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ENERGY MANAGEMENT FOR ELECTRIC VEHICLES WITH BATTERY AND SUPERCAPACITOR

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Abstract. This paper proposes an energy management strategy for battery and supercapacitor hybrid energy storage systems for electric vehicles. The main objective of the hybrid energy storage systems is to extend the durability of the battery pack by minimising peak currents of the battery during the charging and discharging of the battery in high power demand operations. During regenerative braking, energy is captured in the supercapacitor and is later used in high-power demand operations. In the proposed approach, energy consumption is reduced, the size of the battery pack is reduced, and the vehicle range is extended. The approach is based on a simple rule of power splitting in average, peak, and regenerative modes. The proposed hybrid energy management system is implemented and tested in MATLAB Simulink environment for different standard drive cycles.

Keywords: Hybrid energy storage system, energy management system, supercapacitor, regenerative braking, electric vehicle.

1. Introduction

Internal combustion engine vehicles are a significant source of environmental pollution and present a challenge for the automotive industry. Electric technologies like HEVs have been developed with various energy storage options to address this issue, though some still depend on internal combustion engines [1]. Initial studies show that EVs can overcome these obstacles and meet the fuel economy demands if battery designers collaborate with the development team to improve power and energy density and battery cycle life [2]. Electric vehicles are considered a promising solution for sustainable urban transportation due to their high efficiency and local emissions. The primary challenges regarding electric vehicles (EVs) are their short range compared to internal combustion engine vehicles (ICEV) that meet the practical needs of consumers and the long battery recharge time. One effective approach is to use regenerative braking energy to extend the range of electric vehicles and prevent the need for extra energy storage [3]. When an electric vehicle accelerates at high speeds, the transient current resulting from regenerative braking feedback in the motor current can surge up to 200 A or more [4]. The high current generated during regenerative braking can cause damage to lithium-ion batteries, whereas supercapacitors with higher power density enable efficient and quick charging from significant braking energy through the conversion of kinetic energy into electrical energy [5, 6].

However, according to previous research, the drastic change in battery charging/discharging power requirements, especially in urban areas, can reduce battery life [7]. One possible solution could be high-specific energy storage devices that can support high-peak power applications without a significant loss of durability [8]. Regenerative braking systems depend mostly on batteries alone as their energy storage component. However, this system has several drawbacks, including poor temperature characteristics, low specific power, and short life cycle. Additionally, the high power demands of vehicles, particularly in cities where there are loads is a lot of starting, accelerating, and decelerating, might damage the battery [9]. To address this problem, high-power density energy sources such as supercapacitors (SC) can help reduce the surge of high current charging and discharging on the battery [5]. The proposed Energy Management System (EMS) higher-level strategy includes using a supercapacitor to supply high power during peak demand and recover the braking energy. This is achieved through the implementation of the adaptive low-pass filter technique [10]. For optimal utilisation of regenerative braking (RB), an energy management system (EMS) is necessary. The EMS enables efficient distribution of power consumption among different sources within the vehicle's energy storage system. This ensures effective utilisation of kinetic energy, optimal vehicle performance, and improvement of battery life cycle [11].

Supercapacitors are an attractive option for electric vehicles, because of their many benefits, including high power density, extended life cycle, and strong transient charge and discharge performance [6, 12, 13]. The switched structure of battery/supercapacitor (SC) hybrid energy storage systems (HESS) allows for switching between the battery and the SC energy storage during different vehicle operations [12]. A control strategy for a fully-active hybrid energy storage system that uses two bidirectional DC/DC converters to regulate battery and supercapacitor currents as well as DC bus voltage can be seen here [11]. A control algorithm for the fully active HESS, is shown in reference [13]. Various aspects of lithium-ion batteries, including EV systems, energy management systems, challenges, and recommendations for future work, including battery components, energy storage, management systems, monitoring, and protection, can be found in reference [5]. Integrating the battery and SC units in to the DC-bus of the inverter is a major challenge when designing a hybrid energy storage system (HESS). There are many challenges faced in HESS development, such as the size of energy storage devices, controlling the supercapacitor charge, and maintaining the DC bus voltage constant [9, 14]. The size and type of the Energy Storage System (ESS) used mainly depend on driving patterns, which can vary based on factors, such as driver behavior, location, and traffic conditions [15]. Therefore, it's important to understand the impact of these driving patterns on the ESS size to prevent under or oversizing [16]. There are several commonly used methods for designing an Energy Management System (EMS) with a hybrid Energy Storage System (HESS), Fuzzy logic [17, 18], rule base [12, 19], nonlinear programming [7], sliding mode [13], classical controller and hysteresis controller [20].

This paper presents an innovative control strategy for regenerative braking systems, an allocation control mechanism that effectively splits the required optimal brake torque into two different components. These components are then precisely assigned to the friction brakes and regenerative brakes, respectively, optimising their functions [21]. The rule-based energy management strategy incorporates primary and secondary hierarchical energy management strategies. These strategies are integrated into the charge-depleting/charge-sustaining (CD/CS) control strategy [19]. The approach involves a setup of the drive system and an execution of the frequency separation technique [22]. The DC bus voltage regulation ensures energy balance in the hybrid system. A supercapacitor pack, known for its high power density and dynamic characteristics, supplies energy and maintains a stable DC bus voltage [23]. The sequential logic controller plays an important role in activating various regulation controllers and facilitating the switching between the storage devices based on the system's different driving modes [24]. The main objective of the controller is to ensure correct tracking of the reference values for the battery current, supercapacitor (SC) current, and DC bus voltage. The control inputs used are the duty cycles of two DC/DC converters. The SC current is also controlled as it helps maintaining the DC bus voltage at a constant level. Specifically, the reference values for battery and SC currents are calculated by the Energy Management System (EMS), which uses a rule-based controller to regulate the DC bus voltage within the desired value range. Additionally, the proposed rule-based controller regulates both the battery and the SC currents.

