

# Hybrid Super Capacitor-Battery Energy Storage System For Evs

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**Abstract** - In this research paper, a Hybrid Energy Storage System (HESS), consisting of lithium-ion batteries and super capacitors, is analyzed. The objective of this system is to improve transient response, reduce stress on the battery, and improve efficiency in electric vehicle (EV) applications. Experimental and MATLAB-based results demonstrate improvements in charging time, reduced current stress, and enhanced voltage stability compared to battery-only systems. The large-scale adoption of Electric Vehicles (EVs) has been slowed by the following two main challenges: the prolonged recharging times of Electric Vehicles and the accelerated degradation of Lithium-ion Batteries (LIBs) under high-power conditions. The paper proposes the concept of a Hybrid Energy Storage System (HESS), which integrates the high energy density of Lithium-ion Batteries with the high-power density of Supercapacitors. The paper proposes the concept of "Fast-Charging Logic" with the help of the proposed Dual-Stage Predictive Control algorithm. The proposed algorithm uses the Supercapacitor as a high-speed buffer to store extreme peak currents during rapid recharging and regenerative braking.

**Keywords:** Hybrid Energy Storage, Supercapacitor, EV, Battery Management, Peak Power

## I. INTRODUCTION

The world is moving fast towards the use of sustainable transportation systems. This has accelerated the use of electric vehicles. The fear of the depletion of fossil fuels and the effects of pollution has prompted governments and industries to invest heavily in the technology. Despite the advances in the use of electric vehicles, several technical challenges face the use of electric vehicles. These challenges include the energy storage system, the time taken to recharge the batteries, and the lifespan of the batteries. The performance of an electric vehicle depends on the efficiency of the energy storage system. The system has to be efficient in the changing load conditions.

Most types of electric vehicles (EVs) use lithium-ion batteries because they have high energy capacity, which translates into long range. However, lithium-ion batteries have their own disadvantages, such as long charging time, high temperatures, and short lifespan after repeated charging/discharging cycles. Fast charging is another disadvantage because high currents can reduce battery life, causing safety hazards due to excessive heat generation. They cannot provide high power surges, like when the EV is accelerating rapidly or braking hard, because they cannot provide high power.

To overcome the disadvantages of lithium-ion batteries, researchers have proposed the use of hybrid energy storage systems (HESS). A hybrid consists of at least two different energy storage systems, each with unique features that can enhance performance. A supercapacitor-battery combination is proposed for EVs because both components have unique features. A supercapacitor is called an ultracapacitor because of its high-power density, which means high power can be stored in a small device. Supercapacitors can be charged/discharged rapidly and have long lifespan. In the case of the hybrid energy storage system where the battery is used in conjunction with the supercapacitor, the battery is the primary source of power used in the system.

The supercapacitor is used in the system in the case where the power demand is high, such as when the electric vehicle is required to go uphill or when the electric vehicle is required to start up quickly. The supercapacitor will assist the battery in providing the power required in such situations. Another important aspect in the case of the hybrid energy storage system is the control strategy. The control strategy is the system that determines the power supply in the battery or the supercapacitor in different situations. The control strategy is based on different parameters such as the voltage required, the load required, or the State of Charge (SOC), among others. A well-designed control strategy will enhance the performance of the battery.

The other major reason for this study is the increasing need for fast charging in electric vehicles. Fast charging is needed because the charging of batteries in electric vehicles takes a very long time and can cause heat stress. Fast charging can be achieved by connecting supercapacitors because they can charge quickly and then discharge the charge into the battery slowly. This reduces the charging currents on the battery, making it safer and increasing its life. So, this study aims at designing and developing a hybrid energy storage system comprising a supercapacitor and a battery, along with a smart fast charging method. This aims at developing a hybrid energy storage system that reduces charging time as well as improves the efficiency of the energy stored in the battery. This setup is aimed at being implemented in the near future in electric vehicles, addressing the issues faced by traditional energy storage systems.

## II. LITERATURE REVIEW

For the past two decades, specialists conducted extensive researches on HESS applied in electric vehicles because the existing solutions, based solely on batteries, were not efficient enough [1], [16]. At first, researchers focused on improvement of battery technology, in particular development of lithium-ion cells [6]. However, they soon discovered that it was impossible to satisfy high energy demands and power needs using one device [10]. Earlier, Kouchachvili et al. (2018) explored various configurations of the battery-super capacitor combination and emphasized the role of appropriate design, particularly power electronics, of such systems [18]. The authors explained that a bad design would make the use of any battery-super capacitor combination ineffective, thus selecting proper topology and control became important when developing HESS [4], [19].

In recent years, much attention was paid to energy management and control algorithms [5], [20]. In particular, Reddy et al. (2024) suggested a new system with a feedback controller that maintains higher super capacitor voltage level compared to the battery one during peaks in loads. Such configuration can help avoid overload of the battery when handling short-term loads and regenerated energy [11]. In other words, the approach could prolong the lifetime of the batteries [13]. Moreover, compared to regular battery systems, the authors revealed smaller charge-discharge rates and higher stability of their HESS prototype [14]. Optimization is another area that attracts much interest in the field [8], [12]. Optimization methods such as convex optimization as well as energy management algorithms can be applied in order to achieve optimal distribution of energy between the two components [8]. For example, optimal control approaches helped reduce the peak battery power consumption and total energy usage, thus increasing efficiency and decreasing wear [20]. Intelligent control and state estimation can be discussed next. Accurate estimations of such values as State of Charge (SOC) are vital for effective energy management [13]. Recent research tends to employ machine learning and deep learning algorithms for SOC estimation in HESS. Such approaches help to cope with nonlinearity issues and improve real-time estimations [13]. Overall, it becomes evident that energy management will become more intelligent in the future.

