Faculty of Engineering, Environment and Computing

Department of Computing, Electronics and

Mathematics

7011CEM

INDIVIDUAL PROJECT

Improving the performance of the battery pack of the powertrain of the electric bike using supercapacitors.

Student Name: Nomaan Sayed

SID: 13509902

Supervisor: **Dr Khaled Choudhury**

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Declaration of originality

I solemnly affirm that all the content presented in this project is the culmination of my individual endeavours, and any semblance to pre-existing work is either coincidental or duly acknowledged through proper citation. This encompasses various forms of published information, including text sourced from books, academic papers, magazines, and internet resources, which have been appropriately referenced within the project's body and catalogued in the References or Bibliography sections. Moreover, I consent to the retention and utilization of an electronic rendition of this project for purposes associated with the prevention and detection of plagiarism.

Statement of Copyright

Acknowledgments

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Abstract

This research focuses on optimizing Hybrid Energy Storage Systems (HESS) for electric vehicles by integrating supercapacitors with traditional lithium-ion battery packs. Recognizing the limitations of batteries, such as gradual degradation and slow charging, the study explores the complementary role of supercapacitors, which offer rapid energy storage, high power density, and durability. The combination of lithium-ion batteries for steady, long-term power and supercapacitors for handling high-demand situations like acceleration and regenerative braking reduces battery stress, enhances energy management, and extends system lifespan. By analyzing supercapacitor and bidirectional converter topologies, the project identifies configurations that maximize efficiency and performance. A robust controller for the bidirectional converter is also developed to optimize power distribution. The findings demonstrate that integrating supercapacitors significantly improves HESS efficiency, sustainability, and operational life, providing a promising solution for advancing electric vehicle technology and increasing market competitiveness.

Contents

Chapter 1

Introduction

Electric and hybrid vehicles rely heavily on energy storage systems (ESSs), with lithium-ion battery packs being the most common choice due to their high energy density. However, these batteries have drawbacks like gradual degradation and slow charging times. Supercapacitors offer a complementary solution, bridging the gap between traditional batteries and capacitors (G Subramanian, Joseph Peter, 2020). They excel in rapid energy storage and release, high power density, and long-lasting performance, making them valuable for EV technology.

Combining lithium-ion batteries with supercapacitors creates a hybrid energy storage system (HESS), where each component has a specific role. The lithium-ion battery provides steady, long-term power, while the supercapacitor handles brief, high-demand situations like acceleration and energy recovery from regenerative braking. This partnership reduces stress on the battery, minimizing wear from frequent charge-discharge cycles and extending its lifespan. Supercapacitors also efficiently capture energy from regenerative braking, further reducing battery strain. Increasing the range of electric vehicles is crucial for them to compete with conventional gasoline-powered cars. By optimizing energy management between lithium-ion batteries and supercapacitors, HESS improves overall EV performance and significantly extends the system's operational life compared to battery-only setups. This hybrid approach offers a promising solution to enhance EV efficiency, sustainability, and market competitiveness.

Project objectives

Thisproject aimstooptimize the efficiency of hybrid energy storage systems (HESS) for electric vehicles by integrating supercapacitors with traditional battery packs. The primary goal is to leverage the complementary characteristics of batteries and supercapacitors to enhance overall system performance, extend battery life, and improve energy management.

The project will determine the optimal supercapacitor topology that best complements the battery pack. This involves analyzing various supercapacitor configurations and their integration with different battery types to identify the most effective combination for improved performance and efficiency. Factors such as power density, energy density, response time, and cycling capability will be considered in this analysis. Additionally, the project will focus on identifying the optimal bidirectional converter topology for the HESS. This converter is crucial for managing power flow between the battery, supercapacitor, and the vehicle's electrical system. The selection will be based on criteria such as efficiency, power handling capability, size, cost, and reliability.

Furthermore, the project will design a robust controller for the bidirectional converter to ensure optimal performance of the HESS. This controller will manage the power distribution between the battery and supercapacitor, optimizing energy usage based on driving conditions, state of charge, and power demands.

Throughout the project, emphasis will be placed on practical implementation, considering factors such as cost-effectiveness, scalability, and compatibility with existing electric vehicle architectures. The outcome will be a comprehensive HESS design that significantly enhances the performance and efficiency of electric vehicles.

Research Plan

This research plan aims to optimize hybrid energy storage systems (HESS) for electric bicycle powertrains by integrating high-energy-density batteries with supercapacitors. The study will follow a structured approach to investigate, simulate, and analyze the potential benefits of this integration.

The first phase of the research will involve an extensive literature review and theoretical analysis. This will include a comprehensive study of current literature on high-energy-density batteries, supercapacitors, and HESS applications in electric vehicles. Existing electric bicycle powertrain designs will be analyzed to identify areas for potential improvement through HESS integration. Various HESS topologies and control strategies applicable to electric bicycles will also be studied during this phase.

The second phase will focus on system modeling and simulation. A comprehensive MATLAB/Simulink model of the proposed HESS for electric bicycles will be developed. This model will allow for the implementation and comparison of different energy management strategies. Various riding scenarios will be simulated to assess system performance under different conditions, providing a thorough understanding of the HESS behavior in real-world situations.

The third phase will involve performance analysis and optimization. Simulation results will be analyzed, with a focus on key performance metrics such as range, efficiency, and power delivery characteristics. The HESS performance will be compared against traditional battery-only systems across various riding scenarios. Based on these simulation outcomes, the HESS design will be optimized, considering factors like component sizing and control parameters.

The final phase will encompass validation and conclusion. Simulation results will be validated against available real-world data on electric bicycle performance to ensure the accuracy and relevance of the findings. The research will conclude by synthesizing all findings to determine the effectiveness of HESS in improving electric bicycle powertrain performance. The results will be and

thoroughly documented, including potential benefits, challenges encountered, recommendations for future research or practical implementation.

This comprehensive research plan provides a systematic approach to evaluating and optimizing HESS for electric bicycle applications. The outcomes of this study have the potential to lead to significant advancements in electric bicycle technology, paving the way for more efficient and high-performance electric bicycles.

Chapter 2

Literaturereview Hess system

M.S.Whittingham, (2012) highlights the advancements and significance of batteries and capacitors in energy storage. Lithium-ion and Ni-MH batteries have revolutionized portable electronics over the past 40 years and are now pivotal in the transportation industry, with predictions that all vehicles will incorporate some form of hybridization by the decade's end. Batteries are essential for integrating renewable energy sources into the utility grid, handling peak demands, and mitigating the intermittent nature of solar and wind power. Capacitors, on the other hand, store energy as surface charge, allowing for rapid charging and discharging, making them ideal for short-term energy storage and frequency regulation. The paper emphasizes the importance of developing cost-effective, long-lasting energy storage solutions to support the growing demands of renewable energy and electrified transportation. Future advancements are expected in the integration of these storage solutions with smart grids, enhancing energy distribution efficiency and reliability.

Kouchachvili et al., (2017) explores the integration of batteries and supercapacitors (SCs) to enhance electric vehicle (EV) efficiency and performance. Lithium-ion batteries, while advanced, face degradation issues from rapid power consumption changes. To mitigate this, a hybrid energy storage system (HESS) combines batteries for high energy density with SCs for high power density, managing peak power demands and regenerative braking. Various HESS configurations, involving bidirectional DC/DC converters, optimize power flow and performance. This integration reduces battery stress, extends battery life, improves energy recovery, and enhances EV performance, making them more viable for widespread adoption, especially in applications with frequent braking and acceleration, like city buses. Yang et al., (2020) presents a robust control strategy for a Hybrid Energy Storage System (HESS) that combines batteries and supercapacitors for electric vehicles (EVs), leveraging the high energy density of batteries and the rapid response of supercapacitors. Utilizing a fully active setup with two bidirectional DC/DC converters, the system employs a Rule-Based Strategy (RBS) to optimally distribute power and a Robust Fractional-Order Sliding-Mode Control (RFOSMC) for handling real-time nonlinearities and uncertainties. This innovative control method requires only battery current and DC bus voltage measurements, simplifying implementation while enhancing performance. RFOSMC improves tracking and reduces conservativeness, extending battery life and increasing overall efficiency. Validation through simulations and Hardware-in-the-Loop (HIL) testing confirms the strategy's practical effectiveness, making it a promising solution for advanced EV applications.

HESS topologies

Bysani et al.,(2021) explores the design and optimization of hybrid energy storage systems (HESS) specifically for electric bikes, focusing on passive, fully active, and semi-active topologies.

Passive HESS: In a passive system, the battery and supercapacitor are directly connected without any power electronics. This simplicity and low cost are its primary advantages. However, it offers limited control over energy distribution, which can result in suboptimal performance and faster battery degradation due to the inability to manage power peaks effectively.

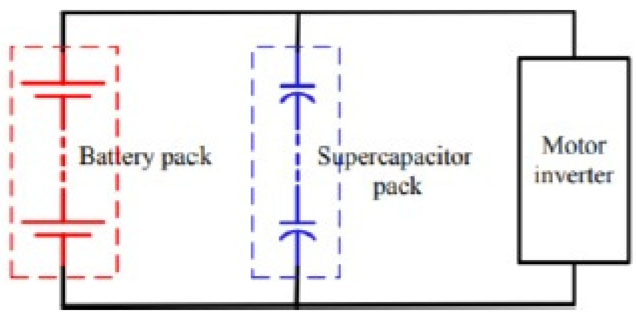


Figure 1 Passive HESS (source: Bysani et al., 2021)

Fully Active HESS: This topology utilizes power electronic converters for both the battery and the supercapacitor, providing precise control over energy flow. This configuration ensures optimal performance and efficiency, as it can actively manage power distribution based on demand. However, the increased complexity and higher costs due to the need for multiple converters make it less attractive for cost-sensitive applications like e-bikes.

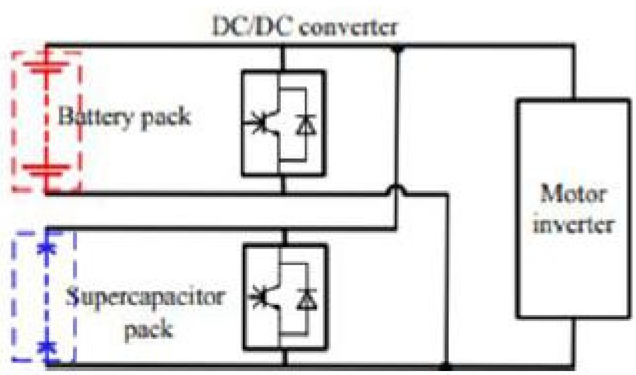


Figure 2 Fully active HESS (source: Bysani et al., 2021)

Semi-active HESS: The focus of the paper is on semi-active HESS, which strikes a balance between passive and fully active systems. It uses a single DC-DC converter either with the battery or the supercapacitor to manage energy flow.

