International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347 - 6435 (Online) Volume 14, Issue 2, February 2025)

Multi-Mode Battery and Supercapacitor based Hybrid Energy Storage System for Electric Vehicle

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***Abstract*— The increasing demand for high-performance and energy-efficient electric vehicles (EVs) has driven significant advancements in hybrid energy storage systems (HESS). A multi-mode battery-supercapacitor hybrid energy storage system (MM-HESS) has emerged as a promising solution to enhance vehicle efficiency, lifespan, and energy management flexibility. By integrating multiple operational modes, MM-HESS intelligently switches between battery-dominant, supercapacitor-dominant, and hybrid operation based on driving conditions. This approach optimizes energy utilization, improves regenerative braking efficiency, and reduces stress on the battery, thereby extending its lifespan. This paper provides an MM-HESS architectures, operational strategies, control methodologies, and energy management systems for EV applications.**

***Keywords*— EV, Ultracapacitors/Supercapacitors, Battery Charger, Power, Capacity, ESS, Current, Voltage.**

I. INTRODUCTION

Electric vehicles (EVs) are rapidly emerging as a sustainable alternative to conventional fossil fuel-powered transportation, driven by the urgent need to reduce carbon emissions and dependence on non-renewable energy sources. However, a major challenge in EV adoption is the limitation of battery technology, which struggles to simultaneously provide high energy storage, fast charging, and long cycle life. Lithium-ion batteries, widely used in EVs, offer high energy density but suffer from slow charge-discharge rates, limited lifespan under high-power demands, and performance degradation over time. These limitations necessitate the development of hybrid energy storage systems (HESS) that can efficiently manage energy distribution and improve vehicle performance.

Supercapacitors have emerged as a complementary technology to batteries due to their high-power density, rapid charge-discharge capability, and extended lifespan. Unlike batteries, which store energy through chemical reactions, supercapacitors store energy electrostatically, allowing them to deliver and absorb high power within seconds. This makes them particularly suitable for handling transient power demands such as acceleration and regenerative braking. By integrating batteries and supercapacitors into a hybrid energy storage system, EVs can achieve a balance between high energy density and rapid power delivery, leading to improved efficiency and longevity.

A traditional battery-supercapacitor hybrid energy storage system (HESS) typically operates in a single-mode configuration, where power distribution between the battery and supercapacitor is predetermined. However, real-world driving conditions involve highly dynamic energy demands that require a more flexible approach. This has led to the development of multi-mode hybrid energy storage systems (MM-HESS), which dynamically switch between different operational modes based on driving conditions, energy availability, and power demand. MM-HESS enables optimal power flow management, reduces battery stress, and enhances regenerative braking efficiency.

In MM-HESS, three primary operational modes are utilized: battery-dominant mode, supercapacitor-dominant mode, and hybrid mode. During steady-state cruising, the system primarily relies on the battery for energy supply. When high-power demands arise, such as during

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acceleration, the system shifts to supercapacitor-dominant mode to handle peak power requirements. In hybrid mode, both the battery and supercapacitor work together to optimize energy utilization. This intelligent switching between modes minimizes energy losses and extends the lifespan of both storage components.

The successful implementation of MM-HESS depends on an efficient energy management system (EMS) that governs power distribution and mode selection. Advanced control strategies, including rule-based, optimization-based, and artificial intelligence (AI)-based approaches, are employed to enhance energy utilization. AI-driven techniques, such as machine learning and deep reinforcement learning, have shown promise in predicting driving patterns and optimizing real-time power allocation. These strategies not only improve vehicle efficiency but also contribute to the sustainability of EVs by maximizing regenerative energy recovery.