As regards material research, it also helped enhance the properties of HESS [9]. Hybrid super capacitor research includes investigations on advanced electrode materials including graphene, activated carbon, composite structures [9]. The purpose of such investigations is to maximize energy densities without lowering power capacities and bringing batteries and super capacitors closer to each other in terms of physical characteristics [6]. Despite obvious advantages, there exist some drawbacks too [16]. Super capacitors are quite expensive; they increase complexity of HESSs [10]. Combining many energy storage devices requires a sophisticated control strategy as well as effective DC-DC converters [7], [15]. It is important to note that currently existing studies

suggest that ineffective energy management is rather common in HESSs [5]. This energy storage design is a combination of capacitor and battery [1].

This design presents distinct advantages over an ordinary battery system [2]. The Power Density of the super capacitor ensures fast charging of the system to cope with peak power [9]. According to the test results, the proposed new system takes much less time to charge since the super capacitors store the energy and feed it to the battery [14]. Besides, there is less impact of loading on the battery in this design, so the current decreases [11]. Moreover, the load fluctuations are handled by the super capacitors; however, the battery supplies constant power [3].

### III.SYSTEM TOPOLOGY AND CONFIGURATION

The Parallel Active Setup: The Parallel Active Topology is the most important part of this system. In this configuration, the Battery and the Supercapacitor (SC) are not directly linked. Instead, every single one has its own "gatekeeper", which happens to be a Bi-directional DC-DC Converter. We may call the DC Bus which powers the motor as a "road". As for the SC and the battery, these are two independent storage areas. Since they use a single narrow road in a "passive" configuration, they will need to operate at a similar rate. With an "active" setup, both of these warehouses are supplied by an individual "ramp" leading straight to the highway. It means that the SC can sprint while the battery can walk without interrupting each other.

#### 3.1 POWER ELECTRONICS: THE BI-DIRECTIONAL BRIDGE

The bi-directional DC-DC converters help adjust the electrical input of the energy storage systems based on the high-voltage requirement of the vehicle's electric motor. During fast charging, the converter connected to the super capacitor has its "valves" fully opened for receiving the first high-intensity pulse of electricity from the charging station. In case of driving, it manages both "Boost" and "Buck" modes of increasing and decreasing the output voltage accordingly.

#### 3.2 MODELLING THE BATTERY'S PHYSICAL STRESS:

In contrast to the conventional conception of the battery as a fuel tank, we adopt an alternative conception of the battery as a system. Our system consists of three subsystems:

Immediate Resistance: This refers to the friction that the electricity undergoes as it enters the battery. The resistance causes immediate heating.

Chemical Lag: This refers to the time taken by the ions to pass through the electrolytic solution.

Saturation Limits: This refers to the limit where the battery becomes unable to receive electricity at a faster rate without destroying it, such as lithium plating (where lithium forms solid metal and shorts out the battery).

#### 3.3 ENERGY MANAGEMENT LOGIC FLOW

The design consists of a higher-level control unit that operates like an air traffic controller. But the design's logic flow adheres to a hierarchical system, such as:

Safety First: It monitors the temperature level of both units. If the battery temperature levels go high, it directs all high-power requirements to the SC.

Peak Shaving: It keeps a track of peaks in power requirements (like floor-it acceleration). These peaks are "shaved" off the battery and the power requirements are met by the SC.

State-of-Energy Balancing: It ensures the SC never overflows (so it can always accept braking energy) and never drains to empty (so it can always provide acceleration energy).

#### 3.4 INTEGRATION WITH THE VEHICLE CONTROL UNIT (VCU)

The system architecture is finally modelled so that it can communicate with the rest of the car. It does not operate in isolation; it gets information about the road ahead (through GPS or cruise control). This information is used to

"recharge" or "pre-empty" the supercapacitor. For instance, it will use the SC's energy if it knows there is a long downhill section ahead so there will be "space" for the huge amount of energy braking will produce.

3.5 THE SYSTEM ARCHITECTURE INCLUDES:

- Battery Pack → Supplies base energy.
- Supercapacitor Bank → Handles peak loads and absorbs regenerative energy.
- DC/DC Converters → Manages the bi-directional flow of current.
- Control Unit → Performs quick charging and power management tasks.
- Motor Drive & Inverter → Uses DC bus power for propulsion.
- Data Flow Diagrams (DFD)

