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**DEPARTMENT**

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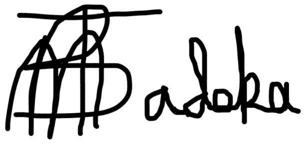
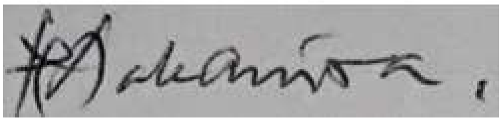
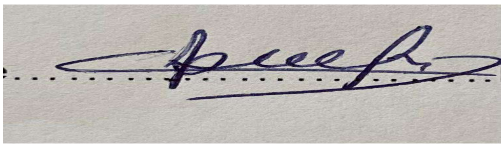
**TITLE: Lithium-ion battery, Super-Capacitor Hybrid Energy Storage System to enhance battery performance**

**Student's signature:** 

**Supervisor's signature:** 

**Chairperson's signature:** 

## Declaration

I declare that the project titled "Lithium-ion battery, Super-Capacitor Hybrid Energy Storage System to enhance battery performance", submitted to Bindura University of Science Education, is my original work, completed under the guidance of Engineer M Takawira. This project has not been submitted for any other degree or diploma and follows the institution's academic and ethical guidelines. All external sources have been properly acknowledged.

**Acknowledgements**

First and foremost, I want to express my deep gratitude to Jehovah for providing me with strength, wisdom, and guidance throughout this project. I am profoundly grateful to my supervisor, Engineer M Takawira, for his valuable support and direction. Special thanks to my fellow classmates, especially Andreas Mapfumo and Melusi shoko for their collaboration and encouragement during this journey. To my family, thank you for your unwavering love, patience, and support. Lastly, I would like to acknowledge the contributions of the research community and open-source platforms, whose work and insights greatly enriched the technical aspects of this project.

Thank you to everyone who helped make this project a success.

## Abstract

This project aims to develop a hybrid energy storage system that optimally manages power distribution between a lithium-ion battery and a supercapacitor in a solar-powered systems. The system is designed to handle variable power demands, using the supercapacitor for high-frequency, short-duration power surges, while the lithium battery supplies steady, long-term energy. A PIC16F877A microcontroller is used for energy management, controlling the switching between the two storage components based on real-time load measurements. Initial results show significant improvements in battery lifespan and system efficiency by reducing stress on the battery during power surges. The system offers a reliable, cost-effective solution for optimizing energy usage in renewable energy systems.

# Contents

# Lithium-ion battery, Super-Capacitor Hybrid Energy Storage System to enhance battery performance.

## CHAPTER 1: Introduction

### 1.1 Background

As fossil fuels have been considered as main cause of global warming in recent years, electric energy has received a great deal of attention as substitute. One of the advantages of electricity is that it can be generated in clean and efficient ways, i.e., solar, hydro and wind power renewable sources. In recent decades, solar has become the most prominent renewable energy technology due to its modularity, easy installation and low operating cost. The major problem with solar renewable energy is the nonlinear electrical characteristic of Photovoltaic (PV) cells and intermittency nature of solar radiation, therefore the need of integration of intermediate energy storage system in order to provide stable electricity supply to the load.

Energy Storage Systems are methods of technologies used to store energy and their main application in power systems is load leveling and stability enhancement. These Energy Storage Systems (ESS) are grouped according to their technological characteristics such as mechanical, electro-chemical, electrical and thermal, and each technology has its own traits. In residential energy systems, the electrochemical technology is mostly used and that is Lithium-ion and Lead-acid batteries. Lithium-ion batteries have higher energy density and longer cycle life than lead-acid batteries

### 1.2 Problem statement

Solar system batteries in their own nature, they have relatively high energy density but low power density which means batteries cannot supply large burst of power for a short period of time. In situations where the electric load requires large burst supply of current for a short time, batteries are not able to supply this dynamic component of current from these pulsed current loads. If they supply the current, the battery's life is diminished through these large variations of current flow which generate excessive heat and increase internal resistance of the battery.

Lithium batteries are designed with detection circuitry inside the BMS (Battery Monitoring System), which continuously monitors the current flowing through the BMS discharge MOSFETS. If this current rises above a certain threshold, the BMS switches off the MOSFETS and effectively removes the battery pack's electrical connection to the electrical load, hence protecting the battery from these large surge currents. Using lithium batteries without the protection of the BMS is very risky. Overcharging or over discharging can cause irreversible damage to cells as large variation of current flow that generate excessive heat and increase the internal resistance of the battery leading to failure and potentially hazardous conditions like thermal runaway and eventually sparks an electrical fire.

## 1.3 Aim

To cater for load large surge currents, a large number of battery packs are needed to provide sufficient peak power to electrical loads which is way more expensive and bulkier. Integration of different ESS technologies turns out to be the best solution to mitigate the battery discharge stress by directing the short-term power fluctuations to another form of ESS which complement the battery's weakness, i.e., making a Hybrid Energy Storage System (HESS) which constitutes of a high energy density and a high-power density energy storage system.

This project proposes to develop a Battery-Super Capacitor Hybrid ESS that can continuously supply power efficiently to electric loads and caters for high surge currents.

## **1.4 Objectives**

Integrate lithium battery and super capacitors.

To design Energy Management System that provides the following features:

- Voltage Protection
- Current protection.

## **1.5 Research Questions**

To what extent is the fluctuation and magnitude of Battery Current minimized by hybridization?

Does hybridization deliver continuous power over the ESS?

What value on power system network does a hybridized energy storage have over single ESS?

Can Simulations characterize HESS?

How does hybridization affect the cycle life of battery?

## **1.6 Hypothesis**

Technological trends hypothetically show that the use of hybrid energy storage systems is currently the evolving technology that is being used in electric vehicles and its integration with Renewable Energy sources has not been exhaustively implemented. Single ESS are still abundant used but they possess limited characteristics in terms of durability, power and energy density, therefore hybrid energy storage systems has been proposed for use to get rid of these limitations.

# CHAPTER 2: Literature review

## 2.1 The need for Hybridization of Energy Storage Systems

The best and most effective way to harness energy produced by renewable resources like solar and wind energy is to store the energy when it is abundantly available in energy storage devices and retrieve it during peak demand times. However, due to the sporadic nature of renewable energy and nature of the load which can strain single storage units, it is paramount to have more than one type of storage systems that complement each other with fast and long response times to meet peak power demand times. Hybrid energy storage systems are favored over single storage units due to their nature to offer combined power and energy features, increased efficiency and the charging and discharging cycles are extensive hence cycle lifespan of the storage device is prolonged.

## 2.2 Differentiation between Energy Density and Power

For the right combination of energy storage systems for hybridization, the knowledge of energy density and power density is essential. Attention is most drawn to electric systems with high energy densities and power densities. To explain better this scenario, an example of two ESS devices is presented:
Device 1 is rated at 500kW takes 30 seconds to deliver energy and ESS device 2 is rated at 500kW delivers energy in 2 hours when fully charged. The energy from device 1 is 4.17 kWh (500kW x 30 sec). This implies that the device delivers a large burst amount of power at shorter duration but has small measure of energy relative to the amount of power. The energy provided by device 2 is 1000kWh (500kW x 2hrs) which is a high amount of energy in proportional to the quality of power.

Energy storage systems with greater power density dispense large burst of power over a short time span and are suitable for loads which require large burst of current, and voltage stabilization. Energy storage systems with higher energy density are capable of dispensing low power for long time span and are applied in load shift requiring high energy density.


Figure 2.1 shows the differentiation between power density and energy density.

## 2.3 Types of Hybrid Energy Storage Systems

### 2.3.1 Battery-Supercapacitor Systems

*Description*

Battery-supercapacitor hybrid energy storage systems (HESS) combine the high energy density of batteries with the high-power density and rapid charge-discharge capabilities of supercapacitors. This combination leverages the strengths of both storage technologies to improve overall system performance, efficiency, and lifespan.

*Components:*

*Batteries*

Types: Commonly used batteries include Lithium-ion (Li-ion), Lead-acid, Nickel-Metal Hydride (NiMH), and others.

Figure 2.2 showing prismatic Lithium-ion battery bank

Characteristics: Batteries store large amounts of energy and are capable of providing a steady power output over a prolonged period. They have a high energy density but relatively lower power density compared to supercapacitors.

*Supercapacitors*


Figure 2.3 showing supercapacitor bank.

Characteristics: Supercapacitors, also known as ultracapacitors or electrochemical capacitors, can store and release energy very quickly. They have a high-power density, which allows for rapid charging and discharging, but a lower energy density compared to batteries.

*Working Principle*

In a battery-supercapacitor system, the supercapacitor handles high power demands and rapid charge-discharge cycles, while the battery manages the long-term energy storage. The supercapacitor acts as a buffer, reducing the stress on the battery and thereby extending its lifespan. During periods of high-power demand, the supercapacitor supplies the necessary power, while during steady-state operation or lower power demands, the battery provides the required energy.