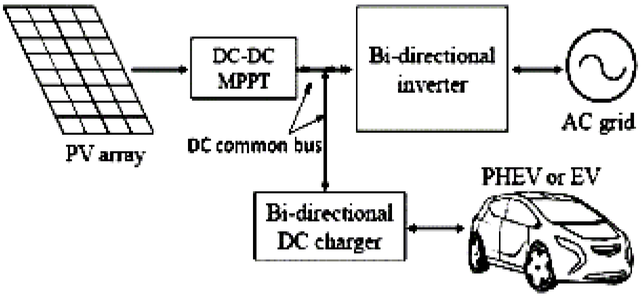

Figure 1: PV based charger

Ongoing research is focused on improving MM-HESS through innovations in supercapacitor materials, power electronics, and predictive energy management algorithms. The development of hybrid supercapacitors with higher energy density aims to bridge the gap between traditional batteries and supercapacitors. The use of wide-bandgap semiconductors, such as silicon carbide (SiC) and gallium nitride (GaN), in power converters enhances system efficiency and reduces energy losses. Additionally, vehicle-to-grid (V2G) integration is being explored to enable bidirectional energy transfer, allowing EVs to act as energy storage units for the grid.

As the demand for EVs continues to grow, MM-HESS is expected to play a crucial role in enhancing performance, extending driving range, and reducing overall energy consumption. By intelligently managing energy flow and adapting to real-time driving conditions, MM-HESS offers a promising solution to the challenges faced by conventional battery-based EVs. With ongoing advancements in power electronics, AI-driven energy management, and high-performance storage materials, MM-HESS has the potential to become a standard feature in next-generation electric vehicles, paving the way for a more efficient and sustainable future in transportation.

II. PROPOSED MODEL & METHODOLOGY

The proposed model and methodology description is as following-

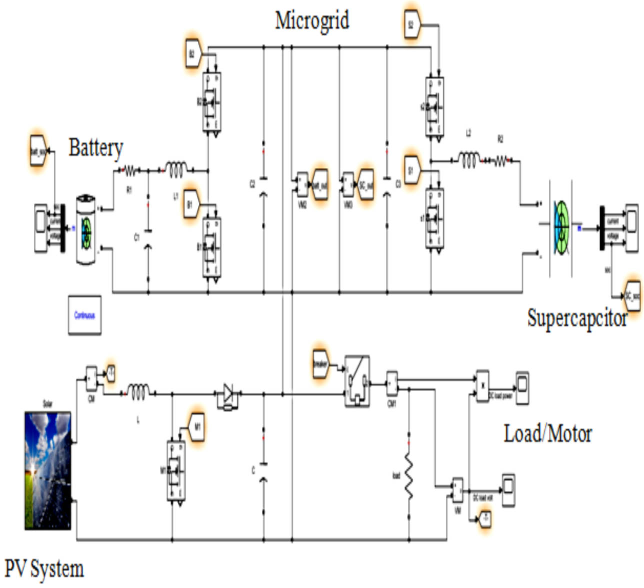

Figure 2: Proposed Model

Figure 2 is showing present HESS EV model. This model consist various sub models which is described in details.

Solar Power-

Photovoltaic solar panels use the energy they capture from the sun to produce electricity. 96 solar cells are packaged and connected into a photovoltaic (PV) module. The photovoltaic array of a photovoltaic system, which

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produces and provides solar power for commercial and residential uses, is made up of photovoltaic modules. The core power conversion component of a PV generating system is the photovoltaic (PV) array, which is made up of modules.

MPPT Techniques

DC-DC Transverse Capacitor In a renewable energy system, a bidirectional dc to dc converter is a crucial component for connecting the storage devices between the source and the load to ensure a constant flow of electricity. Bidirectional converters are also used in electric cars to transfer power from the battery to the motor. By employing a particular switching technique and phase-shifted control approach, bidirectional dc to dc converters may regulate the flow of power in both directions between two dc sources and a load. As a result, surplus energy is created and can be stored in batteries or super capacitors.

