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*Original Article*

# Dynamic Modelling of Hybrid Supercapacitor-Battery Energy Storage for Electric Vehicles

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***Abstract*** *- Due to various economic, environmental, and societal challenges, Electric Vehicles (EVs) have emerged as an integral component of modern transportation. The adoption of EVs has been primarily influenced by charging time, charging infrastructure, and the range of EVs. To address these issues, this paper proposes the development of a hybrid energy storage system for EVs with the integration of a supercapacitor and a battery. The supercapacitor is chosen as it has high-power density, and is particularly suitable for handling peak power demands. On the other hand, the battery provides the required energy density for sustained operation. The integration in the proposed approach offers extended battery life through stress reduction, shortens the charging time, and enhances energy storage capacity, thereby improving the driving range of EVs. The proposed approach is studied using the simulation modelling of a hybrid energy storage system with a supercapacitor and a battery modelled in MATLAB. The investigation is conducted by focusing on the charging and discharging characteristics of the supercapacitor and the intervention of the battery system with the EV drive system. The obtained results demonstrate the potential of the proposed approach to improve EV performance, reliability, and sustainability.*

***Keywords*** *- Electric vehicle, Supercapacitor, Charging and discharging, Battery, Hybrid energy storage systems.*

## 1. Introduction

In today's era of rapid modernization, the emission of carbon footprints is inevitable. The transport sector plays a vital role in reducing carbon usage. Therefore, in the current sector, EVs are focusing people's attention all over the world. India’s Environmental Pollution Index (EPI) rank is 176 out of 180 countries [1]. The country’s initiation of Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME) provides subsidies to promote EV adoption in India. To promote environmentally friendly and affordable transportation, subsidies are provided for e-2Ws, e-3Ws, e-4Ws, and e-buses. The e-2W has received tremendous acceptance among the people due to its convenience.

Most of the fuel-based transport is being replaced by e-buses by the government, especially in metropolitan cities in India. The EV market in India is estimated to increase from 3 million units in 2019 to 29 million units by 2027, with a CAGR of 21.1 % [2]. The significant challenges in EV adoption can be divided into customer-end challenges and supplier-end challenges. The customer end challenges can be further divided into charging time, charge anxiety, and range anxiety. The supplier end challenges can be divided into grid stabilization, renewable energy penetration, and technology upgradation of the power grid. This work focuses on the extended range, increased battery longevity, and sustainable development with the help of a Hybrid Energy Storage System (HESS) based on a Supercapacitor and battery in EVs. The primary objective of this research work is to introduce HESS, incorporating a supercapacitor and a battery. This would reduce the EV charging time and extend the EV range. The proposed HESS would provide additional benefits such as improved battery life, increased range of EVs, and the reduction of environmental impacts. Overcharging and over-discharging are significant causes that lead to battery degradation. Degradation causes physical and chemical changes inside the cell.

The most observable changes caused by degradation are capacity fade and power fade [3]. Capacity fade causes the reduction of usable capacity of the cell, and power fade causes the reduction of deliverable power. When the battery gets decomposed after its lifetime, it would release various fluorinated phosphorus, carbon dioxide, Nickel, Manganese, and Cobalt (NMC), and lithium-based components, which would contaminate water bodies and landfills [4]. The burning of fossil fuels for electricity production would produce oxides of Nitrogen (NOx), Sulfur (SOx), and particulate matter, contributing to greenhouse gas emissions [5]. The EV battery decomposition components produce more harm to the environment than fossil fuel-based electricity generation. Proper battery recycling would decrease environmental harm.

The Lithium ore is also a rare material and is not readily available. The incorporation of a supercapacitor increases the lifetime of the battery and, in turn, reduces the battery decomposition rate per year. Also, the components of the supercapacitor are activated carbon, carbon nanotubes, and conducting polymers.

Their material decomposition makes supercapacitors easier to recycle than batteries at the end of life [6]. In this research work, the EV hybrid energy storage system based on a supercapacitor and a battery has been simulated using MATLAB Simulink. The supercapacitor used is simulated based on the real-time charging and discharging data taken from the supercapacitor of 500F, 2.7V. The battery used in this work is based on the real-time data taken from the MATLAB Simulink itself. Based on the part number of the battery, the charging and discharging characteristics of the data are taken and considered for the simulation. The supercapacitor bank and battery bank are designed for 48V, and both energy levels should be equal.

The simulation is done in such a way that the supercapacitor is charged to its nominal value by the CC-CV mode of charging. Simultaneously, the battery is also charged from the same supply with its own characteristics by the controller unit. Once the supercapacitor and battery reach the nominal value, the charging process will stop. Battery charging is measured using the State of Charge (SoC) of the battery. The battery's minimum charge is kept at 2.8V to avoid deep discharge, which avoids the internal damage of the battery. The proposed EV charging technology is more adaptable, robust, and energy-efficient than current hybrid storage systems due to its innovative intelligent control, enhanced power-energy coordination, longer battery life, improved regenerative performance, and increased efficiency. This paper is summarized as follows: Section 1 is an Introduction that provides insights about HESS with the incorporation of a supercapacitor and a battery. Section 2 provides background and literature survey regarding EV battery fast charging technologies and HESS used in EVs. Section 3 gives the system description of the overview of the HESS designed with the incorporation of a Supercapacitor and a battery.

Section 4 shows the simulation circuit diagram of HESS with the help of a Supercapacitor and a Battery. In addition to that, this section explains how the supercapacitor has been simulated directly from the hardware model and how the part number of the battery has been selected. Section 5 represents the results and discussion of the simulation model and provides a comparative analysis of the charging time required for Individual battery charging and supercapacitor-assisted battery charging, and then Section 6 concludes the charging time reduction and range extension of the proposed technology, a hybrid energy storage system with supercapacitor and battery integration.

## 2. Background and Literature Survey

The need for HESS is essential nowadays to fulfil all the performance requirements, such as high energy density, high power density, larger range, faster response, and longer life. Battery, supercapacitors, flywheel, and fuel cell are the most used components for making HESS. A supercapacitor is one of the versatile components to be used as a HESS. Supercapacitors are mostly used as a backup component to store power supply fluctuations. Unlike a battery, which can wear out after a thousand cycles, a supercapacitor can handle millions of charge and discharge cycles. Unlike other energy storage systems, supercapacitors are easily compatible with batteries. In addition to that, supercapacitors are used to increase the lifespan of the battery by decreasing the stress on the battery [7]. Therefore, in this work, a supercapacitor is used for designing an HESS of EVs along with the battery. In addition to that, a supercapacitor can be easily accompanied by any other energy storage device. In [8], it is discussed that the fast charging of EV batteries can be achieved by increasing the C-rate of the battery. Also, the challenges of increasing the C-rate and the charging framework are given. In [9], it discusses unravelling the charge transfer kinetics to extreme fast charging of Li-ion cells.

In [10], the importance of HESS in EVs is discussed, which helps to increase the energy availability for long range, improve the life cycle, limit surge discharge, and improve efficiency. [11] explains that the HESS, designed by a battery and supercapacitor combination, becomes popular because of its prominent features. [12] discusses the challenges, advantages, cost, and applications of the HESS used in e-transportation. [13] discusses how the energy management between hybrid storage systems in EVs has been done based on Sant Cat Swarm Optimization (SCSO). Here, the HESS utilizes a battery, a supercapacitor, and a fuel cell. In [14], the details of the allocation of power and management of energy needs are provided based on deep learning and improved model predictive control. In [15], the implementation of a power management system among battery, supercapacitor banks, and solar cells is described. In [16], the importance of monitoring and maintaining parameters such as voltage, current, power, temperature, heat management, charging and discharging control, and cell balancing is explained.

An optimal thermal management for EVs based on dual crucial objectives, such as heating energy consumption and charging time, is discussed in [17, 18] discusses the solar-powered battery – supercapacitor hybrid energy storage system and is analyzed in MATLAB Simulink environment as per Indian scenarios. It is proven that the stress of the battery has been reduced with the introduction of a supercapacitor. In [19], a rule-based technology is introduced for an active hybrid energy storage system using a battery and supercapacitor combination. The satisfactory operating performance is observed with various operating conditions.

A Fuzzy Logic Controller (FLC) based energy management system is developed in [20] for hybrid energy storage systems to improve the performance. In [21], the thermal and energy management of HESS is optimized simultaneously for the excellent performance of EVs. In contrast to the current technology's restricted power handling capacity, the suggested technique uses a supercapacitor to enable fast cycles of charging and discharging while maintaining the battery's high energy density. By handling transient peaks, the supercapacitor extends the battery's life and reduces the battery stress. Better recovery of braking energy is offered by the suggested technology. A supercapacitor can absorb energy bursts during braking, but the proposed technology is unable to absorb high power instantaneously. The features of the proposed technology have dual source support and a longer system life, which increases reliability.

## 3. System Description

This work is designed based on driving an EV motor with the help of HESS, with the incorporation of a supercapacitor and a battery. The supercapacitor can charge and discharge faster because of its high-power density. This property is used for charging an EV battery faster. The supercapacitor unit and battery unit are kept inside the EV. The 230V, 50 Hz AC supply is converted to 48V DC with the help of a rectification unit, and the supercapacitor and battery unit are charged simultaneously with their own control circuitry. The supercapacitor unit is charged by the Constant Current (CC) and Constant Voltage (CV) modes of charging. Compared to the battery unit, the supercapacitor unit would charge faster. Since its self-discharge rate is higher, it would continuously charge in the CV mode. The CC mode would provide constant current to the supercapacitor unit irrespective of its internal voltage.

Because of its constant current, the supercapacitor unit would charge faster. Until the supercapacitor unit reaches 95% of SoC, the supercapacitor unit is in CC mode of charging. Afterwards, it would change to the CV mode of charging. The CV mode would provide a constant voltage with less current to maintain the 100% SoC. Once both the supercapacitor unit and battery unit reach 100% of SoC, the charging will stop. Once the charging was over, the EV drive could connect to the HESS, and it would start to run. The EV drive would take power from the HESS. The charging and discharging of the supercapacitor unit and the battery unit are monitored with the help of the microcontroller unit. The decision of the supercapacitor unit and the battery unit charging and discharging would be taken care of by the controller unit by monitoring the voltage level of both units. Proper current and voltage sensors would be connected to the controller unit in order to control the whole operation effectively.

Figure 1 describes the overview of HESS based on a supercapacitor and a battery. The 230V, 50Hz AC supply has been converted into 48V DC with an in-built Power Factor Correction (PFC), H-bridge, and a CLLC circuit. A CLLC is a Capacitor-Inductor-Capacitor-Inductor-based resonant DC-DC converter provided for isolation between source and load. From this 48V DC supply, the supercapacitor unit and battery unit are charged in parallel. A separate charging circuit for the supercapacitor unit and the battery unit is provided. The discrete components of supercapacitors and batteries are connected in series and parallel fashion to form a 48V unit with the desired energy level. A balancing circuit is mandatory in order to maintain the proper voltage among all the individual cells. The balancing of voltage and temperature among individual cells is taken care of by the microcontroller unit.