This paper proposes a simplified rule-based control strategy for a hybrid energy storage system (HESS) using supercapacitors and a battery, connected by a bidirectional DC/DC converter. The control strategy regulates the supercapacitors output and charging current, which are calculated based on the energy management strategy, which controls the DC/DC converter's switching between the battery and supercapacitors in different driving modes. Additionally, the study examines the contribution of battery-supercapacitor energy for city and highway driving cycles in order to determine the appropriate sizing for both components with regenerative braking systems. Energy recovery is analysed for various driving cycles to evaluate the effectiveness of the proposed strategy and analysing the energy recovery for different driving cycles.

The contributions of the paper are as follows:

(1.) Implementing a rule-based power management for the battery and supercapacitors.

(2.) Proposing a model for utilisation of regenerative braking energy using supercapacitors and battery as the energy storage system.

(3.) Analysing the battery-supercapacitor energy management at different driving conditions.

The paper is organised as follows, Section 2 consists of mathematical modelling of system components: battery, supercapacitor, vehicle body, and DC/DC converter. Section 3 discuses the power-train components, necessities and challenges faced in HESS vehicles. Section 4 discusses a detailed introduction of EMS and the implementation of rule-based Energy Management strategy in a HESS. Section 5 discusses the Simulation and Analysis of the proposed Hybrid Energy Storage System. Section 6 discusses the results obtained from the proposed rule-based energy management strategy. At the end all simulation results data are presented in a comparative form in a table to evaluate the performance of each case and for different driving cycles.

2. Modelling of system components

2.1. Electric vehicle model

It is crucial to comprehend the dynamics of electric vehicles (EVs), in order to optimize their performance and improve their efficiency. This study introduces a fundamental model that captures the primary forces affecting an electric vehicle and establishes their connection with the power demand required for propulsion. The model incorporates various factors, including rolling resistance, aerodynamic drag, vehicle mass, incline angle, and powertrain efficiencies. The dynamics of the vehicle are shown in Figure 1.

The fundamental model that describes the dynamics of an electric vehicle is presented as:

$$rV\cos\beta + 0.5C_d A\rho V^3 + mV_x\frac{dv}{dt} + mgV\sin\beta = P_{\text{demand}}\,\eta_t\eta_m. \tag{1}$$

The variables used in the model include the mass of the vehicle (m), gravitational acceleration (g), the rolling resistance coefficient (r), the velocity of the vehicle (V), the incline angle of the road (β), the aerodynamic drag coefficient C_d, the front area of the vehicle (A), the density of the medium (ρ), the transmission efficiency (η_t), and the efficiency of the electric motor (η_m).

$$mV = F_x - F_d - mg\cdot\sin\beta, \tag{2}$$

$$F_x = n\left(F_{xf} + F_{xr}\right), \tag{3}$$

$$F_d = \frac{1}{2}C_d\rho A\left(V + V_w\right)^2\cdot\operatorname{sgn}\left(V + V_w\right), \tag{4}$$

$$F_{zf} = \frac{-h\left(F_d + mg\sin\beta + mV\right) + b\cdot mg\cos\beta}{n(a+b)}. \tag{5}$$

The normal force acting on the front and the rear tyre are calculated by zero normal acceleration and zero normal pitch torque:

$$F_{zr} = \frac{+h\left(F_d + mg\sin\beta + mV\right) + a\cdot mg\cos\beta}{n(a+b)}, \tag{6}$$

$$F_{zf} + F_{zr} = mg\frac{\cos\beta}{n}, \tag{7}$$

where a and b are the distance between the front and rear axles, h is the height of the vehicle, n is the number of wheels on the n axle, V_w is the wind speed, F_d is the aerodynamic drag force, F_{xf} and F_{xr} are longitudinal forces on the front and rear tire, F_{zf} and F_{zr} are normal load forces on the front and rear tire.

2.2. Battery model

In an energy storage system, battery modelling is very important to study the behaviour of the system by considering all parameters, which affect the overall battery performance. For an electric vehicle, a lithium-ion battery is modelled in a MATLAB Simulink environment. For modelling the lithium-ion battery in MATLAB battery specific ratings are required and they are given in the simulation section. The battery model is designed using various control system blocks to simulate an actual battery performance, and it is based on fundamental mathematical equations which are discussed below. Figure 2 shows the circuit of the battery block model in MATLAB [25].

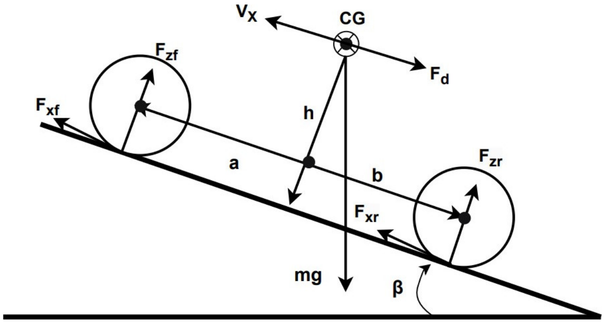


Figure 1. Vehicle body dynamics.

