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Enhancing Electric Vehicle Energy Management Through ANFIS-Controlled Hybrid Storage Systems

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CANDIDATE'S DECLARATION

I, **ASHISH KUMAR DIXIT**, Roll No. 2K22/PES/06 student of MTech (Power Electronics & Systems), hereby declare that the project Dissertation titled **"Enhancing Electric Vehicle Energy Management Through ANFIS-Controlled Hybrid Storage Systems"** which is submitted by me to the Department of Electrical Engineering, Delhi Technological university, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

Place: Delhi (**Ashish Kumar Dixit**)

Date: 31/05/24

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CERTIFICATE

I hereby certify that the project Dissertation titled **"Enhancing Electric Vehicle Energy Management Through ANFIS-Controlled Hybrid Storage Systems"** which is submitted by Ashish Kumar Dixit, Roll No. 2K22/PES/06, Department of Electrical Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is a record of the project work carriedout by the student under my supervision. To the best of my knowledge thiswork has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Prof. Mini Sreejeth
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Asst. Prof. Himanshu Singh
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ABSTRACT

The introduction of Adaptive Neuro-Fuzzy Inference System (ANFIS) controllers into hybrid energy storage systems for electric vehicles (EVs) is the primary topic of this thesis. The goal of this thesis is to promote long-distance performance while simultaneously reducing operational expenses. Since electric vehicles (EVs) are becoming increasingly popular as a more ecologically friendly alternative to vehicles powered by internal combustion engines, it is of the utmost importance to optimize energy management in light of this trend. The vast majority of conventional energy storage systems are founded on either high-power ultracapacitors or high-energy batteries because of their superior energy storage capabilities. When it comes to energy density, power delivery, and cost, both of these forms of energy storage devices have their own unique collections of limitations. Through the utilization of a hybrid storage system that combines the benefits of ultracapacitors and batteries, the work that is being presented here is able to circumvent these limitations. Specifically, the primary focus of this research is on developing an ANFIS controller that is designed to optimize the state of charge and discharge cycles between these storage units based on the dynamic demands of the vehicle and the variables that are present in the environment. As a component of this research, the controller will be designed and put into motion. Increased energy economy, lower wear on components, and improved performance of the vehicle are all possible outcomes that can be achieved with this action. The validation of the suggested system is performed through simulation as well as through actual driving scenarios, which highlights significant improvements in comparison to control systems that have been utilized in the past. The results of this study indicate that ANFIS controllers have the potential to revolutionize energy management in electric vehicles, which would make these vehicles a more practical and cost-effective option for consumers.

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Date: 31/05/24

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LIST OF ABBREIVIATION

EV	Electric Vehicle
PEV	Plug-In Electric Vehicle
FEV/HEC	Fuel/Hybrid Electric Vehicle
PHEV	Plug-In Hybrid Electric Vehicle
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
HESS	Hybrid Energy Storage System
ANFIS	Adaptive Neuro Fuzzy Inference System
V2G	Vehicle to Grid
ICE	Internal Combustion Engine
BDC	Bi-Directional Converter
ES1 & ES2	Energy Storage 1&2
PID	Proportional Integral Derivative
DC	Direct Current
SPWM	Sinusoidal Pulse Width Modulation
ANN	Artificial Neural Network
FIS	Fuzzy Inference System
SR	Synchronous Rectifier
CS	Control Switch
HV	High Voltage
LV	Low Voltage

LIST OF SYMBOLS

V_{ES1}	Voltage of Energy Source 1
V_{ES2}	Voltage of Energy Source 2
L_1 & L_2	Two Phase Inductor 1 & 2
C_B	Charge Pump Capacitor
V_H	High Side DC Link Voltage
I_{L1}	Current in L1
I_{L2}	Current in L2
I_H	Current in Charge pump capacitor
S, S_{ES1} & S_{ES2}	Bi-Directional Power Switch
Q_1, Q_2, Q_3, Q_4	Active Switches
D, D_U, D_d	Duty Ratio, Duty Sourcing mode, Duty in Regenerative mode
F_{SW}	Switching Frequency
C_{ES1} & C_{ES2}	Capacitor of Voltage Sources
SOC	State of Charge
i_{L2ref} & i_{L1ref}	Reference Current of generate Pulses
T_S	Switching Period

CHAPTER_1

INTRODUCTION

1.1 Background

Electric vehicles (EVs) have becoming an predominant component in the trend towards more environmentally friendly forms of transportation. This evolution is a direct outcome of the requirement to reduce dependency on fossil fuels and to lessen the impact that pollution has on the environment. Because of its massive dependence on imported crude oil, which accounts for 82.8% of its petroleum basket, and natural gas imports, which account for another 45.3% of its petroleum basket, India is particularly susceptible to the effects of global warming [1]. The existing position of India as the third largest oil importer in the world is in place. There has been a drive to reduce the usage of fossil fuels and the economic burden that this places on the population as a result of the well-documented relationship between the use of petroleum and the pollution of the air [2]. This push has been a result of the fact that the connection between the two has been well-documented.

One of the most significant consumers of petroleum products is the transportation industry, which, in turn, is responsible for a significant portion of the pollution that occurs in the atmosphere. Because of this, the rate at which India is adopting plug-in electric vehicles (PEVs) and plug-in hybrid electric vehicles (PHEVs) that are powered by batteries has accelerated [3]. Plug-in electric cars (PEVs) and plug-in hybrid electric vehicles (PHEVs) are able to draw electricity from external sources such as the electrical grid, in contrast to traditional automobiles, which are unable to do so. The utilisation of India's growing capacity for renewable energy is not only beneficial to the reduction of emissions of greenhouse gases, but it also helps to lower costs.

Despite the positive environmental effect of EVs, widespread adoption of these vehicles faces significant challenges, particularly in terms of energy storage. Despite these challenges, EVs are becoming increasingly popular. When compared to the energy density of petrol, the energy capacity of the battery systems used in EVs, such as lithiumion batteries, is roughly 90-100 Wh/kg. This is a substantial amount lower than the energy density of petrol [4]. Due to the fact that EVs have a lower capacity for energy storage compared to conventional vehicles that are powered by internal combustion engines, the driving range of EVs is significantly reduced. In addition, the high cost of EVs, the lengthy charging times, and the concerns over the durability of batteries all further complicate the process of determining whether or not EVs are viable for frequent use.

This research examines the capabilities of hybrid energy storage systems (HESS), which integrate the strong power output of ultracapacitors with the large energy storage capacity of batteries.. Specifically, the study focused on the potential of HESS. The primary purpose of this investigation is to find solutions to the problems that have been recognised that have been identified. The goal of this hybrid approach is to improve the overall efficiency and cost-effectiveness, and performance of EVs by exploiting the capabilities of both storage systems, which complement one another very well. It is a novel method that has the potential to improve the operational efficiency of energy storage systems for EVs [5]. This is accomplished through the utilisation of the implementation of an Adaptive Neuro-Fuzzy Inference System (ANFIS) as a control strategy. for the purpose of controlling the state of charge and energy distribution between these components.

By incorporating ANFIS-controlled HESS, the objective of this project is to construct a framework for energy management in EVs that is both more robust and efficient than the current system. This framework has the potential to broaden the selection of EVs and lower the overall cost of ownership, which would result in EVs becoming a more tempting alternative for consumers. This strategy has the ability to not only contribute to the technological advancements in electric vehicle technology, but it also has the potential to help broader environmental and economic goals by supporting transportation choices that are cleaner and more sustainable. This is because it has the capacity to contribute to the technological breakthroughs itself.

1.2 Motivation

Our research was prompted by these extremely critical difficulties because of the enormous obstacles that stand in the way of the general adoption and operation of electric vehicles (EVs), particularly with regard to energy storage and management The subsequent paragraphs will provide a more comprehensive analysis of these challenges. In light of the growing need for environmentally responsible transportation solutions on a global scale, it is of the utmost importance to find answers to the limitations of the technologies that are currently available for EVs in order to increase their appeal and use. Existing battery technologies continue to suffer with high costs, lengthy charging periods, and low energy densities in compared to fossil fuels [1]. Despite the fact that they are already the backbone of electric mobility, these battery technologies continue to face challenges. This is the critical obstacle that needs to be conquered at this particular moment in time.

Considering the dependence on imported oil as well as the associated economic and environmental repercussions, it is imperative that additional energy alternatives that are more efficient for EVs be investigated [2]. The findings of this study are especially relevant in India, which is a country that relies heavily on oil that is delivered from other countries. It is becoming increasingly important to make advancements in the technology of EVs as a result of key difficulties such as the large weight that oil imports place on the national economy and the environmental degradation that is caused by automotive emissions [3]. Improving the technology of EVs is becoming increasingly vital.

In addition, the practical challenges that are involved with the operation of EVs, such as the extended amount of time that is required to recharge batteries and the anxiety that is associated with the limited driving range, are a barrier to the mainstream acceptance of these vehicles. There is a growing demand for a more advanced energy management system that is capable of effectively managing the requirements of electric vehicle operation in a variety of driving circumstances and extending the range of the vehicles without compromising their overall performance [4]. This demand is a direct result of the problems that have been described above.

Adaptive Neuro-Fuzzy Inference System (ANFIS)-based control in hybrid energy storage systems (HESS) is a potential answer to these problems that can be found in the possibility of using this control method. The capacity of ANFIS to proactively manage the flow of power between ultracapacitors and batteries enables it to effectively optimise the amount of energy that is utilised, hence enhancing the overall performance of EVs. The purpose of this method is to successfully bridge the gap between the capabilities that are currently available and the operational requirements that will be required by future EVs [5]. This technique takes advantage of the benefits that are offered by both types of storage.

As a consequence of this, The aim of this study is to enhance the present state of technology in the electric car industry, with the goal of increasing the practicality, efficiency, and usability of EVs for a wider customer base. This research aims to make a significant contribution to the field of electric transportation by addressing the primary challenges of energy storage and management through the implementation of new ANFIS-controlled HESS. This will be accomplished by addressing the energy storage and management issues. With the help of this aid, the shift to vehicles that are more environmentally friendly, efficient, and economically feasible will be made easier.

1.3 Thesis Objective

The aims of this work are to

- Conduct detailed research on EVs systems to enhance understanding and optimization of energy management through advanced control strategies.
- Reduce the system's functional limitations by employing specialized algorithms and ANFIS controllers are used to improve the effectiveness and reliability of hybrid energy storage systems in electric cars.

1.4 Thesis Organisation

This thesis is organised as follows:

1. **Chapter_1**: This introduction examines the need of electric vehicles (EVs) and their hybrid energy storage systems (HESS). It also explores how the challenges related to EVs and storage systems might be addressed using Adaptive Neuro-Fuzzy Inference System (ANFIS) as a viable solution.

2. **Chapter_2**: This provides complete review of EVs and HESS and implication it creates when comes to power and storage management. Complete study is shown and ANFIS is introduces in this chapter.

3. **Chapter_3**: This text explains the Bi-directional converter and its several working modes, which are controlled by switches throughout different operation periods.

4. **Chapter_4**: This chapter provides an introduction to the PI and ANFIS, including its implementation. It also gives a concise overview of ANFIS and its internal architecture.

5. **Chapter_5**: The chapter is results and simulation and compare the both controlling strategies on the basis of change observed in parameter and findings and conclude the results.

6. **Chapter_6**: This chapter gives brief about the conclusion and future scope that this study can offer in term of integration of various energy storage system and with renewable system.

CHAPTER_2

LITERATURE REVIEW

2.1 Introduction

The electric vehicle and its integration with various components of systems is studied with the help of literature and it is found that EVs integration with converter and various storage technologies can contribute to optimum power consumption and performing control strategies is beneficial in terms of system performance.

2.2 Hybrid Electric Vehicle

The [1] studies the idea of constructing a bidirectional DC/DC converter that is purpose-built for hybrid electric vehicle systems and makes use of dual-battery storage capabilities. This converter would be designed to convert direct current to direct current. The converter was designed specifically with the intention of efficiently controlling the flow of power between the various storage units, which would ultimately result in the vehicle's operational efficiency being maximised and its overall performance being improved. According to the findings of the study, the ability of the converter to integrate into the system of the vehicle without causing any obvious interruption is taken into consideration. It is because of this that the energy is distributed between the batteries in a manner that is acceptable and appropriate, taking into consideration the instantaneous power requirements of the vehicle.

A different piece of research investigates the foundations of hybrid EVs by providing a detailed examination of their design as well as the multiple configurations that are available in [2]. This research was carried out to conduct an investigation the foundations of HEV. In this article, the incredible environmental benefits and improved energy efficiency that these vehicles offer in comparison to normal gasoline-powered automobiles are highlighted. These vehicles give a significant advantage over conventional automobiles. In this study, a number of hybrid electric vehicle architectures are investigated, their performance is evaluated, and it is determined whether or not these architectures are suitable for a variety of transportation purposes.

A complete assessment that is outlined in [3] provides an analysis of the numerous designs and components that are a vital part of hybrid EVs. This research investigates the benefits that can be gained from utilising a number of hybrid topologies, including series, parallel, and series-parallel approaches. When discussing these configurations, the ability of these combinations to enhance vehicle efficiency and remove emissions is taken into consideration. It provides a fresh viewpoint on the ways in which these technologies are progressing and making a contribution to the overarching goals of modern transportation with regard to technology.

There is a study that is centred on the modelling and simulation of series-parallel hybrid EVs that can be found in the [4]. Insights into the dynamic behaviour of these systems under a wide range of various operational parameters are provided by this body of study. In this study, the overall performance and efficiency of hybrid EVs are investigated, as well as the ways in which alternative configurations may have an impact on those general characteristics. The results of this study offer valuable information that may be put to use in the process of carrying out additional research and development on these systems.

More information regarding the technology that is responsible for bidirectional integrated on-board chargers for EVs may be found in [5]. This provides additional elaboration on the various new strategies for charging. In addition to highlighting the higher charging efficiency, The results of this investigation also emphasise the possibility off these systems to give capabilities for vehicle-to-grid (V2G) connections. It highlights the manner in which such technologies can assist the greater absorption of EVs into smart grids, which will ultimately lead to a more sustainable use of energy and a more stable grid. Ultimately, this will lead to a more stable grid.

The [6] has a discussion on the design and implementation of a bidirectional battery charger for EVs. This topic may be found in the reference. According to the findings of the research, there are novel control systems that optimise the charging process, increase efficiency, and guarantee that the battery life is extended. This particular charger design is capable of adapting to a wide range of energy requirements and storage conditions, which is an example of a significant advancement in the technology that is utilised for EVs.

Better energy management capabilities and seamless contact with grid infrastructures are being researched through the investigation of a smart bidirectional power interface between smart grids and EVs, as stated in [7]. This interface is being investigated. This study's objective is to give a detailed examination of the ways in which such interfaces can promote more efficient management of energy flows. As a result, this study will enable an optimal use of energy during peak and off-peak hours, which will eventually contribute to the overall energy efficiency of the grid.

2.3 Hybrid Energy Storage System

It is provided in [8] that the design and development of a hybrid energy storage system that is specifically adapted for EVs has been completed. The system's objective is to improve the performance of the vehicle by utilising efficient energy management in order to achieve this goal. The fact that hybrid systems have the ability to increase operational efficiency and extend the range of the vehicle is highlighted by this.

There is a scaling method for hybrid energy storage devices that are used in EVs that is presented in the [9]. The objective of this study is to provide a complete analysis of the ways in which these systems could be optimised to produce better results in terms of energy management and vehicle performance. The study provides a rigorous methodology to determining the appropriate size and combination of energy storage components, and it gives the findings of this evaluation. The purpose of the study is to achieve the highest possible level of efficiency while simultaneously reducing the levels of operational expenses.

Last but not least, the [10] delves into the modelling and analysis of hybrid energy storage systems, which are employed in EVs. The article explores the potential of these systems to improve the overall efficiency and performance of the vehicles by implementing increased energy management tactics. This is accomplished through the utilisation of these systems. An investigation into the effects that a variety of various configurations have on the energy system is being carried out as part of this project. In order to provide a fundamental understanding that can be of assistance in the design and implementation of energy storage solutions that are more efficient, the objective of this study is to provide such understanding.

Specifically, the control mechanisms of a hybrid energy storage system that is integrated within an electric vehicle are explored in [11]. A complete examination of how the management of the interaction between various storage technologies, including as batteries and supercapacitors, may contribute to the optimisation of the power consumption of the vehicle and the improvement of the overall performance of the drive is provided by the study. The purpose of this article is to describe a number of different control methods that provide efficient management of power. The long-term viability and dependability of EVs are significantly improved using these strategies, which make a significant contribution.

An investigation of the incorporation of hybrid energy storage systems in EVs is presented in [12], with a particular focus on the synergistic advantages that can be attained through the combination of batteries and supercapacitors. The usefulness of such systems is evaluated in this study based on their capacity to even out the distribution of energy, lessen the strain placed on the battery, and boost the vehicle's overall efficiency in terms of its operation. An in-depth explanation of how hybrid systems can be changed to meet specific performance criteria is provided in the paper. As a result, the versatility of EVs is increased to accommodate a wider variety of driving conditions.

The design of a high-efficiency energy storage system for hybrid EVs is demonstrated in [13], with the ability of the system to integrate with motor drive systems being the primary focus of the design. In this study, it is explained how innovative methods can be utilized to improve energy usage while simultaneously minimizing losses through integrated system design. The study also indicates how such integration can lead to considerable improvements in the performance of vehicles as well as improvements in their energy economy.

Specifically, the potential of hybrid energy storage systems to increase the performance of high-performance hybrid EVs is studied in [14]. To show the substantial role that energy management plays in optimizing the interaction between various storage components and the drivetrain, which eventually results in improvements to acceleration, range, and overall vehicle dynamics performance, the goal of this study is to emphasize the significance of the function that energy management plays.

In [15], there is a presentation that discusses an inquiry that is being conducted into the development of a hybrid energy storage system for EVs that have DC motors. In this study, the emphasis is placed on the design and operational procedures of the system. These techniques enable enhanced management of energy flows, which in turn improves the responsiveness and efficiency of the vehicle.

A review of alternative energy storage systems for hybrid EVs is included in [16]. This reference also includes an appraisal of the potential for these systems to either replace or enhance conventional battery systems at some point in the future. This study aims to investigate a variety of technologies, such as flywheels and supercapacitors, and to investigate the benefits and drawbacks of these technologies in terms of energy density, power delivery, and overall vehicle performance. Specifically, the study will focus on the advantages and disadvantages of these technologies.

The [17] focuses on these strategies and discusses power management methods for hybrid energy storage systems in EVs. These solutions are the subject of the reference. It studies a range of approaches that can optimize the distribution and use of electricity within the vehicle in an effort to enhance the overall efficiency of the vehicle as well as the battery life. This is done in an effort to increase the overall efficiency of the vehicle. In this study, a paradigm is proposed for the purpose of managing the dynamic interactions that take place between different sources of energy. The end consequence of this study is an improvement in the operating capabilities of the vehicle.

An investigation on power optimization for a hybrid energy storage system of an electric automobile [18]. This study can be found in [18]. In order to accomplish effective power distribution and energy conservation, the research is centered on the development of solutions that can be utilized to enhance the synergy that exists between batteries and supercapacitors. When it comes to maximizing the driving range and reducing the amount of wear and tear on the system, these are two variables that are absolutely necessary.

There is a discussion [19] about a recent development in hybrid energy storage devices for EVs. The incorporation of a variety of energy sources is the primary focus of this conversation, with the goal of improving the operational capabilities and fuel efficiency of transportation vehicles. As part of the study, the design and implementation of these systems are analyzed, and insights are presented into the ways in which they could be improved to meet the ever-evolving standards of the automotive industry as well as the expectations of consumers.

Not the least of the topics covered [20] is the administration of hybrid energy storage systems as well as the management of batteries for EVs. Providing a complete overview of battery management strategies that increase the performance and longevity of EVs, this article offers a comprehensive look at these strategies. In addition to this, it studies the challenges and strategies that are associated with the integration of complex storage systems.

A hybrid energy storage system that is fed by solar energy and is put in an electric car is the subject of an investigation that is presented in [21]. The objective of this study is to investigate the ways in which solar energy can be incorporated into on-board energy storage systems in order to enhance their charging capabilities and overall efficiency. The purpose of this research is to investigate whether or not it is feasible to utilize solar panels as a primary or supplementary source of energy. The research focuses specifically on the architecture of the system and the potential for reducing dependency on the traditional power grid.

There is a [22] that provides an analysis of the dimensions of a hybrid energy storage system and propulsion unit that is designed for EVs. In order to establish the proper size and design of energy storage systems, the objective of this work is to provide approaches that can be utilized to determine the appropriate size. In order to improve the overall performance and efficiency of vehicles, these techniques take into account a wide range of driving conditions and the amount of energy that is required.