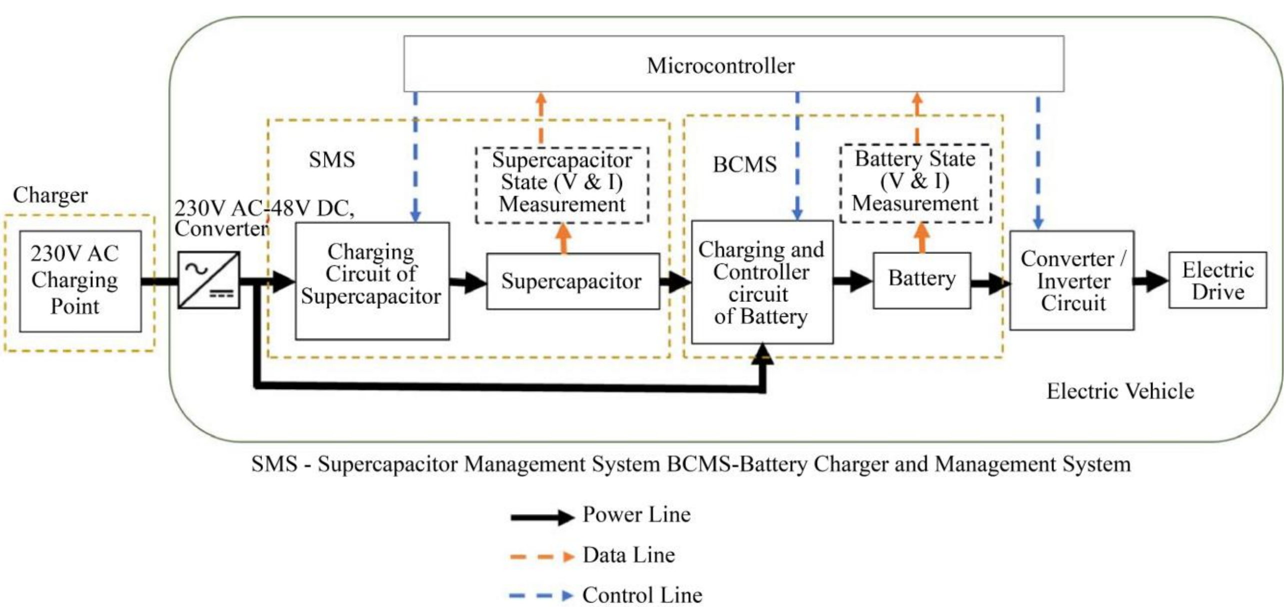


**Fig. 1 Overview of a hybrid energy storage system based on a supercapacitor and a battery**

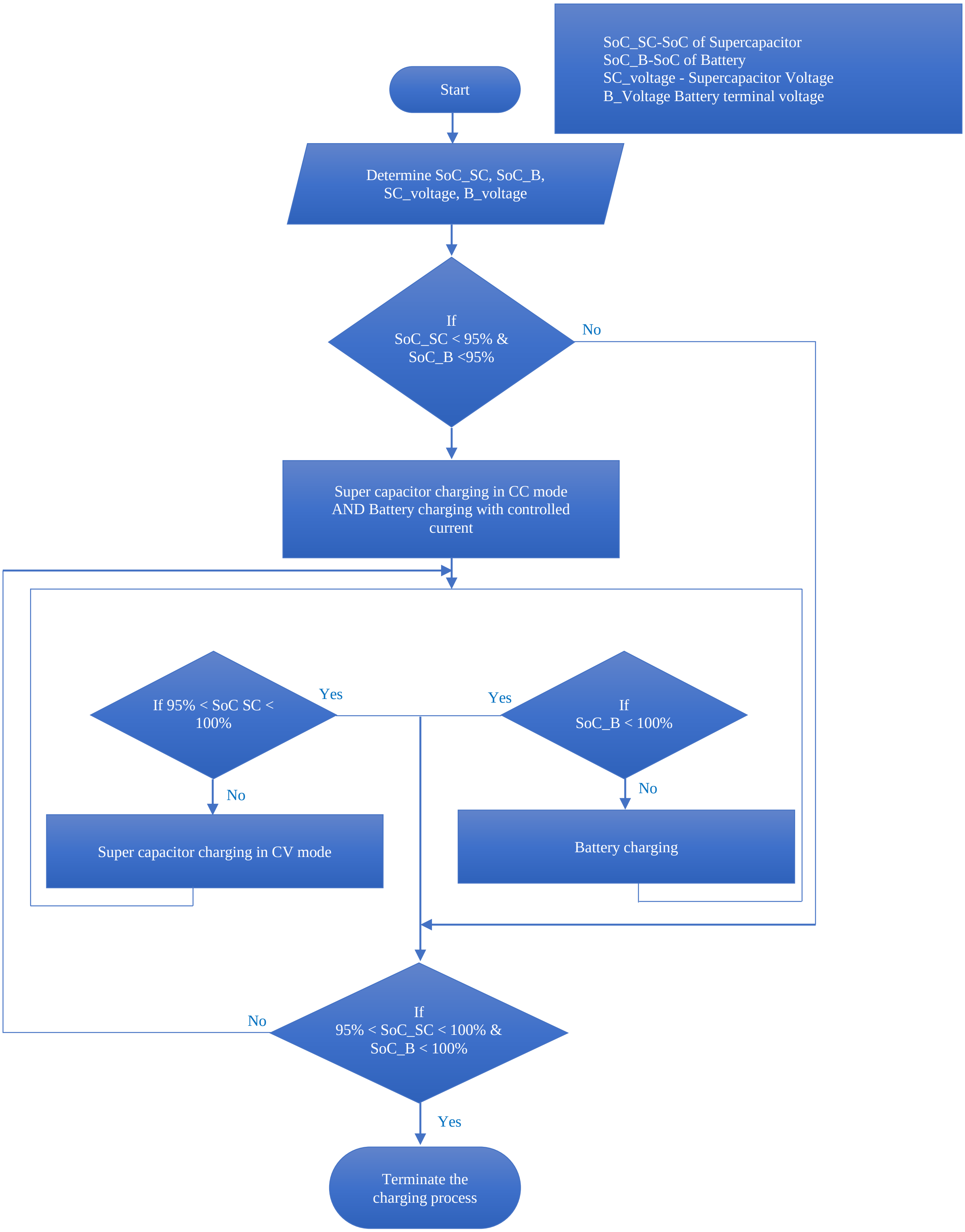


**Fig. 2 Flowchart of charging hybrid energy storage system**

In this work, voltage is the primary factor for monitoring cell balancing. Therefore, a state measurement unit is provided individually for the supercapacitor unit and the battery unit. Proper current and voltage sensors are provided to monitor current and voltage value with the microcontroller. Since the SoC of the supercapacitor and battery is directly proportional to the voltage, the voltage is considered a prime factor to determine the complete charging of the supercapacitor and battery. The SoC of the battery is determined based on the Open Circuit Voltage (OCV) method [22]. With a MATLAB Simulation, once the part number has been specified, the complete characteristics of the specified Li-ion battery can be obtained. The battery voltage and its corresponding SoC value are also obtained directly. Equation (1) helps to determine the SoC of the supercapacitor. In this work, once the supercapacitor measured voltage reaches the nominal voltage, then it is assumed that the supercapacitor reaches 100% of SoC.

The charging circuit of the supercapacitor, the supercapacitor unit, and the state measurement of the supercapacitor (including voltage and current sensors) form the Supercapacitor Management System (SMS). The charging and control circuit of the battery unit, along with the state measurement of the battery (V & I), form the Battery Charger and Management System (BCMS). Once the supercapacitor and battery units reach 100% of SoC, then the charging will stop. The state of the supercapacitor and battery is monitored by the microcontroller, which provides corresponding control signals to charge/discharge the supercapacitor and battery units. The EV drive is connected to the HESS to receive power after charging is complete. The SoC percentage of a supercapacitor can be determined by,

$$\%\, SoC\ of\ Supercapacitor = \left(\frac{Measured\ Voltage}{Design\ Voltage}\right)^2 \times 100 \quad (1)$$

Where, Design Voltage - Nominal voltage of the supercapacitor.

The Figure 2 depicts the flow of the charging process. To prevent internal damage, the supercapacitor and battery retain a certain amount of residual voltage. The microcontroller used measures the supercapacitor voltage, battery voltage, and SoC of the supercapacitor and battery. When the SoC of the Supercapacitor and battery is less than 95%, the supercapacitor goes to the CC mode of charging, and the battery also starts to charge with controlled current. Until the supercapacitor reaches 95% of its SoC, it charges in CC mode; then, it switches over to CV mode. The battery also charges in parallel until it reaches 100% of its SoC. The charging will continue until the battery and supercapacitor reach 100% of SoC. When both the supercapacitor and battery reach 100% of SoC, the charging would stop. Overcharging would reduce the battery's lifespan. The microcontroller would monitor the battery voltage and turn off charging once the battery reaches 100% of SoC.

### *3.1. Different Topologies Applied for Hybrid Energy Storage Systems*

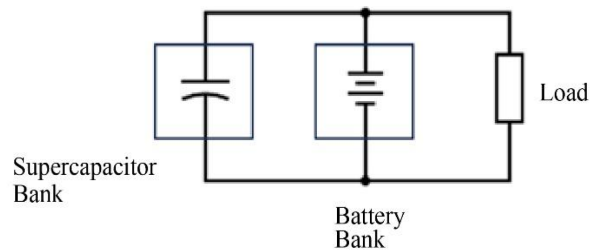


**Fig. 3 Passive hybrid energy storage system**

For HESS based on supercapacitors and batteries, different topologies are recommended depending on the output [2]. The various topologies include: Passive HESS, Semi-active HESS, and Fully active HESS. In the Passive HESS, the supercapacitor bank and the battery bank are connected in parallel and connected directly to the load. The advantage of this topology is a simple design and low cost. The drawback of this system is that there is no control over whether any variations occur in the output. Figure 3 illustrates the connection of Passive HESS.

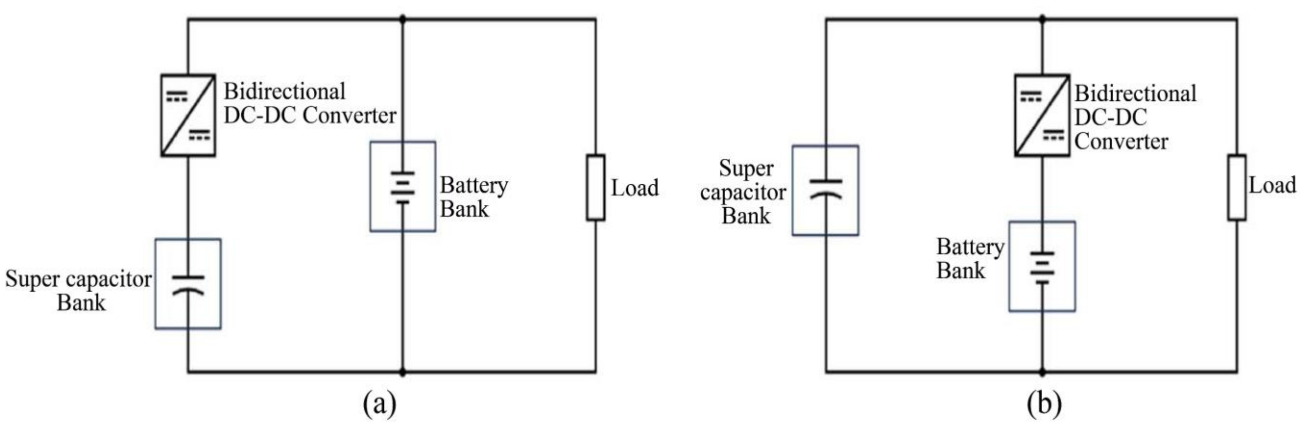


**Fig. 4 Semi-active hybrid energy storage system**

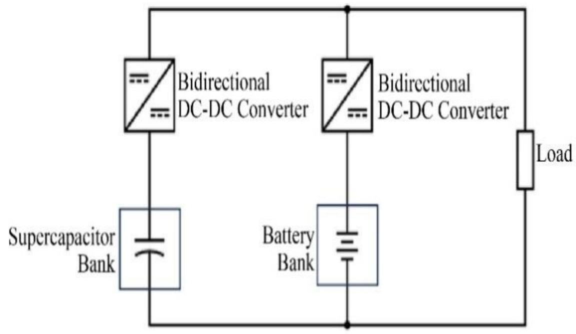


**Fig. 5 Fully active hybrid energy storage system**

In the Semi-active HESS, the bi-directional DC-DC converter is connected to either the supercapacitor bank or the battery bank, and both are connected in parallel with each other, forming a source and load. The different connections of the Semi-active HESS are illustrated in Figure 4 based on the load requirement.

Figure 5 illustrates the connection of the fully active HESS. In the fully active HESS, both the supercapacitor bank and the battery bank are connected to a bi-directional DC-DC converter, and this combination is connected in parallel with the load.