Battery

A battery is a device that has at least one electrochemical cell and is used to power electrical devices like flashlights, mobile phones, and electric cars. A battery's positive terminal serves as the cathode and its negative terminal serves as the anode while it is generating electricity. The source of electrons that will flow via an external electric circuit to the positive terminal is the terminal that is marked negatively. When a battery is linked to an electrical load outside of it, reaction transforms high-energy reactants into lower-energy products, and the difference in free energy is transferred as electrical energy to the outside circuit. Clearly, the term "battery" originally referred to a device made up of many cells, but its use has now expanded to include devices constructed out of a single cell.

Ultra-High Capacitor

A supercapacitor (or ultracapacitor) differs from a standard capacitor in two key ways: its plates successfully have a much higher surface area and the space between them is much less because the separator between them functions differently than a traditional dielectric. Despite the fact that the terms "supercapacitor" and "ultracapacitor" are commonly used interchangeably, there is a difference: since they are typically made from different materials and arranged in somewhat different ways, they store different amounts of energy.

III. SIMULATION RESULTS

The design and analysis of the proposed model is performed using MATLAB software.

Battery Discharging Mode- When the battery is fully charge then it supplies the power to the load or motor, so battery is in the discharging mode.

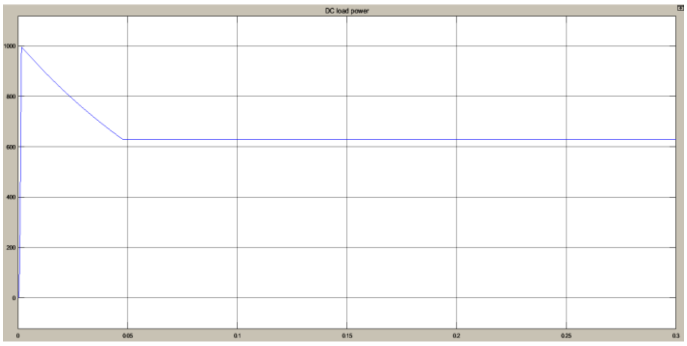

Figure 3: DC Load Power

Figure 3 is presenting the DC load power graph. The value of the DC load power is 630W.

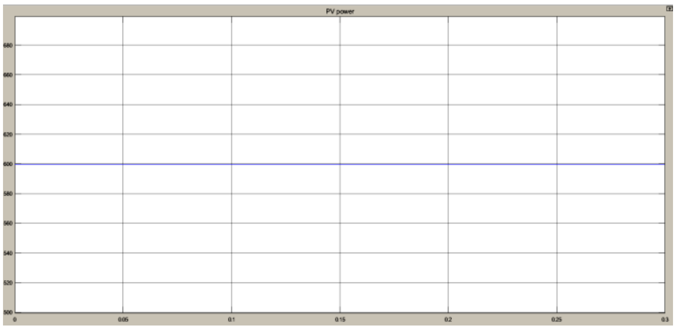

Figure 4: Solar Power

Figure 4 is presenting the solar power graph. The collected solar power value is 600W.

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Load Shedding Mode (LSM)- When the battery is fully discharge then the load is disconnected and battery is stop giving the power to the load.

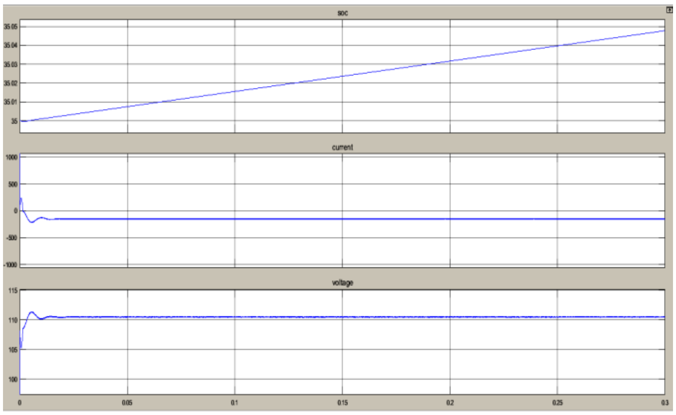

Figure 5: Battery Performance

Figure 5 is presenting the performance of the battery in terms of the state of charge, voltage and current. At the load shedding mode, the state of charge of the battery is approx 30%.