The output voltage of the battery is given by the equation:

$$V_{\text{bat}} = E_{\text{bat}} - R_i i_{\text{bat}}, \tag{8}$$

where V_{bat} denotes the battery's output voltage, E_{bat} denotes its open-circuit voltage, R_i denotes its internal resistance of the battery, and i_{bat} denotes the battery current. The charging and discharging voltage of the battery is represented by dynamic mathematical Equations (9) and (10):

$$E_{\text{bat}_{\text{dis}}} = E_0 - K\frac{Q}{Q-q}i_d - K\frac{Q}{Q-q}q + M\exp(-N*q), \tag{9}$$

$$E_{\text{bat}_{\text{ch}}} = E_0 - K\frac{Q}{q+0.1Q}i_d - K\frac{Q}{Q-q}q + M\exp(-N*q), \tag{10}$$

where Q represents the maximum battery capacity, E_0 represents the constant voltage, i_d represents the altered current from the low pass filter to the battery current, K serves as the polarisation constant, M exp represents the exponential voltage, q represents the extracted capacity, and N represents the exponential capacity. The SOC of the battery is given by Equation (11):

$$SOC = 100\left(1 - \frac{\int_0^t i_{\text{bat}}\,dt}{Q}\right). \tag{11}$$

2.3. Supercapacitor model

Supercapacitors are widely used in various applications where a fast and dynamic response is required in a short time period. When modelling a supercapacitor, all characteristics must be accounted for. In hybrid energy storage, a supercapacitors are used mainly for providing peak power for a short duration and storing regenerative braking energy effectively without degrading the life of the supercapacitor and helping the battery to maintain its SOC. Compared to batteries, the relations between the terminal voltage and the remaining capacity of supercapacitors is more linear. Therefore, the SOC of a supercapacitor is used to indicate its remaining capacity, which can be calculated using the expression provided in [18]. The supercapacitor model circuit is shown in Figure 3.

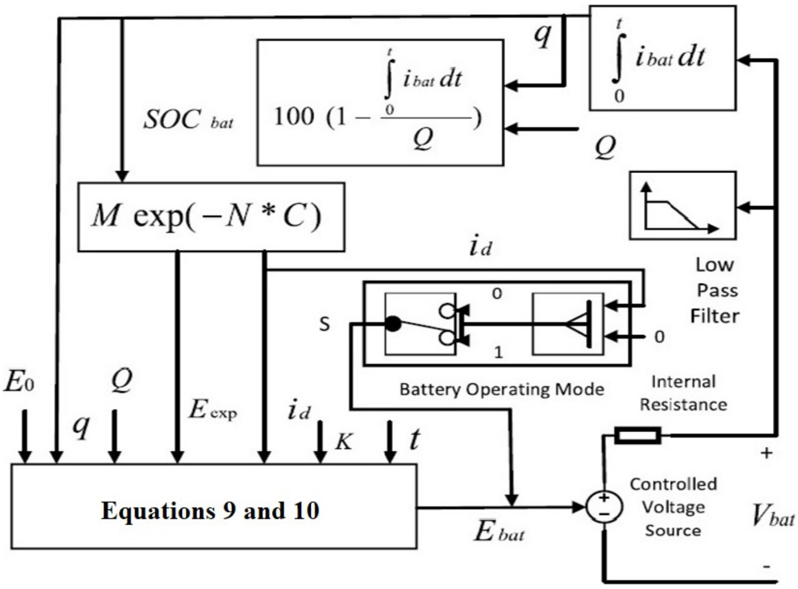


FIGURE 2. The equivalent circuit of the battery block model in MATLAB [25].

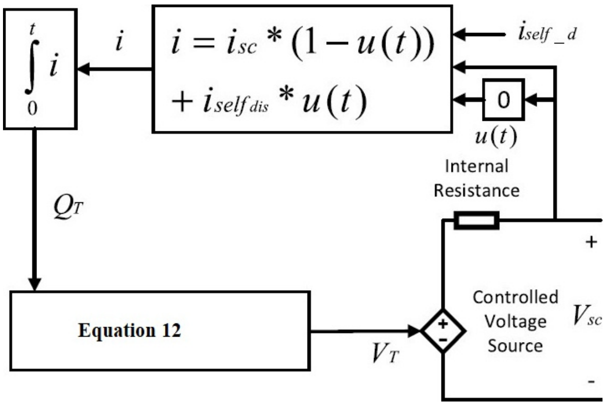


FIGURE 3. Supercapacitor model circuit in MATLAB platform.

The supercapacitor output voltage is expressed in mathematical form by a Stern equation:

$$
\begin{aligned}
V_{\mathrm{sc}} &= \frac{N_s Q_T d}{N_p N_e \varepsilon \varepsilon_0 A_i} + \frac{2 N_e N_s R T}{F} \\
&\cdot \sinh^{-1}\left(\frac{Q_T}{N_p N_e^2 A_i \sqrt{8RT\varepsilon\varepsilon_0 c}}\right) - R_{\mathrm{sc}} \cdot i_{\mathrm{sc}},
\end{aligned}
\tag{12}
$$

where V_{sc} is the output voltage of the SC, N_p represents the number of parallel capacitors, N_s represents the number of series capacitors, N_e represents the number of layers of electrodes in the SC, Q_T represents the electric charge (C), d is the molecular radius, R is the ideal gas constant, T is the operating temperature, q represents the extracted capacity, A_i is the interface area between the electrodes and electrolyte in (m^2), F is faraday constant, and $\varepsilon, \varepsilon_0$ are the permittivity of material and free space.

With:

$$Q_T = \int i_{\mathrm{sc}} dt, \tag{13}$$

the self-discharge of a supercapacitor is represented by the electric charge of a supercapacitor is modified as follows ($i_{\mathrm{sc}} = 0$):

$$Q_T = \int i_{\mathrm{self_{dis}}} dt, \tag{14}$$

$$
i_{\mathrm{self_{dis}}} = \begin{cases} \dfrac{C_T \alpha_1}{1 + sR_{\mathrm{SC}} C_T}, & \text{if } t - t_{OC} \le t_3 \\ \dfrac{C_T \alpha_2}{1 + sR_{\mathrm{SC}} C_T}, & \text{if } t_3 < t - t_{OC} \le t_4 \\ \dfrac{C_T \alpha_3}{1 + sR_{\mathrm{SC}} C_T}, & \text{if } t - t_{OC} > t_4 \end{cases} \tag{15}
$$

where i_{sc} is the current of the supercapacitor, C_T is the total capacitance, R_{SC} is the internal resistance of the supercapacitor, and α_1, α_2 and α_3 show the constraints and the rate of change of supercapacitor voltage during the time intervals ($t_{OC}; t_3$), ($t_3; t_4$) and ($t_4; t_5$), respectively. The SOC of a supercapacitor is used to indicate its remaining capacity, which can be calculated using the expression provided in [16]:

$$\mathrm{SOC_{SC}} = \frac{V_{\mathrm{ter}} - V_{\mathrm{min}}}{V_{\mathrm{max}} - V_{\mathrm{min}}}, \tag{16}$$

where the variable V_{ter} refers to the terminal voltage of the SC, while V_{min} and V_{max} denote the minimum and maximum cutoff voltages of the supercapacitor, respectively.