## 4. Simulation Data

MATLAB 2025a is used for simulating the charging of HESS. A comparative analysis of charging the battery unit individually and charging the HESS is noted. The simulation of the supercapacitor and battery units is designed based on the electric vehicle EV) drive specifications. Based on the energy storage and the mileage of the EV, the battery and supercapacitor units are chosen.

### *4.1. Drive Specification*

The drive specification is given as follows,

| | | |
|---|---|---|
| Motor Type | : | DC Motor |
| Motor Voltage | : | 48 V |
| Motor Current | : | 1.54 A |
| Motor Speed | : | 3000 rpm |
| Motor Torque | : | 1800 mNm |

### *4.2. Battery Selection*

The specifications of battery selection are given as follows, Li-ion Battery rating: 2.84 mAh, 4.2 V, and the Number of Batteries connected in series is 12. The Energy Stored in a Battery = Voltage of the battery string×Ah of the battery. Therefore, the Energy Stored in a battery string is 12 × 4.2 × 2.84 = 143.136 W.

The simulation parameters of Li-ion batteries are available in MATLAB 2025a. It is simpler to select the part number and obtain the characteristics of the Li-ion battery. The part number selected for the Li-ion battery simulation is PanasonicNCR18650PF.

### *4.3. Supercapacitor Selection*

The supercapacitor selection specification is discussed in this section. The supercapacitor rating is selected as 2.7V, 500F. For 48V, the supercapacitors should be connected in series. The energy stored in a supercapacitor is given as,

$$\boldsymbol{E_{sup\,ercapacitor} = \frac{\frac{1}{2}CV^2}{3600}Wh} \tag{2}$$

The supercapacitor series-parallel combination is chosen as 18S16P. The total capacitance of the bank for the 18S16P combination is 444.4 F. The estimated voltage across the supercapacitor string is 48.6V. Therefore, the energy stored in the supercapacitor estimated by Equation (2) is 145.8 Wh.

### *4.4. Supercapacitor Parameter Determination*

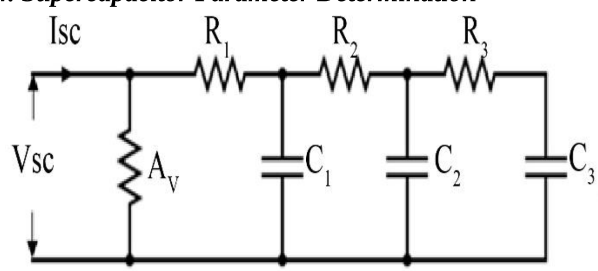


**Fig. 6 Supercapacitor equivalent model**

The determination of supercapacitor parameters with MATLAB/Simscape is provided in [24]. A supercapacitor is characterised by simulating a model with fixed resistances, fixed capacitances, and voltage-dependent capacitor gain parameters, as shown in Figure 6.

The following steps are to be followed for identifying the supercapacitor parameter: The first step is to charge the fully discharged supercapacitor by constant current $(i_1)$. When the charging current reaches, $t_1 = 20e^{-3}s$, note down the corresponding voltage $(v_1)$. The fixed resistance of the immediate branch parameter is,

$$R_1 = \frac{v_1}{i_1} \tag{3}$$

The second step is to note down $t_2$when the voltage increases to $v_1 + 50e^{-3}\,V$.

$$C_1 = i_1 \frac{t_2 - t_1}{v_2 - v_1} \tag{4}$$

Once the voltage reaches the nominal voltage of 2.7 V$(v_3)$, note down the time $t_3$ and turn off the charging current. When the charging current reaches zero, the time $t_4 = t_3 + 20e^{-3}s$, is taken and the corresponding voltage $v_4$ is noted down. The voltage-dependent capacitance coefficient is calculated by using,

$$A_v = \frac{2}{v_4}\left[\frac{i_1(t_4 - t_1)}{v_4} - C_1\right]F/v \tag{5}$$

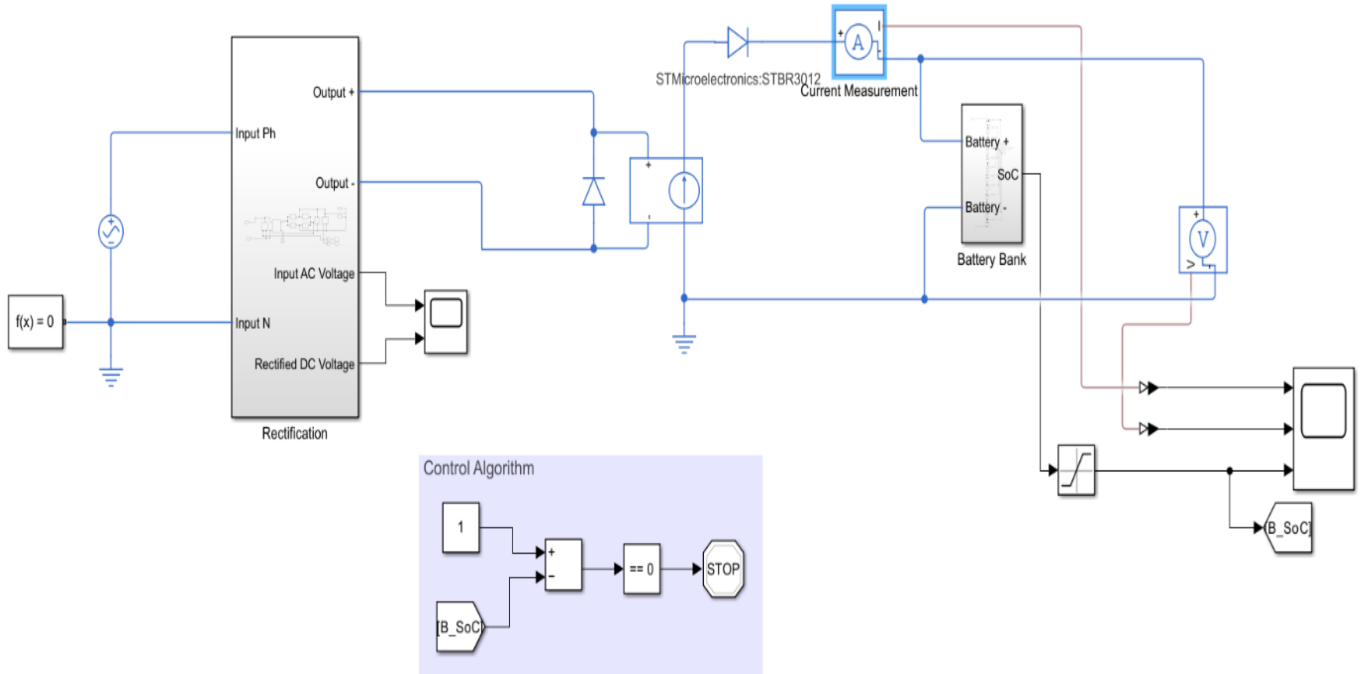


**Fig. 7 Existing battery charging system**

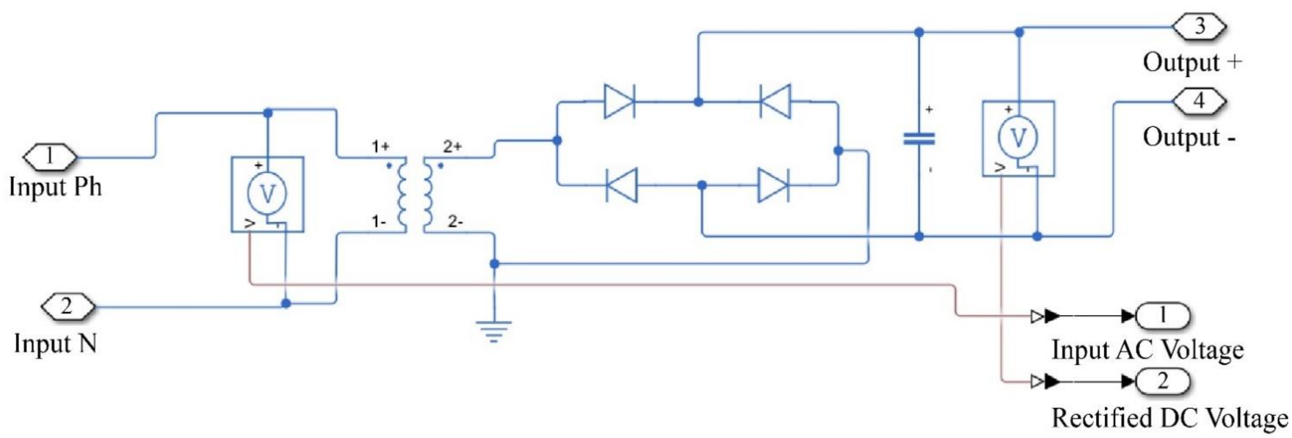


**Fig. 8 Rectification block of the proposed system**

For delayed branch parameters identification, measure the time $t_5$ when the voltage reduces from $v_4$ to $v_5 = 50e^{-3}V$. Now measure the change in voltage $\Delta V = v_4 - v_5$.

$$v_{ci} = v_4 - \frac{\Delta V}{2} \quad (6)$$

$$C_{diff} = C_1 + A_v v_{ci} \quad (7)$$

$$R_2 = \frac{\left(v_4 - \frac{\Delta V}{2}\right)(t_5 - t_4)}{C_{diff} \Delta V} \quad (8)$$

Then wait for 300 seconds to measure $t_6$ and find out the delayed branch capacitance $C_2$.

$$Q_{total} = i_1(t_4 - t_1) \quad (9)$$

$$C_2 = \frac{Q_{total}}{v_6} - \left(C_1 + \frac{A_v}{2} v_6\right) \quad (10)$$

Once, the voltage decreases $v_6$ over $50e^{-3}V$ time, and the voltages are noted down $t_7$ *and* $v_7$ respectively. To identify long-term parameters, measure the change in voltage $\Delta V = v_6 - v_7$.

$$R_3 = \frac{\left(v_6 - \frac{\Delta V}{2}\right)(t_7 - t_6)}{C_{diff} \Delta V} \quad (11)$$

After 1800 seconds, the time and voltage are noted down as $t_8$ *and* $v_8$ respectively for calculating $C_3$.

$$C_3 = \frac{Q_{total}}{v_8} - \left(C_1 + \frac{A_v}{2} v_8\right) - C_2 \quad (12)$$

Then, the configuration of the 18S16P combination is provided to simulate the supercapacitor bank. From Equation [3-12], provide details of how to calculate the branch parameters of a supercapacitor.

The calculated parameters of the 48V Supercapacitor are listed in Table 1.

**Table 1. Supercapacitor parameters calculated**

| Parameter | Calculated Values | Units |
|---|---|---|
| $A_v$ | 190 | F/V |
| $R_1$ | 0.02293 | ohm |
| $R_2$ | 2.095 | ohm |
| $R_3$ | 14.13 | ohm |
| $C_1$ | 19.6 | F |
| $C_2$ | 39.932 | F |
| $C_3$ | 40.89 | F |

## 5. Results and Discussion

According to the prevailing approach, batteries are charged directly from the Electric Vehicle Supply Equipment (EVSE). The Panasonic NCR18650PF Li-ion battery charging is demonstrated with the MATLAB Simulink circuit in Figure 7. The rectification block shown Figure 8 provides a 230 V, 50 Hz AC source, which is transformed into a 48 V DC. Figure 9 also shows the rectified output. A 48 V DC is produced from the AC peak voltage of 230√2 V. In practice, a PFC correction unit, an H-bridge, and a CLLC circuit are used for an accurate 48 V filtered DC output. The battery string connected in series to achieve the required 48V for EV is depicted in Figure 10. To prevent battery overcharging, MUX is used to detect if any of the batteries have reached full SoC and stops further charging. Here, multiple signals are combined into a single signal using a MUX, which is then transmitted to the channel. Figure 11 shows the battery current, battery voltage, and battery SoC observed by the scope. Once the battery SoC reaches 100%, the charging process will stop. The simulation results show that the charging time would take 837.37 seconds to charge the battery alone.