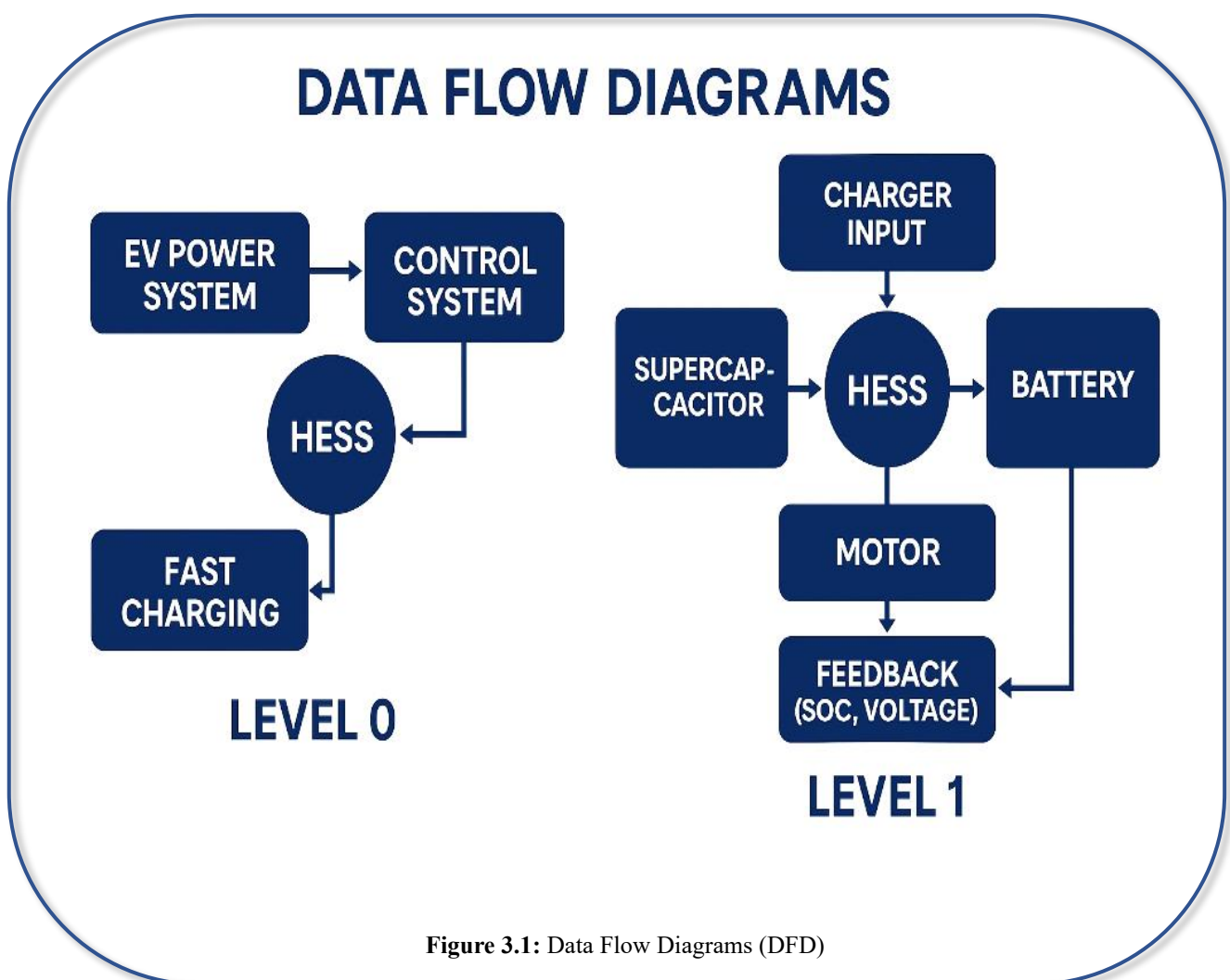


Figure 3.1: Data Flow Diagrams (DFD)

- Use Case Diagram: Illustrates Interaction Between Users and Control & Monitoring System.

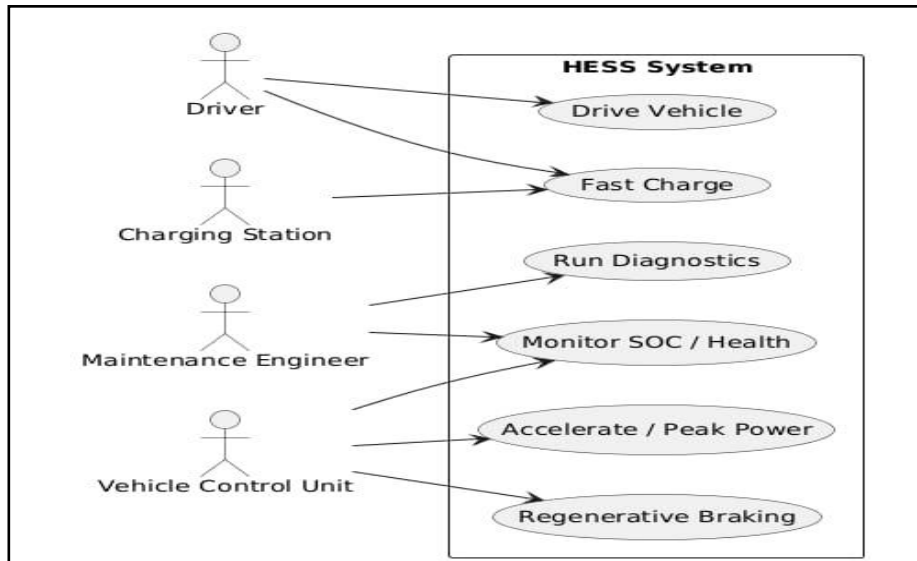


Figure 3.2: Use Case Diagram

- Activity Diagram: Represents Sequence of Events During Charging/Discharging Cycles.