[23] discusses a hybrid energy storage system, which provides power sharing techniques that can be used in EVs. These mechanisms can be adopted by EVs. The purpose of this study is to investigate many ways that can be used to successfully transfer power across numerous storage units, such as batteries and supercapacitors, with the intention of enhancing the overall energy management and performance of the vehicle. Specifically, the primary objective of this study is to improve the overall performance of the vehicle.

The hybrid energy storage system that is used in EVs is described in [24]. This system is comprised of a battery and a supercapacitor, and it is used to store energy. The goal of this research is to evaluate the benefits that can be obtained by combining these two distinct types of storage technologies into a single system. These benefits include an enhanced lifespan, improved peak power control, and improved regeneration efficiency, all of which have the potential to lead to significant advancements in the use of EVs.

Research on a hybrid energy storage system for hybrid EVs is provided in [25]. This research was conducted using simulation. The purpose of this study is to evaluate the effects that including many types of energy storage has on the dynamics and efficiency of the vehicle in relation to energy storage. The research provides a comprehensive analysis of the numerous configurations of the system, as well as the influence that these configurations have on several performance indicators, including acceleration and range.

The [26] has an analysis of a hybrid energy storage system that is reconfigurable and capable of storing energy for a DC–AC inverter inside of an electric vehicle. In order to examine the design and implementation of a system that is capable of dynamically modifying its configuration in response to operational needs, the objective of this article is to investigate the design and implementation of such a system. It is anticipated that this would lead to an improvement in the responsiveness and efficiency of the procedures involved in power conversion.

In [27], a hierarchical energy management technique is provided for a hybrid energy storage system in EVs that comprises of a battery and a supercapacitor. This system is used to store alternative forms of energy. The document includes a summary of a multi-level control structure that can be found in its entirety. By optimizing energy consumption across a wide range of subsystems, this framework contributes to an overall improvement in the operational efficiency of the vehicle that is the subject of this inquiry.

The research that is given in [28] addresses the feasibility of harvesting energy from electric autos through the utilization of regenerative braking and a hybrid storage system. The goal of this research is to determine whether or not it is possible to effectively capture and recycle kinetic energy that is generated during the braking process. More specifically, the study will concentrate on addressing ways to improve range extension and energy efficiency

The [29] investigates the implementation of a battery-ultracapacitor combination as an energy storage system in EVs. This combination is used to store energy in EVs. The objective of this research is to investigate the performance advantages that hybrid energy systems offer, particularly with relation to response times, energy density, and power delivery. In addition to this, the study offers some insights into the ways in which such systems can enhance the operation of vehicles.

In conclusion, the [30] provides an analysis of a hybrid energy storage system that is designed for an electric vehicle and proves the efficiency of the system. The study gives a detailed analysis of system design and operational methodologies, consequently validating the advantages of integrated energy solutions in terms of enhancing the dependability and performance of EVs.

The research that is described in [31] examines the control methods that are utilized by a number of hybrid energy storage systems for applications that involve electric automobiles. A number of distinct control strategies that are intended to improve the performance and efficiency of hybrid systems that mix batteries and supercapacitors are going to be reviewed and compared in this study. The objective of this work is to examine and compare these control strategies. Additionally, it discusses the ways in which these strategies can be altered to enhance the operational flexibility and energy efficiency of various types of EVs. This is done in order to improve the overall performance of EVs.

A hybrid energy storage system that was created specifically for EVs is the subject of an inquiry that is given in [32]. This work, which aims to improve energy management in general, places a primary emphasis on the integration and optimization of battery and supercapacitor units so that they can operate together more effectively. Through the implementation of this technique, the power fluctuations of the vehicle are smoothed out, and the capacity of the vehicle to handle sudden changes in load is improved. Maintaining the functionality of the vehicle and extending the life of the battery are both dependent on this component, which is a crucial component.

It is possible to find a [33] that provides an overview of energy management strategies and topologies that are suitable for hybrid energy storage systems that are driven by EVs. Within this comprehensive research, a wide range of system designs and management strategies are dissected and explored. By utilizing these tactics, it is possible to optimize the flow of energy between the various storage components of the vehicle, which ultimately leads to an improvement in the efficiency of the vehicle as well as its capacity to be driven.

The purpose of this [34] is to examine the optimization of a hybrid energy storage system and drivetrain for an electric vehicle that is comprised of an ultracapacitor and a battery. The scenario in question is one that involves driving in an urban environment. For the objective of determining how well the system performs, the research replicates a number of different driving scenarios. In addition to this, it provides recommendations for enhancing energy efficiency and lowering the impact on the environment by implementing intelligent energy management principles.

An in-depth discussion of the design considerations and operating benefits of an energy storage system for EVs may be found in [35]. This article's objective is to highlight the necessity of efficient energy management systems in improving the performance of cars while also highlighting the importance of these systems. To be more specific, the article focuses on the ways in which different storage technologies might be employed to improve energy consumption while concurrently regulating emissions that are produced.

According to [36], the interface of a hybrid energy storage system for EVs is explored. The focus of the discussion is on the function that the system plays in improving power delivery and reducing reliance on traditional charging methods. The objective of this project is to investigate the integration of advanced electronics and control systems that are able to manage energy flows between multiple storage units in a seamless manner. This will ultimately result in an improvement in the performance of the vehicle as well as its energy efficiency.

A discussion of the hybrid energy sources that are utilized for the propulsion of hybrid electric cars may be found in [37]. This study investigates a variety of hybrid energy storage system configurations with the purpose of identifying whether or not these systems have the capacity to increase propulsion efficiency and reduce environmental impact. The research is being conducted in order to determine whether or not these systems have the potential to do so. The findings of this study shed light on how the integration of multiple energy sources could potentially result in improvements to the capabilities of vehicles, decreases in the amount of energy that is consumed, and overall benefits in sustainability activities.

2.4 Conclusion

The survey is conducted and it is concluded on the basis literature that by integration of EVs with various hybrid Energy storage systems with technologies has substantial potential to optimize the power consumption and by utilizing proper control strategies we can improve performance and enhance integrations.

CHAPTER_3

BIDIRECTIONAL DC-DC CONVERTER

3.1 Introduction

A hybrid electric vehicle (HEV) is equipped with two distinct kinds of energy storage units electric and gasoline. Electricity implies the usage of a battery (occasionally aided by ultra-caps) to store energy and the traction motor is an electromotor (henceforth referred to as motor).

Fuel needs a tank and either an Internal Combustion Engine (ICE, from now on referred to as engine) or a fuel cell to transform fuel to electrical energy. Traction would be given solely by the electromotor in the above situation. The car would have both an engine and a transmission in the first instance.

Non-electric energy sources as combustion (ICE), fuel cell, hydraulic or pneumatic strength, or human power, depending on their type. In the first example, the ICE is either a spark ignition engine (gasoline) or a fuel injection compression ignition engine (diesel). The energy conversion machine may be fuelled by diesel, methanol, compressed natural gas, hydrogen, or other alternate fuels in the first two scenarios Fig 3.1 shows basic block representation.

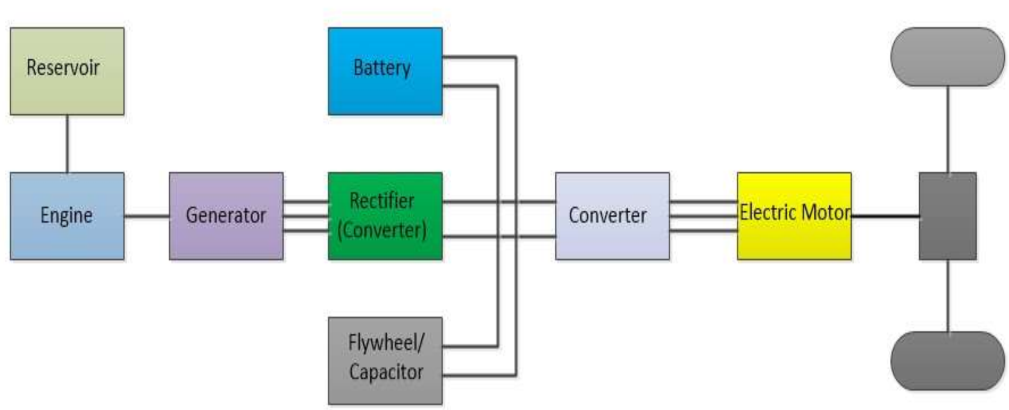


Fig 3. 1 Block Representation of EV

3.2 Hybrid Electric Vehicle

Bi-directional structure that has been proposed to for dual battery energy storage system is shown by Fig 3.2. The HV DC-bus voltage is contained inside this topology, which is comprised of both ES1 and ES2 as respective components. Two bidirectional control switches, which are referred to as S_{ES1} and S_{ES2} are utilised in the structure of the converter at various points in its operation. With the help of these switches. It is feasible to activate and deactivate the current loops of ES1 and ES2 in the most appropriate method. C_B with four active switches and 2-phase inductor L_1 and L_2 are used as a voltage divider. In order to maximise static gain of voltage between two dual sources V_{ES1}, V_{ES2} and DC voltage of high side V_H is used. This is done to support the purpose of increasing the static voltage gain. This activity is conducted to achieve the goal. The inclusion of an extra C_B effectively minimises the voltage stress on active switches, completely eliminating the need for high duty ratio operation. Another advantage is that this is a benefit. In addition, there are three bidirectional power switches S, S_{ES1}, and S_{ES2} that are depicted in Fig 3.2 are utilised to regulate the flow of power between two low-voltage dual sources V_{ES1} & V_{ES2} and operate in four quadrants. These are depicted in Fig 3.2.

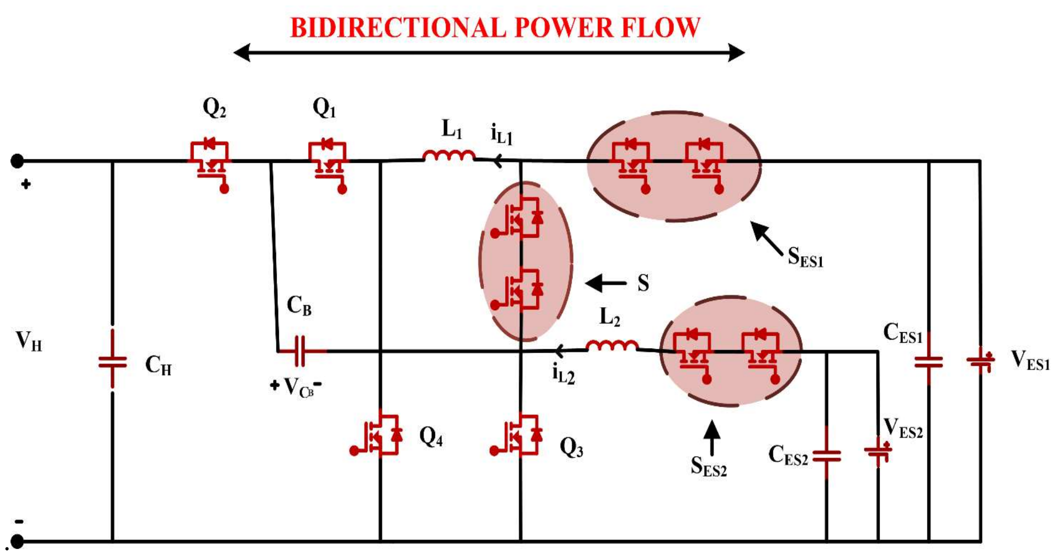


Fig 3. 2 BDC Dual Battery Source

TABLE I OPERATING MODES

Operating Modes	ON	OFF	CS	SR
LV Dual Source powering mode (X_1=1, X_2=1)	S_{ES1}, S_{ES2}	S	Q_3, Q_4	Q_1, Q_2
HV DC bus energy rengerating Mode (X_1=1, X_2=1)	S_{ES1}, S_{ES2}	S	Q_1, Q_2	Q_3, Q_4
LV Dual Source Buck Mode (X_1=0, X_2=0)	S_{ES1}, S_{ES2}	Q_1, Q_2, Q_4	S	Q_3
LV Dual Source Boost Mode (X_1=0, X_2=0)	S_{ES1}, S_{ES2}	Q_1, Q_2, Q_4	Q_3	S
System Shutdown		$Q_1, Q_2, Q_4, S_{ES1}, S_{ES2}$		

Additionally, in order to suppress either positive or negative voltage, it is important to do so before moving forward with the process. The objective of combining two MOSFETs in series is to provide real-time control of bi-directional power flow. As a consequence, it is possible to effectively pass on control in both ways. X_1 and X_2 act as means of controlling distinct modes of operation.

Table I illustrates the conduction states of all power devices that have an active role in each operational mode. This is done to better understand the concept of the converter being provided. This is done to guarantee comprehension of the term. The next explanation aims to enhance comprehension of the four distinct modes of operation that are now accessible. By employing ANFIS, it can be achieved to enhance this controller.

3.3 LV Dual Source Powering Mode

Fig 3.3(a) and 3.3(b) depict the diagrams of the circuit and the steady-state waveforms, respectively, for the LV dual-source-powering mode of the converter. The switch S is in the off state, while the switches S_{ES1} and S_{ES2} are turned on. Two low voltage sources, VES1 and V_{ES2}, provide power to the dc-bus and loads. In this arrangement, the low-side switches Q_3 and Q_4 alternate their switching states with a phase-shift angle of 180°, while the high-side switches Q_1 and Q_2 function as synchronous rectifiers.

The Four operating states of circuit is obtained when duty cycle of switches is more than 50%, that is shown in waveforms of Fig. 3.4 indicate four alternative circuit states. To describe the working of the BDC in LV dual-source-powering mode, consider the on/off condition of active switches and its operating principle.

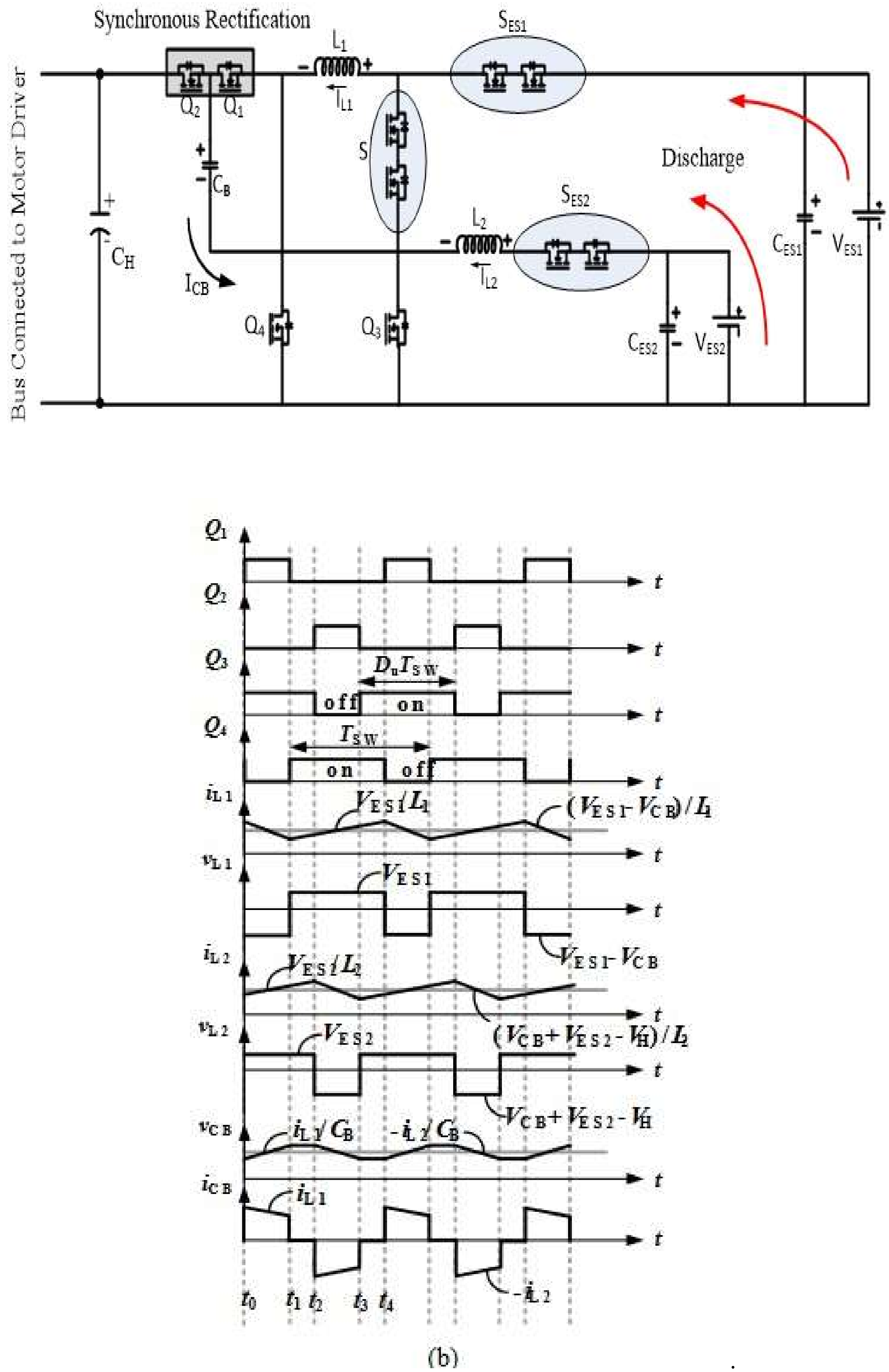


Fig 3. 3 LV dual source powering mode of BDC: (a) Schematics (b) Steady State waveform

A. Mode 1 ($t_0<t<t_1$): During the interval time $(1-D_u)T_{sw}$, Q_1 and Q_3 switches are On, where t switches Q_2 and Q_4 are off. The difference of low side voltage source V_{ES1} and voltage of charge pump C_B results into the voltage across the inductor L_1., resulting in a linear reduction from the original value. Additionally, the energy source V_{ES2} charges the inductor L2 and voltage across L_1 and L_2.

$$L_1\frac{di_{l1}}{dt} = V_{ES1}-V_{CB} \quad \text{Eq. 3.1}$$

$$L_2\frac{di_{l2}}{dt} = V_{ES2} \quad \text{Eq. 3.2}$$

B. Mode 2 ($t_1<t<t_2$): Switches Q_3 and Q_4 are in on state and switches Q_1 and Q_2 are in off state in duration of time $(Du-0.5)*T_{sw}$. Voltages sources V_{ES1} and V_{ES2} are joined to L_1 and L2 inductors, levelling up inductor currents and storing energy. In Mode 2, L1 and L2 inductors voltage can be written as below:

$$L_1\frac{di_{l1}}{dt} = V_{ES1} \quad \text{Eq. 3.3}$$

$$L_2\frac{di_{l2}}{dt} = V_{ES2} \quad \text{Eq. 3.4}$$

C. Mode 3 ($t_2<t<t_3$): Switches Q_1 and Q_3 are in switched off state, while switches Q_2 and Q_4 are in On state in interval time of $(1-D_u)*T_{SW}$. Inductors L1 and L2 voltages can be written as

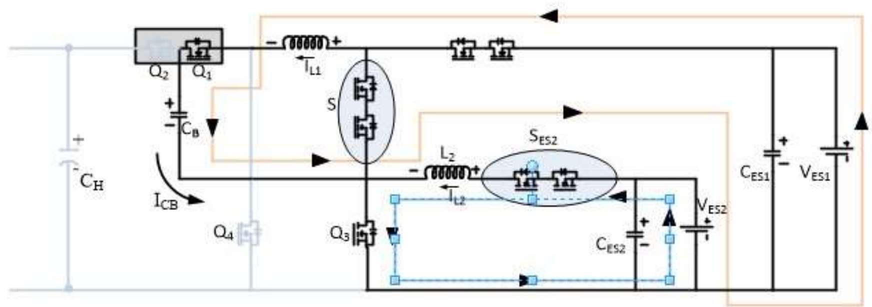
$$L_1\frac{di_{l1}}{dt} = V_{ES1} \quad \text{Eq. 3.5}$$

$$L_2\frac{di_{l2}}{dt} = V_{CB} + V_{ES2} - V_H \quad \text{Eq. 3.6}$$

D. Mode 4 ($t_3<t<t_4$): Switches Q_3 and Q_4 are switched on and Q_1 and Q_2 turned off in interval duration of $(D_u-0.5)*T_{sw}$. Inductors $\mathbf{L_1}$ and L2 Voltages can be indicated as

$$L_1\frac{di_{l1}}{dt} = V_{ES1} \quad \text{Eq. 3.7}$$

$$L_2\frac{di_{l2}}{dt} = V_{ES2} \quad \text{Eq. 3.8}$$



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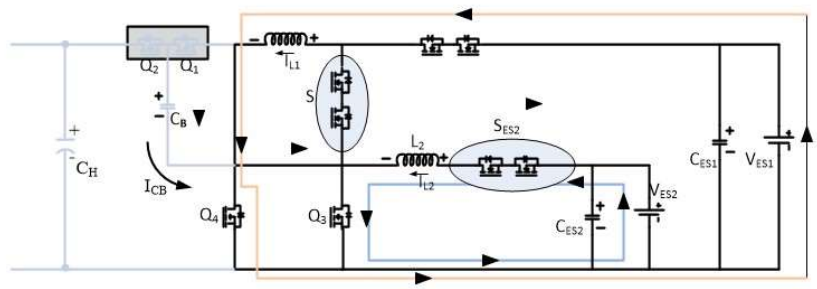