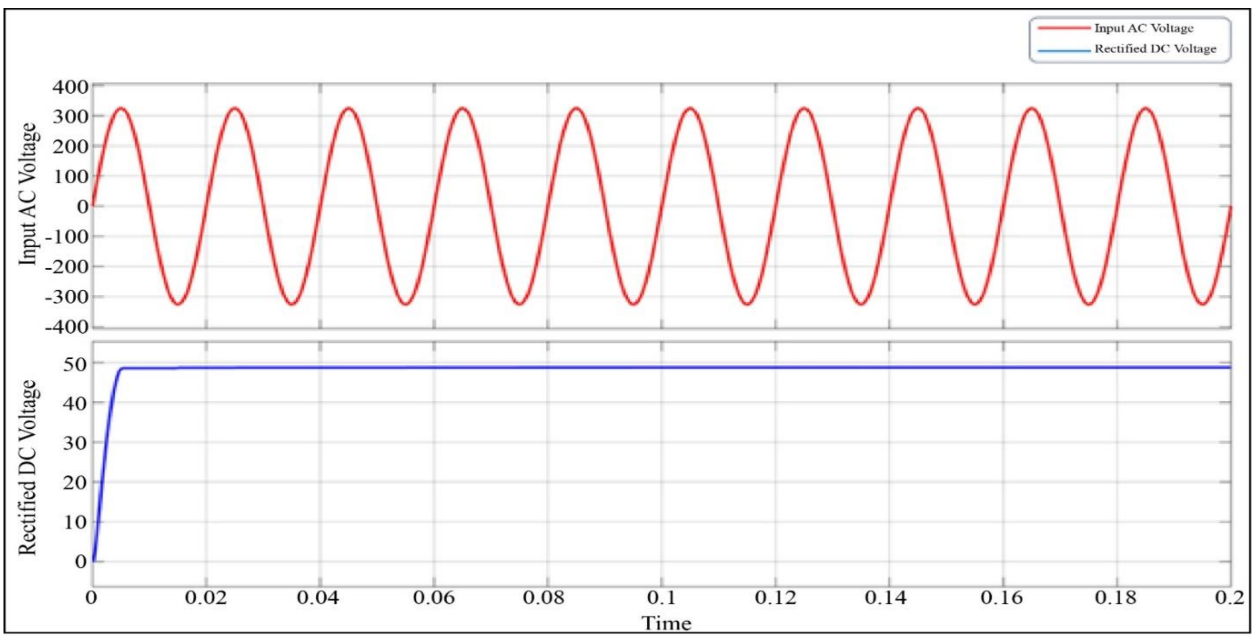


**Fig. 9 Rectification output**

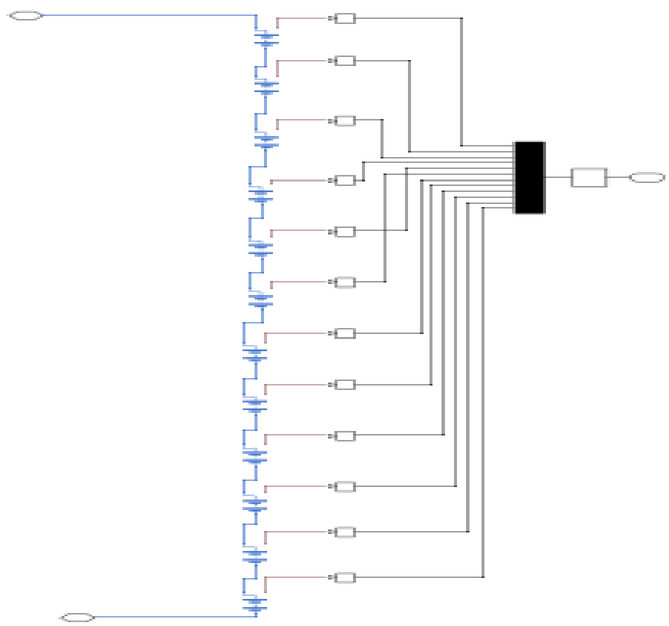

**Fig. 10 Battery bank simulated**

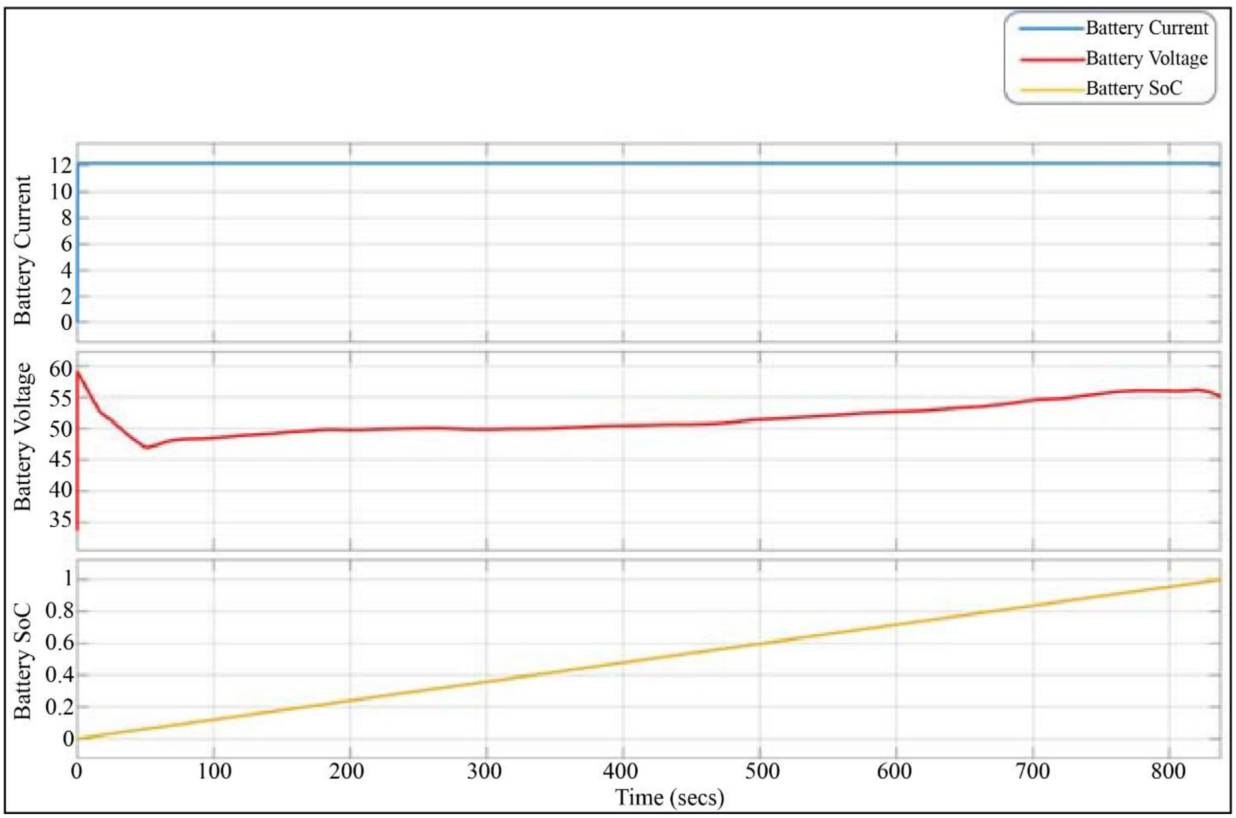


**Fig. 11 Battery charging characteristics**

The battery voltage initially exhibits an abrupt spike, and then, depending on the applied battery current, it progressively rises. The electrochemical reaction and RC element modelling emphasize this transient behavior of the battery. The simulation findings provide a comprehensive description of the current hybrid supercapacitor-battery and individual electric vehicle EV) battery charging techniques. In HESS, energy storage is dependent on both the battery and the supercapacitor, but in HESS, energy storage is only dependent on the battery. The chemistry of the battery limits the charging speed, whereas the composition of the supercapacitor increases it. The supercapacitor exhibits high thermal stability, thereby reducing the need for cooling equipment. Supercapacitors' high-power density allows them to absorb power surges, reducing battery stress and extending battery life. The disadvantage of employing a hybrid supercapacitor-battery system is that it raises the system's overall cost and network complexity.

