higher education. I further declare that all sources cited or quoted are indicated and acknowledged by means of a comprehensive list of references.

[redacted] 24/10/2023

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Buasa Andy Mayingi Date

DEDICATION

My heartfelt thanks go to my family, supervisors and friends for their unwavering support and engaging discussions throughout my Master of Engineering degree journey.

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Abstract

Lithium-ion Battery (LIB) are seen as viable solution to replace the current Lead-Acid Battery (LAB). It is due to the potential of obtaining higher power and energy density, as well longer lifespan compared with LAB. In order to balance the efficiency in terms of long lifespan, high energy and power density; there is need to hybridise with an Energy Storage System (ESS). Therefore, this research study seeks to design a hybrid Lithium-Ion-Ultracapacitor energy storage system (ESS) that will have a high storage capacity and longer lifespan at a reduced weight compared to a single LAB ESS.

The proposed research study employs MATLAB/Simulink software to model and validate its findings. Three different scenarios are considered, namely Case-1 (12V-40Ah), Case-2 (12V-70Ah), and Case-3 (12V-90Ah), and the results are compared with manufacturers' data for lead-acid batteries (LABs) of corresponding ratings, focusing on storage capacity and lifespan. The converters have ensure the voltage stays above the set nominal value 12 V and that the battery State-of-Charge (SOC) is kept above 98% during cold cranking mode. Ultracapacitors (UCs) play a crucial role on hybrid energy storage systems (HESSs) due to the capacity of supplying high power density in very short time. As a result, this enhances the lifespan of the LIB significantly.

The analysis shows that the lifespan of the LIBs is increased by 2.85-year, 3.41 years and 3.42 years respectively for Case-1, Case-2 and Case-3. These enhancements are achieved without altering the chemical composition of the lithium-ion batteries. The study underscores the potential for the automotive industry to gain significant benefits, including a minimum three-year extension of battery lifespan, by implementing HESS technology.

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Abbreviations

CCA	Cold Cranking Ampere
BMS	Battery Management System.
DC	Direct Current.
DC-DC	Direct Current-to-Direct Current.
DOD	Depth of Discharge
DP	Dynamic Programming
EOL	End-of-life
EMS	Energy Management System
ESS	Energy Storage System
ESU	Energy Storage unite
EVs	Electric Vehicles.
HESS	Hybrid Energy Storage System
HBESS	Hybrid Battery Energy Storage System
HEVs	Hybrid Electric Vehicles
FLC	Fuzzy Logic Control.
ICE	Internal Combustion Engine
ICEVs	Internal Combustion Engine Vehicles
LABs	Lead-Acid Batteries.
LCO	Lithium Cobalt Oxide.
LFP	Lithium-ion Phosphate.
LIBs	Lithium-Ion Batteries
LPF	Low Pass Filter
PWM	Power Width Modulation.
RC	Resistor and Capacitor.
SC	Supercapacitor.
SLAB	Single Lead-Acid Battery
SLAB	Single Lithium-Ion Battery
SLI	Starting-Lighting-Ignition
SOC	State of Charge.
SOH	State of Health.
TVs	Transport vehicles
UP	Ultracapacitor`

1. Chapter 1: Introduction

1.1. Introduction

Lead-acid batteries have been subjected to deep discharge due to the increase in load demand in transportation vehicles, which shortens their lifespan [1, 2]. To address this, the research aims to design a hybrid Lithium-Ion-Ultracapacitor Energy Storage System (ESS) to enhance storage capacity and extend battery life. The background and motivation, problem statement, sub-question, hypothesis, benefit, and the technique of the suggested research project are all covered in this chapter.

1.2. Background/Justification

Since the first vehicles were used in the early 20th century, lead-acid batteries (LABs) have provided starting-lighting-ignition (SLI) and secondary energy storage for transport vehicles (TVs) due to their low cost [3]. Lithium-ion batteries (LIBs) and other cutting-edge technologies, such as a number of post-lithium technologies and ultimately fuel cell batteries, are reshaping the technology quickly [4]. The increase in load demand for TVs lead to performance failures in LABs as a result of overcharging and deep discharge. This overcharging and deep discharge of LABs results in shortening their lifespan. For high-powered transport vehicle applications, lithium-Ion batteries have a number of benefits over other battery types [5]. It has a long lifespan, low discharge rate and high energy density [6-8].

Due to its high energy and power density as well as long lifespan, lithium-ion batteries are the best choice of batteries, making it the best technology for portable electronics, power devices, and electric vehicles [9, 10]. At the moment, lithium-ion batteries are leading the market in the production of electric vehicles.

The best technology now available for delivering high energy and power density are LIBs, also allows them to be lighter and smaller than other rechargeable batteries. Currently, electronics like digital cameras, cell phones, laptops, and video games are the main uses for LIBs. LIBs have a variety of advantages over Nickel Hydride and Lead Acid batteries, including a long lifespan and high efficiency [6, 11]. In terms of efficiency, energy density, power discharge, longevity, and charging operations, lithium-ion batteries perform better than lead-acid batteries at the moment due to falling lithium-ion battery costs [12].

Finding a way to extend TV batteries' lifespan while employing a smaller, less expensive lithium-ion battery is crucial. A possible solution to extend the lifespan of the batteries in the TV system is the HBESS, which uses a lithium-ion battery and an Ultracapacitor [13, 14]. Due to their high efficiency, high power density, and longer lifecycles, Ultracapacitors can be used in ICE cars as well. When a significant amount of power is needed to absorb the transitory peak power, Ultracapacitors are ideal [15, 16]. A battery may become intensely polarized as a result of excessive charge and discharge operations at high current rates, which can reduce the discharge capacity and reduce the driving range [17, 18]. With due consideration of the high price and heavyweight of the batteries compared to Ultracapacitors, it is justified that batteries and Ultracapacitor can be combined in order to maximise the benefits of the two components which will reduce the cost and weight of the battery pack [11]. Therefore, Ultracapacitors are used as a companion source to satisfy the SLI of the ICEV [19]. Due to their high power density, long lifespan, little losses, and low maintenance requirements, Ultracapacitors are well equipped to handle such a high power load [20]. Li-Ion battery in combination with the Ultracapacitor as HBESS will have the potential to deliver power and energy within the wide range of necessities as needed in the ICE vehicle battery application [21]. This will bring about ICE vehicle battery energy storage systems' performance improvement in terms of lifespan. A better hybrid battery management method for ICE with LIB and Ultracapacitors is hence the goal of the proposed research study. In addition to replacing LABs, the hybrid lithium-ion-Ultracapacitor system will also drastically reduce the storage system's weight. The Ultracapacitor operate as a short-time energy storage device with a high rate of charging and discharging capacities and thus the LIB is not stressed too much by the cold cranking current demand of ICE vehicles during starting [22].

The various lithium-ion battery types were investigated and analysed, and the majority of authors recommended using lithium-ion phosphate batteries because they are best suited for SLI applications and provide sensible chemistry performance with low resistance, high current rating, and long lifespan. Compared to other Li-Ion batteries, $LiFePO_4$ batteries have a higher self-discharge rate [23]. The research investigation has found that $LiFePO_4$ batteries are the best choice for transportation vehicles.

An EMS with real-time limitations is proposed by *Hussain et al.* [24] and is based on a bi-adaptive controller. A fuzzy logic controller (FLC) based low-pass filter and PI charge controller are used by the system to properly divide the power. This EMS's primary function during acceleration is to distribute the power coming from the battery and Ultracapacitor. Second, based on the Ultracapacitor's SoC, distribute the regenerative braking energy to it. The results demonstrate that for the understudied driving cycle, the Ultracapacitor's steady state charging performance is 98%, 95%, and 96%, respectively. According to the study, the proposed EMS can extend battery life by lowering peak charge or discharge. The study did not, however, quantify the lengthened battery lifespan.

Power must be supplied at a particular steady voltage. Additionally, as both batteries and Ultracapacitor have fluctuating voltage levels during the course of their charge, DC-DC conversions is frequently appropriate [25]. An energy management method for TVs is put forth by *Kumar et al.* [26] and includes techniques for cell balancing, charge regulation, and monitoring and evaluating battery state. Field Programmable Logic Array (FPLA) is the foundation of the EMS, and the results indicate good accuracy of greater than 99%. The study does not, however, analyse the battery's lifespan performance.

According to *Khayyam et al.* [27], a multi-level energy management system of HESS with a battery and Ultracapacitor combo uses a rule-based optimisation technique. The first tactic is predicated on a set of guidelines (strategic decisions). A second strategy uses a meta-heuristic technique to build an enhanced optimisation strategy. The results first apply a dynamic rule to condense the search space and then use a meta-heuristic approach. The general outcomes of power sharing from the two sources, as well as a decrease in power losses, seem adequate.

A cycle-oriented control technique is put out by *Zhang et al.* [28] for a novel battery and Ultracapacitor HESS topology. The tactic is based on a rule-based approach. This method helps to reduce battery deterioration during various driving cycles and boost regenerative braking capture. Power and energy allocation are distributed via the control between the battery and the Ultracapacitor. On all driving cycles, the results indicate a reduction in battery degradation of more than 80%. Urban dynamometer (UDDC), highway fuel economy cycle (HWFET), and high speed (US06) driving cycles are among the available driving cycles. The performance of the new topology technique and previously published topologies in the literature was not, however, compared in the study.

George et al. [29] discuss the utilisation of Hybrid Energy Storage Systems (HESS) for enhancing electric vehicle (EV) performance. HESS combines multiple energy storage systems, leveraging their individual strengths and employing adaptive control strategies to optimise power management. The study proposes a battery and Ultracapacitor hybrid with a fuzzy control strategy. Ultracapacitors handle peak power demands efficiently, allowing for a smaller battery size and reduced charging/discharging cycles. The fuzzy controller improves system operation, extending the battery's lifespan by minimizing frequent charging and discharging. Thus, by controlling the charging and discharging current, the battery is protected from overcharging and deep discharge, resulting in a longer lifespan.

Wangsupphaphol et al. [30] Investigate energy management systems and control algorithms for hybrid energy storage systems in electric vehicles. It covers vehicle characteristics, hybrid system architecture, converter topology, and energy management techniques. Using systematic literature review and keyword analysis, the study identifies frequently used terms and assesses their suitability. The evaluation rates a non-isolated DC-DC converter connected to an Ultracapacitor as suitable due to its simplicity, reliability, and improved vehicle performance. Deterministic and fuzzy rule-based control methods are successful in real-scale vehicle experiments.

To manage the transient peak-power and high-frequency part of the overall power demand, Ultracapacitors must be used [31]. To implement the hybrid energy storage systems, *Jaarsveld et al.* [14] recommend an active topology using two DC/DC converters and a switch. The topology's closed-loop management structure for the DC/DC converters uses fuzzy logic. In contrast, the HESS, which consists of a battery pack and an Ultracapacitor, is controlled using a rule-based control technique. Because of this, using a hybrid power system that combines an Ultracapacitor and lithium-ion battery is preferable.

Therefore, with the increase in load demand for TVs, LABs experience failure due to over-charging and have been subjected to deep discharge. It causes stress in LABs and consequently reduces the lifespan of LABs. Hence, this research study seeks to design a HBESS using Lithium-Ion battery and Ultracapacitor that will have a high storage capacity and longer lifespan at a reduced weight to replace the current LAB ESS.

1.3. Problem Statement

The background research makes it clear that LABs are subjected to deep discharges as a result of the increased load demand in TVs, which damages and shortens their lifespan. The lifespan of transport battery storage devices needs to be increased. This research study seeks to design a hybrid Lithium-Ion-Ultracapacitor energy storage system (ESS) that has a high storage capacity and longer lifespan compared to a single LAB ESS. In addition, this hybrid energy storage system weighs less than its equivalent LAB. The research question is stated as below:

What energy management strategy would be most effective for a hybrid lithium-ion battery and Ultracapacitor energy storage system to extend the lifespan of the energy storage system over a single LAB in TVs without changing the chemical composition of LIB and UC?

1.4. Research question

This research study addresses the following research question:

In order to extend the lifespan of the hybrid lithium-ion battery and Ultracapacitor ESS without changing the chemical composition, which Energy Management Strategy needs to be developed?

1.5. Hypotheses

The hypotheses of the proposed research are as follows:

Energy management strategy can be developed for the hybrid Lithium-Ion battery and Ultracapacitor ESS by using a fully active parallel topology to achieve the flow of energy and power independently for the HBESS. In order to extend the lifespan of the hybrid energy storage system, the Fuzzy rule-based management technique will be employed to control the states of charge and power.

1.5.1 Design a Hybrid Energy Storage System

To design a hybrid Lithium-Ion-Ultracapacitor energy storage system (ESS) that has a high storage capacity and a longer lifespan compared to a single Lead-Acid Battery (LAB) ESS. In addition, this hybrid energy storage system weigh less than its equivalent LAB.

1.5.2 Develop an Effective Energy Management Strategy

To determine the most effective energy management strategy for a hybrid lithium-ion battery and Ultracapacitor energy storage system to extend the lifespan of the energy storage system over a single LAB in TVs without changing the chemical composition of the Lithium-Ion Battery (LIB) and Ultracapacitor (UC).

1.5.3 Use Fully Active Parallel Topology

An energy management strategy can be developed for the hybrid Lithium-Ion battery and Ultracapacitor ESS by using a fully active parallel topology to achieve the flow of energy and power independently for the Hybrid Battery Energy Storage System (HBESS).

1.5.4 Implement Fuzzy Rule-Based Management Technique

In order to extend the lifespan of the hybrid energy storage system, the Fuzzy rule-based management technique will be employed to control the states of charge and power.

1.6. Importance/Benefits of Study

The benefits of the research include but are not limited to the following:

- The proposed hybrid Lithium-Ion battery and Ultracapacitor ESS replaces the LABs for TVs, and it improves the performance in terms of high energy density and high power to meet the load demand of TVs.
- The hybrid Lithium-Ion battery and Ultracapacitor ESS has various benefits. It is

lightweight, low self-discharging, with longer battery lifespan.

- It can be used in ICE cars with a provision for extending its application to HEVs and EVs.

1.7. Delimitation of Study

This research study does not cover the following topics since they present themselves as separate research fields:

- Driver's behaviour analysis.
- Prototype design.

The following are the research's underlying presumptions:

- Before doing a charge/discharge analysis, batteries must be fully charged.
- The working temperature of TVs is maintained between -10°C and +75°C.
- The storage conditions are absolute.
- Analysing vehicle loads while using a constant-current and constant-voltage supply.

1.8. Research Methodology

For this research study, the methodology is formulated as below:

- Literature review of LIB, UC and LAB with a primary focus on the factors influencing the hybrid Lithium-Ion and Ultracapacitor performance in terms of energy and power density, lifespan and efficiency.
- Modelling of a single LAB and a hybrid Lithium-Ion-Ultracapacitor ESS are performed separately using MATLAB/Simulink as a software tool.
- Simulation of a Single LAB, single LIB and the hybrid Lithium-Ion–Ultracapacitor ESS

model is accomplished using MATLAB/Simulink tools. The lifespan and storage capacity of the proposed HESS with EMS results is compared with the single LAB and single LIB.

- Analysis and validation of results are performed through computer simulation using MATLAB/Simulink software.
- A conclusion and suggestions regarding how the performance of a hybrid lithium-ion battery and Ultracapacitor ESS can be improved in terms of lifespan are made based on the analysis and validation discussed above.

1.9. Contributions

The research study has contributed the following:

This study addressed the challenges faced by lead-acid batteries (LABs) in meeting the growing demands of transport vehicles (TVs) and proposes a hybrid Lithium-Ion-Ultracapacitor energy storage system (ESS). Utilising MATLAB/Simulink, the research employs power-sharing strategies and two- level Fuzzy Logic Control (FLC) to enhance battery performance. Results demonstrate a substantial increase in the lifespan of Lithium-ion Batteries (LIBs) without altering their chemical composition, emphasising the potential for a minimum three-year extension in battery lifespan in the automotive industry.

The above contributions have been published as follows:

B. A. Mayingi, A. T. Puati Zau, S. P. D. Chowdhury, and L. J. Ngoma, "Design of an Improved Hybrid Lithium-Ion-Ultracapacitor Energy Storage System for Transport Vehicles," *Electric Power Components and Systems,* pp. 1-22, 2023.

1.10. Outline of final dissertation

Chapter 1: The proposed Hybrid Lithium-Ion-Ultracapacitor Energy Storage System for Transport Vehicles with Energy Management Strategy is introduced in this chapter. It also discusses the problem statement, research justification, objective, the methodology and the importance of this research.

Chapter 2: literature survey of the research project is conducted in this chapter. It outlines the functionality and elements that affect LABs lifespan, the distinction between LABs and LIBs, HESS topology, energy management system, and the specifications of SLI batteries. In this chapter, issues that affect the lifespan, storage capacity, and efficiency of Lithium-Ion with Ultracapacitors are further discussed.

Chapter 3: The research methodology of the proposed HESS with EMS in TVs is discussed. The fully-active topology DC/DC converter is designed. The Fuzzy logic controller's strategy for improving the lifespan of Lithium-Ion batteries is presented and simulated using MATLAB/Simulink software.

Chapter 4: The battery modelling and Ultracapacitor modelling are developed. Two level Fuzzy Logic Control Controller is modelled as well in this chapter.

Chapter 5: The simulation results of the suggested HESS with EMS is presented and analysed.

Chapter 6: This chapter presents the studies' conclusion and recommendation for future studies.

2. Chapter 2: Literature Review

2.1. Introduction

Most Internal combustion engines (ICEs) use lead-acid batteries (LABs) primarily for starting and lightning ignition (SLI) due to their widespread availability and affordability. However, as the rise of advanced electronic features, performance problems with LABs are being caused by the rise in load demand for transport vehicles (TVs). Batteries experience deep discharge and shorter lifespans as a result of being unable to meet load requirements. Hence, it is necessary to increase the lifespan of TV batteries.

The study aims to combine LIB and Ultracapacitor technologies using power electronic DC/DC converters to improve the lifespan of the battery. This chapter discusses the Lithium Battery Fundamentals, Hybrid Battery Energy System (HBESS), various HESS topologies, and various Energy management techniques.

2.2. Lithium Battery Fundamentals

When looking at types of electrochemical cell, Lithium-Ion batteries is a good choice due to its large standard electrode potential (3.04 V) that leads to a high operating voltage [32]. When comparing Lithium-Ion batteries to Nickel Hydride and Lead Acid batteries, the Li-Ion batteries have the benefits of high energy density (140 Wh/kg), low discharge rate and long lifespan. However, when looking at battery cost, lithium-ion battery cost is a bit higher. By using Li-Ion batteries and Ultracapacitor hybrid system, it balances its cost with its high performance [33]. Ultracapacitors have the benefits of longer cycle life, fast charging and wide operating temperature. With the use of the hybrid energy storage system (HESS), the Lithium-Ion battery and Ultracapacitor have complementary advantages [34].

Lithium-Ion batteries are the best existing technology that deliver high energy and power density, making them to be smaller than other rechargeable batteries and light in weight as shown in Figures 2.1 and 2.2. These clarify why Lithium-Ion batteries are currently mostly utilised for electronics devices like digital cameras, cell phones, computers, and video games. Lithium-Ion batteries offer several advantages over Nickel Hydride and Lead Acid batteries, including their extended lifespan and exceptional efficiency (see Figure 2.2) [35] [36].

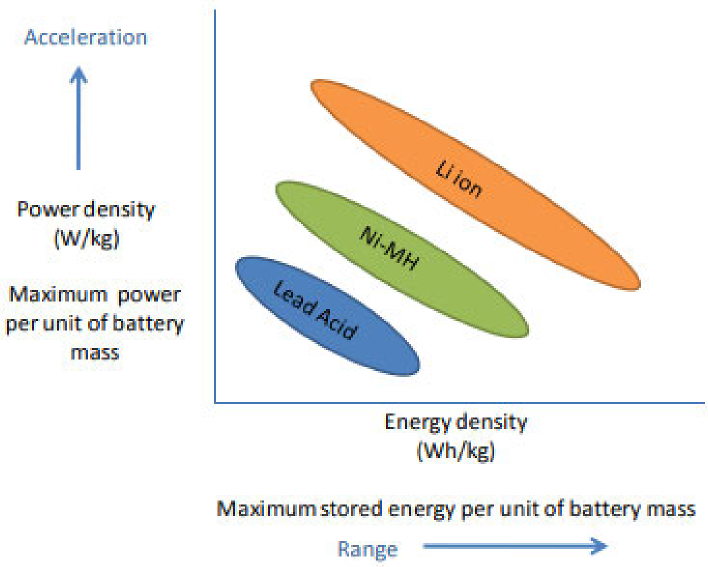

Figure 2.1. Power (acceleration) and energy (range) by battery type

Technical performance by existing battery type

Battery type	Lead acid	Ni-Cd	Ni-MH	Lithium-ion
Energy density [a] (Wh/Kg)	35	40-60	60	120
Power density (W/kg)	180	150	250-1000	1,800
Cycle life [c]	4,500	2,000	2,000	3,500
Cost ($/kWh) [d]	269	280	500-1,000	Consumer electronics: 300-800 Vehicles: 1,000-2,000
Battery characteristics	High reliability, low cost	Memory effect	Currently, best value and most popular battery for HEVs	Small size, light weight
Application	Car battery, forklift, golf cart, backup power	Replacement for flashlight battery	HEVs, replacement for flashlight battery	Consumer electronics

Figure 2.2. Technical performance by existing battery type

Lithium-Ion batteries costs have been decreasing, and at this time Li-Ion batteries have better performances compared to Lead-Acid batteries in terms of efficiency, energy density, power discharge, lifespan and charging operations [37].

Lithium-Ion batteries produce heat throughout the discharge cycle, which results in the temperature of the unit cells to extend. Once the operation temperature rises beyond the recommended temperature, it will shorten the battery lifespan. LIBs' performance depends on temperature distribution across the cells. For achieving the most effective performance of a Lithium-Ion batteries, it is necessary to provide uniform temperature distribution among the unit cells of the battery pack at an appropriate operating temperature. Therefore, in order to design a battery pack, the temperature distribution is duly taken into consideration [38].

SOC of the battery is essential to measure the battery performance, which ensures safe and reliable charge and discharge procedure [39]. Estimation of SOC must be very accurate to protect the battery from overcharging or deep discharging. This can prolong the battery lifespan. Direct measurement technique is one of the methods to measure the battery SOC. However, is not suitable for LIB due to the LIB's of the discharge curve in the middle section. This technique estimates the SOC from the discharge characteristics whereby either open-circuit voltage or loaded cell voltage is measured. Hence cell balancing becomes imperative which is achieved via active balancing. The BMS model is achieved by state-space method where state of the system is SOC while using polynomials equations to predict the Open Circuit Voltage. *Muratoglu et al.* [40] proposed using a combined dynamic battery model and the unscented Kalman filter based state of charge estimation. The lithium-ion battery is modelled with a 2nd order Thevenin equivalent circuit.

Positive electrodes for Li-ion batteries may contain phosphate materials. Thermal stability, a high current rating, and long cycling life are all advantages of lithium-iron phosphate ($LiFePO4$) [23]. These batteries can function between -30°C and +60°C and have a wide temperature range. Compared to alternative Li-Ion batteries, LiFePO4 batteries have a higher self-discharge rate. Temperature-dependent self-discharge rates are unlikely to experience a thermal runaway [23]. *Agbli et al* [19] suggestion is to use lithium-ion phosphate (LiFePO4). The LiFeP04 chemistries provide the best match for criteria, including matching the voltage window, high power density, good safety, and thermal stability. They are also widely available commercially and have a long cycling life.

2.3. Hybrid Battery Energy System (HBESS)

Lithium-Ion batteries operate more effectively, perform better, and have longer operational lives when paired with Ultracapacitors. Multi-source TVs will be improved with the use of a HESS that combines Ultracapacitors and a lithium-ion battery [5, 41-43].

According to *Castaings et al.* [13], combining a Li-Ion battery and an Ultracapacitor results in a system with a high energy-density and high power-density, a lightweight design, an extended battery life, and improved system performance. The Ultracapacitor's ideal function in this method is to maintain battery power across transients, reducing the stress on the battery and extending system lifespan.

According to *Shu et al.* [44], a high pass filter or low pass filter, which may supply power to entirely distinct energy sources, supports the management of the majority of hybrid energy storage systems. The Ultracapacitor responds to high frequency unstable power, which may increase system longevity, as opposed to the battery, which only provides power to loads at steady state. To allocate the power between the LIB and UP, a Low Pass Filter (LPF) is used. Since LIBs are low-power-density devices, they should not be subjected to deep discharge, as this can cause significant stress on the battery; a LPF is used to divide the total reference power between the LIB and UP. The LPF allocates the LIB reference power and UP reference power.

2.4. HESS Topologies

The many topology strategies for ESSs with hybrid batteries and Ultracapacitors are covered in this section. The three primary kinds of HESS topologies are passive, semi-active, and active topologies. The cost of the system, efficiency, controllability, general complexity, and rate of utilisation are some of the considerations in choosing the best topology for a certain application.

2.4.1 Passive-parallel topology approach

Comparatively speaking to other topologies, passive topology is easier to implement. As shown in Figure 2.3, the energy storages are connected to one another instead of using a dc-dc converter. It is the least expensive topology, but it cannot divide the required power between the energy sources effectively. This type of topology leads to high current peaks and may cause the internal temperature of the battery to rise in battery technology [14, 45-47], which may shorten the battery's lifespan. As a result, this configuration is not considered in this study.

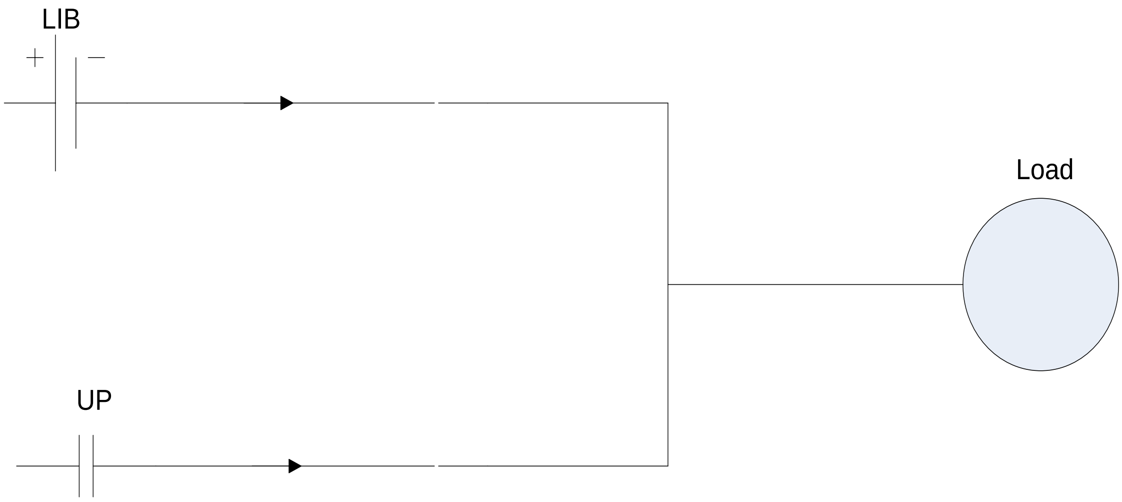

Figure 2.3. Configuration with a parallel connection between the battery and Ultracapacitor

2.4.2 Semi-active-parallel topology approach

The best option for lowering battery stress and extending battery life is the semi-active approach. The usage of a DC-DC converter with an additional control is appropriate due to the varying voltages between the two sources. As seen in Figure 2.2, this topology uses a single DC-DC converter and offers an exceptional performance and cost-effectiveness balance. This is done to regulate the current, voltage, and SOC variation that goes along with them, controlling the flow of power and energy between the ESSs [13, 14, 46, 48-50]. The drawback of this design is that, depending on whether the passive element is a battery or an Ultracapacitor, the DC bus voltage might vary widely and have a negative impact on the power quality [13, 51].

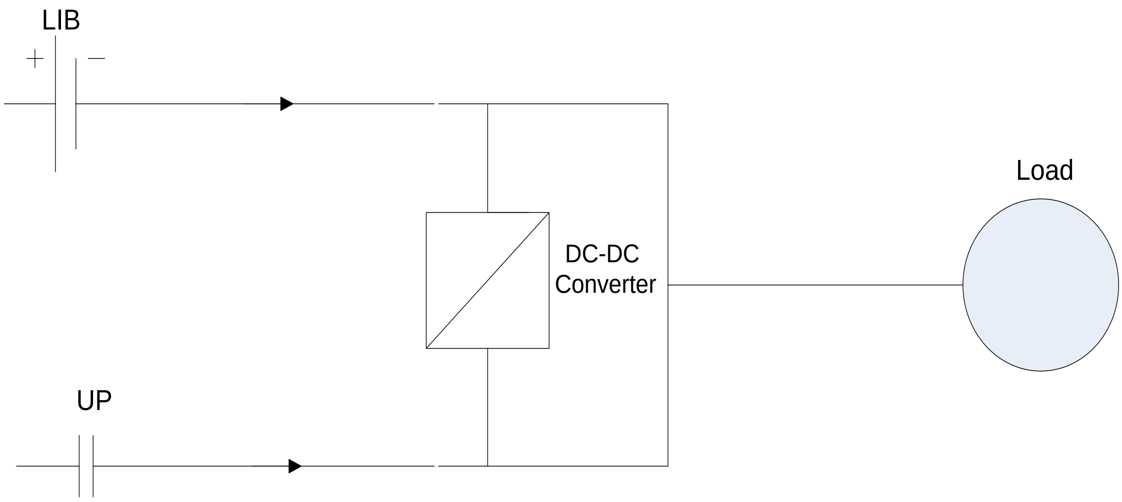

Figure 2.4. Configuration with a parallel connection between the load, an Ultracapacitor, and a dc-dc converter

2.4.3 Active-parallel topology approach

These topologies are known as fully active and fully active multi-input topology techniques. Due to its versatility, this topology uses two dc-dc converters as illustrated in Figure 2.3 to produce the best control effect [13, 14, 49, 51-53]. The drawback of this approach is that it requires a second DC-DC converter for the Ultracapacitor in addition to the one already in use for the battery. Due to the losses associated with the additional DC-DC converters, the active architecture unfortunately causes an increase in power loss across the system, increasing the cost of the system and making a more complex solution [13, 46, 48, 51].

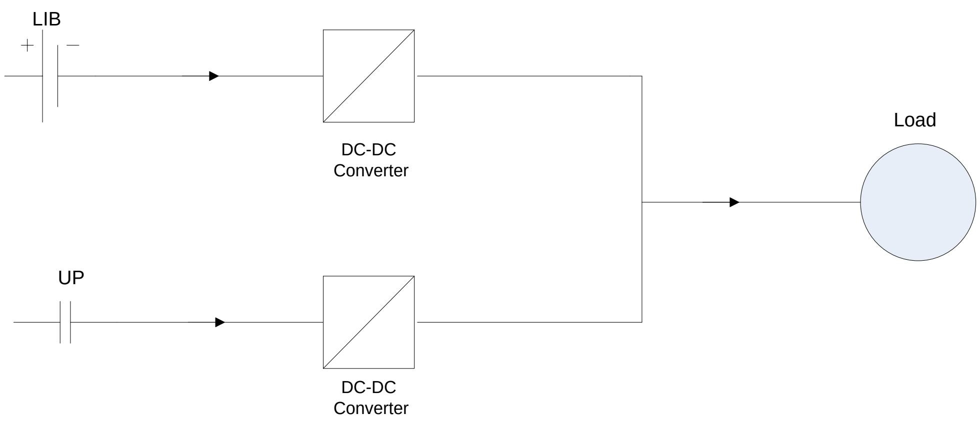

Figure 2.5. Configuration with the load and the DC-DC converter linked in parallel and series, respectively

A semi-active topology technique for a real-time bi-adaptive EMS for HESS is proposed by *Agbli et al.*[54]. The study devises a plan to address the lack of power density in energy storage systems. The results demonstrate that the proposed technique significantly decreased battery stress, improved efficiency, and minimized battery power loss. The results' ability to be demonstrated in terms of battery life, however, is limited.

A new semi-active topology concept is put out by *Zhang et al*. [28] for a battery and Ultracapacitor HESS. A unidirectional or bidirectional DC-DC converter and two extra switches are used in this design. The innovative hybrid topology easily controls the current flow through batteries. When the Ultracapacitor is fully charged, regenerative braking energy is accepted by the battery. When compared to alternative topologies, this link is inexpensive. Due to the power electronic converter's high energy consumption, they have a low charging efficiency.

An active topology that incorporates DC-DC converters is suggested by *Zhang et al.* [55] for the power management technique for electric vehicles. It is necessary to divide the load current in a buck or boost converter operation mode in order to stabilise the voltages of the ESS, where each battery is coupled in series with a DC-DC. The study demonstrated the ability of an active topology created with EMS to smooth power flow. In order to safeguard the battery from high-peak currents during charge or discharge cycles in electric vehicles, manage the level of charge as well.

Power and energy transfer between ESSs can be effectively and adaptably controlled using an active topology method. As flexible regulation of power and energy flow between ESSs is essential in this study, the research will adopt the Active topology (totally active) HESS technique based on the analysis.

2.5. Energy Management System (EMS)

Effective energy management from hybrid batteries and Ultracapacitors is crucial for improving the performance of transportation vehicles. Additionally, this increases battery lifespan under demanding working conditions and contributes to a solution for the performance and financial problems. The current solutions have been proposed in many contributing articles. This study's part provides enough information to the body of knowledge to aid in the search for an appropriate EMS that will help prolong battery life while maintaining a low cost and minimizing the weight of the hybrid system for ICE cars.

According to *Silvas et al.* [56], a thorough understanding of the existing status in design selections and optimisation method is essential before choosing the right algorithm for optimizing the design strategy for HEVs. It is suggested to employ existing methods and techniques for optimizing HEV design. Therefore, the majority of algorithms are divided into two categories for energy management systems and component control: rule-based algorithms and optimisation-based strategies.

A hybrid battery and Ultracapacitor energy management technique is put out by Fathabadi [57] and is based on a PWM control strategy for the power supply in HEVs. The experiment's findings are accurate, and at rated power, the combined efficiency of the hybrid fuel cell, battery, and Ultracapacitor power sources was above 96%. The suggested control precisely kept the voltage link between the DC-bus at constant levels. The car's range was increased to 545 km. The study compares the results to other works that have been published. To support the experimental findings, though, there are no numerical simulations. An energy management plan for a hybrid battery and Ultracapacitor is put forth by *Singh et al.* [58]; the plan is based on fuzzy logic control and pulse width modulation (PMW). This plan tries to lengthen battery life. The passive hybrid topology, which is also used in this work, has disadvantages that make it ineffective for extending battery life.

Zhao et al. [59] propose an enhanced fuzzy-based energy management strategy (EMS) for a hybrid power system in a tourist ship. This strategy integrates fuel cell (FC), photovoltaic cell (PV), battery (BAT), and Ultracapacitor (SC) as power sources. The strategy employs maximum power point tracking (MPPT) for PV optimisation, dynamic programming (DP) with wavelet analysis and PI control for power distribution, and FC for stable power output. The system achieves efficient power utilisation, extended battery and FC lifetimes, and reduced hydrogen consumption. However, the simulation results did not reveal the performance of the control technique in comparison to others.

A study to test the battery/Ultracapacitor HESS is suggested by *Zhang et al.* [60]. The study is based on a strategy with rules. The proposed study's objectives are to lengthen battery life and boost system effectiveness. These steps make up the methodology: The created current controller divides load current across energy sources first. A voltage controller also makes sure that the SoC of the Ultracapacitor swings within acceptable limits. Due to its versatility in producing high peak current, the Ultracapacitor can supply a high current frequency component while the battery can only supply a low current frequency component. According to the study's results, this lengthens battery life. Some of the study's other findings, meanwhile, make it impossible to distinguish between the current levels in a battery and an Ultracapacitor. FLC was suggested by *Marzougui et al.* [61] for the rule-based algorithm. In HEVs, a rule-based algorithm is used to distribute power among the sources and loads while taking converter losses into account. Although they are more expensive, this EMS provides greater design options. In [62], the battery's current fluctuation was reduced, and Karush-Kuhn-Tucker (KKT) conditions were used to control the power flow from the Ultracapacitor.

Mohammed et al. [63] review energy management strategies and power source sizing for fuel cell/battery/Ultracapacitor hybrid electric vehicles (HEVs). It emphasises the need for effective strategies to optimise power splitting, achieve cost-effective sizing, and minimize degradation. The study covers predictive strategies like Artificial Neural Networks, Reinforcement Learning, and Model Predictive Control. It discusses hybrid algorithms combining rule-based, predictive, real-time, and learning-based approaches for efficient energy management. The evaluation of methods based on power demand and state of charge is presented, favouring the latter for real-time management. The rule-based techniques are reviewed by *Behih et al.* [64].

It claims that whereas optimisation theory-based techniques have computational complexity, rule-based control strategies have control complexity, strong robustness, and simple implementation.

Pathak et al. [65] propose an Fuzzy logic-DPID MPPT for battery charging circuit under varying solar irradiance in between 400–1000 W/m^2. In comparison to previous research, the proposed MPPT technique contains nine fewer rules than that (*Yilmaz et al.* [66]). A fuzzy logic-based system with the fewest rules minimizes the system's complexity and computing time.

Boumediene et al. [67] address the challenge of using electric energy solely for automotive propulsion due to storage limitations. It suggests combining Li-ion batteries and Ultracapacitors for an electric scooter, optimizing energy transfer to motors. A fuzzy logic-based energy management algorithm is developed to maintain optimal states of charge, meet load demands, and enhance energy system autonomy. Simulation results in MATLAB and Simulink confirm the effectiveness of the proposed approach, presenting the fuzzy logic-based EMS as a promising solution for energy management. Overall, the results from the two sources appear to be adequate in terms of power sharing and power loss reduction.

Different forms of rule-based energy management strategies include state machines, operating modes, sliding mode controls, and fuzzy logic controls. Robust structure, optimisation, and mathematics are features of fuzzy logic control. A power management system is suggested by *Sellali et al.* [68] to regulate the ideal power-sharing between the hybrid energy sources in various modes of operation. The real-time fuzzy logic stepping control method used in electric vehicle batteries and Ultracapacitors. Additionally, it controls the DC-bus voltage. The outcomes demonstrate that the control performs effectively and produces the best results.

Fares et al. [69] introduce an integrated multiport non-isolated DC–DC converter system for combining battery–Ultracapacitor hybrid energy storage with photovoltaics in solar-powered unmanned aerial vehicles. The proposed converter achieves a significant size reduction of the Ultracapacitor while maximising energy utilisation and further reduces inductor size through phase-shifted carrier modulation. Experimental validation on a 500 W prototype demonstrates enhanced performance. The study only focused on energy efficiency and did not consider battery lifespan.

In order to increase battery lifespan, *Akar et al.* [70] suggest an EMS employing a bidirectional Multi-input converter (MIC). The plan uses a rate limiter and a fuzzy logic controller to control the UP's SoC and filter out the battery power profile. The study's results seem promising because there was a decrease in the number of unpredictable battery power peaks. As a result, battery ESS combined with EMS results increased battery lifespan.

Ghavidel et al. [71], the paper addresses the control of hybrid energy storage systems (HESS) encompassing fuel cells (FC), batteries (BA), and Ultracapacitors (SC). A filtered dynamical model for DC-DC converters is introduced to stabilise power source. A robust observer-based control method ensures stable DC-bus voltage and optimal source performance. A type-2 fuzzy algorithm for energy management compensates for uncertainties using knowledge-based rules. Stability is verified through Lyapunov analysis. The proposed approach is applied to control a hybrid tramway with FC, battery, and SC. Diverse applications. . The study did not quantify the sizing of the HESS.