*Applications*

*Electric Vehicles (EVs)*

*Benefits:* Enhances acceleration by providing quick bursts of power, improves regenerative braking efficiency, and extends battery life by reducing peak power loads.

*Example:* Hybrid electric buses and cars where the supercapacitor handles rapid energy fluctuations.

*Renewable Energy Systems*

*Benefits:* Smoothens power output from intermittent sources like solar and wind, provides quick power to compensate for sudden drops in energy generation, and stabilizes grid connection.

*Example:* Solar power systems with integrated supercapacitors to handle short-term fluctuations in energy production.

*Grid Stabilization*

*Benefits*: Supports frequency regulation, load levelling, and peak shaving by quickly responding to changes in power demand and supply.

*Example:* Utility-scale energy storage systems that assist in maintaining grid stability.

*Portable Electronics*

*Benefits:* Extends battery life and improves performance in devices that require rapid power delivery for short periods.

*Example:* Smartphones and laptops that use supercapacitors to handle peak power demands.

*Benefits*

Enhanced Performance

The combination provides both high energy and power density, enabling the system to handle a wider range of applications effectively.

*Improved Efficiency*

Supercapacitors can charge and discharge rapidly with minimal losses, improving the overall efficiency of the energy storage system.

*Extended Lifecycle*

By reducing the frequency and intensity of peak loads on the battery, the overall lifespan of the battery is extended.

*Fast Response Time*

Supercapacitors can respond to power demands almost instantaneously, providing quick bursts of energy as needed.

*Reduced Maintenance*

Supercapacitors have a long cycle life and require minimal maintenance, contributing to the overall reliability of the system.

*Challenges*

*Cost*

Supercapacitors are generally more expensive per unit of energy stored compared to batteries, which can increase the initial cost of the system.

*Complexity*

The integration of batteries and supercapacitors requires sophisticated control systems to manage the power flow and ensure optimal operation.

*Energy Density*

Despite the benefits, the lower energy density of supercapacitors compared to batteries limits their use to applications requiring short-term energy storage.

*Size and Weight*

Supercapacitors may add additional size and weight to the system, which can be a consideration in applications like portable electronics and EVs.

*Conclusion*

Battery-supercapacitor hybrid systems represent a powerful and versatile solution for modern energy storage challenges. By combining the strengths of both batteries and supercapacitors, these systems can deliver high performance, improved efficiency, and extended lifespan across a wide range of applications. Despite the challenges, ongoing advancements in materials science and control technologies are expected to enhance the viability and adoption of battery-supercapacitor systems in the future.

### 2.3.2 Battery-Flywheel Systems

*Description*

Battery-Flywheel hybrid energy storage systems (HESS) combine the long-term energy storage capabilities of batteries with the high-power density and rapid response characteristics of flywheels. This combination enhances overall system performance, efficiency, and reliability, making it suitable for various applications that require both steady energy supply and rapid power delivery.

*Components*

*Batteries*

*Types:* Commonly used batteries include Lithium-ion (Li-ion), Lead-acid, Nickel-Metal Hydride (NiMH), and others.

*Characteristics:* Batteries store large amounts of energy and can provide a steady power output over a prolonged period. They have a high energy density but a lower power density compared to flywheels.

*Flywheels*

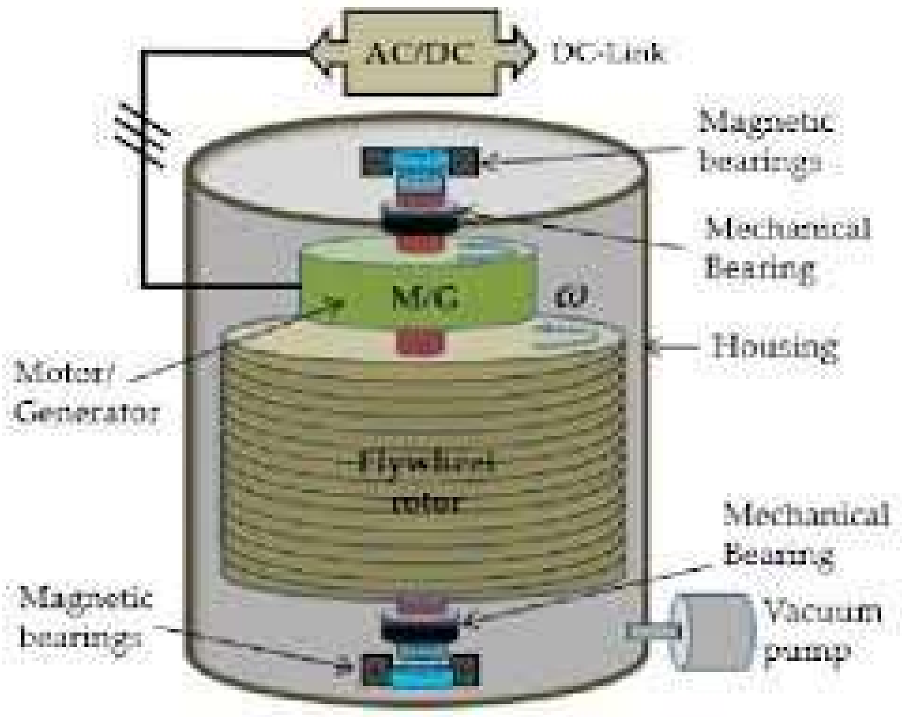



Figure 2.4 showing the Flywheel energy storage system

*Characteristics:* Flywheels store energy in the form of rotational kinetic energy. They can charge and discharge very quickly, providing high power density and rapid response times. Flywheels are known for their durability and long cycle life.

*Working Principle*

In a battery-flywheel system, the flywheel handles rapid charge-discharge cycles and high-power demands, while the battery provides long-term energy storage. The flywheel acts as a buffer, absorbing and delivering power as needed to reduce the load on the battery. This arrangement minimizes the wear and tear on the battery, extending its lifespan and enhancing overall system efficiency.

*Applications*

**Uninterruptible Power Supplies (UPS)**

*Benefits:* Provides immediate power during outages and stabilizes voltage fluctuations, ensuring continuous power supply for critical systems.

*Example:* Data centres and hospitals where reliable and uninterrupted power is essential.

*Grid Frequency Regulation*

*Benefits:* Maintains grid stability by rapidly responding to frequency changes and balancing supply and demand.

*Example:* Utility-scale energy storage systems that assist in grid frequency control.

*Renewable Energy Integration*

*Benefits:* Smoothens the intermittent output of renewable energy sources like wind and solar, ensuring consistent power delivery.

*Example:* Solar and wind power plants where flywheels manage short-term power fluctuations.

*Transportation Systems*

*Benefits:* Enhances the performance of electric and hybrid vehicles by providing rapid energy bursts for acceleration and regenerative braking.

*Example:* Hybrid buses and trains that use flywheels for energy recovery and boost during acceleration.

*Benefits*

*High Power Density*

Flywheels can deliver large amounts of power in a short period, making them ideal for applications requiring rapid energy bursts.

*Rapid Response Time*

Flywheels can respond almost instantaneously to power demands, providing quick energy delivery.

*Extended Battery Life*

By absorbing high power demands, flywheels reduce the cycling stress on batteries, extending their operational life.

*High Efficiency*

Flywheels have high round-trip efficiency (typically 85-95%), meaning most of the energy put into them can be recovered.

*Durability and Low Maintenance*

Flywheels have a long operational life and require minimal maintenance compared to other mechanical systems.

*Environmental Benefits*

Flywheels are environmentally friendly, with no chemical reactions involved, and can be made from recyclable materials.

*Challenges*

*Cost*

Initial investment for flywheel systems can be high, although they can be cost-effective in the long run due to low maintenance and long lifespan.

*Energy Density*

Flywheels have lower energy density compared to batteries, limiting their use to applications requiring short-term energy storage.

*Complexity*

Integrating flywheels with batteries requires advanced control systems to manage the energy flow efficiently.

*Mechanical Wear*

Although durable, flywheels are mechanical devices that can experience wear and tear, particularly in high-speed applications.

*Space Requirements*

Flywheel systems can be bulky, which may be a consideration in space-constrained applications.

*Conclusion*

Battery-flywheel hybrid systems represent a robust and effective solution for energy storage, combining the high energy density of batteries with the rapid response and high-power density of flywheels. This hybrid approach can significantly enhance the performance, efficiency, and lifespan of energy storage systems, making it suitable for a wide range of applications from grid stabilization to transportation. Despite the challenges, ongoing technological advancements are likely to further improve the feasibility and adoption of battery-flywheel systems in the future.

### 2.3.3 Supercapacitor-Flywheel Systems

*Description*

Supercapacitor-flywheel hybrid energy storage systems (HESS) combine the high-power density and rapid charge-discharge capabilities of supercapacitors with the mechanical energy storage of flywheels. This combination leverages the strengths of both technologies to provide fast response times, high power output, and robust energy storage for various applications.