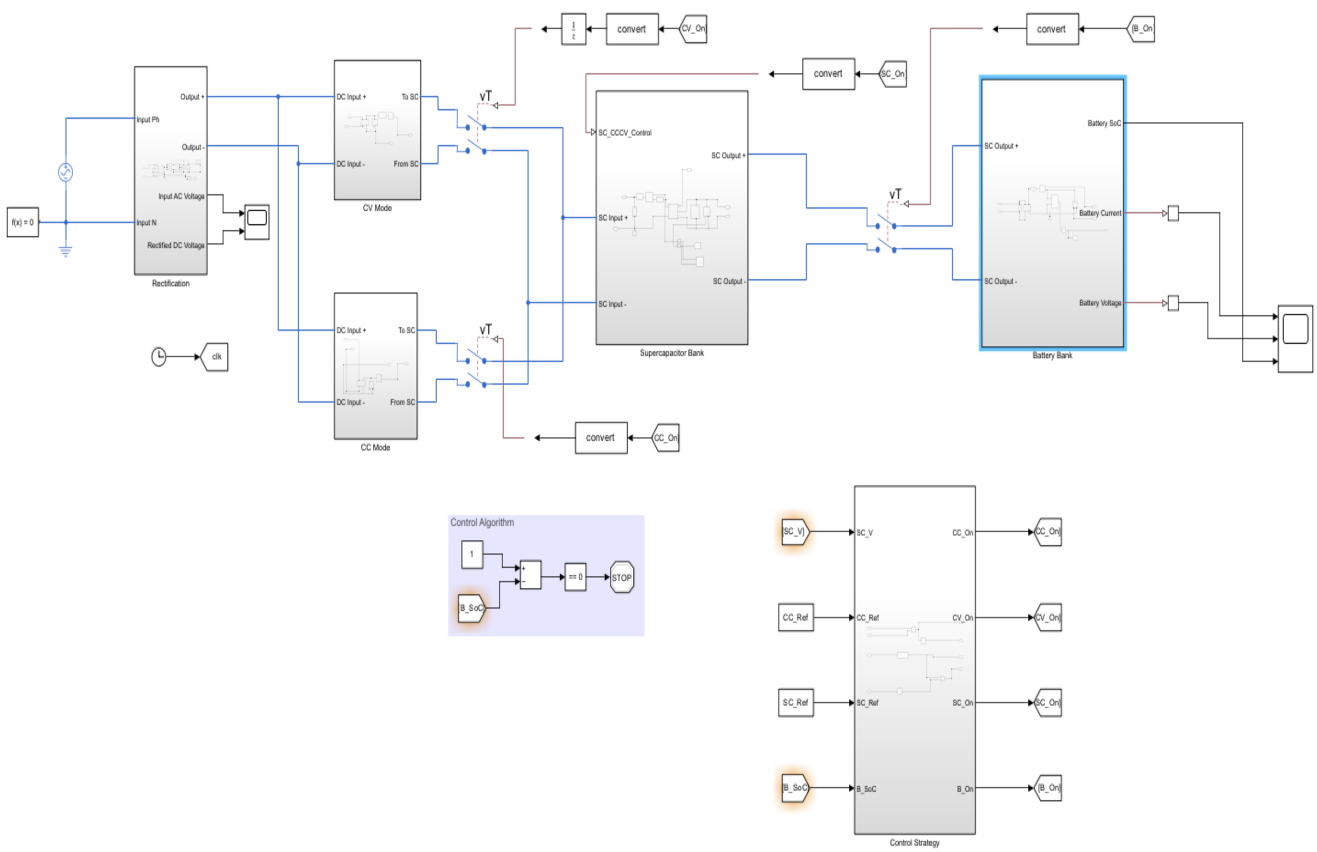


Fig. 12 Charging of a hybrid energy storage system

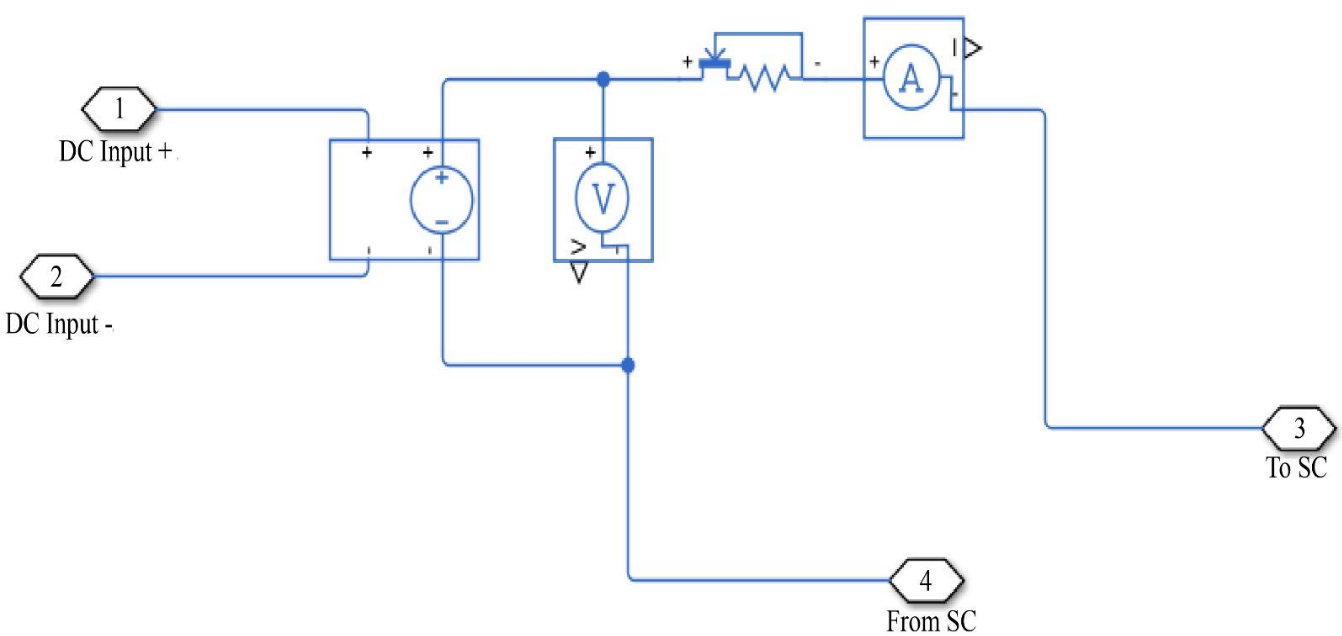


Fig. 13 CV mode of supercapacitor charging

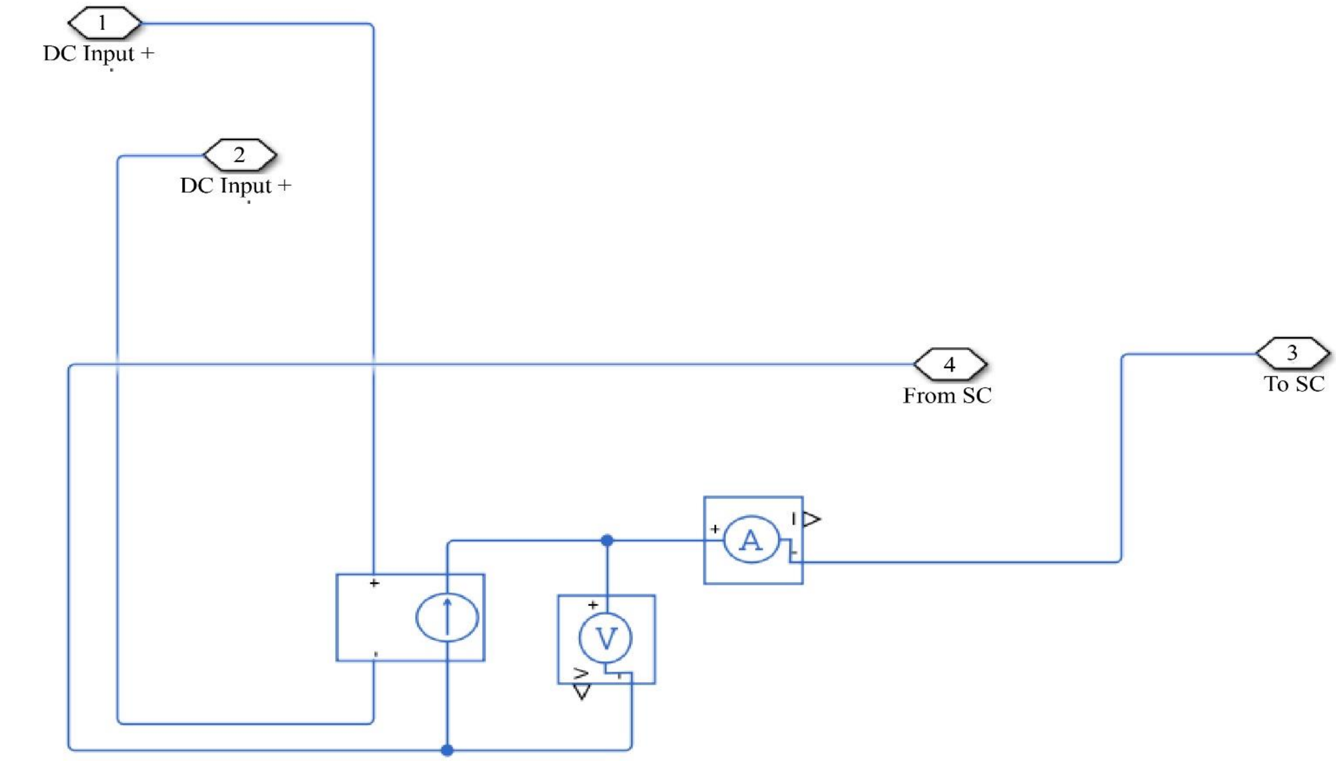


**Fig. 14 CC mode of supercapacitor charging**

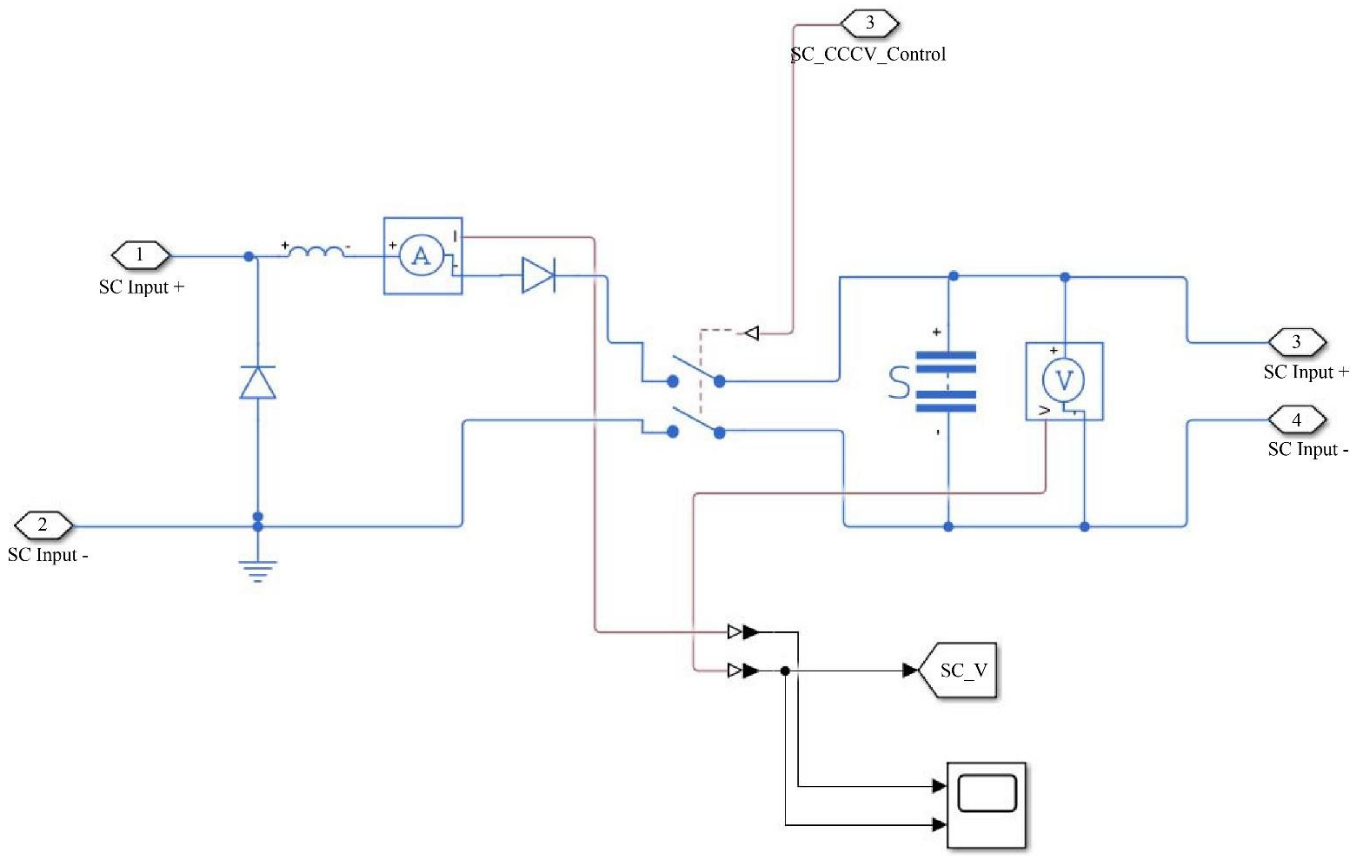


**Fig. 15 Supercapacitor bank charging circuitry**

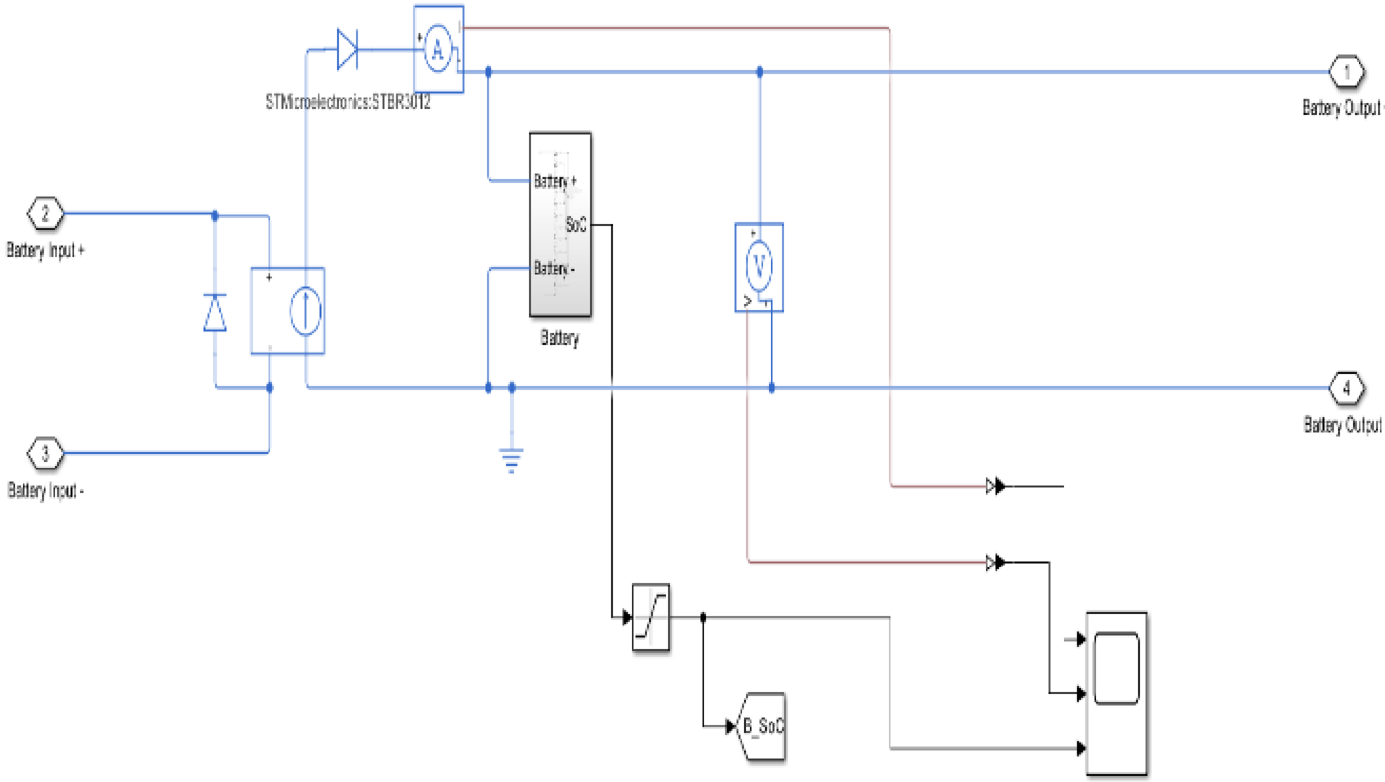


**Fig. 16 Battery bank charging circuitry**

### *5.1. Proposed Hybrid Energy Storage System*

Figure 12 illustrates the proposed charging of a hybrid energy storage system incorporating a supercapacitor and battery from the Electric Vehicle Supply Equipment (EVSE). The proposed HESS charges until both the energy storage devices reach 100% SoC. The microcontroller is programmed to measure the SoC values. Figure 13 shows the CV mode of supercapacitor charging with the help of a Constant Voltage controlled Voltage Source. The voltage is kept constant at 48V, and the current is limited to 5A with the help of a current limiter._Figure 14 shows the CC mode of supercapacitor charging using a Constant Current controlled Current Source. The current is kept constant at 48 A. The voltage of the supercapacitor would gradually increase when the current starts to flow through the supercapacitor. Once the supercapacitor reaches 48V, then the charging would change to CV mode. With the help of real-time observation of the supercapacitor's charging and discharging characteristics, its parameters are identified. The 2.7V, 500F supercapacitor is designed for 48V and can store 145.8Wh of energy through a series and parallel combination. Figure 15 illustrates the circuit connection of the supercapacitor bank, along with current and voltage measurements. Figure 16 shows the charging of the Li-ion battery charging circuit. The voltage-controlled current source is used to charge the battery bank. Fig describes the control strategy followed for charging the HESS. The control strategy block finds when the CC mode and CV mode are turned on/off, and when the supercapacitor and battery charging should start/stop.

In Fig, the MATLAB findings demonstrate that the charging time of the supercapacitor takes 233.47 seconds in CC mode, and then, to restore the nominal voltage, it would relate to the CV mode of charging. In Fig, the MATLAB results show that the charging time of the Li-ion battery is 931.37 seconds. Here, the charging current of the battery increases gradually.

This would reduce the transient overshoot. The overall charging time of the hybrid energy storage system takes 931.37 seconds. The total energy stored in the hybrid energy storage system is approximately 288.936 Wh. The changeover time from CC to CV is depicted in the charging characteristics. A unit delay is provided for the changeover from CC to CV. Fig and Fig can be compared to observe the difference in battery charging current. With the use of a supercapacitor, the battery's charging current increases gradually, preventing internal damage to the battery cell from a sudden high current supply. Sustainable environmental practices result from this.