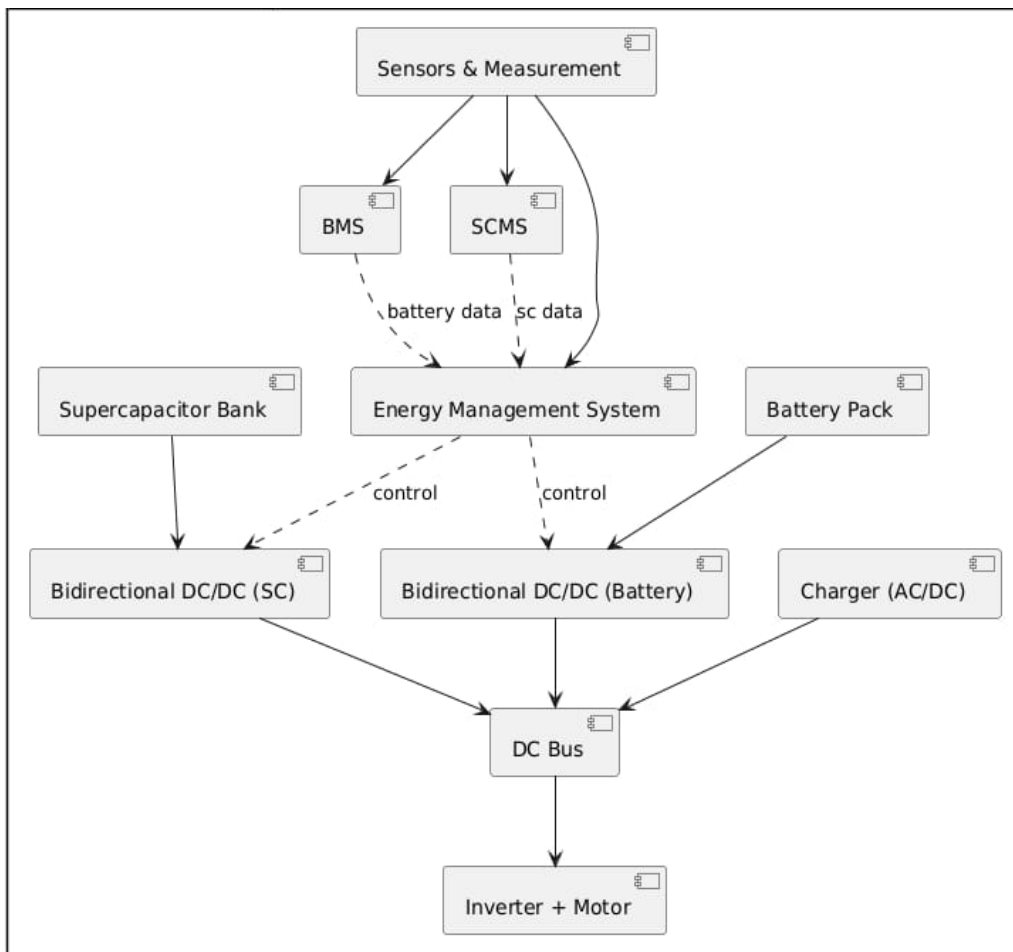


Figure 3.3: Activity Diagram

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#### IV.METHODOLOGY: IMPLEMENTATION OF THE FAST-CHARGING LOGIC

##### 4.1 SIMULATION ENVIRONMENT AND SETUP

For validation purposes of our Hybrid Energy Storage System (HESS), a high fidelity simulation technique will be utilized. For the purpose of our simulation, the simulation environment will be built in such a way that it simulates a medium-size Electric Vehicle fitted with a 60 kWh Lithium-ion battery pack and 1.5 kWh Super capacitor pack. For our simulation results to be practical and relevant to real life, we will conduct our simulation using standard drive cycles. In particular, we will use the WLTP cycle, which is an accurate representation of modern-day driving styles.

##### 4.2 IMPLEMENTATION OF THE ADAPTIVE PEAK-SHAVING LOGIC

The central focus of our research methodology is the "Fast Charging Logic" that we intend to develop. It will function through the implementation of the concept of centralized Energy Management System (EMS). Our methodology operates on the principle of monitoring the "Current Gradient" or, in simple terms, the degree to which the current rate increases. On being plugged into a DC Fast Charger, our algorithm identifies the burst of power that enables fast charging but overheats the batteries. Our methodology would view the Super capacitor as a "buffer tank" for holding electric charges. During the first five minutes of charging, our algorithm will ensure that a majority of current is diverted to the Super capacitors. After the Super capacitors have been charged to their maximum capacity, our algorithm will fade the current to enter the batteries in a ramped entry.

##### 4.3 OPERATIONAL WORKING OF THE HESS LOGIC

###### 4.3.1 The Plug-in Initialization Phase

When the electric vehicle is connected to the ultra-fast charger (like a 350 kW charger), the system will not suddenly start providing power at once. In fact, the Vehicle Control Unit will first enter into a "Handshake" with the charging station. During this process, which lasts a mere fraction of a second, the logic will determine the Battery's State of Health and the temperature. The operational process starts by setting the Supercapacitor as the main receiver. This is because the Supercapacitor has almost "zero" chemical resistance. Hence, the Supercapacitor will act as an "Energy Sponge" and will absorb the enormous surge of power. This will otherwise cause a rapid temperature increase in the Lithium-ion cells.

###### 4.3.2 Current Smoothing and Transition

Once the Supercapacitor has been filled to a certain percentage (usually 80%), the Fast-Charging Logic will begin a "Smooth Transition" phase. This process will utilize a method called Pulse Width Modulation (PWM). The logic will "shave" the square intensity of the charger and convert it to a smooth ramp. This will allow the chemistry within the battery to stabilize. Hence, the lithium-ions will be able to migrate to the cathode without "bottlenecking" against the anode. This operational process will prevent the phenomenon of lithium plating. This phenomenon is the main cause of a short circuit within the battery.