*Components*

*Supercapacitors*
*Characteristics*: Supercapacitors, also known as ultracapacitors, store energy electrostatically. They can charge and discharge rapidly, providing high power density but relatively lower energy density compared to batteries.
*Key Features:* High cycle life, fast response, low maintenance, and high efficiency.

*Flywheels*

*Characteristics:* Flywheels store energy in the form of rotational kinetic energy. They can deliver large amounts of power quickly and have a long operational life with minimal maintenance.

*Key Features:* High power density, rapid response times, and durability.

*Working Principle*

In a supercapacitor-flywheel system, the supercapacitor handles short-term, high-power demands and rapid fluctuations in energy requirements. The flywheel provides a steady supply of power and can store energy for medium-term needs. The supercapacitor acts as a buffer, smoothing out spikes in power demand and supply, while the flywheel ensures a stable energy flow.

*Applications*

*Frequency Regulation*

*Benefits:* Provides quick response to frequency changes in the power grid, maintaining grid stability.

*Example:* Utility-scale systems that help balance the supply and demand of electricity.

*Power Quality Improvement*

*Benefits:* Enhances the quality of power supplied by mitigating voltage sags, spikes, and interruptions.

*Example:* Industrial facilities where stable power is critical for operations.

*Transportation Systems*

*Benefits:* Improves energy efficiency and performance of electric and hybrid vehicles by providing rapid energy bursts and supporting regenerative braking.

*Example:* Hybrid buses and trams that use supercapacitors for acceleration and flywheels for energy recovery.

*Uninterruptible Power Supplies (UPS)*

*Benefits:* Ensures a reliable and continuous power supply during outages and disturbances.

*Example:* Data centres and hospitals where uninterrupted power is essential.

*Benefits*

*High Power Density*

Both supercapacitors and flywheels can deliver high power output quickly, making them ideal for applications requiring rapid energy delivery.

*Fast Response Time*

Supercapacitors can respond almost instantaneously to power demands, while flywheels also provide rapid energy release.

*Extended Lifecycle*

Both technologies have long cycle lives and low maintenance requirements, contributing to the overall durability and reliability of the system.

*Enhanced Efficiency*

The high efficiency of supercapacitors and flywheels results in minimal energy losses during charge and discharge cycles.

*Environmental Benefits*

Supercapacitors and flywheels are environmentally friendly, with no harmful chemical reactions involved and the potential for using recyclable materials.

*Challenges*

*Cost*

The initial cost of supercapacitors and flywheels can be high, although operational savings and long lifespans can offset this over time.

*Energy Density*

Both supercapacitors and flywheels have lower energy densities compared to batteries, limiting their use to applications requiring short-term energy storage.

*Complexity*

Integrating supercapacitors with flywheels requires sophisticated control systems to manage the energy flow efficiently.

*Size and Weight*

Flywheels, in particular, can be bulky and heavy, which may be a consideration in certain applications.

*Conclusion*

Supercapacitor-flywheel hybrid systems offer a powerful solution for applications requiring high power density, rapid response, and reliable energy storage. By combining the complementary strengths of supercapacitors and flywheels, these systems can effectively address the needs of grid stabilization, power quality improvement, transportation, and UPS applications. Despite challenges related to cost, energy density, and complexity, ongoing advancements in materials science and control technologies are likely to enhance the feasibility and performance of supercapacitor-flywheel systems, making them an increasingly valuable component of modern energy storage solutions.

### 2.3.4 Battery-Battery Hybrid Energy Storage Systems

*Description*

Battery-battery hybrid energy storage systems (HESS) combine different types of batteries within the same system to leverage their complementary characteristics. This approach enhances overall system performance, efficiency, and reliability by optimizing the strengths of each battery type while mitigating their individual limitations.

*Components*

*High-Energy Batteries*
*Examples*: Lithium-ion (Li-ion), Sodium-sulphur (NaS)
*Characteristics:* High energy density, capable of storing large amounts of energy for extended periods. Suitable for applications requiring long-duration energy supply.
*Key Features*: Long cycle life, high energy capacity, steady discharge rate.

*High-Power Batteries*

*Examples:* Nickel-cadmium (NiCd), Lithium-titanate (LTO)


Figure 2.5 shows Nickel Cadmium cells

*Characteristics:* High power density, capable of delivering large amounts of power quickly. Suitable for applications requiring rapid energy discharge.

*Key Features:* Fast charge-discharge cycles, high power output, good thermal stability.

*Working Principle*

In a battery-battery hybrid system, high-energy batteries provide long-term energy storage, while high-power batteries handle short-term, high-power demands. The high-power battery acts as a buffer, supplying rapid energy bursts when needed, thereby reducing the stress on the high-energy battery and prolonging its lifespan. Advanced control systems manage the energy flow between the two types of batteries to ensure optimal performance and efficiency.

*Applications*

*Electric Vehicles (EVs)*

*Benefits:* Enhances acceleration and overall performance by using high-power batteries for rapid energy bursts and high-energy batteries for long-range travel.

*Example:* EVs that use high-power lithium-titanate batteries for acceleration and lithium-ion batteries for extended driving range.

*Renewable Energy Systems*

*Benefits:* Manages the intermittency of renewable energy sources by using high-power batteries for immediate energy needs and high-energy batteries for long-term storage.

*Example:* Solar power systems that store excess energy in high-energy batteries and use high-power batteries for grid stability.

*Grid Energy Storage*

*Benefits*: Provides grid stabilization, frequency regulation, and load levelling by using high-power batteries for rapid response and high-energy batteries for sustained energy supply.

*Example:* Utility-scale energy storage systems that enhance grid reliability and integrate renewable energy sources.

*Portable Electronics*

*Benefits*: Extends battery life and improves performance in devices that require quick power delivery and sustained energy supply.

*Example*: Smartphones and laptops that use hybrid battery systems for better performance and longer usage times.

*Benefits*

*Enhanced Performance*

Combines the high energy density of one battery type with the high-power density of another, optimizing overall system performance.

*Extended Lifecycle*

Reduces the cycling stress on high-energy batteries by using high-power batteries for rapid discharge, thereby extending the lifespan of the high-energy batteries.

*Improved Efficiency*

Advanced control systems ensure efficient energy management, reducing energy losses and optimizing charge-discharge cycles.

*Cost-Effectiveness*

Balances the cost of different battery types, using more expensive high-power batteries only, when necessary, thus optimizing overall system cost.

*Flexibility*

Provides flexibility in design and application, allowing for tailored solutions based on specific energy storage needs.

*Challenges*

*Complexity*

Integrating and managing different battery types require sophisticated control systems and power electronics, increasing system complexity.

*Cost*

The initial cost of implementing a hybrid system can be higher due to the need for multiple battery types and advanced control systems.

*Maintenance*

The need for regular maintenance and monitoring to ensure optimal performance and longevity of the hybrid system.

*Conclusion*

Battery-battery hybrid systems represent a versatile and effective solution for a wide range of energy storage applications. By combining the strengths of high-energy and high-power batteries, these systems can deliver enhanced performance, improved efficiency, and extended lifecycle. Despite challenges related to complexity, cost, and compatibility, ongoing advancements in battery technology and control systems are likely to further improve the feasibility and adoption of battery-battery hybrid systems, making them a valuable component of modern energy storage strategies.

## 2.4 Review of Existing Hybrid Energy Storage

Although the technology of HESS is still evolving, it is an exciting feature for research within the energy domain. There are researchers who have made some significant work in this area of study as will be discussed under this section.

**2.4.1 Dr. Mehrdad Ehsani's** research on hybrid energy storage systems (HESS) is extensive and influential, particularly in the context of electric vehicles (EVs) and renewable energy integration. Below is a detailed outline of his research, highlighting the strengths and weaknesses.

### Overview of Research

Dr. Mehrdad Ehsani's work primarily focuses on the integration of various energy storage technologies, such as batteries and supercapacitors, to enhance the performance, efficiency, and lifespan of electric powertrains. His research includes modelling, control strategies, and real-world applications of HESS in EVs.

### Strengths of Ehsani's Research

*Comprehensive Approach:*

Ehsani's research covers a broad spectrum, from theoretical modelling to practical applications, providing a holistic view of HESS.

This comprehensive approach ensures that the proposed solutions are not only theoretically sound but also practically viable.

*Innovative Control Strategies:*

Development of sophisticated control algorithms that significantly enhance the efficiency and reliability of hybrid systems.

These strategies contribute to better energy management and prolong the operational life of storage components.

*Real-World Applications:*

Focus on real-world applications, particularly in the automotive industry, making his research highly relevant and impactful.

Practical solutions for common challenges in EVs, such as battery degradation and range limitations.

**Weaknesses of Ehsani's Research**

*Complexity of Models:*

The dynamic models and control algorithms developed by Ehsani can be highly complex and may require significant computational resources.

This complexity might limit the practical implementation of these models in certain scenarios, especially in resource-constrained environments.