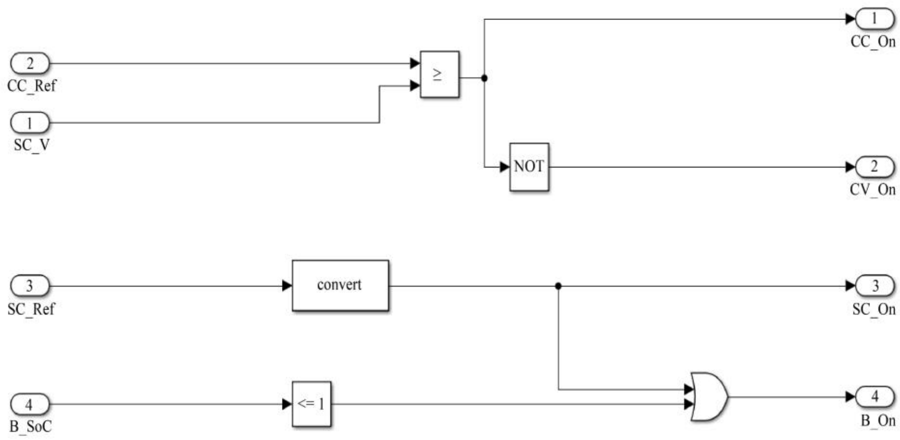


**Fig. 17 Control strategy of HESS**

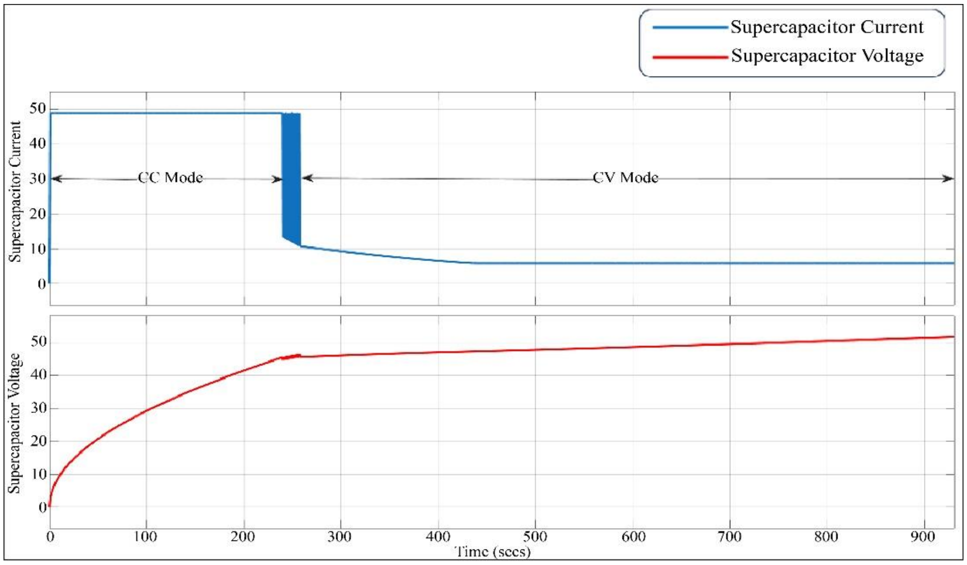


**Fig. 18 Supercapacitor charging in CC-CV mode**

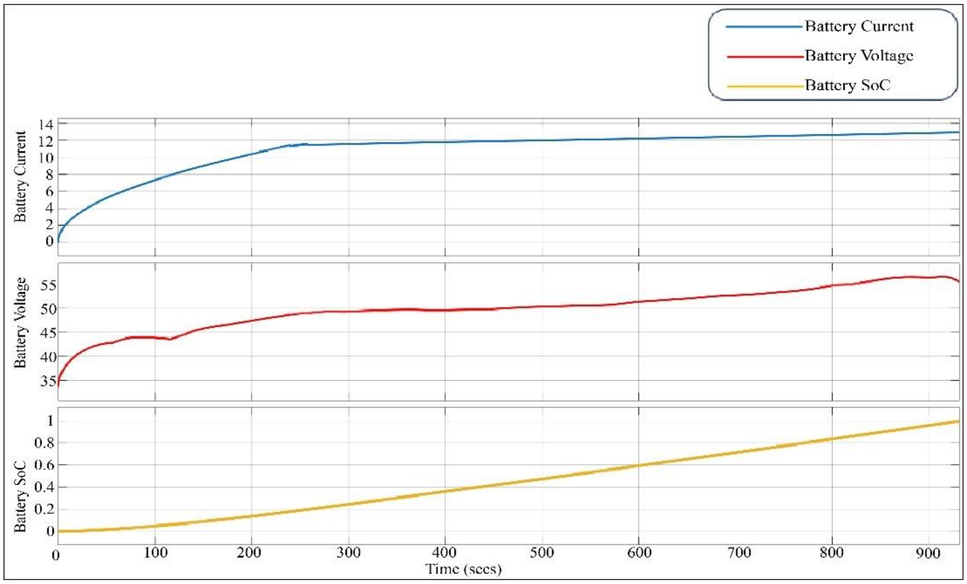


**Fig. 19 Battery charging characteristics**

### 5.2. EV Drive Connected with Hybrid Energy Storage System

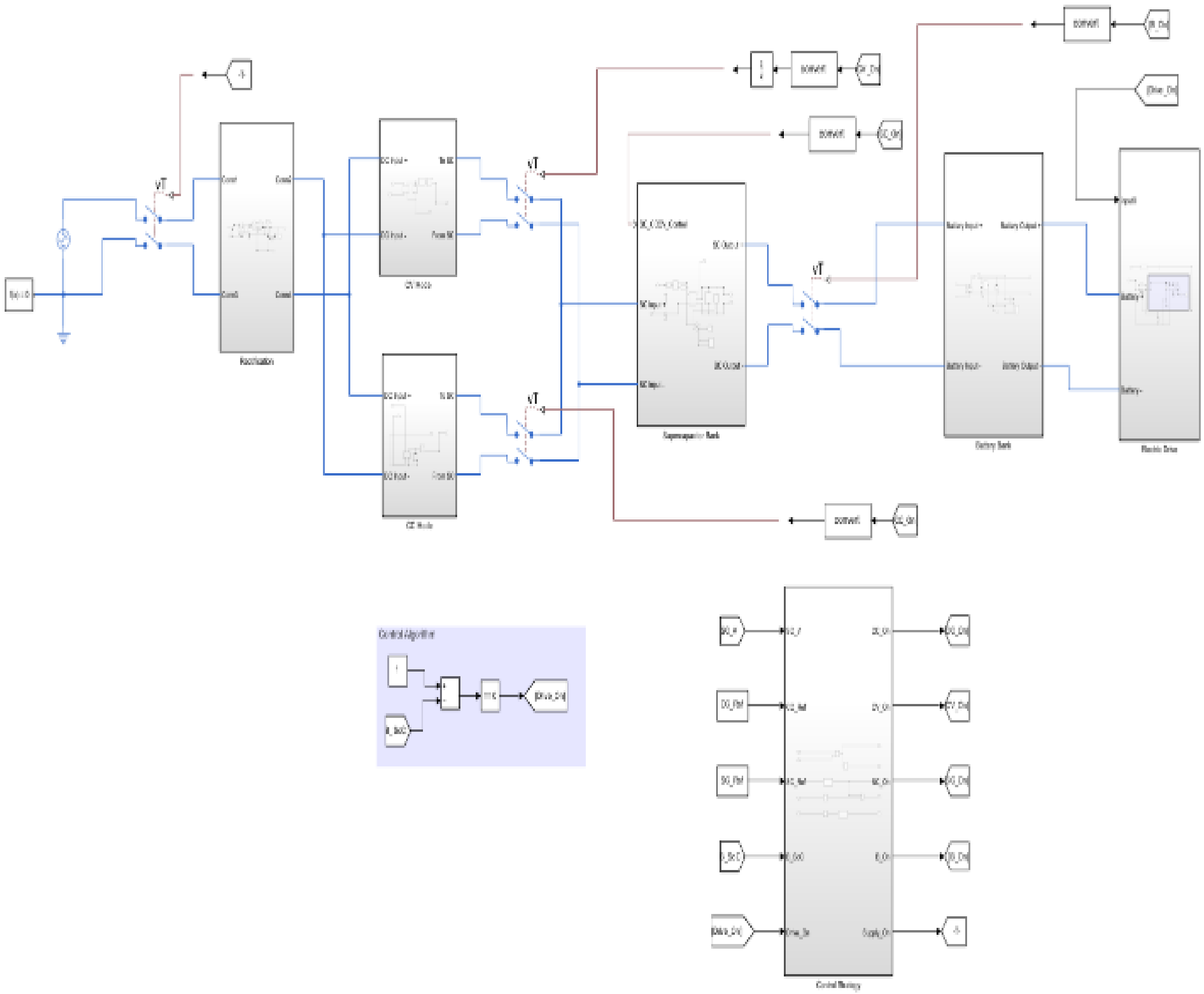

Fig. 20 EV drive connected with hybrid energy storage system

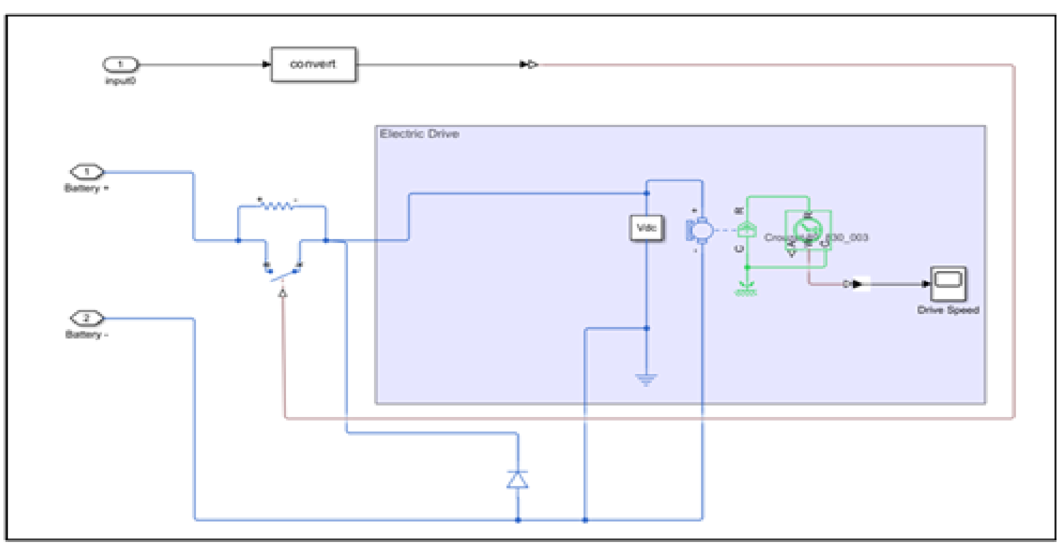


Fig. 21 EV drive

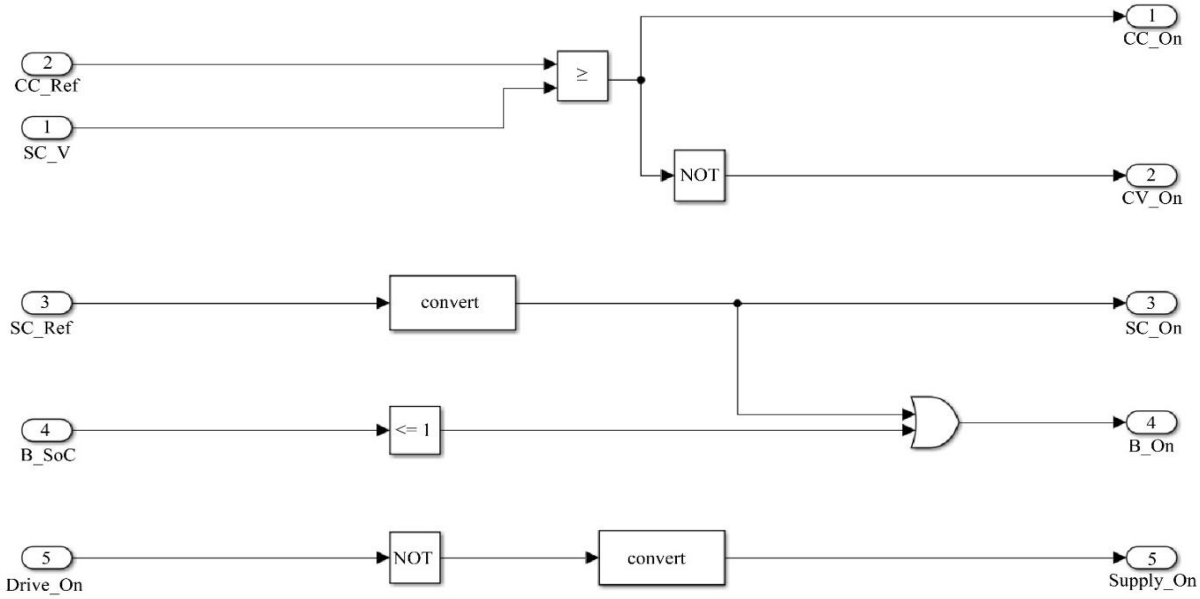


**Fig. 22 Control strategy of HESS with EV drive**

Figure 20 shows the EV drive connected with the HESS. Here, a DC motor is selected as an EV drive. The specification of the EV drive used is provided in section 4.a. The simulation is designed in such a way that once the charging of the supercapacitor and battery both stop, the EV drive starts to run.

Figure 21 shows the EV drive, which is 48V, 1.54A, 3000 rpm, and 1800Nm, connected to the hybrid storage system. The EV drive is connected with a Passive HESS topology. Figure 22 illustrates the control strategy of a passive HESS connected to the EV drive. When the HESS is fully charged, the EV drive is connected and powered on.