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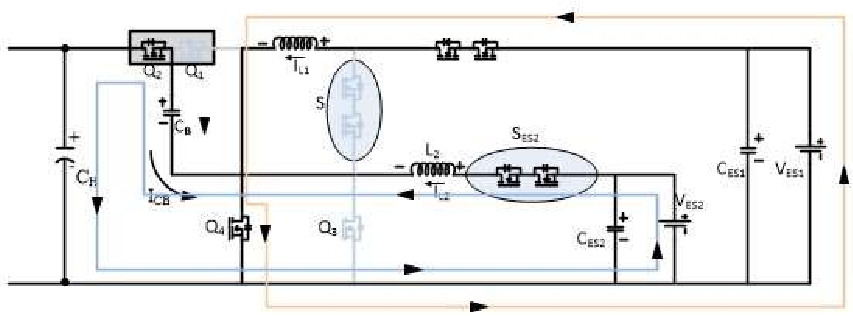

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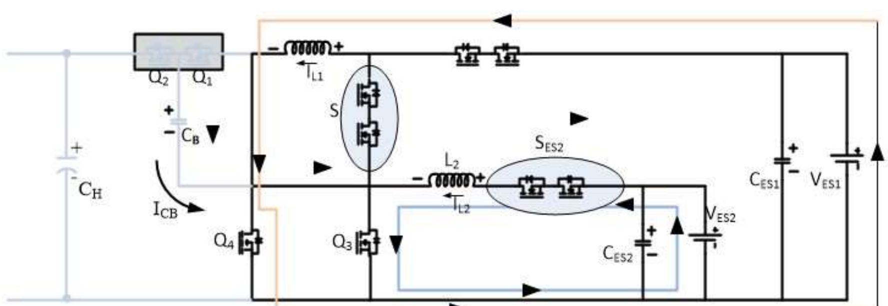


(d)

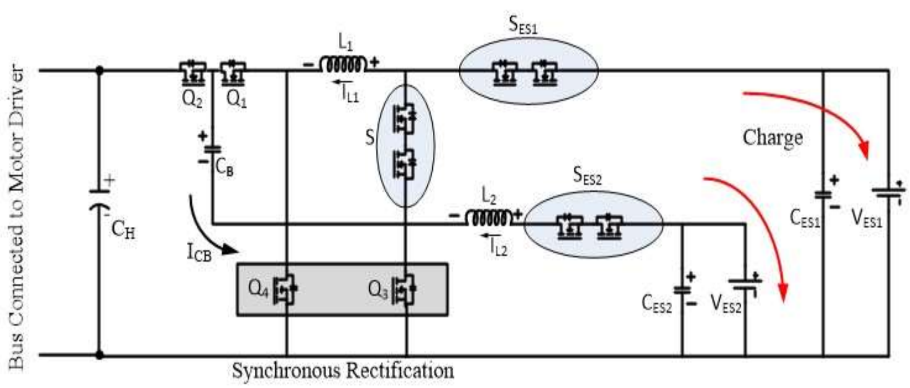
Fig 3. 4 LV dual source powering mode of BDC: (a) Mode 1 (b) Mode 2 (c) Mode 3 (d) Mode 4

3.4 HV DC Link Bus Regenerating Energy Mode

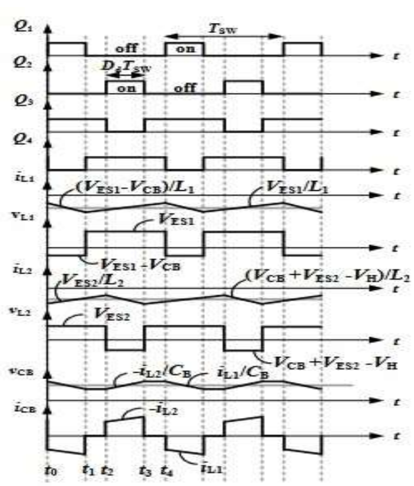
Motor drive system has stored kinetic energy which is utilised by regenerative braking to return it to the source. Regenerative power sometimes may exceed the battery's capacity. In the regenerative mode of operation extra energy is used for storage devices of the system. The circuit diagram and waveform of the components in steady state of HV DC link bus regenerative mode are represented below.

Diversion of current from DC link bus in direction of dual energy storage devices is govern with Q_1 and Q_2 switches, whereas Q_3 and Q_4 serve the purpose of SR to improve the conversion efficiency.

The waveforms in steady state depicts in Fig. 3.5 (b) that, when the duty cycle is less than 50%, four mode of circuit operation occur.



(a)



(b)

Fig 3. 5 HV DC bus link regenerative Mode of BDC: (a) Schematics (b) Steady State waveform

A. Mode 1 (t_0<t<t_1): In the time interval of t_o to t_1, where in terms of duty and switching period is Dd*T_{sw}. switches Q_1 and Q_3 are switched on while switches Q_2 and Q_4 are switched off. The difference of low side source voltage V_{ES1} and Charge pump voltage V_{CB} appeared across inductor L_1 Voltage, resulting in a linear drop in inductor current (i_{L1}) from the original value. Additionally, a linear rise in current can be seen as energy storage V_{ES2} is charging L_2 inductor. L1 and L2 voltages can be written as below

$$L_1\frac{di_{l1}}{dt} = V_{ES1}\text{-}V_{CB} \qquad \text{Eq.3.9}$$

$$L_2\frac{di_{l2}}{dt} = V_{ES2} \qquad \text{Eq. 3.10}$$

B. Mode 2 (t_1<t<t_2): In the time interval of t_1 to t_2, where in terms of duty and Switching period is (0.5-D_d)*T_{sw}. switches Q_3 and Q_4 operates in switched on and Q_1 and Q_2 operates in switched off. L_1 and L2 inductors have positive low-side voltages (V_{ES1} and V_{ES2}), make their currents i_{L1} and i_{L2} to grow linearly. L_1 and L_2 Voltages can be expressed as

$$L_1\frac{di_{l1}}{dt} = V_{ES1} \qquad \text{Eq. 3.11}$$

$$L_2\frac{di_{l2}}{dt} = V_{ES2} \qquad \text{Eq. 3.12}$$

C. Mode 3 (t_2<t<t_3): In the time interval of t_2 to t_3, where in terms of duty and switching period is $D_{d*}T_{sw}$. Q_1 and Q_3 Switches operate in OFF condition, while switches Q_2 and Q_4 operate in ON condition. Voltage of L_1 is represented by the positive low-side voltage V_{ES1}. In result, the current i_{L1} increases in a linear manner from its original value. Furthermore, the voltage of L_2 is the subtraction of the V_H (high-side voltage), the V_{CB} (charge-pump voltage), and the low-side voltage V_{ES2}. It is important to note that the voltage level is negative. L_1 and L2 voltages can be expressed as below.

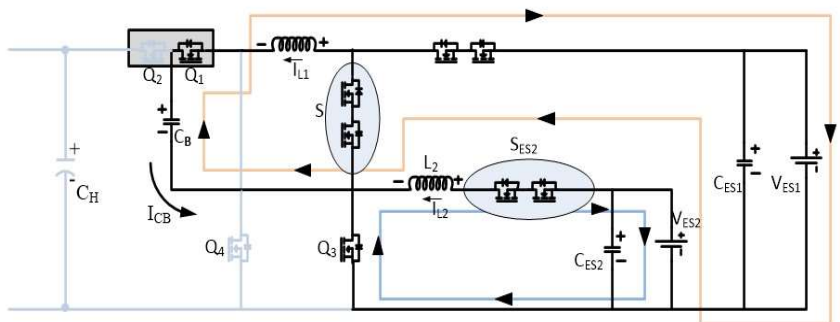
$$L_1\frac{di_{l1}}{dt} = V_{ES1} \qquad \text{Eq. 3.13}$$

$$L_2\frac{di_{l2}}{dt} = V_{CB} + V_{ES2} - V_H \qquad \text{Eq. 3.14}$$

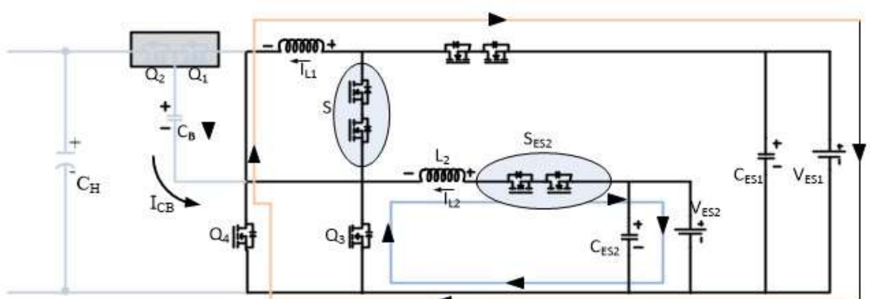
D. Mode 4 ($t_3<t<t_4$): In the time interval of t_2 to t_3, where in terms of duty and switching period is $(0.5\text{-}D_d)*T_{sw}$. Q_3 and Q_4 switches operate in ON condition and Q_1 and Q_2 operate in OFF condition. L_1 and L_2 voltages can be expressed as below

$$L_1\frac{di_{l1}}{dt} = V_{ES1} \qquad \text{Eq. 3.17}$$

$$L_2\frac{di_{l2}}{dt} = V_{ES2} \qquad \text{Eq. 3.18}$$



(a)



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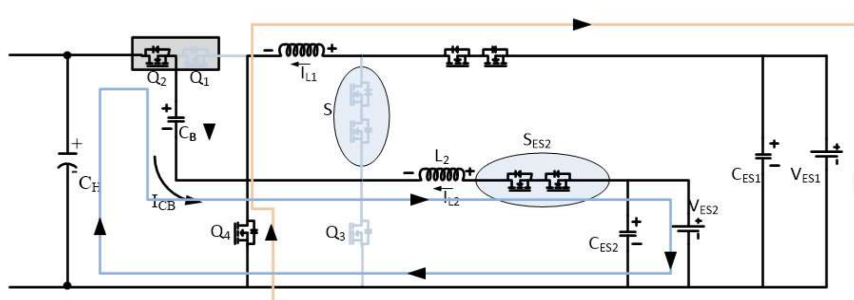

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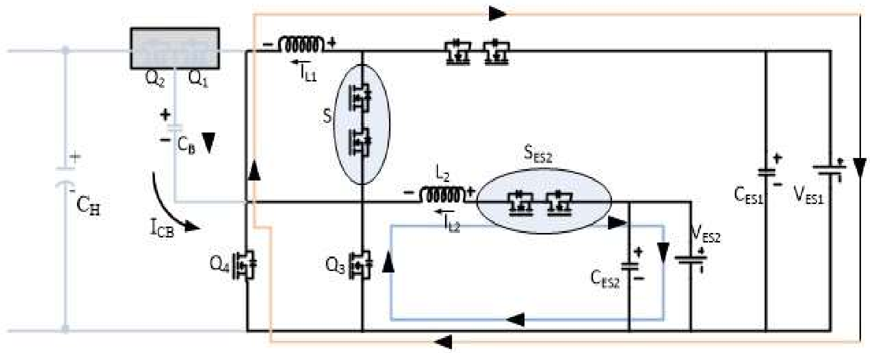
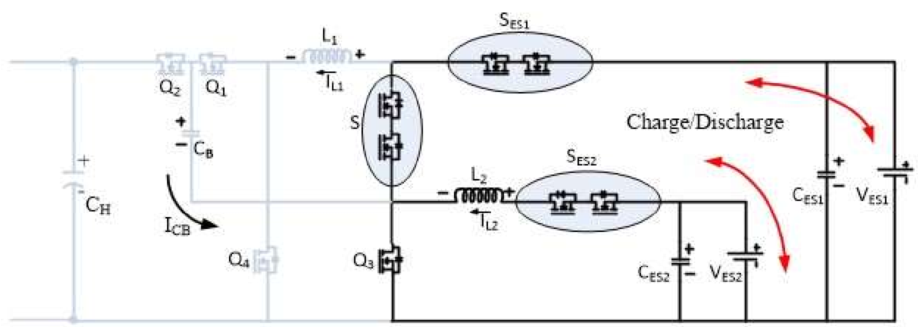


(d)

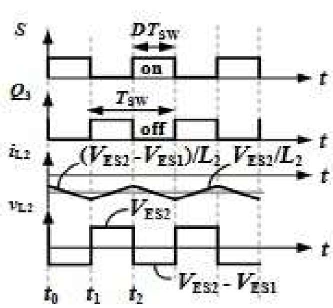
Fig 3. 6 HV DC link regenerative Mode of BDC: (a) Mode 1 (b) Mode 2 (c) Mode 3 (d) Mode 4

3.5 LV Dual Source Buck/Boost Mode

Transferring of energy from main to auxiliary storage system and vice versa can be represented by Fig 3.7(a). on the basis of the need of system buck and boost mode of operation for BDC can be observed. In buck mode of operation inductor current L_2 is negative where in boost mode of operation this current is positive.



(a)



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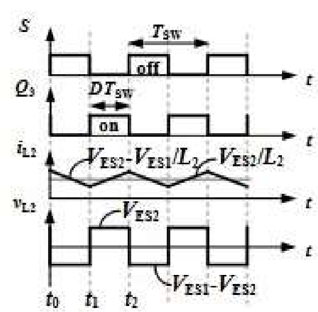
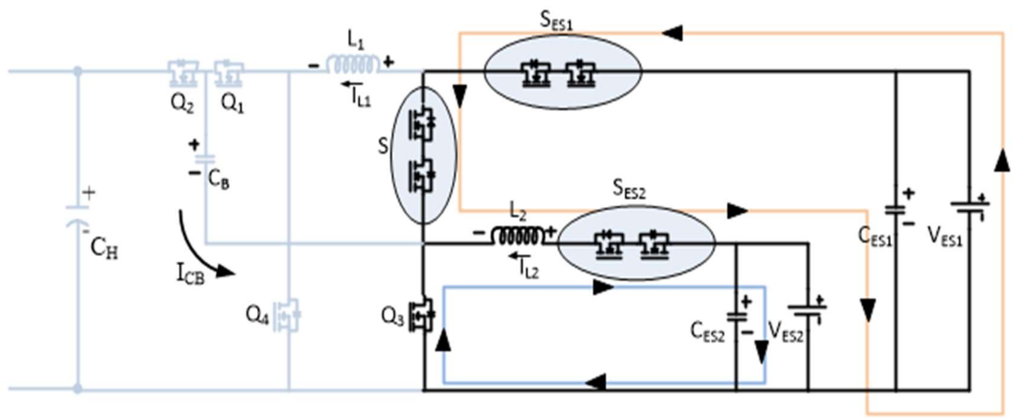
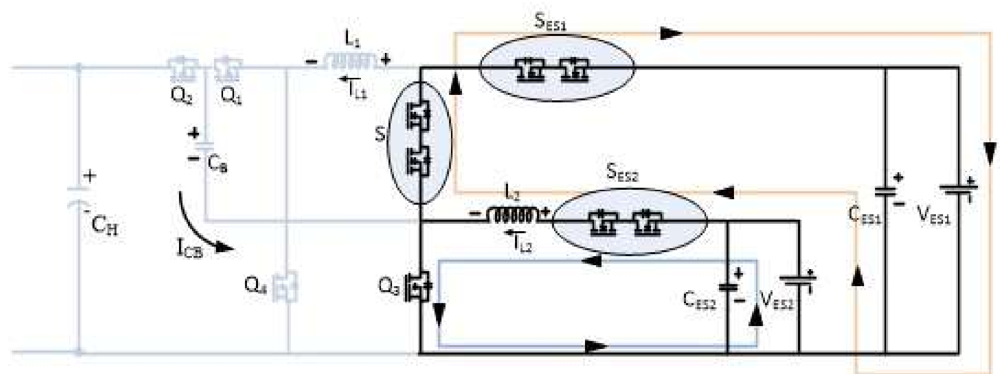


(c)

Fig 3. 7 LV Dual Source Buck/Boost Mode: (a) Schematics (b) Steady State waveform observe in Buck mode (c) Steady state waveform observe in Boost mode



(a)



(b)

Fig 3. 8 Low voltage Dual Source Buck/Boost Mode: (a) Buck mode (b) Boost Mode

By controlling the duty cycle of active bi-directional switch S, power is flow from main energy source to auxiliary energy source and in contrast to this if duty cycle of Q_3 is control power flow from auxiliary to main energy is observed.

A. (Buck Mode) $V_{L2} = V_{ES2} - V_{ES1}$ Eq. 3.17

$V_{L2} = V_{ES2}$ Eq. 3.18

$V_{ES2}=D_s*V_{ES1}$ Eq. 3.19

B. (Boost Mode) $V_{L2} = V_{ES1} - V_{ES2}$ Eq. 3.20

$V_{L2} = V_{ES2}$ Eq. 3.21

$$V_{ES1} = V_{ES2} * \left(\frac{1}{1-D}\right) \qquad \text{Eq. 3.24}$$

TABLE II SIMULATION PARAMETER

SPECIFICATIONS	VALUES
ES1 (Supercapacitor)	V_{ES1}=96V, 15Ah, SOC=100%
ES2 (Battery Source)	V_{ES2}=48V, 15Ah, SOC=100%
DC link Bus Voltage	430V
P_o	1KW
Switching Frequency	F_{sw}=40KHz
L_1, L2 (Inductors)	250 μH
Low Side Capacitor	C_{ES1}=400uf, C_{ES2}=400uF
High Side Capacitor	C_H=1880uF
Charge Pump Capacitor	C_B=10uF
Active Switches	S, Q_1, Q_2, Q_3, Q_4, S_{ES1}, S_{ES2}

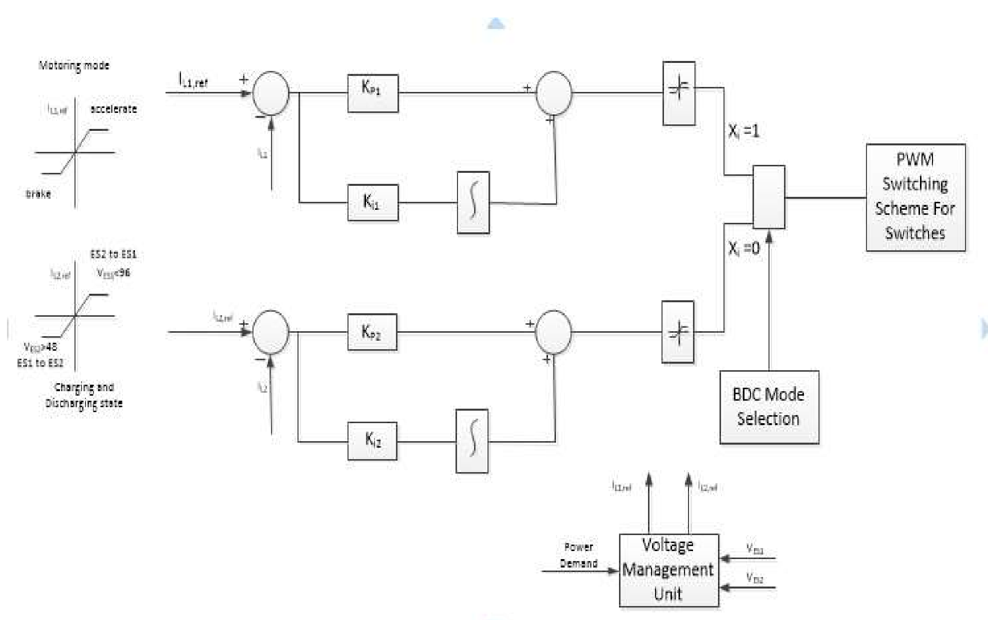


Fig 3. 9 Controller for Bi-Directional Converter [1]

- When power demand is positive and I_{L1ref} current is negative at that condition operation is in HV DC energy regenerative mode of action and control signal of X_1 and X_2 are high.
- when there is power demand and I_{L1ref} is current is positive at that scenario operation is in LV dual source powering mode with control signal X_1 and X_2 high.
- When power demand is negative, source V_{ES1} potential drop from its rating and I_{L2ref} is positive in that condition operation is in LV dual source boost mode with control signal X_1 and X_2 are low.
- When power demand is negative, source V_{ES2} potential drop from its rating value and IL2ref is negative in that scenario operation is in low voltage dual buck mode with control signal X and X are low.

Fig 3.9 provides a visual representation of the block diagram of the controller for the bidirectional converter. This diagram represents the controller.