An approach to power management is put out by *Jin et al.* [72] by employing a battery degradation model based on fuzzy logic control. A battery deterioration model is used in the investigation. As a result, the study established a link between battery discharge/charge behaviour and how long batteries last. According to the study's findings, the control approach can cut down on battery deterioration by 17%.

Robayo et al. [73] propose an energy management in hybrid battery-Ultracapacitor energy storage systems (ESSs) for electric vehicles. It highlights the importance of efficient power distribution by matching the dynamic nature of each ESS through Discrete Wavelet Transform (DWT)-based real-time energy management. However, delays caused by DWT signal processing can impact hybridisation benefits. The study analyses SC's contribution in mitigating battery usage with and without time delay compensation using demand prediction. Different DWT-based energy management strategies are evaluated, emphasising energy circulation and SC assistance during acceleration and braking. Simulation results under different driving cycles demonstrate that compensating for time delay enhances SC assistance, but adding demand prediction complexity doesn’t significantly improve SC performance.

Anitha et al. [74] suggest a system using a fuzzy logic control to optimise the BMS while using a non-linear, time-varying model for charging and discharging the battery. Setting the minimum and maximum SoC limits on the battery allows for control by preventing deep discharge and overcharging. The findings demonstrate that the suggested fuzzy logic control can regulate SoC, lengthening battery life as a result.

Using two connected DC-DC converters, *Oukkacha et al.* [75] suggest an energy management system for electric vehicles (Evs) to regulate the flow of energy between lithium-ion batteries and ultracapacitors. The anti-windup PI controller is used to achieve control, allowing the ultracapacitor to handle dynamic loads while the battery manages constant loads with no fluctuations. The system employs a Voltage-Source-Inverter (VSI) that is powered by the suggested hybrid system and controls a Permanent Magnet Synchronous Machine (PMSM). By preventing fluctuations throughout the battery’s discharge/charge cycles, this energy management lengthens its lifespan.

Movahhed-Ghodsinya et al. [76] The study focuses on electric vehicles (Evs) as a solution for clean transportation, emphasising the role of energy storage systems in improving EV energy efficiency and distance. Batteries are the main energy source in Evs, with potential auxiliary sources like ultracapacitors. The research proposes a fuzzy optimised controller for energy management in a hybrid vehicle equipped with a fuel cell, battery, and ultracapacitor. The simulation demonstrates that the proposed control strategy effectively provides required vehicle power for standard driving scenarios and optimally distributes power among different sources.

Yi et al. [77] develops an energy management strategy (EMS) for hybrid energy storage electric vehicles, aiming to optimise power distribution between batteries and ultracapacitors to reduce power consumption and battery degradation. The study employs Pontryagin's minimum principle (PMP) and a battery degradation model to create an effective EMS. A hybrid energy storage vehicle model is established, and a rule-based approach and PMP optimisation algorithm are utilised for power allocation. Simulation experiments using urban driving conditions validate the EMS, demonstrating lower energy consumption and battery deterioration rates compared to a rule-based method.

Two EMS components that are based on optimisation-based and rule-based techniques are contrasted in the energy management plan proposed by *Castaings et al.* The crucial aspect of both approaches is that the difference in current between the battery and ultracapacitor is less than 5%. The proposed study uses two DC-DC power electronic converters for the investigation, which has a substantial impact on the vehicle's costs.

Kachhwaha et al. [78] address challenges in electrical energy storage with the increasing use of green energy and growing demand for electric vehicles (Evs) with extended range. To address the limitations of single power sources, a hybrid energy storage system (HESS) combining chemical batteries and Ultracapacitors is proposed. The study explores the benefits of using Ultracapacitors to meet dynamic EV load characteristics and presents a HESS technique for regulating active power in low-powered EV simulations. Simulation results in MATLAB/Simulink show efficient DC link voltage regulation, reducing battery stress and extending battery life. The results show that the proposed system can control SoC and increase the lifespan of the battery.

The fuzzy logic control as indicated in [79] is suitable for complex systems and has a more resilient structure, more design freedom, and more robustness against system uncertainties. Fuzzy logic control is employed as the energy management method in the algorithm proposed by *Truong et al.* [17] in order to properly distribute power to the battery and Ultracapacitor. In order to boost efficiency, extend lifespan, and lower costs, it focuses on how to run every component in its best possible state. An optimal mapping fuzzy logic control is systematically developed based on a self-tuning methodology to generate the optimised parameters of all devices, hence altering power-sharing, in order to address these issues.

Lei et al. [80] address energy management strategies for fuel cell/battery hybrid electric power systems (HEPS) in high-altitude unmanned aerial vehicles (UAVs). Different strategies, including rule-based and fuzzy logic control, are proposed to enhance efficiency and fuel economy. Fuzzy logic (FL) shows improved robustness to power fluctuations but relies on heuristic methods. An improved FL strategy incorporating particle swarm optimisation (PSO) is suggested, aiming to optimise membership function thresholds and minimize hydrogen consumption. Simulations and experiments on a UAV mission profile validate the proposed strategies, highlighting the PSO-FL algorithm’s potential to improve fuel economy and dynamic performance.

The fundamental issue in fuzzy logic control design is how to properly tune scaling factors, control rules, and membership functions in order to achieve the controller’s best performance. *Pathak et al.* [81] proposed a robust rule basis for PID-type fuzzy control. The rule-based structure system has successfully attained all the properties including continuity, completeness, interaction, and consistency.

According to *Wang et al.* [15], a DC-DC converter can be used to regulate the charging and discharging of a battery and an ultracapacitor using a half-bridge topology. The DC-DC converter can be used in boost or Buck modes. When the system is depleted, the bidirectional DC-DC converter operates in boost mode; when the system is charged, it operates in buck mode.

To manage the transient peak-power and high-frequency portions of the overall power demand, Ultracapacitors must be used [31]. A hybrid energy storage system with an active topology is proposed by *Jaarsveld et al.* [14]. (HESS). The method relies on a topology with two DC-DC converters that is active (Buck and Boost converter). It discusses rule-based strategies and fuzzy logic for controlling the system's DC-DC converters, whilst a rule-based control strategy is employed to regulate the battery-Ultracapacitor HESS's working state. Table 2.1 shows the comparison of different energy management strategy [51, 82-92].

Table 2.1. Advantages and disadvantage of different EMS

EMS	Advantages	Disadvantages
Rule- Based	Easily applied in Off-line and Online applications simple implementation, high calculation efficiency, great robustness, and quick experimental validation.	• Is not flexible. • It delivers inadequate dynamic adaptability in varying load circumstances, not ensuring the desired performance under various driving conditions.
Fuzzy Logic	Flexible design that works well for complex systems	In a controller, a robust structure, optimisation, and mathematical manipulation take up time and memory.
Optimisation –based.	• Used to test the viability and efficiency of complicated systems. • It is wise to distribute power among various storage devices and reduce cost function during driving cycles.	• Computational complexity. • Not used for online applications. • Not used in real-time drive cycles.
Dynamic Programming	• Efficiently solves problems with optimal substructure • Reducing time complexity and enabling versatile applications. • great technique for reducing costs over the course of the driving cycle in a complex system	• Complexity in formulation, • High memory usage, and • Limited applicability to problems not exhibiting optimal substructure.

2.6 Summary of Findings:

Internal Combustion Engine cars (ICE cars) mostly use Lead-Acid Batteries (LABs) for cold cranking current and as backup storage. However, with the increase load demand in transport vehicles, Lead-Acid (LABs) batteries experience performance failure because of deep discharges and as a result it damages and reduce their lifespan. For high energy and power density, Lithium-Ion batteries (LIBs) are far better than LABs. However, the Lithium-Ion batteries (LIBs) are costlier than LABs. With the use of Li-Ion batteries and Ultracapacitor hybrid system, it will balance its cost with its high performance since a smaller LIB will be needed for the hybrid storage system. Thus, this research seeks to extend battery lifespan by using a HESS based on LIB and Ultracapacitor to improve the ESS power, increase lifespan and to minimize the weight of the hybrid system.

The different types of lithium-ion batteries were studied and analysed, and most authors proposed the utilisation of Lithium-Ion Phosphate as they are the most suited for SLI applications, they offer sensible chemistry performance with low resistance, high current rating and long lifespan. LiFePO4 batteries have a higher self-discharge than alternative Li-Ion batteries. It is concluded that LiFePO4 battery is the best option for transport vehicles and are used for the research study.

The simplest and cheapest topology to implement is the passive topology. However, it cannot effectively split the power between the energy sources. Also, it is difficult to utilise Ultracapacitor effectively for maximum efficiency. And Semi-active topology has been acknowledged to be crucial for energy saving, minimizing the cost, reaching high overall efficiency and increasing system dynamics. However, the Semi-active have limitation of not been able to control the current flow during the charging and discharging modes of the two batteries in different driving conditions. A fully active topology approach provides effective and flexible control of power and energy flow between ESSs. Based on the analysis, this research adopts the Active topology (fully active) HESS method for this study, as flexible control of power and energy flow between ESSs is crucial in this study.

Various EMS studies are discussed, with a focus on Dynamic Programming (DP), Rule- Based, Optimisation –based and Fuzzy Logic Control. The following was determined after review:

1. Dynamic Programming (DP): DP is a great technique for reducing costs over the course of the driving cycle in a complex system. It is still challenging because of its computational complexity and lack of application in online or real-time drive cycles.
2. Optimisation –based: utilised for testing system viability and efficiency, optimizing power distribution across storage devices to minimize costs during driving cycles. However, it faces challenges with computational complexity and is unsuitable for real-time or online applications.
3. Rule- Based: Dynamic Programming offers straightforward implementation, high computational efficiency, robustness, and quick validation. However, it lacks flexibility and dynamic adaptability under varying load and driving conditions, potentially impacting performance consistency.
4. Fuzzy Logic Control (FLC): FLC consumes memory and time in the controller. But its ease of design and implementation in intricate systems is attributed to its flexibility. In reference to the proposed HESS, FLC has a minor edge over DP based on review.

The following justifications support FLC's proposal for the research:

- Simple to design
- Indicates human intelligence in the controller
- Cost-effective
- Does not require mathematical modelling of the system

- Uses linguistic variables instead of numerical values
- Easily handles system non-linearity
- Provides fast system response
- Achieves a high degree of accuracy

2.7 Contribution to Knowledge

In this research, a controller for an active HESS that uses fuzzy logic controllers to regulate the DC/DC converters is designed. The written contributions include:

- Development of a hybrid LIB and UP ESS that will have a high storage capacity and longer lifespan at a reduced weight compared to a single LAB ESS.
- Development of a two-level FLCs to control power flow in a hybridised LIB and UP ESS, to enable effective power sharing among the hybridised LIB and UP ESS.

2.8 Conclusion

This research presents the study of the battery and Ultracapacitor fundamental, hybrid battery-Ultracapacitor topologies and energy management system (EMS) for transport vehicles from published literature. Different hybrid energy storage systems approaches were analysed to estimate the lifespan of the battery and identified some of the most efficient and robust schemes.

Several articles offer the currently proposed solutions. However, there is currently no single battery technology that can meet the power requirements of TVs, be lightweight, and extend battery life all at once. This is a gap in the battery-Ultracapacitor HESS research. As a result, this research study seeks to design a hybrid Lithium-Ion-Ultracapacitor Energy storage system (ESS) that will have a high storage capacity and longer lifespan at a reduced weight compared to a single LAB ESS. Furthermore, there exists no literature that has applied two-level FLCs to control power flow in a hybridised LIB and UP ESS, to enable effective power sharing among the hybridised LIB and UP ESS.

The incorporation of EMS within the hybrid energy storage system is significant to ensure that each energy source operates within its parameter's restrictions and most importantly shield the battery from high current pulses. This is achieved by the control algorithms within the EMS which distributes the demanded power amongst the sources according to their strengths. This research seeks to develop an improved hybrid lithium- ion – Ultracapacitor energy storage system with EMS. The full-active topology with EMS based of two bidirectional dc-dc buck-boost converters, two level FLCs will be developed. The proposed strategy is expected to increase the lifespan of the batteries without changing the current chemical composition of the batteries.

3 Chapter 3: Methodology

3.1 Introduction

This chapter describes the modelling of electrical circuits for Lithium-Ion batteries, Ultracapacitors, and electronic power converters. It also covers the sizing of the hybrid system, weight comparison between a single lead-acid battery and the hybrid system, minimum and maximum State of Charge (SOC) limitations during charging/discharging modes, the proportion of current sharing between the hybridised batteries, and finally, the simulation of the proposed Hybrid Energy Storage System (HESS) with the Energy Management System (EMS). Fuzzy logic, using two-level Fuzzy Logic Controllers (FLCs), makes up the full-active topology of the EMS, developed using MATLAB/Simulink software (version 2021a). FLC 1 provides the total reference power to start the Internal Combustion Engine (ICE) and charge the energy storages based on the power demand while ensuring that the State of Charge (SOC) remains within the minimum and maximum battery range. FLC 2 is responsible for allocating complete control and managing the reference power of the energy storage (Lithium-ion and Ultracapacitor).

3.2 Vehicle electric power flow system

The ICE is used as the primary energy source for the vehicle's electric system in this research. It converts chemical energy into mechanical power (Pice). The mechanical power generated is split into two parts: drive power (Pdr), which is utilised for propulsion, and alternator (Palt), which receives it and transforms it into electrical power. As seen in Figure 3.1, the alternator typically produces energy to meet the power demand (PD) for charging the HESS as required. The circuit developed is based on an analogy described by [2].

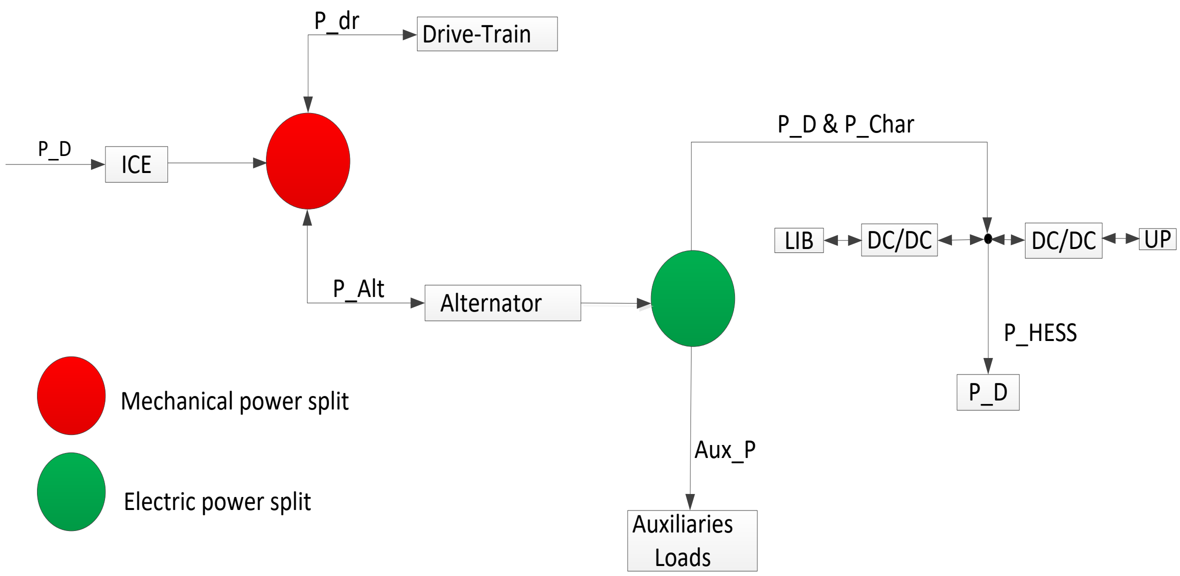

Figure 3.1. Electric power flow system with HESS in Transport vehicle

Splitting the load current in buck-boost converter mode of operation enhances the study's capacity to stabilise the voltages of the ESS. A fully-active topology is the recommended choice, as it enables effective and adaptable control of power and energy transfer between ESSs. To minimize losses, the load bus connects to both the LIB and UP through interconnected dc-dc converters, each in series with another dc-dc converter. The topology of the current flow during charging is shown in the Figure 3.2.

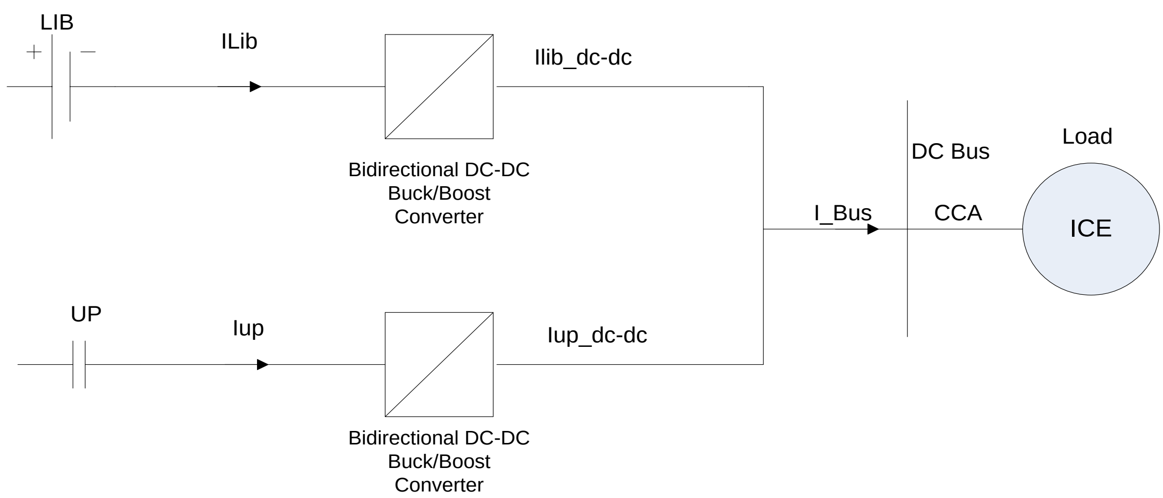

Figure 3.2. Topology of the HESS charging electrical power system for TVs.

3.3 Lithium-Ion modelling

The simplest and most common way for describing the dynamic behaviour of a lithium-ion battery is an equivalent circuit model. This approach was recommended because it provides one of the most precise values between the needs for battery computation and the approximate accuracy of voltage [93, 94]. The suggested research project makes use of the MATLAB/Simulink library's lead-acid and lithium-ion battery models. This battery already had the settings modified to match the specifications of the commercial battery recommended for the research study. According to the literature [93-95] and based on Figure 3.3, the battery parameters were estimated.

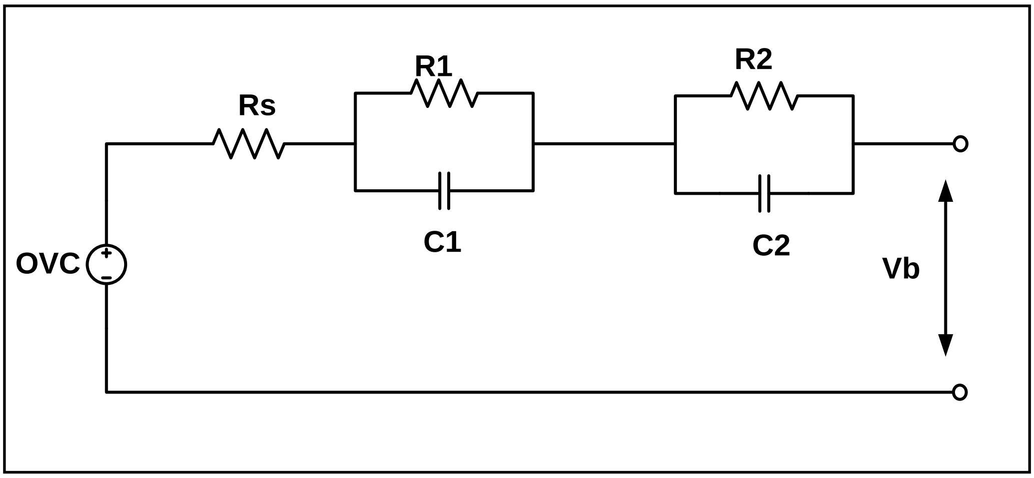

Figure 3.3. Battery equivalent circuit [95]

The model consists of a DC voltage source, two RC parallel circuit networks, and a series DC internal resistance (also known as ohmic resistance). Internal DC resistance is displayed through series resistance. When a current is applied to the battery cell, this resistance causes the voltage to drop immediately. The model open circuit voltage (V_{OC}) of a battery cell is displayed using a DC voltage source or controlled voltage source.

Two RC parallel networks were used to determine the terminal voltage's transient response. The double layer capacitance and the charge transfer processes were modelled using the prime RC network (R1 and C1), which also reveal the small-time constant of the battery cell feedback.

The secondary RC network (R2 and C2) was used to model the diffusion processes and showed the long-time constant of the battery cell feedback. The parameters of the examined model were dependent by temperature, SOC, and current. Figure 3.3 shows the equivalent circuits (RC network) models.

A subsystem is designed for the determination of the SOC. Current and initial SOC were considered as inputs to the subsystem. Capacity is considered as a function of current.

Additionally, the battery SOC is calculated as shown in Equation (3.1):

$$\mathrm{SoC} = \frac{\mathrm{Q(t)}}{\mathrm{Q_{batt}}} \tag{3.1}$$

where Q(t) is the storage capacity at time (t) and $\mathrm{Q_{batt}}$ is the rated battery capacity.

The dynamic equation shown below can be used to further re-express the SOC stated in equation (3.1):

$$\mathrm{SoC(t)} = -\frac{\mathrm{i_b(t)}}{3600 \times \mathrm{Q_{batt}}} \tag{3.2}$$

where $\mathrm{i_b(t)}$ is the amount of current going into the battery, which, according to Equation (3.2) above, is expected to be positive when the battery is being discharged and negative when it is being charged.

Equation (3.3) from Figure 3.3, which describes the steady-state condition, is utilised to determine parameters R1, R2, using the experimental battery findings

$$R_1 = \frac{V_1 - V_2}{I} \; R_2 = \frac{V_2 - V_3}{I} \tag{3.3}$$

The following equation from Figure 3.1 is used to determine the DC transient voltage across the two RC parallel branches as shown in Equation (3.4):

$$V_1 = \left(\frac{1}{S}\right)\left[\frac{\mathrm{I}}{C_1}\ \frac{V_1}{C_1 R_1}\right] \; V_2 = \left(\frac{1}{S}\right)\left[\frac{\mathrm{I}}{C_2}\ \frac{V_2}{C_2 R_2}\right] \tag{3.4}$$

V_{RS} Calculation, V_{RS} refers to the voltage reduction from Rs. The amount of V_{RS} was considered as a function of SOC, current, and temperature. Accordingly, a 2-D lookup table was used to demonstrate the amount of Rs. The amount of VRS could be easily determined by employing Equation (3.5):

$$V_{RS} = I \; X \; R_S \tag{3.5}$$

Therefore, the battery terminal voltage is given by Equation (3.6) as follows:

$$V_b = OCV - V_1 + V_2 + V_S \tag{3.6}$$

The following equation is used to get the battery current:

$$\mathrm{I_b} = \frac{\mathrm{V}}{\mathrm{R}} + \mathrm{sCV} \tag{3.7}$$

3.4 Ultracapacitor Modelling

For various vehicle purposes, several battery sizes are produced. In order to reduce weight and expense, it is crucial to choose a battery/ultracapacitor hybrid system that can replace the whole battery. According to the literature [1, 96], the following formulas were used to determine the UP parameters.

3.4.1 Case one

For a Battery Vehicle with 40Ah the following parts are utilised in a battery/Ultracapacitor hybrid system to supply the same amount of power and energy to a typical vehicle:

$$Capacity = \frac{Q \times V}{3600} \tag{3.8}$$

$$Ah = \frac{500\,F \times 15\,V}{3600} = 2.08\,Ah$$

$$\frac{500\,F}{x} = \frac{2.08\,Ah}{40\,Ah}$$

$x = 9615.385\, F$

For

$$10\ Ah = \frac{9615.382}{40} \times 30 = 7211.54\ F$$

Therefore, a 10Ah battery with 7500F Ultracapacitor Capacitance can suffice the vehicle power and energy requirement.

By assuming that a 10Ah battery will be used instead of a 40Ah battery, the vehicle's needs can be met by integrating a 10Ah battery with a 7500F Ultracapacitor.

Table 3.1. HESS parameters summary for case one

Device	Parameter	Value
LIB	Output Voltage	12V
	Capacity	10Ah
UP	Output Voltage	12V
	Rated Capacitance	7500F

3.4.2 Case two

A Battery Vehicle with 70Ah, similar steps (using equation 3.1) are taken for cars powered by 70Ah batteries.

$$Ah = \frac{500\ F \times 15\ V}{3600} = 2.08$$

$$\frac{500\ F}{x} = \frac{2.08\ Ah}{70\ Ah}$$

$x = 16826.923$

For

$$20\ Ah = \frac{16826.923}{70} \times 50 = 12019.23\ F$$

The vehicle requirement can be met by integrating a 20Ah battery with a 12000F Utracapacitor.

Table 3.2. HESS parameters summary for case two

Device	Parameter	Value
LIB	Output Voltage	12V
	Capacity	20Ah
UP	Output Voltage	12V
	Capacitance	12000F

3.4.3 Case three

For a Battery Vehicle with 90Ah, a battery/Ultracapacitor hybrid system is used to give a normal car the same amount of power and energy.

$$Ah = \frac{500F \times 15V}{3600} = 2.08$$

$$\frac{500F}{x} = \frac{2.08Ah}{90\ Ah}$$

$$x = 21634.615 \approx 21700\ F$$

For

$$25\ Ah = \frac{21700}{90} \times 65 = 15672.22\ F$$

If a 25Ah battery is used instead of a 90Ah battery, the vehicle's needs can be met by integrating the 25Ah battery with a 15500F ultracapacitor.

Table 3.3. HESS parameters summary for case three

Device	Parameter	Value
LIB	Output Voltage	12.2733V
	Capacity	25Ah
UP	Output Voltage	12V
	Capacitance	15500F

3.5 HESS VS Single LABs weight comparison

The single LABs 12V-50Ah, 12V-70Ah, and 12V-90Ah made by Auto X Powertech South Africa will be replaced by the proposed HESSs. Table 3.4 summarises the SLABs specifications.

Table 3.4. SLABs specifications

Technology	LAB (90Ah)	LAB (70Ah)	LAB (40Ah)
Voltage	12 V	12 V	12 V
Storage Capacity	90 Ah	70 Ah	40 Ah
CCA	650A	590A	350A
Weight	**24 kg**	**21.6 kg**	**14.5 kg**

3.5.1 Case one

Case 1 of the proposed research is to replace single 12V-40Ah LAB with the proposed HESS. This battery is normally used in small vehicles where the required CCA for 3-4 seconds is 330A.

Table 3.5. SLAB parameters for case one

Device	Parameter	Value
LAB	**Weight**	**12.5 kg**

Table 3.6. HESS parameters for case one

Device	Parameter	Value
LIB (12V-10Ah) [82]	Weight	$Series\_connection = 3$ batteries of 4.2 V (12.6V total voltage) $Parallel\_connection = 4$ batteries of 2.6 A (10.4A total current) $Total\ number\ of\ batteries\ =\ 12$ $Single\ LIB =\ 46.5g$ $Total\ weight =\ 12\ \times\ 46.5 = \mathbf{558g}$
UP (12V- 7500F)	Weight	$Series\_connection = 5$ Ultracapacitors of 2.7 V (13.5V total voltage) $Parallel\_connection = 2$ Ultracapacitors of 3000F (6000F total capacitance) $Parallel\_connection = 3$ Ultracapacitors of 500F (1500F total capacitance) $Single\ 2.7v = 475g\ (10)$ $Single\ 2.7v5 = 79g\ (15)$ $Total\ weight = \mathbf{5.985kg}$

The proposed HESSs weighed less than the Single Lead-acid battery. The HESSs reduce the weight of the storage system by 5.851 kg, it will reduce the vehicle's weight, consequently lowering fuel consumption.

3.5.2 Case two

In case two, the proposed research is to replace the single 12V-70Ah LAB with HESS. This battery is normally used in midsize vehicles which have required CCA for 3-4 seconds is 580A.

Table 3.7. SLAB parameters case two

Device	Parameter	Value
LAB	Weight	**21.6 kg**

Table 3.8. HESS parameters for case two

Device	Parameter	Value
LIB	Weight	Series-connection=3 batteries of 4.2 V (12.6V total voltage) Parallel-connection=8 batteries of 2.6 A (20.8A total current) $Total\ number\ of\ batteries\ =\ 24$ $Single\ LIB\ =\ 46.5g$ $Total\ weight\ =\ 24\ \times\ 46.5 = \mathbf{1.1kg}$
UP	Weight	$Series\_connection = 5$ Ultracapacitors of 2.7 V (13.5V total voltage) $Parallel\_connection = 4$ Ulracapacitors of 3000F (12000F total capacitance) $Total\ number\ of\ UPs\ =\ 5 \times 4 = 20$ $Single\ 2.7v = 475g\ (20)$ $Total\ weight\ =\ 20\ \times\ 475 = \mathbf{9.6kg}$

The proposed HESSs weighed less than the Single Lead-acid battery. The HESSs reduce the weight of the storage system by 10.9 kg, it will reduce the vehicle's weight, consequently lowering fuel consumption.

3.5.3 Case three

In this case, the proposed HESS is to replace single 12V-90Ah LAB with the proposed HESSs. This battery supplies the required CCA of 630A for 3-4 seconds.

Table 3.9. SLAB parameters for case three

Device	Parameter	Value
LAB	Weight	**25 kg**

Table 3.10. HESS parameters for case three

Device	Parameter	Value
LIB	Weight	Series-connection=3 batteries of 4.2 V (12.6V total voltage) Parallel-connection=10 batteries of 2.6 A (26A total current) $Total\ number\ of\ batteries\ =\ 30$ $Single\ LIB\ =\ 46.5g$ $Total\ weight\ =\ 30\ \times 46.5 = \mathbf{1.4kg}$
UP	Weight	Series-connection=5 Ultracapacitors of 2.7 V (13.5V total voltage) Parallel-connection=5 Ultracapacitors of 3000F (15000Ftotal capacitance) Parallel-connection=1 Ultracapacitors of 500F $Total\ number\ of\ UPs\ =\ 5 \times 5 = 25$ $Single\ 2.7v = 475g\ (25)$ $Single\ 2.7v50 = 79g\ (5)$ $Total\ weight = \mathbf{12.3kg}$

The proposed HESSs weighed less than the single Lead-acid battery. The HESSs reduce the weight of the storage system by 11.2 kg, it will reduce the vehicle's weight, consequently lowering fuel consumption.

According to the calculations above, it is evident that the battery can be replaced out for a hybrid battery-Ultracapacitor system that is lighter and still produces the same amount of power. The system's benefits include the smaller battery size. Lessens the weight of the car, and since Ultracapacitors can rapidly produce high currents, the battery will be relieved of some of the strain experienced during engine starting. This will prevent a deep discharge of the battery.

3.6 Hybrid LIB and UP Energy Storage Modelling

The HESS modelling and its associated parameters are covered in this subsection and is further elaborated in the reference [2] . The operating points of the battery technology in a HESS rely on how the current is divided among them.

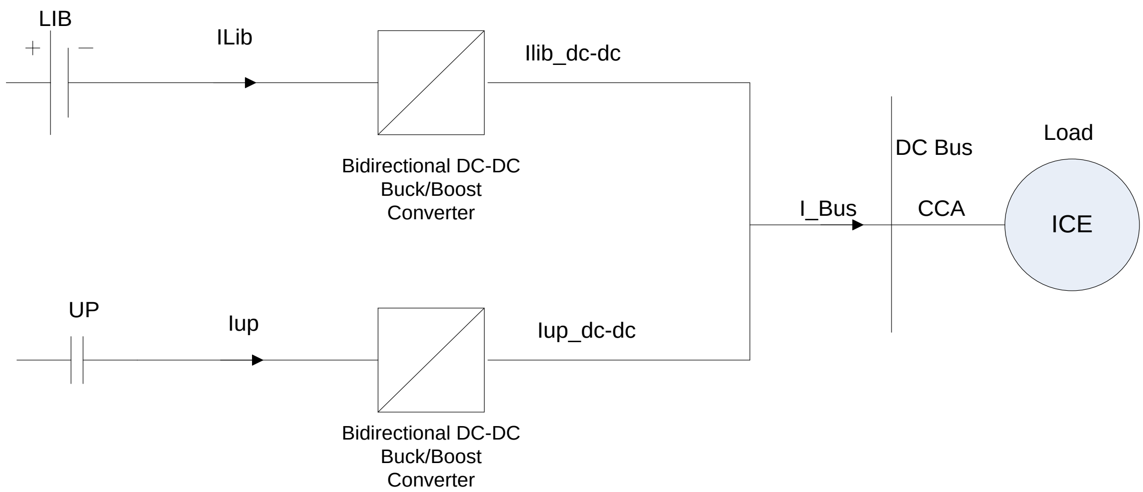

Figure 3.4. The present flow of the proposed HESS architecture

The total required power is allocated between the LIB and Up. The reference power is used to control the bidirectional DC/DC buck and boost converters for charging and discharging of HESS. Based on the [2, 14], Since the battery response is lower than of Up, the reference power during cracking is allocated based on the following equation:

$$P_{LIB_{Ref}} = P_D \times K \tag{3.10}$$

$$P_{Up_{Ref}} = P_D \times (1 - K) \tag{3.11}$$

Where the power demand is calculated as follows:

$$P_D = P_{LIB_{Ref}} + P_{U_{Ref}} \tag{3.12}$$

Where,

P_{LIB_Ref} is the LIB reference power.

P_{Up_Ref} is the Up-reference power.

K is partition coefficient.

The charging of the LIB and Up is done by the alternator, when the alternator produces enough power, it supplies the vehicle and same time charges the energy storages. Figure 3.5 Shows the TVs electrical system topology of the current flow during charging and is further elaborated in [2].

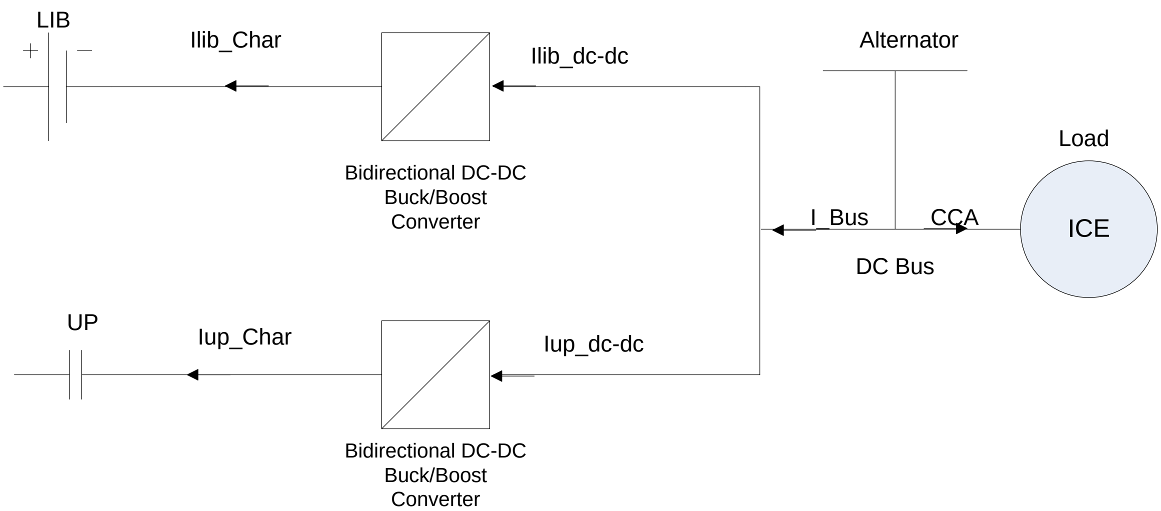

Figure 3.5. Topology of TV electrical power system when HESS charges.

From Figure 3.5, based on the references[2, 14] the charging current and power are calculated as follows:

$$I_{alt}(t) = \mathrm{I}_{\mathrm{HESS}_{\mathrm{Char}}}(\mathrm{t}) + \mathrm{ICE}(\mathrm{t}) \tag{3.13}$$

$$I_{HESS_{Char}}(t) = \mathrm{I}_{\mathrm{alt}}(\mathrm{t}) - \mathrm{ICE}(\mathrm{t}) \tag{3.14}$$

And the following formula is used to get the charging power:

$$P_{HESS_{Char}}(t) = P_{alt}(t) \; - \mathrm{P}_{\mathrm{ICE}}(\mathrm{t}) \tag{3.15}$$

3.7 Energy Management Strategy

The operating of the proposed research study is done by the EMS. The modelling of the EMS is done based on the characteristics of the energy sources.

3.7.1 Fuzzy Logic Control Design

Fuzzy logic was chosen as a viable control architecture to regulate both DC/DC converters since fuzzy logic does not require a precise mathematical model or transfer function of the system and is tolerant of inaccurate data. Figure 3.6 depicts the fuzzy logic control structure that was employed in this study. A fuzzifier, a fuzzy rule base, a fuzzy knowledge base, an inference engine, and a defuzzifier are the main parts of an FLC system. It also has normalisation-related parameters. The fuzzifier in place transforms sharp values into fuzzy ones. In the fuzzy rule basis, knowledge is kept. It also comprises the membership functions that provide the output variables for the controlled plant and the input variables for the fuzzy rule base. The core of an FLC system is the inference engine, which can replicate human decisions by applying approximation reasoning to arrive at the appropriate control strategy. An inferred fuzzy control action by the inference engine is transformed into crisp quantities by the defuzzifier.

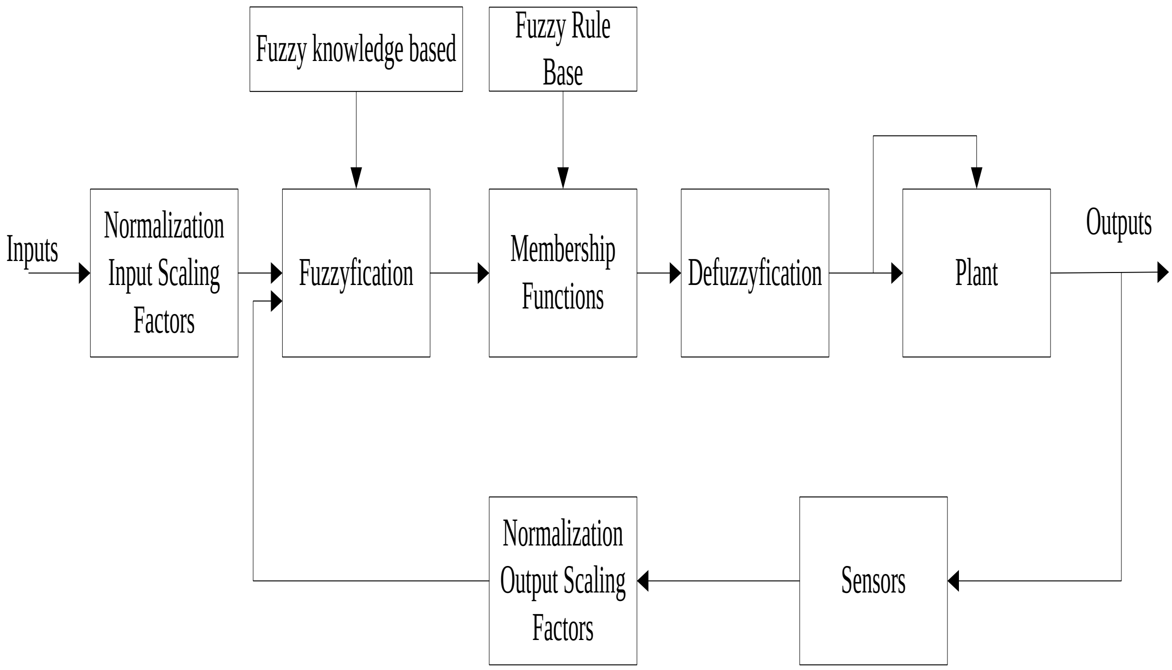

Figure 3.6. Fuzzy Logic Control Structure

3.7.2 Fuzzy Logic Controller based on total reference power charging and discharging conditions

The primary aim of FLC is to determine the total reference power (PD_p_{Ref}) based on the power demand (P_{Demand}) while ensuring the LIB SoC is within the minimum and maximum range. Secondly, is to allocate the reference LIB ($PLib_{\_Ref}$) and Up (($PUp_{\_Ref}$) power based on the total reference power by trigging the bidirectional dc-dc buck and boost converters. The proposed EMS based on FLC with rule-based uses two levels of FLCs. The FLC 1 as is shown in Figure 3.7, is designed to provide the total reference power ($PD_{\_Ref}$) to start the ICE and to charge the energy storages based on the power demand, while ensuring that the SOC is within the minimum and maximum range. The minimum and the maximum range of the battery protects the battery from over charging and deep discharging.