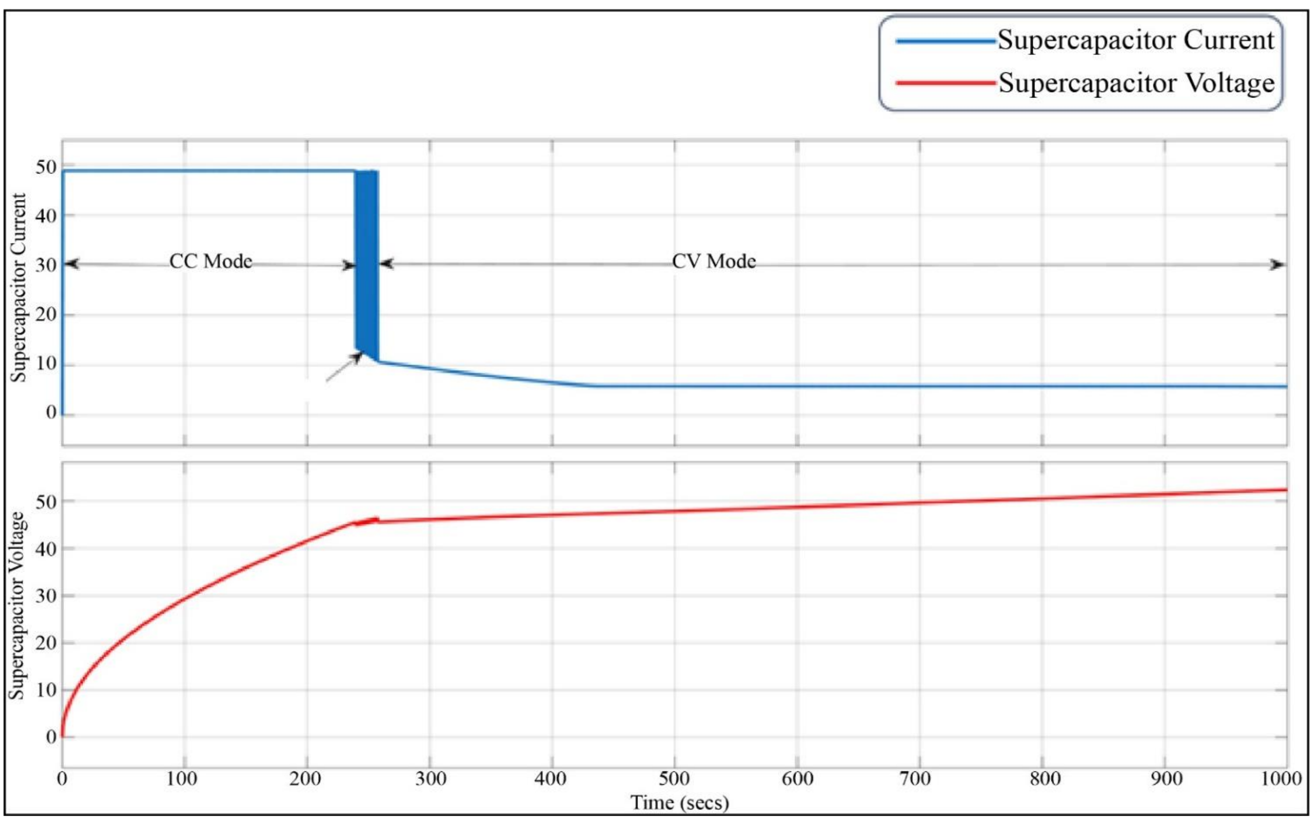


**Fig. 23 Charging of a supercapacitor**

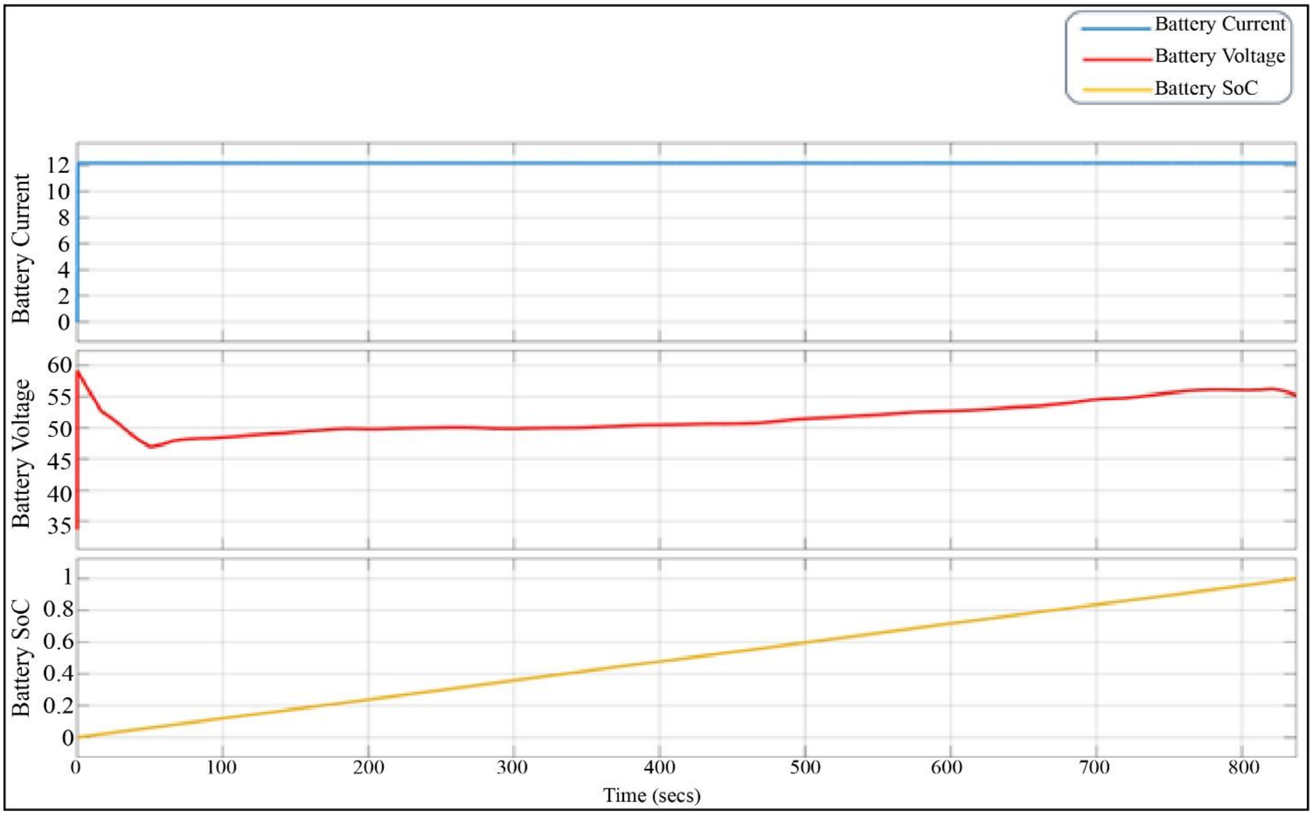


**Fig. 24 Charging of the battery**

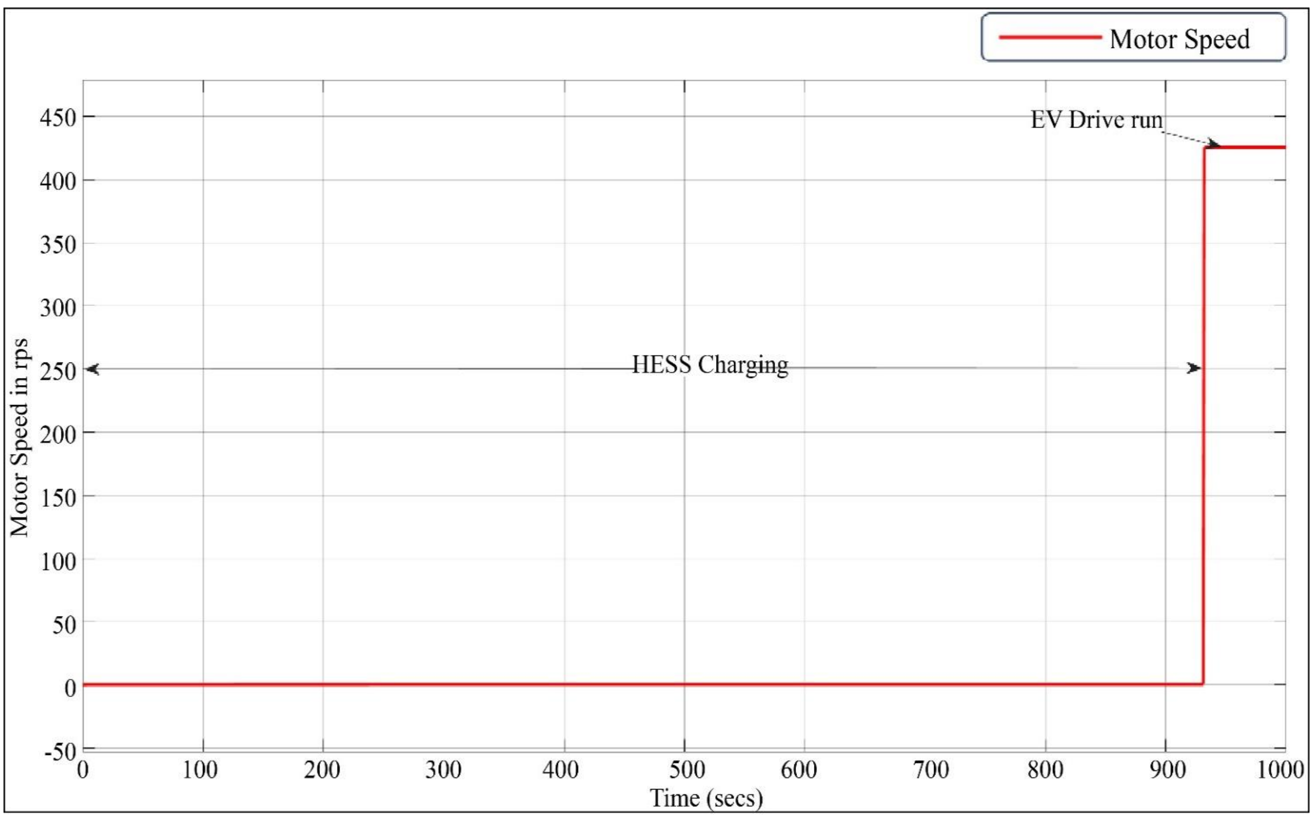


**Fig. 25 Output of the drive connected with the hybrid energy storage system**

Figure 23 shows the charging of a supercapacitor, Figure 24 shows the charging of the battery, and Figure 25 shows the output of the drive connected with a hybrid energy storage system. As per the calculation, the wattage of the DC motor used is 73.92 Watts. With the help of the energy storage system, the drive can run for a maximum of 3 hours, 54 minutes, and 30 seconds, depending on road and traffic conditions. Table 2 compares the performance of an individual battery storage system with a Hybrid Energy Storage System (HESS) that integrates a battery and a supercapacitor.

The results show that the HESS achieves a higher total energy storage capacity of 288.936 Wh, which is almost double the individual battery storage at 143.136 Wh. In terms of operational lifespan, the HESS sustains energy delivery for 3 hours and 55 minutes, compared to the individual battery delivering 1 hour and 56 minutes only. This enhancement demonstrates that integrating a supercapacitor not only increases the available energy but also reduces stress on the battery, thereby extending both the runtime and the overall durability of the storage system.

**Table 1. Comparison between individual battery storage and hybrid energy storage systems**

| Specifications | Individual Battery Storage | Hybrid Energy Storage System |
|---|---|---|
| Energy Storage | 143.136 Wh | 288.936 Wh |
| Life span of Energy Storage in hrs. | 1 hr 56 mins | 3 hrs 55 mins |

## 6. Conclusion

This paper outlines the passive hybrid energy storage technology that combines a battery and supercapacitor in electric vehicles. This paper presents the comparative modelling results of hybrid energy storage and individual battery energy storage. Furthermore, the simulation findings demonstrate the integration of two distinct energy sources with disparate properties. Since the presence of a battery and a supercapacitor is two distinct energy storage devices, the EV's range has also been extended. The introduction of a supercapacitor increases the life cycle of the battery.

This would decrease the environmental degradation of the battery due to a slower decomposition rate because of fast charging. Compared to a battery, the composition of a supercapacitor has a less negative impact on the environment. Additionally, the life cycle of the supercapacitor would be significantly higher compared to a battery. The introduction of supercapacitors requires more space, and currently, the cost of supercapacitors is significantly higher compared to batteries, which leads to an increase in the overall cost of the hybrid energy storage system with the incorporation of both supercapacitors and batteries. There is considerable research being conducted on supercapacitors that aims to make them affordable to everyone. The use of a Hybrid Energy Storage System increases energy efficiency, prolongs battery life, boosts performance, and facilitates better power flow control.

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## References

[1] Shekar Bose, Asadul Hoque, and Olaf Weber, “Enhancing Environmental Performance: Evidence from SAARC Countries,” *Contemporary South Asia*, vol. 33, no. 2, pp. 206-229, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[2] Arpita Pandey, and Rudrodip Majumdar, *Technological Trends in Electric Passenger Car Segment in India and Medium-Term Demand for Magnet-Based Rare Earth Materials*, E-Mobility in Electrical Energy Systems for Sustainability, IGI Global Scientific Publishing, pp. 321-342, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[3] Joselyn Stephane Menye, Mamadou-Baïlo Camara, and Brayima Dakyo, “Lithium Battery Degradation and Failure Mechanisms: A State-of-the-Art Review,” *Energies*, vol. 18, no. 2, pp. 1-43, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[4] Zeshan Ali Sandhu et al., “Green Revolution of Lithium-Ion Batteries: Prospects, Challenges and Environmental Impact,” *Chemistry-An Asian Journal*, vol. 20, no. 16, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[5] Somayeh Gooneh-Farahani, and Mansoor Anbia, “Strategies to Reduce NOx Emissions from Flue Gas: Trends and Prospects,” *Water, Air, and Soil Pollution*, vol. 236, no. 11, pp. 1-48, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[6] Nabil El Mounafia et al., “Eco-Friendly and Sustainable Solutions: Optimized LIB Recycling for High-Performance Supercapacitors,” *Journal of Power Sources*, vol. 656, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[7] Chrispin Tumba Tshiani, and Patrice Umenne, “The Impact of the Electric Double-Layer Capacitor (EDLC) in Reducing Stress and Improving Battery Lifespan in a Hybrid Energy Storage System (HESS) System,” *Energies*, vol. 15, no. 22, pp. 1-19, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[8] Bibaswan Bose et al., “Study on Li-Ion Battery Fast Charging Strategies: Review, Challenges and Proposed Charging Framework,” *Journal of Energy Storage*, vol. 55, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[9] Yu-Xing Yao et al., “Unlocking Charge Transfer Limitations for Extreme Fast Charging of Li-Ion Batteries,” *Angewandte Chemie*, vol. 135, no. 4, pp. 1-9, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[10] Rayavarapu Srinivasa Sankarkumar, and Rajasekar Natarajan, "Energy Management Techniques and Topologies Suitable for Hybrid Energy Storage System Powered Electric Vehicles: An Overview," *International Transactions on Electrical Energy Systems*, vol. 31, no. 4, pp. 1-30, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[11] Muhammad Bin Fayyaz Ahsan et al., "Lithium-Ion Battery and Supercapacitor-Based Hybrid Energy Storage System for Electric Vehicle Applications: A Review," *International Journal of Energy Research*, vol. 46, no. 14, pp. 19826-19854, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[12] Hossein Rezaei et al., "Energy Management Strategies of Battery-Ultracapacitor Hybrid Storage Systems for Electric Vehicles: Review, Challenges, and Future Trends," *Journal of Energy Storage*, vol. 53, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[13] C. Srinivasan, "Energy Management of Hybrid Energy Storage System in Electric Vehicle Based on Hybrid SCSO-RERNN Approach," *Journal of Energy Storage*, vol. 78, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[14] Xilei Sun et al., "An Energy Management Strategy for Plug-In Hybrid Electric Vehicles Based on Deep Learning and Improved Model Predictive Control," *Energy*, vol. 269, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[15] Nur Rachman Supadmana Muda, "Implementation of a Power Management System on Combat Robots Based on a Hybrid Energy Storage System," *Asian Journal of Engineering, Social and Health*, vol. 3, no. 3, pp. 475-485, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[16] Mohammad Kamrul Hasan et al., "Review of Electric Vehicle Energy Storage and Management System: Standards, Issues, and Challenges," *Journal of Energy Storage*, vol. 41, pp. 1-10, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[17] Zhaopu Zhang et al., "An Optimal Thermal Management System Heating Control Strategy for Electric Vehicles Under Low-Temperature Fast Charging Conditions," *Applied Thermal Engineering*, vol. 207, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[18] Kiran Raut et al., "Modeling and Simulation of Photovoltaic Powered Battery-Supercapacitor Hybrid Energy Storage System for Electric Vehicles," *Journal of Energy Storage*, vol. 82, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[19] N. Kumaresan, and A. Rammohan, "A Comprehensive Review on Energy Management Strategies of Hybrid Energy Storage Systems for Electric Vehicles," *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 46, no. 3, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[20] Hari Maghfiroh, Oyas Wahyunggoro, and Adha Imam Cahyadi, "Energy Management in Hybrid Electric and Hybrid Energy Storage System Vehicles: A Fuzzy Logic Controller Review," *IEEE Access*, vol. 12, pp. 56097-56109, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[21] Yue Wu et al., "Integrated Battery Thermal and Energy Management for Electric Vehicles with Hybrid Energy Storage System: A Hierarchical Approach," *Energy Conversion and Management*, vol. 317, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[22] Haifeng Dai et al., "State of Charge Estimation for Lithium-Ion Pouch Batteries Based on Stress Measurement," *Energy*, vol. 129, pp. 16-27, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[23] Federico Ibanez, *Hybrid Energy Storage Systems in Electric Vehicle Applications*, Electric Vehicles-Design, Modelling and Simulation, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[24] Sergio Marín-Coca et al., "New Parameter Identification Method for Supercapacitor Model," *IEEE Access*, vol. 11, pp. 21771-21782, 2023. [CrossRef] [Google Scholar] [Publisher Link]