The presence of a vehicle power and voltage control unit, in addition to an assessment of the amount of electrical power that is utilised, is one of the characteristics that are associated with the strategic management level. It is necessary for the overall outcomes of management to optimise the utilisation of the source that best satisfies the power demand of drive while also satisfying the requirements of the driver and the route.

3.5 Conclusion

It infers that the operational state of the BDC converter has been verified in each mode of operation, changes in system parameters can be witnessed. The opening and closing of a certain switch, signal the state of operation of the system, and the corresponding power transfer in the system is detected. Controller scheme is seen to utilised to compare the currents with reference current to regulate power flow.

CHAPTER_4

IMPLEMENTATION OF BI-DIRECTIONAL CONVERTER

4.1 Introduction

A bi-directional converter is capable of transferring power from both ends of the systems by manipulating signals in such a manner that it can transfer power in both directions. In this project, we will be developing a system that utilises two energy storage systems, V_{ES1} and V_{ES2}, to efficiently transport energy from one location to another. By implementing appropriate switching techniques on the available switches, many operating modes of the system may be achieved, such as the LV dual power sourcing mode, HV DC link regeneration mode, and low voltage dual source buck and boost mode. In order to establish a system, we are deploying two controllers, a Proportional-Integral (PI) controller and an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller. Initially, Proportional-Integral (PI) controller is implemented to regulate the converter and monitoring the resultant control outcomes. Subsequently, we endeavour to apply the same control strategy using Adaptive Neuro-Fuzzy Inference System (ANFIS) to enhance the integration of the system by optimising the real-time dynamic parameter adjustments.

4.2 Proportional Integral Derivative Controllers Background

Controller: A controller is a device that uses mechanism to minimises the error generated by adjusting its parameter on real time. Error of the system is the difference between the actual value of system and targeted output.

PID controllers are the most used form of controller. They have a basic structure and operate well under various operating situations. In the lack of thorough process information, these controllers produce good results in terms of accuracy. The three primary parameters are proportional (P), integral (I), and derivative (D). The proportional component maintains the intended set-point, while the integral and derivative parts handle error and rate of change in the process of system.

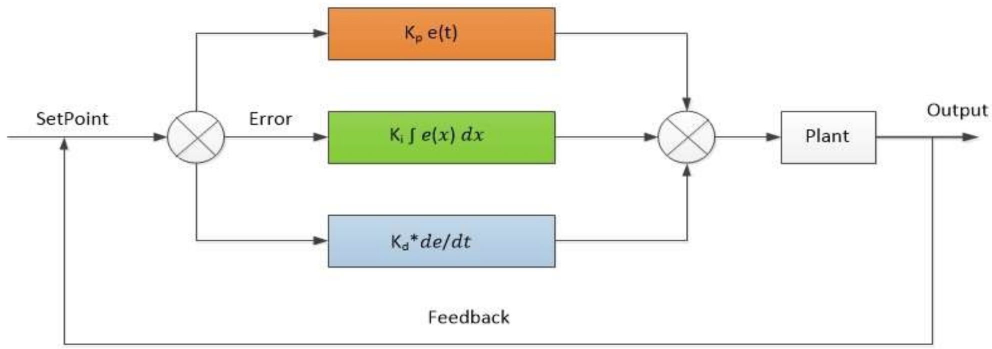


Fig 4. 1 Block diagram of Basic PID controller

$$\text{PID Output, } u(t) = K_p\, e(t) + K_i \int e(x)dx + K_d \frac{de(t)}{dx}$$

Where, Error, e(t) =Setpoint (Reference) – Process output

K_p = proportional gain constant, K_i = integral gain constant, K_d = derivative gain constant

1) With K_p: Response of system increase, steady state error decreases, Overshoot of the system Increases.
2) With K_i: However, reducing the error at steady state sometimes may provide oscillatory responses with decreasing or rising amplitudes, which are typically undesirable.
3) With K_d: Stability of the system get increased.

- **PI Controller: (Proportional Integral Controller)**

PI is widely used controller to reducing error as it is providing capability of both proportional and integral controller. Output of PI controller represents sum of proportional error and integral of error.

$$U(t)= K_P\, e(t) + K_i \int_0^t e(t)dt$$

Where K_P is proportional constant and K_i is integral constant respectively.

1. PI is predominantly used controller where error of the system gets reduced but adjusting parameter or the constant of the system.
2. It provides ease of use and improve transient response with the help of proportional component on the basis of current error conditions.

3. It also requires minimal computational requirements of power for real time applications.

4.3 Implementation of Simulink Model using PI Controller

In Fig 4.2 as shown, the implementation of the bidirectional DC converter (BDC) for hybrid energy storage systems (HESS) is essential for optimising power and energy management in EVs. This is illustrated by the Simulink model that is presented in the section. In addition to a switching network and battery components, this model incorporates a direct current (DC) motor, which is a representation of the energy vehicle. A dual-battery system that is distinguished by a HV DC bus voltage V_H is incorporated into the design, in addition to primary and auxiliary energy storage systems ES1 and ES2, respectively. Two bidirectional power switches, known as S_{ES1} and S_{ES2}, are responsible for managing these energy storage components and regulating the current loops of the system.

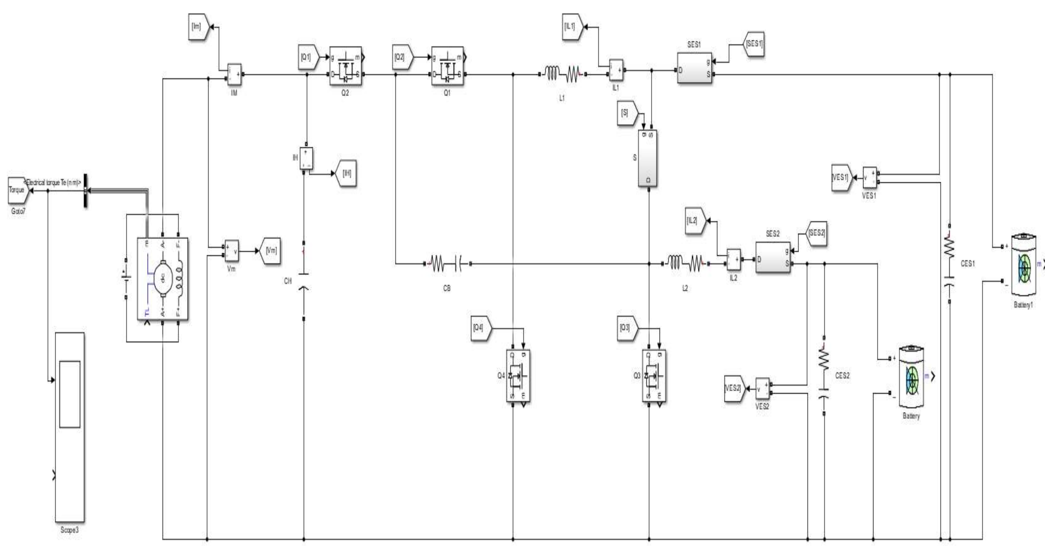


Fig 4. 2 Bidirectional DC Converter Model for various operational mode

The suggested converter topology makes use of a charge-pump capacitor (C_B) to perform the function of a voltage divider. In addition, it incorporates Q_1, Q_2, Q_3, and Q_4 as switch and L_1, L_2 as phase inductor. Because of this setup, the static gain of voltage between the LV sources V_{ES1} and V_{ES2} and the HV DC bus (V_H) is greatly increased. Additionally, the incorporation of the C_B helps to reduce the voltage stress that is placed on the switches, which eliminates the requirement for an unnecessarily high duty ratio in order to accomplish voltage upscaling.

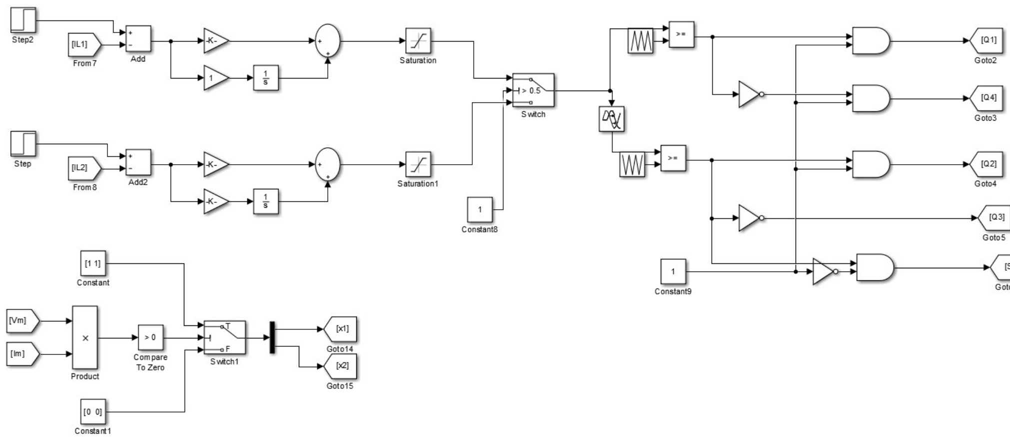


Fig 4. 3 Bidirectional DC Converter Control Mechanism

A representation of the control system of the BDC can be found in Fig 4.3. This system makes use of a Proportional-Integral (PI) controller in conjunction with Sinusoidal Pulse Width Modulation (SPWM) in order to extract gate pulses. When it comes to regulating the energy, power, and voltage of the vehicle depending on different operational factors, such as the power demand of different operating state of drive and the dual-source voltages V_{ES1} and V_{ES2}. This control arrangement is absolutely necessary. This ensures that the proper current references ($i_{L1,ref}$ or $i_{L2,ref}$) are selected in order to manage the active switches S, Q_1 to Q_4 in an efficient manner and to keep the system functioning at its highest possible level..

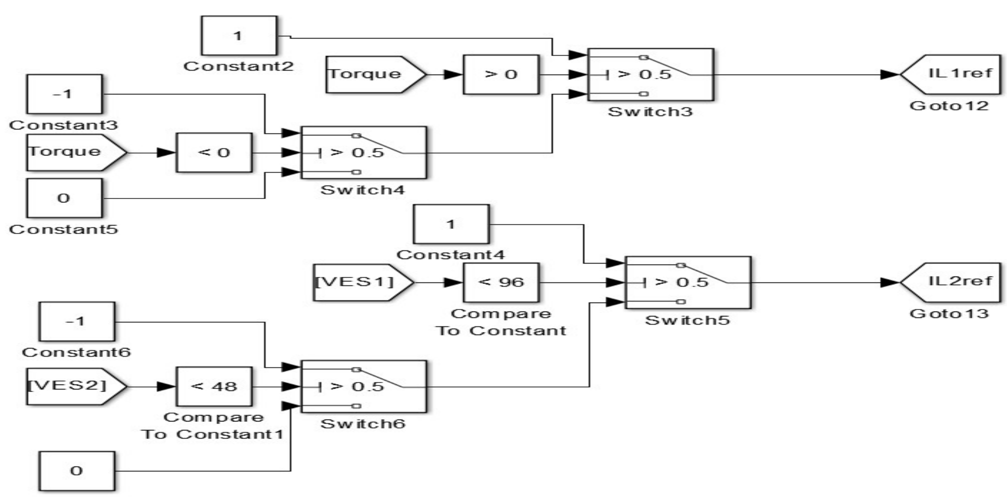


Fig 4. 4 Control System for Mode Switching in BDC

As a final point of discussion, Fig 4.4 provides an overview of the control system that is responsible for mode switching in the BDC. This technique makes it possible to share the average current in a uniform manner, meaning that the average current i_{L2} exactly matches the regulated average current i_{L1}, independent of the control approach that is being utilised. Furthermore, the current reference $i_{L2,ref}$ is specifically utilised to manage the power flow between the main and auxiliary energy storage units, which in turn facilitates effective energy transfer and enhances the overall performance of the vehicle.

4.4 Adaptive Neuro Fuzzy Inference System Controller

- ANFIS, or Adaptive Neuro-Fuzzy Inference System, is a hybrid intelligent system that combines the advantages of artificial neural networks (ANN) with fuzzy logic. Artificial Neural Network is supervised learning which predict on the basis of historical data trained from the past and composed of interconnected nodes (neurons) that adjust their weights based on the input data whereas fuzzy logic is set of rules used to solve complex non-linear system by creating sample function or membership of the available inputs.

- **Structure of ANFIS:**

1) Layer_1: Input layer : The system consists of no. of nodes and each node represents the input variables for the systems.
2) Layer_2: Membership function layer : Nodes in the layer represents fuzzy sets and each node define membership function for each available input.
3) Layer_3: Rule layer : This layer uses the fuzzy AND (product) operation to combine the degrees of membership for the input variables.
4) Layer_4 Normalization layer : Firing strength of each rule represent with Each node.
5) Layer_5 Output layer : This layer represent output of the system and it performs weighted average of output.

- **How it works?**

1) Initialization: Determine the structure of the FIS (membership functions, rule base).
2) Training Phase: Using a dataset, tweak the membership function parameters and rule weights. This is often accomplished by a mix of least squares and backpropagation techniques.
3) Testing Phase: Run fresh data through the trained ANFIS model to generate predictions or judgements.

- **Importance of ANFIS**

The capacity of the Adaptive Neuro-Fuzzy Inference System (ANFIS) to handle complex, nonlinear systems and provide adaptive control and optimisation solutions makes it an essential instrument in the power electronics industry. The real-time application, such as BDC, undergoes constant changes in its state and generates signals that can introduce errors and affect performance. This issue can be effectively addressed by ANFIS, which utilises adaptive control to monitor non-linear or complex systems in real-time. By setting fuzzy rules for each input variable, ANFIS can improve system performance. It may optimise the settings of power electronic controllers, such as PI controllers, to satisfy desired performance requirements, such as minimising overshoot, settling time, rise time, fall time, and slew rate, among others.

4.5 Implementation of Simulink Model using ANFIS Controller

The development of a dual battery storage system for EVs is illustrated by a MATLAB Simulink model, which can be found in Fig 4.5. In this configuration, an ANFIS controller block design is incorporated, and neural network techniques and fuzzy logic are simultaneously combined. It is necessary for the neural network to receive a wide variety of inputs in order to develop outputs that are dependent on them. Following this, the outputs are processed using fuzzy logic in order to create If-Then rules and membership functions, which ultimately results in the creation of an all-encompassing control strategy.

An example of the integration of an ANFIS controller with a Sinusoidal Pulse Width Modulation (SPWM) controller is shown in Fig 4.6. This integration demonstrates the usefulness of the SPWM controller in effectively controlling non-linear systems. The adaptive capabilities of the ANFIS controller are a significant advantage over those of classic controllers such as the PID controller. These characteristics are essential in applications that need a high level of precision, such as for aviation control systems and autonomous technologies.

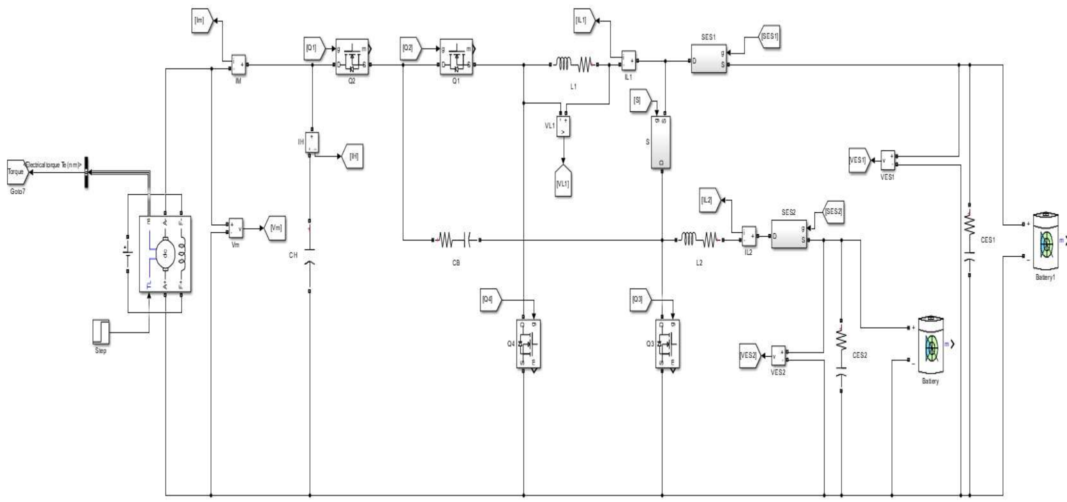


Fig 4. 5 Dual Battery Storage Source Implementation in EVs

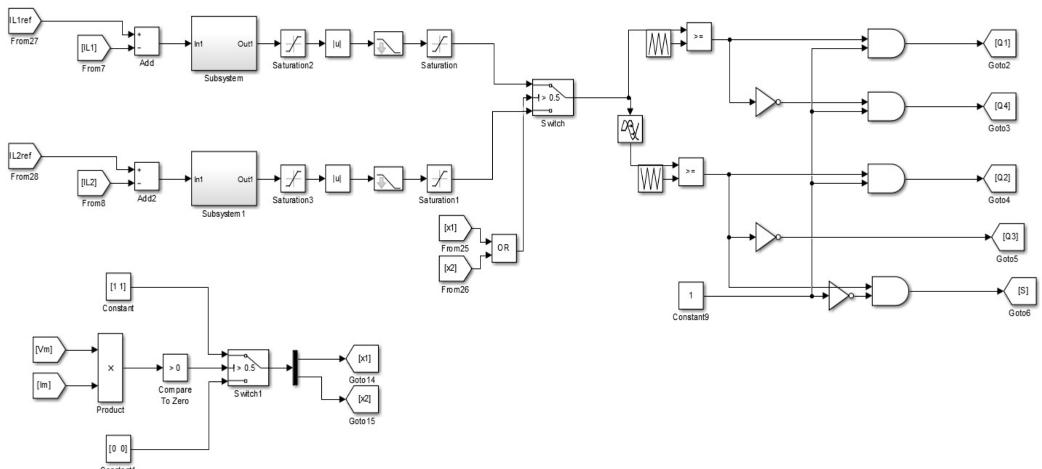


Fig 4. 6 ANFIS and SPWM Control System

An illustration of the inputs for the fuzzy logic component of the ANFIS controller can be found in Fig 4.7. These inputs include error and change in error. The precision and efficiency of the controller in industrial settings is highlighted by the fact that these inputs make it easier to apply ANFIS rules in a bi-directional DC-DC conversion process to the system.

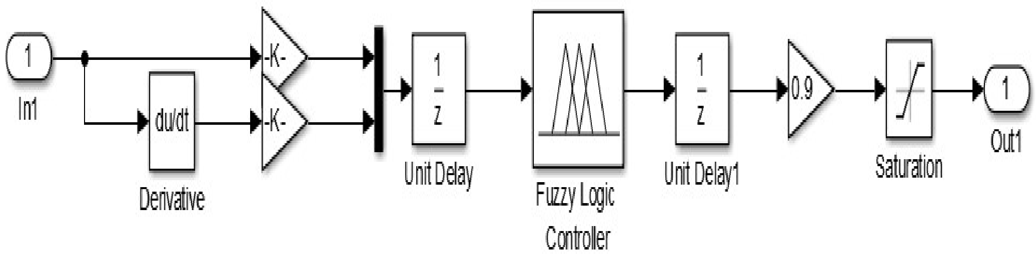


Fig 4. 7 ANFIS Controller Error Handling

Within the ANFIS configuration, the fuzzy rule input and output are depicted in Fig 4.8. Inputs such as error and the rate of change of error are responsible for adjusting the duty cycle fluctuations. Controlling the outputs and ensuring that the controller's responses remain stable are both achieved through this crucial factor.

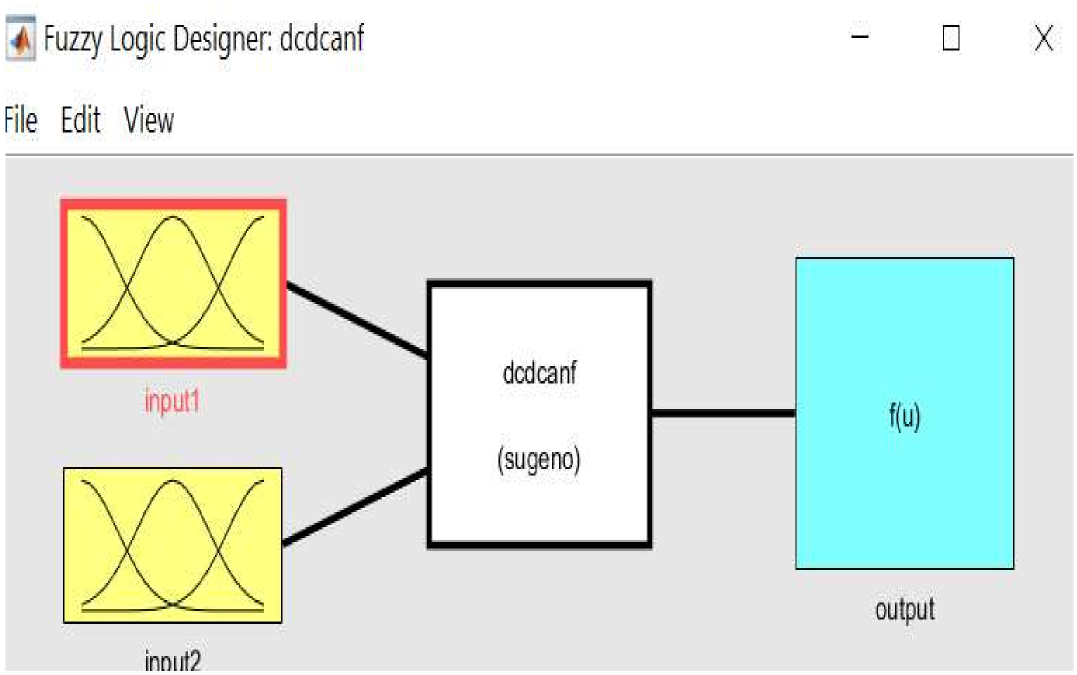


Fig 4. 8 Fuzzy Logic Rule Application in ANFIS

The rule screen for a Sugeno-type fuzzy system is displayed in Fig 4.9. This screen demonstrates how rules are determined based on predefined membership functions, which classify input data on a scale from 0 to 1 according to specific criteria.