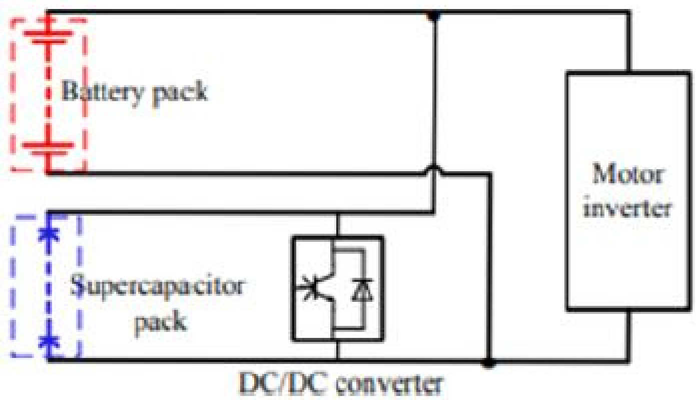


Figure 3 Semi-Actie HESS (source: Bysani et al., 2021)

Xiong et al., (2018) discusses the development and optimization of hybrid energy storage systems (HESS) for electric bikes, specifically focusing on semi-active topologies. HESS integrates batteries and supercapacitors (SC) to leverage the high energy density of batteries and the high-power density of SCs. Among the three primary topologies—passive, fully active, and semi-active—the semi-active topology is deemed superior. Passive topology is the simplest and most cost-effective, connecting batteries and SCs directly to the DC bus. However, it fails to utilize SCs effectively due to inherent limitations in system complexity and initial cost. Fully active topology uses multiple bi-directional DC/DC converters for precise control, offering the best performance but at a high cost, increased weight, and complexity. Semi-active topology strikes a balance by using a single DC/DC converter, optimizing performance while maintaining lower cost and complexity. This topology decouples the battery from the DC bus via the converter, enhancing system efficiency and battery lifespan by smoothing power fluctuations and maintaining stable charge-discharge cycles. Therefore, the semi-active topology provides an optimal trade-off between performance, cost, and complexity, making it the most practical choice for e-bike HESS applications

The integration of Li-ion batteries and supercapacitors in electric bikes (e-bikes) forms a Hybrid Energy Storage System (HESS) that optimizes performance and efficiency. This innovative approach leverages Li-ion batteries as the primary energy source for sustained power delivery, while supercapacitors manage power spikes during rapid acceleration and regenerative braking. By distributing energy demands, this hybrid system mitigates the rapid depletion and high-current stresses that typically shorten battery life. Central to this design is the DC/DC power converter, which must be carefully optimized to balance the load between the two energy storage components. The study utilizes advanced tools like the PowerForge professional platform and MATLAB to explore various topologies and methodologies for effectively sizing and integrating these components. Through modeling diverse driving cycles, the research team assesses energy requirements and validates the HESS configuration's performance. Their findings reveal that the chosen driving cycle significantly influences the sizing needs for both the battery and supercapacitor, directly impacting the energy storage system's overall weight and volume. The research confirms the viability of the proposed design approach, underscoring the advantages of combining Li-ion batteries and supercapacitors in e-bikes. These benefits include enhanced energy management, improved performance, and extended battery lifespan. By addressing the limitations of conventional energy storage in electric vehicles, this hybrid system presents a promising solution for ensuring a more reliable and efficient energy supply capable of adapting to fluctuating power demands. This approach not only enhances the technical performance of e-bikes but also contributes to their practicality and appeal as sustainable urban transportation options (L. Mamouri et al., 2020).

Semi-active HESS topology

Song et al., (2015) examines four semi-active hybrid energy storage system (HESS) topologies designed to optimize the performance and cost-efficiency of electric vehicles (EVs) by integrating supercapacitors (SCs) with batteries.

Topology #1: This configuration uses a bidirectional DC/DC converter to interface the SC with the battery/DC bus. It effectively decouples the SC voltage from the battery, allowing optimal use of the SC's high-power density. However, the bidirectional converter is costly and must handle significant power flow, which can reduce overall system efficiency.

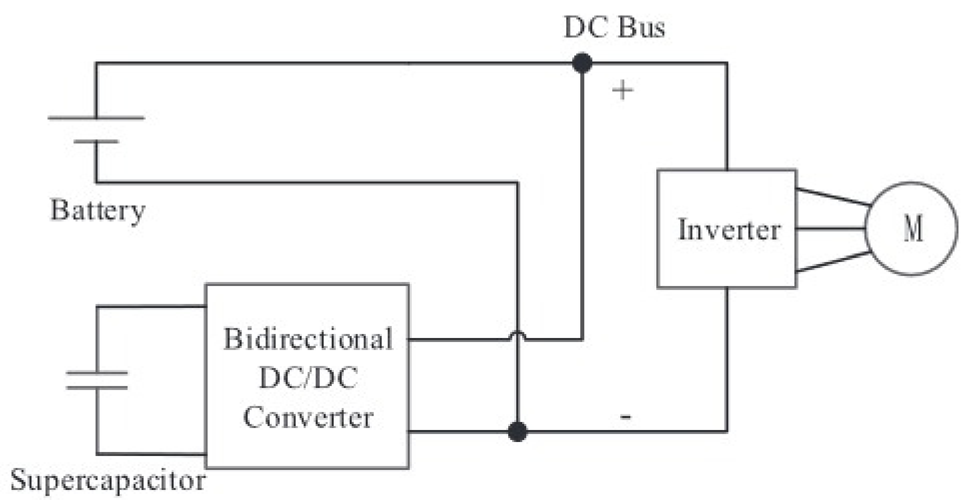


Figure 4 HESS semi-active topology #1 (source: Song et al., 2015)

Topology #2: In this design, a DC/DC converter interfaces the battery with the SC/DC bus. This reduces the power requirements of the converter compared to Topology #1. Nonetheless, it suffers from a wide range of DC bus voltage variations, which can be problematic in applications requiring stable voltage, such as high-speed motor operations. This instability can affect vehicle performance, particularly in acceleration.

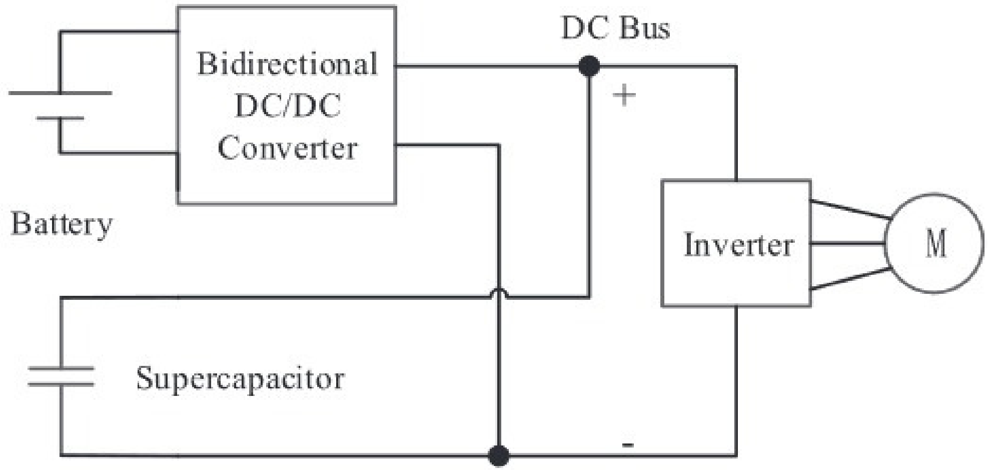


Figure 5 HESS semi-active topology #2 (source: Song et al., 2015)

Topology #3: This setup includes a small DC/DC converter and a diode to decouple the battery from the SC/DC bus. The SC voltage is thus limited by the battery voltage, which can restrict the SC's effective operation range. While the converter's power level is reduced, and costs are lower, the DC bus voltage still varies significantly, posing similar challenges as Topology #2.

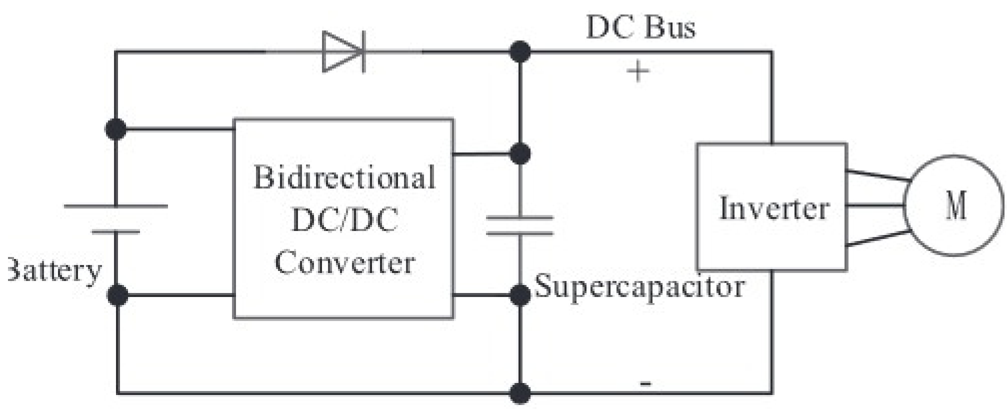


Figure 6 HESS semi-active topology #3 (source: Song et al., 2015)

Topology #4: This topology features a small unidirectional DC/DC converter for charging the battery from the SC under regenerative braking conditions. It offers simplicity and reduced converter costs, with an efficient power flow that inherently depends on the relative voltages of the SC and battery. However, the control strategy lacks flexibility under traction mode, and the DC bus voltage variation remains a significant drawback.

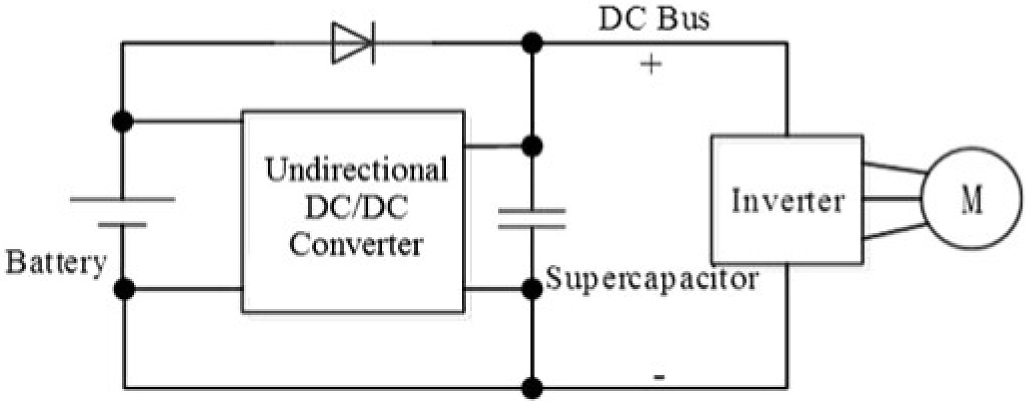


Figure 7 HESS semi-active topology #4 (source: Song et al., 2015)

Each topology presents a trade-off between cost, complexity, and performance. The integration of SCs within these systems has been shown to substantially reduce operational costs compared to battery-only configurations, demonstrating their effectiveness in extending battery life and improving the overall efficiency of electric vehicle energy storage systems.