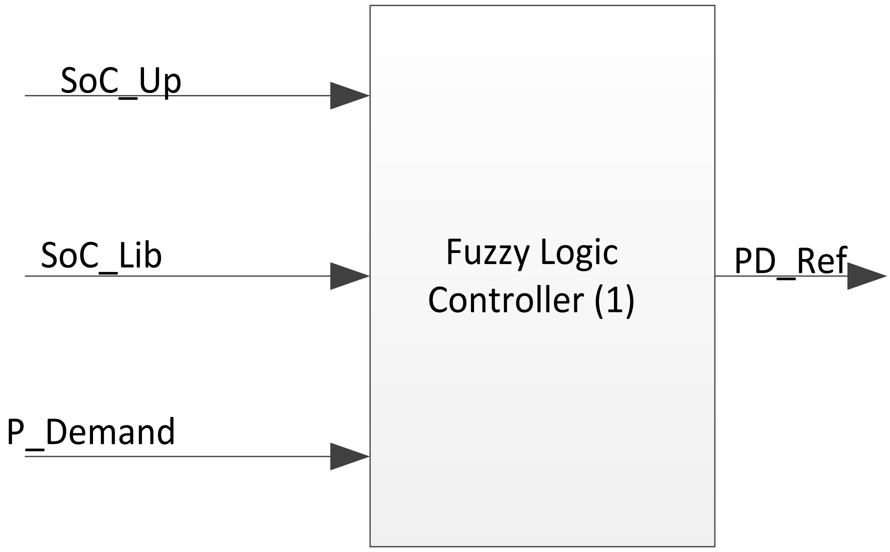

Figure 3.7. Fuzzy Logic Controller 1

To allocate the power between the LIB and UP, a Low Pass Filter (LPF) is used. Since the LIB is a low power density device, as well should not be expose to deep discharge which would cause stress on LIB; a LPF is used to divide the total reference power ($PD_{\_Ref}$) between the LIB and UP. The LPF allocates the LIB reference power ($PLib_{\_Ref}$) and UP reference power ($PUp_{\_Ref}$). The output of the LPF is used as the LIB reference power ($PLib_{\_Ref}$) and the difference between the total reference power ($PD_{\_Ref}$) with LIB reference power ($PLib_{\_Ref}$) which is $\pm 40\%$ is allocated to UP reference power ($PUp_{\_Ref}$). The transfer function of the LPF is shown in Equation 3.16.

$$G_f = \frac{2\pi f_{cf}}{s + 2\pi f_{cf}} \tag{3.16}$$

Where, f_{cf} is the cutoff frequency (1Hz).

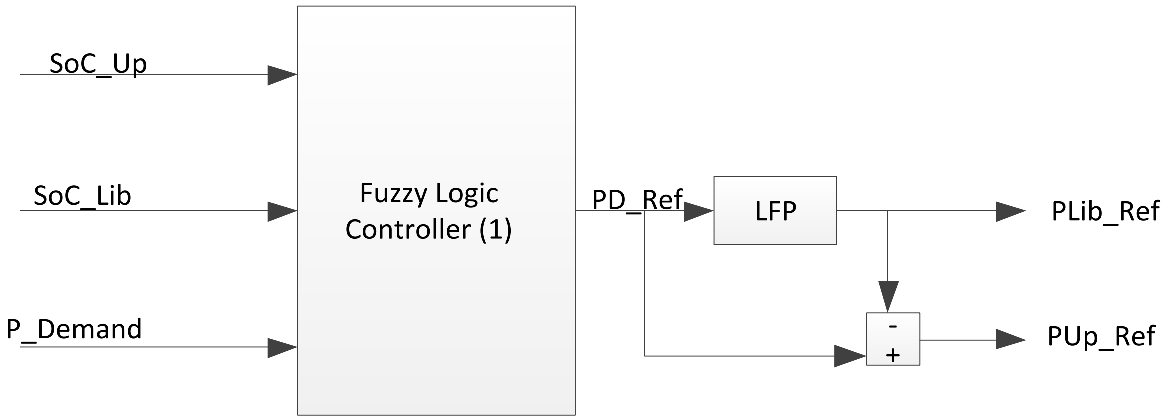

Figure 3.8. Fuzzy Logic Controller 1 and LPF

3.7.3 Fuzzificaton FL1

The proposed FLC 1 uses three input variables ($\mathrm{SoC_{UP}}$,$\mathrm{SoC_{Lib}}$ and $\mathrm{P_{Demand}}$), where the $\mathrm{P_{Demand}}$ is the power demand which varies based on the type of the vehicle. The $\mathrm{SoC_{UP}}$ and $\mathrm{SoC_{Lib}}$ are the SoC of the UP and LIB which determine the reference power demand that the energy storages supplies. The proposed studies are done in three cases having different power demand and difference sizes of the energy storages. The input membership functions are shown in Figures 3.9 and 3.10.

The input variables of $\mathrm{SoC_{LIB}}$ & $\mathrm{SoC_{UP}}$ has lower and upper limits of 0% and 100%, which represents SoC of the LIB and UP. The $\mathrm{SoC_{LIB}}$ & $\mathrm{SoC_{UP}}$ has membership functions of L (Low), M (Medium) and H (High). The trapezoidal shaped is used. The L has ranges between 0% to 55%, M is 35% to 90%, whereas H is 70% to 100%. The L and H membership function protects the LIB and UP from deep discharge and overcharge. The M represents a normal operation of the energy storages.

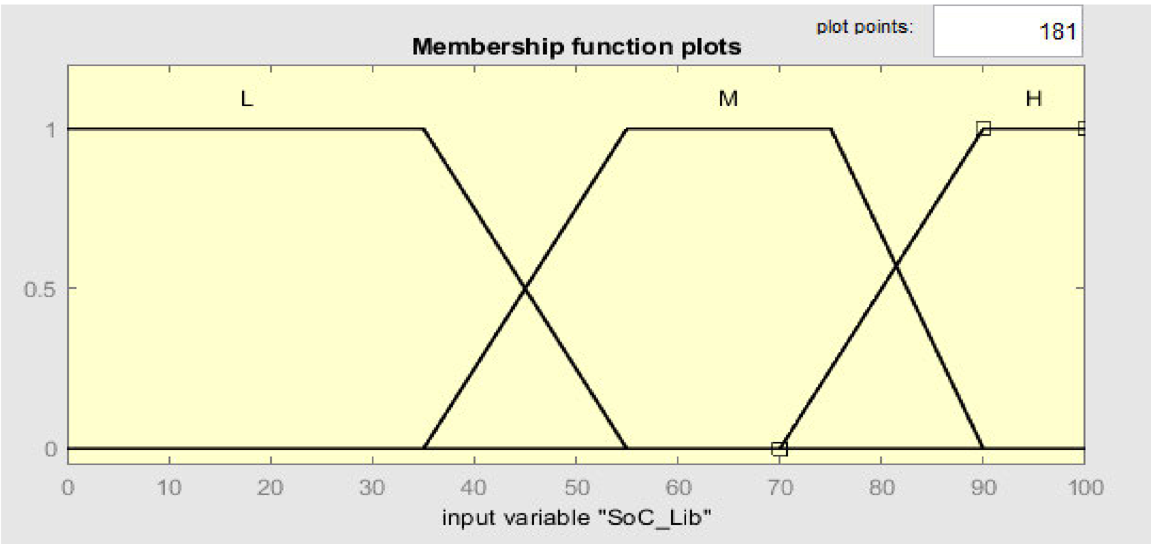

Figure 3.9. The membership function of SoC_LIB variables

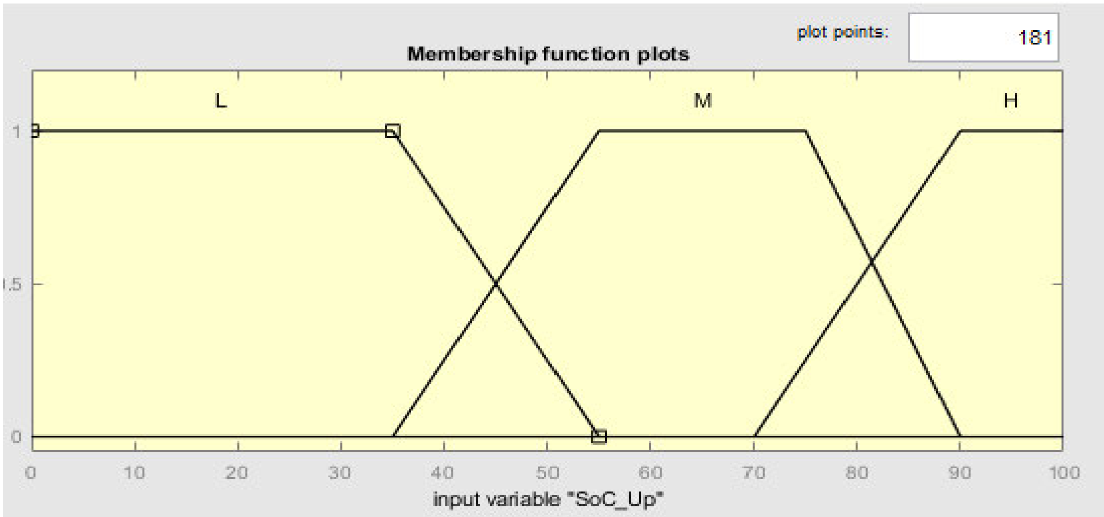

Figure 3.10. The membership function of SOC-UP variables

The P_{Demand} has membership function $PD_{\_N}$ (Negative power demand), Z (Zero) and $PD_{\_P}$ (Positive power demand), the triangular shape is used for the membership function. The $PD_{\_N}$ and $PD_{\_P}$ membership function represents the charging and discharging conditions, respectively; whereas Z represents the condition is balanced, which means the power demand is 0 and the alternator is supplying the full the load. The P_{Demand} has lower and upper limit of -4200 and 4200 for case one, -7080 and 7080 for case two, as well -7800 and 7800 for case three.

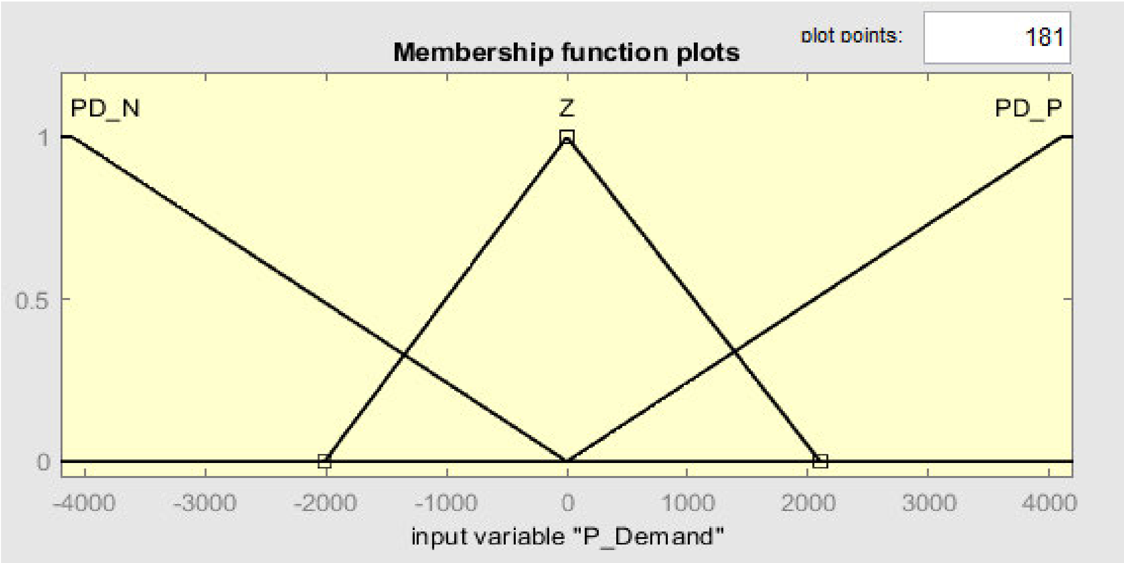

Figure 3.11. The membership function of P_demand variables for case 1

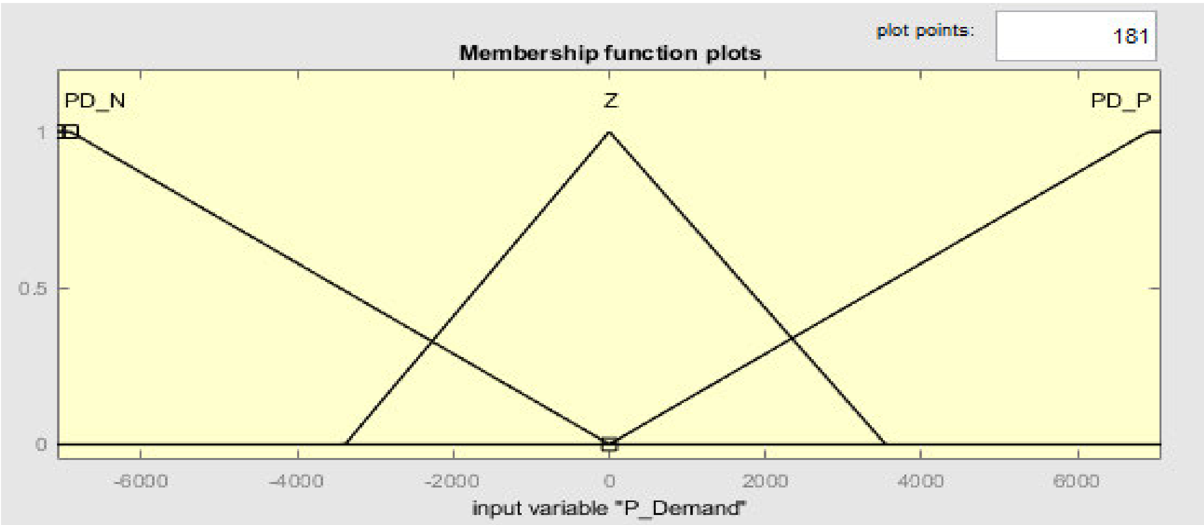

Figure 3.12. The membership function of P_demand variables for case 2

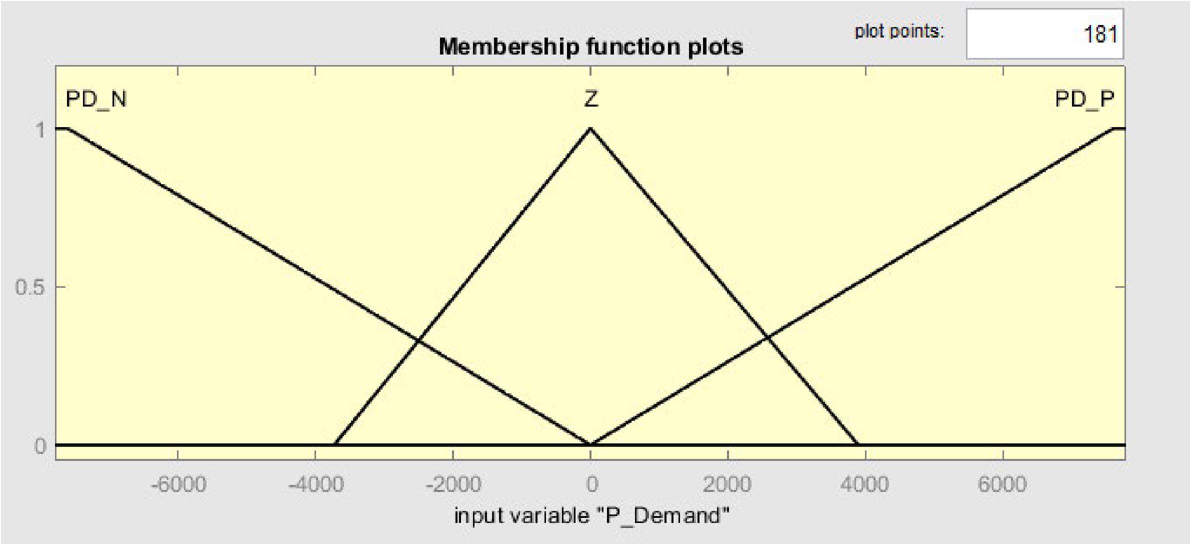

Figure 3.13. The membership function of P_demand variables for case 3

The output variables PD $_{Ref}$, has membership functions of N (Negative), Z (Z) and P (Positive); The triangular shape is used for the membership function. The N and P membership function represents the charging and discharging reference power, respectively; whereas Z represents the condition is balanced, which means the power demand is 0 and there is not any reference power. The PD $_{Ref}$ varies based on the energy storages sizes and the power demand as shown in Figures 3.14 to 3.16.

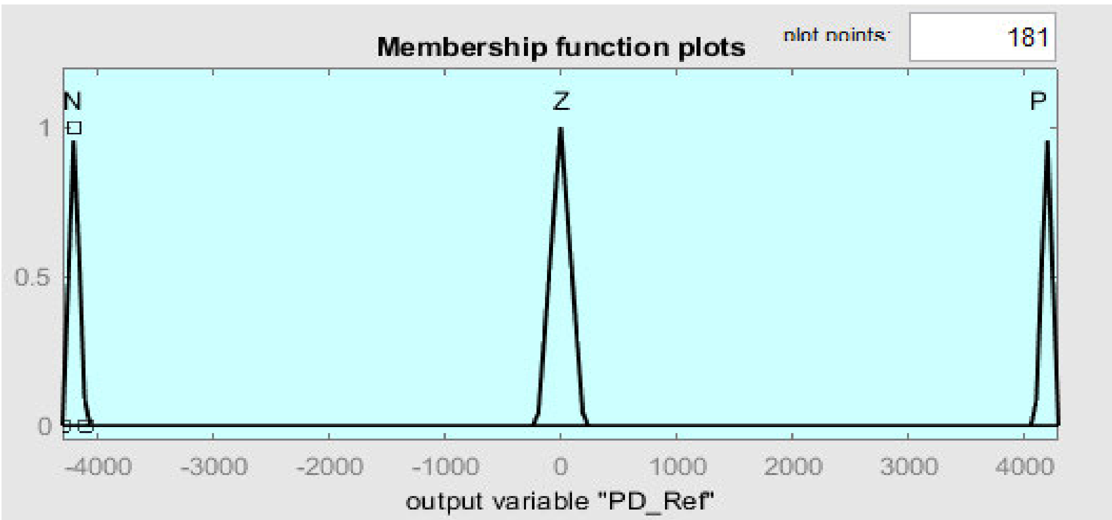

Figure 3.14. The membership function of PD_Ref case 1

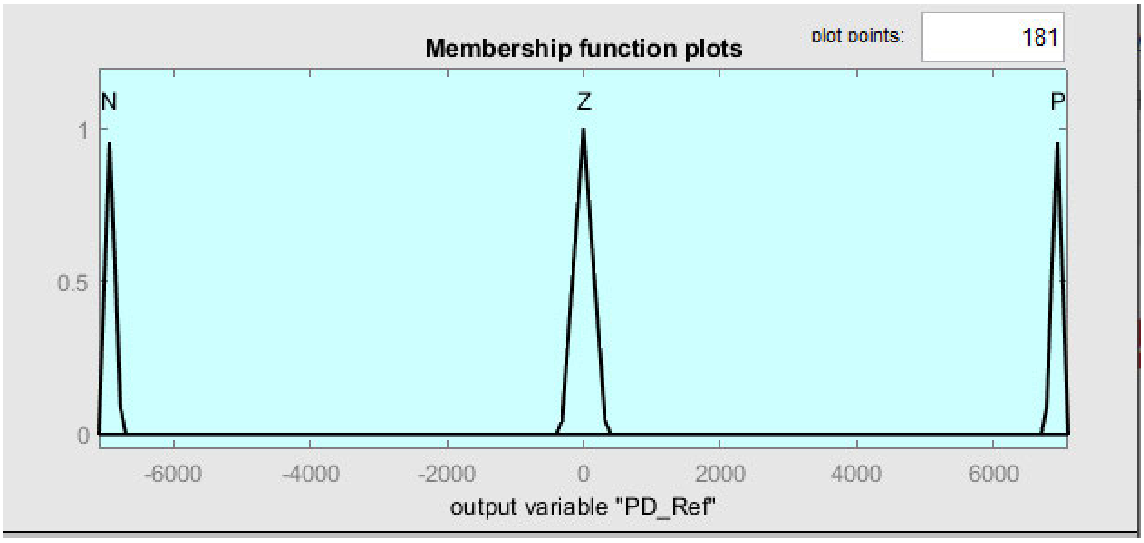

Figure 3.15. The membership function of PD_Ref case 2

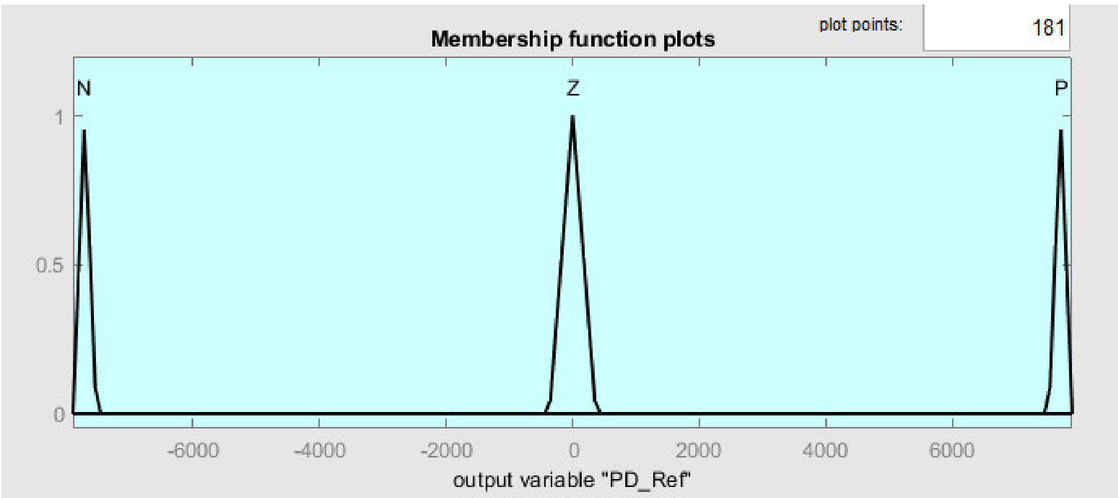

Figure 3.16. The membership function of PD_Ref case 3

3.7.4 Fuzzy Inference or Ruled based for FLC 1

The decision making of the FLC is made in the inference system, the defined rules are developed to meet the desire output reference of the system. As there are three inputs variables and each input having three membership functions. The FLC 1 has total of 27 fuzzy rules as shown in Table 3.11, with the output meaning of N (negative), Z (Zero) and P (Positive).

Table 3.11. FLC1 rules

$PD_{\_Ref}$		When $SoC_{\_Lib}$ is L		
		$SoC_{\_Up}$		
		L	M	H
$P_{\_Demand}$	PD_N	N	N	N
	Z	N	N	N
	PD_P	Z	Z	Z
$PD_{\_Ref}$		When $SoC_{\_Lib}$ is M		
		$SoC_{\_Up}$		
		L	M	H
$P_{\_Demand}$	PD_N	N	N	N
	Z	N	N	N
	PD_P	Z	P	P
$PD_{\_Ref}$		When $SoC_{\_Lib}$ is H		
		$SoC_{\_Up}$		
		L	M	H
$P_{\_Demand}$	PD_N	N	N	Z
	Z	N	N	Z
	PD_P	Z	P	P

where,

- IF P_{Demand} is Z and the SoC_{LIB} & SoC_{UP} are L or M; THEN $PD_{\_Ref}$ is N. It means that, the FLC 1 will provide the reference power to charge the HESS.
- IF P_{Demand} is $PD_{\_N}$ and the SoC_{LIB} & SoC_{UP} are L; THEN $PD_{\_Ref}$ is Z. It means that, the FLC 1 will not provide the reference power to charge or discharge, although HESS capacity is low. In this condition is when the alternator is not producing enough power to supply to TV and charge the TV.
- IF P_{Demand} is $PD_{\_P}$ and SoC_{LIB} & SoC_{UP} are H; THEN $PD_{\_Ref}$ is P. It means that, the FLC 1 will provide the discharging reference power.

3.7.5 Defuzzification

To generate the required output reference, the centroid method is used. The membership function of the output variable for FLC 1 is shown in Figure 3.8. Where, $PD_{\_Ref}$ it is the reference power during charging and discharging conditions.

3.7.6 Fuzzy Logic Controller 2 based on reference power of LIB and UP

The total reference power from FLC 1 is sent to the LPF, which generates the reference power of LIB and UP. From LPF goes to the FLC 2. The purpose of the FLC 2 is to allocate the total control and manage the reference power of the energy storage (LIB and UP) to monitor the bidirectional buck and boost converters during charging and discharging of the HESS. Figure 3.17, shows the FLC 2.

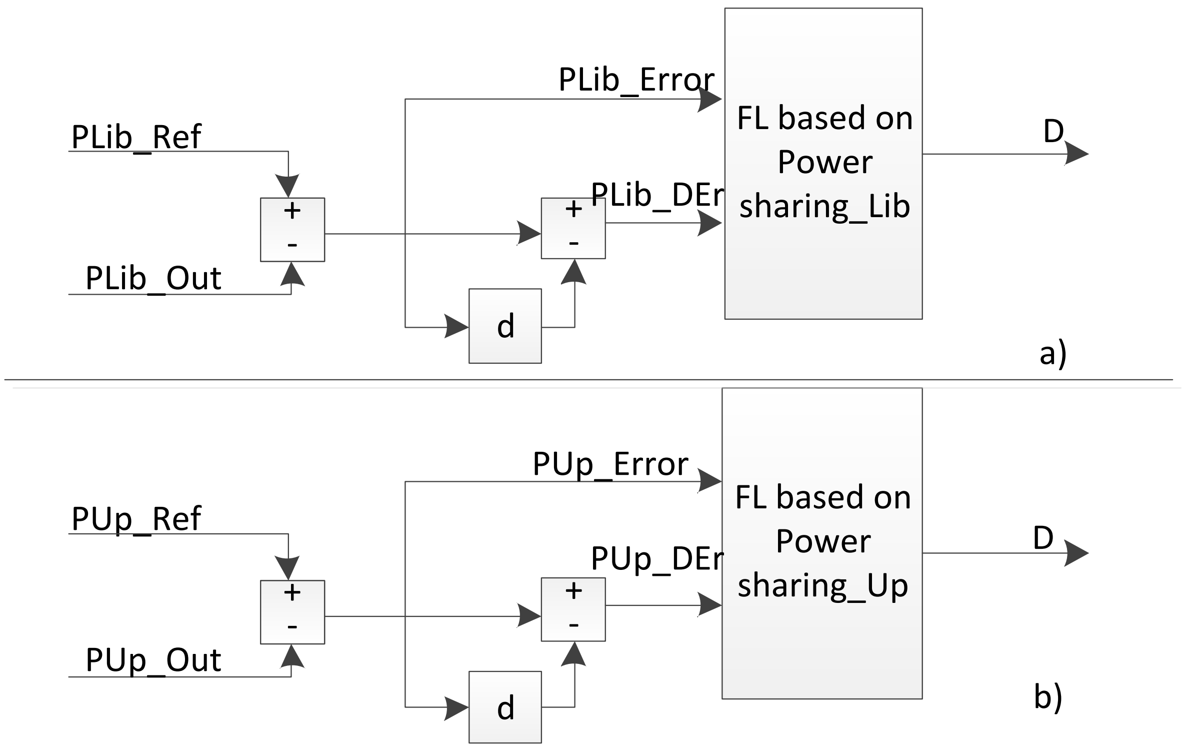

Figure 3.17. FLC 2 based on power sharing; a) LIB and b) UP

3.7.7 Fuzzification FLC 2

The proposed FLC 2 has FLC 2a and FLC 2b. Where the input variables of the FLC 2a are $\text{PLib}_{\text{\_Error}}$ and $\text{PLib}_{\text{\_DError}}$; whereas FLC 2b is $\text{PUp}_{\text{\_Error}}$, $\text{PUp}_{\text{\_DError}}$ and $\text{PUp}_{\text{\_DError}}$. From Figure 3.18 to 3.19, shows the output LIB and UP reference power from the LPF, the difference between LIB and UP reference power and the individual DC-DC buck and boost output power, represents the $\text{PLib}_{\text{\_Error}}$ and $\text{PUp}_{\text{\_Error}}$. The difference between $\text{PLib}_{\text{\_Error}}$ and the derivative of $\text{PLib}_{\text{\_Error}}$ representsPLib$_{\text{_DError}}$. The principle applies in FLC 2b for $\text{PUp}_{\text{\_DError}}$.

The membership functions of FLC 2a and FLC 2b are shown in Figures 3.18 and 3.19, the input variables are used to determine the sharing coefficient to trigger the converters. Seven membership function (NH, NM, NA, Z, PL, PM and PH) are used in FLC 2. Where NH is Negative High, NM is Negative Medium, NL is Negative Low, Z is Zero, PL is Positive Low, PM is Positive Medium, and PH is Positive High. For NM, NL, Z, PL and PM membership function, triangular shape are used. Trapezoidal shape is used for NH and PH.

The input variables of $\text{PLib}_{\text{\_Error}}$ and $\text{PLib}_{\text{\_DError}}$ have lower and upper limits of -1680 W and 1680 W, while $\text{PUp}_{\text{\_Error}}$ and $\text{PUp}_{\text{\_DError}}$ have -2520 W and 2520 W, respectively.

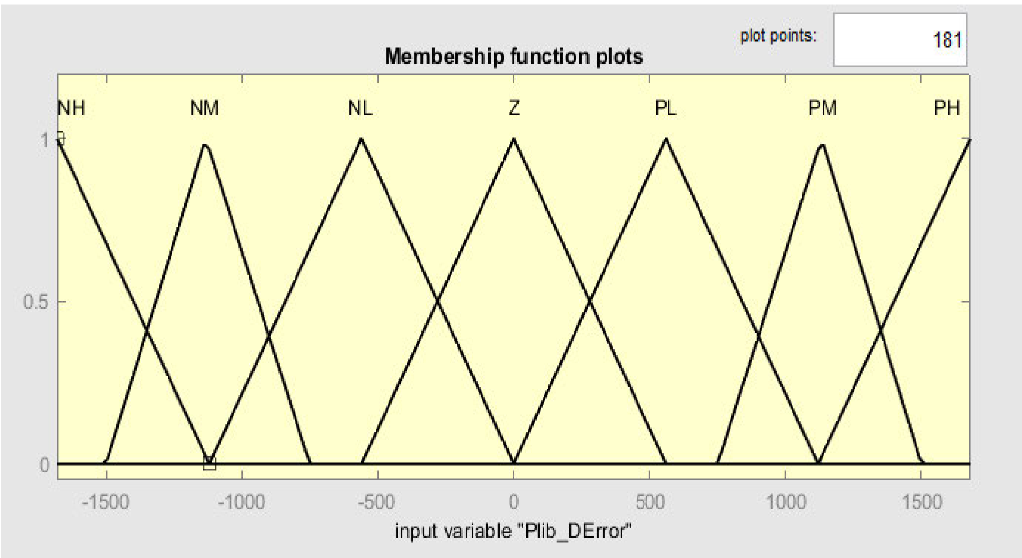

Figure 3.18. Input membership functions of PLib_DError for FLC 2 based on reference power of LIB

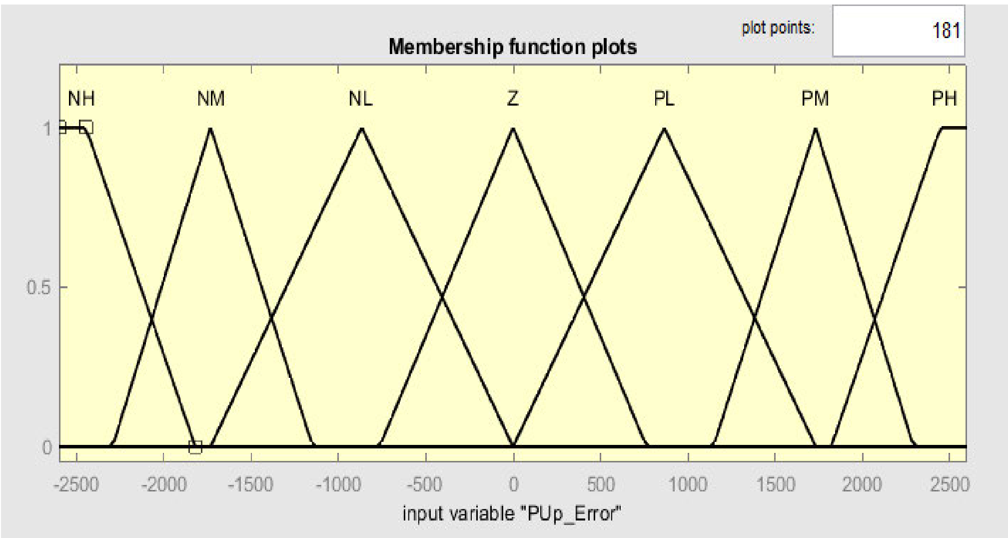

Figure 3.19. Input membership functions of PUp_Error for FLC 2 based on reference power of UP

The output variable of the FLC 2 is shown Figure 3.20, which represents the Duty cycle. The lower and upper membership function set to be 0 to 1. The same output variable is used for LIB and UP.

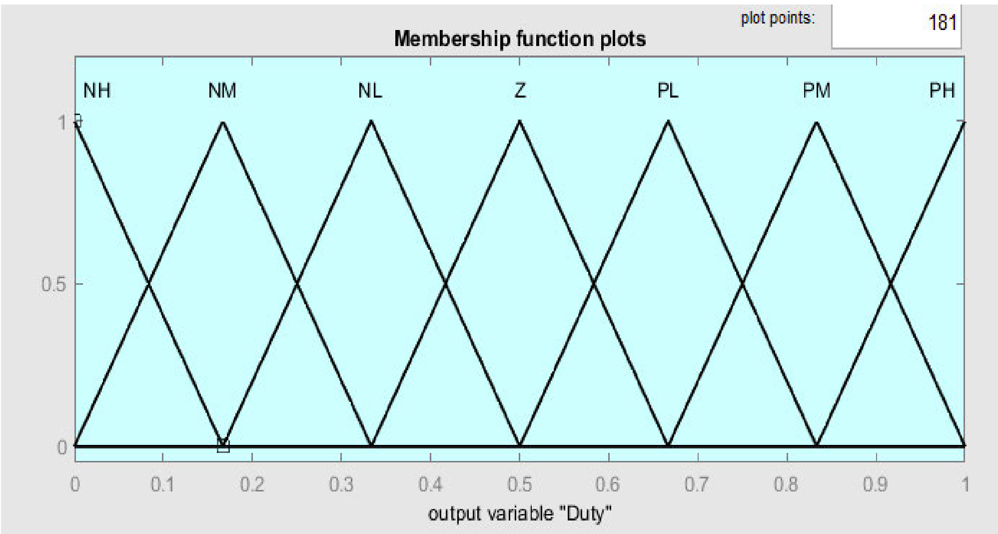

Figure 3.20. The output variables

3.7.8 Fuzzy Inference or Ruled based for FLC 2

The fuzzy rules of the FLC 2a and FLC 2b are shown in Tables 3.12 and 3.13. There are two inputs variables and each input having seven membership functions. It has one output (Duty) which gives the reference and control the operation of bidirectional buck-boost converter. The FLC 2a and FLC 2b, each has total of 49 fuzzy rules respectively.

Table 3.12. FLC 2a fuzzy rules

Duty		$PLib_{\_Error}$						
		PH	PM	PS	Z	NS	NM	NH
$PLib_{\_DError}$	NH	Z	DNS	DMM	DNH	DNH	DNH	DNH
	NM	DPS	Z	DNS	DNM	DNH	DNH	DNH
	NS	DPM	DPS	Z	DNS	DNM	DNH	DNH
	Z	DPH	DPM	DPS	Z	DNS	DNM	DNH
	PS	DPH	DPH	DPM	DPS	Z	DNS	DNM
	PM	DPH	DPH	DPH	DPM	DPS	Z	DNS
	PH	DPH	DPH	DPH	DPH	DPM	DPS	Z

Table 3.13. FLC 2b Fuzzy rules

Duty		$PUp_{\_Error}$						
		PH	PM	PS	Z	NS	NM	NH
$PUp_{\_DError}$	NH	Z	DNS	DMM	DNH	DNH	DNH	DNH
	NM	DPS	Z	DNS	DNM	DNH	DNH	DNH
	NS	DPM	DPS	Z	DNS	DNM	DNH	DNH
	Z	DPH	DPM	DPS	Z	DNS	DNM	DNH
	PS	DPH	DPH	DPM	DPS	Z	DNS	DNM
	PM	DPH	DPH	DPH	DPM	DPS	Z	DNS
	PH	DPH	DPH	DPH	DPH	DPM	DPS	Z

3.7.9 The proposed Hybrid Lithium-Ion and Ultra capacitor with Energy Storage System

The Figure 3.21 shows the diagram of the proposed Hybrid Lithium-Ion and Ultracapacitor with Energy Storage System based on fully active with two dc/dc bidirectional buck and boost converter and two levels FLCs. The lithium battery and Ultracapacitor is connected to the Buck-Boost converter. The converters are linked in parallel to generate the stable output voltage and power needed at the DC bus. The EMS comprise of two bidirectional dc-dc buck-boost converter and two levels of FLCs with rule-based uses. The FLC 1 will provide the total reference power to start the ICE and to charge the energy storages based on the power demand, while ensuring that the SoC is within the minimum and the maximum range of the battery protects the battery from over charging and deep discharging. Since the LIB is a low power density device, as well should not be expose to deep discharge which would cause stress on LIB; a Low Pass Filter (LPF) is used to divide the total reference power between the LIB and UP. The total reference power from FLC 1 is sent to the Low Pass Filter (LPF), which generates the reference power of LIB and UP. From LPF goes to the FLC 2. The purpose of the FLC 2 is to allocated the total control and manage the reference power of the energy storage (LIB and UP) to monitor the bidirectional buck and boost converters during charging and discharging of the HESS.