2.4. CONVERTER MODEL

Figure 4 shows the circuit diagram for the fully active HESS that is being used. It is composed of a battery, supercapacitor, and a motor load, along with two standard bi-directional DC/DC converters. The load, which includes the motor has a predictable power demand, represented as a varying current i_m. The model only takes into account the inner series resistance of the battery and supercapacitor models, R_{bat} and R_{sc}, respectively, to simplify it. During the charge and

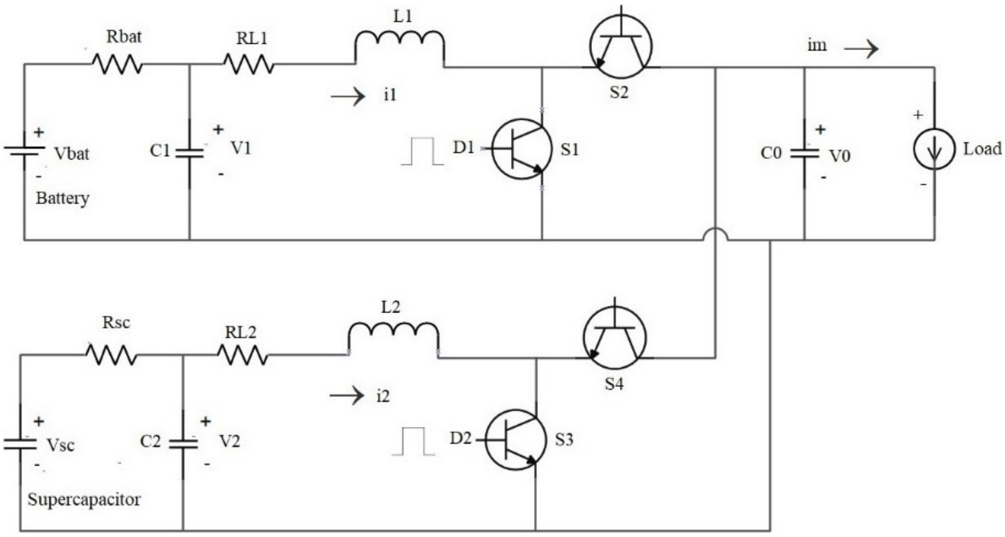


Figure 4. Circuit diagram of fully active HESS.

discharge operations, there are two DC/DC converters used as current controllers for both the battery and the supercapacitor. The bi-directional DC/DC converter comprises two IGBTs, a capacitor, and an inductor with its series resistance considered. The two IGBTs operate synchronously, with S1 and S2 operating in opposite phases, and the same applies to S3 and S4. The duty cycle of the IGBT is represented as D1, with the on-resistance of switch S1 represented as Ron1. Additionally, Vbat and Vsc represent the open-circuit voltages of the battery and the supercapacitor, respectively.

The HESS circuit diagram, shown in Figure 4, includes a battery pack, an SC pack, and two bidirectional DC/DC converters consisting of resistors, inductors, and capacitors. To connect the battery pack to the DC bus, an IGBT is used. Another bidirectional DC/DC converter, consisting of two IGBTs ($S1$ and $S4$), a capacitor ($C0$), and an inductor ($L2$) is used to link the SC pack to the DC bus. The model of the DC/DC converter incorporates the inductor series resistance, the equivalent IGBT resistance, and the IGBT freewheel diode. The motor load current is represented as Im.

The HESS's average model over a single switching period can be defined as follows:

$$V_1 = -\frac{V_1}{R_{\mathrm{bat}}C_1} - \frac{i_1}{C_1} + \frac{V_{\mathrm{bat}}}{R_{\mathrm{bat}}C_1}, \tag{17}$$

$$V_2 = -\frac{V_2}{R_{\mathrm{SC}}C_2} - \frac{i_2}{C_2} + \frac{E_{\mathrm{SC}}}{R_{\mathrm{SC}}C_2}, \tag{18}$$

$$\begin{aligned} i_1 = \frac{V_1}{L_1} - i_1\frac{R_{\mathrm{L1}} + R_{\mathrm{on2}}}{L_1} - \frac{V_0}{L_1} \\ + D_1 i_1 \frac{R_{\mathrm{on2}} - R_{\mathrm{on1}}}{L_1} + V_0\frac{D_1}{L_1}, \end{aligned} \tag{19}$$

$$\begin{aligned} i_2 = \frac{V_2}{L_2} - i_2\frac{R_{\mathrm{L2}} + R_{\mathrm{on4}}}{L_2} - \frac{V_0}{L_2} \\ + D_3 i_2 \frac{R_{\mathrm{on4}} - R_{\mathrm{on3}}}{L_2} + V_0\frac{D_3}{L_2}, \end{aligned} \tag{20}$$

$$V_0 = \frac{i_1 + i_2}{C_0} - \frac{i_{\mathrm{m}}}{C_0} - D_1\frac{i_1}{C_0} - D_3\frac{i_2}{C_0}. \tag{21}$$

Capacitor voltages V_0, V_1, and V_2, along with inductor currents i_1, and i_2, are used to represent the typical HESS model through a single switching cycle. Since the SC has a large capacitance, its voltage change within a switching period is disregarded. Using the aforementioned average model, a 5^{th} order state-space model for the HESS can be derived, which has been previously confirmed in [5].