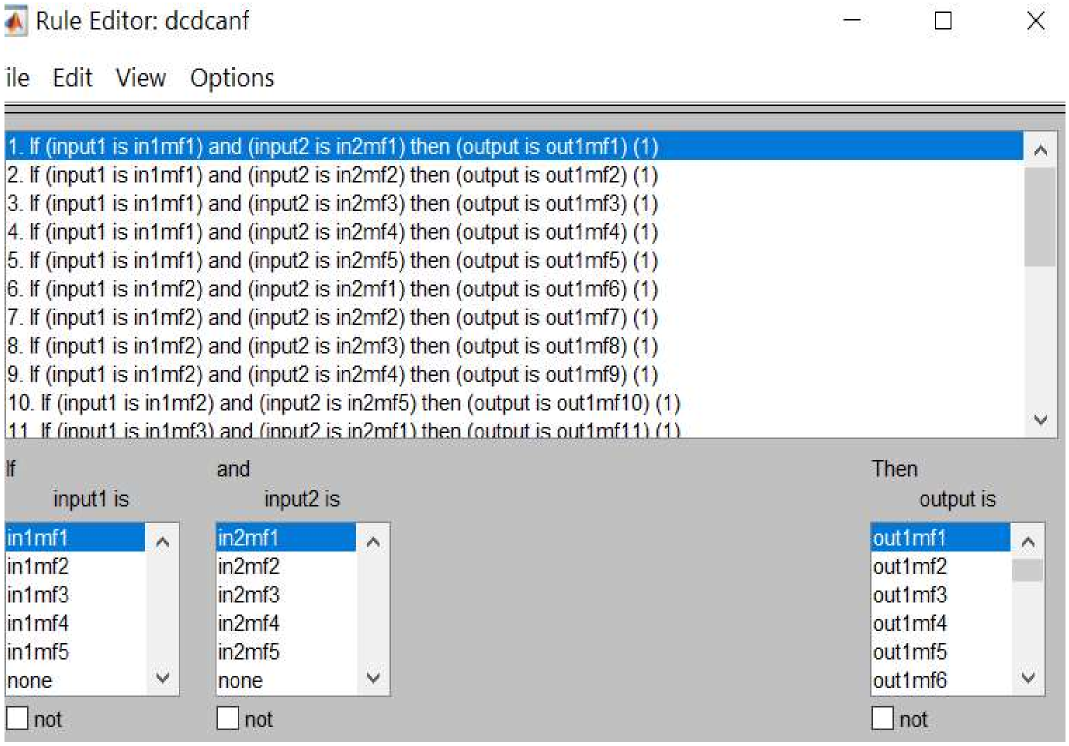


Fig 4. 9 Sugeno-Type Fuzzy Rules Screen

Fig 4.10 illustrates the five input membership functions used in the ANFIS controller. These functions are essential for categorizing input values and influencing the system's response accuracy.

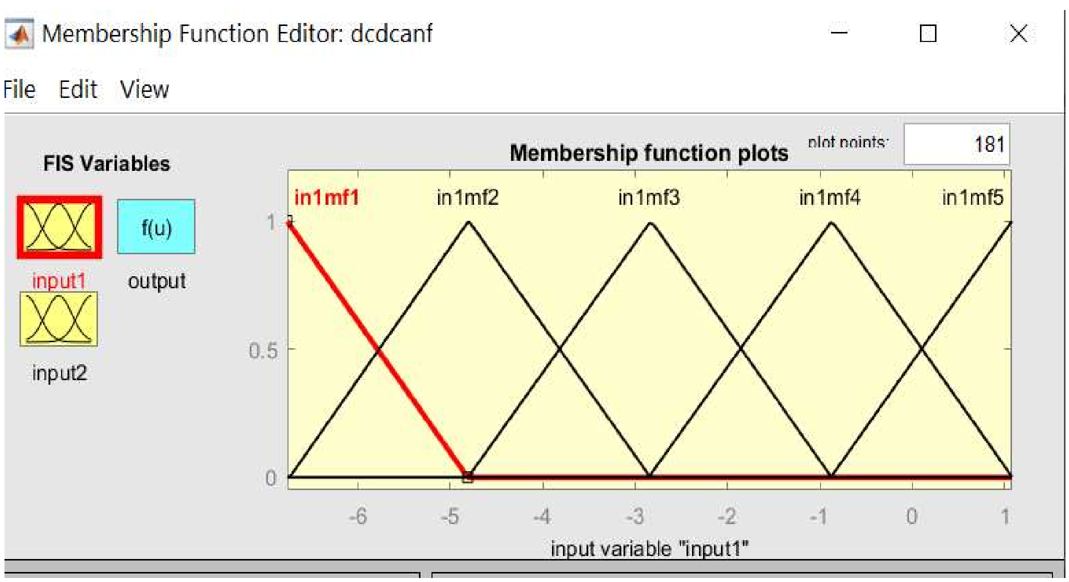


Fig 4. 10 Input Membership Functions for ANFIS

Fig 4.11 outlines the five output membership functions, which are critical in establishing the confidence levels or truth degrees for inputs, based on self-defined linguistic values such as high/low or positive/negative.

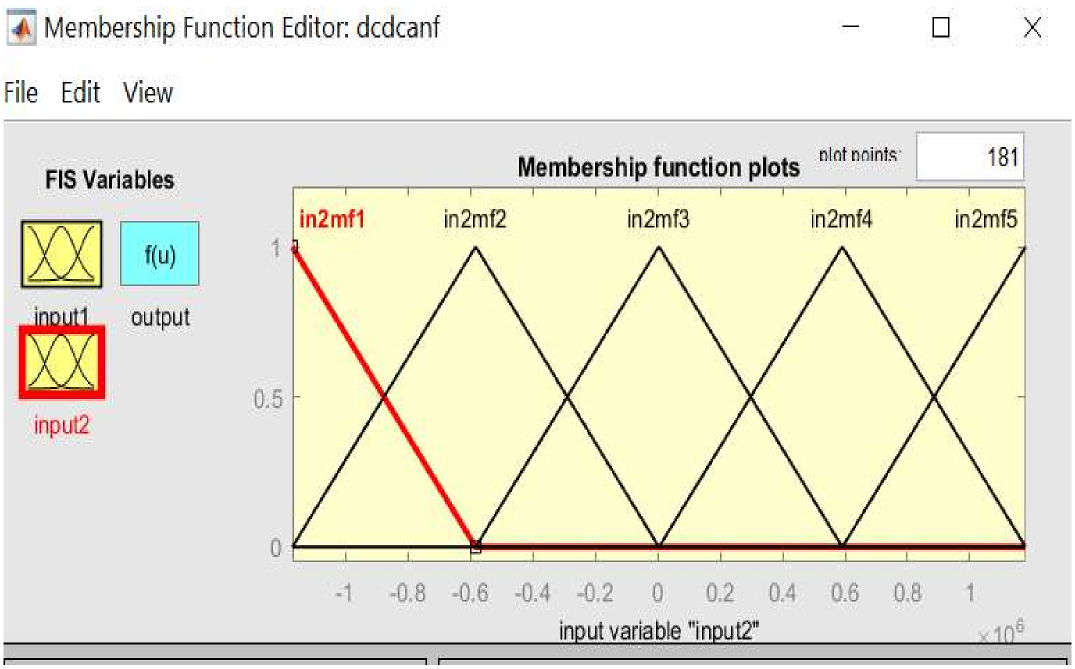


Fig 4. 11 Output Membership Functions for Bidirectional DC Converter

Fig 4.12 presents the membership functions specific to the output of a BDC within a hybrid energy storage system. This visualization helps in understanding how outputs are processed and interpreted within the system.

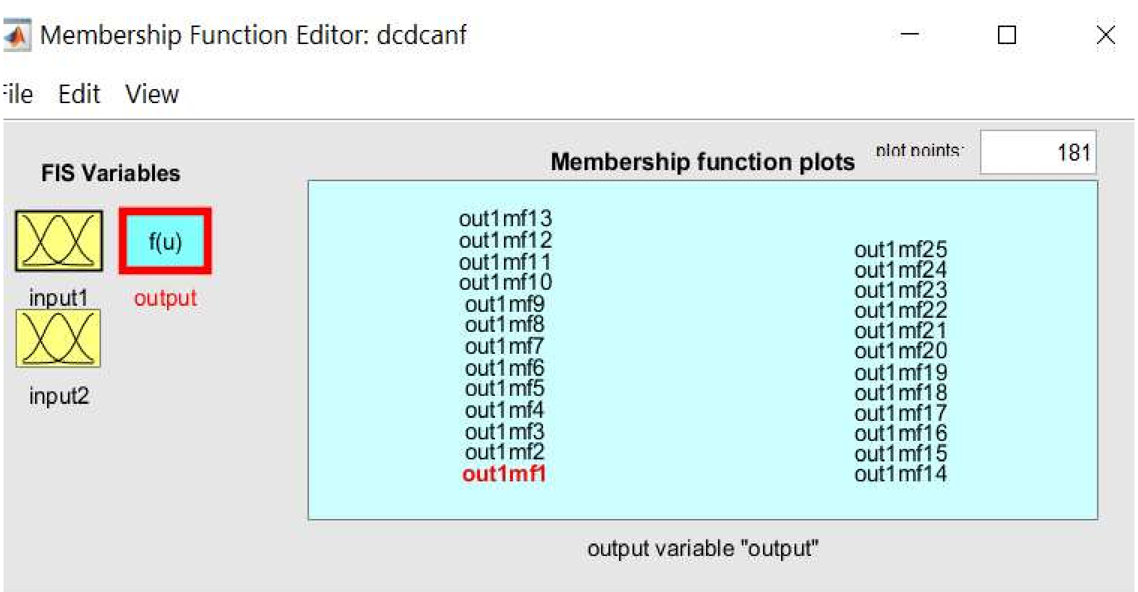


Fig 4. 12 Membership Functions for BDC Output

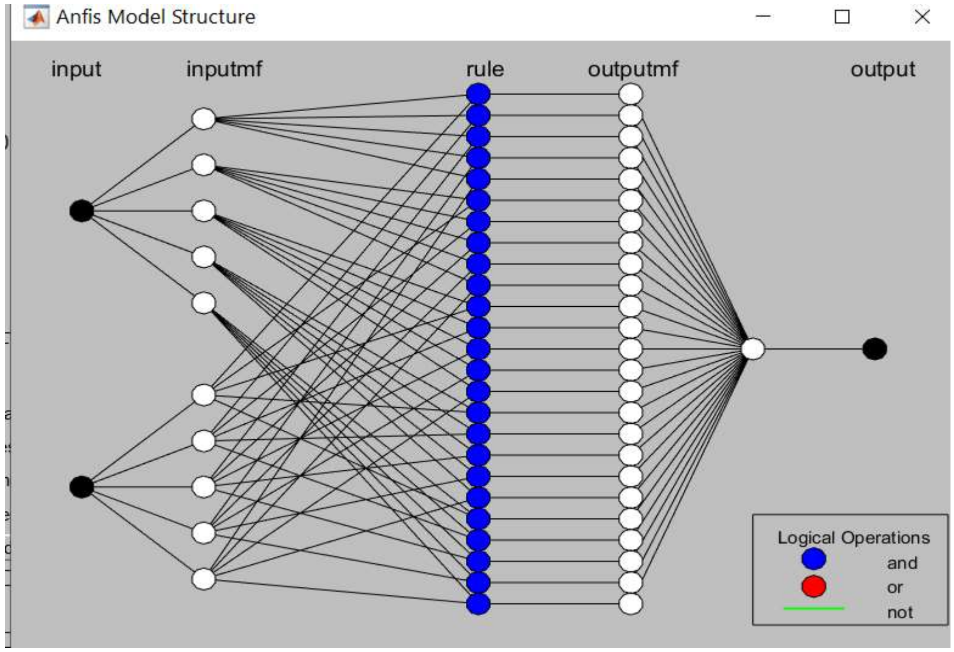


Fig 4. 13 Membership Functions for BDC Output

Finally, Fig 4.13 shows the complete ANFIS structure designed for integration of storage systems in EVs. The overall objective of the structure to enhance the overall performance of the system and rectify non-linearity, inefficiencies observed with traditional PI controllers, demonstrating significant improvements in energy management.

The work that is being presented is focused on the construction of an improved control system for hybrid energy storage in EVs. This is accomplished via the utilisation of an Adaptive Neuro-Fuzzy Inference System (ANFIS) that is paired with a Sinusoidal Pulse Width Modulation (SPWM) controller. The goal of this implementation is to enhance the effectiveness of the process of energy management by controlling the distribution of power between the dual battery storage system and the drive system of the electric automobile in a manner that is both efficient and effective.

It is recommended that the deployment of the ANFIS controller, which is an innovative mix of the ideas of neural networks and fuzzy logic, be regarded as the most important component of the system that has been proposed. When compared to conventional controllers, this combination gives the controller the ability to learn from the dynamics of the system in an adaptive manner. As a result, the controller's ability to deal with nonlinearities and uncertainty is enhanced. An extensive number of inputs are employed in order to train the neural network component that is a part of ANFIS.

In addition to this, the implementation makes use of the SPWM approach in order to accomplish the goal of achieving efficient power conversion. A significant contribution to the creation of the necessary gate pulses for the power switches in the converter is made by the utilisation of pulse width modulation, also known as SPWM. As a result, this helps to ensure that the levels of voltage and current are maintained appropriately in order to complete the energy requirements of the electric car in a range of driving situations. This method not only improves the efficiency of the power conversion process

For the purpose of accommodating the integration of a number of different technologies, it is important to develop a MATLAB Simulink model that displays the whole control architecture of the hybrid energy storage system. In order to ensure the system's resilience and reliability, it is important to conduct an analysis of the system's performance in a number of different operational scenarios. Through the use of simulation, it has been demonstrated that the ANFIS controller is capable of effectively managing the flow of energy between the dual battery system and the HV DC bus. Taking everything into consideration, it is clear that the ANFIS controller possesses higher performance in comparison to more traditional control schemes.

Furthermore, the system that is being proposed is intended to be scalable and adaptable, which makes it possible for subsequent adjustments to be applied. These modifications may include the incorporation of renewable energy sources or the addition of additional storage components. Because of its adaptability, the system is able to handle future demands as well as technological advancements in the field of energy management for EVs. This is because the system is able to accommodate both of these things. The ultimate goal of this implementation is to develop a solution that is dependable, efficient, and cost-effective for controlling hybrid energy storage systems in EVs. This is the final purpose of this implementation. As a result, this will stimulate the widespread use of these systems and support the move towards modes of mobility that are less harmful to the environment.

4.6 Conclusion

In this we can conclude that implementation of topology can be done by both the controllers and various result can be seen but due to utter advantages of ANFIS In real time basis system it makes the system more meaningful in performance and integration with EVs environment.

CHAPTER_5

RESULTS AND DISCUSSION

5.1 Introduction

A comparative analysis of Bi-directional converter has been performed with two different controllers to observe the various parameter changing and making performance of converter more improved to integrate with electric vehicle. PI controller and ANFIS are the two controller which are implementing to deliverer 1KW output power and by implementing ANFIS controller there are considerable change in overshoot, undershoot, rise time, fall time and slew rate of the system that make the system enhance in its performance. The smoothness of curve depicts the faster response and achieve faster settling time for result to get desired value. ANFIS implementation enhance the performance as compare to conventional PI controller in terms of its parameter and make system more viable to integrate with EV environment.

5.2 Simulation Results comparison for Both PI and ANFIS Controller

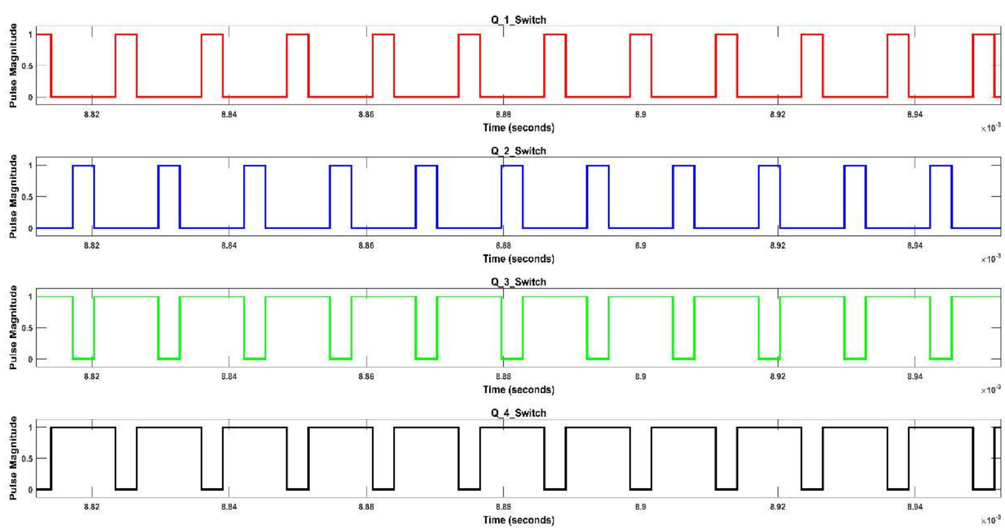


Fig 5. 1 Gate Switching Pulses of Switches

Fig 5.1 illustrates the operational dynamics of the gate switching in system. By varying duty ratio of switches more than or less than 50% we can control the LV dual powering mode, HV DC link regenerative mode of operation and LV Buck and boost mode of operations in the given system.

- The given Fig 5.2 (a), (b), (c) and (d) representing LV dual power sourcing mode that is describe in chapter 3. The Fig 5.2 (a) and 5.2(b) and representing results with use of PI controller in BDC, where as 5.2 (c) and and 5.2(d) shows the observation from the ANFIS controller.