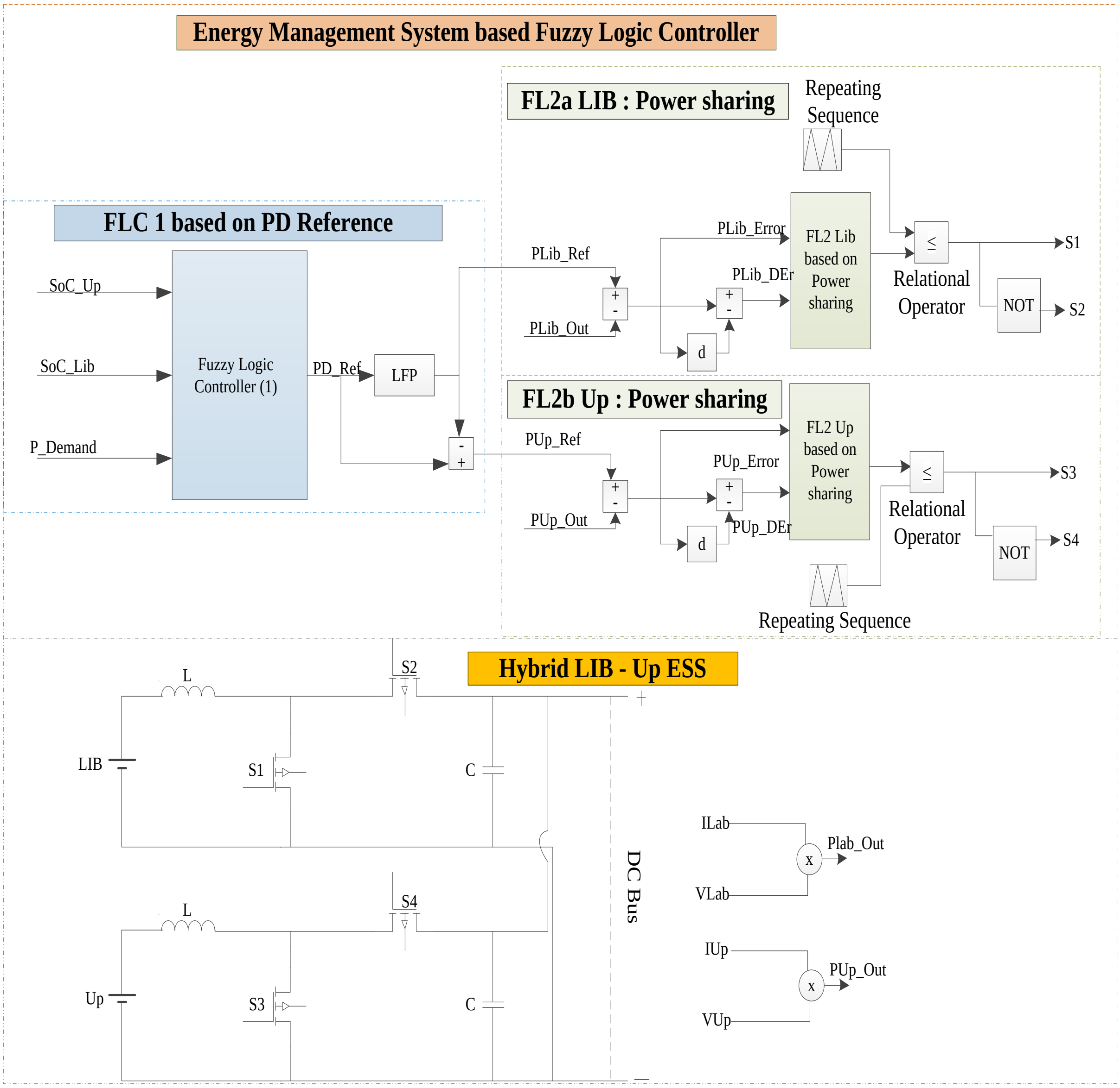

Figure 3.21. Energy Management System based on Fuzzy Logic Controller

3.8 Lifespan estimation

The lifespan estimation is crucial for this study, a wrong estimation might not be able to validate the research studies. *Sauer et al* [97] compare various battery lifespan estimation methods, each with its own advantages and limitations. The cumulates losses of battery based on discharging cycles is used for this research studies [97]. It is called a fatigue model, which assumes that each CCA or discharge of the battery affects the battery's lifespan. The following scenarios were considered to estimate the battery's lifespan.

The battery cycle life graphs, which plot Depth-of-Charge (DOC) or State-of-Charge (SOC) versus the number of cycles, are used to estimate the battery's lifespan. The battery lifespan is estimated using data from [98] and Figure 3.22.

- In Figure 3.22, both State-of-Charge (SOC) and Depth-of-Discharge (DOC) represent the battery's capacity in percentage.
- The Depth-of-Discharge (DOD) during discharging is used to identify the cycle number for lifespan estimation.
- The number of cycles on the graph represents the estimated lifespan of the battery

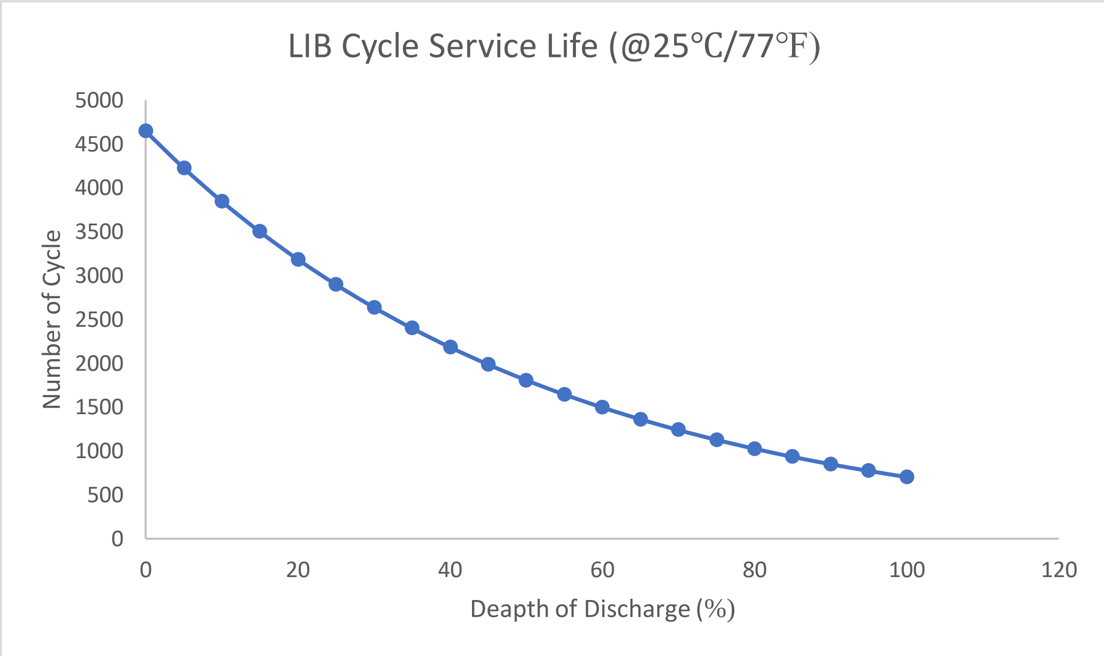

Figure 3.22. Extended version cycle life graph of LIB based on manufacture data

Based on sources [97, 99], the LIB's lifespan is determined. The LIB's loss of life (LoL) and maximum anticipated lifespan in years are evaluated using Figure 3.22. The aggregate of all discharges over a predetermined period of observation is the LoL.

$$\mathrm{LoL} = \sum_{i=0}^{K} \frac{N_b(\mathrm{i})}{N_b^{max}} \tag{3.17}$$

Where

i ={0 … … … … . K} = {0 … . .100%}

K is the LIB's DOD

i is the DOD during a single operation during discharging condition, the i is 100%, it means the battery is fully discharged.

$N_b(i)$ is the number of cycles performed at i^{th} DOD

N_b^{max} represents the maximum number of charge and discharge cycles a battery can undergo.

When LoL equals 1 [97, 99], the LIB reaches the end of its operational lifespan. Following is a determination:

when $N_b(i)$ = N_b^{max}; than LoL = 1

The LIB's overall operational service life ($N_{\max_s}$), and represented by [2]:

$$N_{\max_s} = \frac{1}{\mathrm{LoL}} \tag{3.18}$$

The maximum estimated battery lifespan (LSp) is determined by [2] if the number of operations (Nop) of the vehicle per day:

$$\mathrm{L_{sp}} = \frac{\mathrm{N_b^{max}}}{\mathrm{N_{op}}} \times \frac{N_{\max_s}}{365{,}5} \ \text{(years)} \tag{3.19}$$

3.9 Conclusion

The methodology approach for developing an improved hybrid Lithium-Ion-Ultracapacitor energy storage system is addressed. The proposed HESS with EMS using fully active topology was presented. Three topologies are created, with each topology representing a different case. The three topologies were developed as a result of the various battery specifications and required power in each case.

The Energy Management System consist of two Fuzzy Logic Controls (FLC1, FLC2a and FLC2b). The FLC1 determines the total reference power ($\mathrm{PD\_p_{Ref}}$) based on the power demand ($\mathrm{P_{Demand}}$) while ensuring the LIB SoC is within the minimum and maximum range. The FLC2 (FLC2a and FLC2b) allocate the reference powers to LIB and Up based on the total reference power, by controlling the LIB's and UP's voltage and current flow during the charging and discharging process.

4 Chapter 4: Modelling and Simulation

4.1 Introduction

In this chapter, the proposed HESSs with EMS are examined using a simulation model to determine how well they function in terms of supplying the required power and extending battery's lifespan. The simulation models of the Ultracapacitor and lithium-ion battery, the full-active topology of hybrid lithium-ion and Ultracapacitor energy storage system with EMS based of two bidirectional dc-dc buck-boost converters, FLC simulation were built using the Matlab/Simulink Software.

4.2 Lithium-Ion modelling simulation

Table 4.1 displays the chosen lithium-parameters ion's for each size of battery. The LIBs are made from the readily available lithium iron phosphate (LiFeP04), which is primarily used in transportation vehicles at the moment.

Table 4.1. Parameters of lithium-ion batteries

Parameters	**Case one**	**Case two**	**Case three**
Voltage	12 V	12 V	12 V
Storage Capacity	10 Ah	20 Ah	25 Ah
SoC (%)	100	100	100

To assess battery characteristics such as open circuit voltage, internal resistance (R), polarization constant (K), exponential voltage (A), and exponential capacity (B), the three LIBs are tested in MATLAB Simulink with a range of currents and C rates. 6.5 A, 13 A, and 32.5 A of continuous current are used throughout the 2.5-hour test.

Figure 4.1 shows the result of the testing on 12V – 10Ah LIB. The results show that the open voltage (EO) is 13.0123 V, internal resistance (R) is 0.012 Ω, polarization constant (K) is 0.0089902, exponential voltage (A) is 1.0077 V and exponential capacity (B) is 6.1062.

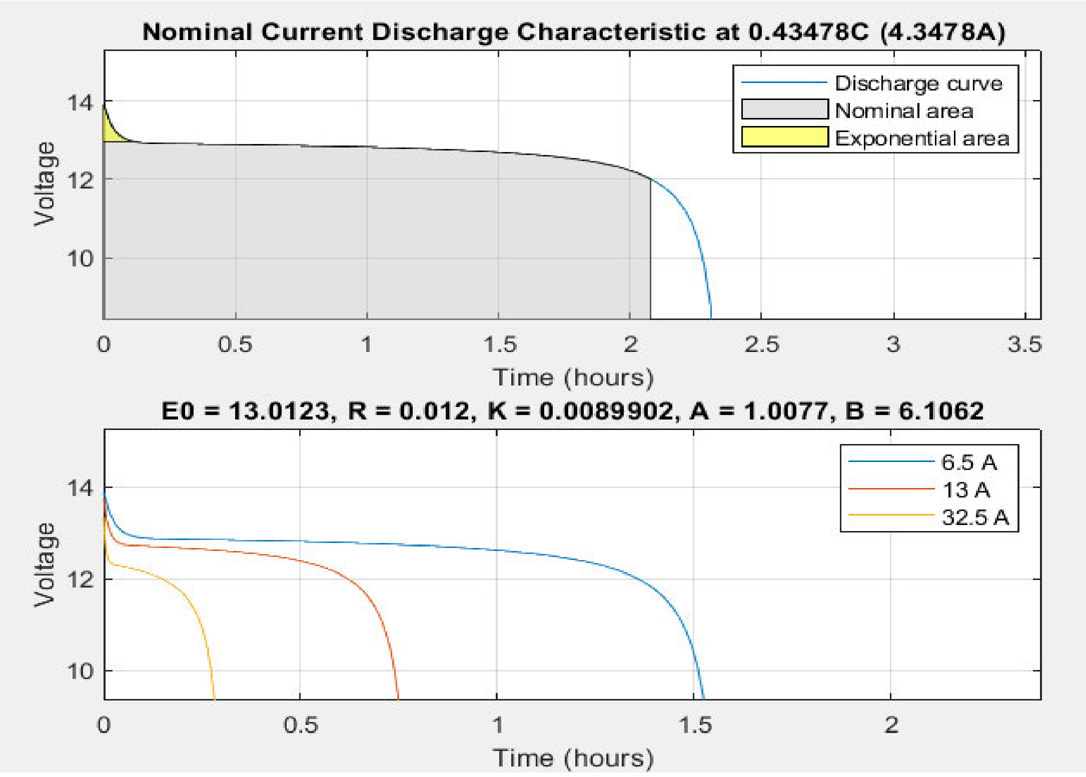

Figure 4.1. Discharge characteristics of 12V – 10Ah

The testing on 12V – 2 0Ah LIB is conducted. Figure 4.2 shows that the open voltage (EO) is 13.0123 V, internal resistance (R) is 0.006 Ω, polarization constant (K) is 0.0044951, exponential voltage (A) is 1.0077 V and exponential capacity (B) is 3.0531.

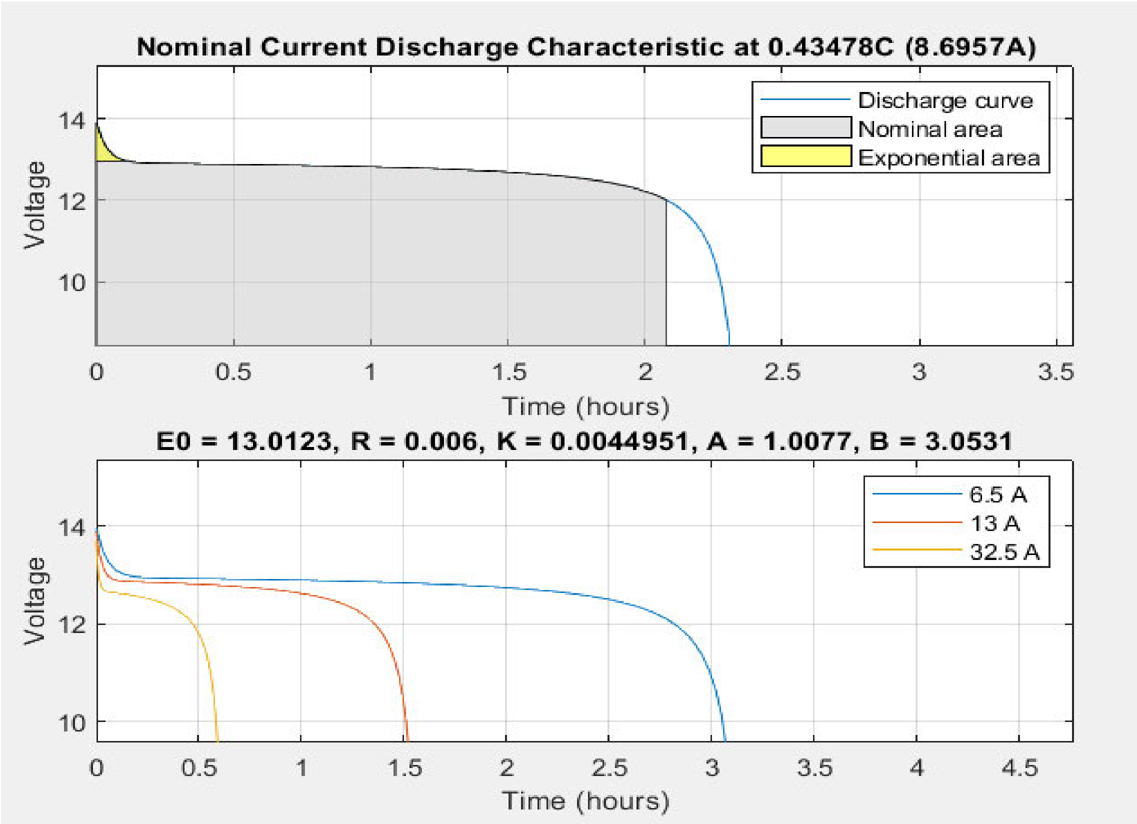

Figure 4.2. Discharge characteristics of 12V – 20Ah

The testing on 12V – 25 Ah LIB is conducted. Figure 4.3 shows that the open voltage (EO) is 13.0123 V, internal resistance (R) is 0.0048 Ω, polarization constant (K) is 0.0035961, exponential voltage (A) is 1.0077 V and exponential capacity (B) is 2.4425.

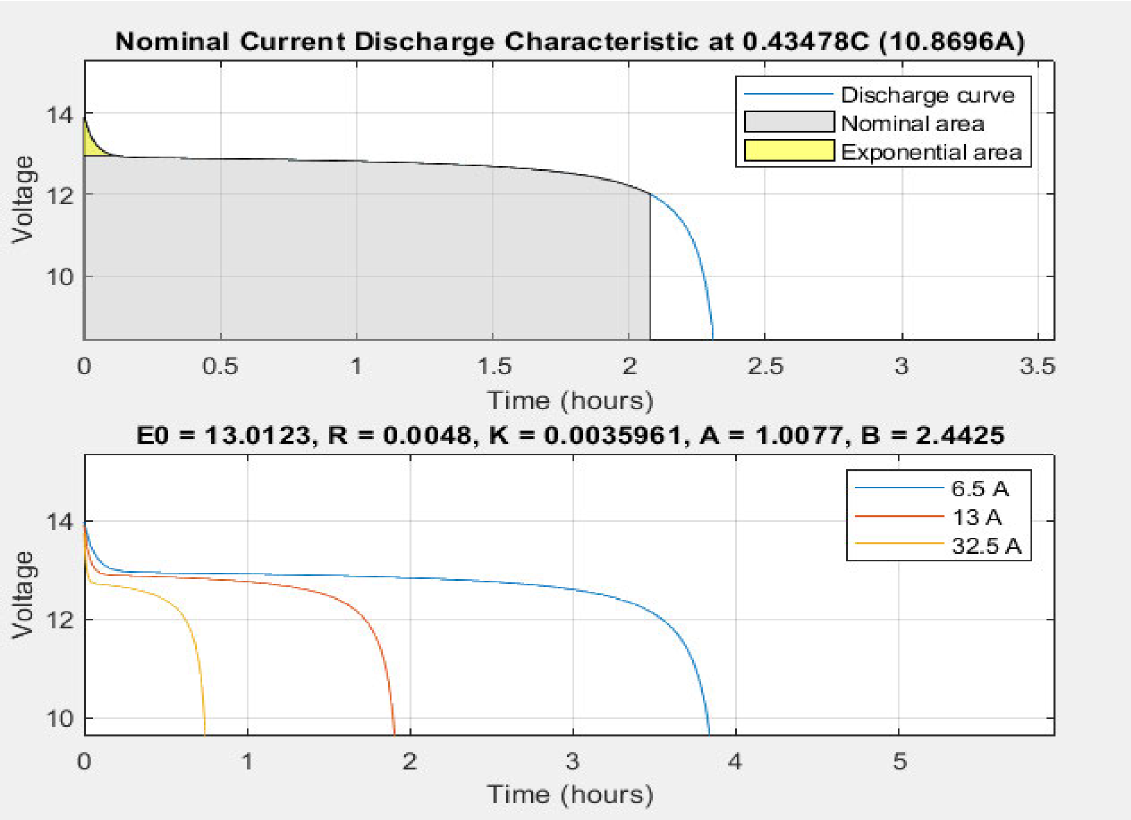

Figure 4.3. Discharge characteristics of 12V – 25Ah

4.3 Ultracapacitor Modelling simulation

The UPs parameters used for this research is shown in Table 4.2. The UPs are tested in MATLAB Simulink using the same output parameters as in LIB which consist of rated voltage and current. The output parameters characteristics of the Ups is shown in Table 4.2.

Table 4.2. Parameters of Ultracapacitor

Parameters	Case one	Case two	Case three
Voltage	12 V	12 V	12 V
Storage Capacity	7500 F	12000 F	15500 F
SoC (%)	100	100	100

The Figures 4.4 to 4.6, shows the charge characteristics of UPs voltage versus time. The three sizes of UPs are tested with the same rated currents such as 9A, 9.5A, 10A and 10.2A for 4.4 hours as is shown in Figure 4.4, 4.5 and 4.6. The charging time for UPs to reach 100% SoC is determined by the rating currents.

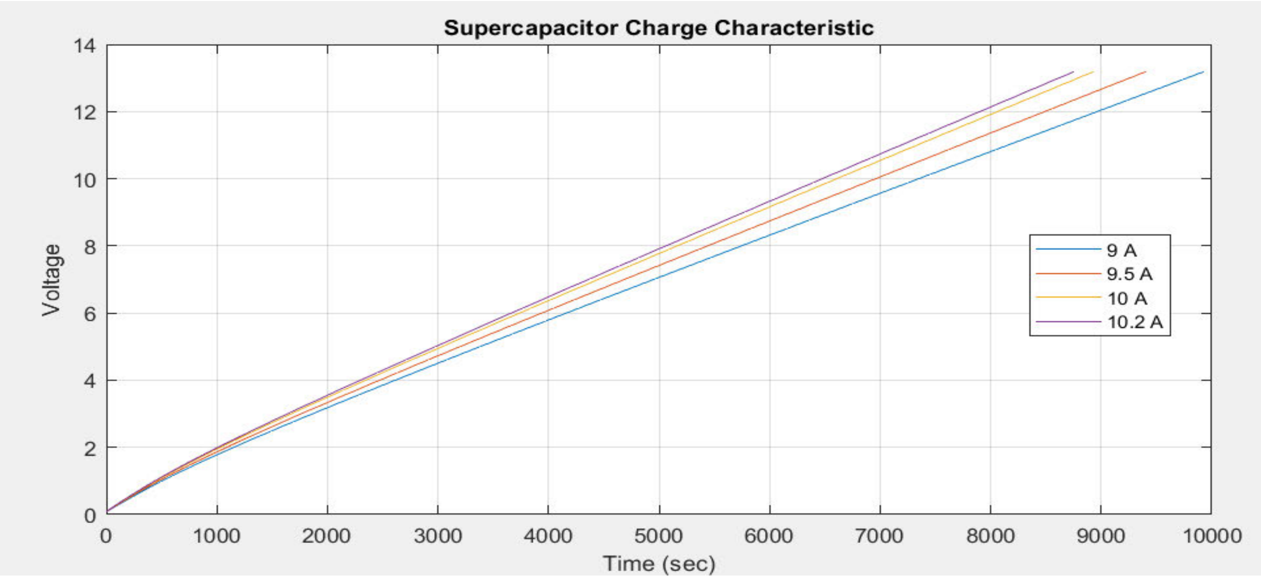

Figure 4.4. Ultracapacitor charge characteristics for case one

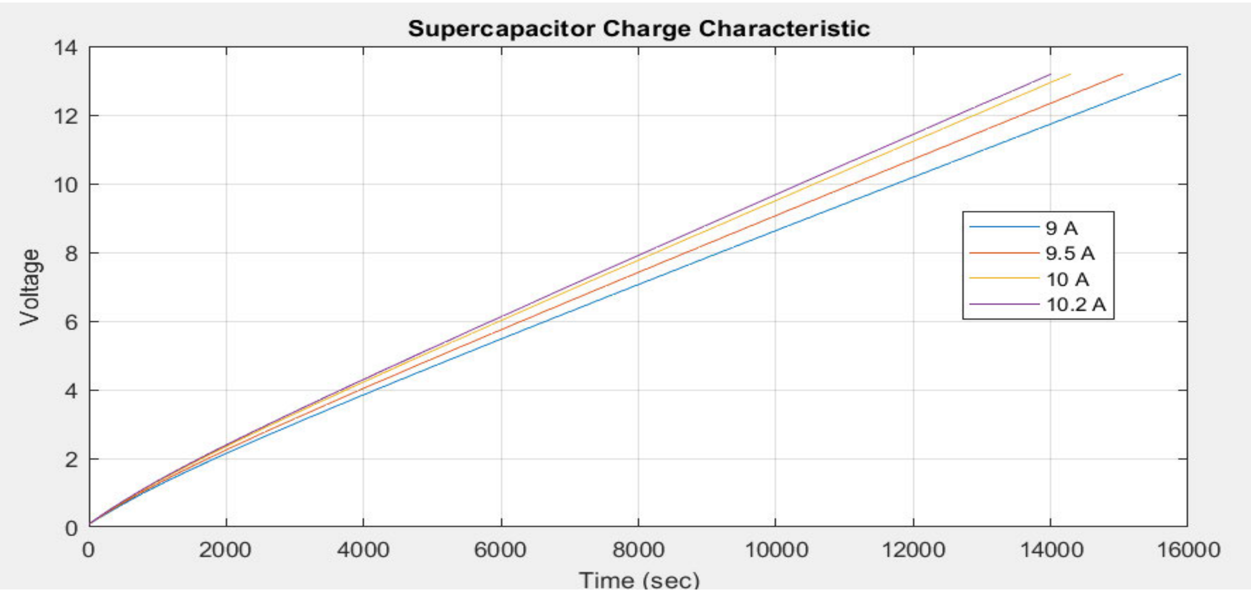

Figure 4.5. Ultracapacitor charge characteristics for case two

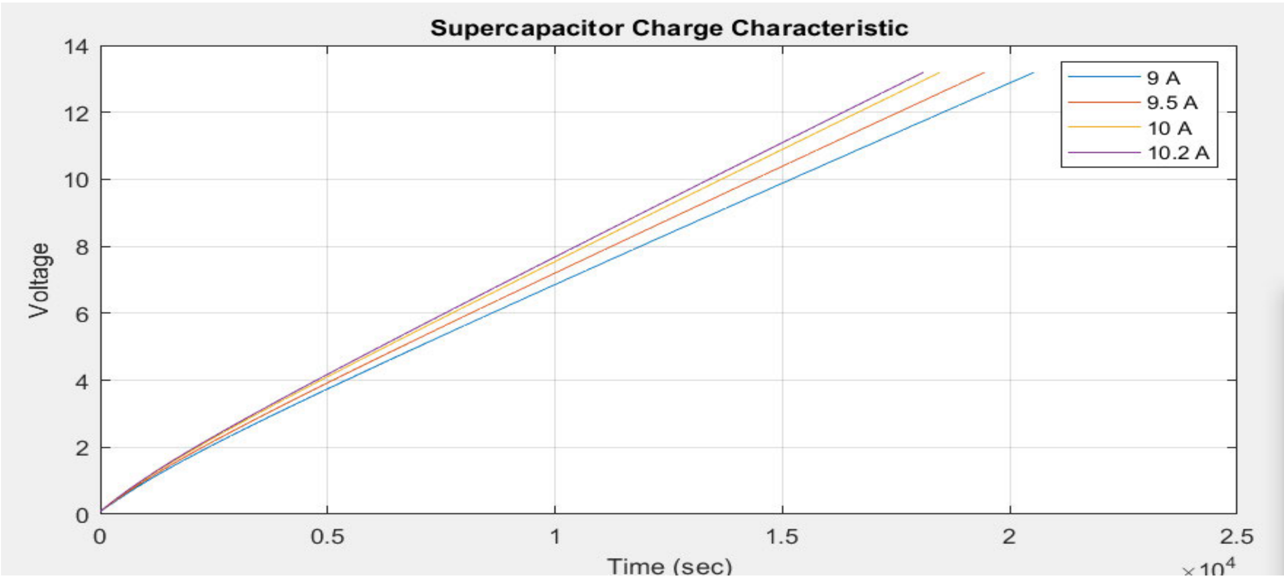

Figure 4.6. Ultracapacitor charge characteristics for case three

4.4 The Bidirectional dc/dc buck-boost Converter simulation mode

The MATLAB/Simulink software's bidirectional DC/DC buck and boost converter model for LIB and UP is displayed in Figure 4.7 The bidirectional inverters are monitored and managed by two-level FLCs. When the energy storage devices are in the charging or discharging modes, it generates the reference currents, regulates the voltage levels, and makes sure the SoC is between the minimum and maximum range.

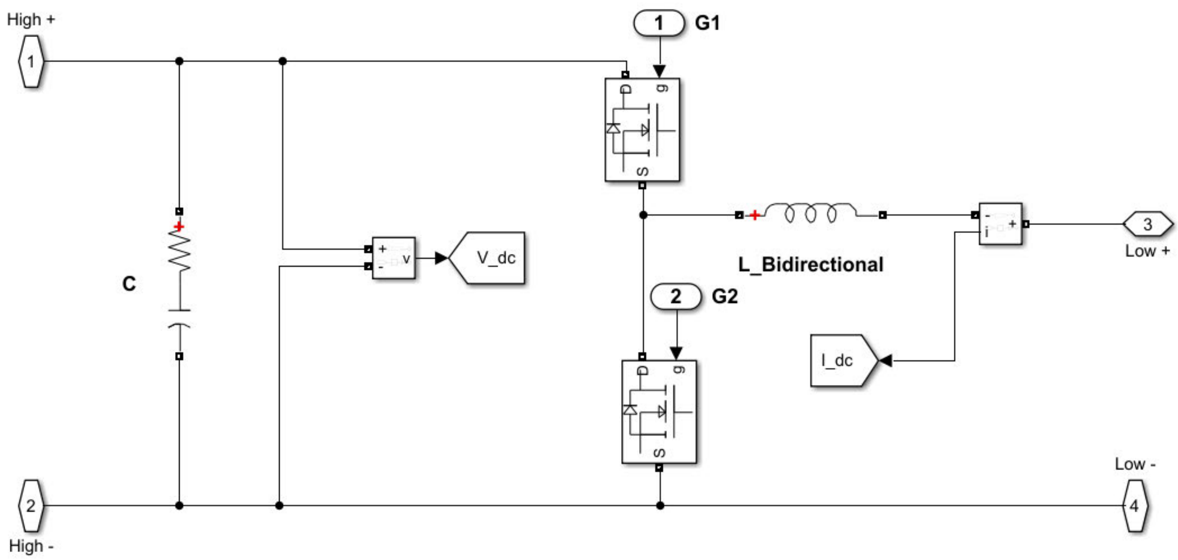

Figure 4.7. The MATLAB/Simulink-modelled bidirectional dc-dc buck-boost equivalent circuit

4.5 Fuzzy Logic simulation mode

The FLC rules is determined based on the power demand and battery's SoC modelled in MATALAB/Simulink. A peak demand of 4200 W is used to model the proposed HESS. Tables 4.3 and 4.4 show the inference based on Rule based control.

Table 4.3. The inference based on Rule based control for FLC 1

1. If (SoC_Up is L) and (SoC_Lib is L) and (P_Demand is PD_N) then (PD_Ref is N)
2. If (SoC_Up is M) and (SoC_Lib is L) and (P_Demand is PD_N) then (PD_Ref is N)
3. If (SoC_Up is H) and (SoC_Lib is L) and (P_Demand is PD_N) then (PD_Ref is N)
4. If (SoC_Up is L) and (SoC_Lib is M) and (P_Demand is PD_N) then (PD_Ref is N)
5. If (SoC_Up is M) and (SoC_Lib is M) and (P_Demand is PD_N) then (PD_Ref is N)
6. If (SoC_Up is H) and (SoC_Lib is L) and (P_Demand is PD_N) then (PD_Ref is N)
7. If (SoC_Up is L) and (SoC_Lib is H) and (P_Demand is PD_N) then (PD_Ref is N)
8. If (SoC_Up is M) and (SoC_Lib is H) and (P_Demand is PD_N) then (PD_Ref is N)
9. If (SoC_Up is H) and (SoC_Lib is H) and (P_Demand is PD_N) then (PD_Ref is Z)
10. If (SoC_Up is L) and (SoC_Lib is L) and (P_Demand is Z) then (PD_Ref is N)
11. If (SoC_Up is M) and (SoC_Lib is L) and (P_Demand is Z) then (PD_Ref is N)
12. If (SoC_Up is H) and (SoC_Lib is L) and (P_Demand is Z) then (PD_Ref is N)
13. If (SoC_Up is L) and (SoC_Lib is M) and (P_Demand is Z) then (PD_Ref is N)
14. If (SoC_Up is M) and (SoC_Lib is M) and (P_Demand is Z) then (PD_Ref is N)
15. If (SoC_Up is H) and (SoC_Lib is M) and (P_Demand is Z) then (PD_Ref is N)
16. If (SoC_Up is L) and (SoC_Lib is H) and (P_Demand is Z) then (PD_Ref is N)
17. If (SoC_Up is M) and (SoC_Lib is H) and (P_Demand is Z) then (PD_Ref is N)
18. If (SoC_Up is H) and (SoC_Lib is H) and (P_Demand is Z) then (PD_Ref is Z)
19. If (SoC_Up is L) and (SoC_Lib is L) and (P_Demand is PD_P) then (PD_Ref is Z)
20. If (SoC_Up is M) and (SoC_Lib is L) and (P_Demand is PD_P) then (PD_Ref is Z)
21. If (SoC_Up is H) and (SoC_Lib is L) and (P_Demand is PD_P) then (PD_Ref is Z)
22. If (SoC_Up is L) and (SoC_Lib is M) and (P_Demand is PD_P) then (PD_Ref is Z)
23. If (SoC_Up is M) and (SoC_Lib is M) and (P_Demand is PD_P) then (PD_Ref is P)
24. If (SoC_Up is H) and (SoC_Lib is M) and (P_Demand is PD_P) then (PD_Ref is P)
25. If (SoC_Up is L) and (SoC_Lib is H) and (P_Demand is PD_P) then (PD_Ref is Z)
26. If (SoC_Up is M) and (SoC_Lib is H) and (P_Demand is PD_P) then (PD_Ref is P)
27. If (SoC_Up is H) and (SoC_Lib is H) and (P_Demand is PD_P) then (PD_Ref is P)

Table 4.4. The inference based on Rule based control for FLC 2

1. If (PLib_Error is NH) and (PLib_DError is NH) then (Duty is NH)
2. If (PLib_Error is NH) and (PLib_DError is NM) then (Duty is NH)
3. If (PLib_Error is NH) and (PLib_DError is NL) then (Duty is NH)
4. If (PLib_Error is NH) and (PLib_DError is Z) then (Duty is NM)
5. If (PLib_Error is NH) and (PLib_DError is PL) then (Duty is NM)
6. If (PLib_Error is NH) and (PLib_DError is PM) then (Duty is NL)
7. If (PLib_Error is NH) and (PLib_DError is PH) then (Duty is Z)
8. If (PLib_Error is NM) and (PLib_DError is NH) then (Duty is NH)
9. If (PLib_Error is NM) and (PLib_DError is NM) then (Duty is NM)
10. If (PLib_Error is NM) and (PLib_DError is NL) then (Duty is NM)
11. If (PLib_Error is NM) and (PLib_DError is Z) then (Duty is NL)
12. If (PLib_Error is NM) and (PLib_DError is PL) then (Duty is NL)
13. If (PLib_Error is NM) and (PLib_DError is PM) then (Duty is Z)
14. If (PLib_Error is NM) and (PLib_DError is PH) then (Duty is PH)
15. If (PLib_Error is NL) and (PLib_DError is NH) then (Duty is NH)
16. If (PLib_Error is NL) and (PLib_DError is NM) then (Duty is NM)
17. If (PLib_Error is NL) and (PLib_DError is NL) then (Duty is NL)
18. If (PLib_Error is NL) and (PLib_DError is Z) then (Duty is NL)
19. If (PLib_Error is NL) and (PLib_DError is PL) then (Duty is Z)
20. If (PLib_Error is NL) and (PLib_DError is PM) then (Duty is PL)
21. If (PLib_Error is NL) and (PLib_DError is PH) then (Duty is PM)
22. If (PLib_Error is Z) and (PLib_DError is NH) then (Duty is NM)
23. If (PLib_Error is Z) and (PLib_DError is NM) then (Duty is NL)
24. If (PLib_Error is Z) and (PLib_DError is NL) then (Duty is NL)
25. If (PLib_Error is Z) and (PLib_DError is Z) then (Duty is Z)
26. If (PLib_Error is Z) and (PLib_DError is PL) then (Duty is PL)
27. If (PLib_Error is Z) and (PLib_DError is PM) then (Duty is PL)
28. If (PLib_Error is Z) and (PLib_DError is PH) then (Duty is PM)
29. If (PLib_Error is PL) and (PLib_DError is NH) then (Duty is NM)
30. If (PLib_Error is PL) and (PLib_DError is NM) then (Duty is NL)
31. If (PLib_Error is PL) and (PLib_DError is NL) then (Duty is Z)
32. If (PLib_Error is PL) and (PLib_DError is Z) then (Duty is PL)
33. If (PLib_Error is PL) and (PLib_DError is PL) then (Duty is PL)
34. If (PLib_Error is PL) and (PLib_DError is PM) then (Duty is PM)
35. If (PLib_Error is PL) and (PLib_DError is PH) then (Duty is PH)
36. If (PLib_Error is PM) and (PLib_DError is NH) then (Duty is NL)
37. If (PLib_Error is PM) and (PLib_DError is NM) then (Duty is Z)
38. If (PLib_Error is PM) and (PLib_DError is NL) then (Duty is PL)
39. If (PLib_Error is PM) and (PLib_DError is Z) then (Duty is PL)

40. If (PLib_Error is PM) and (PLib_DError is PL) then (Duty is PM)
41. If (PLib_Error is PM) and (PLib_DError is PM) then (Duty is PM)
42. If (PLib_Error is PM) and (PLib_DError is PH) then (Duty is PH)
43. If (PLib_Error is PH) and (PLib_DError is NH) then (Duty is Z)
44. If (PLib_Error is PH) and (PLib_DError is NM) then (Duty is PL)
45. If (PLib_Error is PH) and (PLib_DError is NL) then (Duty is PM)
46. If (PLib_Error is PH) and (PLib_DError is Z) then (Duty is PM)
47. If (PLib_Error is PH) and (PLib_DError is PL) then (Duty is PH)
48. If (PLib_Error is PH) and (PLib_DError is PM) then (Duty is PH)
49. If (PLib_Error is PH) and (PLib_DError is PH) then (Duty is PH)

Figures 4.8 to 4.10 shows the rule viewer of the FLC 1, FLC 2a and FLC 2b. The reference power during charging and discharging modes, the coefficient percentage supply of the LIB and UP is shown in the rule viewer graphs.