Bidirectional Buck-Boost Converter

Onar et al. (2012) introduce a novel approach to enhance the integration of Plug-in Hybrid Electric Vehicles (PHEVs) with the power grid, cantering on a bidirectional buck-boost converter. This innovative design allows for two-way power flow, enabling battery charging from the grid in buck mode and power transmission back to the grid or the motor drive in boost mode. A key advantage of this converter is its ability to maintain voltage polarity, eliminating the need for an inverting transformer and consequently reducing size, complexity, and cost compared to conventional converters. The system's design facilitates grid-connected operations by efficiently managing charge and discharge cycles while maintaining high power quality, minimizing disturbances in power factor and harmonic distortion. In driving mode, the converter provides a controlled DC link voltage to the motor drive and effectively captures regenerative braking energy, benefiting from simpler controls and reduced switching losses. This advanced system addresses the growing concerns of increased load and power quality issues associated with widespread PHEV adoption by ensuring high-power quality and efficient power conversion. The researchers thoroughly evaluate the converter's performance through both modelling and experimental data, highlighting its potential to meet the comprehensive demands of the PHEV industry and streamline the transition from traditional Hybrid Electric Vehicles (HEVs) to Vehicle-to-Grid (V2G) enabled PHEVs. The significance of this innovation extends beyond immediate technical improvements, emphasizing the converter's crucial role in developing a more sustainable transportation ecosystem. By enhancing energy security, reducing environmental impact, and improving fuel economy and overall vehicle performance, this technology contributes to the broader goals of sustainable mobility. The bidirectional buck-boost converter's ability to seamlessly integrate PHEVs with the power grid represents a significant step forward in addressing the complex challenges of electrifying transportation while maintaining grid stability and efficiency. As the automotive industry continues its shift towards electrification, innovations like this play a vital role in overcoming technical barriers and accelerating the adoption of PHEVs. The research not only demonstrates the technical feasibility of the new converter design but also underscores its potential to revolutionize the relationship between electric vehicles and the power infrastructure, paving the way for a more integrated and sustainable energy ecosystem in the future.

A. Sharma et al. (2018) present an innovative approach to improving electric bike (e-bike) efficiency through the design and implementation of a bidirectional DC-DC converter (BDC) for regenerative braking. Recognizing the lack of regenerative braking in most e-bikes, which results in wasted kinetic energy and reduced battery life, the researchers developed a BDC capable of facilitating both power propulsion and energy recovery during braking. The proposed converter utilizes a non-isolated half-bridge topology, selected for its efficiency, compact design, and cost-effectiveness. Operating between fixed voltage levels of 12V and 24V, the BDC switches between buck mode during braking (converting higher motor voltage to charge the 12V battery) and boost mode for motor propulsion (powering the motor from the 12V battery). Simulations using NI Multisim software demonstrated an impressive efficiency exceeding 92% in both power flow directions, with these results subsequently validated through a hardware prototype. The design process prioritized minimizing the converter's size, weight, and cost while ensuring rapid response to sudden braking and acceleration events and maintaining reliable, efficient power flow. By effectively capturing energy typically lost during braking, this BDC implementation promises to significantly extend e-bike range and efficiency, promoting a more sustainable and economical urban transportation option. The study concludes that integrating such technology can substantially enhance e-bike performance and appeal, potentially driving increased adoption in urban areas. This research not only addresses the technical aspects of improving e-bike efficiency but also contributes to the broader goals of sustainable urban mobility by offering a practical solution to extend the range and usability of electric bicycles.

BLDC motor

M. Yildirim et al., (2014) researchers evaluated Switched Reluctance Motors (SRMs), Induction Motors (IMs), Brushless DC Motors (BLDC), and Permanent Magnet Synchronous Motors (PMSMs) across various criteria. SRMs emerged as a strong contender, offering a compelling combination of low weight, high reliability, cost-effectiveness, fault tolerance, and superior acceleration performance compared to IMs and BLDCs. IMs were noted for their simple structure, reliability, robustness, and lower cost, but suffered from lower efficiency and higher losses compared to PMSMs. PMSMs, particularly PM BLDC motors, demonstrated the highest efficiency and power density, making them highly effective for EV propulsion, albeit at a higher cost due to the use of permanent magnets. BLDC motors, despite their mature technology, were found to be less suitable for EVs due to their limited constant power range. The study concluded that while PMSMs offer superior efficiency and power density, SRMs are deemed the most appropriate for EV applications. This conclusion was based on SRMs providing an optimal balance of cost, efficiency, weight, reliability, and fault-tolerant operation. These factors collectively contribute to the overall performance, affordability, and reliability of electric vehicles, making SRMs a compelling option for manufacturers looking to optimize their EV powertrains. The choice of motor type significantly impacts the vehicle's performance, range, cost, and reliability, underscoring the importance of this analysis in the rapidly evolving EV market. As the automotive industry continues its shift towards electrification, such comparisons play a crucial role in guiding manufacturers' decisions and ultimately shaping the future of electric mobility.

In the era of electric bicycles, motor selection plays a crucial role in determining overall performance, efficiency, and user experience. A comparative analysis of different motor types reveals distinct advantages and limitations for each. Induction motors (IMs) are appreciated for their simple structure, reliability, and robustness, making them a cost-effective option. However, they fall short in terms of efficiency, exhibiting higher losses and a lower power factor compared to their counterparts, particularly permanent magnet (PM) motors and switched reluctance motors (SRMs). This efficiency gap can significantly impact the e-bike's range and overall energy consumption. On the other hand, PM Brushless DC (BLDC) motors stand out with their high efficiency and power density. These motors eliminate the need for energy expenditure in magnetic pole production and effectively dissipate heat, contributing to their superior performance. The absence of brushes also reduces maintenance requirements, enhancing long-term reliability. However, the use of expensive magnets in BLDC motors increases their cost, which can be a limiting factor in some e-bike designs. Additionally, these magnets impose constraints on maximum speed and torque capabilities due to mechanical limitations and sensitivity to high temperatures. SRMs offer a middle ground with their simple and rugged construction, inherent fault tolerance, and effective torque-speed characteristics. While they face challenges such as acoustic noise and torque ripple, these issues are generally not significant in the context of e-bike applications. Despite these alternatives, BLDC motors emerge as particularly advantageous for e-bikes. Their superior efficiency directly translates to extended range and enhanced performance, critical factors in the e-bike user experience. The compact size of BLDC motors aligns well with the lightweight design requirements of modern e-bikes, facilitating sleek and efficient bicycle designs. Moreover, the ability to extend their speed range through conduction-angle control enhances their versatility across various riding conditions, from urban commutes to more challenging terrains. This adaptability, combined with lower maintenance needs compared to brushed motors, makes BLDC motors an attractive option for e-bike manufacturers and consumers alike. While the higher cost of BLDC motors remains a consideration, the benefits in terms of performance, efficiency, and long-term reliability often outweigh this initial investment for many users and manufacturers. Consequently, BLDC motors have become the preferred choice in many modern electric bicycle designs, driving innovation and improvements in e-bike technology and contributing to the growing popularity and versatility of electric bicycles in urban mobility and recreational cycling (X. D. Xue et al., 2008).

Chapter 3

Model Analysis

The system consists of a Hybrid Energy Storage System (HESS), a universal bridge inverter, and a brushless DC motor. The HESS combines high energy density batteries and high-power density supercapacitors to dynamically manage and efficiently deliver the required energy. It supplies a constant DC voltage through its positive (POS) and negative (NEG) terminals to suit the load's power requirements. The universal bridge inverter, which is connected to these terminals, is made up of six semiconductor switches (such as IGBTs or MOSFETs) and diodes coupled in a bridge configuration. Gate pulses govern these switches' timing and duration of operation, transforming the DC input into three-phase AC output. This AC output is then sent to the BLDC motor's three phases (A, B, and C). The BLDC motor runs on three-phase AC power and is noted for its great efficiency, dependability, and speed control. The control circuitry achieves precise commutation of the motor phases by providing the universal bridge with the exact sequence of gate pulses. This synchronized commutation allows the BLDC motor to run efficiently and generate the necessary mechanical motion.

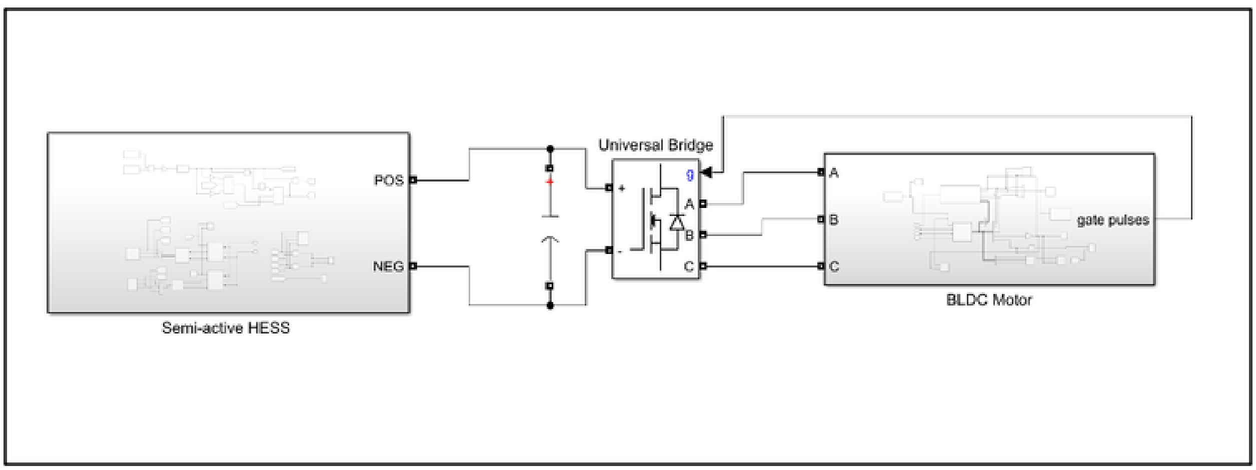


Figure 8 Simulink model of the whole system

3.1 Hybrid energy storage system (HESS)

The topology of HESS that was selected for this project was semi-active HESS. A semi-active HESS consists of a primary energy storage device, usually a high-energy density battery, and a secondary high-power density device, such as a supercapacitor (Song et al., 2015). The primary device connects directly to the load and handles baseline power demands, while the secondary device communicates via a DC/DC converter. This architecture offers dynamic power management: the converter regulates the secondary device's contribution, allowing it to handle rapid power fluctuations while the primary device provides steady-state power.

The system's control unit continuously analyzes load needs and system parameters to determine when to activate secondary storage through the converter. The secondary device complements the primary device during high power demands or unexpected load shifts, while storing excess energy during low-demand periods or regeneration events. This configuration strikes a balance between system complexity and performance, maximizing energy efficiency and extending the core device's lifespan by decreasing its exposure to harsh cycling conditions (Song et al., 2015). The semi-active topology improves efficiency over fully active systems by reducing conversion losses while still allowing for a wide range of power profiles. This makes semi-active HESS ideal for applications with fluctuating power demands, such as electric vehicles or renewable energy systems, where it can efficiently balance the trade-off between long-term energy supply and rapid power response.