*Focus on Specific Applications:*

While Ehsani's research is extensive in the context of EVs, it may not fully address other potential applications of HESS, such as stationary energy storage for renewable energy integration.

This focus might limit the generalizability of some of his findings to other domains.

*Experimental Validation:*

While the research includes simulations and theoretical models, there is often a need for more extensive experimental validation to confirm the real-world performance of the proposed solutions.

Limited real-world testing might hinder the immediate adoption of these technologies by industry.

*Cost Considerations:*

The implementation of hybrid energy storage systems can be costly, and Ehsani's research might not always fully address the economic aspects of deploying these systems at scale.

Cost-benefit analysis and economic feasibility studies are essential for the widespread adoption of HESS.

**Conclusion**

Dr. Mehrdad Ehsani's research on hybrid energy storage systems is characterized by its depth, innovation, and practical relevance, particularly in the field of electric vehicles. His work on dynamic modelling, control strategies, and real-world applications has significantly advanced the understanding and potential of HESS. However, the complexity of his models, the focus on specific applications, the need for more experimental validation, and economic considerations present areas for further exploration and improvement. Overall, Ehsani's contributions have laid a strong foundation for future research and development in hybrid energy storage systems.

**2.4.2** **Dr. Ziyad Salameh** is known for his research in the field of hybrid energy storage systems (HESS), which combines different energy storage technologies to optimize performance for various applications. His work generally focuses on integrating batteries with other storage technologies, such as supercapacitors, to leverage their complementary strengths.

**Strengths of Dr. Ziyad Salameh's Research:**

*Comprehensive Analysis:*

Dr. Salameh's research often provides a thorough analysis of the performance characteristics of different energy storage systems. This includes detailed modelling and simulation to predict the behavior of hybrid systems under various operating conditions.

*Innovative Integration Approaches:*

He has contributed innovative methods for integrating different energy storage technologies. For instance, his work on combining batteries and supercapacitors aims to balance energy density and power density, providing a more efficient and effective storage solution.

*Real-World Applicability:*

His research frequently addresses practical issues related to the implementation of HESS in real-world scenarios, such as in renewable energy systems, electric vehicles, and smart grids. This practical focus helps ensure that his findings are not only theoretically sound but also applicable in real-life applications.

*Optimization Techniques:*

Dr. Salameh's work often includes the development of optimization techniques to enhance the performance and longevity of hybrid energy storage systems. This includes strategies for improving charge-discharge cycles, energy management, and system efficiency.

*Environmental and Economic Impact:*

He places significant emphasis on the environmental and economic benefits of hybrid systems. By optimizing the use of different storage technologies, his research aims to reduce costs and minimize environmental impacts, making renewable energy more viable.

**Weaknesses of Dr. Ziyad Salameh's Research:**

*Complexity of Implementation:*

While his research provides detailed theoretical models and simulations, the practical implementation of these systems can be complex. The integration of multiple storage technologies requires sophisticated control systems and can face technical challenges.

*Scalability Issues:*

Some of the hybrid systems proposed in his research may face scalability issues. What works well in a controlled environment or on a small scale may not always be easily scalable to larger applications without encountering significant obstacles.

*Cost of Hybrid Systems:*

Although the research aims to reduce costs in the long term, the initial investment for hybrid energy storage systems can be high. The cost of developing and integrating multiple storage technologies can be a barrier to widespread adoption.

**2.4.3 Dr. Shuhui Li** has made significant contributions to the field of hybrid energy storage systems (HESS), focusing on integrating different energy storage technologies to improve the efficiency, reliability, and sustainability of energy systems. His work often emphasizes the practical application of HESS in smart grids, renewable energy systems, and electric vehicles.

**Strengths of Dr. Shuhui Li's Research:**

*Advanced Control Strategies:*

Dr. Li's research extensively explores advanced control strategies for hybrid energy storage systems. He has developed sophisticated algorithms to manage the energy flow between different storage components, optimizing performance and extending the lifespan of the systems.

*Focus on Smart Grids:*

His work places a strong emphasis on the integration of HESS with smart grids. This focus helps in enhancing grid stability, reliability, and efficiency, particularly in the context of incorporating renewable energy sources like solar and wind power.

*Modelling and Simulation:*

Dr. Li has conducted comprehensive modelling and simulation studies to predict the behavior of hybrid energy storage systems under various scenarios. These simulations are crucial for understanding the dynamic interactions within HESS and for designing more effective systems.

*Renewable Energy Integration:*

A significant portion of his research addresses the challenges of integrating renewable energy sources with HESS. By mitigating the intermittency and variability of renewables, his work supports the broader adoption of clean energy technologies.

*Practical Implementations:*

Dr. Li has been involved in several practical implementations of HESS, demonstrating the feasibility and benefits of his theoretical work. These real-world applications provide valuable insights and validate his research outcomes.

**Weaknesses of Dr. Shuhui Li's Research:**

*Complexity of Control Systems:*

The advanced control strategies proposed in his research can be complex and challenging to implement. These sophisticated algorithms require high computational power and robust control systems, which might not be readily available in all applications.

*Cost Considerations:*

While Dr. Li's research aims to optimize the performance of HESS, the initial costs of implementing such systems can be high. The complexity of hybrid systems and the need for advanced control technologies can make them expensive, potentially limiting their adoption.

*Scalability Challenges:*

Similar to other researchers in this field, Dr. Li's proposed solutions might face scalability issues. Implementing HESS on a large scale, such as in national grids or large industrial applications, can present significant technical and economic challenges.

*Dependency on Technology Maturity:*

The effectiveness of hybrid energy storage systems often depends on the maturity of the individual storage technologies being integrated. If certain technologies (e.g., advanced batteries or supercapacitors) do not progress as expected, it could impact the overall performance and viability of HESS.

*Integration with Existing Infrastructure:*

Integrating HESS with existing energy infrastructure can be difficult. Compatibility issues, regulatory barriers, and the need for significant modifications to current systems are potential obstacles that could impede the implementation of Dr. Li's research findings.

Overall, Dr. Shuhui Li's research on hybrid energy storage systems is highly regarded for its innovative control strategies, focus on practical applications, and contribution to renewable energy integration. However, challenges related to complexity, cost, scalability, and integration with existing infrastructure need to be addressed to fully realize the potential of his research.

## 2.5 HESS Coupling Topologies

Several HESS topologies have been proposed in various applications aiming to optimally exploit the benefits of different ESS elements. The various kinds of existing or future topologies can be categorized based on number of ESS elements, the strategies of power sharing among ESS elements and interfacing methods.

Passive topology is the simplest topology where the short-term and long-term ESS devices are connected in parallel and directly coupled to DC bus. The major advantage is its simplicity in operation and low cost.

Semi-active topology – in this method, the converter is used to interface one of the ESS devices to the dc bus. The advantage of this topology is that when interfaced to long term storage, the latter can be guarded from power spikes and frequent load dynamics. The demerits of this method are the fluctuation of the dc bus voltage which becomes identical to the short-term ESS.

Full active topology – this method has all the paired ESS interfaced with the power converters. The advantage of this mode is that the converter for short term ESS regulates the voltage of the dc bus which result in optimized usage of the ESS capacity and enhances the quality of power supplied to the load. As compared to other topologies, this topology has high power losses.