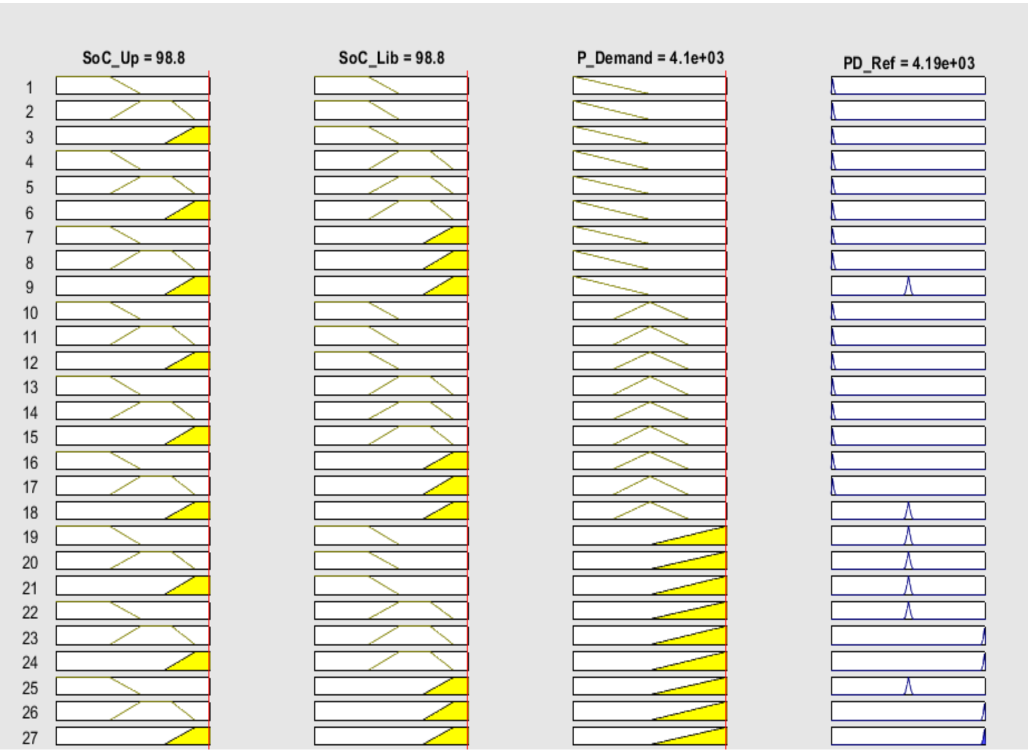

Figure 4.8. Rule readers for the proposed FLC 1

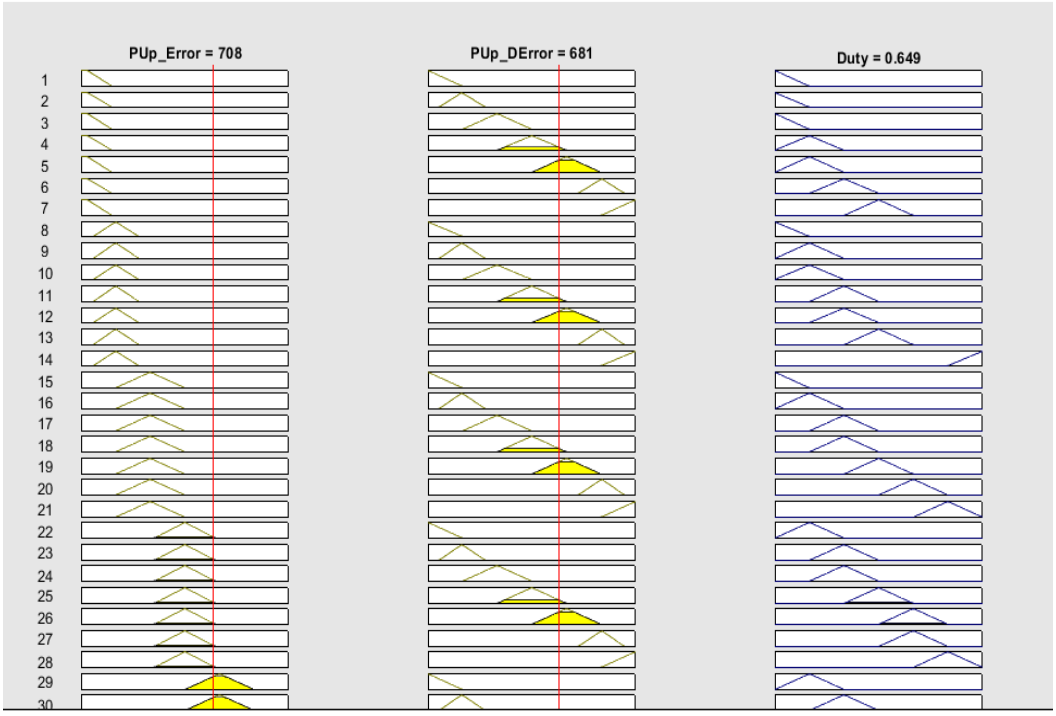

Figure 4.9. Rule readers for the proposed FLC 2a

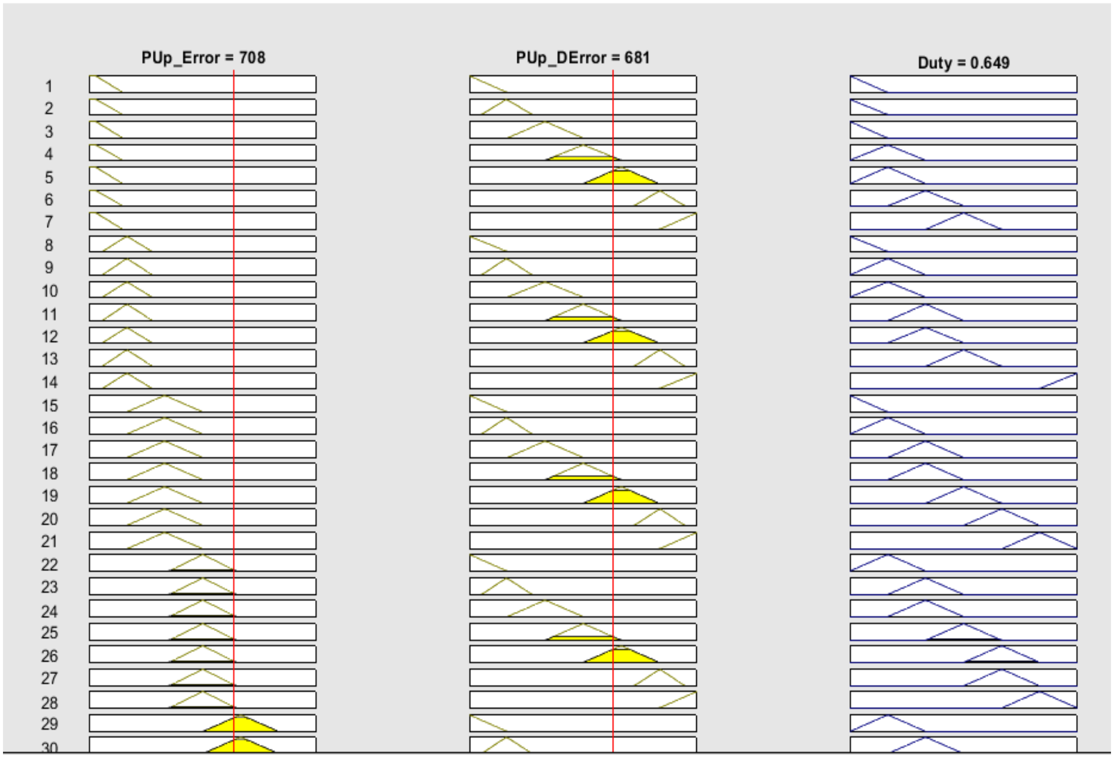

Figure 4.10. Rule readers for the proposed FLC 2b

Figure 4.11 shows the FLC models and their input and output variables modelled in MATLAB/Simulation.

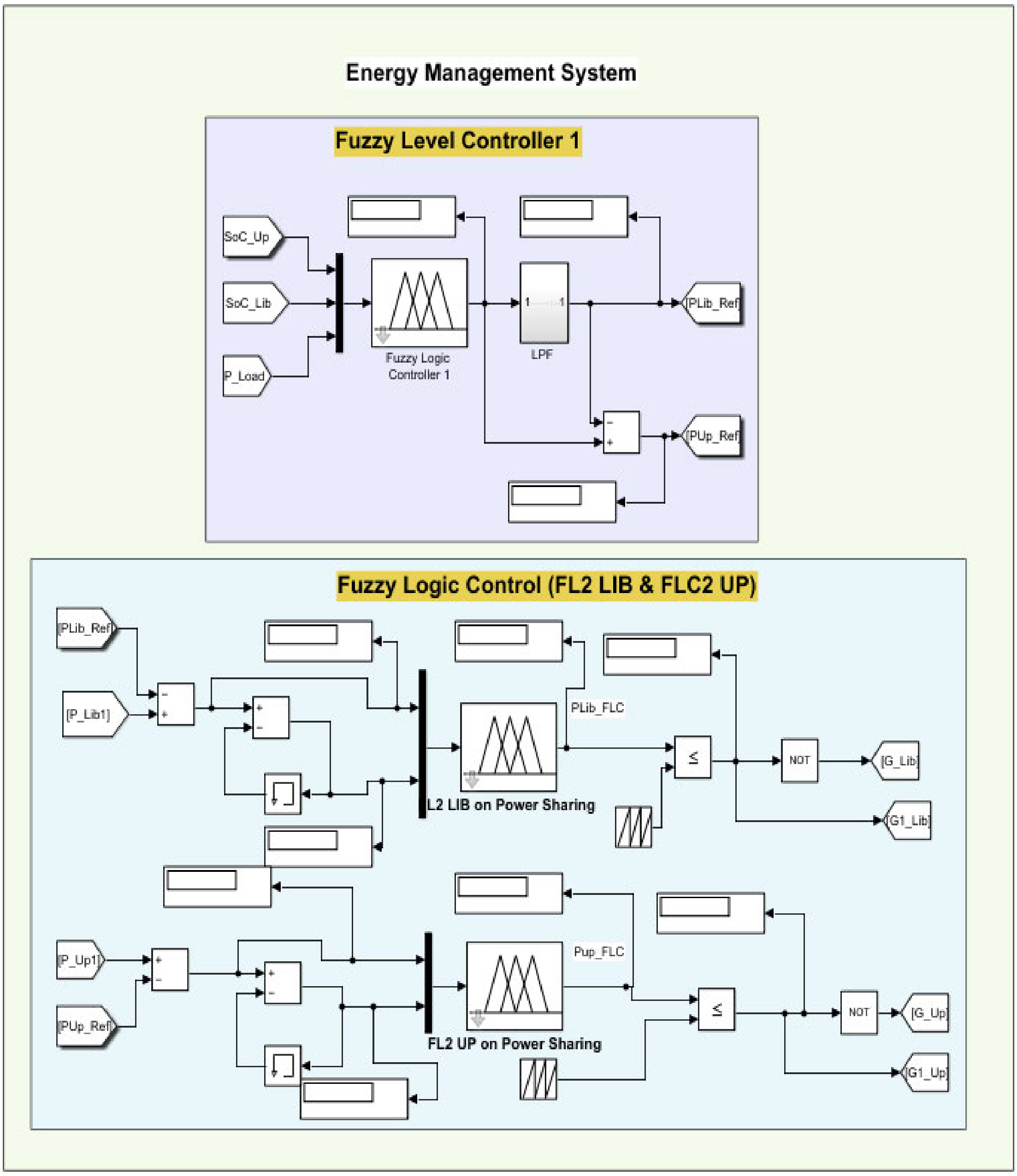

Figure 4.11. FLC model in MATLAB/Simulink

The membership functions of the input variables are shown in Figure 4.12 to 4.14.

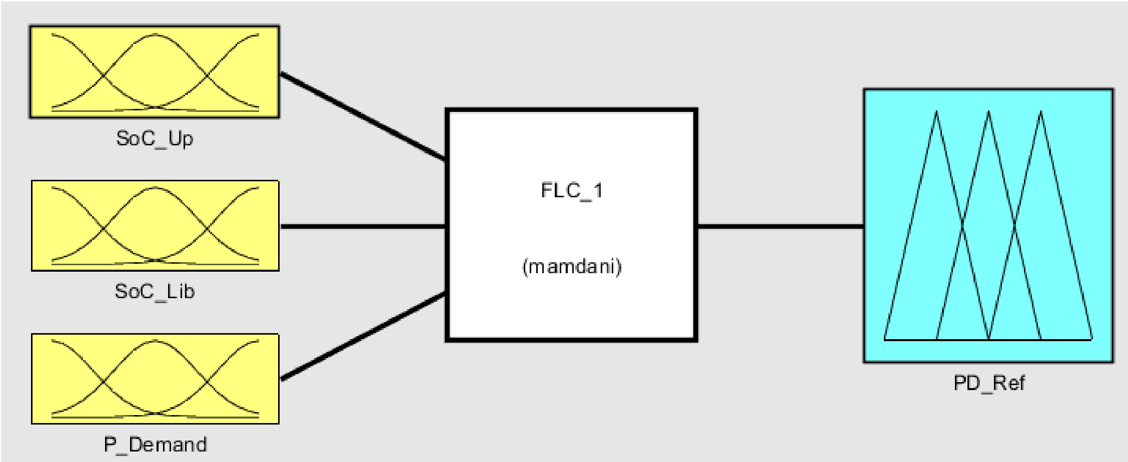

Figure 4.12. FLC 1 membership functions

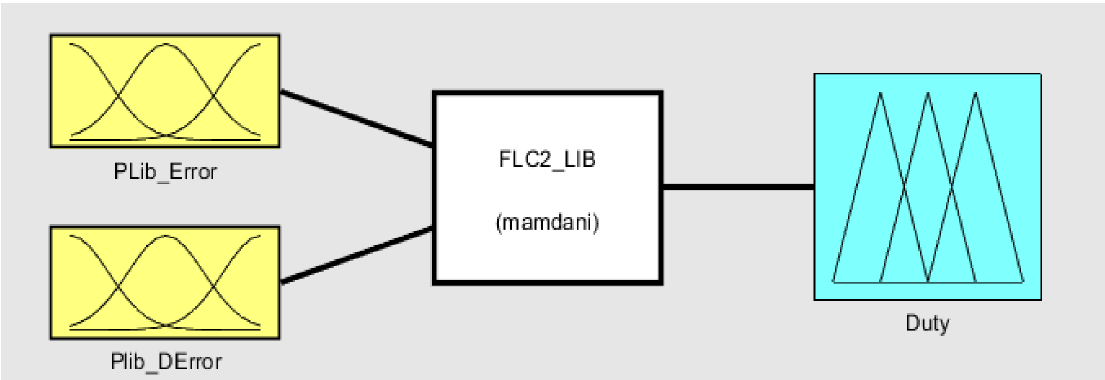

Figure 4.13. FLC 2a membership functions

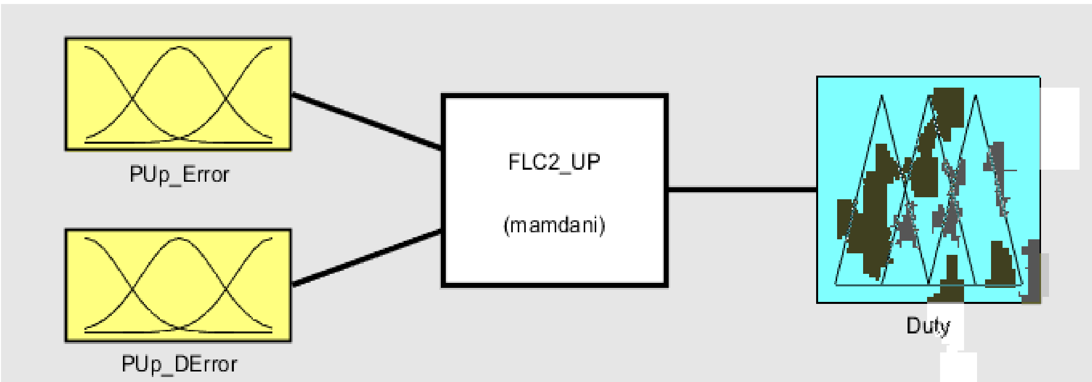

Figure 4.14. FLC 2b membership functions

Figure 4.15 shows $PD_{\_Ref}$ versus $SOC_{\_Lib}$ and $SOC_{\_UP}$ for FLC 1. Figure 4.16 shows Duty versus $PLib_{\_Eroor}$ and $PLib_{\_DError}$ for FLC 2a, and Duty versus $PUp_{\_Eroor}$ and $PUp_{\_DError}$ for FLC 2b.

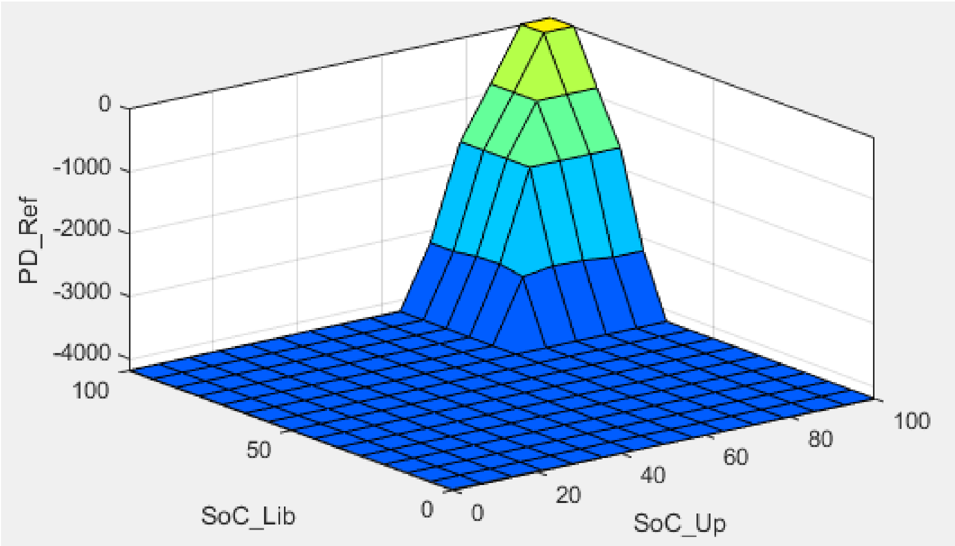

Figure 4.15. The proposed FLC 1's generated surface

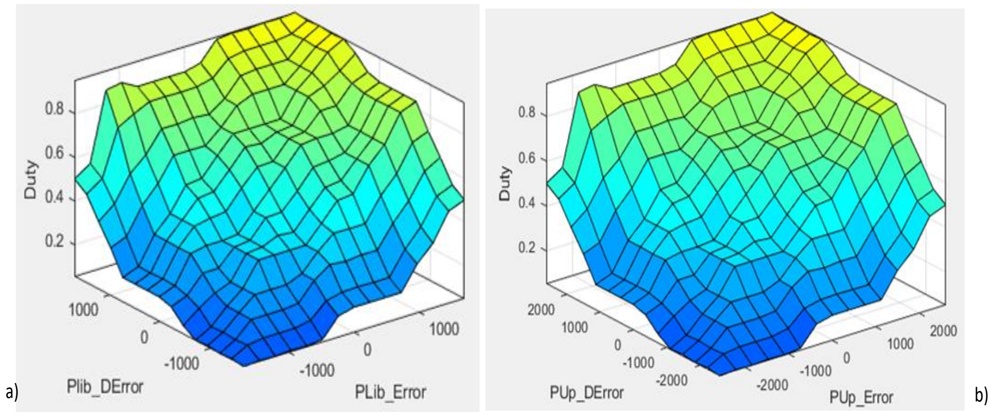

Figure 4.16. The proposed FLC 2a and FLC 2b's created surface.

4.6 Hybrid Lithium-Ion-Ultracapacitor Energy Storage System with Energy management System

The fully Hybrid Energy Storage System with Energy Management Strategy is developed, demonstrated and simulated using MATLAB/Simulink software as is shown in Figure 4.17.

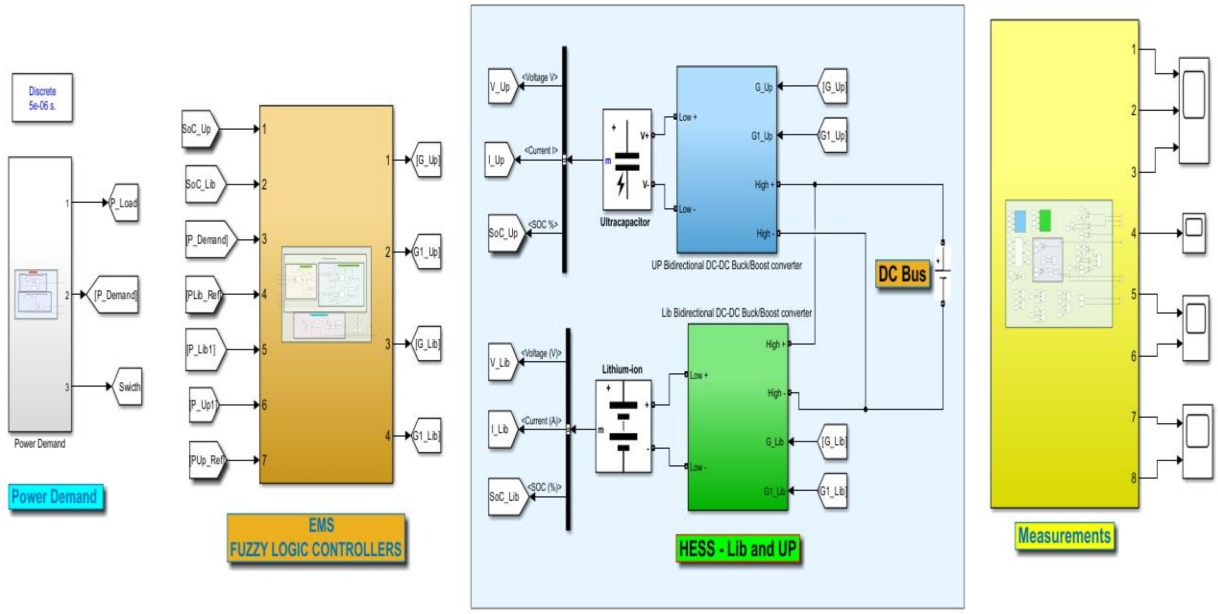

Figure 4.17. The proposed HESS LIB and UP ESS

4.7 Conclusion

The suggested hybrid Lead-Acid and Ultracapacitor Energy Storage System with Energy Management Strategy for Transport Vehicles is designed, presented, and simulated using the MATLAB/Simulink software. Mathematical models and the conditions outlined in chapter 3 are used to model the system. Current demand, the characteristics, and the parameters of the battery and Ultracapacitor technology are taken into consideration when deciding how much current to share between the hybrid system.

To distribute the current demand within the hybrid system, the FLC toolbox (mamdani) from the MATLAB/Simulink library is used to create the EMS based on FLC. The FLC1 determines the total reference power (PD_p_{Ref}) based on the power demand (P_{Demand}) while ensuring the LIB SoC is within the minimum and maximum range. The FLC2 (FLC2a and FLC2b) allocate the reference powers to LIB and Up based on the total reference power, by controlling the LIB's and UP's voltage and current flow during the charging and discharging process.

5 Chapter 5: Results and Discussion

5.1 Introduction

The suggested hybrid lithium-ion and Ultracapacitor energy storage system with energy management strategy is modelled and simulated in the MATLAB/Simulink software, and the results are presented in this chapter. The proposed model ensures that meets the load demand while increasing the lifespan of the LIB. Furthermore, the proposed HESS is compared with a single LABs and LIBs of the same size based on the delivery power, SoC and the voltage. The power demand of the three cases is based on the size of TVs. Case one has power demand of 4200 W, 7080 W for case two, and 7800W for case three.

5.2 Load demand

The power demand of the three cases is generated in MATLAB/Simulink software based on - the size of TVs. Figure 5.1 shows that the case one has power demand of 4200 W, 7080 W for case two, and 7800W for case three.

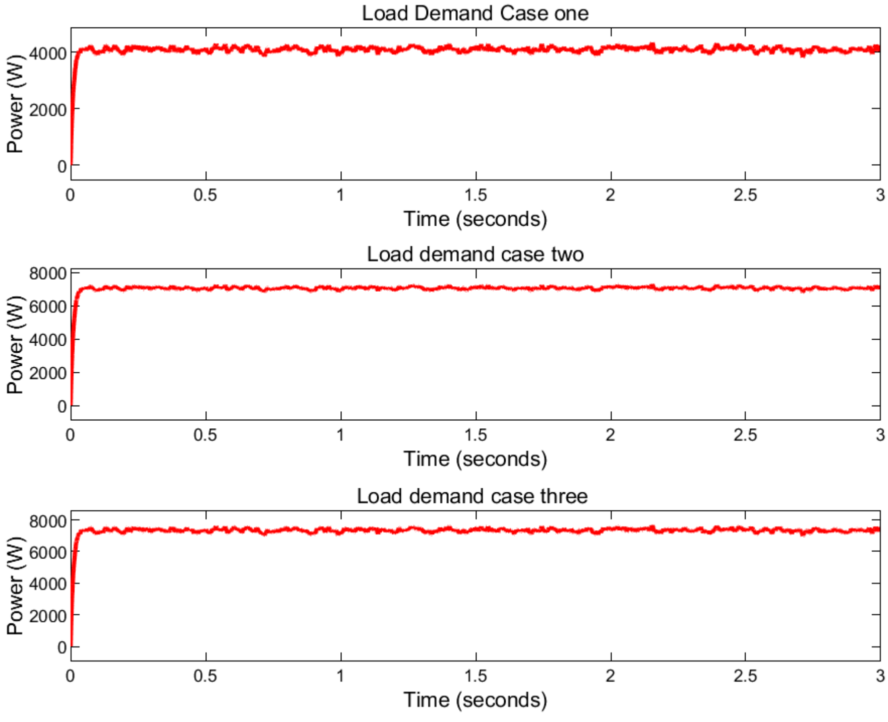

Figure 5.1. The load demand results for Cases one, two and three

5.3 Bidirectional DC/DC Buck-Boost *Converter*

Figures 5.2 and 5.3 display the current and voltage responses of the two bidirectional dc-dc buck-boost converters (LIB and UP). The average LIB responses in terms of voltage and current are 12.8 V and 50 A. The typical UP responses in terms of current and voltage are 60 A and 12 V. The voltage response of the UP is slightly lower compared with LIB, while the current response of UP is slightly higher compared with LIB. It is due to the UP has a good power density, which allows to supply high power in very short time. From 0.1 second as is shown from the results, the energy storages start charging from alternator with a reference charging voltage of 14 V. The reference charging current is determined through FLC, and it varies based on the type of the load demand and the characteristics of the energy storages.

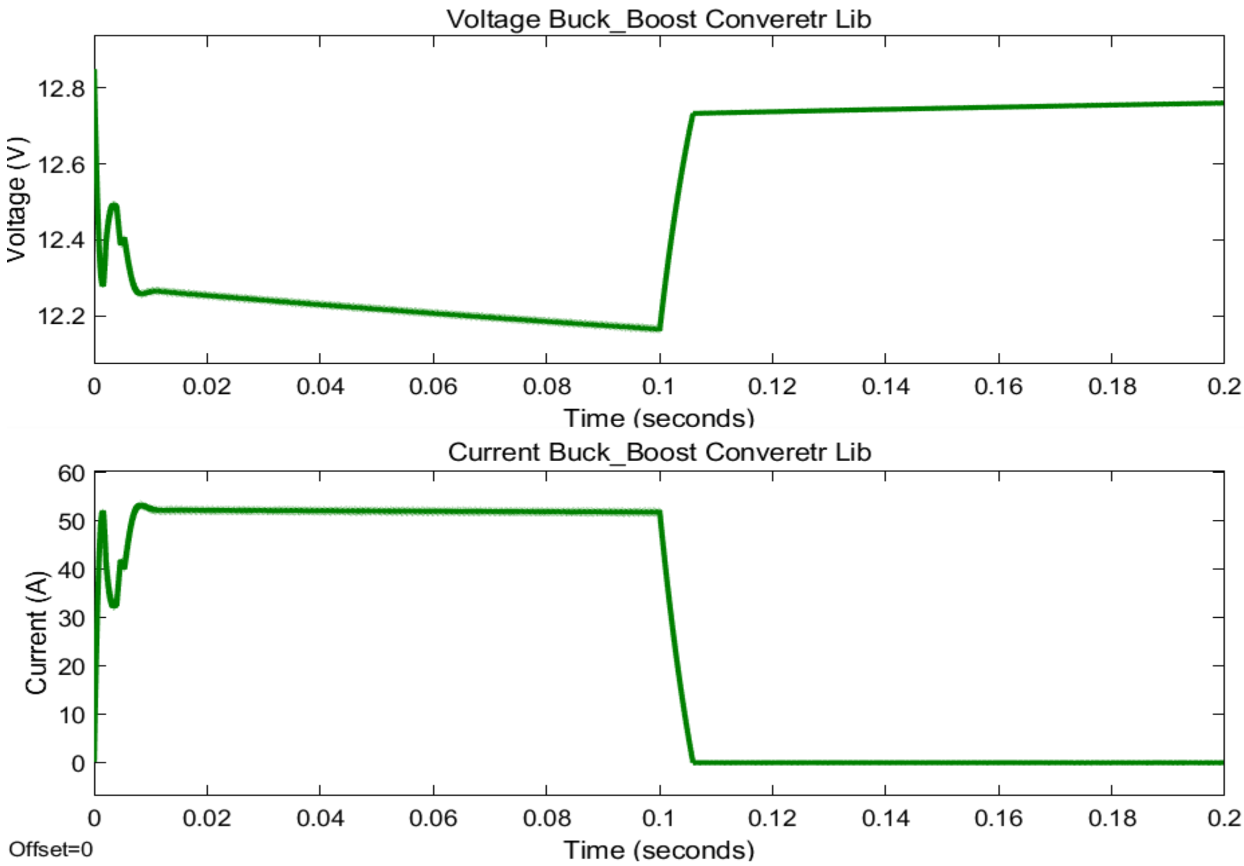

Figure 5.2. Bidirectional DC-DC buck and boost converter from Lib's output voltage and current

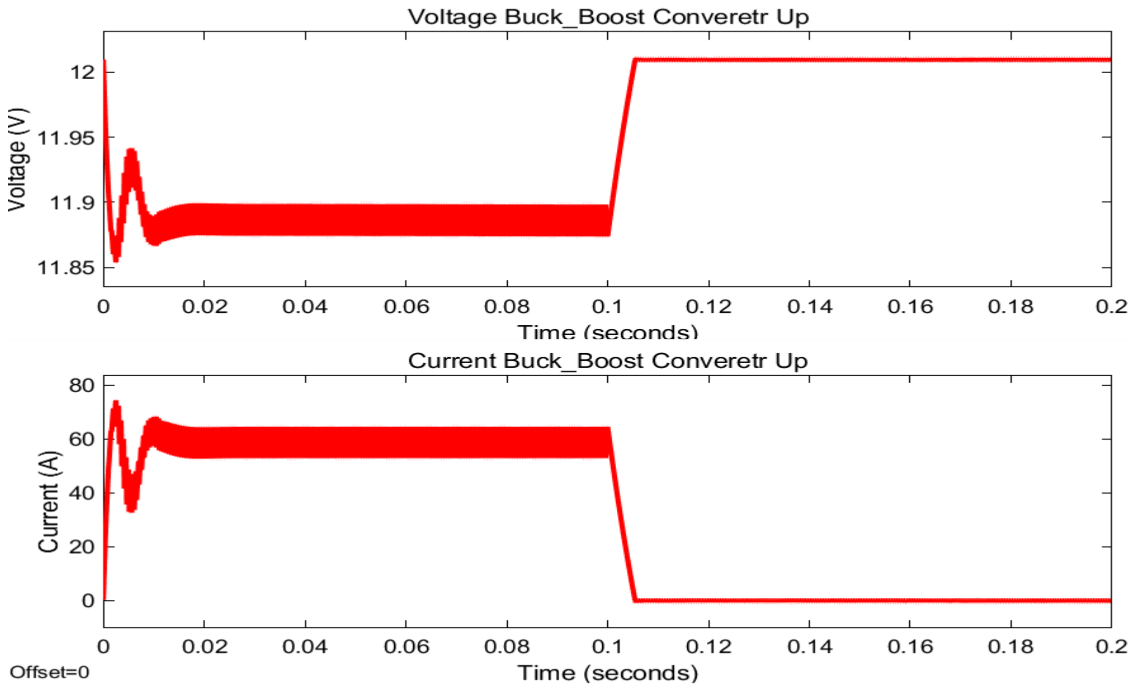

Figure 5.3. Up bidirectional DC-DC buck and boost converter output voltage and current

5.4 FLC ouput response

Figure 5.4 shows the FLC 1 output response for case one. The same approach is applied for case two and three. The results show the reference power of each energy storage. The reference power for LIB is 1680 W which correspond to 40% of the required power, while the remind 60%, 2520 W is the reference power for UP.

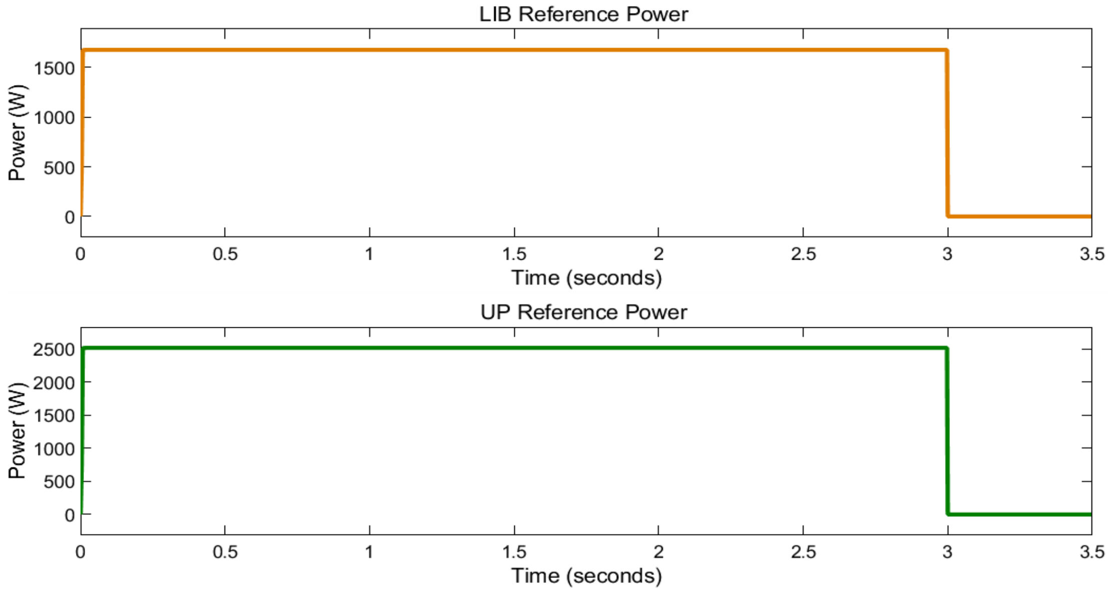

Figure 5.4. FLC 1 Reference Power Demand

The reference power from the FLC1 is send to power sharing FLC 2. Figure 5.5 shows the FLC 2 power sharing relational operator.

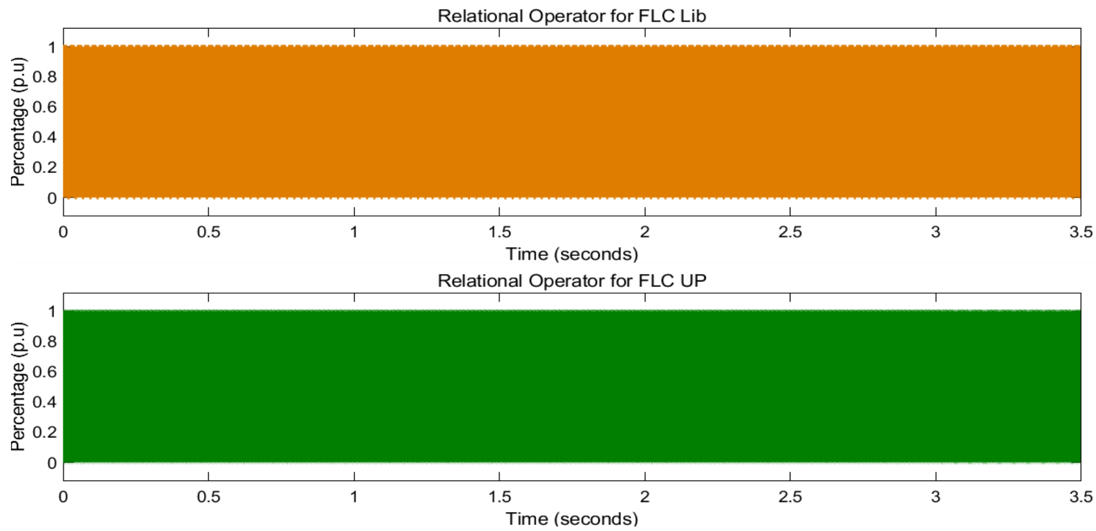

Figure 5.5. FLC 2 Power sharing Rational Operator

The two gates for the DC-DC generators are interconnected; one conducts when the other tuner is off. The output of the two gates, which are functioning at different times and are coupled to one another in Figure 5.6, is seen in action. The outcome reveals that the switch for gate 2 is open during charging mode.

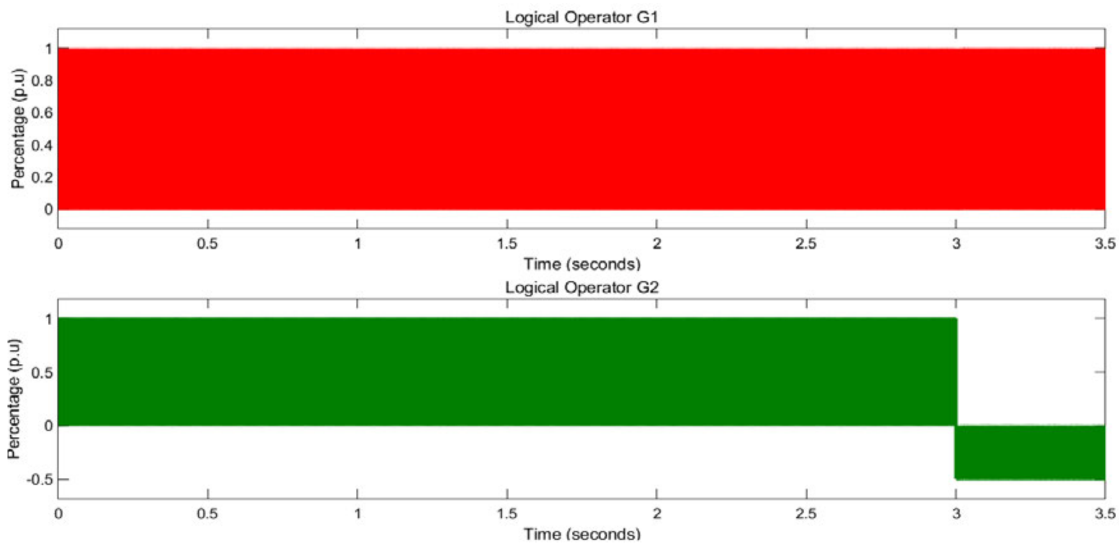

Figure 5.6. Bidirectional dc-dc buck-boost converter generator and logic operator

5.5 The Proposed HESSs with EMS Results

The simulation results of the proposed research study on HESS with EMS are detailed in this section. To analyse and validate the research study of HESSs, simulation is used. The improvement of LIBs' lifespan performance is the foundation for the validation. The HESS charges itself from the alternator, which is represented with a bus voltage, and then provides the necessary power demand for the TVs to start for 3 seconds.