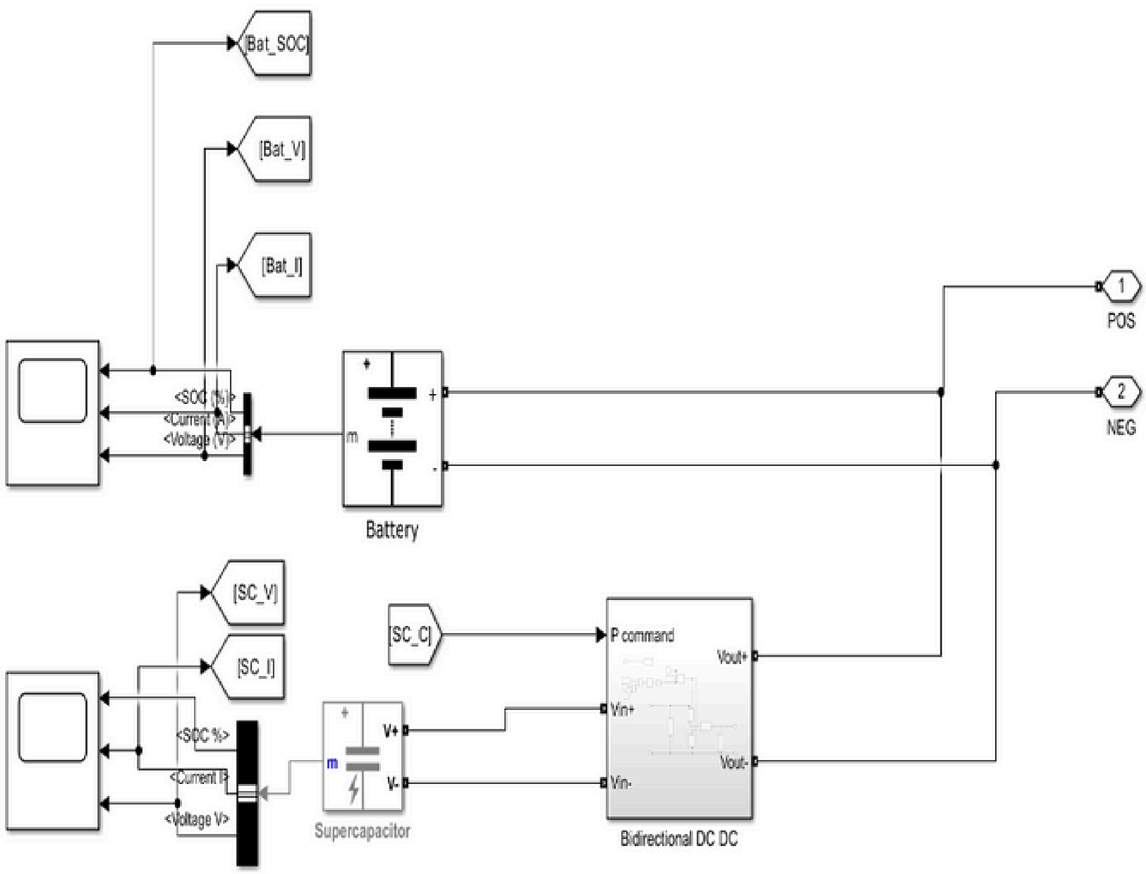


Figure 9 semi active HESS

3.1.1 Battery

For this project, a lithium-ion (Li-ion) battery has been selected as the primary energy storage component of our whole system. The battery specifications have been carefully

chosen to meet the requirements of typical E-bike applications while optimizing system efficiency and performance.

Type:	**Lithium-ion**
Capacity:	**22.5 AH**
Weight:	**4.7 Kg**
Operating Temperature:	**-10 ~ 40°C**
Rated Voltage:	**48V**
Energy:	**3.888MJ**

3.1.2 Supercapacitor

The supercapacitor in this project acts as a secondary power source. The intention of such integration is to provide fast and uninterrupted power transfer whenever the battery cannot deliver power fast enough.

Type:	**Supercapacitor**
Rated Capacitance:	**500F (20*25f)**
Rated Voltage:	**16.2V (6*2.7v)**
Weight:	**0.816kg (120*6.8g)**
Operating Temperature:	**-40 ~ 65 °C**
Energy:	**65.610 kJ**

3.1.3Ratelimiter

Its main purpose is to deduce the rate of change of torque for each interval. When the torque changes from high to low the limiter will deduce whether the supercapacitor or the battery

will charge. The limiter will have a random arbitrary value, beyond which the supercapacitor will charge or if not, the battery will charge. This is implemented by the rate limiter along with a comparator.

3.1.4 Bi-directional DC-DC converter

The purpose of using a bidirectional DC-DC Buck-Boost converter is to boost the supercapacitor voltage from 16.2V to 48V during motoring and to step down the voltage during regenerative braking. The circuit includes several key components. When the torque is negative, the power should be delivered from the motor to the battery. This means that the power is changing its direction constantly. The motor input torque represents the torque required by the motor and acts as an input to the control system. The Control Block processes this input torque signal, generating duty cycle signals (`dutyCycle1` and `dutyCycle2`) to control the converter switches, using feedback to regulate the operation and maintain desired performance. Duty Cycle Generators produce PWM signals based on the duty cycles from the control block, essential for controlling the MOSFET switches. The PWM and Driver Circuits modulate the duty cycles to generate PWM signals, which drive the gates of the MOSFET switches, controlling their on and off states, with driver circuits ensuring appropriate gate signals. The circuit includes two MOSFET switches that act as switches to control the current flow direction, allowing the converter to operate in either boost or buck mode depending on the power flow direction. An inductor stores energy when current flows through it and releases energy when the current flow is interrupted, smoothing the current and reducing ripples. Capacitors filter the voltage, reducing ripples and ensuring a stable DC output. Lastly, voltage and current measurement devices measure voltage and current at various points in the circuit, providing feedback to the control block.

The torque signal from the motor input is fed into the control block, which determines the required operation mode (boost or buck) and calculates the necessary duty cycles for the switches. The control block outputs `dutyCycle1` and `dutyCycle2` signals based on the required operation, and the PWM generators use these duty cycles to create corresponding PWM signals that control the MOSFET gates. The PWM signals drive the MOSFET switches, turning them on and off rapidly. In boost mode, the switches increase the voltage from a lower to a higher level, while in buck mode, the switches decrease the voltage from a higher to a lower level. The inductor and capacitors facilitate energy storage and transfer, with the inductor storing energy during the on-state of the switches and releasing it during the off-state, and the capacitors smoothing the voltage and current. Voltage and current measurements provide real-time feedback to the control block, which adjusts the duty cycles dynamically to ensure the desired output voltage and current are maintained, compensating for any changes in load or input conditions. To operate the converter as a boost converter, the

MOSFET in series with the battery (M2)
is turned off, while the MOSFET in parallel with the battery (M1) is turned on with a 75% duty cycle. This implies that M1 remains on for 75% of each switching cycle. When M2 is turned off, the diode parallel to M1 becomes forward biased, enabling the circuit to transfer

power from the supercapacitor to the battery. As a result, the battery is charged. The process begins with M1 conducting for 75% of the cycle, allowing current to flow through the inductor and store energy. During the remaining 25% of the cycle, M1 turns off, and the energy stored in the inductor is released through the forward-biased diode into the battery. This continuous switching action boosts the voltage from the supercapacitor of 16.2V to a higher level of 48V that is suitable for charging the battery. The efficient operation of this boost converter ensures that the energy stored in the supercapacitor is effectively utilized to maintain the battery charge, thereby supporting the power requirements of the system.

To operate the converter as a buck converter, the MOSFET in series with the battery (M2) is turned on with a 25% duty cycle, while the MOSFET in parallel with the battery (M1) remains turned off. This means M2 is active for 25% of its entire switching cycle. During the on-time of M2, the branch containing M1 is inactive, allowing power to flow from the battery to the supercapacitor, thus charging it. Once M2 turns off, and with M1 still off, the direct path for power flow from the battery is interrupted. At this point, power cannot flow back from the battery to the supercapacitor. Instead, the power is redirected from the motor to the supercapacitor, effectively charging it. This dual-mode operation enables the converter to manage energy flow efficiently: initially utilizing the battery to charge the supercapacitor and subsequently using regenerative energy from the motor to continue charging the supercapacitor when the battery path is inactive. This process ensures optimal energy usage and storage, critical for maintaining the performance and longevity of hybrid energy systems, particularly in applications requiring dynamic energy management such as electric vehicles and renewable energy systems.

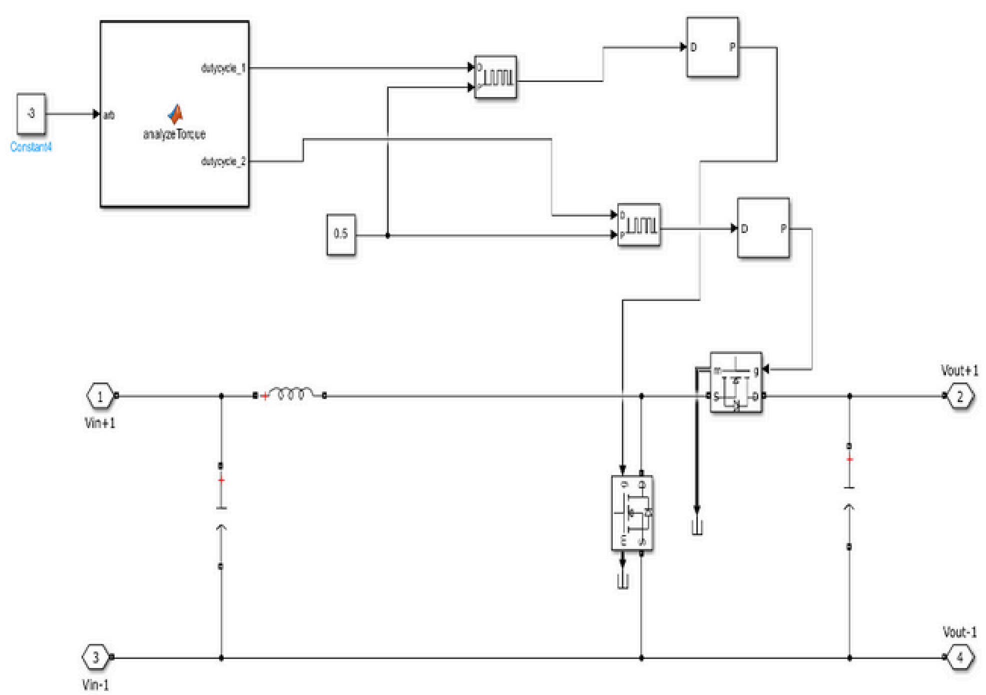


Figure 10 DC-DC Converter

3.1.5 Master Controller

Thecontroller's algorithm is divided into two main parts. In the first part, an arbitrary threshold value is determined. If the rate of change of torque exceeds this threshold, the converter operates as a buck converter, charging the supercapacitor. Conversely, if the rate of change of torque is below this threshold, the converter functions as a boost converter, charging the battery. The second part of the algorithm involves monitoring the state of charge (SOC) of the supercapacitor. If the SOC is below 50%, the algorithm prioritizes charging the supercapacitor. However, if the SOC is equal to or greater than 50%, the supercapacitor is allowed to discharge. This dual-criteria approach ensures that both the supercapacitor and the battery are managed effectively, maintaining optimal energy levels and ensuring efficient power distribution based on the torque demands and the SOC of the supercapacitor. This comprehensive control strategy enhances the performance and longevity of the energy storage system, particularly in dynamic applications such as electric vehicles and renewable energy systems.