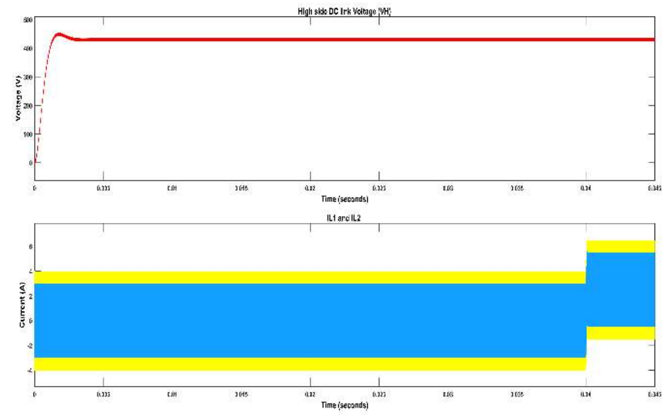


Fig 5. 2 (a) Waveform measured for LV power sourcing mode with PI

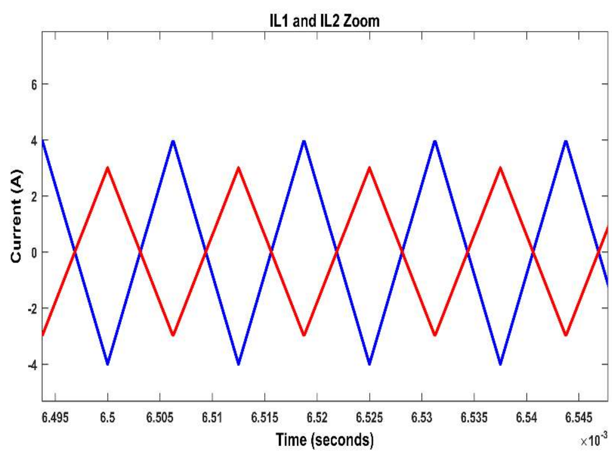


Fig 5. 2(b) I_{L1} and I_{L2} Zoom Waveform measured for LV power sourcing mode with PI

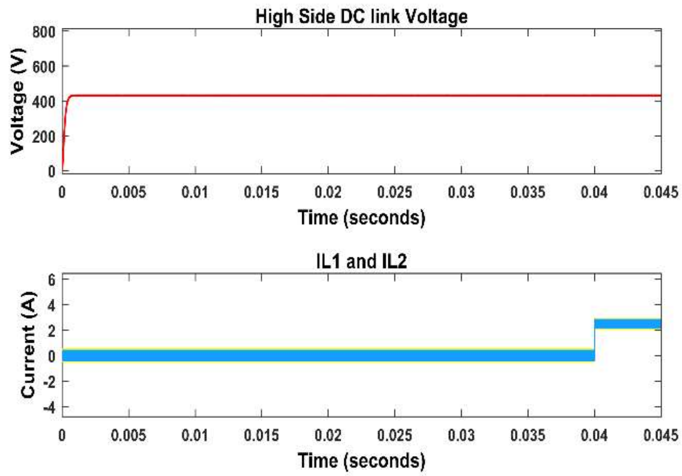


Fig 5.2(c) Waveform measured for LV dual power sourcing mode with ANFIS

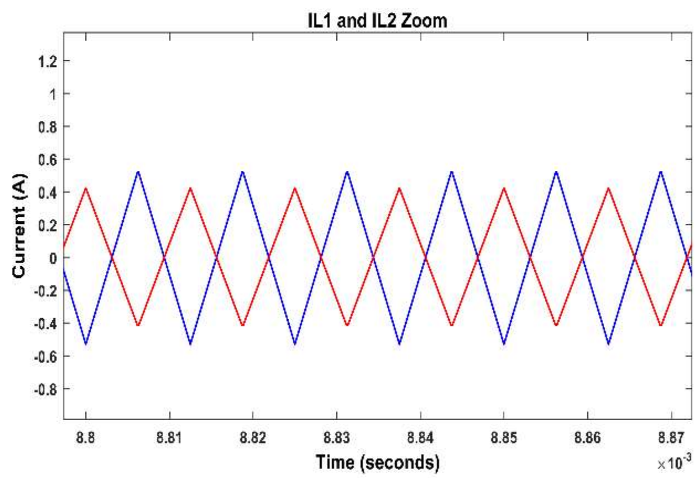


Fig 5. 2(d) I_{L1} and I_{L2} Zoom Waveform measured for LV power sourcing mode with ANFIS

Analysis: In Fig 5.2 (a) and 5.2 (b) we can see the higher ripple content and peak overshoot as compare to 5.2 (c) and 5.2 (d). In first two images the V_H and I_{L1}/I_{L2} have some problem in term of ripple V_H includes peak value of 428.3V, Amplitude of 421.3V is seen and overshoot of 5.978% is observed with settling time of 2.251 msec with rise time of 805.396 µsec where smoothness of curve is observed with ANFIS with Overshoot of 0.497% with settling time of 411.25 µsec and rise time of 396.25usec. In PI controller charging and discharging current I_{L1} and I_{L2} shows the rise time of 1.186 µsec and 1.147 µsec respectively whereas ANFIS has the value 0.987 µsec and 1.05 µsec.

TABLE III COMPARISION OF PARAMETERS_1

	Overshoot		Rise Time		Setting Time	
	ANFIS	PI	ANFIS	PI	ANFIS	PI
V_H	0.50%	5.97*%	396.25usec	805.396 usec	411.25 usec	2.251 msec
I_{L1}	-	-	0.987 usec	1.186 usec	-	-
I_{L2}	-	-	1.05 usec	1.147 usec	-	-

- The given Fig 5.3(a) and 5.3(b) represent the step change of current in LV dual power sourcing mode.

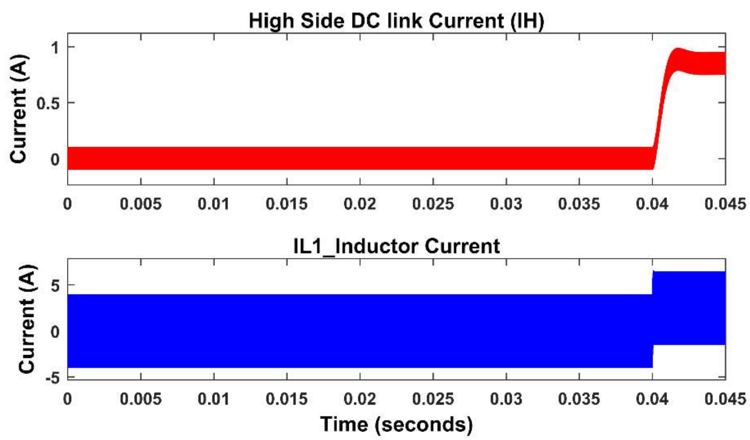


Fig 5. 3(a) Current Step change in LV dual source powering mode in PI Controller

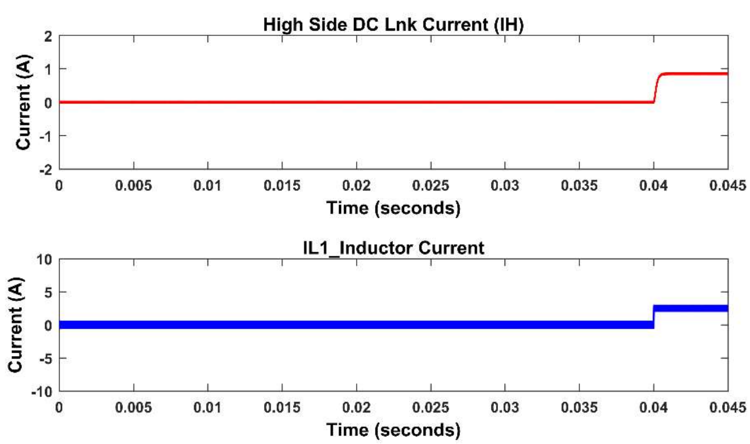


Fig 5. 3(b) Current Step change in LV dual source powering mode in ANFIS Controller

Analysis: In the above figure we can conclude the result by seeing this that there is smoother transition is ANFIS controller. In Fig 5.3 (a) PI high side DC link current I_H has rise and slew rate 568.256 µsec and 1.192/msec respectively where as in ANFIS we can see the 327.027 µsec and 2.088/msec, this can make the transition faster and smoother and band of current has lesser ripple. In 5.3 (a) the transition of high side current is seen from 0 to 0.83A which makes it deliver approximately 358W power in LV dual source powering mode.

TABLE IV COMPARISION OF PARAMETERS_2

	Rise Time		Slew rate	
	ANFIS	PI	ANFIS	PI
I_H	327.027 usec	568.256 usec	2.088/msec	1.192/msec

- In the Fig 5.4(a) and 5.4(b) represents the current step change high side DC link regenerative mode which is mentioned in chapter 3.

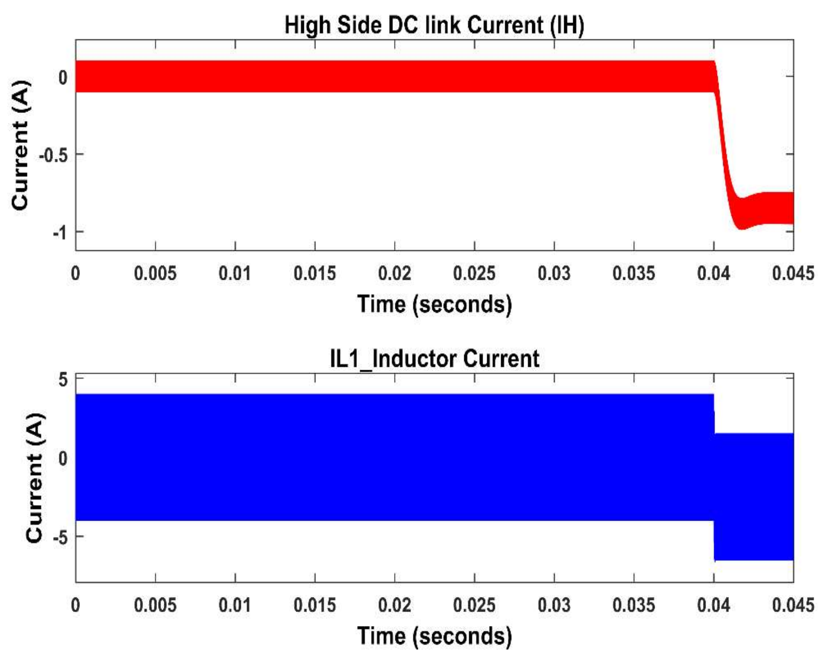


Fig 5. 4(a) Current Step change in High Side DC link regenerative mode in PI Controller

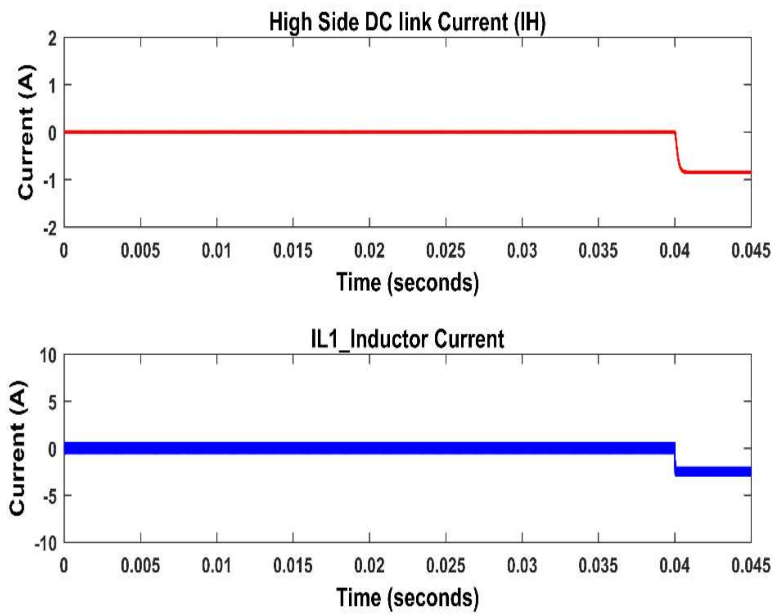


Fig 5. 4(b) Current Step change in High Side DC link regenerative mode in ANFIS Controller

Analysis: In the above Fig 5.4 (a) and 5.4 (b) we depict that reversal of power is done. In Fig 5.4 (a) PI controller give results which has higher ripple content and has lesser smoothness in transition as compare to ANFIS controller use. In Fig 5.4 (a) has ripple in I_H and I_{L1} which is equal to 0.22 and 7.89 respectively and in 5.4 (b) it reduces to 0.048 and 1.2 respectively. In 5.4 (a) Here result observes fall time of 554.296 µsec and slew rate of -1.123/msec in I_H and I_{L1} includes fall time of 1.11 µsec and -1.829/msec when implemented PI Controller where as in 5.4 (b) which is implemented ANFIS reduced results to 325.980 µsec and -2.116 /msec in I_H and in I_{L1} this results into fall time of 0.895 µsec and slew rate of -2.081/msec.

TABLE V COMPARISION OF PARAMETERS_3

	Ripple content		Fall time		Slew rate	
	ANFIS	PI	ANFIS	PI	ANFIS	PI
IH	0.048	0.22	325.980 usec	554.296 usec	-2.116/msec	-1.123/msec
IL1	1.2	7.89	0.895 usec	1.11 usec	-2.081/msec	-1.829/msec

- In Fig 5.5(a), 5.5(b) and 5.5(c) shows the LV boost mode describe in chapter 3.

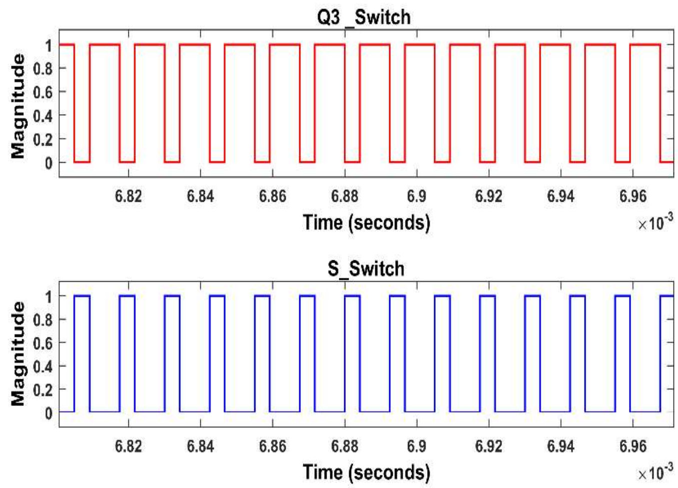


Fig 5. 5(a) Switching Sequence for LV Boost Mode

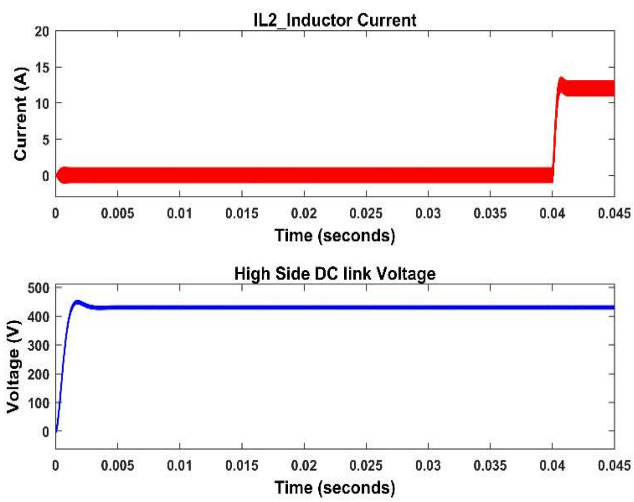


Fig 5. 5(b) LV Boost mode Output voltage and Current fluctuations in PI Controller

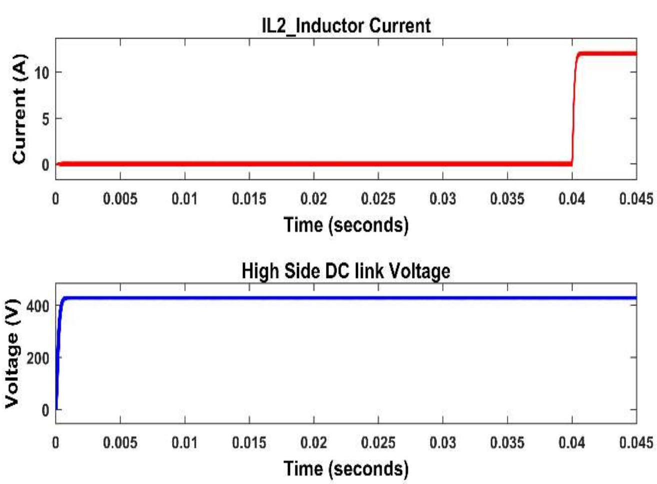


Fig 5. 5(c) LV Boost mode Output voltage and Current fluctuations in ANFIS Controller

Analysis: Similarly, Fig 5.5 (b) presents the output voltage transitions, which exhibit significant fluctuations, indicating areas for potential improvement in system stability and voltage regulation. When in ANFIS in implemented then we can see in the 5.5 (c) the smooth transition and lesser ripple is seen.

In 5.5 (c) With ANFIS controller results show the rise time of 265.44 µsec and slew rate of 36.72/msec in I_{L2} where in PI it is observed 268.66 µsec and slew rate of 37.33/msec. Ripple content in the current I_{L2} is 2.08 in PI where as in ANFIS it is reduces to 0.412.

In 5.5 (c) In high side voltage we observe settling time of 398.193 µsec and overshoot 0.50% in ANFIS in comparison to 22.13 msec and 5.91% in PI controller.

TABLE VI COMPARISION OF PARAMETERS_4

	Rise Time		Slew rate		Settling time		Overshoot	
	ANFIS	PI	ANFIS	PI	ANFIS	PI	ANFIS	PI
I_{L1}	265.44 usec	268.66 usec	36.72/msec	37.33/msec	-	-	-	
V_H	-	-	-	-	398.193 usec	22.13 msec	0.50 %	5.91 %

- In Fig 5.6(a), 5.6(b) and 5.6(c) shows the LV buck mode describe in chapter 3.

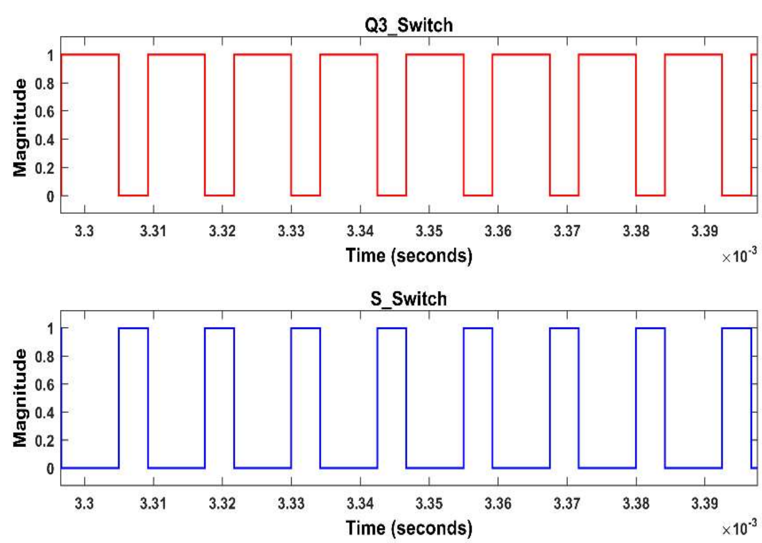


Fig 5. 6(a) Switching Sequence for LV Buck Mode

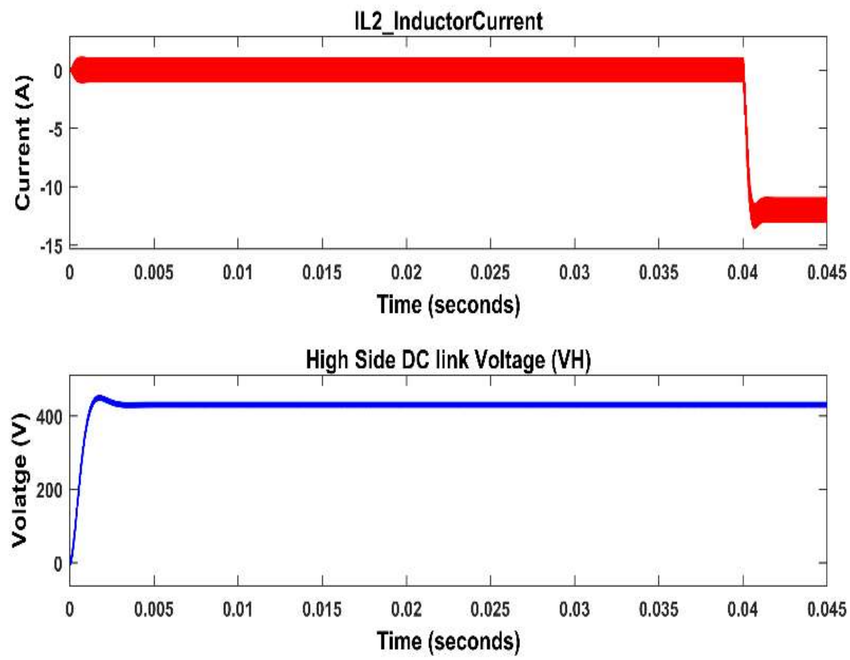


Fig 5. 6(b) LV Buck mode Output voltage and Current fluctuations in PI Controller

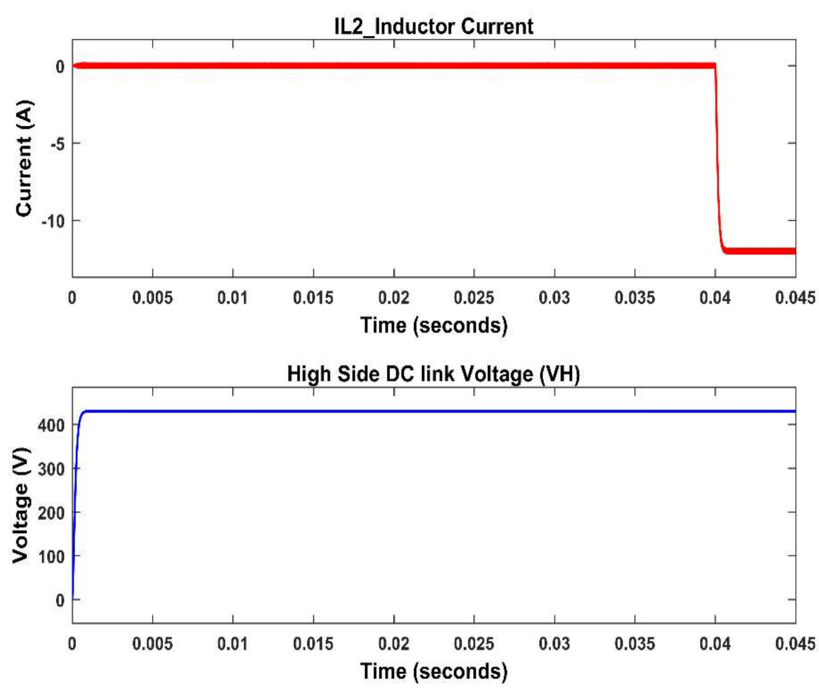


Fig 5. 6(c) LV Buck mode Output voltage and Current fluctuations in ANFIS Controller

Analysis: In Fig 5.6 (b) we can observe the ripple band and transition shown which can create trouble in performance. I_{L2} has fall time of 257.394 µsec and slew rate of -37.14/msec which is improve in ANFIS by 240.394 µsec.