Three cases were studied, developed and simulated in MATLAB/Simulink. The case studies are represented in different power demand. The simulations were done using the following conditions:

i) Case 1 shows the research study's peak demand of 4200 W, Case 2 shows the peak demand of 7080 W, and Case 3 shows the peak demand of 7800 W. The two models that were constructed were the charging and discharging modes.

ii) The peak demand is supplied for 3 seconds to start the TV.

iii) During discharging mode, the HESS supplies the required power to start the TVs through an output voltage of 13 V and reference current which varies based on the load demand, size and characteristics of the batteries.

iv) In charging mode, a voltage source (alternator) with a voltage of 14.5 V is used to charge the HESS. Two bidirectional dc-dc buck-boost converters carry out this procedure by stepping up the voltage of the energy storages to 13 V during discharging mode and stepping down the voltage of the V bus to the charging reference voltage of 13.5 V during charging mode.

v) The maximum simulation time is 4.5 seconds. The HESS supplies power for 3 seconds and is then charged for 1.5 seconds from the alternator (bus voltage). This shorter charging time is due to limitations in MATLAB's memory capacity

5.5.1 The Proposed HESSs with EMS Case one (12 V – 40 Ah) Results

A peak demand of 4200 W is used to model the proposed HESS with EMS for case one over a period of 4.5 seconds. Comparing the outcomes to a single 12V-40 Ah LIB. The simulation results of the proposed HESS for case one is shown in Figure 5.7. The results indicate that the HESS can meet the peak demand of 4200 W to run the TVs by supplying a maximum power of 4355 W for 3 seconds.

The load demand is 0 W after 3 seconds, indicating that the TV is running. The car receives the necessary energy from the alternator (bus voltage), which also charges the HESS. The HESS is charged with maximum charging power of -679.1 W. The charging current of – 77.3 A, which varies based on HESS's SOC. The HESS has a maximum charging voltage V_{bus} of 14.5 V. As the HESS's SOC is close to 100%, the charging current is near to 0 A, and charging voltage near to 14.5 V.

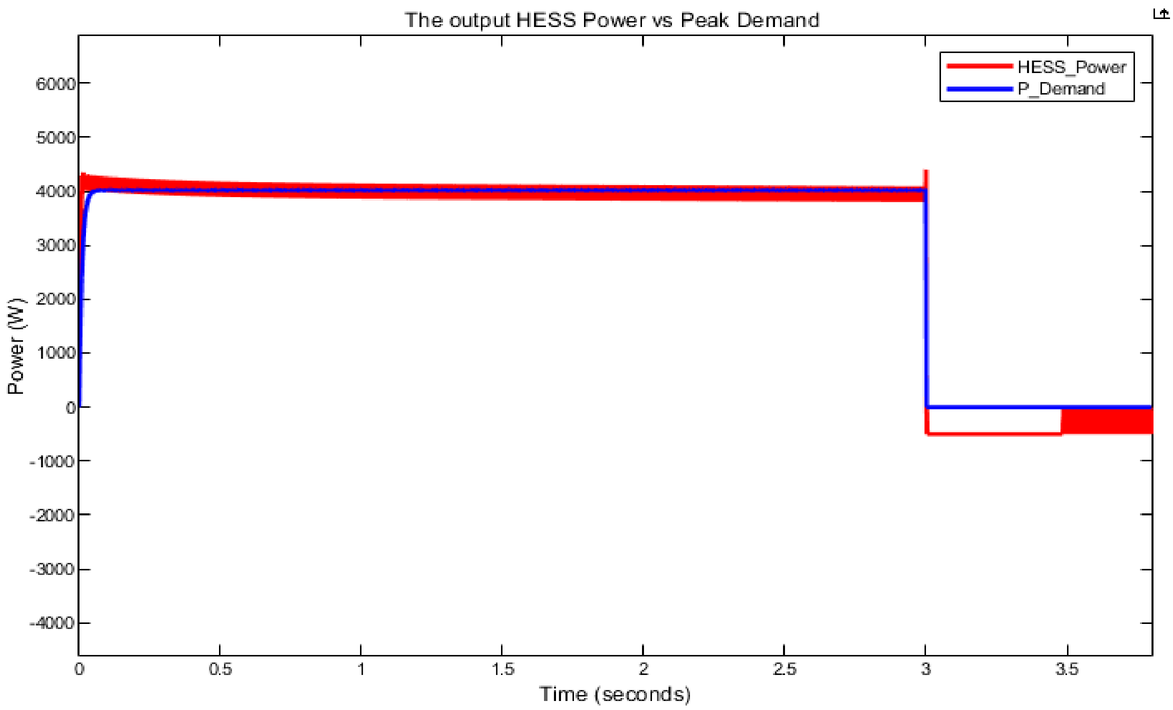

Figure 5.7. Simulation result for case one using the proposed HESS

The section provides details on the energy storages in HESS during the discharging and discharging modes, including the % power supplied, charged, SOC, and current voltage responses.

The results in Figure 5.8 shows that the LIB supplies 1742 W which represents to the 40% of the peak demand. The minimum voltage is 13.3 V and SOC is 99.52%. The UP supplies 2613 W which represents to the 60% of the peak demand. The minimum voltage is 12.88 V and SOC is 90.62%.

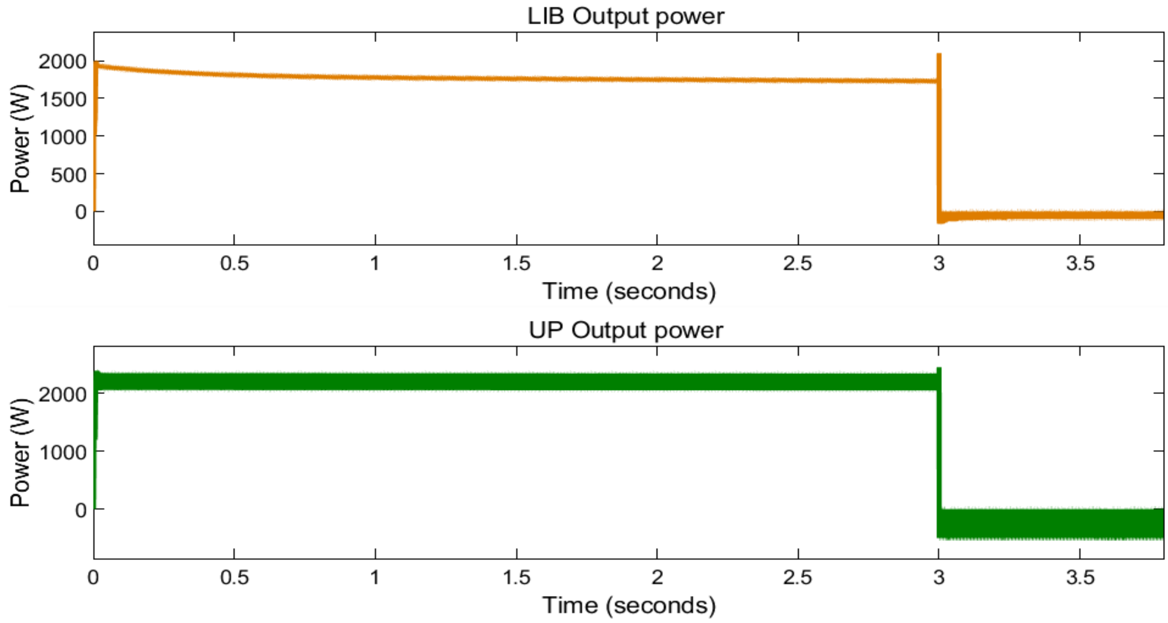

Figure 5.8. The percentage power supplied and the charging power for LIB and UP for case one

The detailed simulation results of the energy storage parameters (the current, voltage, and SOC) of the HESS energy storages in the discharging and charging modes are shown in Figures 5.9 and 5.10.

Figure 5.10 shows that the LIB's SOC starts to charge from 99.52 %, while the voltage response increases is from 13.3 V with charging reference voltage of 14.5 V and charging reference current of – 7.314 A. The Up's SOC starts to charge from 90.62 %, while the voltage response increases from 12.46 V with charging reference voltage of 14.5 V and charging reference current of – 73.3 A.

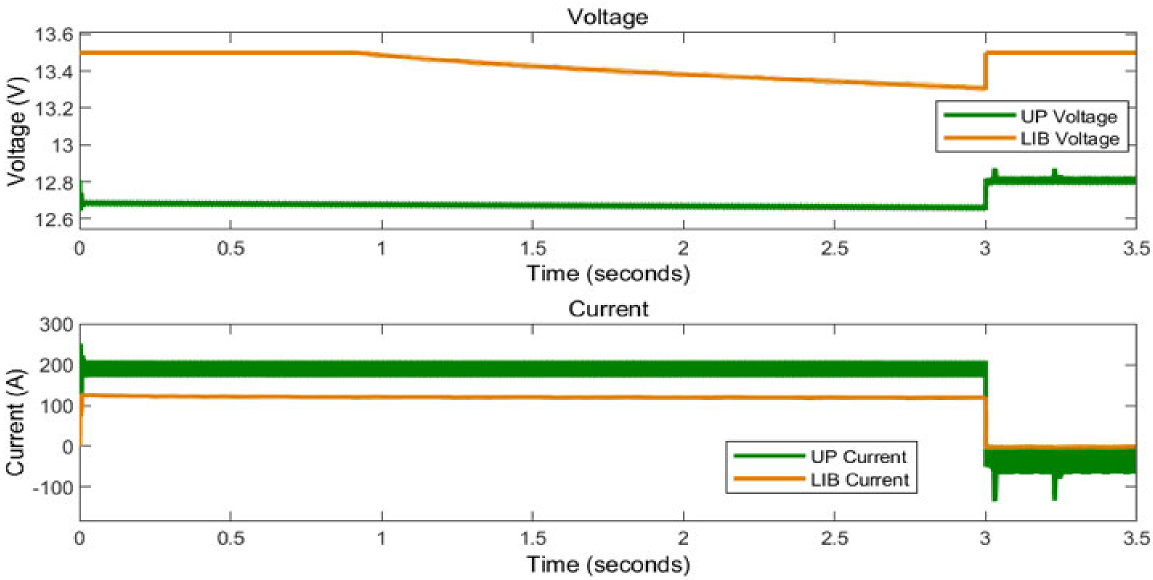

Figure 5.9. The energy storage systems' current and voltage responses in case one

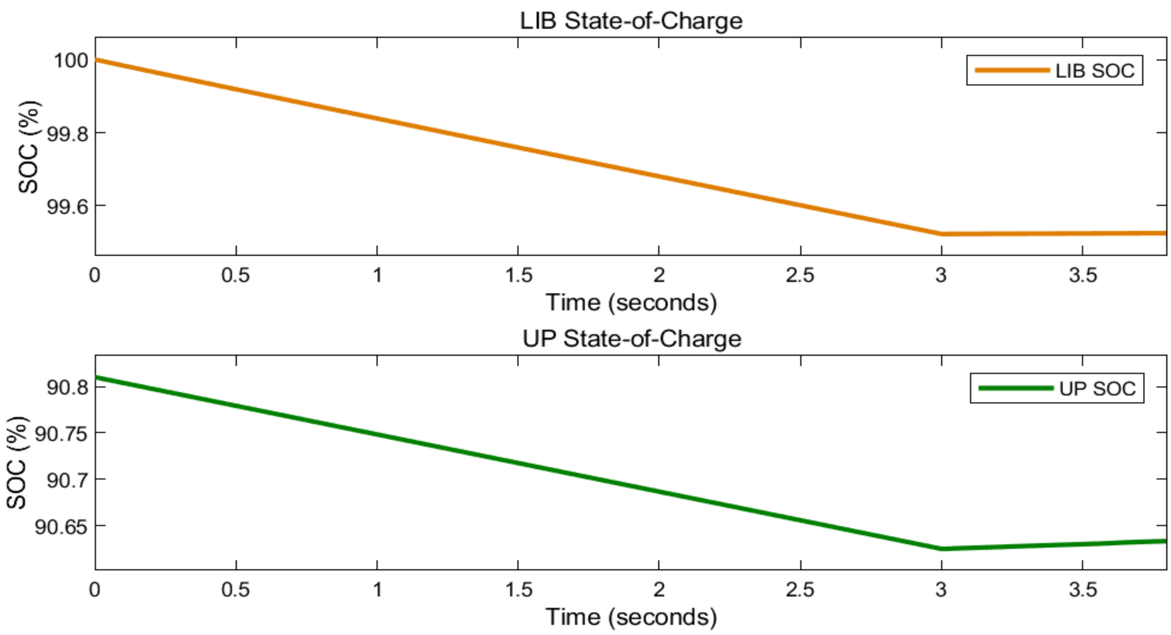

Figure 5.10. The detailed SOC of LIB and UP during charging and discharging modes for case one

5.5.2 The Proposed HESSs with EMS Case two (12 V – 70 Ah) Results

A peak demand of 7080 W is used to model the proposed HESS with EMS for Case one over a period of 4.5 seconds. Comparing the outcomes to a single 12V-70 Ah LAB.

The simulation results of the proposed HESS for case two are shown in Figure 5.11. The results indicate that the HESS can meet the peak demand of 7080 W needed to run the TVs by supplying a maximum power of 7381 W for 3 seconds.

The load demand is 0 W after 3 seconds, indicating that the TV is running. The car receives the necessary energy from the alternator (bus voltage), which also charges the HESS. The HESS is charged with maximum charging power of – 899 W. The charging current of – 66.9 A, which varies based on HESS's SOC. The HESS has a maximum charging voltage V_{bus} of 14.5 V. As the HESS's SOC is close to 100%, the charging current is near to 0 A, and charging voltage near to 14.5 V.

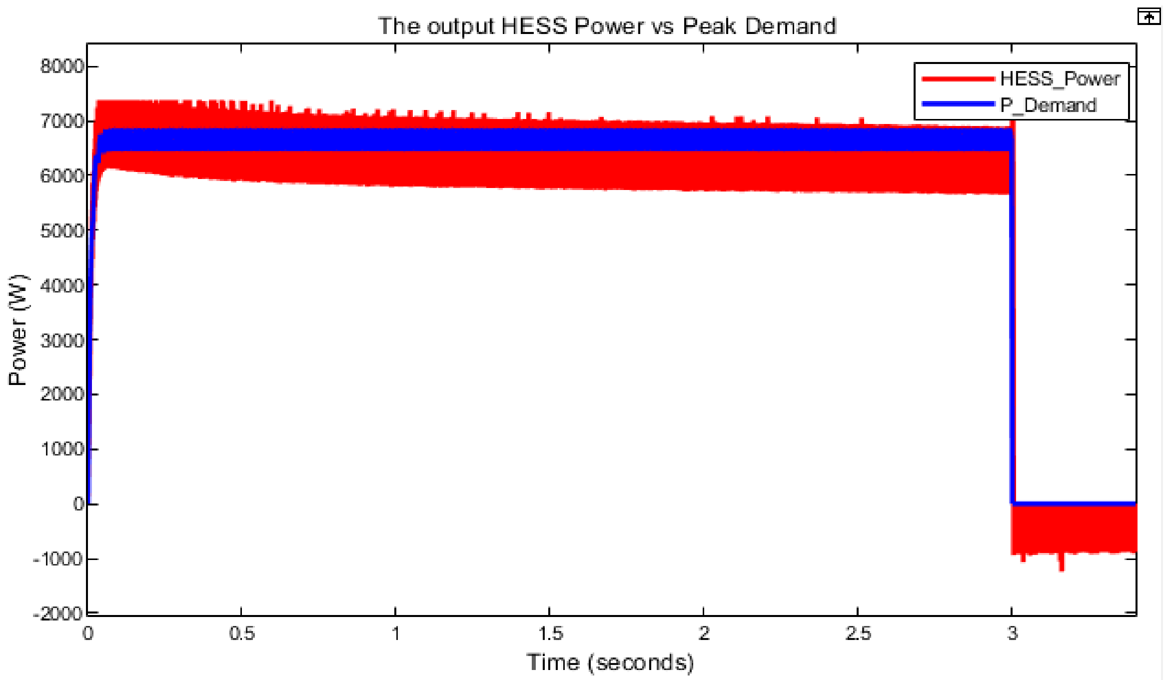

Figure 5.11. Simulation result for case two using the proposed HESS

This section provides details on the energy storages in HESS during the discharging mode, including the percentage power supplied, SOC, and current voltage responses. The results in Figure 5.12 shows that the LIB supplies 3199 W which represents to the 40% of the peak demand. The minimum voltage is 13.2 V and SOC is 99.05%. The UP supplies 4211 W which represents to the 60% of the peak demand. The minimum voltage is 12.81 V and SOC is 89.48 %.

The percentage power supplied, charged, SOC, current voltage responses of the energy storages in HESS during discharging and discharging modes are detailed in the section.

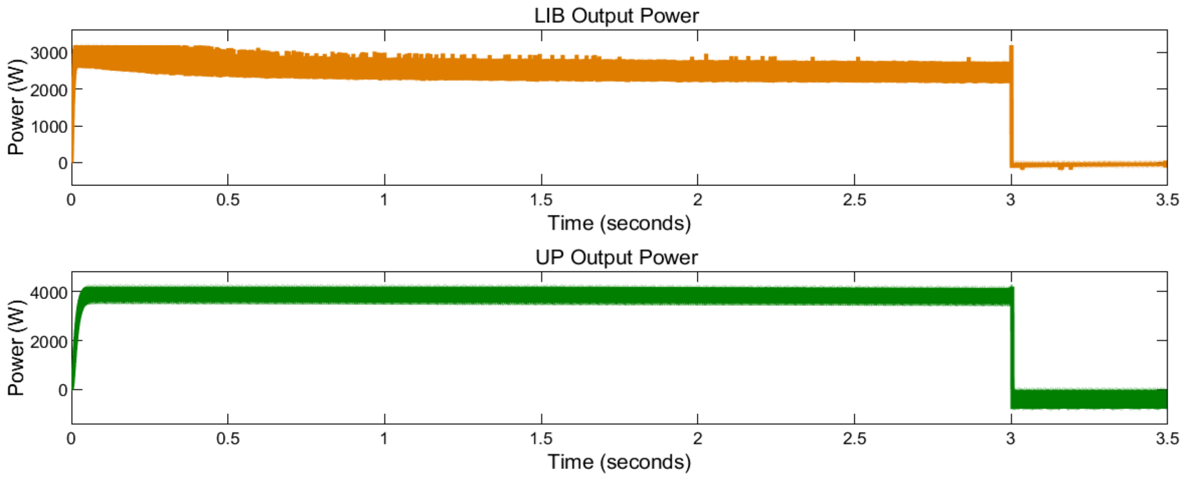

Figure 5.12. The percentage power supplied and the charging power for LIB and UP for case two

The detailed simulation results of the energy storage parameters (the current, voltage, and SOC) of the HESS energy storages in the discharging and charging modes are shown in Figures 5.13 and 5.14.

Figure 5.14 shows that the LIB's SOC starts to charge from 99.05 %, while the voltage response increases is from 12.3 V with charging reference voltage of 14.5 V and charging reference current of – 9.984 A. The Up's SOC starts to charge from 89.48 %, while the voltage response increases is from 11.41 V with charging reference voltage of 14.5 V and charging reference current of – 9.984 A.

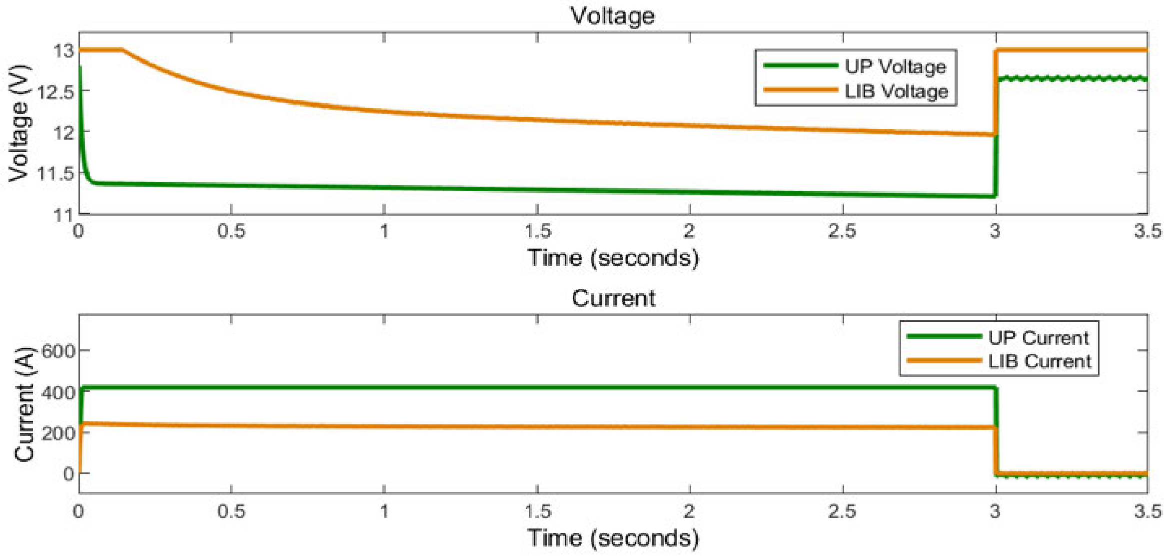

Figure 5.13. The energy storage systems' response to current and voltage in case two

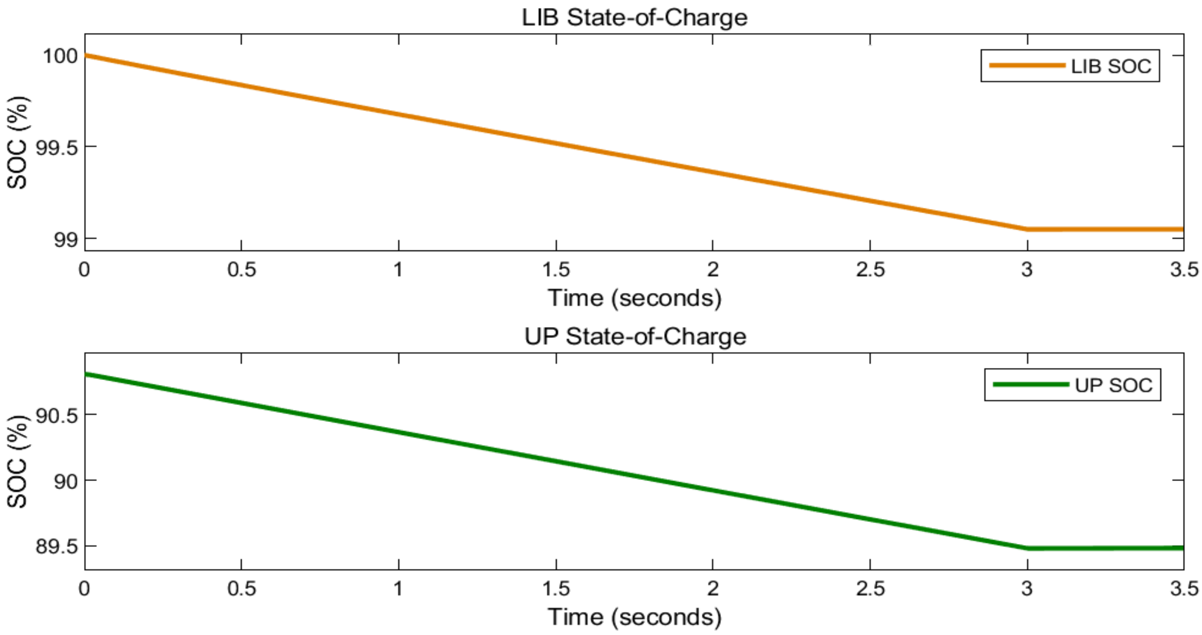

Figure 5.14. The detailed SOC of LIB and UP during charging and discharging modes for case two

5.5.3 The Proposed HESSs with EMS Case three (12 V – 90 Ah) Results

For case three, a simulation of the proposed HESS with EMS during 3.5 seconds. There is a 7 800 W peak demand. The results are compared with one 12V-90 Ah LIB. The simulation results of the proposed HESS for case three are displayed in Figure 5.15. The results indicate that the HESS can meet the peak demand of 7800 W needed to turn on TVs by supplying a maximum power of 7920 W for 3 seconds.

The load demand is 0 W after 3 seconds, indicating that the TV is running. The car receives the necessary energy from the alternator (bus voltage), which also charges the HESS. The HESS is charged with maximum charging power of - 995.8 W The charging current of – 78.78 A, which varies based on HESS's SOC. The HESS has a maximum charging voltage V_{bus} of 14.5 V. As the HESS's SOC is close to 100%, the charging current is near to 0 A, and charging voltage near to 14.5 V.

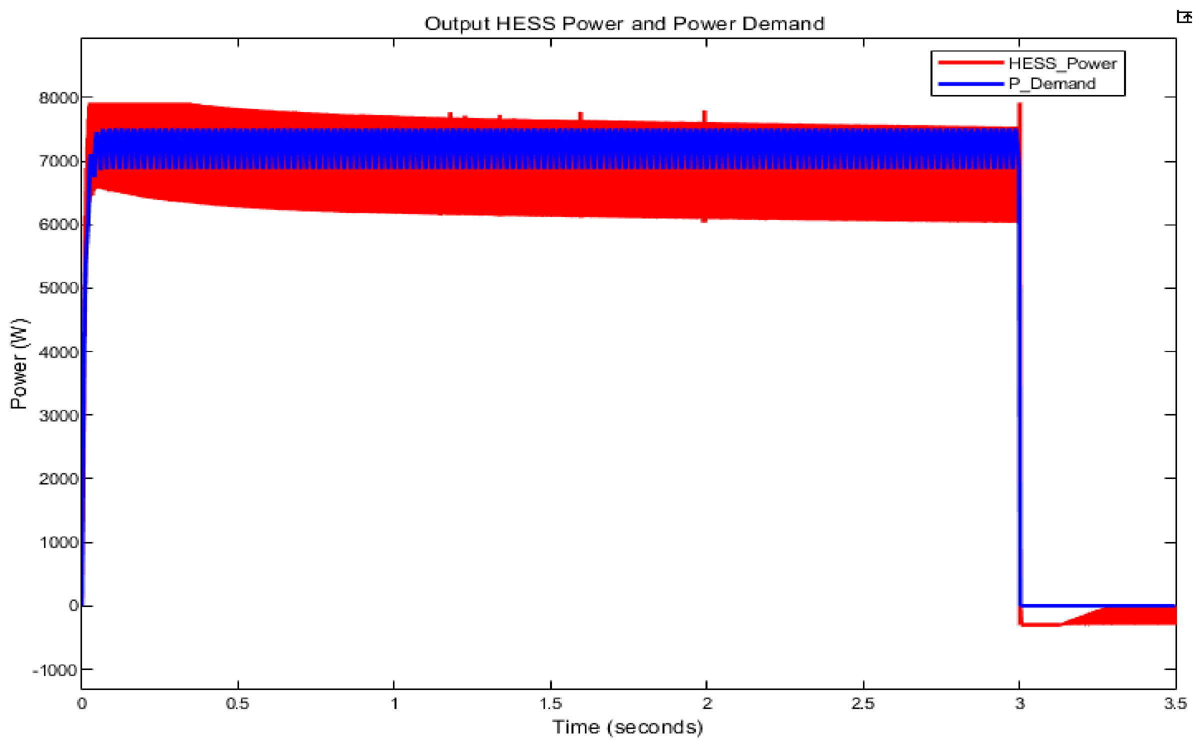

Figure 5.15. Simulation result of the HESS for case three

The percentage power supplied by each energy storage device during charging and discharging, and the individual charging power is shown in Figure 5.16. The results show that the LIB supplies maximum power of 3247.2 W, which represents to the 41% of the peak demand. It charges with maximum power of - 206.2 W. While UP supplies maximum power of 4672.8 W, which represents to the 59% of the peak demand. It charges with maximum power of – 889.7W.

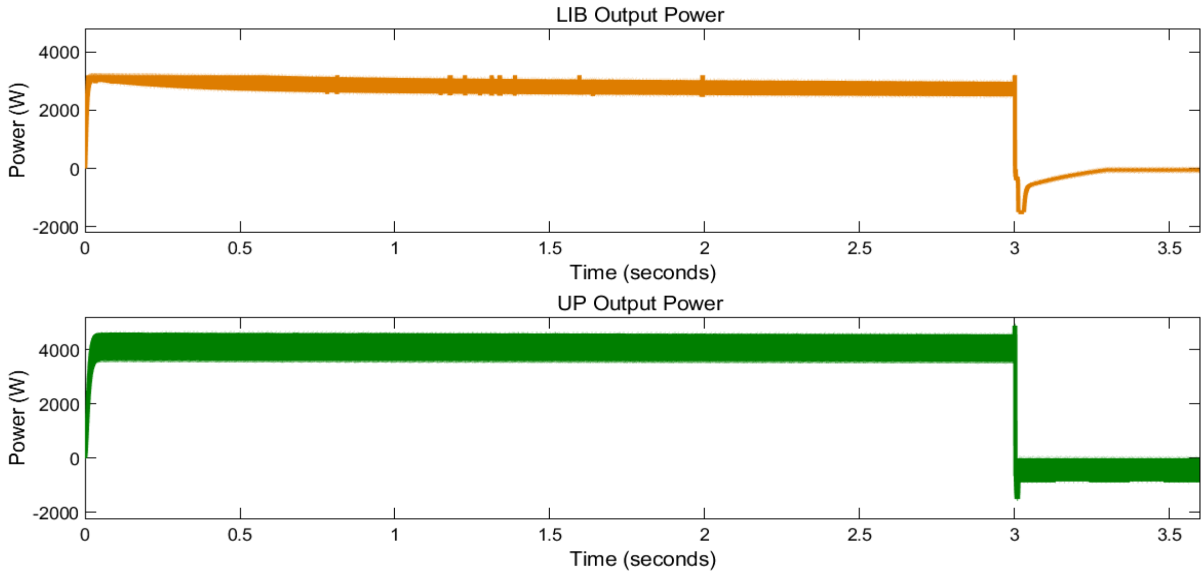

Figure 5.16. The percentage power supplied and the charging power for LIB and UP for case three

The individual parameters of the UP and LIB are shown in Figures 5.17 and 5.18, the results shows that LIB has a minimum voltage of 12.5 V, maximum current of 309 A, and minimum SOC of 99.07%. The UP has a minimum voltage of 11.68 V, maximum current of 495.5 A, and minimum SOC of 90.07% during charging mode.

During charging mode, the proposed HESS were analysed in 6 seconds. LIB's SOC starts to charge from 99.12 %, while the voltage response increases from 12.5 V with charging reference voltage of 14.5 V and charging reference current of – 8.23 A. The Up's SOC starts to charge from 90.07 %, while the voltage response increases from 11.68 V with charging reference voltage of 14.5 V and charging reference current of – 45.46 A.

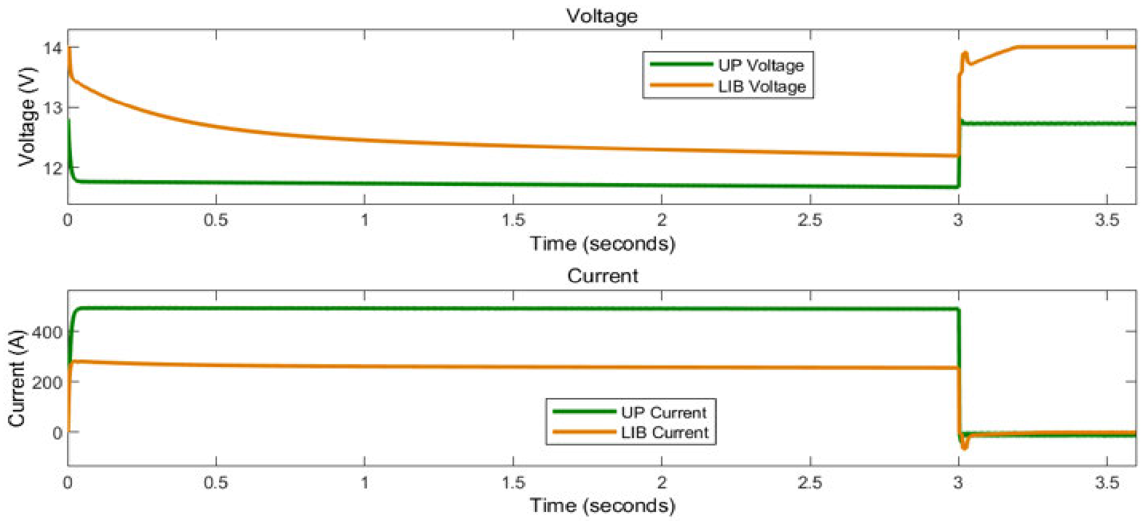

Figure 5.17. The Voltage and Current responses of the LIB and UP

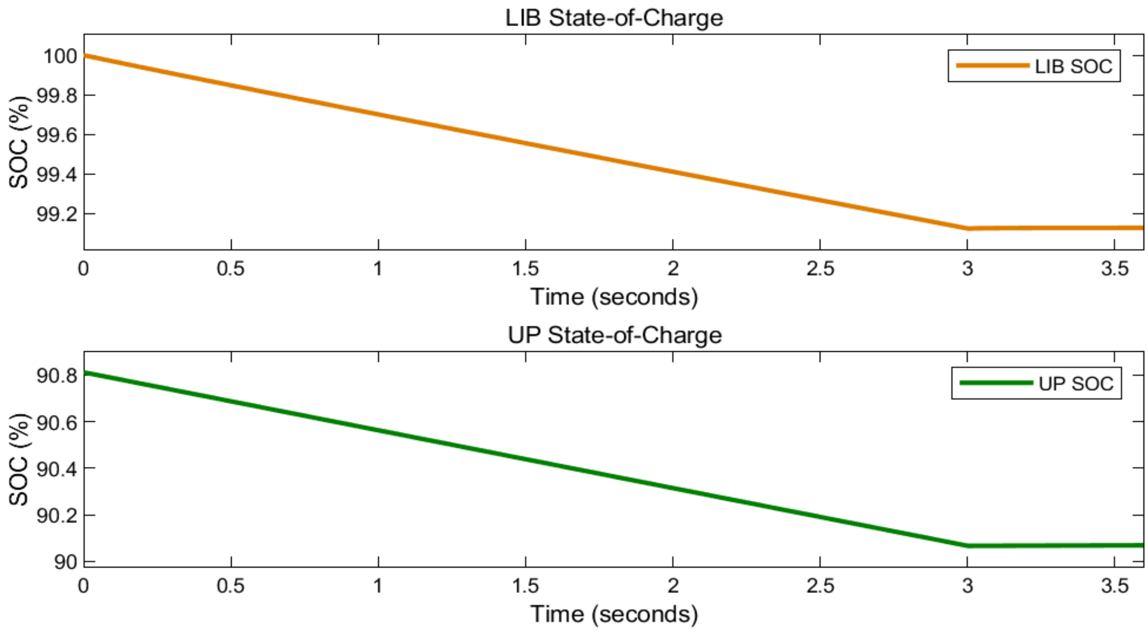

Figure 5.18. Detailed SOC of LIB and UP for case three

5.6 The proposed HESSs compared with Single LAB and Single LIB.

Results from single LAB and single LIB that are currently on the market are compared with those from the proposed HESS. In order to compare performance in terms of output power, voltage, current, SOC, and lifetime, the comparison is done in discharging mode. The evaluation of the output power's impact on the SOC, voltage, and lifetime of the LABs is done by analysis. The Single LAB and Single LAB model was simulated separated from HESS due to the high running time. The following conditions was considered:

- The SLAB and SLIB models were simulated for 3 seconds and separated from HESS model due to the high running time.
- The SLAB and SLIB Power were compared with the power demand.

Figure 5.19 shows SLAB results for case one. The SLAB 12V-40Ah supplies a maximum power of 4159 W. Figure 5.20 shows SLIB results for case one. The SLIB 12V-40Ah supplies a maximum power of 4320 W.

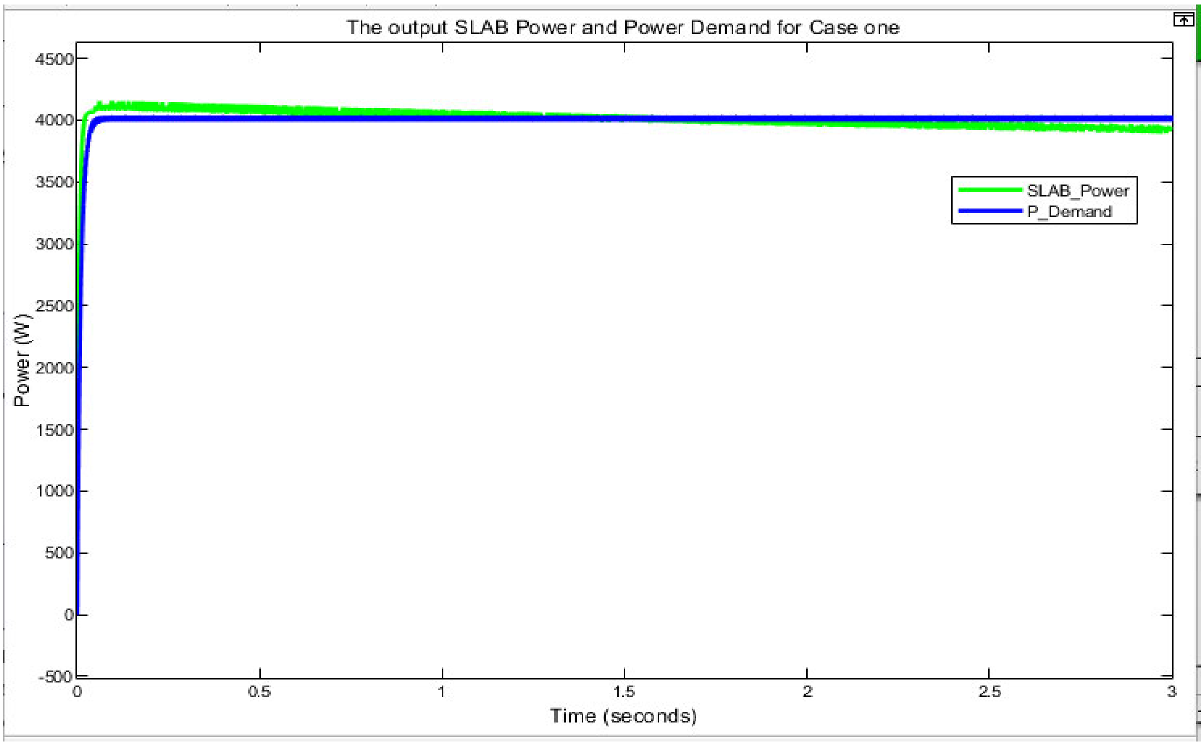

Figure 5.19. The delivered SLAB Power for case one

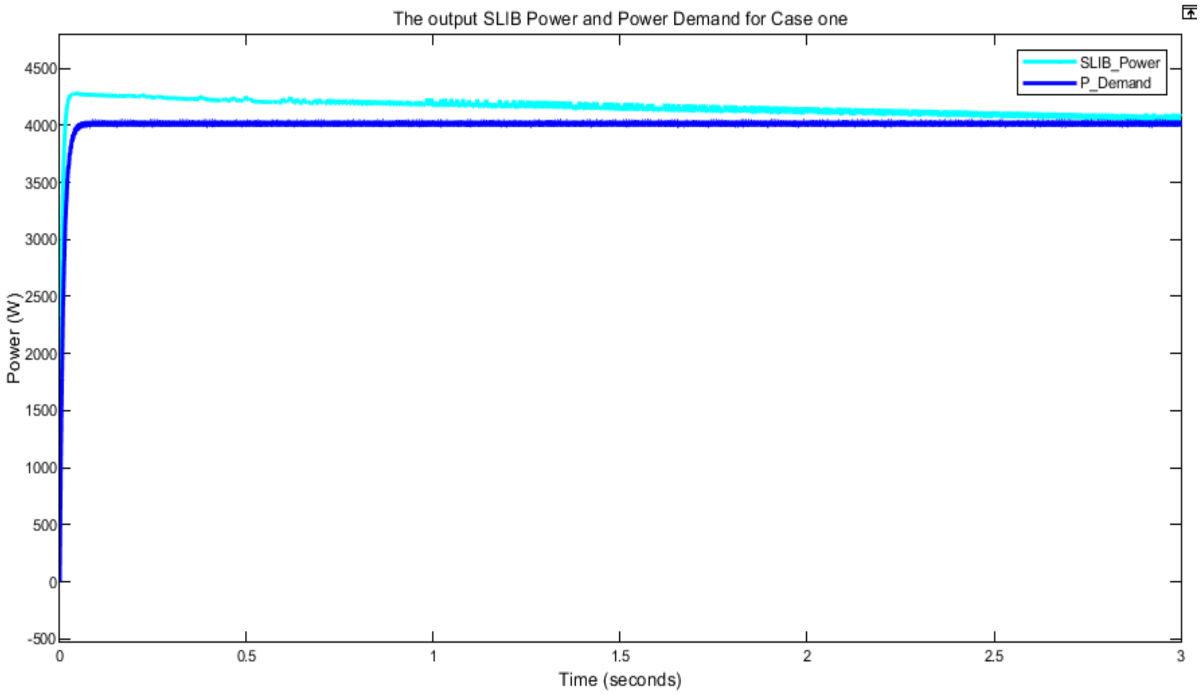

Figure 5.20. The delivered SLIB Power for case one

Figure 5.21 shows the minimum voltage response and maximum current of SLAB for case one is 11.3 V and 349 A. Figure 5.22 shows the minimum voltage response and maximum current of SLIB for case one is 11.32 V and 363.6A.