The controller in this code implements a simple threshold-based control strategy for assigning duty cycles based on torque values. It iterates through a predefined array of torque values, comparing each to a threshold value 'arb' (which is presumed to be an input parameter to the function). For torque values exceeding this threshold, it assigns a duty cycle of 0 to the first output (dutyCycle1) and 0.25 to the second output (dutyCycle2). Conversely, for torque values at or below the threshold, it assigns 0.75 to dutyCycle1 and 0 to dutyCycle2. This process repeats for a fixed number of iterations (up to 20), with a brief pause between each iteration. Essentially, the controller is making a binary decision for each torque value, allocating different duty cycle patterns based on whether the torque is high (above threshold) or low (at or below threshold). This could represent a simple control scheme for managing power distribution or motor control in response to varying torque demands.

```
function [dutyCycle1, dutyCycle2] = control(torque)
    % Initialize the arbitrarily chosen threshold for torque
    arb = -3;

    % Preallocate arrays for duty cycles with the same length as the torque input
    dutyCycle1 = zeros(length(torque), 1); % Initialize dutyCycle1 to zeros
    dutyCycle2 = zeros(length(torque), 1); % Initialize dutyCycle2 to zeros

    % Loop through each element in the torque array
    for i = 1:length(torque)
        % If the current torque value is greater than the threshold (arb)
        if torque(i) > arb
            % Set dutyCycle1 to 0.75
            dutyCycle1(i) = 0.75;
            % Set dutyCycle2 to 0
            dutyCycle2(i) = 0;
        else
            % Otherwise, set dutyCycle1 to 0
            dutyCycle1(i) = 0;
            % Set dutyCycle2 to 0.25
            dutyCycle2(i) = 0.25;
        end
    end
end
```

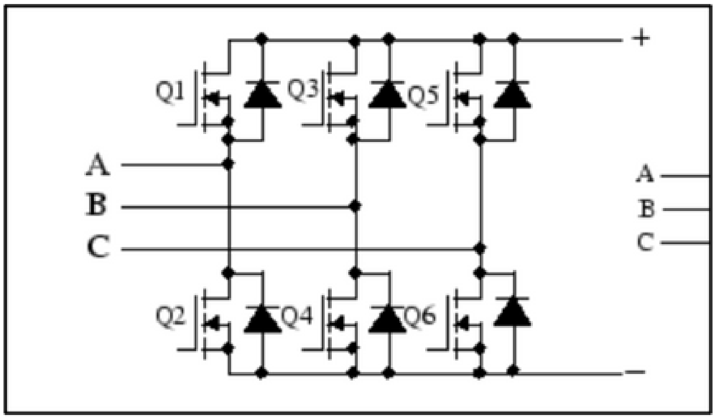
Figure 11 controller code

3.2 Inverter

The three-phase inverter is a sophisticated power electronic device that transforms direct current (DC) into three-phase alternating current (AC). Its core structure consists of six power semiconductor switches, which are MOSFETs in this case, arranged in three pairs or legs. Each leg is responsible for generating one phase of the three-phase output. The heart of the inverter's operation lies in its switching strategy. The switches in each leg operate in a complementary fashion, when one is on, the other is off. This switching is controlled by a technique called Pulse Width Modulation (PWM). In PWM, a reference sinusoidal waveform is compared with a high-frequency triangular carrier wave. This comparison generates the switching pulses that control the semiconductor switches.

As the switches open and close rapidly, they create a series of voltage pulses. In each leg, this produces a square wave voltage that alternates between the positive and negative DC bus voltages. The key to generating three-phase power is that the switching patterns for each leg are offset by 120 degrees from each other. This phase shift creates the characteristic three-phase output. The resulting output from each leg is a high-frequency square wave. However, the fundamental component of this square wave approximates a sine wave at the desired frequency. To refine this output, the inverter typically incorporates low-pass filters. These filters smooth out the high-frequency components, leaving a much cleaner sinusoidal waveform. One of the primary advantages of this design is its flexibility. By adjusting the PWM parameters, the inverter can control both the frequency and amplitude of the output voltage. This makes it invaluable in applications like variable speed drives for AC motors, where precise control of motor speed and torque is required.

Moreover, three-phase inverters are crucial in renewable energy systems. They allow DC power from sources like solar panels or fuel cells to be converted into grid-compatible AC power. In some configurations, these inverters can also handle bidirectional power flow, enabling functions like regenerative braking in electric vehicles or energy storage system integration. The efficiency of modern three-phase inverters is quite high, typically above 95% in many applications. This high efficiency, combined with their precise control capabilities, makes them essential in a wide range of industrial and power system applications, from manufacturing to power distribution. Advanced control techniques like space vector modulation (SVM) can further enhance the performance of these inverters, offering improved harmonic profiles and better DC bus utilization. Additionally, multilevel inverter topologies are being developed to handle higher power levels and improve output quality, especially in high-voltage applications.



3.3 BLDC motor

TheBrushless DC (BLDC) motor operates through the interaction between a permanent magnet rotor and electromagnetic coils in the stator, using electronic commutation instead of mechanical brushes. The rotor, equipped with permanent magnets, can be either inside or outside the motor, while the stator contains laminated steel stacks with windings that create a rotating magnetic field. Powered by direct current, BLDC motors have three phases energized in a specific sequence, with electronic controllers using Hall effect sensors or back EMF detection to determine rotor position and switch current to the appropriate stator windings. This process involves initial position detection, current switching, and magnetic interaction, resulting in continuous rotation as the rotor aligns with the rotating magnetic field. BLDC motors are highly efficient, have a high torque-to-weight ratio, and offer precise speed control, making them ideal for applications like electric vehicles, drones, computer peripherals, industrial automation, and household appliances.

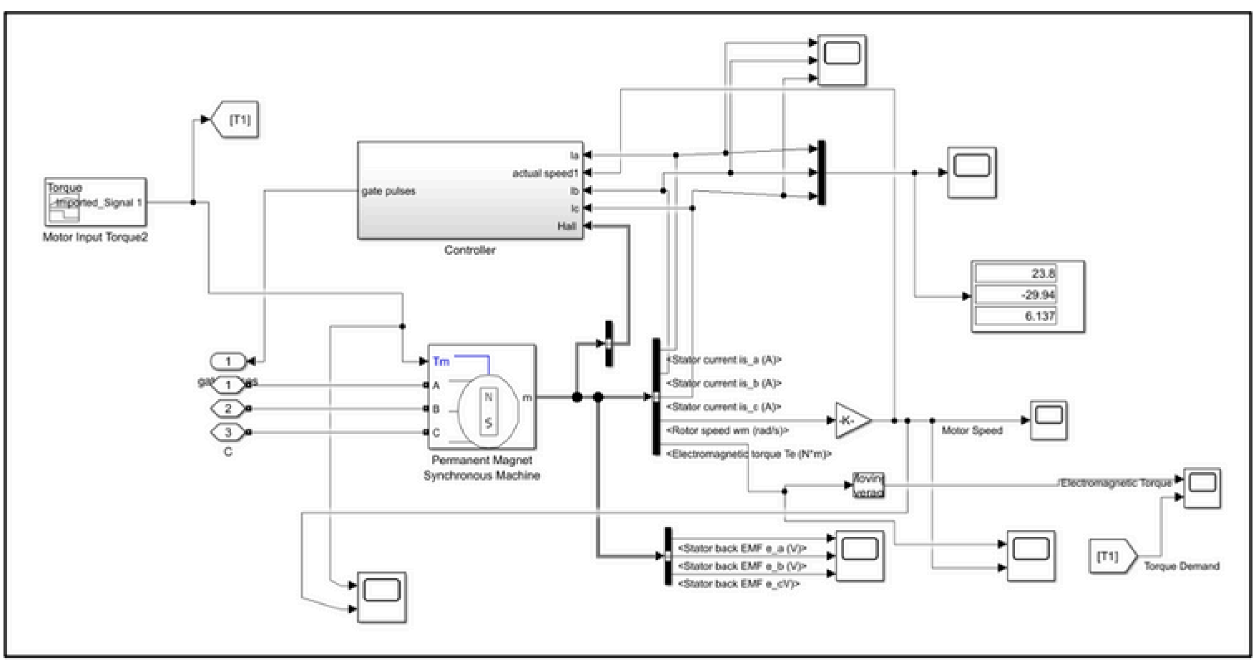


Fig- bldc motor

Chapter 4

Criticaldataanalysis

Thiscritical analysis thoroughly examines the changes that occur whenever we add the super capacitor with our battery in the HESS system and the effect it has on the battery. The objective is to show have adding a super capacitor can increase the efficiency and the life span of the battery. Additionally, we will see how our system reacts to regenerative breaking when we add bi-directional converter which buck-boosts the capacitor.

Torque demand

Forthis project we will be taking a constant drive cycle for both case and simulate it for 20 seconds where we will observe the changes that occurs to our output and changes when we have positive change in torque, negative change in torque and no change in torque.

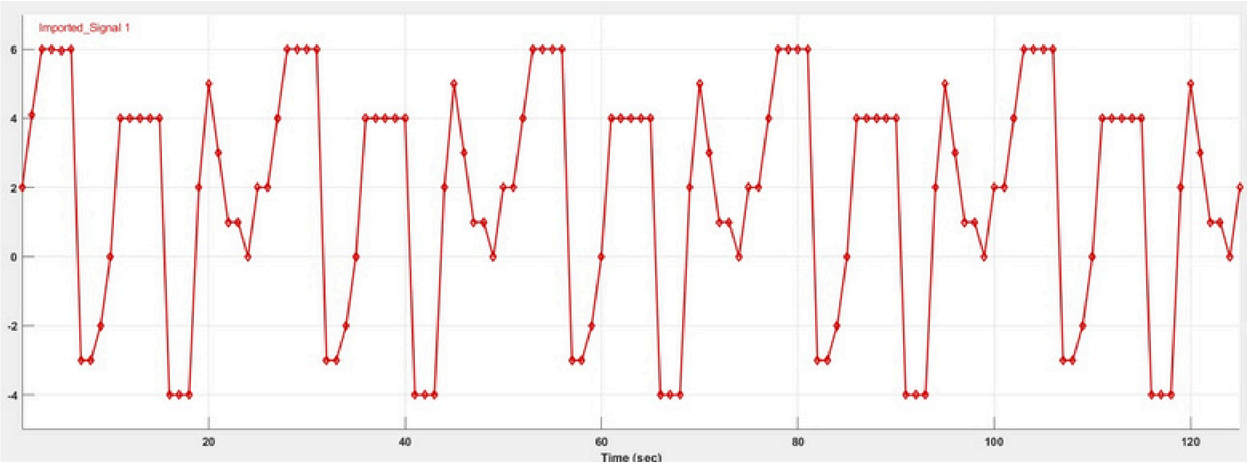


Figure 12 Torque demand for the e-bike

Current and voltage output

Here wewill becomparingtwo scenarios one is our normal system and the second one is our HESS system with bi-directional converter connected with the super capacitor