- In Fig 5.7(a) and 5.7(b) shows low voltage buck mode mentioned in chapter 3. I_{L1} and V_{ES1} shows fluctuations.

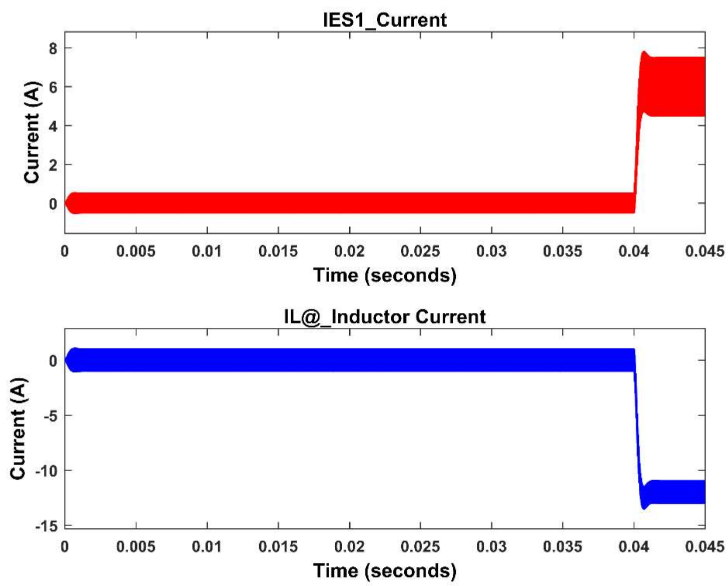


Fig 5. 7(a) Low voltage Buck mode Inductor L_1 Current and Source I_{ES1} fluctuations in PI Controller

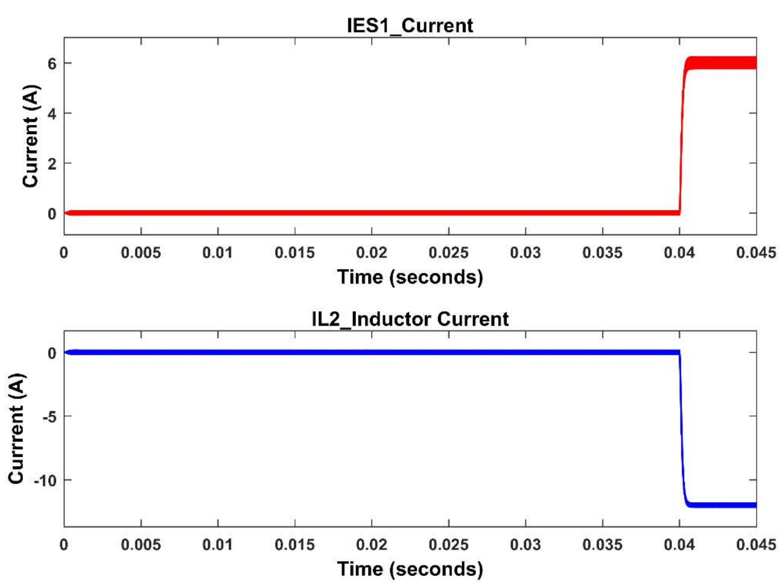


Fig 5. 7(b) Low voltage Buck mode Inductor L_1 Current and Source I_{ES1} fluctuations in ANFIS Controller

Analysis: In 5.7 (a) and 5.7 (b) we can see that in low voltage buck mode of operation the source current I_{ES1} and Inductor current I_{L2} has improve waveform in terms of rise time and slew rate. In ANFIS controller result for source I_{ES1} the rise time for current is

194.888 µsec and slew rate is 24.600/msec but in PI controller the rise time is 240.112 µsec and slew rate is 19.747/msec For inductor L_2 current I_{L2} the fall rate is 264.139µsec and slew rate is -36.896/msec in PI controller result and in ANFIS the fall rate is 257.394 µsec with slew rate of -37.098/msec. Ripple content in source is reduced from 0.98 to 0.325 in source I_{ES1} current and in inductor current it reduces from 2.11 to 0.244.

Taking all of these findings into consideration, it is clear that sophisticated control techniques, and in particular ANFIS, have the potential to dramatically enhance the management and performance of hybrid energy storage systems in EVs. Enhancements parameter leads to dependability are particularly important for the advancement of technology that is required for the development of electric mobility solutions that are both sustainable and high-performing.

TABLE VII COMPARISION OF PARAMETERS_5

	Rise Time		Slew rate		Fall Time	
	ANFIS	PI	ANFIS	PI	ANFIS	PI
IES1	194.888 usec	240.112 usec	24.600 /msec	19.747 /msec	257.394 usec	264.139 usec
IL1	-	-	-37.098 /msec	-36.896 /msec	-	-

5.3 Conclusion

On comparison the operation of the BDC with the two controller PI and ANFIS Respectively we can see viable change in the control parameters of curve in same condition for both the controller and we observe the reduction in peak overshoot, improvement in transition of curve and improvement in settling time which make the system enhancement in its performance.

CHAPTER_6

CONCLUSION AND FUTURE SCOPE

6.1 Conclusion

Using an Adaptive Neuro-Fuzzy Inference System (ANFIS), the research that is described in this thesis sheds light on the substantial breakthroughs that have been made in the regulation of hybrid energy storage systems for EVs. A strategy that has proven to be particularly beneficial in improving the overall performance and efficiency of EVs is the combination of ANFIS with traditional components such as bidirectional DC converters and energy storage systems among other components.

There is a strong framework that is capable of handling the complex dynamics and non-linearities that are inherent in energy storage systems, and the implementation of ANFIS provides this framework. At the same time that the fuzzy logic component of ANFIS fine-tunes the control process by constructing flexible, rule-based decision-making pathways, the neural network component of ANFIS enables adaptive learning based on the behaviour and conditions of the system. Taking advantage of both of these approaches guarantees that the system is not just able to adjust to different circumstances, but that it also continues to be highly efficient and stable.

The ANFIS-controlled system has been shown to outperform typical PI controllers in a number of important areas, including stability, efficiency, and the quality of power delivery, as evidenced by the results of simulations and experimental validations. As a result of the reduced fluctuations and smoother transitions that were noticed in the inductor currents and voltage outputs under a variety of operational modes, the capacity of ANFIS to provide accurate control is demonstrated, especially when confronted with difficult circumstances.

Furthermore, the research makes a contribution to the wider field of electric vehicle technology by demonstrating the possibility to include advanced control systems such as ANFIS into the designs of EVs that are currently in use as well as those that will be designed in the future. This integration not only improves the performance and dependability of EVs, but it also contributes to the greater goal of reducing reliance on fossil fuels and minimising the damage that humans have on the environment.

As a conclusion, the findings of this research demonstrate that it is possible to make use of advanced control systems, such as ANFIS, in order to enhance the administration and performance of hybrid energy storage systems in EVs. This research not only lays the way for future technological advancements in EVs, but it also makes a contribution to the environmental goals of lowering the amount of carbon emissions that are produced across the world. In order to accelerate the adoption of EVs and improve their efficiency on a worldwide scale, it will be essential to continue the development and integration of such technologies going forward.

6.2 Future Scope

A number of new paths for further investigation and development in the field of energy management systems for EVs have been opened up as a result of the study that was carried out for this thesis. The ongoing improvement and optimisation of ANFIS controllers is a direction that should be considered as something promising. It is possible that future research would investigate the possibility of incorporating real-time adaptive learning algorithms into ANFIS controllers. These algorithms would enable the controllers to dynamically react to shifting environmental conditions and driving habits. The efficiency and reactivity of electric cars could be improved as a result of this, making them more flexible to the requirements of their users and the conditions of their surroundings.

There is also the possibility of doing research in the future on the incorporation of renewable energy sources, such as solar panels, into the hybrid energy storage systems of EVs. Not only would this integration aid in lowering reliance on the electrical grid, but it would also encourage the use of the clean energy that is currently available. An investigation into whether or not ANFIS controllers are compatible with some of these renewable energy sources might result in electric car systems that are more environmentally friendly and self-sufficient.

In addition, the scalability of the systems that are managed by the ANFIS presents still another fruitful topic for research. The existing technologies might be scaled up to manage larger networks of batteries and other energy storage solutions, which would make it easier for these solutions to be used in heavier EVs or even in industrial applications. It is possible that this scalability could have a considerable impact on the efficiency and feasibility of electric buses, lorries, and other heavy-duty vehicles. These vehicles play a more significant role in lowering carbon emissions on a broader scale.

In addition, it is essential to do additional research into the demands placed on the ANFIS-controlled systems in EVs in terms of their longevity and maintenance requirements. Studies that are conducted over an extended period of time could yield useful information regarding the lifespan and performance degradation of components that are subjected to continuous usage. This information would be essential for commercial acceptance and consumer trust.

In conclusion, the creation of standardised protocols and frameworks for the installation of advanced control systems in electric cars, such as ANFIS, across a variety of manufacturers has the potential to encourage wider adoption and interoperability. Standardisation may also be of assistance in lowering costs and improving the dependability of these systems, which would hasten the transition towards a transportation infrastructure that is more environmentally friendly and powered by EVs.

The foundation that was created by this thesis can be continued to be built upon by future study if these areas are addressed. This will allow for additional technological advancements in the field of EVs and will contribute to the global drive to find transportation options that are more environmentally friendly.

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LIST OF PUBLICATIONS

Paper	Author list, Title, Conference/Journal	Status
[1]	Ashish Kumar Dixit, Mini Sreejeth, "**Enhancing Electric Vehicle Energy Management Through ANFIS-Controlled Hybrid Storage Systems**" First International conference on Recent Advances in Smart Energy Systems and Intelligent Automation (Rasesia 2024)	Accepted

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Enhancing Electric Vehicle Energy Management Through ANFIS-Controlled Hybrid Storage Systems

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Abstract. This paper investigates the enhancement of electric vehicle (EV) performance through an Adaptive Neuro-Fuzzy Inference System (ANFIS)-controlled Hybrid Energy Storage System (HESS). Utilizing a bidirectional DC/DC converter with dual-battery storage, the system dynamically manages power flows to optimize energy efficiency and vehicle responsiveness. By integrating ANFIS, which merges neural network adaptability with fuzzy logic precision, the system adjusts to varying driving conditions and power demands in real-time. Analysis demonstrate that this approach significantly outperforms traditional controllers in terms Performance. Simulation results are presented, confirming the system's capability to reduce energy fluctuations and enhance power delivery accuracy. This research not only underscores the potential of advanced fuzzy logic systems in automotive applications but also highlights the broader applicability of such technologies in promoting sustainable and efficient energy management in electric vehicles.

Keywords: Electric Vehicles, Hybrid Energy Storage Systems, ANFIS, Bidirectional DC/DC Converter, Energy Management, Fuzzy Logic, Neural Networks, Power Efficiency, Sustainable Transportation, LV/HV

.

1 Introduction

During the move towards more environmentally friendly means of transportation, there has been a growing emphasis placed on the development of electric vehicles (EVs), which have become an increasingly essential alternative to traditional vehicles that are powered by internal combustion engines. This shift is occurring as a direct consequence of the requirement to reduce our reliance on fossil fuels and to limit the impact that we have on the environment. The widespread adoption of electric cars is still met with challenges, the bulk of which are linked with energy management and storage efficiency [1]. This is the case despite the significant progress that has been made in this area. The presence of energy storage devices that are efficient is an absolute requirement for any vehicle that wishes to improve both its range and its performance. It is necessary to come up with innovative ideas in order to overcome these obstacles [15-16].

In order to meet the stringent energy requirements of electric vehicles, hybrid energy storage systems (HESS), which integrate a variety of storage technologies, have emerged as a potentially useful option [2]. In order to take advantage of the complementary features of high energy density and high-power density, batteries and supercapacitors are usually integrated in these systems [12]. This is done in order to maximize the potential of the system. In order to successfully manage the complex dynamics that exist between the various storage components, it is required to utilize sophisticated control algorithms in order to improve power distribution and energy utilization. This is necessary in order to achieve the desired results [6].

A solution that is both reliable and efficient is provided by the Adaptive Neuro-Fuzzy Inference System (ANFIS), which is created by combining the learning capabilities of neural networks with the reasoning method of fuzzy logic. With the help of this integration, it is feasible to develop a control system that is not only flexible but also adaptable, and it is also capable of dealing with the nonlinearities and uncertainties that are inherent in hybrid energy storage systems [3]. As a result of its ability to model complex systems in a manner that is both dynamic and adaptive, ANFIS has been successfully utilized in a wide range of domains, including industrial control and robotics [4].

Within the scope of this discussion, the application of ANFIS for the administration of HESS for electric vehicles constitutes a significant innovation. It is conceivable for ANFIS to increase the overall efficiency and performance of the vehicle by making intelligent management decisions regarding the flow of power between the batteries and the supercapacitors. This is something that can be accomplished. An investigation into an ANFIS-controlled bidirectional DC/DC converter for a dual-battery storage system in electric vehicles is included in the scope of this work. Additionally, the development and implementation of this converter are among the topics that are being explored [8]. In order to illustrate how such a system may successfully reduce energy fluctuations, increase the precision of power supply, and finally expand the operational range and lifespan of the vehicle for a longer period of time, the goal of this research is to demonstrate how such a system can be implemented [5].

It is possible that the introduction of this technology into electric vehicles could result in enhanced vehicle autonomy,

Shortened charging periods, and decreased pricing. All of these factors would contribute to the increased adoption and success of electric transportation options [13]. Other potential outcomes include decreased prices. The future of transportation will be significantly impacted by the adoption of advanced control systems like ANFIS into energy management methods. This will play a crucial role in deciding energy management tactics. The reason for this is because the automotive industry is in the process of continuing its move towards electrification [14].

2. Related Work

Electric vehicles (EVs) have undergone a rapid evolution, which has been pushed by the rising needs of the global community for sustainability as well as advancements in technology. This evolution has been pushed forward by the combination of these two factors. The industry has placed a large emphasis on the optimization of energy storage systems in order to improve both their performance and their efficiency [7]. This is being done in order to improve the overall environment. Recent studies have shown that Hybrid Energy Storage Systems (HESS), which are a combination of different energy storage technologies, have the potential to significantly improve the operational capabilities of electric vehicles (EVs) by striking a balance between high energy density and high-power density [2]. This possibility has been demonstrated by the fact that HESS are a combination of these technologies. When there is a high demand for power, the exploitation of this synergy can help improve power management, and it can also help increase the overall utilization of energy [10].
It has been established that the introduction of bidirectional DC/DC converters into electric cars can facilitate the efficient transfer of energy between the various storage units. The capacity of the vehicle to handle varying loads, as well as its range and performance, are all improved as a result of this [1]. Nevertheless, the challenge is in efficiently controlling these complex systems in order to derive the most possible amount of efficiency from inside them. Traditional methods of control, such as proportional-integral-derivative (PI) controllers, have been widely used; however, they typically fail to appropriately address the non-linearities and dynamics that are observed in modern electric vehicle energy systems [11]. There have been several applications of these techniques.
The deployment of the technology known as the Adaptive Neuro-Fuzzy Inference System (ANFIS) is a particularly interesting technique that can be utilized in order to overcome these challenges. ANFIS is a system that combines the learning capabilities of neural networks with the intuitive control advantages of fuzzy logic [3]. This allows for the development of a control system that is highly adaptive. Due to the fact that it enables alterations to be performed in real time depending on elements such as varied driving circumstances and variations in energy demands, this technology offers a control that is more dynamic and precise than the approaches that have been used in the past [9]. The potential of ANFIS in automotive applications is particularly remarkable, particularly with regard to the enhancement of HESS management [4]. This is because ANFIS has been shown to be useful in a range of industrial applications, and it has been demonstrated to be beneficial in these applications.

In addition, the implementation of ANFIS for the purpose of controlling HESS in electric vehicles is in accordance with the overarching aims of reducing the impact that automobiles have on the environment and enhancing the technology that is used in automobiles. As a result of the fact that such systems have the potential to significantly improve energy efficiency and vehicle performance, they have the potential to act as a catalyst for the widespread adoption of electric vehicles, which would contribute to a reduction in emissions of greenhouse gases and a shift towards renewable energy sources [5]. The research and development that is presently being undertaken in these subject throws light on the crucial part that enhanced control systems will play in the development of transportation technology in the future.

3. Proposed Work

For the purpose of optimizing the management of a dual-battery hybrid energy storage system in electric vehicles, the study that is being presented attempts to integrate an Adaptive Neuro-Fuzzy Inference System (ANFIS) with a bidirectional DC/DC converter. It is anticipated that the application of ANFIS will improve the adaptability and efficiency of the energy management system. This will be accomplished by using the strengths of both neural networks and fuzzy logic. In this configuration, the bidirectional DC/DC converter plays a crucial function, as it enables the smooth transfer of energy between the high-energy-density battery and the high-power-density supercapacitor. The amount of energy that can be transferred between the two components is determined by the operational requirements of the vehicle.

In order to put this into action, a comprehensive simulation model will be constructed with the help of MATLAB/Simulink. The ANFIS controller will be designed and fine-tuned using this model, which will act as a testbed for the process. For the purpose of training the controller, historical data will be collected from typical driving cycles. These cycles will contain fluctuations in speed, load, and power requirements all during the cycle. Adjusting the weights of the neural network and the membership functions of the fuzzy logic will be part of the training process. The goal of this process is to reduce the amount of deviation that exists between the desired performance of the energy storage system and the actual performance.

Following the completion of the necessary training for the ANFIS controller, it will be implemented within the simulation environment in order to exercise control over the bidirectional converter. When evaluating the performance of the controller, various criteria will be taken into consideration. These criteria include the energy utilization, the consistency of the power supply, and the response time to variations in load demands. These evaluations will assist in determining whether or not there are any possible problems or areas in which the control method could be improved.

It is the ultimate objective of this project to demonstrate that a hybrid energy storage system that is managed by an ANFIS may greatly outperform standard control systems that are utilized in electric vehicles, such as PID controllers, particularly in terms of energy efficiency and operational dependability. This method, if it proves to be successful, has the potential to be scaled up and maybe commercialized, which would represent a significant advance over the energy management practices that are now utilized in electric vehicles. It is possible that this will result in a longer battery life, an increased vehicle range, and overall improved performance, which would be in line with the current worldwide trend towards more environmentally friendly and energy-efficient transportation alternatives.

The development of a dual battery storage system for electric vehicles is illustrated by a MATLAB Simulink model, which can be found in fig.1. The parameters for the BDC used in this simulation can be refer from Table I. In this configuration, an ANFIS controller block design is incorporated, and neural network techniques and fuzzy logic are simultaneously combined. It is necessary for the neural network to receive a wide variety of inputs in order to develop outputs that are dependent on them. Following this, the outputs are processed using fuzzy logic in order to create If-Then rules and membership functions, which ultimately results in the creation of an all-encompassing control strategy.

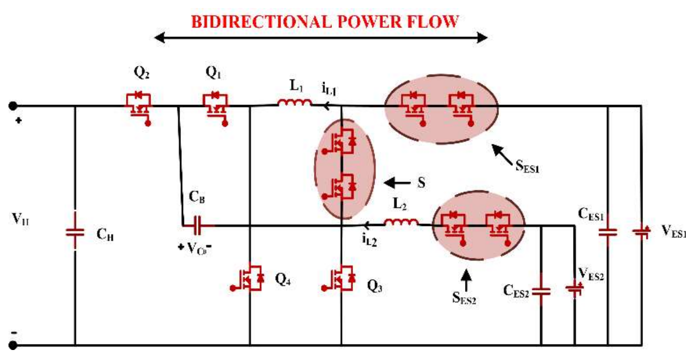


fig.1 Dual Battery Storage Implementation in Electric Vehicles

TABLE I
PARAMETER CONSIDERED

Specifications	Values
ES1 (Supercapacitor) ES2 (Battery Source)	V_{ES1}=96V, 15Ah, SOC=100% V_{ES2}=48V, 15Ah, SOC=100%
DC Bus Voltage	430V
Switching Frequency	Fsw=40KHz
L1, L2 (Inductors)	250uH
Low Side Capacitor	C_{ES1}=400uf, C_{ES2}=400uF
High Side Capacitor	C_H=1880uF
Charge Pump Capacitor	C_B=10uF
Switches	S, S_{ES1}, S_{ES2}, Q_1, Q_2, Q_3, Q_4

An example of the integration of an ANFIS controller with a Pulse Width Modulation (PWM) controller is shown in fig.2 This integration demonstrates the usefulness of the PWM controller in effectively controlling non-linear systems. The adaptive capabilities of the ANFIS controller are a significant advantage over those of classic controllers such as the PID/PI controller. These characteristics are essential in applications that need a high level of precision, such as for aviation control systems and autonomous technologies.