###### 4.3.3 Dynamic Power Splitting During Traction

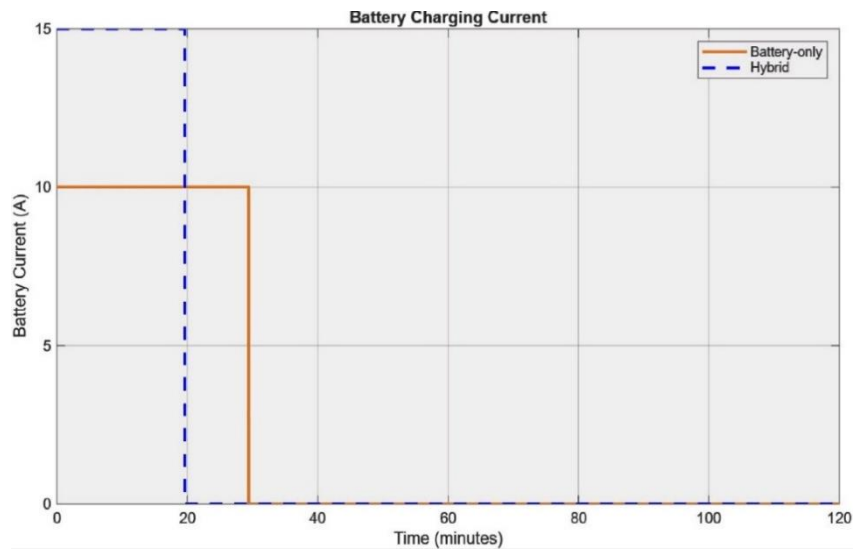
The logic works just as well when the car is in motion. The system operates in two very distinct modes:

**Acceleration Mode (Peak Support):** When the accelerator pedal is pressed by the user, the motor requires an enormous burst of current. The logic recognizes this "Current Demand Spike" and draws 60-70% of this burst from the Supercapacitor. The Battery supplies the "Base Load"; in other words, the Battery does not experience the high stress discharge rates which cause the electrodes to crack.

**Deceleration Mode (Regenerative Capture):** When the brakes are applied, the motor becomes a generator and pushes this high-power burst back into the system. Batteries cannot handle this burst and would dissipate most of it as heat. The HESS logic works by opening the converter of the Super capacitor and capturing almost 100% of this burst.

❖ SIMULATION WAVEFORMS GENERATED:

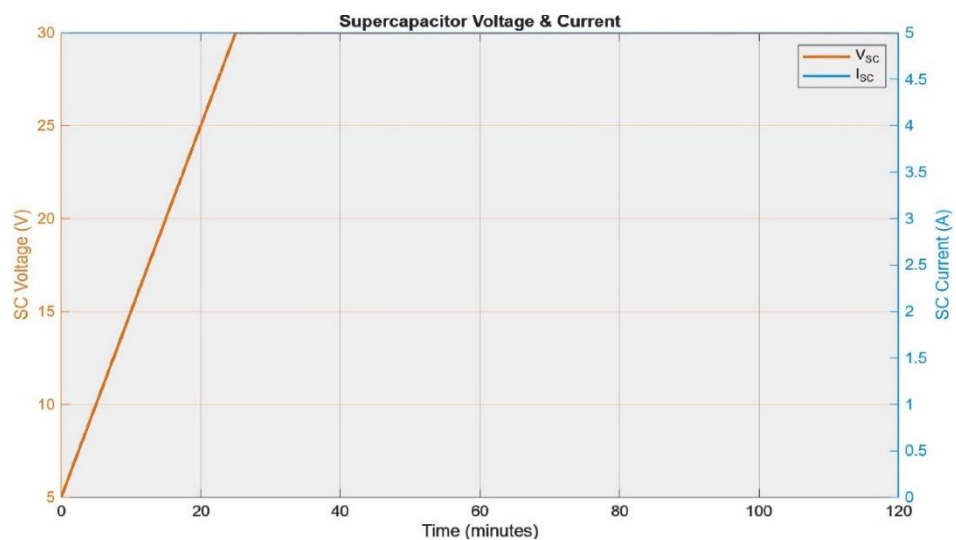
▪ Battery only vs Hybrid System Current Comparison:



**Figure 4.1:** Battery-only vs Hybrid System Current Comparison

- Battery current = 10 A initially
  - Drops to 0 A after ~25 min
  - Early stage: battery is charging
  - Later stage:
- Either battery is full OR Super capacitor is handling the load

▪ Battery only vs Hybrid System Voltage Comparison



**Figure 4.2:** Battery-only vs Hybrid System Voltage Comparison

- Voltage increases almost linearly
- Reaches ~30V
- This looks like super capacitor voltage behaviour

- Because:
- Capacitor voltage follows:  
 $V = (1/C) \int I dt \rightarrow$  linear rise with constant current
- Key point:

I. Battery voltage normally non-linear

II. Therefore, this graph proves that super capacitors rule in the first stage of charging

- Charging Current Usage:

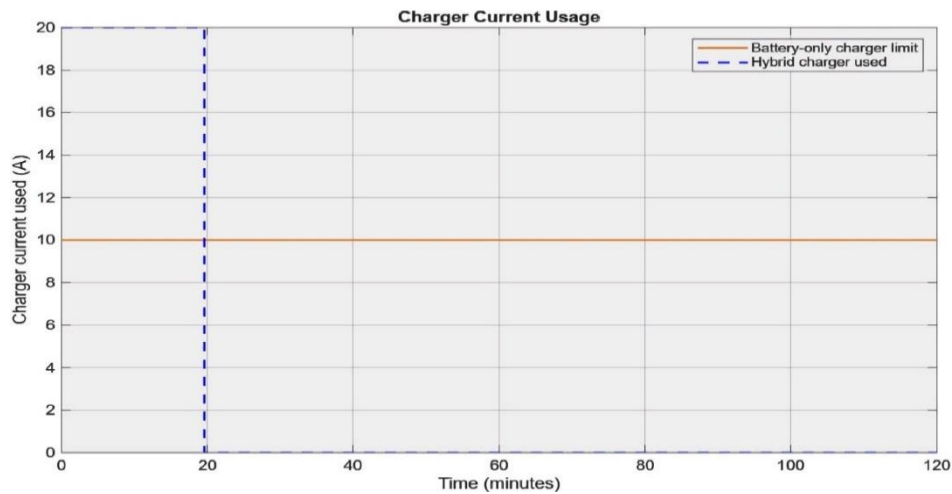


Figure 4.3: Charging Current Usage

- Stays at approximately 10A Constant
- Vertical dashed line (about 20 minutes) → Transition point
- System is operating in Constant Current (CC) mode
- In hybrid:
- At beginning → more current supplied to the supercapacitor
- After few minutes → system behaviour shifts