3. Hybrid energy storage system

3.1. HESS powertrain

The HESS powertrain consists of various components that involve different energy sources with different characteristics, such as electronic converters and mechanical coupling from the motor to the vehicle drive shaft. The energy storage systems have different but complementary characteristics to each other. Two power electronic converters, which convert DC/DC operation and link the motor and the energy storage system, control part of an electric vehicle, which control and transfer energy based on the requirement of the vehicle. The battery and supercapacitor are connected to a motor via a DC/DC converter as shown in Figure 5, which uses a fully active hybrid topology that uses two independent converters. This type of topology was chosen because it actively controls the output current of the battery and the supercapacitor, which helps to maintain a stable DC link voltage at the input motor terminals. The motor is connected to tyres through a mechanical coupling to transfer the rotational mechanical power.

The whole fully active topology is controlled by a main controller, which collects data from powertrain components and instructs them to perform specific control actions based on an energy management algorithm. This design was chosen for the HESS because

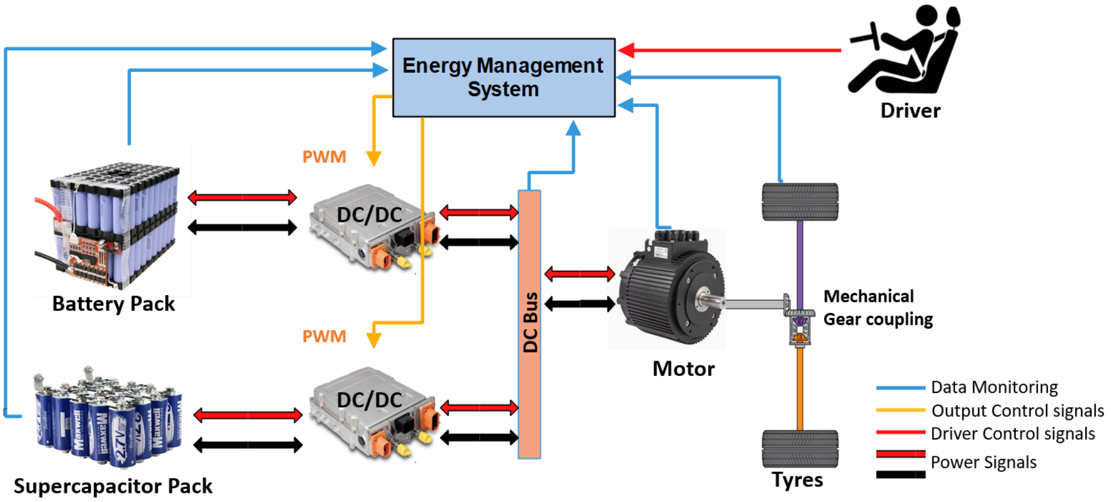


Figure 5. Architecture of electric vehicle powertrain.

it allows for more flexible and efficient regulation of the battery and supercapacitor independently [26]. This configuration of power electronic converters ensures a high system performance and efficiency due to the stable voltage across the DC link, with low cell balancing issues with the battery and SC packs. The topology is widely adopted in smart grid systems, where two or more energy storage devices are integrated for more efficient operation due to its independent control of each source.

3.2. Necessity of HESS

The Li-Ion battery cannot handle rapid changes in power demands during acceleration or regenerative braking due to its dependency on reduction and oxidation reactions for charge transfer [5]. These sudden power demands put excessive stress on the battery and as a result, reduce the lifespan of the battery. These actions result in degradation at the cell level, as a result of increased internal resistance and capacity loss over time [9]. However, flywheel (FW) or supercapacitor (SC) technologies have the power density needed to sustain high power outputs for short time period [27]. The Li-Ion battery is the primary energy storage component in electric vehicles due to its high energy density. When it comes to automotive applications, particularly during extreme braking and traction driving situations, the battery shows several weaknesses related to its chemical reactions during charging and discharging operations [28]. These reactions result in capacity degradation and reduced lifespan, and in extreme cases, fire can also happens and damage the whole vehicle and endanger human life [22]. Due to the fast degradation of the battery, the whole battery pack needs to be replaced, which is very costly. Additionally, the battery is struggling to meet the power requirements specified by the traction and braking control systems during these various intense driving operations [29]. To tackle these challenges and minimise the stress on the battery, it is necessary to add another energy storage device, which supports the battery [30]. This secondary storage system should have the ability to deliver the required power for intense driving scenarios, replacing the battery during periods of high power demand. The secondary energy system has a high dynamic response without affecting its life cycle [16]. The supercapacitor is a promising solution for secondary energy storage elements, because it shows high power density as compared to battery and fuel cell energy storage devices, Figure 6 shows the energy and power characteristics of different energy storage devices [31].

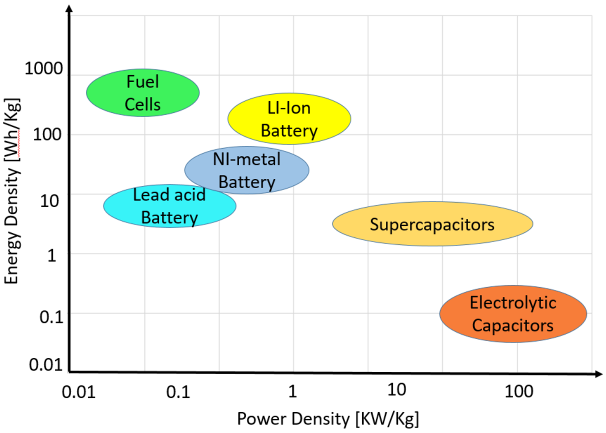


Figure 6. Energy vs power density.