Battery Charging Mode- As the battery is fully discharged, and then the solar power is start to charge the battery. Now battery charges up to the more than 80%

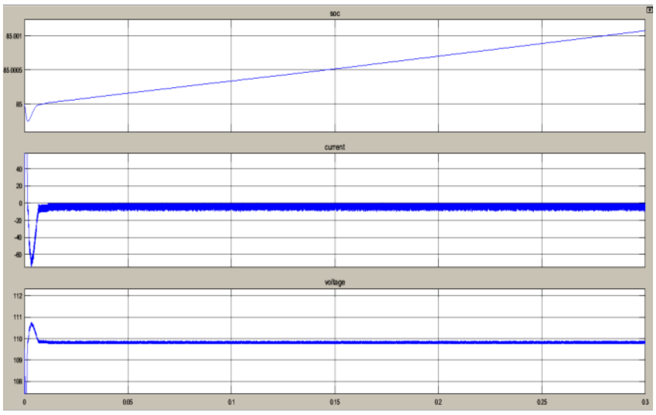

Figure 6: Battery performance

Figure 6 is presenting the battery performance during the charging state. The battery is charging and as completed charge, its start to give power to the load or motor.

Off-MPPT Mode- When the battery is fully charges then the MPPT is off. MPPT is used to track maximum power in the less time. After completion it off and when battery is discharge then it again presents in the ON state.

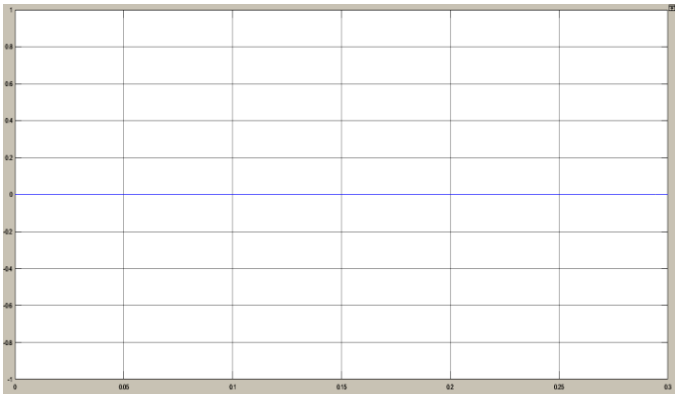

Figure 7: MPPT output

Figure 7 is presenting the MPPT output, at the mode of off MPPT; it shows at the 0 state.

Table 1: Result Comparison

Sr No.	Parameters	Previous Work	Proposed Work
1	State of Charge (SOC)	80%	95%
2	Mode of operation	2	4
3	Lithium-ion battery voltage	4V	12 V
4	Temperature (^{0}C)	43	35
5	Battery Current	60A	100A

Table 1 is presenting the result comparison of the previous and the proposed model simulation results. The

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overall state of the charge of the battery and the super capacitor is approx 95%, while previous it is 80%. The battery current achieved is 100A while previous it is 60A. Proposed model using the solar system to collect the power while in the previous work, it's not mention. The proposed model used MPPT control technique; which is less complex than the previous model control technique. Therefore, proposed model is better than the previous model based on the simulation results.

IV. CONCLUSION

This research presents a hybrid energy storage system that combines a lithium-ion battery with a supercapacitor for use in electric vehicle applications. An electric vehicle storage system consists of two complementing energy sources: chemical batteries and ultracapacitors/supercapacitors. Ultracapacitors are used to increase the extra storage capacity in a hybrid energy storage system (HESS). For simulation, MATLAB/SIMULINK software is used. Simulation results show a considerable improvement in the present model's performance compared to the old model.

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