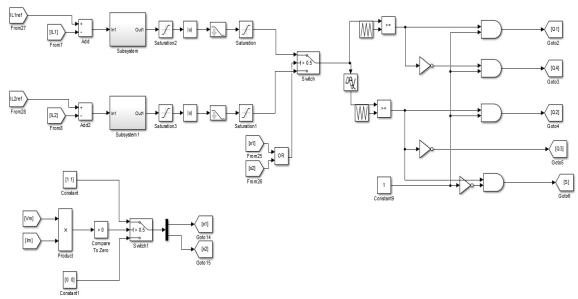


fig.2 ANFIS and PWM Control System

An illustration of the inputs for the fuzzy logic component of the ANFIS controller can be found in fig.3. These inputs include error and change in error. The switching scheme that is derived from the controller action is shown in Table II. The precision and efficiency of the controller in industrial settings is highlighted by the fact that these inputs make it easier to apply ANFIS rules in a bi-directional DC-DC conversion process to the system. This system operates in various modes by incorporating different conduction state of switches.

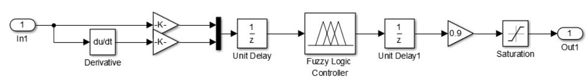


fig.3 ANFIS Controller Error Handling

TABLE II.
CONDUCTION STATE OF DEVICE FOR DIFFERENT STATE

Operating modes	On	Off	Control Switch	Synchronous Rectifier.
LV dual-Source power mode	S_{ES1}, S_{ES2}	S	Q_3, Q_4	Q_1, Q_2
HV DC Regenerating mode	S_{ES1}, S_{ES2}	S	Q_1, Q_2	Q_3, Q_4
Low Voltage Dual Source Buck mode (ES1 to ES2)	S_{ES1}, S_{ES2}	Q_1, Q_2, Q_4	S	Q_3
Low Voltage Dual Source Boost mode (ES2 to ES1)	S_{ES1}, S_{ES2}	Q_1, Q_2, Q_4	Q_3	S

In the ANFIS configuration, the fuzzy rule input and output are depicted in fig.4. Inputs such as error and the rate of change of error are responsible for adjusting the duty cycle fluctuations. Controlling the outputs and ensuring that the controller's responses remain stable are both achieved through this crucial factor.

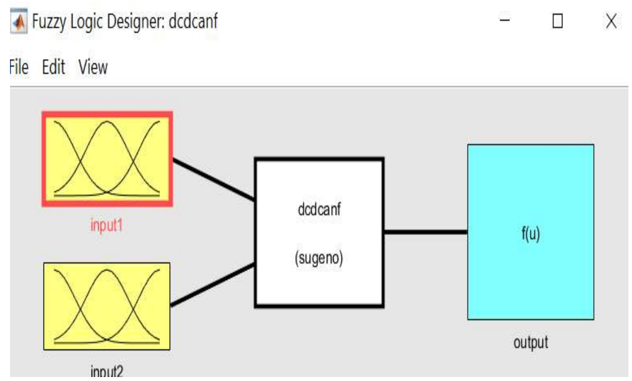


fig.4 Fuzzy Logic Rule Application in ANFIS

The rule screen for a Sugeno-type fuzzy system is displayed in fig.5. This screen demonstrates how rules are determined based on predefined membership functions, which classify input data on a scale from 0 to 1 according to specific criteria.

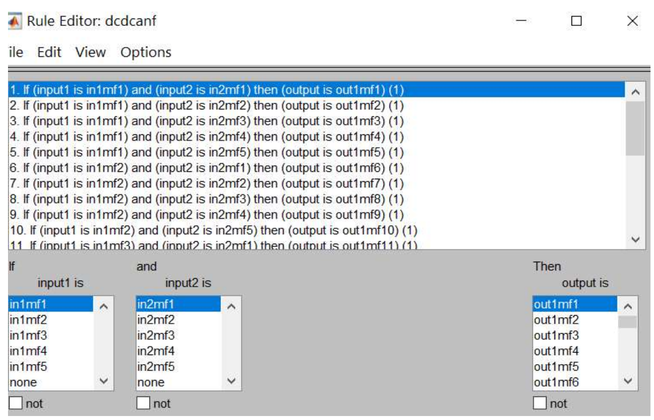


fig.5 Sugeno-Type Fuzzy Rules Screen

Five input membership functions used in the ANFIS controller. These functions are essential for categorizing input values and influencing the system's response accuracy and this can be shown in fig.6.

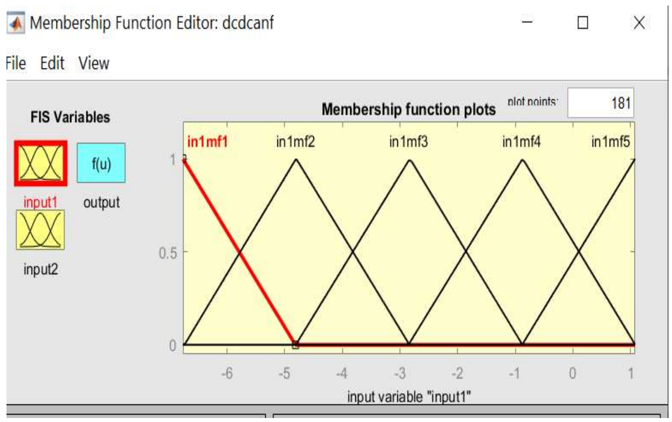


fig.6 Input Membership Functions for ANFIS

Five output membership functions, which are critical in establishing the confidence levels or truth degrees for inputs, based on self-defined linguistic values such as high/low or positive/negative are shown in fig.7.

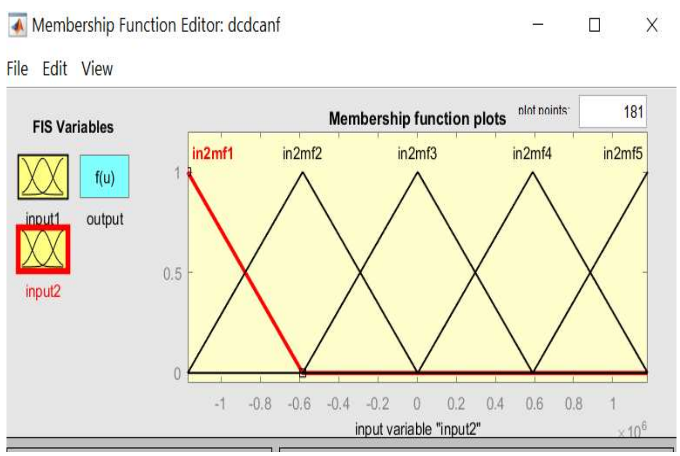


fig.7 Output Membership Functions for Bidirectional DC Converter

Membership functions specific to the output of a BDC within a hybrid energy storage system. This visualization helps in understanding how outputs are processed and interpreted within the system depicted in fig.8.

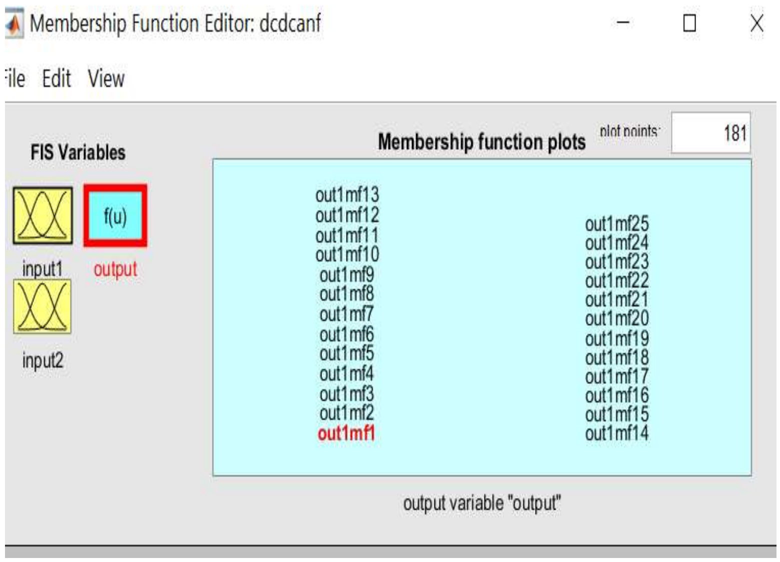


fig.8 Membership Functions for BDC Output

Finally, the complete ANFIS structure designed for a bidirectional hybrid storage system in electric vehicles is depicted in fig.9. This structure aims to enhance the overall performance of the system and rectify inefficiencies observed with traditional controllers, demonstrating significant improvements in energy management.

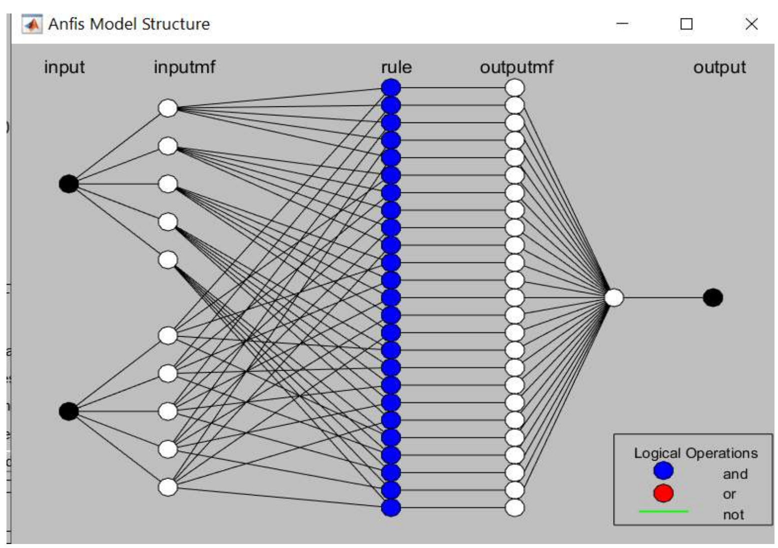


fig.9 Complete ANFIS Structure for Electric Vehicle Energy Management

4. Results

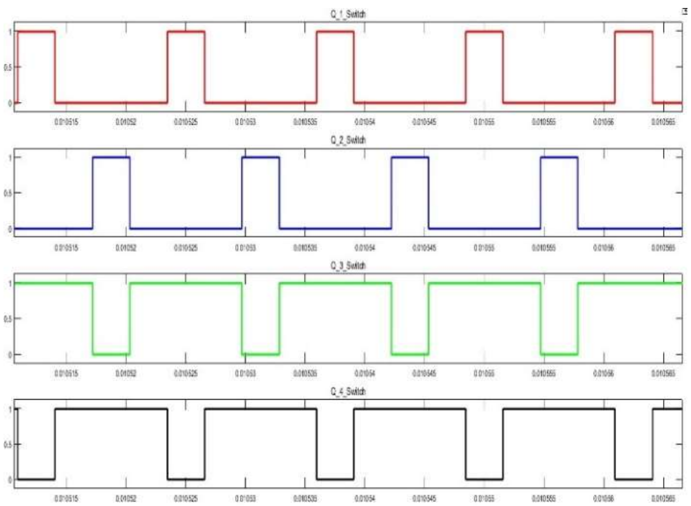
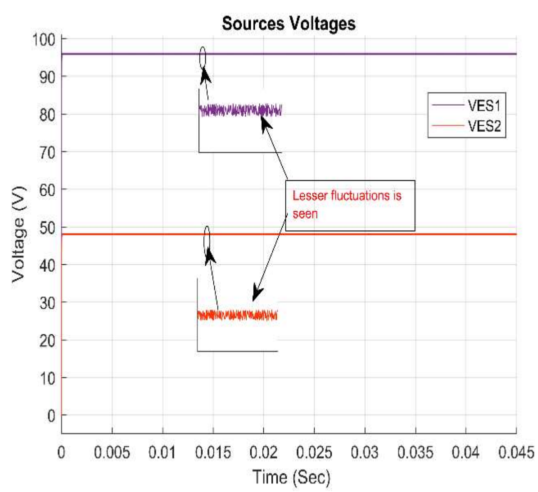
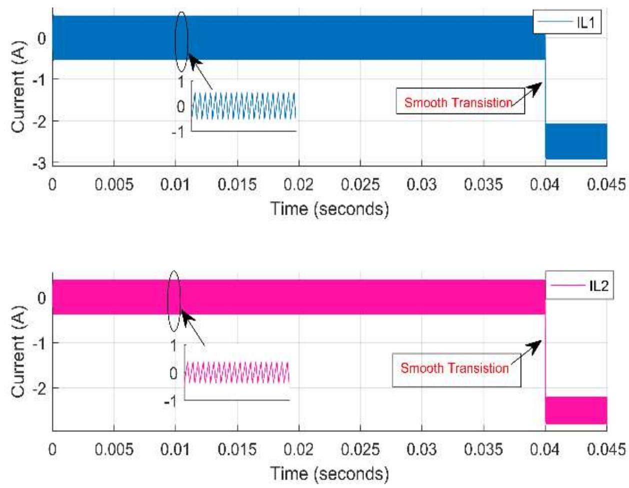


fig.10 Gate Pulse Dynamics

Switching behavior of gate pulse, illustrating how the controller influences the timing and sequence of gate activations within the circuit and this is shown in fig.10. By varying duty ratio of switches more than or less than 50% we can control the LV dual powering mode, HV DC link regenerative mode of operation and LV Buck and boost mode of operations in the given system.



[A]



[B]

fig.11 [A] Source Potential [B] Inductor Current of L_1 and L_2

The dynamics between battery potential and inductor current are shown with minimal fluctuations, indicating enhanced stability and efficiency when controlled by an ANFIS controller compared to other methods and shown in fig.11.

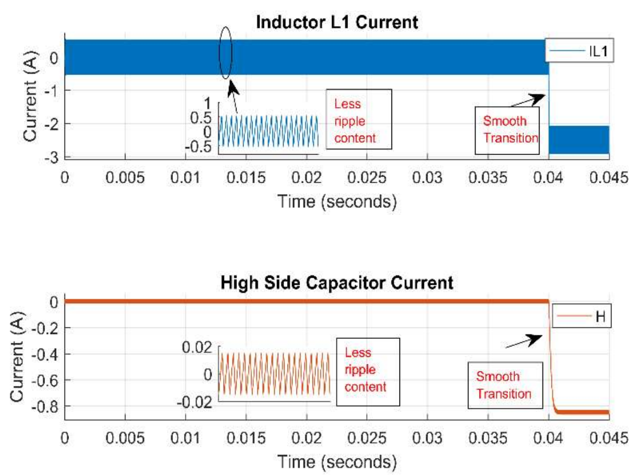


fig.12 Inductor L_1 and High Side Capacitor Current

This highlights the reduced fluctuations and smoother transitions of inductor currents, particularly evident during mode changes, showcasing the effective management capabilities of the ANFIS controller display in fig.12. Ripple content in high side current at

DC link is 0.048 and in inductor current I_{L1} is 1.2. There are also seen in improvement in slew rate and fall time of current at transition of mode.

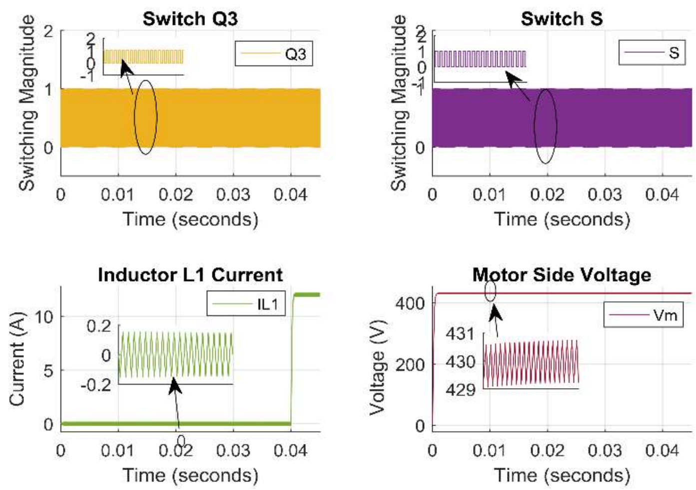


fig.13 Steady state waveform

Output waveforms which exhibit improved transitions and significantly fewer distortions than those managed by a PI controller, demonstrating the superior handling and output quality of the ANFIS controller presented in fig.13. In high side voltage (motor side) we observe settling time of 398.193 µsec and overshoot 0.50% and inductor current I_{L1} is showing 0.4 ripple content.

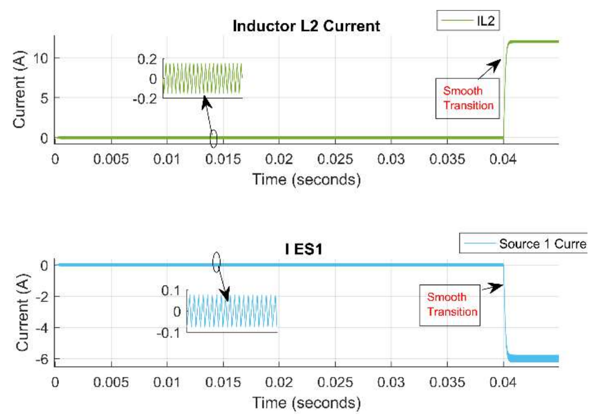


fig.14 Transient Current improvement while changing mode

The final output transitions of inductor currents are illustrated, showing less distortion and smoother waveforms, indicative of the efficient and effective control strategy implemented by the ANFIS system. This demonstrates its ability to maintain stability and performance under various operating conditions is shown in fig.14.

The resilience and precision of the control systems that were implemented within the design of the bidirectional converter are demonstrated by the experimental findings that are displayed in the various figures. The dynamics of gate pulse switching are depicted in fig.10, which also highlights the system's ability to accomplish accurate timing and effective sequence control. It is essential to have this precise control in order to guarantee that the performance of the converter is maximized, and that the overall efficiency of the energy storage system is improved.

fig.11 provides additional insights into the efficiency of the system by illustrating a steady interaction between the potential of the battery and the current passed through the inductor. This interaction is characterized by noticeably low variations. This stability is a testament to the enhanced control dynamics that the ANFIS controller offers in comparison to more conventional approaches, such as the PI controller. An important factor that contributes greatly to this improved performance is the capability of the ANFIS controller to manage complicated variables in real time in an adaptive manner. It can be seen in fig.12 that the fluctuations in the inductor currents are quite low, and the transitions appear to be smoother, particularly when the mode changes. The fact that this is the case is evidence that the system is able to deal with sudden shifts in operational modes without compromising the quality of the power delivery. These kinds of seamless transitions are essential for the durability and dependability of the energy storage system, as they reduce the likelihood of component stress and failure due to increased stress.

The output waveforms that are displayed in fig.13 provide more evidence that the ANFIS controller is superior than many available conventional controllers. The ANFIS controller exhibits superior transitions and fewer distortions when compared to the controls that are maintained by the controller. In addition to ensuring a more dependable delivery of electricity, the better waveform quality also contributes to an increase in the system's overall energy efficiency.

Last but not least, fig.14 illustrates the final inductor currents that have been optimized, demonstrating less distortions and smoother waveform projections. This optimization is a reflection of the exact control that the ANFIS controller exercises, demonstrating how successful it is in fine-tuning the electrical outputs to satisfy certain operational requirements. The waveforms' consistency and reliability are extremely important for ensuring that the drive system of the electric vehicle functions within its ideal efficiency range. This, in turn, helps to extend the vehicle's operational life and reduce the amount of maintenance that is required.

Taking all of these findings into consideration, it is clear that sophisticated control techniques, and in particular ANFIS, have the potential to dramatically enhance the management and performance.

5. Conclusion

The integration of an Adaptive Neuro-Fuzzy Inference System (ANFIS) with a bidirectional DC/DC converter for managing a dual-battery hybrid energy storage system in electric vehicles represents a significant advancement in EV technology.

This study has demonstrated that ANFIS, by leveraging the strengths of neural networks and fuzzy logic, can substantially enhance adaptability of energy management systems compared to traditional controllers. The successful implementation and testing of this system, simulation through, ANFIS can effectively optimize energy distribution and improve the overall performance of electric vehicles. These findings not only contribute to the technical field by enhancing the operational capabilities of EVs but also align with broader environmental goals by promoting more efficient and sustainable vehicle technologies. Future work will focus on refining this technology for commercial application, potentially revolutionizing energy management practices in the automotive industry.

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