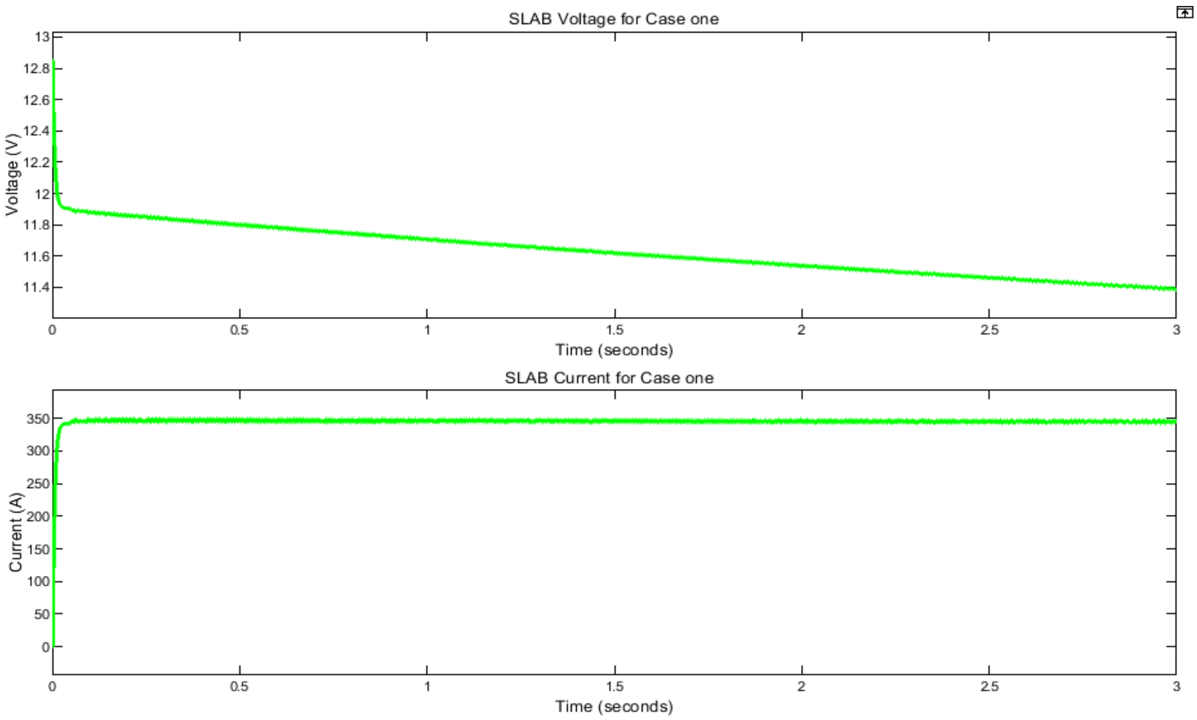

Figure 5.21. The delivery SLAB CCA and voltage response during discharging mode for case one

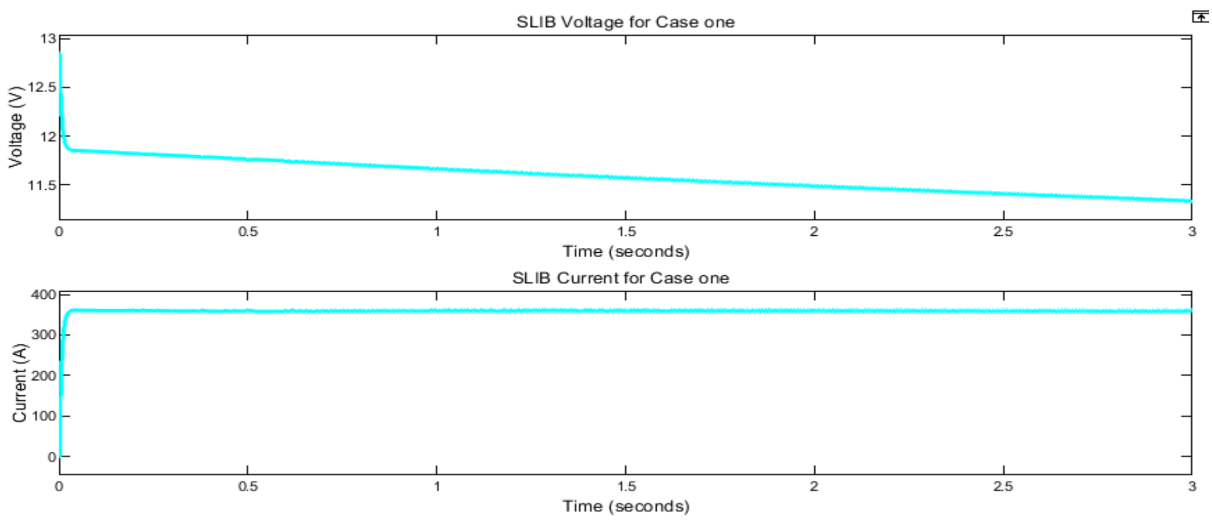

Figure 5.22. The delivery SLIB CCA and voltage response during discharging mode for case one

Figure 5.23 shows the minimum LIB's SOC after supplying the required CCA for 3 seconds is 99.52%.

Figure 5.24 shows the minimum SLAB's SOC after supplying the required CCA for 3 seconds is 99.27%.

Figure 5.25 shows the minimum SLIB's SOC after supplying the required CCA for 3 seconds is 96.25%.

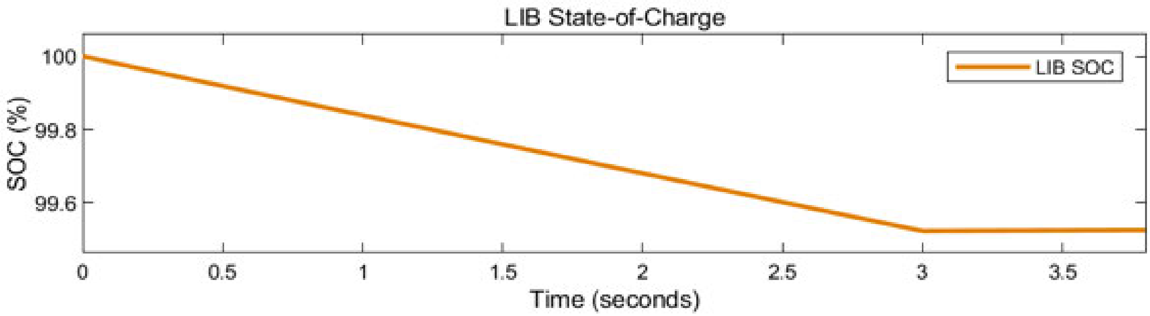

Figure 5.23. LIB State-of-Charge during discharging modes for case one

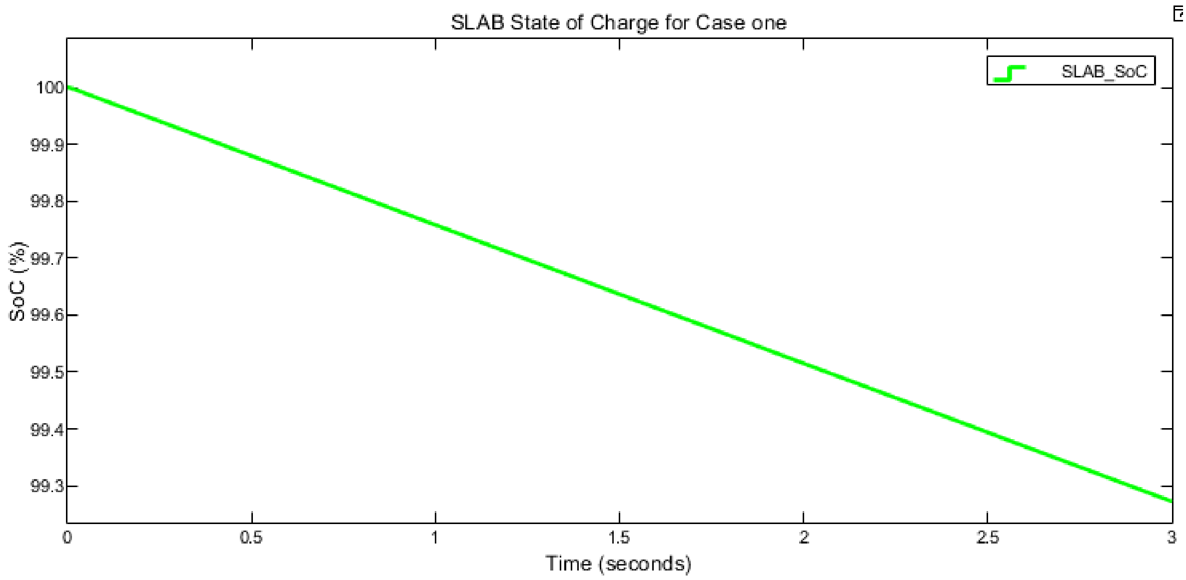

Figure 5.24. SLAB State-of-Charge during discharging modes for case one

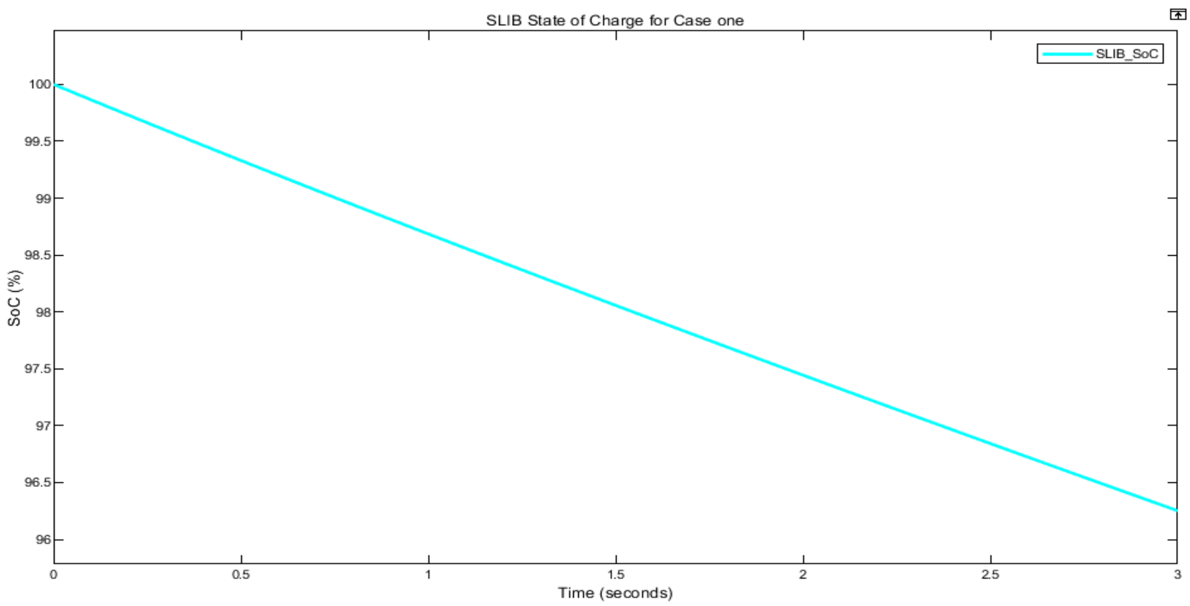

Figure 5.25. SLIB State-of-Charge during discharging modes for case one

For case 2, a single 12V-70Ah LAB in discharging mode for 3 seconds is compared with the proposed HESS for case 2 and Figure 5.26 shows SLAB results for case two. The SLAB 12V-70Ah supplies a maximum power of 7367 W. Figure 5.27 shows SLIB results for case two. The SLIB 12V-70Ah supplies a maximum power of 7371 W.

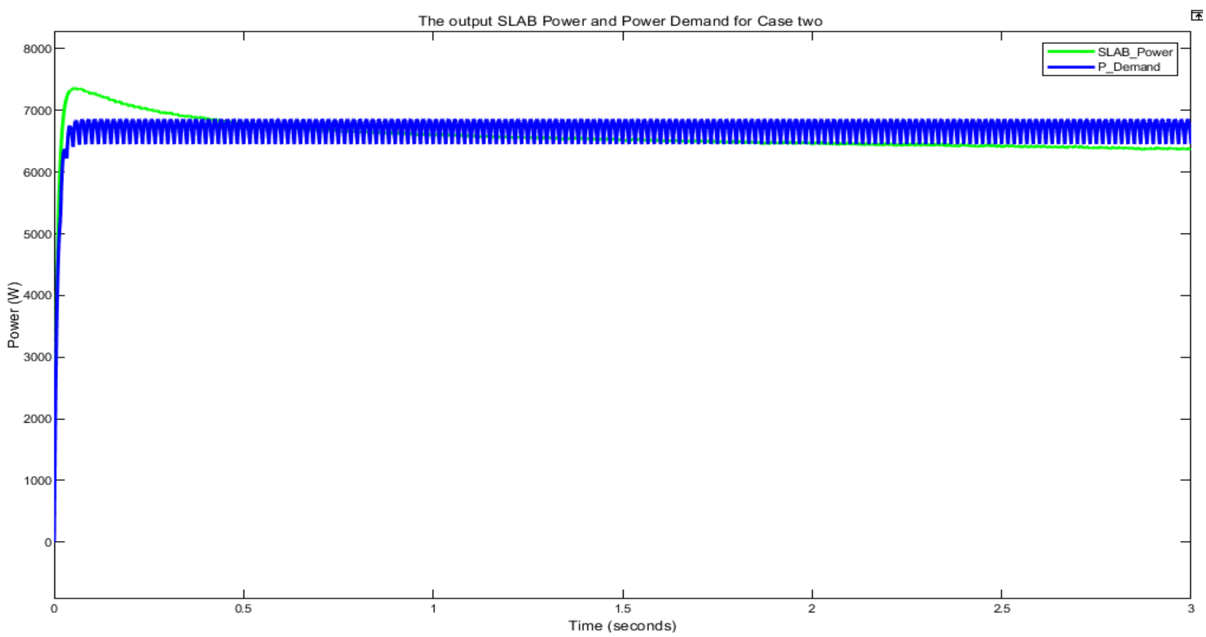

Figure 5.26. The delivered SLAB Power for case two

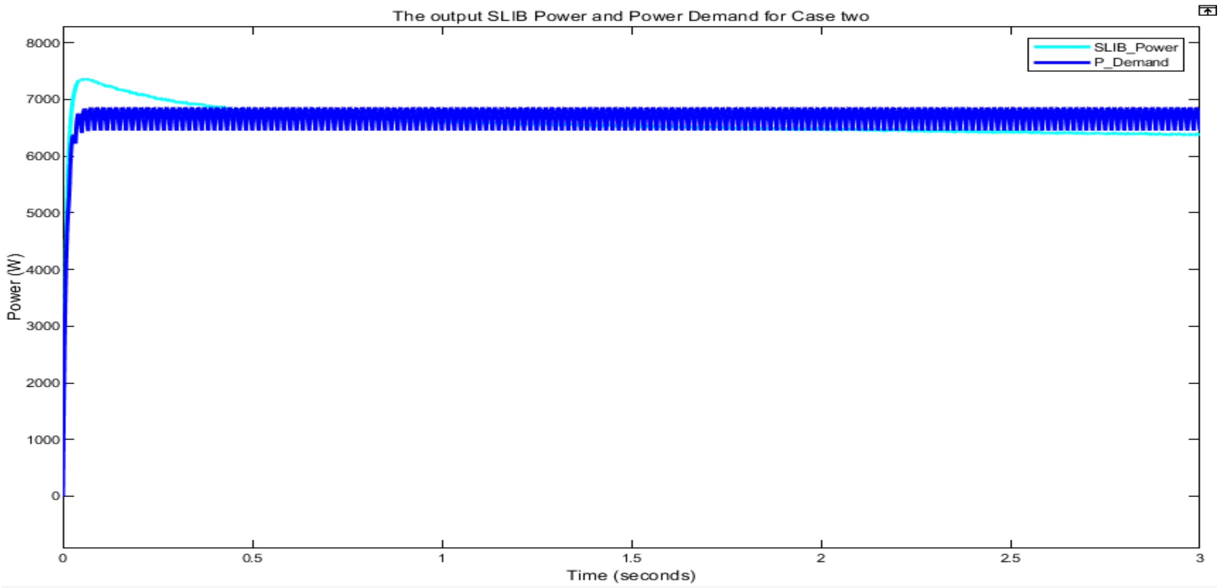

Figure 5.27. The delivered SLIB Power for case two

Figure 5.28 shows the minimum voltage response and maximum current of SLAB for case one is 10.92 V and 610 A.

Figure 5.29 shows the minimum voltage response and maximum current of SLIB for case one is 10.91V and 627.1A

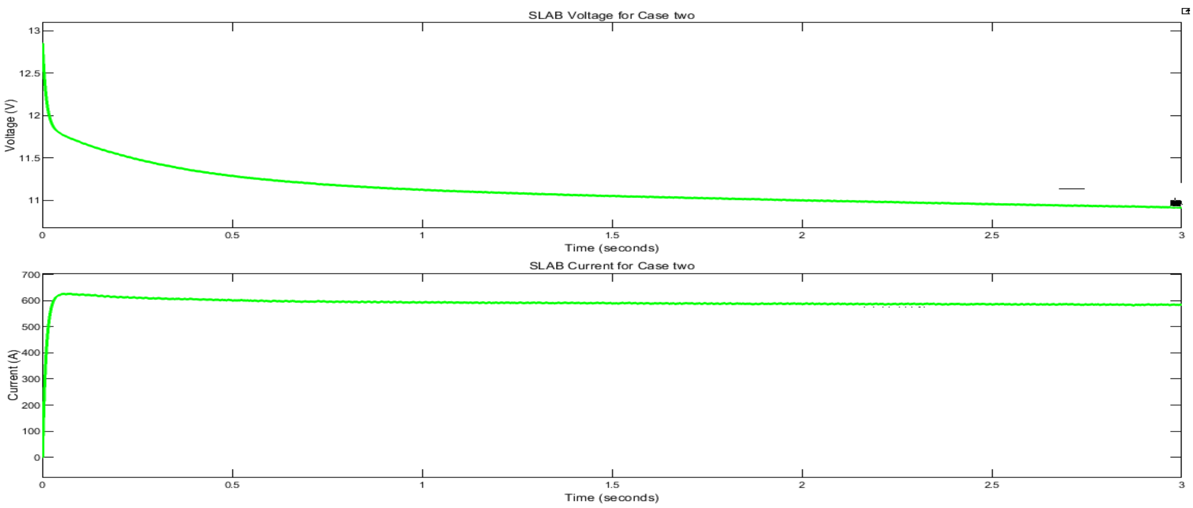

Figure 5.28. The delivery SLAB CCA and voltage response during discharging mode for case two

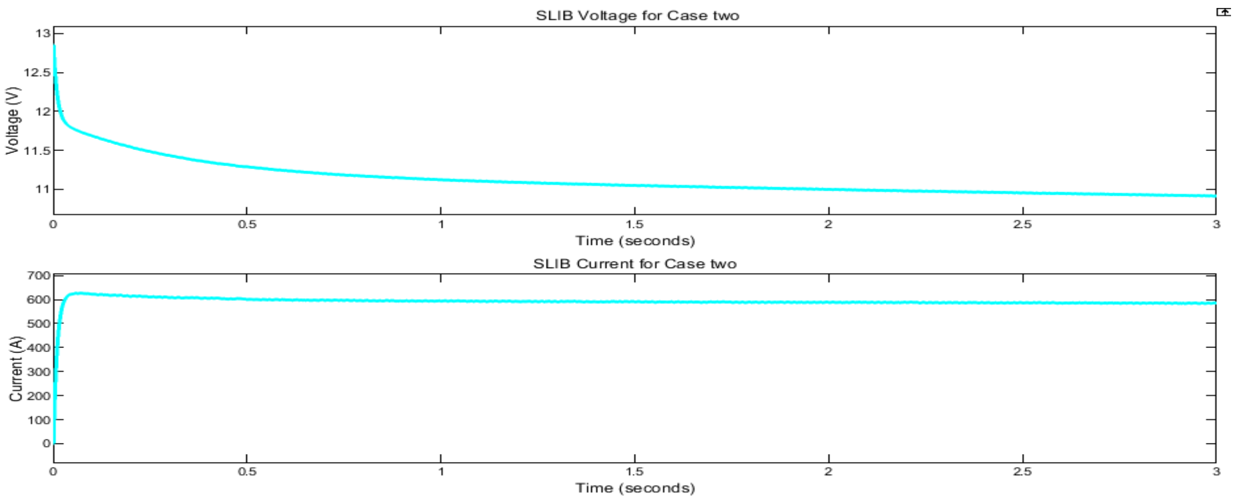

Figure 5.29. The delivery SLIB CCA and voltage response during discharging mode for case two

Figure 5.30 shows the minimum LIB's SOC after supplying the required CCA for 3 seconds is 99.05%.

Figure 5.31 shows the minimum SLAB's SOC after supplying the required CCA for 3 seconds is 99.29%.

Figure 5.32 shows the minimum SLIB's SOC after supplying the required CCA for 3 seconds is 95.79%

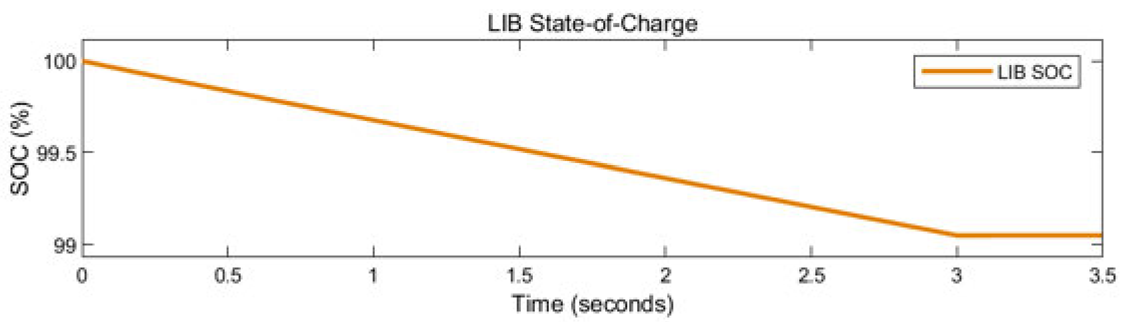

Figure 5.30. LIB State-of-Charge during discharging modes for case two

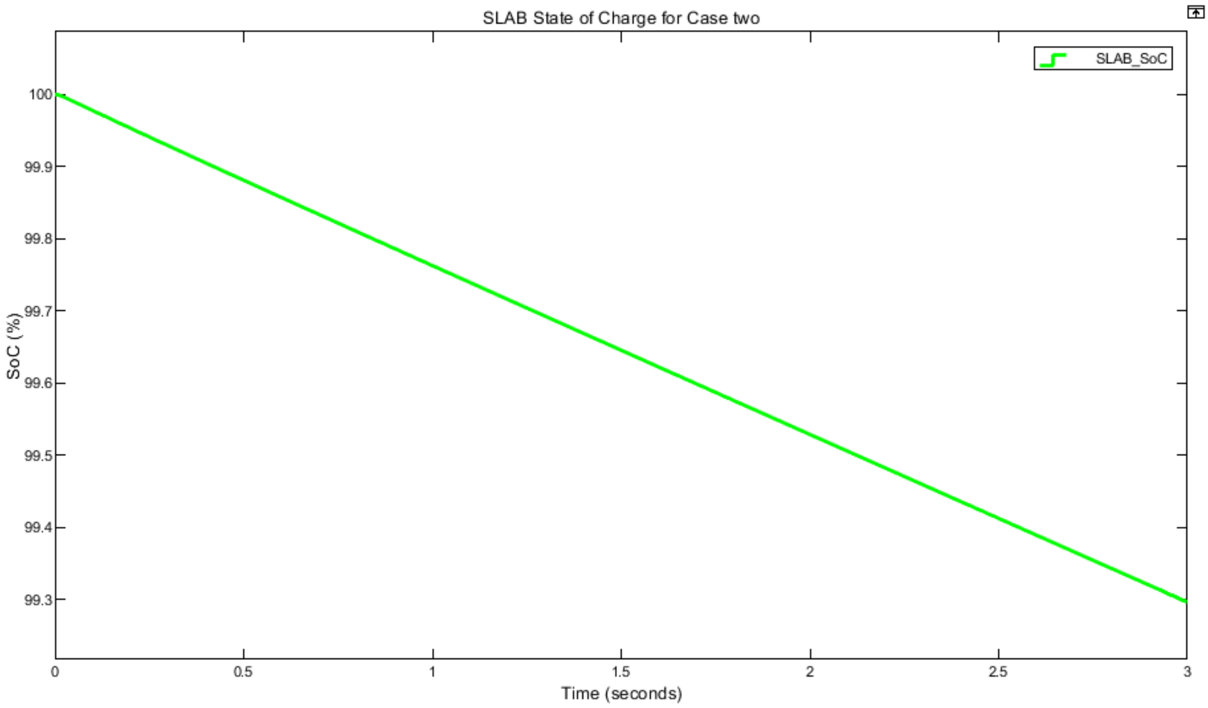

Figure 5.31. SLAB State-of-Charge during discharging modes for case two

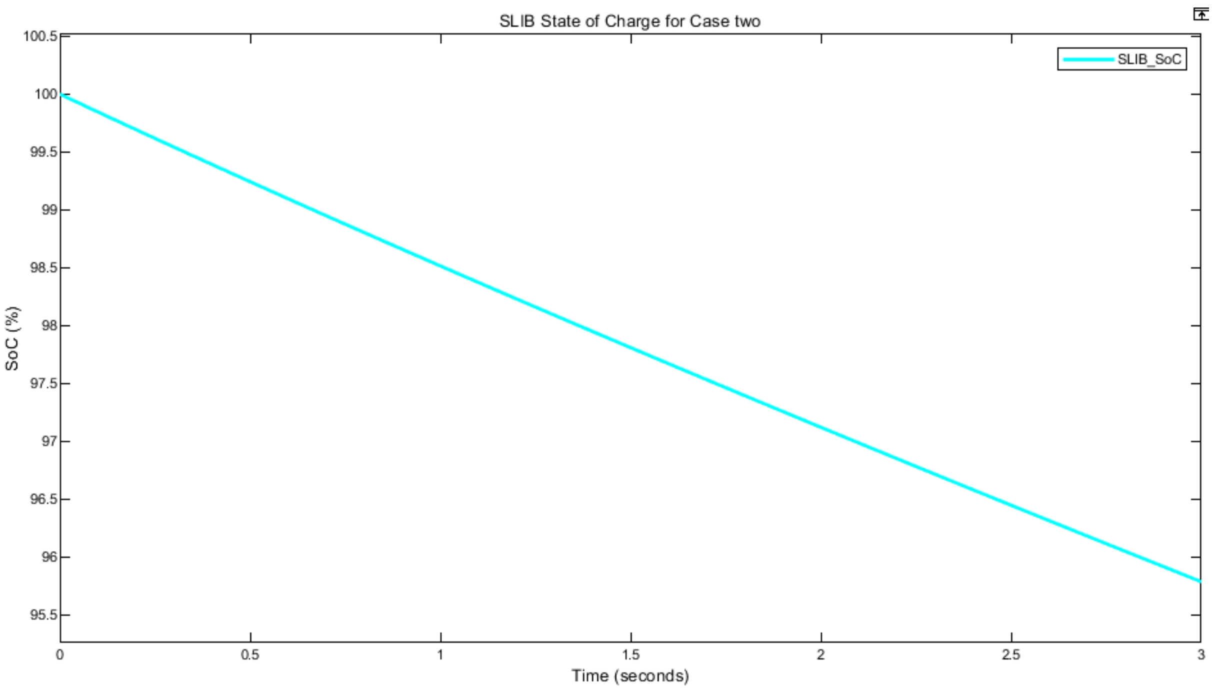

Figure 5.32. SLIB State-of-Charge during discharging modes for case two

For case 3, a single 12V-90Ah LAB in discharging mode for 3 seconds is compared with the proposed HESS for case 3.

Figure 5.33 shows SLAB results for case three. The SLAB 12V-90Ah supplies a maximum power of 7751 W. Figure 5.34 shows SLIB results for case three. The SLIB 12V-90Ah supplies a maximum power of 7855 W.

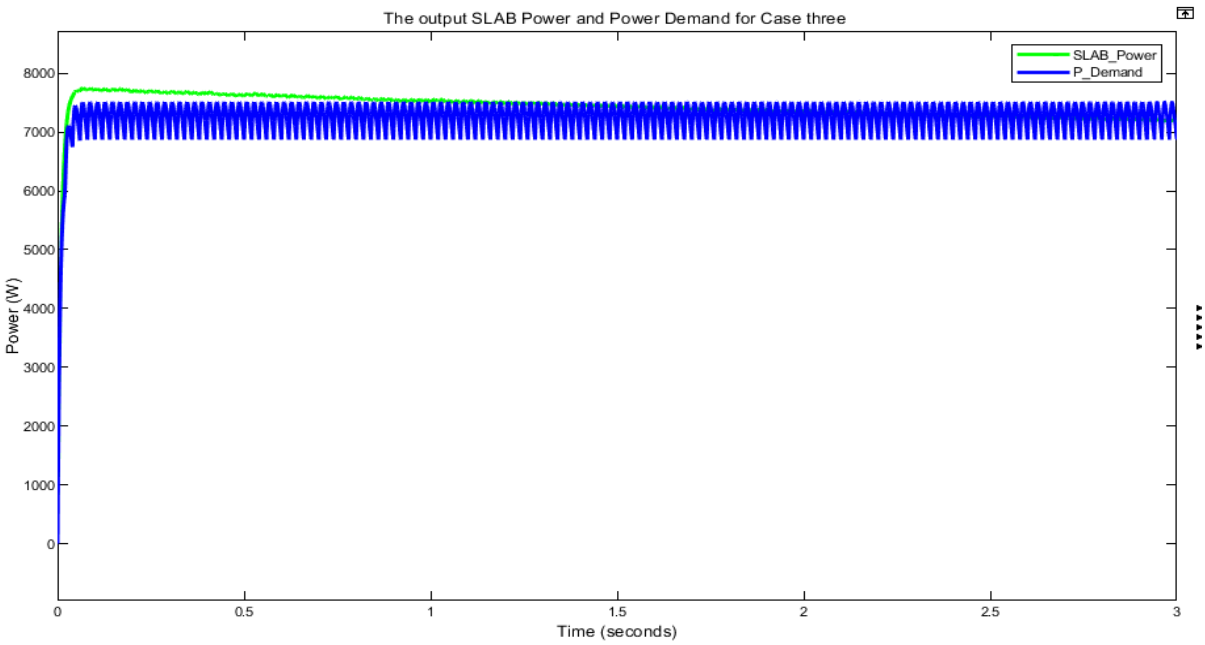

Figure 5.33. The delivered SLAB Power for case three

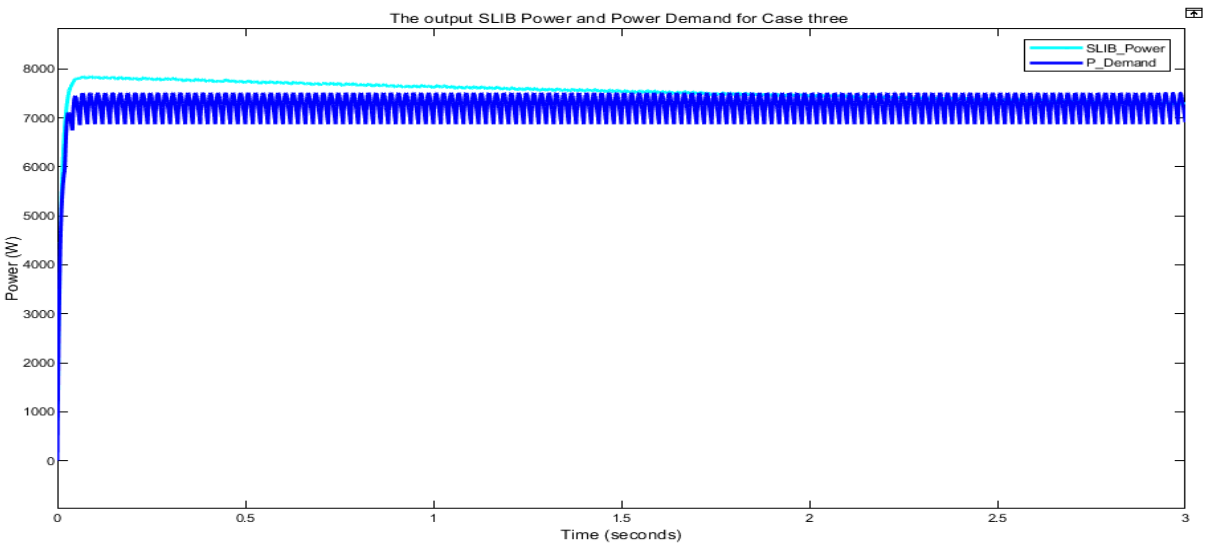

Figure 5.34. The delivered SLIB Power for case three

Figure 5.35 shows the minimum voltage response and maximum current of SLAB for case one is 11.68 V and current 630 A.

Figure 5.36 shows the minimum voltage response and maximum current of SLIB for case one is 11.59 V and current 652.5 A.

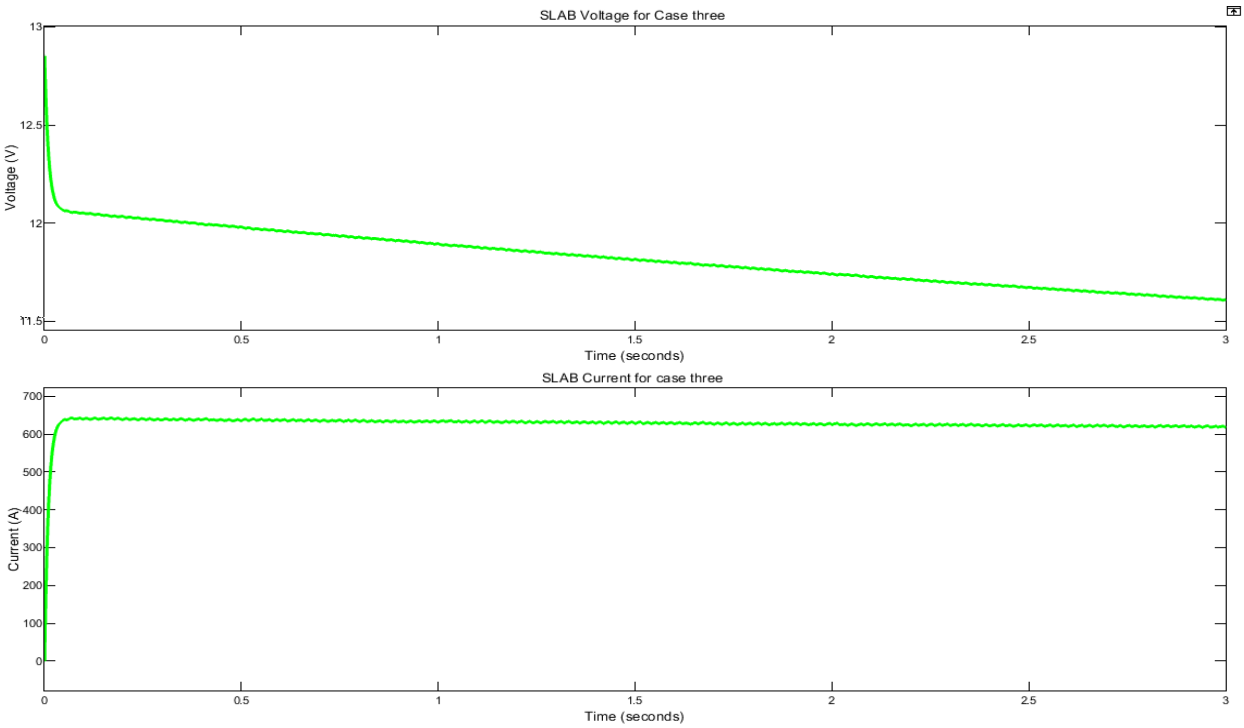

Figure 5.35. The delivery SLAB CCA and voltage response during discharging mode for case three

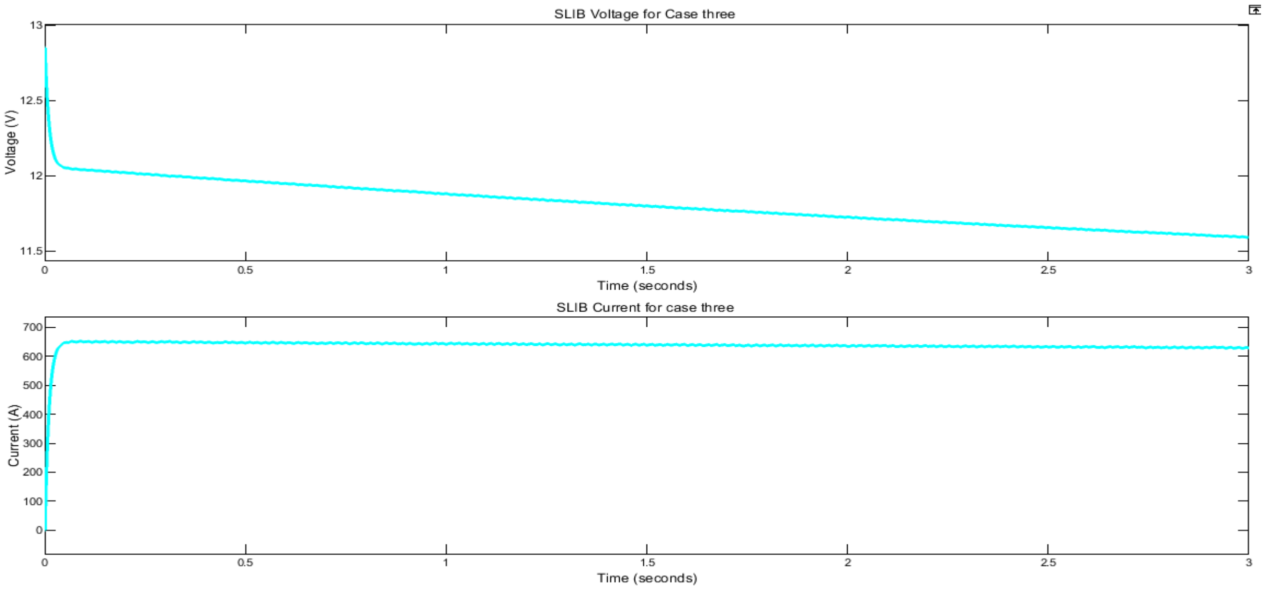

Figure 5.36. The delivery SLIB CCA and voltage response during discharging mode for case three

Figure 5.37 shows the minimum LIB's SOC after supplying the required CCA for 3 seconds is 99.12%. Figure 5.38 shows the minimum SLAB's SOC after supplying the required CCA for 3 seconds is 99.42%

Figure 5.39 shows the minimum SLIB's SOC after supplying the required CCA for 3 seconds is 96.3 %.