High-power energy storage devices have a high response rate and high-energy devices have a slow response rate. This integration proves highly suitable for electric vehicle applications, mostly due to its exponential power density with energy density capabilities. Combining a battery with a supercapacitor offers many advantages, which include high dynamic response, providing peak power during high acceleration and starting operation, storing regenerative braking energy effectively without shortening the life of the supercapacitor, fast charging, and improving the storage system life of the vehicle [32].

There are different topologies by which the battery and supercapacitor are connected to the DC bus, which include the parallel, semi-active, and fully active combinations. The topology is selected based on operational modes and the size of primary and secondary energy storage devices. The supercapacitor allows for smooth energy transfer within the system, which also helps to preserve the vehicle's dynamic load profile and extend the possible driving range. Therefore, in electric vehicles, the use of a battery and supercapacitor together provides an effective method of long-term energy management and dynamic power regulation.

3.3. Challenges in HESS

3.3.1. System design and sizing

When a battery and a supercapacitor are combined, it makes the system complex and challenging to control due to the differences in unpredictable driving patterns. Combining high power and high energy density devices together requires maintaining the DC bus voltage without putting stress on the power converter while shifting between different modes. Another challenge while designing the system is the proper sizing and optimisation of both energy sources with the power and energy density requirement of an EV, for which no standard practices are available. If the size of the battery and supercapacitor pack is not optimal. Without taking specific requirements into account, choosing a large capacitor increases costs and small SC packs fail to provide peak power, putting a strain on the battery and adding weight and space to the EV. On the other hand, choosing a small battery causes faster degradation and reduction of battery life, and the vehicle dynamic response will be significantly affected.

3.3.2. Topology and converter design challenges

Designing a power electronic converter for these HESS applications is very challenging due to the rapidly changing driving patterns, peak-power and regenerative braking demands, and high current flows through converter switches. In addition, they need to be very robust with fast response for safe operation [33]. While designing these hybrid complex systems, the main challenge is to design the system as complex as possible without compromising the vehicle performance. There are different converter topologies available to connect the battery, SC, converter, and the motor together. If we select a single converter topology, it comes with more complex control. On the other hand, if we choose a converter topology for easy control, then it increases system cost, space, and weight. So choosing the right topology is very critical. The power converter faces issues such as switching losses, PWM control, device durability, and its overall reliability to ensure safe operation [34].

The batteries need converters designed for stable, high-energy transfer, supercapacitors demand fast-response, high-power converters capable of handling rapid charge and discharge cycles. Integrating separate converters for the battery and the supercapacitor increases cost and operational complexity, but different vehicle modes of operation need to run the system for the rated power, while maintaining efficiency, stable operation, and proper cooling of these components. While adding regenerative braking, the bidirectional DC/DC converter rating is very important, because during this mode, the converter handles high peak currents to charge the supercapacitor while maintaining a safe DC voltage to ensure stable operation [33]. The converter switch must be selected appropriately for sustaining high peak current and fast switching without affecting the converter's performance and system stability. These challenges can be overcome by optimal design and rating selection synchronised with the energy management system.

3.3.3. Control strategy and energy management challenge

The main challenge of EMS is real-time, precise decision making to calculate how much power should be drawn from the battery and how much from the supercapacitor, the key challenge is to control the EMS for various based objectives effectively and without failure. This requires developing and tuning a controller algorithm based on logic that handles real time driving situations and SOC limitations of storage devices. Real-time, accurate estimation is challenging due to temperature, current transients, and aging effects of energy storage and another power components [35]. To make optimal energy allocation decisions, future power demand must be accurately predicted, so it's challenging to develop and integrate into actual hardware for implementing predictive algorithms that learn or adapt to driving behavior and unexpected changes. In some cases, a primary power source fails to supply power for all components of the system, mainly for the control unit of the vehicle. In this case, a backup power source must be present to supply power in different load demand conditions. Continuous monitoring of all parameters and processing of data is very important to make decisions on power shifting in different driving scenarios while maintaining a safe operating state. The control and coordination of all components in real time is essential for a hybrid system control [36].

3.3.4. Thermal management

The continuous discharging and charging of the HESS based on vehicle acceleration and deceleration and regenerative braking modes, causes high bidirectional peak currents to flow through the system, which causes losses in the form of heat from the battery, SC, converters and motor. As the HESS is complex due to the integration of various components, which results in more heat generated from different units, it is essential to dissipate heat at the fastest rate possible to maintain system temperature in a safe range. For heat dissipation, energy management systems requires auxiliary electrical power, which is drawn from HESS, and therefore impacts the vehicle range. To address this, energy storage devices and converters need to be designed and located in EVs in such a way that they naturally dissipate heat at a faster rate without affecting the performance. Therefore, the thermal management is challenging to implement, so is to maintain a safe range with the available space, low cost, and higher efficiency. The challenge is to design and integrate a thermal management system for all equipment to maintain safe thermal regulation within a limited space, without affecting the performance.

3.3.5. Protection and fault tolerance

The battery and SC both have their safe operational range that depends on their rated design and cell integration. In order for a protection system to be capable of protecting in uncertain conditions, safe operating parameters are needed. When a fault happens in one of the batteries, supercapacitor, or its independent converter, it should not compromise the vehicle's operation. So it is a challenge for designers to design a fault-tolerant system that is very robust for fault detection and isolation mechanisms to bypass the faulty system and not hinder vehicle operation.

3.3.6. Cost and space requirement

A hybrid energy storage system combines two energy storage devices, DC/DC converters, controllers, sensors, and an auxiliary power supply unit, which increases the cost of the system. For a hybrid system, which has multiple components, it is very important to consider the limited space available when designing the placement of the components. Manufacturing this hybrid storage system for an EV at a low price is very challenging.