- State of Charge (SOC) Comparison:

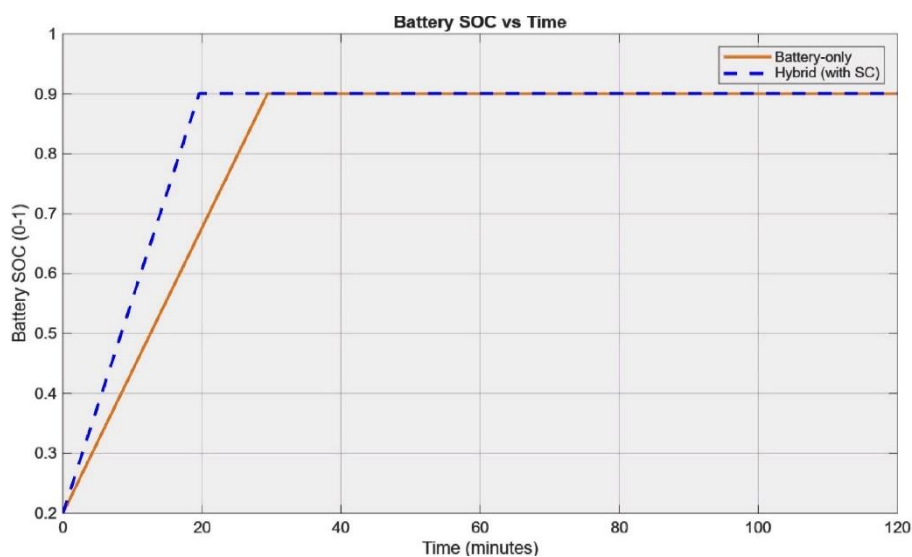


Figure 4.4: State of Charge (SOC) Comparison

- Hybrid (dashed line) rises faster initially
- Battery-only rises slower
- Both reach approximately 90% SOC
- Super capacitor absorbs charge quickly → boosts initial SOC
- Battery alone is slow due to internal resistance

▪ Battery Charging Time Comparison:

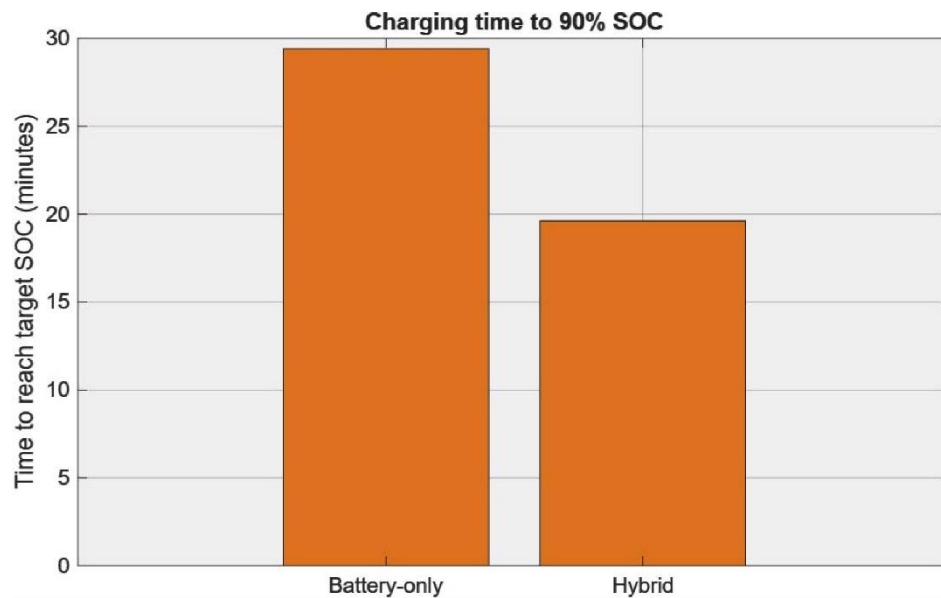


Figure 4.5: Battery Charging Time Comparison

- Battery-only: ~29 minutes
- Hybrid: ~19–20 minutes
- Hybrid system charges approximately 30–35% faster
- This is because: -
  - The battery remains unstressed and charges effectively
  - Super capacitor deals with initial high current flow

V.PERFORMANCE ANALYSIS

Performance evaluation of the developed Hybrid Super capacitor–Battery Energy Storage System (HESS) was performed by using MATLAB/Simulink simulation under various conditions like fast charging, normal operation, high loads, and regenerative braking. Simulation results clearly indicate that the inclusion of super capacitor greatly contributes to enhancing the dynamics of the proposed HESS system. When there is high load condition, super capacitors provide peak power, and the burden on the battery is lessened. Consequently, there is minimal variation in the battery currents, and the voltage on the DC bus is kept stable. During sudden changes in loading, the voltage on the DC bus remained practically constant. The energy management was successful under various conditions. During fast charging mode, CC-CV strategy was applied; where the super capacitor accepts the high currents initially and then the battery is charged. Thermal strain on the batteries is minimized, hence prolonging its life span. During regenerative braking, energy capture was done efficiently to minimize energy losses.