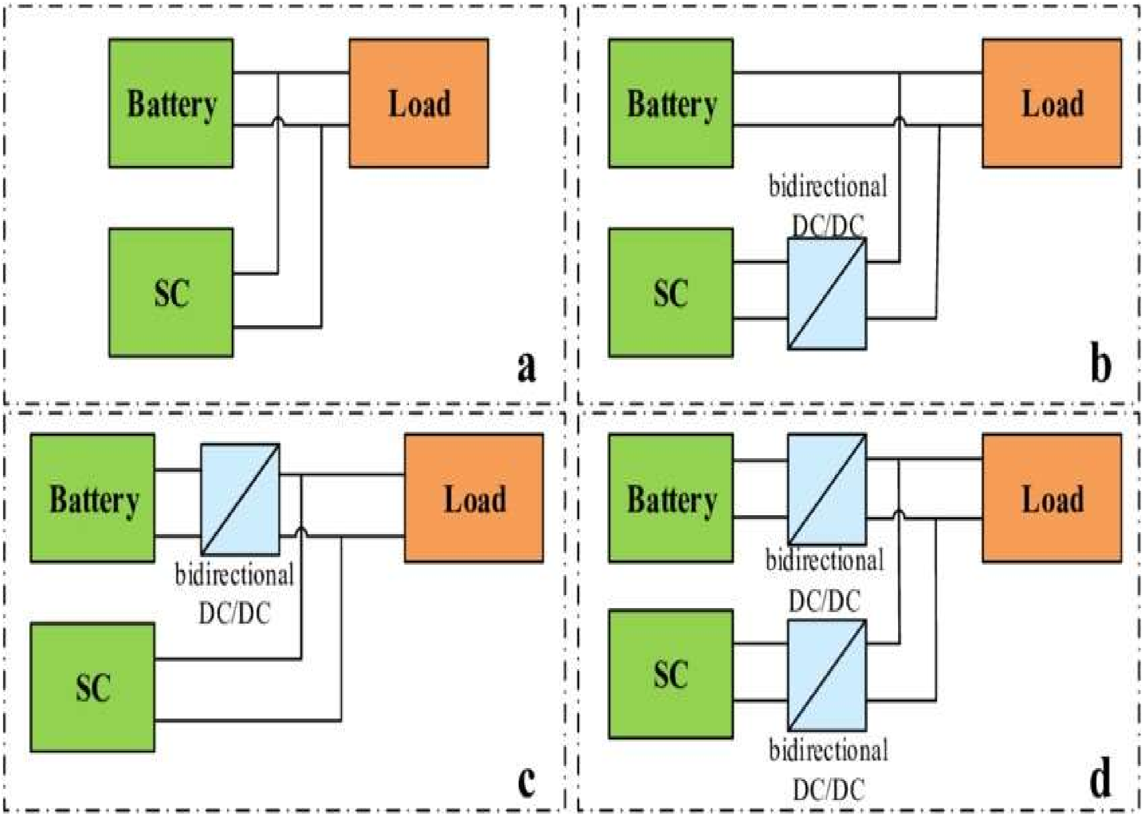



Figure 2.6 shows the coupling topologies that can be used to combine batteries and super-capacitors to make a hybrid energy storage system. (a) is the passive coupling topology, (b)and(c) are the semi-active coupling topology, and (d) is the active coupling topology.

# Chapter 3: Methodology

## 3.1 Introduction

Lithium batteries are the best in providing high energy density and super-capacitors are the best in providing high power density, so in order to offset their opposing weaknesses, a battery/super-capacitor hybrid energy storage system is proposed.

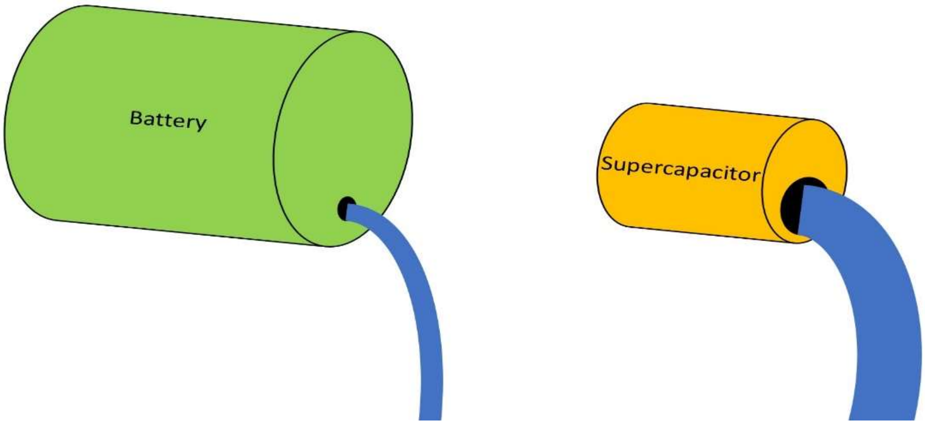



Figure 3.1 shows the energy density of a battery and the power density of a super capacitor.

This project's main objective is to integrate two energy storage systems which complement the weaknesses of one another. These ESSs are sourced from electro-chemical and electrical forms of energy with due consideration of their different properties that complement each other in order to boost the quality of power supplied to electric load. The entire proposed system will have the following components:

- Lithium-ion battery bank.
- Super-capacitor bank.
- Energy Management System for power sharing strategies and protection.

The passive coupling topology is adopted in this project where the battery bank and capacitor bank are connected in parallel and energy flow is monitored and controlled by the energy management system.

## 3.2 Block diagram of proposed system

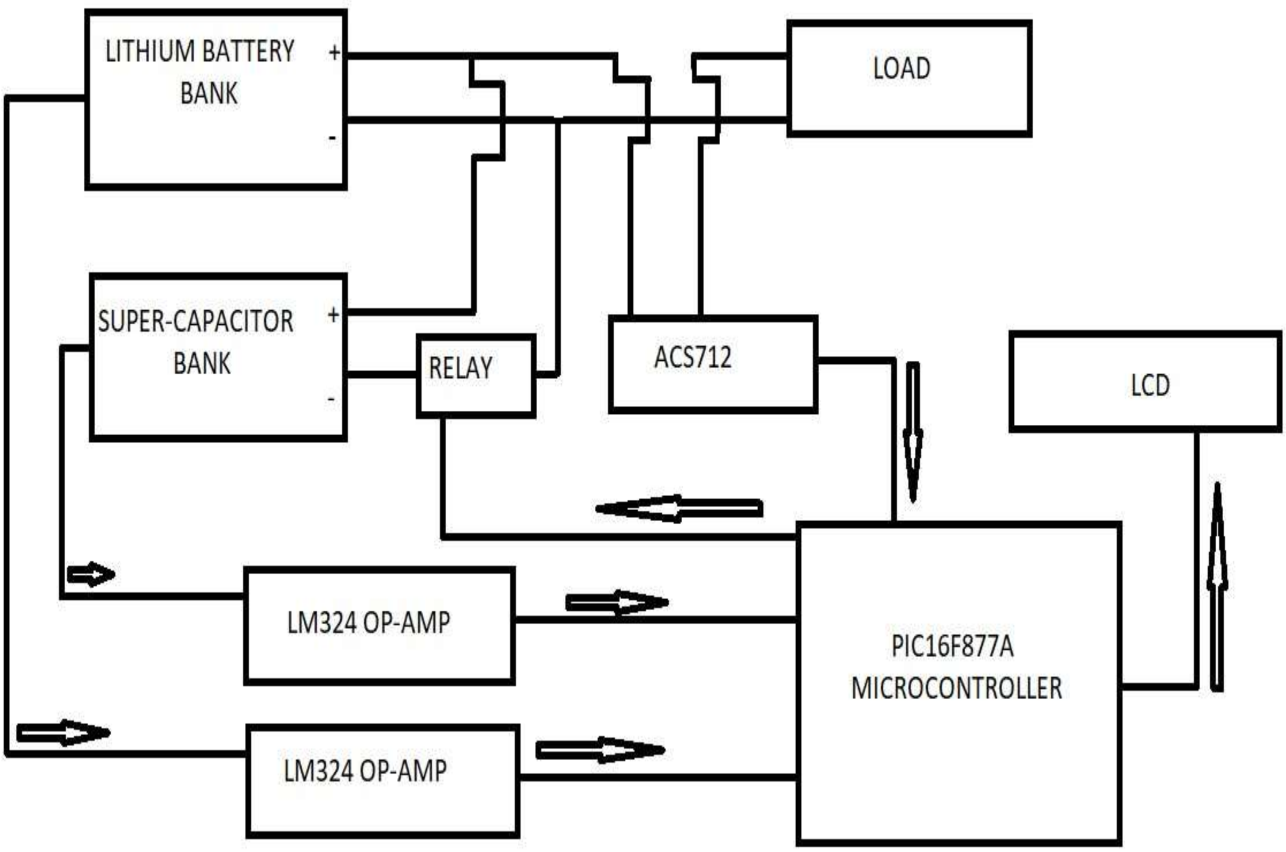



Figure 3.2 Block diagram of a Lithium battery-supercapacitor HESS

The block diagram of the HESS and its Energy Management system is as shown in the figure 3.2. The various functional blocks involved are: Battery bank and its individual cell voltage measurement module, Super-capacitor bank and its cell voltage measurement module, ACS712 current sensor. The EMS should accurately measure battery discharge current, battery voltage and individual cell voltage, super-capacitor voltage and individual cell voltage, as well as able to protect the battery from hazardous and inefficient operating conditions like overcurrent, under voltage and overvoltage.

Voltage measurement is done by Op-Amp differential circuit which uses LM324 Op-Amp IC.  Battery current is measured using the Hall effect sensor ACS712. The measured voltages and current are given to the PIC16F877A microcontroller. Using these measured parameters, the PIC microcontroller continuously monitors them for battery protection and display them on the LCD.

## 3.3 Voltage measurement

The voltage level of the battery pack and capacitor pack represents its current condition. Thus, an EMS has to primarily, measure the individual cell voltages as well as total battery voltage of a battery pack, and also measure the individual cell voltages as well as total super- capacitor voltage of a super-capacitor pack. The proposed work measures individual cell voltage as well as total voltages using an Op-Amp differential amplifier as shown below.