Regardless of the placement of the components, such as additional SC packs, DC/DC converters, supercapacitors and their energy management system (EMS), control units increase the initial cost and space requirements, however, these are countered by a number of significant benefits. The supercapacitor supplies high current transients and absorbs regenerative braking energy efficiently, by reducing peak power spikes on the battery. The rule-based power splitting energy management results in an extended battery life cycle and extend battery replacement time, which leads to reduced maintenance and operational costs. In future work, we plan to conduct a full economic cost-benefit analysis to determine the cost-benefit of the system with the battery alone and the HESS electric vehicle [37].

As the system is more complex due to the multiple components, the complementary characteristics of the battery and supercapacitator, they share workload, which in turn reduces the stress on individual components and increases their lifespan. The modular design of supercapacitor and battery modules with converters and other components makes repairs and replacements easier. Although the initial cost is high due to the extra energy storage elements and its systems and control hardware, the long-term benefits are the longer battery replacement period, which carries a huge percentage of the vehicle maintenance costs, and also due to the energy recovery from regenerative braking, its operational cost are also reduced. Therefore, the initial high cost is compensated by long-term user benefits.

3.3.7. Packaging

We plan a modular system architecture for the battery and SC modules, in which energy storage units and power converters are fit into a single compact unit. This modification provides easier integration into the current EV architecture makes it easier to integrate the system into an EV and it also reduces the need for long wiring harness, significantly reducing space requirements and costs [38]. The prototype unit, with all components combined, was placed directly on the chassis without modifying the vehicle. For minimising space and cost, we suggest a DC/DC semi-active hybrid converter configuration that uses only one converter with advanced control. Implementing a hybrid topology to integrate a battery and supercapacitor in to the motor reduces overall space requirement, constant weight, and additional connections and wiring. We can optimise space and cost at the same time by using a less complex system. However, the exact system and configuration depend on the specific vehicle and its applications.

Based on the vehicle space availability, components such as SC modules can be placed areas that are less sensitive to space, such as near the wheels or on top of the vehicle in electric buses. This balances weight distribution and makes efficient use of available space. However, there are some trade-offs when modifying a standard EV in this way. The integration of SC and its supporting electronic systems adds some weight to the vehicle. However, the added weight is offset by increased regenerative braking, reduced strain on the battery bank, and increased range. This allows the size of the battery pack to be reduced. Introducing these components may lead to a smaller vehicle interior space and reducing the vehicle's usable boot space. However, these effects are minimised in most cases and can be mitigated through proper optimal design planning with the help of an EV design expert.

4. Energy management in HESS

The EMS in a hybrid energy storage system is responsible for controlling and optimising the energy flow between two or more energy storage devices and the electric motor, maximising the efficiency and performance of the EV. Energy management systems

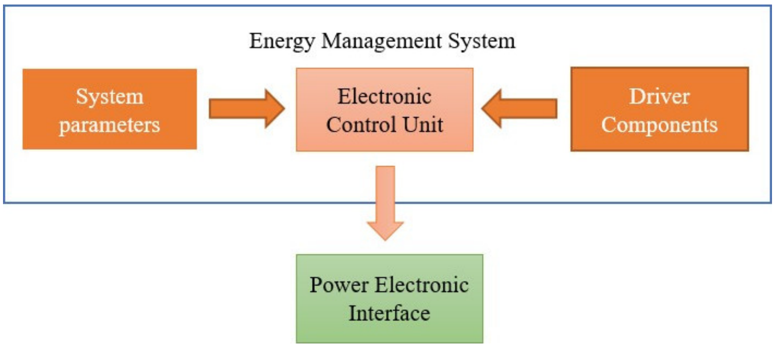


Figure 7. Block diagram of standard EMS.

extend the range of electric vehicles by using different control strategies, which ensure an optimal operation of vehicles.

The need for EMS stems from the integration of different types of energy storages used in electric vehicles for different operating modes, such as average power mode, peak power mode, regenerative braking mode, and charging of one source from another. To effectively transfer and manage the flow of energy from two sources, EMSs require real-time data from the elements in the hybrid energy storage system. The EMS consists of different elements, a fundamental block diagram is shown in Figure 7, which consists of the electronic control unit (ECU), Driver commands that act as input signals, and its output controls the DC/DC converters. System parameters consist of battery and supercapacitor voltage, SOC, current that is supplied to the main electronic control unit where all the data are processed and the appropriate control strategies are calculated. Effective energy capture during regenerative braking of different intensities is ensured by EMS, which controls the converter power using buck and boost modes.

The effectiveness of an energy management strategy depends on the various strategies and algorithms designed using control techniques and vehicle driving scenarios. EMS actively analyses the data from sensor inputs and works to extend the driving range by developing effective control algorithms, in addition to collecting and recording the data during vehicle operation. The choice of EMS depends on several factors, including the driver's inputs, the distance of the travel, the speed of the electric motor/generator, and the battery state of charge (SOC) [39]. It is difficult to control the power distribution without the access to these data and information. The EMS in HESS tries to satisfy power demands, maintain battery voltage and charge, improve overall system efficiency, and extend the battery life [40]. The strategies used for EMS are classified as rule-based strategies and optimization-based strategies, which depend on various battery, supercapacitor, fuel cell, and flywheel combinations. Rule-based strategies are structured methods designed to operate vehicles in different driving modes, based on various input data generated by the system. The control strategies used for EMS are divided into two types, which are rule-based strategies, and optimisation-based strategies. Rule-based strategies are control techniques designed to control electric vehicles using mathematical and logical approaches. These rule-based strategies use various approaches as per the need of control requirements, which include deterministic rule-based, frequency-based, fuzzy logic-based, and neural network based strategies [41].