Without supercapacitor

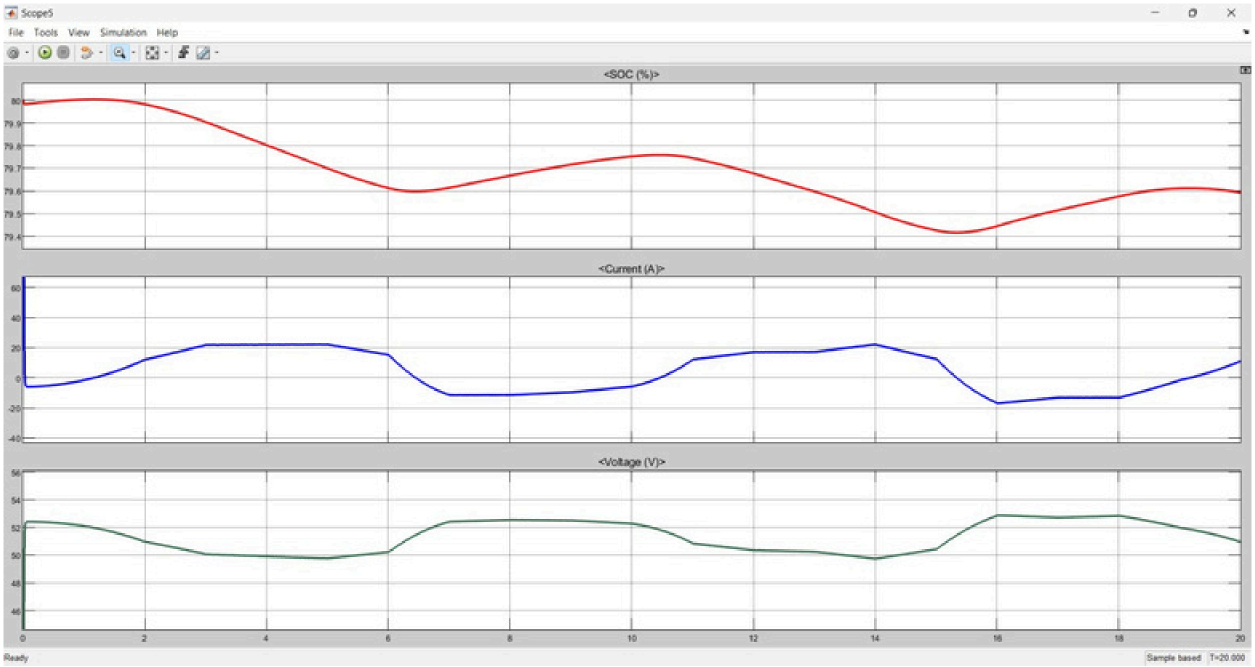


Figure 13 current and voltage output without SC

The torque demandprofilepresentedinfigure12 reveals the highly dynamic power requirements that the battery systemmustmanage.Theseries of rapid changes, with sharp transitions between periods of constantdemand,reflectsthevehicle's operation encompassing acceleration, cruising, and regenerativebrakingphases.Thisreal-world driving pattern places significant stress on the battery, as evidencedbythebatterybehaviorgraph.

When analyzingthebattery'sperformanceconsidering this torque demand, the voltage fluctuations appear relativelyminor,withvaryingbetween50V and 54V. These small voltage variations likely correspond to thechangingtorquedemands,with spikes in torque leading to slight dips in battery voltage and dropsintorqueorregenerativebraking causing the voltage to rise slightly. However, the current profileexhibitsfarmoredramaticswings, ranging from -20A to +25A. These rapid current changesdirectlymirrorthevaryingtorque requirements, with positive current spikes corresponding tohightorquedemandperiodsand negative current representing energy recovery during regenerativebrakingordownhillsections. Without the assistance of a supercapacitor, the battery alone musthandlethesesignificantpower fluctuations, which can ultimately stress the battery and compromiseitslifespan

With supercapacitor

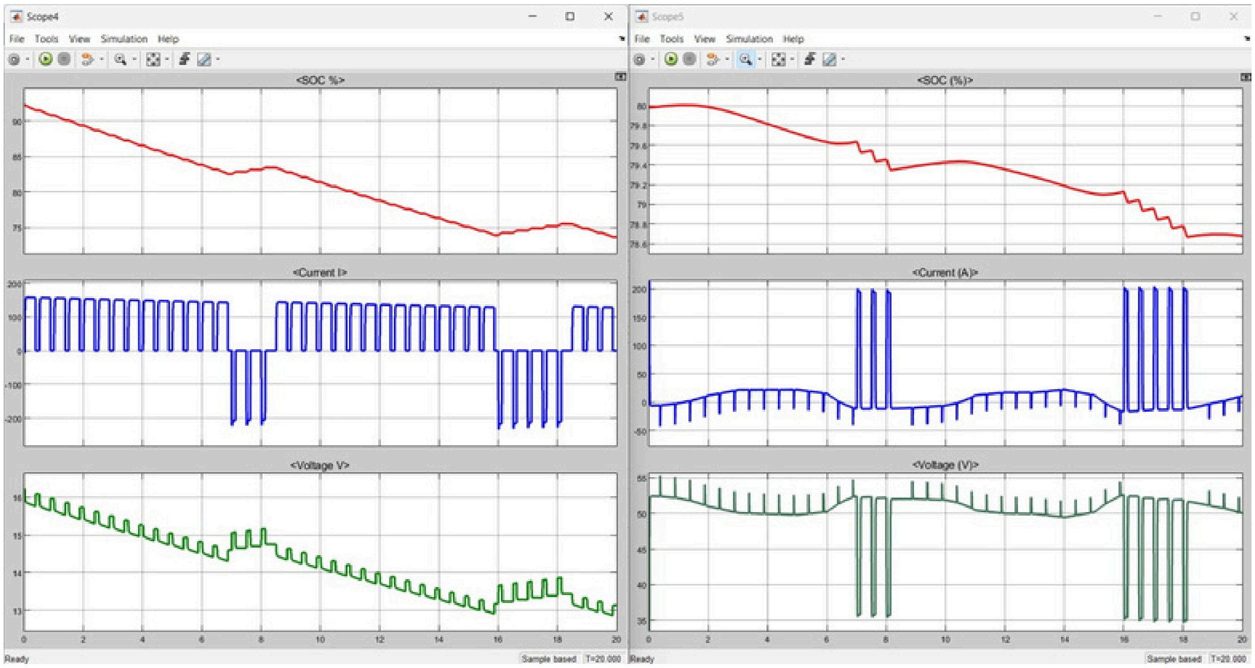


Figure 14 current and voltage output with SC

The graphs depicting the supercapacitor (Scope 4) and battery (Scope 5) performance provide valuable insights into the system's operation. The supercapacitor's voltage profile exhibits a consistent, wave-like pattern, fluctuating between 50V and 55V. This behavior is characteristic of a supercapacitor rapidly charging and discharging to meet the dynamic power demands. The supercapacitor's current waveform shows distinct spikes and troughs, swinging between positive and negative values, indicating its ability to quickly respond to changes in power requirements. In contrast, the battery voltage remains relatively stable, fluctuating between 79V and 80V, showcasing its inherent capacity to maintain a more consistent output.

The integration of the supercapacitor and the bidirectional DC-DC converter, operating with a 75% boosting and 25% bucking duty cycle, has significantly impacted the overall system performance. The supercapacitor's voltage and current profiles demonstrate its role in absorbing the rapid fluctuations in power demand, providing a more stable voltage output. This complementary operation between the battery and supercapacitor, facilitated by the optimized converter, helps to reduce the stress on the battery, potentially extending its lifespan and improving the overall efficiency of the electric bike system. The smoother current waveform observed in the battery graph suggests that the supercapacitor is effectively managing the high-frequency power requirements, allowing the battery to operate in a more consistent and efficient manner.

Discussion

Comparing the current and voltage profiles with the previous scenario without the supercapacitor, several key differences can be observed. The current graph now exhibits a more smoothed-out waveform, with fewer sharp spikes and troughs. This suggests that the supercapacitor is effectively absorbing the rapid power fluctuations, reducing the stress on the battery. Additionally, the voltage graph displays a more stable profile, with less pronounced variations. The presence of the supercapacitor and the bidirectional converter helps maintain a more consistent voltage, improving the overall system performance and efficiency. These changes indicate that the integration of the supercapacitor and the optimized converter design have successfully addressed the challenges faced by the battery-only system, paving the way for enhanced energy management, extended battery life, and improved driving performance in the e-bike.

Power and energy output

Now we will be analyzing the energy of the battery when we have a normal system and when we connect supercapacitor

Without supercapacitors

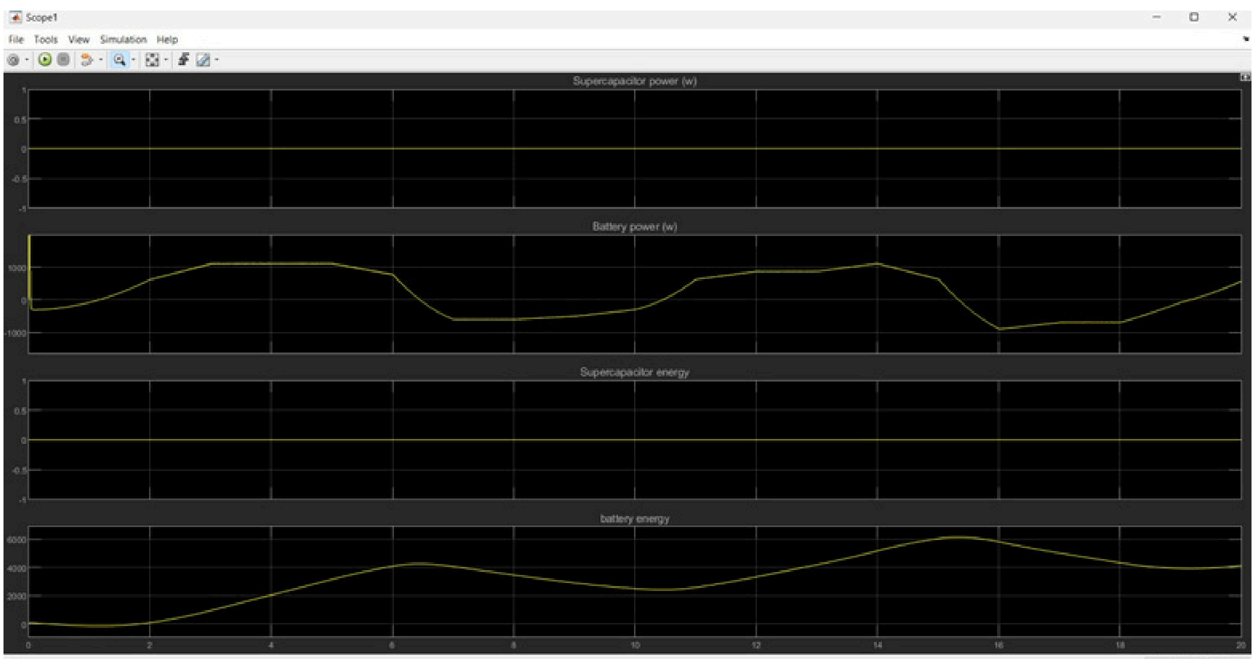


Figure 15 power and energy of HESS without SC

The graph shows the performance of a battery-only energy storage system without the use of a supercapacitor as part of a HESS. The supercapacitor's power and energy profiles stay 0, showing that it is not connected to the system's energy flow. This puts the full weight on the battery to provide the power demands. The battery power profile varies significantly over time, with an early ramp-up, a steady middle portion, and then oscillations. Without the supercapacitor, the battery must meet all power requirements. This is represented in the battery energy plot, which shows an early build-up, then a progressive reduction and partial recovery as the battery discharges and recharges to match the changing load circumstances.

The absence of a supercapacitor means the battery must manage both short-term high-power demands and long-term energy storage, which is not optimal for preserving battery health. The continuous fluctuations in battery power and energy, as seen in the graph, can cause thermal stress and accelerated degradation, reducing the overall performance of the HESS. This scenario highlights the importance of integrating a supercapacitor in a HESS to share the load, improve energy management, and enhance the overall system performance and efficiency, ultimately extending the battery's lifespan.