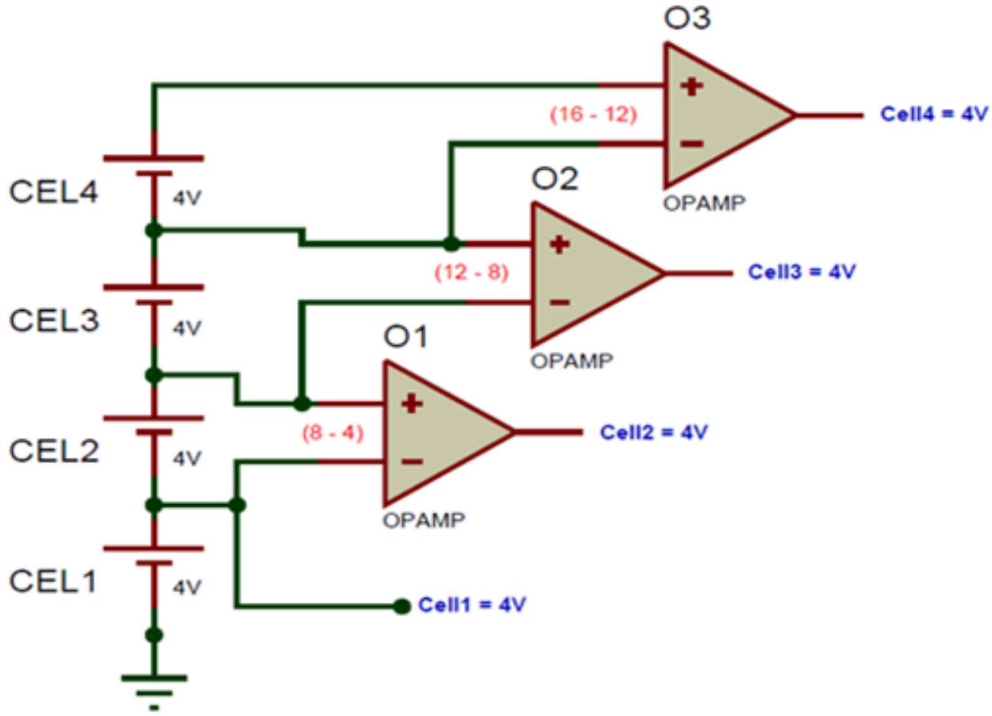



Figure 3.3 op-amp cell voltage measuring circuit.

It is difficult to measure individual cell voltage in a series connected battery pack since the reference point remains the same. The cell voltage that has one end connected to the ground could be measured directly. But when we read the voltage of a cell that is not directly connected to the ground it gives the voltage of that cell along with the voltages of the cells preceding it. The Figure 3.4 illustrates the difficulties faced while measuring the individual cell voltage in cells connected in series.

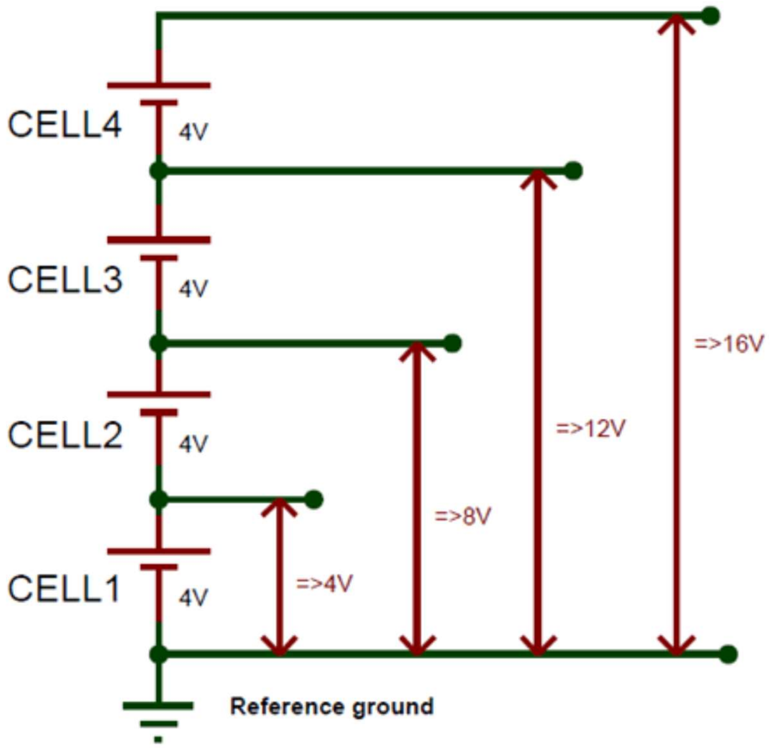



Figure 3.4

## 3.4 Current measurement

Current measurement is very important for battery overcurrent protection. In the proposed work, current measurement is done by ACS712 Hall Effect current sensor. It is a cheap, small package and accurate AC and DC current sensor, fitted for industrial and commercial use. Here, an LED in series with a resistor of value 1kΩ is considered as load. The output of the sensor is voltage proportional to the DC primary sensed current. The value read by a microcontroller is converted into current and displayed on the LCD. Figure 3.5 shows the connection of ACS712 with the battery pack and Arduino UNO.

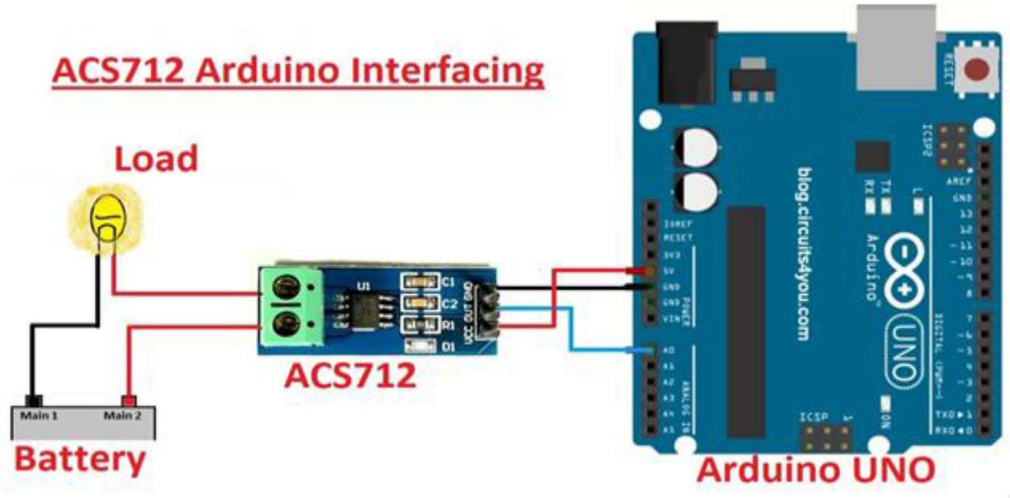



Figure 3.5 shows an Arduino based current sensing circuit.

## 3.5 The Energy Management System (EMS)

The EMS manages the energy distribution between the lithium battery and the supercapacitor based on real-time load demand. The system continuously monitors the load current. The PIC16F877A controls relay switch to selectively connect or disconnect the supercapacitor based on rapid changes in load demand.

### 3.5.1 Components:

*PIC16F877A Microcontroller:*

Acts as the control unit to manage energy flow between the lithium battery and supercapacitor. Monitors the load using current sensor and makes switching decisions.

*Lithium-Ion Battery:*

Provides the primary energy storage for long-term, steady power demands. Has a higher energy density, ideal for continuous power supply but slower in response to rapid power demand.

*Supercapacitor:*

Provides short bursts of power when the load experiences rapid changes, thanks to its fast charge-discharge characteristics. Protects the battery from high current spikes and fast cycling, extending its lifespan.

*Current Sensor:*

Measure the load current and voltage in real time. This data is sent to the microcontroller.

*Relay:*

Controlled by the PIC16F877A to connect or disconnect the supercapacitor from the load.

**3.5.2 Operation Flow:**

*Normal Power Demand:*

Under normal power demand, when appliances are running at their typical load (e.g., lights and fans), the lithium-ion battery supplies energy smoothly. The supercapacitor remains disconnected, conserving its charge.

*Sudden Power Demand (High-Frequency Loads):*

When a high-power appliance like an air conditioner or a refrigerator motor starts up, the load demand suddenly spikes. The EMS detects the rapid increase in current demand (high-frequency power requirement) through the current sensor connected to the PIC16F877A. The microcontroller switches the supercapacitor into the circuit using a Relay switch to handle the power surge.

*Stabilized Power Demand:*

After the surge passes and the load returns to normal levels, the PIC16F877A disconnects the supercapacitor, and the lithium-ion battery resumes supplying steady power. The battery is not exposed to sudden power spikes, which helps to extend its lifespan.

# Chapter 4: Implementation

## 4.1 Introduction

This chapter shows the practical implementation of the designed project to achieve the specified objectives of the project.