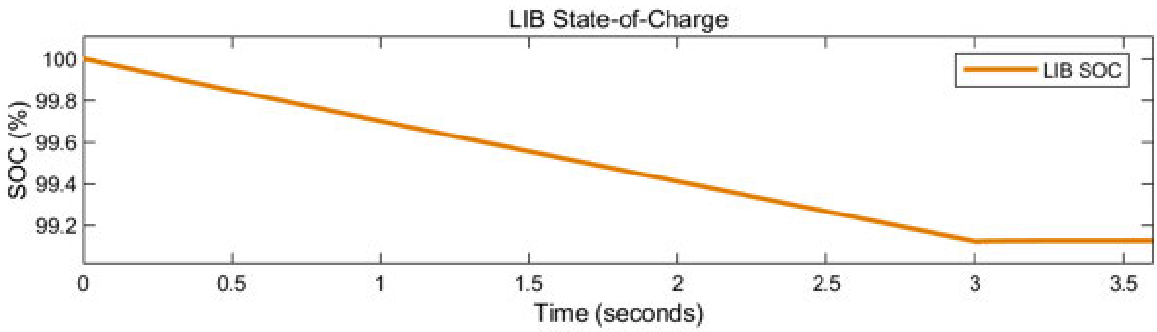

Figure 5.37. LIB State-of-Charge during discharging modes for case three

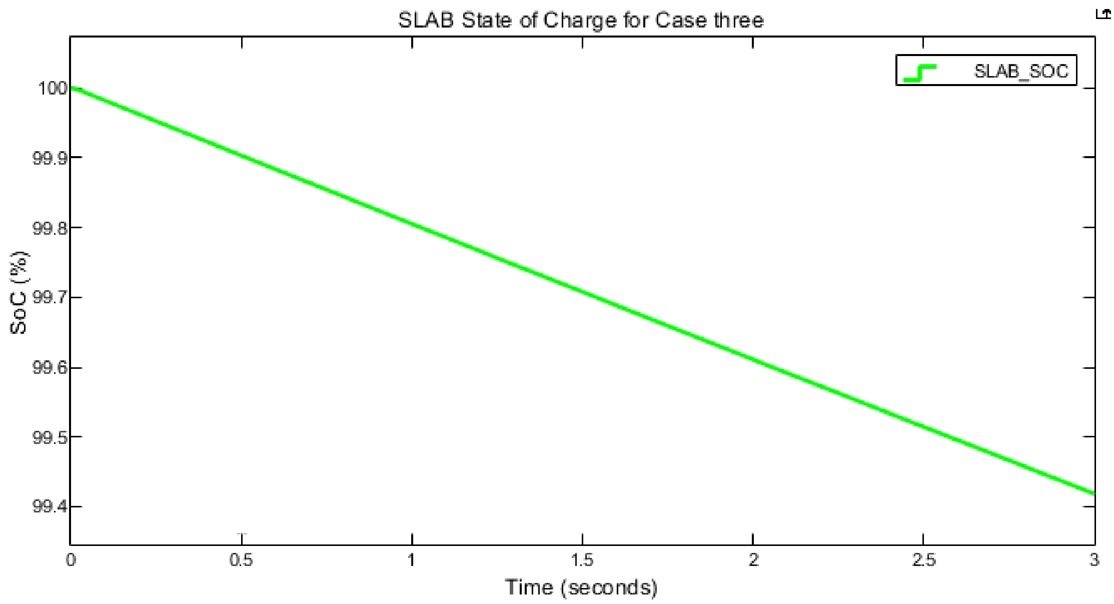

Figure 5.38. SLAB State-of-Charge during discharging modes for case three

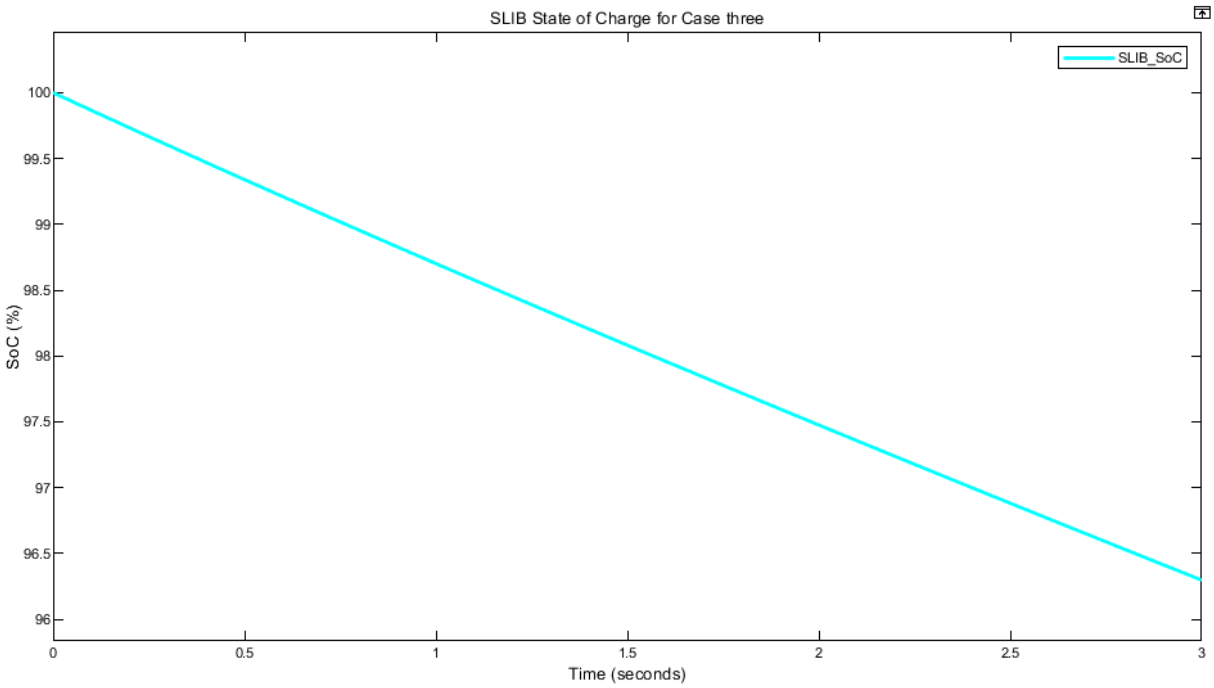

Figure 5.39. SLIB State-of-Charge during discharging modes for case three

Table 5.1 shows the summary results of the proposed HESSs compared to SLAB.

Table 5.1. The summary results of the proposed HESS vs SLAB of the three cases

Cases	Technology	Weight (kg)	Power (W)	Min Voltage (V)	SOC (%)
	HESS	5.985	4355	-	-
One	Hybridised LIB	-	-	13.3	99.52
	SLAB	14.5	4307	11.3	99.27
	SLIB	6.2	4320	11.32	96.25
	HESS	9.6	7381	-	-
Two	Hybridised LIB	-	-	12	99.05
	SLAB	18.5	7367	11.4	99.29
	SLIB	9.8	7371	10.91	95.79
	HESS	12.3	7920	-	-
Three	Hybridised LIB	-	-	12.5	99.12
	SLAB	24	7751	11.6	99.42
	SLIB	13.2	7855	11.59	96.30

The results indicate that the hybrid system provides higher power, and the hybridised LIB SOC is kept above 99% and 12V during CCA. Keeping the battery voltage and SOC at this limit, enhances the battery lifespan. This prevents the battery from being deep discharge and permits the charging algorithm to use the battery with a minimum amount of current. The Ultracapacitors prevent the battery from deep cycling since they have more than 1000 charge/discharge cycles. Consequently, the battery will be able to sustain a longer lifespan.

5.7 The estimated lifetime results

Based on the simulation results stated above, the LIBs' lifetimes are estimated. The datasheet in [98] is used as the reference for LIB and the datasheet in [100] is used as the reference for LAB. Figures 5.40 and 5.41 shows the extended cycle service life graph for the LIB and LAB respectively.

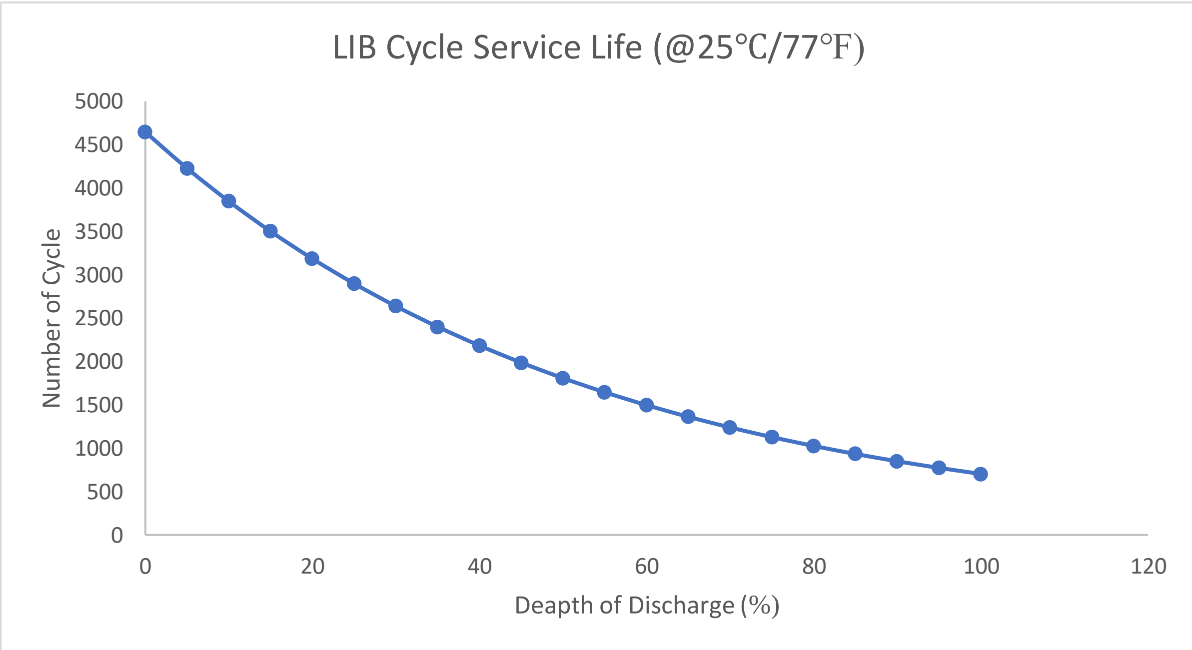

Figure 5.40. The Lithium-Ion Cycle Life

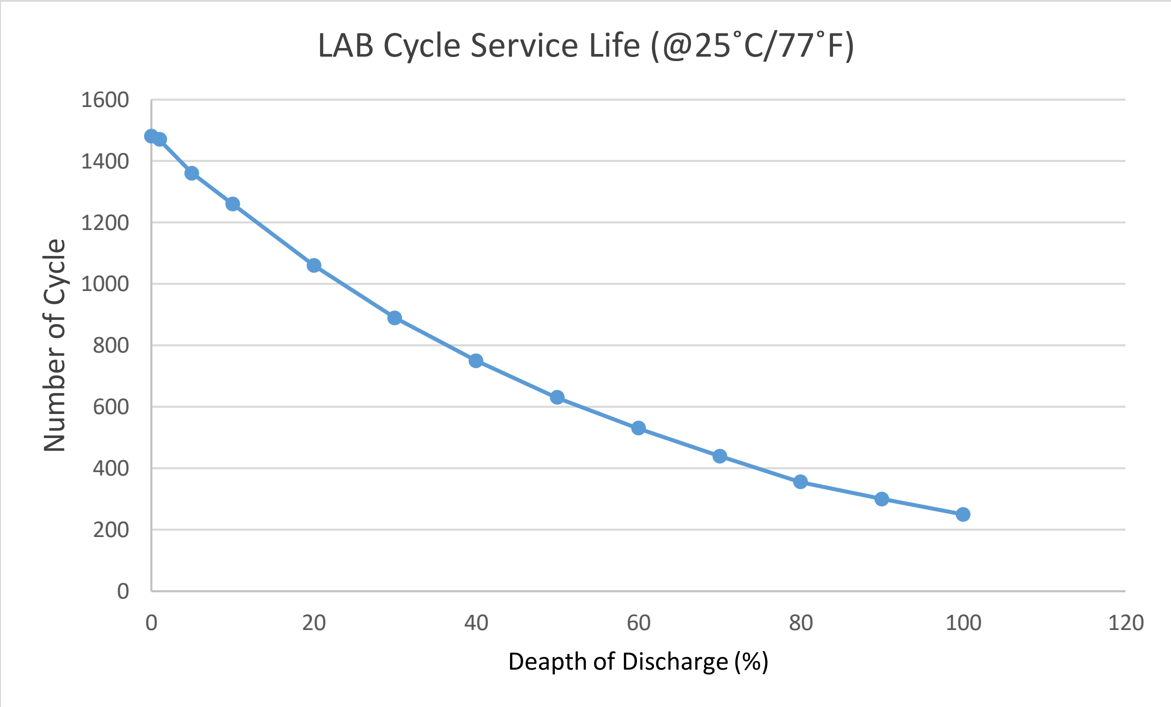

Figure 5.41. The Lead-Acid Cycle Life

The lifetime of the LIB and LAB is estimated based on the data obtained from the Figure 5.40 and 5.41 above with the equations 19, 20 and 21. The battery lifespan is estimated with assumptions of battery having maximum service per day of 2, and average surrounding temperature of 25℃ .

Figure 5.42 displays the results of the lifetime in year of the proposed HESS for case one versus SLAB and SLIB. The results indicate that the hybridised LIB's projected lifetime in Case one is 8.55 years compared with 5.07 of the SLAB and 6.58 of the SLIB.

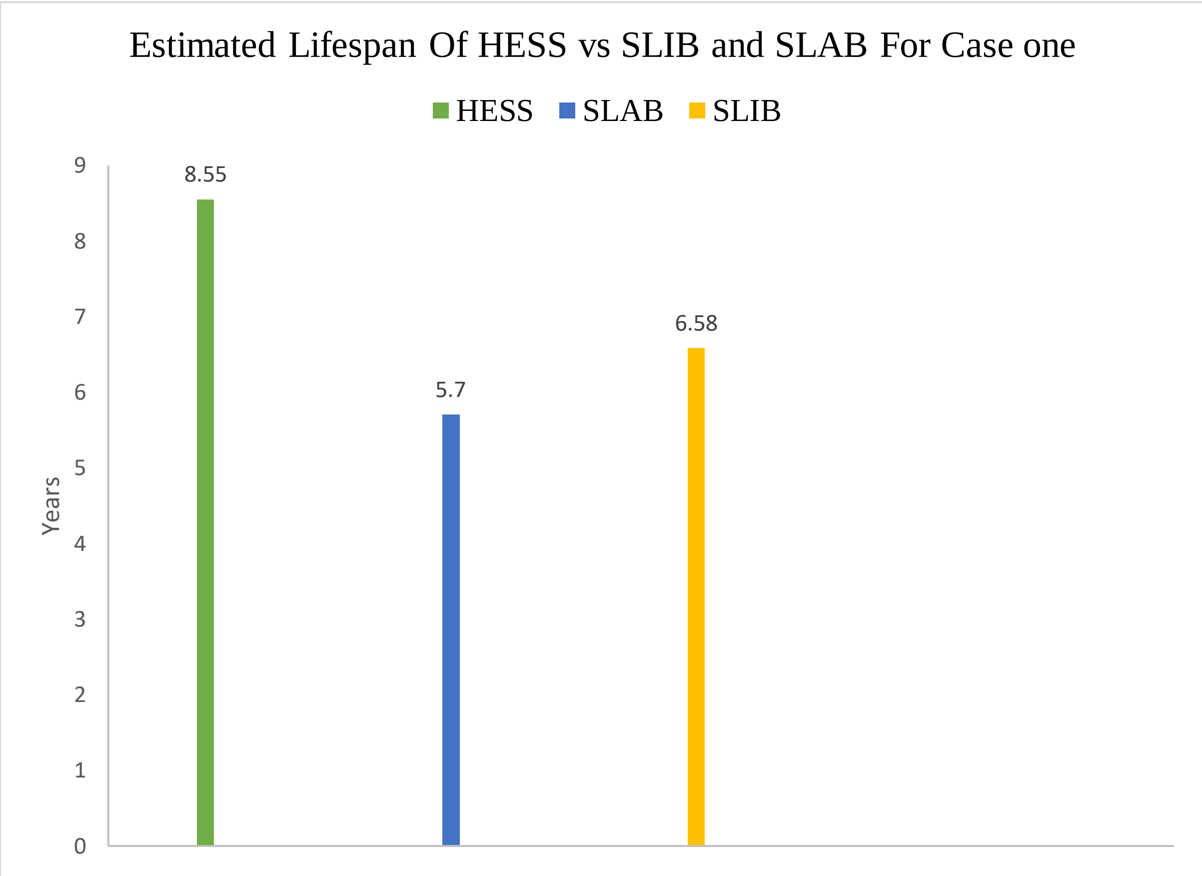

Figure 5.42. The lifetime in year of the proposed HESS for case one versus SLAB and SLIB.

Figure 5.43 displays the results of the lifetime in year of the proposed HESS for case two versus SLAB and SLIB. The results indicate that the hybridised LIB's projected lifetime in Case two is 8.51 years compared with 5.09 of the SLAB and 6.42 of the SLIB.

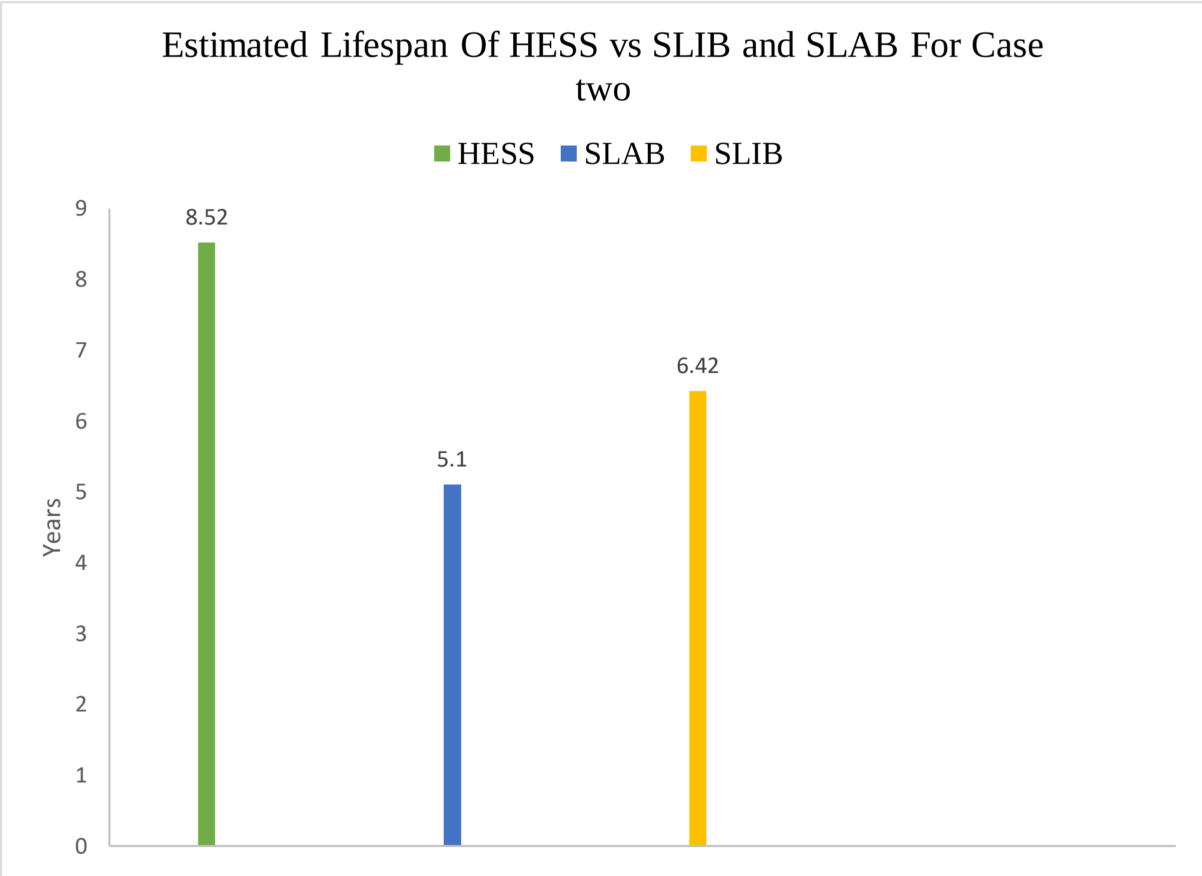

Figure 5.43. The lifetime in year of the proposed HESS for case two versus SLAB and SLIB.

Figure 5.44 displays the results of the lifetime in year of the proposed HESS for case three versus SLAB and SLIB. The results indicate that the hybridised LIB's projected lifetime in Case three is 8.52 years compared with 5.1 of the SLAB and 6.48 for SLIB.

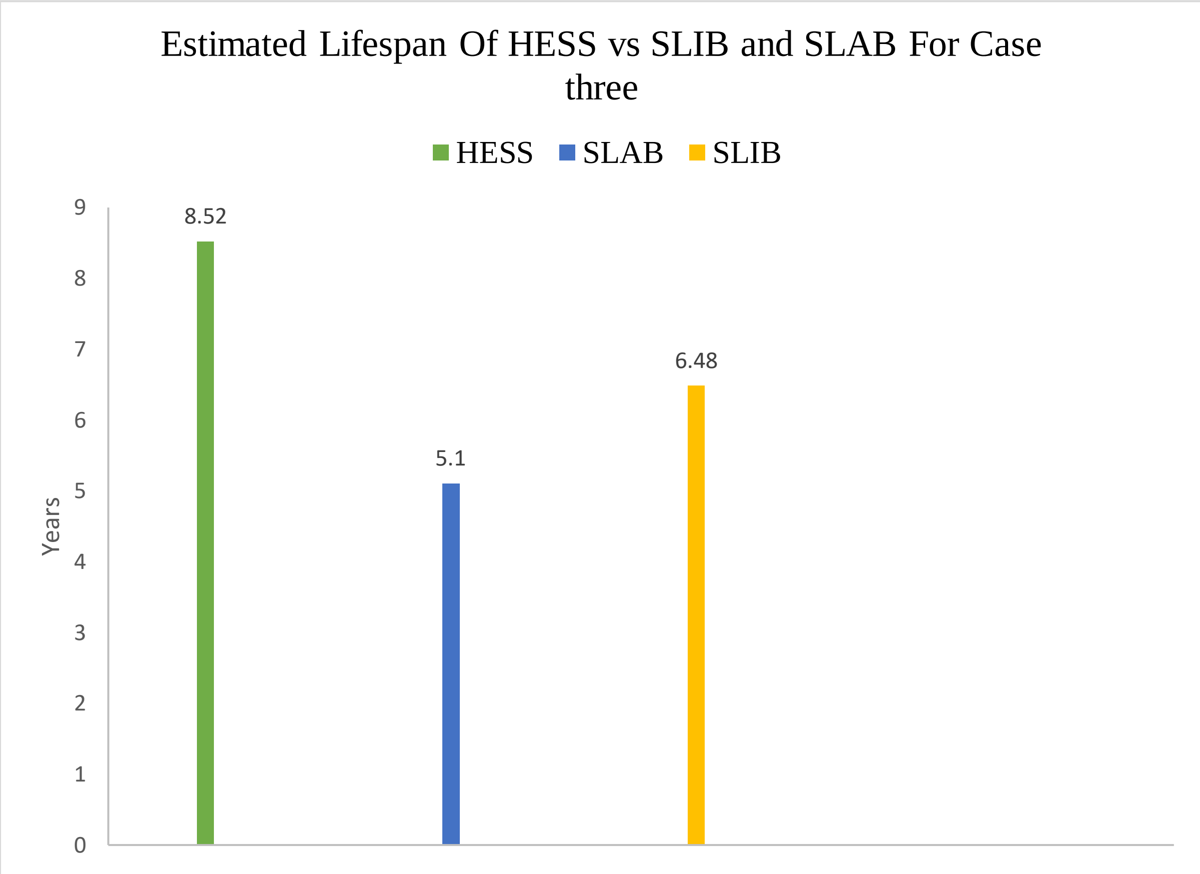

Figure 5.44. The lifetime in year of the proposed HESS for case three versus SLAB and SLIB.

The battery life increased, as illustrated in from Figure 5.42 to Figure 5.44.

5.8 Conclusion

The experimentally applied system demonstrated that the fuzzy logic controllers could control the DC/DC converters as well as the system's power flow. The system limits the maximum amount of power that is drawn from the battery. The results show the reference power of each energy storage.

The goal of this research study is to increase battery performance in terms of lifespan without changing the chemical composition. Based on battery terminal voltage, current, and state-of-charge measurements, the results showed that by combining a lithium-ion battery with an Ultracapacitor, using a fully-active topology DC/DC converter, battery performance can be improved. The findings demonstrated that, as shown in Table 5.1, the battery state-of-charge is maintained at a high statistical value of roughly 99% during CCA and the battery voltage of above is 12V. Since the battery voltage does not change much, keeping the SOC at high statistical values extends the battery's lifespan.

6. Chapter 6: Conclusion and Recommendations

6.1. Introduction

SLI batteries are increasingly sought after for use in transport vehicle (TV) electrical systems due to their advantages in longevity and storage capacity. However, the currently used SLI Lead-Acid Batteries (LABs) are susceptible to deep discharge, which stresses the LABs and shortens their lifespan. This has driven the search for alternative solutions for TVs.

Lithium-Ion Batteries (LIBs) are seen as a promising and sustainable solution to replace current SLABs. This is because LIBs offer the potential for higher power and energy density, as well as a longer lifespan compared to single lead-acid batteries (SLABs). Therefore, the proposed of this research is to develop a Hybrid Lithium-Ion and Ultra-Capacitor Energy Storage System with an efficient Energy Management System (EMS). The EMS consist of two Fuzzy Logic Controls. The primary aim of FLC is to determine the total reference power ($\mathrm{PD\_p_{Ref}}$) based on the power demand ($\mathrm{P_{Demand}}$) while ensuring the LIB SoC is within the minimum and maximum range. Secondly, is to allocate the reference LIB ($\mathrm{PLib_{\_Ref}}$) and Up (($\mathrm{PUp_{\_Ref}}$) power based on the total reference power by trigging the bidirectional dc-dc buck and boost converters.

Using the MATLAB/Simulink software, three cases and different scenarios are developed, presented, and simulations of the proposed HESS with EMS are performed. Based on the delivery power, voltage, and minimum SOC of the energy storages, the results are analysed. To assess the improvement in lifespan, the results of proposed HESSs are compared to those of single lithium-Ion batteries.

6.2. Validation of Research Hypotheses

The following supports the research's hypotheses:

- According to the results of the experiment, fully active hybrid lithium-ion and Ultracapacitor energy storage systems with an energy management strategy greatly minimize the stress on LIBs without changing the chemical composition of the batteries.
- The Mathematical Model is developed for the proposed Hybrid Lithium-Ion and Ultracapacitor Energy Storage System and Energy Storage System through defined rules using parameters and characteristics of the energy storages, by using the advantage of each energy storage. By using their advantages, it is able to allocate the power demand within the LIB and UP based on load demand from Transport Vehicles, as well charge and discharge modes.
- The Energy Management System consist of two Fuzzy Logic Controls (FLC1, FLC2a and FLCb). The FLC1 determines the total reference power (PD_p_{Ref}) based on the power demand (P_{Demand}) while ensuring the LIB SoC is within the minimum and maximum range. Furthermore, the FLC2 (FLC2a and FLC2b) allocate the reference powers to LIB and Up based on the total reference power, by controlling the LIB's and UP's voltage and current flow during the charging and discharging process. It is done trigging the bidirectional dc-dc buck and boost converters.
- Using the computer simulation MATLAB/Simulink software tool, the performance of the designed Hybrid Lithium-Ion and Ultracapacitor Energy Storage System with Energy Management Strategy for TVs is validated.

6.3. Summary of Research Results

With the increased in load demand for Transport Vehicles (TVs), LABs are experiencing performance failure. LABs are not able to meet the load demand, which results in deep discharge, and shorten their lifespan. Lithium-ion Batteries (LIBs) are seen as good solution to replace the current single LABs. It is due to the potential of obtaining higher power and energy density, as well longer lifespan compared with single LABs. In order to balance the efficiency in terms of long lifespan, high energy and power dentistry; there is need to hybridise with an Energy Storage System (ESS). As a result, in this research study, an additional effort is carried out in evaluating methodologies used to limit the power drawn from the battery and increase battery lifespan.

The proposed Lithium-Ion and Ultracapacitor Energy Storage System with Energy Management Strategy is designed, developed, and simulated using MATLAB/Simulink software. The aim of the proposed HESS with EMS is to improve the storage capacity, and the lifespan of the battery in HESS compared with single lead-acid batteries.

The HESS operation is controlled using EMS. The EMS will comprise of two bidirectional dc-dc buck-boost converter and two levels of FLCs with rule-based uses. The FLC 1 will provide the total reference power to start the ICE and to charge the energy storages based on the power demand, while ensuring that the SoC is within the minimum and the maximum range of the battery protects the battery from over charging and deep discharging. To allocate the power between the LIB and UP, a Low Pass Filter (LPF) is used. Since the LIB is a low power density device, as well should not be expose to deep discharge which would cause stress on LIB; a Low Pass Filter (LPF) is used to divide the total reference power between the LIB and UP. The total reference power from FLC 1 is sent to the Low Pass Filter (LPF), which generates the reference power of LIB and UP. From LPF goes to the FLC 2. The purpose of the FLC 2 is to allocated the total control and manage the reference power of the energy storage (LIB and UP) to monitor the bidirectional buck and boost converters during charging and discharging of the HESS. Additionally, this will enhance how power enters and leaves the battery. Since a smaller LIB will be required for the hybrid storage system, using Li-Ion batteries and an ultracapacitor hybrid system will balance its weight with its high performance.

The experimentally applied system demonstrated that the fuzzy logic controllers were capable of controlling the DC/DC converters as well as the system's power flow. The system limits the maximum amount of power that is drawn from the battery. The results show the reference power of each energy storage.

The research study is based on three cases. The HESSs are compared with SLAB and SLIB (of three ratings: 12V-40Ah, 12V-70Ah and 12V- 90Ah). The simulations are conducted for 3 seconds during CCA and between 3 to 3.5 seconds during charging mode.

6.3.1 Case one

A peak demand of 4200 W is used to model the proposed HESS with EMS for case one over a period of 4.5 seconds. Comparing the outcomes to a single 12V-40 Ah LAB. HESS meet the peak demand of 4200 W to run the TVs by supplying a maximum power of 4355 W for 3 seconds. The load demand is 0 W after 3 seconds, indicating that the TV is running. The car receives the necessary energy from the alternator (bus voltage), which also charges the HESS.

LIB supplies 1742 W which represents to the 40% of the peak demand. The minimum voltage is 13.3 V and SOC is 99.52%. The UP supplies 2613 W which represents to the 60% of the peak demand. The minimum voltage is 12.88 V and SOC is 90.62%.

The proposed HESSs for case one (a) is compared with a single 12V-40Ah LAB and single 12V-40Ah LIB. The comparison is made based on Power delivered by HESS versus SLAB and SLIB, as well the minimum voltage and SOC level of Hybridised LIB versus SLAB and

SLIB during CCA mode. It is clear from the results that the HESS delivers 4355 W, whereas its minimum voltage is 13.3 V and SOC is 99.52%. The SLAB delivers 4159 W, whereas the minimum voltage is 11.3 V and SOC of 99.27%. The SLIB delivers 4320 W, whereas the minimum voltage is 11.32 V and SOC of 96.25%.

The proposed HESSs weighed less than the Single Lead-acid battery. The HESSs reduce the weight of the storage system by 5.851 kg, it will reduce the vehicle's weight, consequently lowering fuel consumption.

The estimated lifespan in a year of the proposed HESS for case one versus SLAB and SLIB. The results indicates that the HESS's projected lifetime in case one is 8.55 years compared with 5.07 years of the SLAB and 6.58 years of the SLIB. The results show the LIB' lifespan is significantly enhanced by integrating it with Ultracapacitors and without changing the batteries current chemical composition.

The results show the proposed HESS for case one has a better performance than the single 12V-40Ah LAB in terms of storage capacity and lifespan.

6.3.2 Case two

A peak demand of 7080 W is used to model the proposed HESS with EMS for Case two over a period of 4.5 seconds. Comparing the outcomes to a single 12V-70 Ah LAB. The HESS meet the peak demand of 7080 W needed to run the TVs by supplying a maximum power of 7381 W for 3 seconds. The LIB supplies 3199 W which represents to the 40% of the peak demand. The minimum voltage is 13.2 V and SOC is 99.05%. The UP supplies 4211 W which represents to the 60% of the peak demand. The minimum voltage is 12.81 V and SOC is 89.48 %.

The proposed HESS for case two was compared with a single 12 V–70Ah LAB and single 12 V–70Ah LIB. The comparison was made based on the power delivered by HESS versus SLAB and SLIB, as well the minimum voltage and SOC level of Hybridised LIB versus SLAB and SLIB during CCA mode. According to results, the HESS delivered 7381W, where minimum voltage is 12 V and minimum SOC is 99.05%. The SLAB delivers 7367W, where the minimum voltage is 11.4 V and SOC of 99.29%. The SLIB delivers 7371 W, whereas the minimum voltage is 10.91 V and SOC of 95.79%.

The proposed HESSs weighed less than the Single Lead-acid battery. The HESSs reduce the weight of the storage system by 10.9 kg, it will reduce the vehicle's weight, consequently lowering fuel consumption.

The estimated lifespan in a year of the proposed HESS for case two versus SLAB and SLIB. The results indicates that the LIB's projected lifetime in case two is 8.51 years compared with 5.09 years of the SLAB and 6.42 years of the SLIB. The results show the LIB' lifespan is significantly enhanced by integrating it with Ultracapacitors and without changing the batteries current chemical composition.

The results show the HESS for case two has a better performance than the single 12V-70Ah LAB in terms of storage capacity and lifespan.

6.3.3 Case three

The HESS meet the peak demand of 7800 W needed to turn on TVs by supplying a maximum power of 7920 W for 3 seconds. The LIB supplies maximum power of 3247.2 W, which represents to the 41% of the peak demand. It charges with maximum power of - 206.2 W. While UP supplies maximum power of 4672.8 W, which represents to the 59% of the peak demand. It charges with maximum power of – 889.7 W.

The LIB supplies 3247.2 W which represents to the 41% of the peak demand. The minimum voltage is 12.5 V and SOC is 99.12%. The UP supplies 4672.8 W which represents to the 59% of the peak demand. The minimum voltage is 11.68 V and SOC is 90.07 %.

The proposed HESSs for case three was compared with a single 12 V–90Ah LAB and single 12 V–90Ah LIB. The comparison was made based on the power delivered by HESS versus SLAB and SLIB, as well the minimum voltage and SOC level of Hybridised LIB versus SLAB and SLIB during CCA mode. According to results, the HESS delivered 7920 W, where minimum LAB voltage is 12.5 V and SOC is 99.12%. The SLAB delivers 7751 W, where the minimum voltage is 11.6 V and SOC of 99.42 %. The SLIB delivers 7855 W, whereas the minimum voltage is 11.59 V and SOC of 96.3%.

The proposed HESSs weighed less than the Single Lead-acid battery. The HESSs reduce the weight of the storage system by 11.2 kg, it will reduce the vehicle's weight, consequently lowering fuel consumption.

The estimated lifespan in a year of the proposed HESS for case three versus SLAB. The results indicate that the LIB's projected lifetime in case three is 8.52 years compared with 5.1 years of the SLAB and 6.48 years of the SLIB. The results show the LIB' lifespan is significantly enhanced by integrating it with Ultracapacitors and without changing the batteries current chemical composition.

The results show the proposed HESS for case three has a better performance than the single 12V-90Ah LAB in terms of storage capacity and lifespan.

6.4. Recommendations for Future Studies

The recommendations for the future studies of the proposed research studies are as follows:

- The development and implementation of the prototype to validate the simulation results of the proposed Hybrid Lithium-Ion Battery and Ultracapacitor with Energy Storage System (ESS) in Transport Vehicles.
- One of the main drawbacks of the Fuzzy Logic Control, is it takes time to simulate and requires more memories. Therefore, the proposed research studies would need to be analysed using other approaches. It would help to compare its efficiency with the proposed approach.
- Simulating the proposed HESS with EMS until the energy storages' SOC are 100%.
- The study on the life cycle cost is also recommended to evaluate the improvement of lifetime against the improved cost of batteries.
- Simulation of the proposed HESS with EMS with different driving cycles would be useful to evaluate this improvement in different driving conditions.

6.5. Final Conclusion

In terms of storage capacity and lifespan, LABs-TVs are facing certain difficulties due to an increase in the load demand for TVs. The Objective of this research study is to increase battery performance in terms of lifespan and storage capacity without changing the chemical composition. The results were compared with Single Lead-Acid batteries based on Power demand, voltage, and State-of-Charge. The battery state-of-charge is maintained at a high statistical value of roughly 99% during CCA and the battery voltage of above is 12V. Since the battery voltage does not change much, keeping the SOC at high statistical values extends the battery's lifespan.

The control strategy based on FLC ensured the stability operation of the DC/DC converters. The use of Lithium-Ion-Ultracapacitor in conjunction with the fully active topology improved the energy storage system of transport vehicles performance in terms of power density and lifespan.

The experimentally applied system demonstrated that the fuzzy logic controllers could control the DC/DC converters as well as the system's power flow. The system limits the maximum amount of power that is drawn from the battery. The results show that the LIB supplies 40% of the peak demand while the UP supplies the 60% of the peak demand.

The results of the lifetime in year of the proposed HESS for the three cases versus SLAB and SLIB. The results indicate that the LIB's projected lifespan is increased to more than 2 year compared to the SLAB and SLIB’s lifespan.

The proposed hybrid Lithium-Ion-Ultracapacitor ESS reduced battery weight by more than 50% when compared to the SLAB, resulting in a smaller vehicle and lower fuel usage.

Therefore, the proposed Hybrid Lithium-Ion Battery and Ultra-Capacitor with Energy Storage System (ESS) with Energy Management System based on fully-active topology with two bidirectional DC-DC buck-boost converters and two level FLC (Fuzzy Logic Control) successfully improved the performance of Lithium-Ion batteries in transport vehicles in terms of lifespan and storage capacity without changing the chemical composition of the battery.

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