With supercapacitors

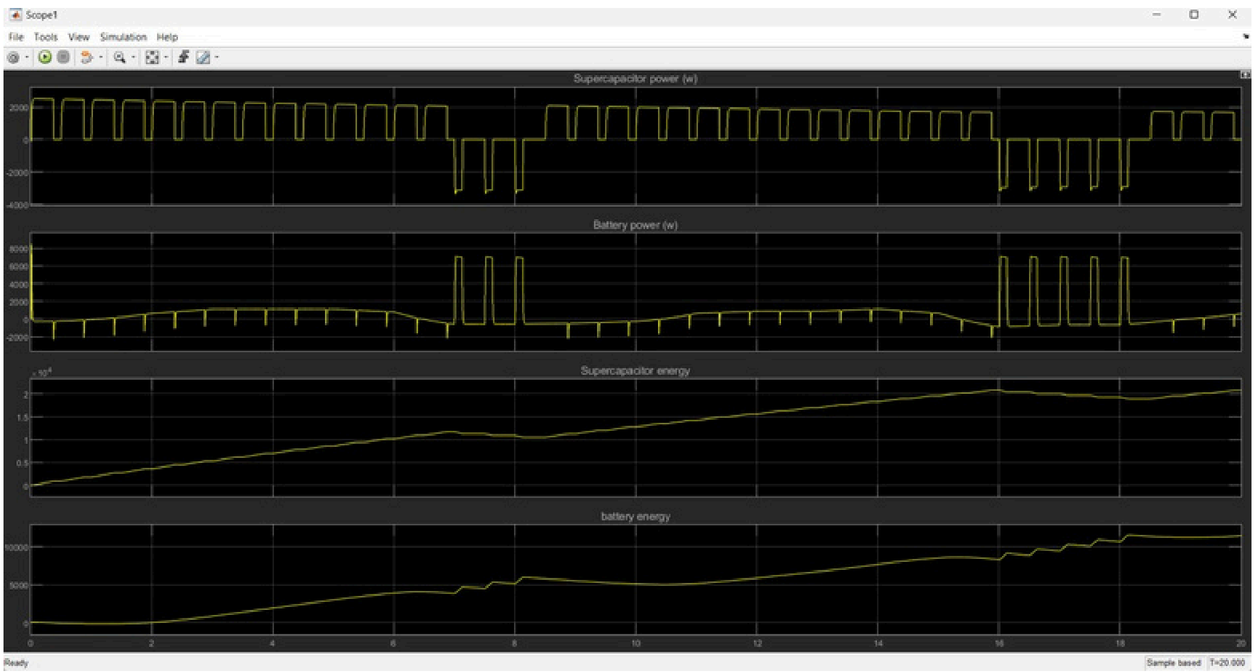


Figure 16 power and energy of HESS with SC

The power and energy graphs reflect the cyclical nature of your torque demand signal. When torque demand peaks, the battery experiences sharp discharge spikes, while sudden drops in torque likely trigger regenerative charging, seen as negative spikes in the power graph. The capacitor, connected via a bi-directional converter, helps smooth these power fluctuations. During high torque demands (boosting at 75% duty cycle), it assists the battery, while during low or negative torque (bucking at 25% duty cycle), it likely aids in charging both itself and the battery.

This system demonstrates efficient energy management, as evidenced by the overall increasing trend in stored energy despite the frequent power cycles. The capacitor's role in buffering rapid power changes allows the battery to operate more efficiently, explaining the distinct power spikes rather than continuous high draws. This setup contributes to the improving system efficiency observed in the original graphs,optimizing energy flow to match the cyclical torque demands.

Chapter 5

5.1 Project management

Project management entails thecoordination, resource allocation, and execution required to accomplish desired outcomes and meet project goals. The goal of project management in the context of the recommended subject, which focuses on investigating and expanding hybrid energy storage systems, is to ensure the timely completion of the project, which includes full discussions and the delivery of a high-quality, standardized report.

5.2 Project schedule

To accomplish the project, several key steps have been undertaken: a thorough literature review from various papers was conducted to understand the concept of hybrid energy storage systems; an analysis of different methodologies for these systems was performed; MATLAB software was utilized to design a hybrid energy storage system; hardware implementation of the wireless power transmission system was carried out; the results of the simulation were observed; and finally, an analysis of the findings was conducted after receiving the results.

5.3 Project timeline

The project spanned a total of 13 weeks, divided into distinct phases. From May 13, 2024, to June 10, 2024, the project criteria were established, and an in-depth study of the project's principles was conducted, taking 4 weeks. From June 11, 2024, to June 30, 2024, the focus shifted to selecting a suitable simulation model and analyzing the findings from the simulation, which took 5 weeks. Finally, from July 8, 2024, to August 7, 2024, data collection, presentation preparation, and comprehensive report writing on the entire project were completed, taking another 4 weeks.

5.4 Risk management

Arisk assessment matrix was employed to identify and list potential risks that could impact the project's progress. These risks were then prioritized based on their potential impact on the project's outcome. Subsequently, mitigation plans were developed for each risk according to their priority. For instance, one of the primary risks was finding a suitable motor model for the analysis of the Hybrid Energy Storage System (HESS). The mitigation strategy involved developing a simple inverter and motor unit with open-loop control. While this approach did not allow for the study of energy recovery through regeneration, it enabled a detailed exploration of the battery and supercapacitor characteristics during discharge, which was crucial for the development of HESS.

5.5 Quality management

Toensure project activities were executed on time and met quality standards, several quality management tools were employed. First, a time schedule chart was created to keep the project on schedule. Next, a risk matrix was used to identify and mitigate potential risks. An open-points list was maintained to track and complete pending sub-activities promptly. Weekly meetings with the project supervisor were held to discuss project progress and the outcomes of various sub-activities.

Feedbackfrom thesemeetings wasdocumented to enhance the quality of thework.

5.6 Social, Legal, Ethical and Professional Considerations

Theprojectfocuses ondeveloping a model forahybrid energy storage system for E-bikes. It is a technical endeavor with no social or legal implications. The research relies solely on publicly available secondary data, with no need for primary data involving individuals. Consequently, no ethical issues or potential harm are associated with this research.

Throughout the project, adherence to the IEEE Code of Ethics was maintained. The project's ethics application was approved, classifying it as a low-risk research project.

Chapter 6

Conclusion

Thisresearch has successfully demonstrated the critical role of integrating a supercapacitor with a battery in a Hybrid Energy Storage System (HESS) for electric bikes. Through comprehensive analysis, we observed that the addition of a supercapacitor significantly enhances the overall system performance by effectively managing the dynamic power demands, particularly during periods of high torque and regenerative braking. The supercapacitor's ability to rapidly charge and discharge reduces the stress on the battery, thereby improving energy management, reducing thermal stress, and extending the battery's lifespan. The presence of a bidirectional DC-DC converter, optimized with a 75% boost and 25% buck duty cycle, further stabilizes the voltage and current profiles, contributing to the smoother operation of the battery and increased system efficiency.

In conclusion, this research provides a solid foundation for the continued development and improvement of HESS in electric vehicles. The integration of supercapacitors not only mitigates power and energy fluctuations that batteries alone would struggle with but also enhances the overall sustainability and efficiency of electric vehicle energy storage systems. These findings have the potential to significantly impact the efficiency and sustainability of future transportation systems, paving the way for more advanced and environmentally friendly electric mobility solutions.

Achievements

Ourachievements include enhanced battery life through reduced stress, improved system efficiency via optimized energy management, effective power management with more stable current and voltage profiles, and better utilization of regenerative braking. These outcomes demonstrate the significant benefits of incorporating a supercapacitor in electric bike HESS designs.

Future works

Looking ahead, several avenues for future work have been identified. Real-world testing of the HESS system in various driving conditions will be crucial to validate our findings and further optimize the system for practical applications. Investigating the scalability of this system for larger vehicles and other types of electric vehicles could broaden its impact across different transport sectors. Exploring advanced control strategies, such as adaptive or machine learning-based controllers, may further enhance the interaction between the battery and supercapacitor. Additionally, conducting long-term durability studies and focusing on energy density optimization of the supercapacitor could address potential challenges and improve the system's suitability for a wider range of applications in electric mobility.

Chapter 7

Student reflection

Engaging in the thesispaper and dedicating three months of rigorous effort to the project has significantly broadened my understanding of hybrid energy storage systems and their methodology. The insights I have gained from the process of thesis submission will undoubtedly benefit me in future endeavors, especially when exploring opportunities or projects within the engineering field.

Moreover, my application of MATLAB has endowed me with an in-depth comprehension of its capabilities. This expertise with MATLAB has illuminated the functions of analogous software tools due to their comparable features. This skill is derived from both a year-long academic curriculum and an exhaustive thesis report, equipping me to navigate various technical challenges and intricacies. My proficiency with MATLAB became intuitive as I grasped its fundamental principles and nuances.

During this endeavor, I faced obstacles such as incorrect results and simulation glitches stemming from my initial lack of familiarity with MATLAB's operational mechanics. Nevertheless, through investigation, problem-solving, and debugging processes, I gradually honed my ability to predict and decipher system behaviors. Additionally, extensive review of pertinent literature like journal publications and other thesis documents enhanced my grasp on MATLAB's core concepts.

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Appendix 1

Notes

<u>Key points</u>

* Bidirectional – ~~to~~ when the torque is negative the power should comeback from the motor to the battery. So we need to show that the power is changing direction.

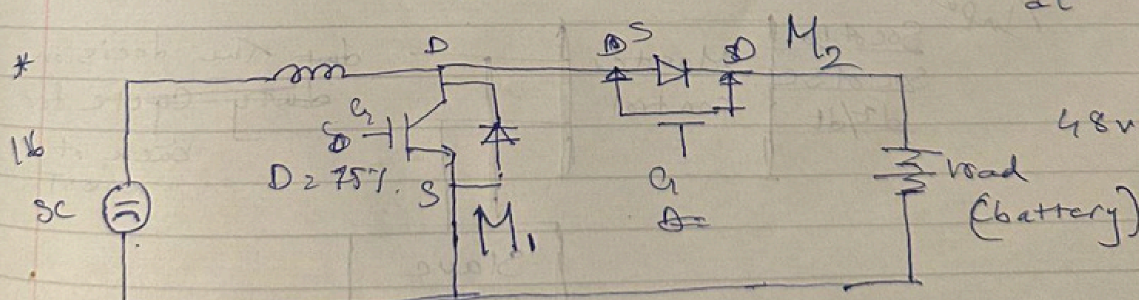
* To show that the ~~biredit~~ bidirectional converter ~~is~~ is working, we need to show that the SC is getting charged ~~and~~ and discharged.

* Add an ammeter to the converter to check the direction of the current flow.

* Add a rate limiter. ~~It~~ When the torque changes from high to low (decreasing?), the limiter will deduce whether the SC or battery will charge. We will take value beyond which the SC will charge or if not the battery will charge. We need to find the rate of change of torque $\frac{d\tau}{dt}$ and the use the comparator block to implement this.

• Calculate many different negative slopes from the torque demand to find $\frac{d\tau}{dt}$

*



For boosting M_2 should be turned off and ~~hat~~ the duty cycle for M_1 = 75%.

For bucking M_2 should be turned on ~~At~~ and and M_1 ~~ss~~ should be turned on with a duty cycle of ~~A~~ 25%.