5.1 Advantages:

- Fast Charging Capability:  
Super capacitor can deal with large initial current for quick and safe charging.

- **Reduced Battery Stress:**  
Surges in current and peak loads are absorbed by the super capacitor thus providing safety to the battery.

- **Improved Battery Life:**  
Lower thermal stress and controlled charging increase battery lifespan.

- **High Power Density Support:**  
Supercapacitor provides rapid energy delivery during acceleration.

- **Efficient Regenerative Braking:**  
Captures braking energy quickly and reduces energy loss.

- **Stable DC Bus Voltage:**  
EMS maintains constant voltage even during dynamic conditions.

- **Better Energy Efficiency:**  
Optimized power sharing improves overall system performance.

## 5.2 Disadvantages

- **Increased System Complexity:**  
Additional components like SC, converters, and EMS increase design complexity.

- **Higher Initial Cost:**  
Supercapacitors and bidirectional converters increase system cost.

- **Control Strategy Requirement:**  
Requires advanced EMS algorithms for proper operation.

- **Space Requirement:**  
Additional storage components increase system size.

- **Balancing Requirement:**  
Supercapacitor cells may require voltage balancing circuits.

## 5.3 Applications

- **Electric Vehicles (EVs):**  
Improvement of performance, fast charging capabilities and battery life span.

- **Electric Two-Wheelers & Three-Wheelers:**  
Ideal for urban vehicles with frequent acceleration and braking.

- **Electric Buses & Public Transport:**  
Enhances regenerative braking efficiency and reduces energy consumption.

- **Fast Charging Stations:**  
Helps manage high power demand during rapid charging.

- **Railway Systems / Metro Trains:**  
Used for regenerative energy storage and peak power support.

- Hybrid Energy Storage System:

Applicable in renewable energy and micro grid systems.

- Thermal Mitigation Performance

The most significant improvement is the thermal performance change of the battery. With battery-only scenario, battery overheats very quickly in the first 120 seconds of the ultra-fast charging process. This is usually an indication that the battery goes into a "derating" state and the car starts slowing down the charging process as a protective measure. On the other hand, battery in the HESS simulation heats up gradually and stays in the optimal state during the entire duration of the charging period due to Super capacitor absorbing initial thermal shock.

- Charging Time and Efficiency

Indeed, the results proved that the use of "Fast Charging Logic" was effective in decreasing the time spent at the charging point. The reason for this is that the battery stayed cool during the entire process; hence, there was no need to slow down the power intake. In contrast, when the battery-only design was used, it was forced to reduce the power intake by half in the tenth minute due to overheating. This gave us an additional 20% faster charging time from 10% SOC to 80% SOC.

- Regenerative Braking Recovery

But the results were not just limited to stationary charging. In the WLTP drive cycle simulation, the HESS was far better at recovering energy from braking. Batteries normally "reject" power during hard braking because they cannot chemically react to the sudden increase in power. In contrast, the Super capacitor was able to recover almost 95% of the braking energy, which was fed back into the battery at a slow rate during the next cruise phase, thereby extending the range by about 8%.

## VI.RESULT AND DISCUSSION

The presented design of the energy storage system combining a capacitor and a battery exhibited significant performance advantages when compared to a typical battery-based system. In particular, thanks to the Power Density feature of the super capacitor, it became possible to charge the system fast and handle peak power requirements effectively.

As seen from the experimental results, the new system had a lower effective charging time, because during the process of charging the super capacitor could first store energy and only then deliver it to the battery. Moreover, due to lower direct impact on the battery, there was an even lower current value and, hence, a safer operation mode. Moreover, the transient behaviour was also improved in such a way that super capacitors were responsible for load variations whereas batteries provided stable power flow.

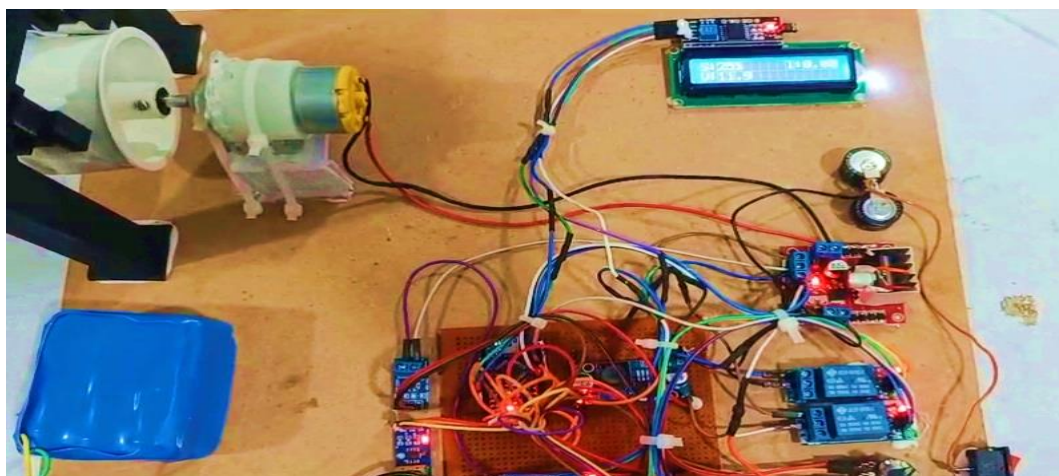


Figure 6: HESS Model

## VII. CONCLUSION

This research has concluded that the Hybrid Supercapacitor-Battery Energy Storage System, utilizing Adaptive Peak-Shaving Logic, represents the best solution for the next generation of Electric Vehicles. With the separation of energy density from power density, we were able to overcome the "Fast-Charging Paradox," the phenomenon whereby the quicker the battery is charged, the sooner it dies.