### 4.2 Battery voltage measurement

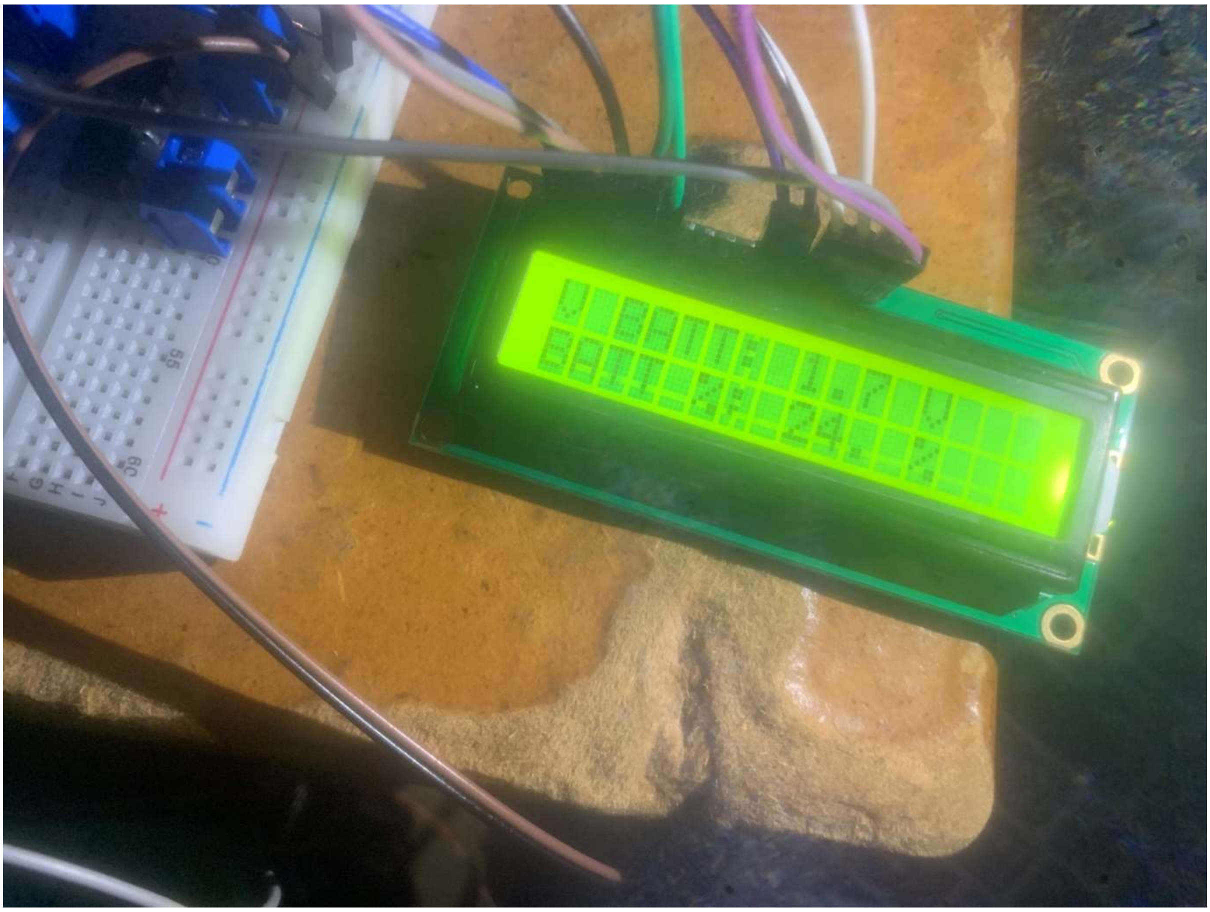


Figure 4.1 shows the breadboard testing of a voltage measuring circuit. The measured battery voltage is displayed on an LCD as V BATT and the microcontroller calculates the battery percentage and also display it as BATT %. The microcontroller continues to monitor the voltage so that the charge MOSFET is activated when the battery voltage reaches the minimum voltage,

and also activates the discharge MOSFET when the battery reaches its maximum threshold voltage.

## 4.3 Supercapacitor voltage measurement

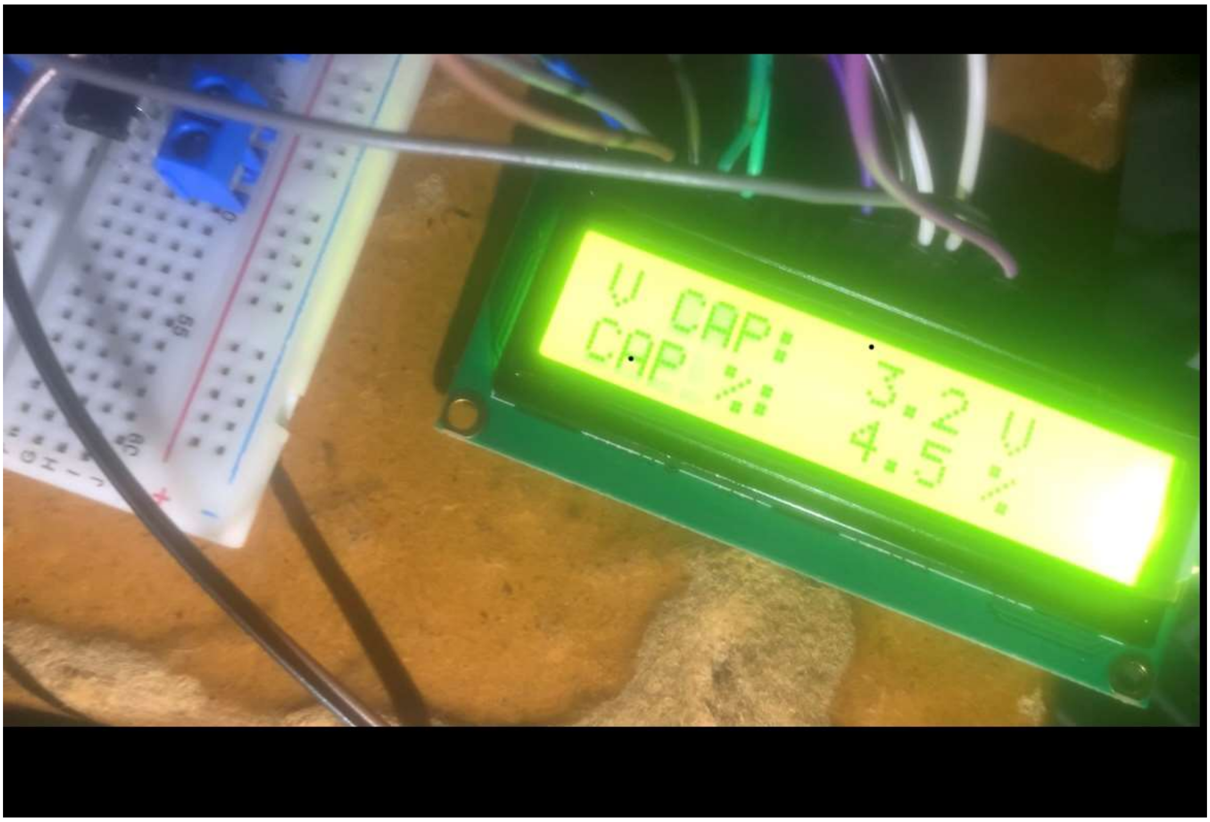



Figure 4.2 shows an LCD displaying supercapacitor voltage and its percentage. The supercapacitor voltage is continuously monitored so that the microcontroller decides if it is possible to kick in the supercapacitor when high power demand situations occur. If the capacitor voltage is too low and the battery voltage is above 50%, the battery provides the power. If the battery voltage is below 25% and supercapacitor voltage is below 25% the system enters into alarm mode. If the battery voltage and capacitor voltage is above 50%, the supercapacitor is kicked in in times of high-power load surges.