* For the control part the algorithms ~~is~~ are

① if $\frac{dz}{dt} > A$ (any arbitary value)

then SC is charging (Bucking)

if $\frac{dz}{dt} \leq A \rightarrow$ for the negative slope.

then Battery is charging (Boost)

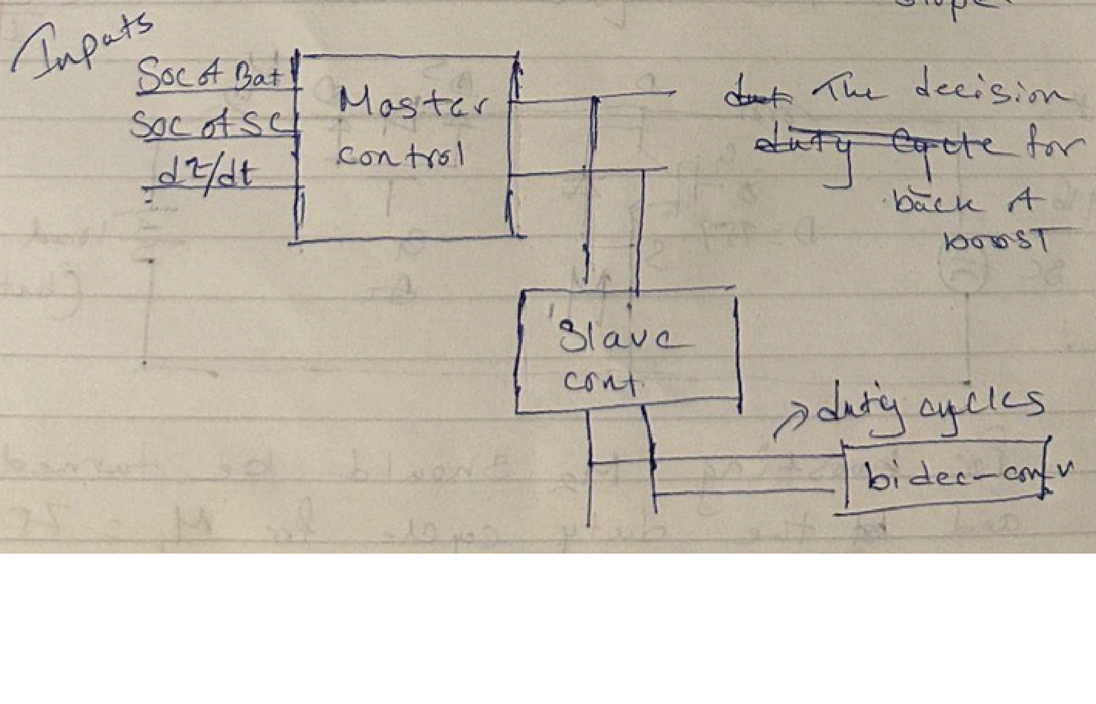
② if SOC < 50% (check for 40%, 50%, 60%)

then SC is charging (it could change from any source)

if SoC ≥ 50%

then SC is discharging

for this: $\frac{dz}{dt} > -M \;\; \Leftarrow\!\!\rightarrow$ for positive slope.



* We need to use a function block to design the controller.

* ~~Wea also nee~~ We only need the torque demand the speed ~~a~~ would come from the motor ~~ou oupu~~ output to make it a closed loop system.

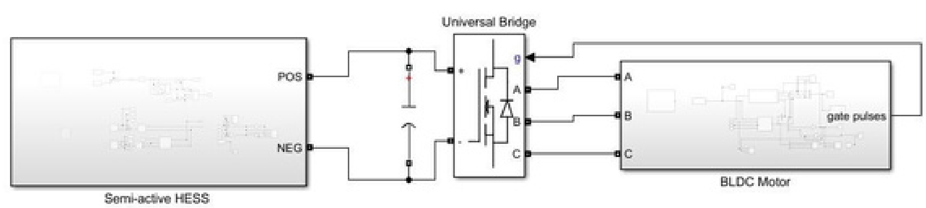
Appendix 2

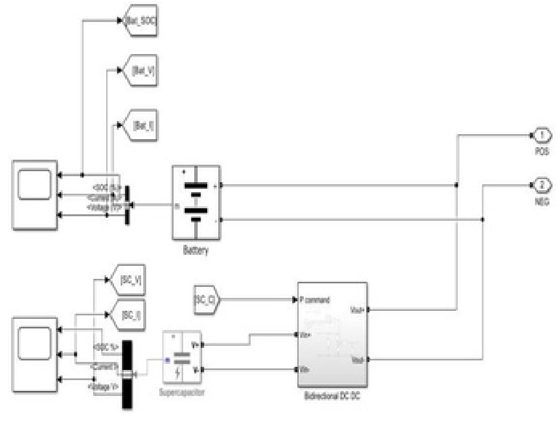
Project presentation

Supervisor:Dr Khaled Choudhury

Name:Syed Musari Mian

Student Id: 14095751


Universal Bridge
POS
NEG
g
A
B
C
A
B
C
gate pulses
Semi-active HESS
BLDC Motor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[Bat_I]
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NEG
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[SC_I]
[SC_C]
P command
Vout+
Vout-
Vin+
Vin-
V+
V-
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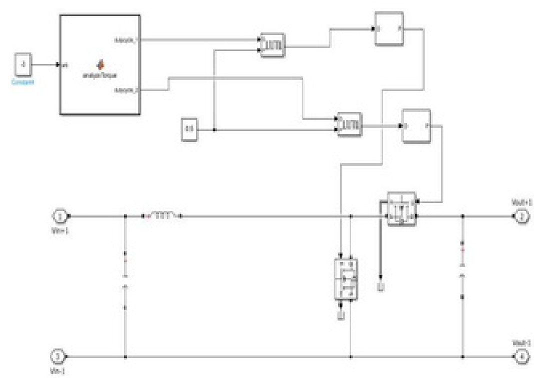
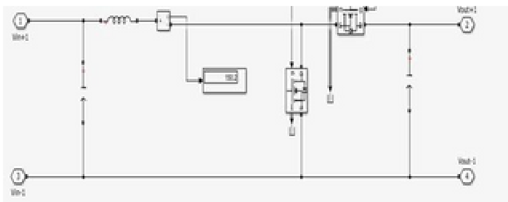
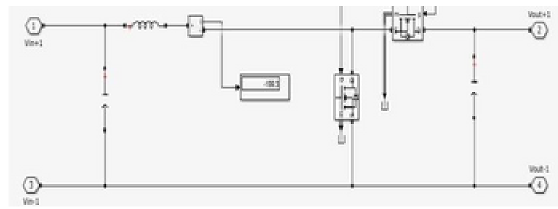
Supercapacitor
Bidirectional DC DC

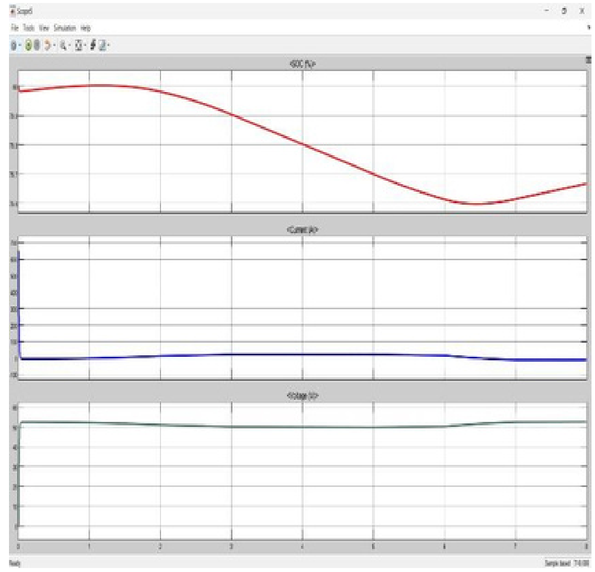

Constant
analyzeTorque
Vin+1
Vin-1
Vout+1
Vout-1

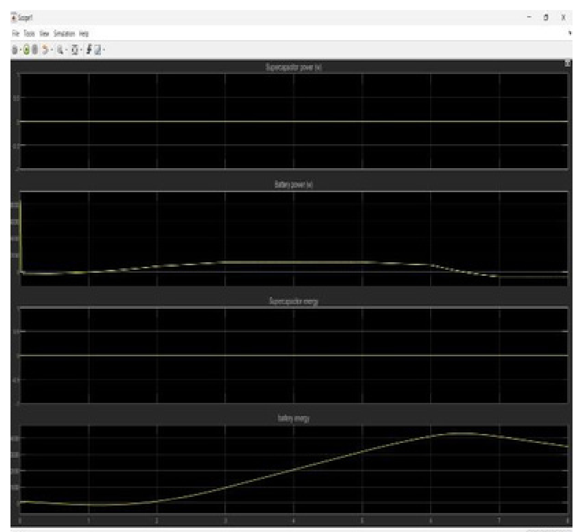


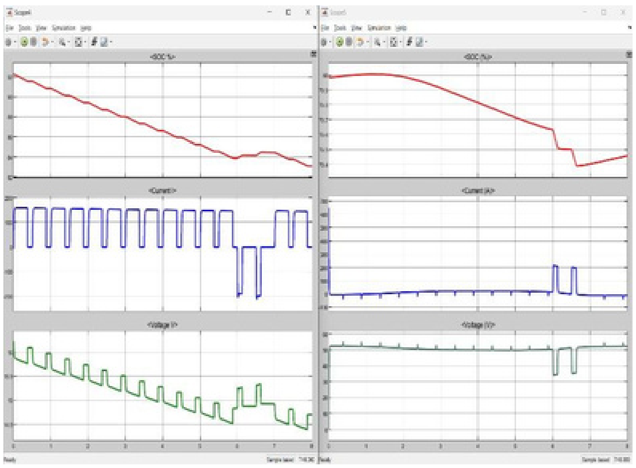


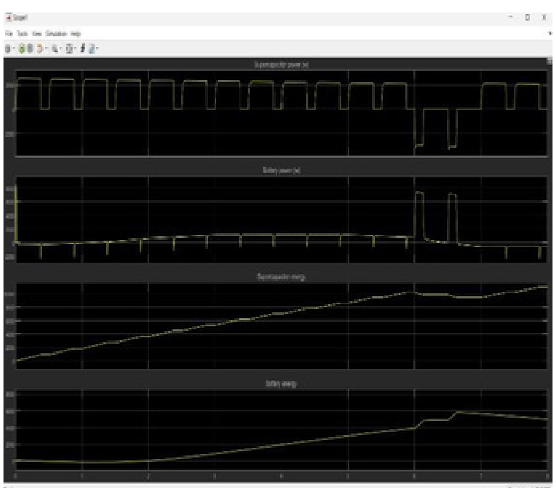
```
function [dutyCycle1,dutyCycle2] = analyzeTorque(arb)
torque = [2, 4, 6,  6,  6,  6,  -3, -3, -2, 0,  4,  4,  4,  4,  4,  -4, -4, -4, 2,  5];
dutyCycle1 = zeros(length(torque),1);
dutyCycle2 = zeros(length(torque),2);
interval = 0.2;
max_iteration = 20;
iteration_count = 0;
while iteration_count < max_iteration
    for i  = 1: length(torque)
        if torque(i) > arb
        dutyCycle1(i) = 0;
        dutyCycle2(i) = 0.25;

        else
        dutyCycle1(i) = 0.75;
        dutyCycle2(i) = 0;
        end
    end
    iteration_count = iteration_count +1;
    pause (interval)
end
disp (dutyCycle1);
disp (dutyCycle2);
end
```


File Tools View Simulation Help


File Tools View Simulation Help
Battery power (w)
battery energy





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J. ***y ri energy storage o ti al si ing for an e i e***