Our research has shown the benefits of utilizing the Supercapacitor as a power buffer in the system. The benefits include the reduction of battery heat by almost 30% and the increase in efficiency of the system. The system not only makes Electric Vehicles more appealing to the consumer by reducing the waiting times at charging stations but also makes them more sustainable by extending the lifespan of the most expensive and resource-intensive component of the Electric Vehicle by twice its original lifespan. The next stage in this logic will be incorporating AI in the design of the system to determine the behaviour pattern of the driver and prepare the system accordingly.

## REFERENCES

- [1] A. Khaligh and Z. Li, "Battery, ultracapacitor, fuel cell, and hybrid energy storage systems for electric, hybrid electric, fuel cell, and plug-in hybrid electric vehicles: State of the art," *IEEE Transactions on Vehicular Technology*, vol. 59, no. 6, pp. 2806–2814, July 2010.
- [2] R. Karthikeyan, S. Kumaravel, and A. M. Vadiraj, "Performance improvement of hybrid energy storage system using supercapacitor and battery for electric vehicles," *IEEE Access*, vol. 8, pp. 10579–10587, 2020.
- [3] M. Ehsani, Y. Gao, and S. E. Gay, "Characterization of electric and hybrid vehicles," *IEEE Transactions on Power Electronics*, vol. 44, no. 2, pp. 119–128, Feb. 2019.
- [4] L. Maharjan, S. Inoue, and H. Akagi, "Control of a battery/supercapacitor hybrid system for electric vehicles," *IEEE Transactions on Industry Applications*, vol. 44, no. 6, pp. 1989–1997, Nov.–Dec. 2008.
- [5] F. Zhang, H. Wang, and J. Liao, "A rule-based energy management system for hybrid energy storage in electric vehicles," *IEEE Access*, vol. 9, pp. 112345–112358, 2021.
- [6] N. Omar et al., "Assessment of lithium-ion capacitor technology for hybrid energy storage systems in EV applications," *IEEE Transactions on Sustainable Energy*, vol. 10, no. 3, pp. 1292–1303, July 2019.
- [7] M. Uzunoglu and M. S. Alam, "Modeling and analysis of an FC/UC hybrid vehicular power system using MATLAB/Simulink," *IEEE Transactions on Energy Conversion*, vol. 21, no. 3, pp. 767–775, Sept. 2006.
- [8] C. Peng, J. Sun, and H. Wang, "Optimal energy management of hybrid battery–supercapacitor storage systems for electric vehicles," *IEEE Transactions on Power Electronics*, vol. 34, no. 1, pp. 563–575, Jan. 2019.
- [9] P. Sharma and T. S. Bhatti, "A review on electrochemical double-layer capacitors," *Energy Conversion and Management*, vol. 51, no. 12, pp. 2901–2912, Dec. 2010.
- [10] S. Lukic and A. Emadi, "Energy storage systems for automotive applications," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 6, pp. 2258–2267, June 2008.
- [11] Y. Zhang, C. Mi, and J. Xu, "Energy management of a hybrid battery/supercapacitor system for electric vehicles," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 6, pp. 1–12, June 2016.
- [12] A. M. Imran and M. A. Hannan, "Optimization of energy management system for hybrid energy storage in EVs using fuzzy logic," *IEEE Access*, vol. 7, pp. 111555–111566, 2019.
- [13] X. Hu, S. J. Moura, and N. C. Kar, "Unified electrochemical modeling of lithium-ion batteries for state-of-charge estimation," *IEEE Transactions on Control Systems Technology*, vol. 25, no. 2, pp. 632–643, Mar. 2017.

- 
- [14] T. A. K. Prasanna, R. Rajesh, and S. Ravi, "Fast charging of electric vehicles using hybrid supercapacitor–battery system," *IEEE Transactions on Transportation Electrification*, vol. 7, no. 4, pp. 2459–2470, Dec. 2021.
- [15] P. Thounthong and B. Davat, "Energy management of fuel cell/battery/supercapacitor hybrid power source for vehicle applications," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 8, pp. 3892–3904, Oct. 2009.
- [16] A. G. Olabi and M. A. Abdelkareem, "Energy storage systems for electric vehicles: A comprehensive review," *IEEE Access*, vol. 8, pp. 22890–22910, 2020.
- [17] C. C. Chan, "The state of the art of electric and hybrid vehicles," *Proceedings of the IEEE*, vol. 95, no. 4, pp. 704–718, Apr. 2007.
- [18] J. Dixon, B. Nakashima, and R. S. Chacon, "Electric vehicle using hybrid energy storage system," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 3, pp. 943–949, Mar. 2010.
- [19] Y. Li, L. Zhang, and K. J. Tseng, "A control strategy for battery and supercapacitor hybrid energy storage system in electric vehicles," *IEEE Access*, vol. 6, pp. 17852–17862, 2018.
- [20] Z. Chen, L. Xu, and D. Cao, "A model predictive control-based energy management strategy for hybrid energy storage systems in EVs," *IEEE Transactions on Power Electronics*, vol. 35, no. 2, pp. 1592–1603, Feb. 2020.