## 4.4 Load current measurement

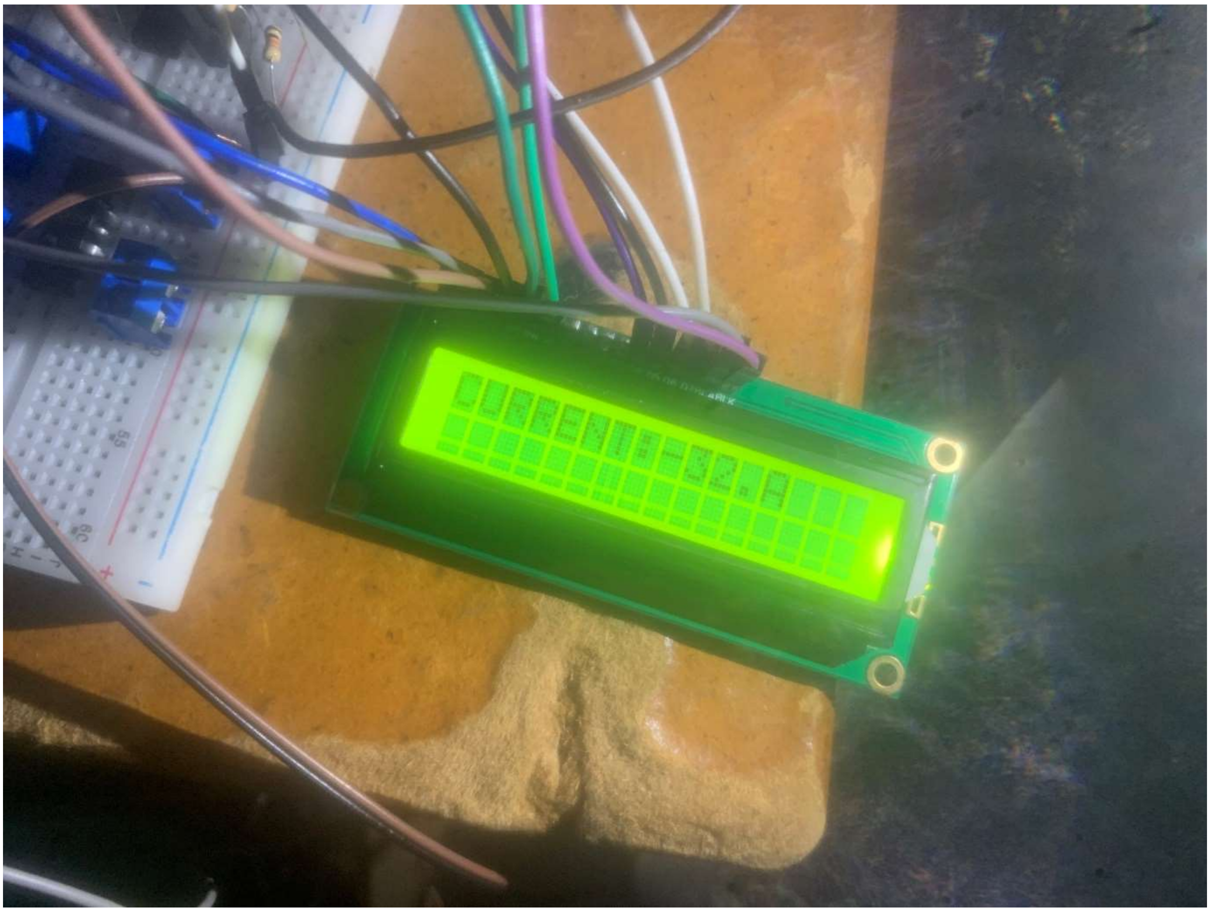


Figure 4.3 shows an LCD display of load current. This load current is continuously monitored so that when a certain threshold is reached, when a sudden spike in demand is detected, the PIC16F877A activates the Relay, connecting the supercapacitor to the load. The supercapacitor quickly supplies the required additional power, relieving the lithium battery from handling the sudden load increase. Once the load stabilizes and returns to normal levels, the PIC16F877A disconnects the supercapacitor from the circuit. The lithium battery resumes supplying steady power to the load.

## 4.5 The battery supercapacitor hybrid energy storage system

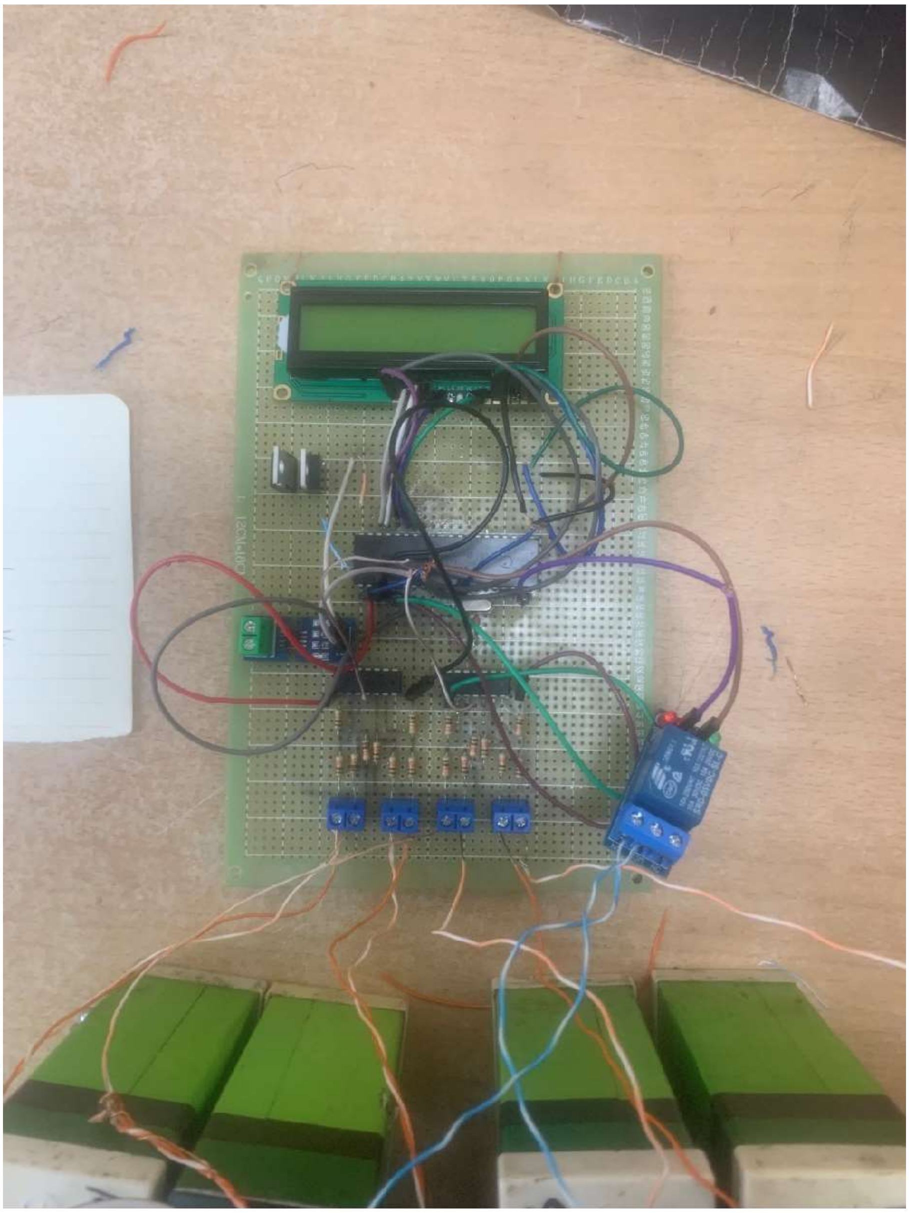


Figure 4.4 shows the battery supercapacitor Hybrid Energy storage system. The circuit is showing the heart of the energy management system, the PIC 16f877A

microcontroller, the ACS712 load current sensor, the voltage sensing circuit and the Relay switch.

## 4.6 Conclusion

In conclusion, the implementation of the BSHESS effectively demonstrates the benefits of combining a lithium-ion battery and a supercapacitor for energy storage. The system, controlled by a PIC16F877A microcontroller, efficiently distributes energy, with the supercapacitor handling rapid load changes and the lithium battery providing steady power for long-term needs. This design improves energy efficiency and extends battery life by reducing stress during high-power surges.

# Chapter 5: Recommendations

## 5.1 Strengths:

*Efficient Energy Distribution:*

The system optimally distributes energy between the lithium battery and the supercapacitor. The supercapacitor handles high-frequency load variations, reducing stress on the lithium battery during rapid load changes.

*Extended Battery Lifespan:*

By engaging the supercapacitor during power surges, the lithium battery is protected from frequent charge/discharge cycles, improving its lifespan.

*Cost-Effective Solution:*

The PIC16F877A is an affordable microcontroller, making the overall system more economical, especially for small-scale renewable energy setups like solar-powered homes.

## 5.2 Weaknesses:

*Limited Processing Power:*

The PIC16F877A is a relatively basic microcontroller with limited processing power, which may be a bottleneck if more advanced energy management algorithms or additional sensors are needed in the future.

*Lack of Advanced Power Monitoring:*

The system may lack advanced power monitoring features (like predictive load forecasting or AI-driven optimizations) due to the constraints of the PIC16F877A, potentially limiting its ability to adapt to complex load patterns.

*Limited Expandability:*

While the PIC16F877A is suitable for basic control tasks, it has limited expandability in terms of handling larger or more complex energy systems with more storage elements, loads, or additional renewable energy sources.

## 5.3 Recommendations:

*Upgrade to a More Powerful Microcontroller:*

If the project is scaled up or requires more advanced features (such as multiple energy sources or real-time data analysis), consider upgrading to a more powerful microcontroller, such as a PIC18F series or ARM-based microcontroller, to handle more complex algorithms and expand system capabilities.

*Improve Power Monitoring:*

Add more sensors to monitor various parameters like temperature and state of charge (SOC) for both the battery and supercapacitor. This would provide more detailed insights into the energy flow and help fine-tune the system for better performance.

*Consider Power Electronics Improvements:*

Explore using more efficient power electronics components (such as low-loss MOSFETs or optimized converters) to reduce energy loss during the switching process and further improve system efficiency.

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