The optimisation strategy predicts the optimal values based on comparing different modules and processes. Optimization strategies are used to determine set points and correct and minimise feedback errors. Prediction accuracy and control optimisation are essential to effective energy management [42]. To perform a complex task and calculations, a large data storage and a processing system is required for an effective optimisation-based approach in EMS. These optimisation strategies are further divided into various types based on different standard equations and principles, which include dynamic programming, instantaneous optimisation, and Pontryagin's principle [43]. These different strategies are based on different problem-solving approaches and behaviour of control algorithms, including numerical analytical models. Machine learning techniques are implemented for EMS to effectively utilise the energy split in different scenarios and extend the range of EVs, by capturing maximum energy by controlling all necessary operations mainly controlling of DC/DC power converters efficiently and without any control malfunctions in real time [41]. An effective EMS should be stable against noise, uncertainty, inaccuracies, and disruptions. Low computing complexity, real-time controllability, accuracy, and global optimization. When an EMS satisfies these requirements, it can manage energy resources efficiently, guarantee system stability, and maximise energy use, resulting in more effective and sustainable energy management strategies [44].

4.1. Implementation of energy management strategy

An energy management strategy for the hybrid storage system comprises several steps. Initially, the algorithm checks whether the vehicle's power demand is above

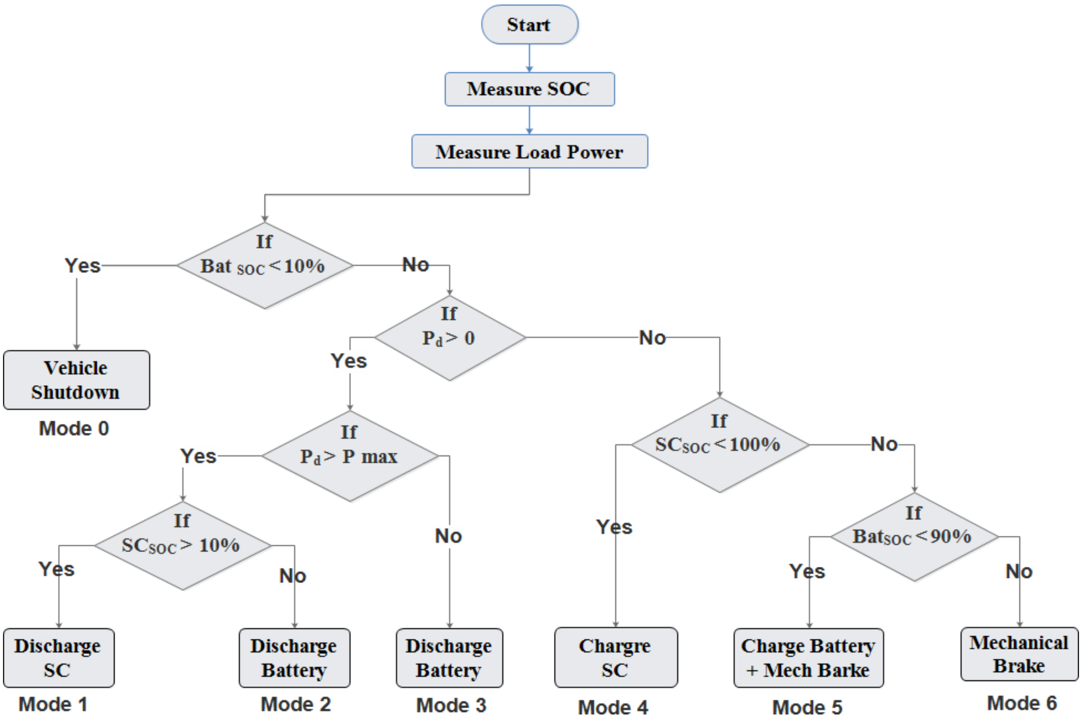


Figure 8. Energy management system flowchart.

zero, and if yes, the system initiate driving. Next, the algorithm verifies whether the power demand exceeds the maximum power level, and in such a case, the system draws power from the supercapacitor pack. On the other hand, if the power demand is below the maximum power level, the algorithm draws the power from the battery pack. During braking, the power demand becomes negative, and the system employs regenerative braking to convert the vehicle's kinetic energy into electrical energy. This energy is then stored in the supercapacitor pack for future use to power the vehicle or supplement the battery pack. Overall, the energy management algorithm provides constant access to the required power and improves the system's efficiency. The flowchart is shown in Figure 8 [45].

Where P_d is the vehicle's power demand and Pmax is the maximum power limit of the battery. The vehicle operates in the following 5 different modes:

- Mode 0: In this mode, if the battery SOC is less than 10 % then the vehicle goes to shutdown mode.
- Mode 1: When the power demand exceeds the maximum demand power (Pmax) limit, the supercapacitor pack is employed in the peak power mode when its SOC is more than 10 %. The supercapacitor pack provides bursts of high power required for rapid acceleration or climbing steep inclines. Its high power density and fast charging/discharging capabilities allow it to supplement the battery pack during high-power demands.
- Mode 2: When SC SOC is less than 10 %, the battery provides the vehicle with power in the event of sudden-high power demands.
- Mode 3: In the average power mode, the EV draws power from the battery pack during normal driving conditions when the power demand is below the maximum power demand (Pmax) limit. This mode ensures continuous operation while keeping the power consumption within the rated limits of the battery pack.
- Mode 4: During deceleration or braking, the EV operates in the regenerative braking mode. In this mode, the electric motor acts as a generator, converting the kinetic energy of the vehicle into electrical energy. In this mode, the first priority is given to the SC. This is achieved by checking whether the SOC of the SC is less than 100 % and if so, the SC is then charged. The regenerative braking mode is activated when the power demand becomes negative, indicating the potential for energy recovery.
- Mode 5: If the SC SOC is 100 %, then the system diverts the power to the battery and checks the SOC of the battery. If it is less than 90 %, then regenerative braking energy is charges the battery. If the battery SOC percentage is more than 90 %, then battery charging is disabled, and the algorithm activates the mechanical brake. Mechanical braking is necessary when the power demand exceeds the capabilities of the regenerative braking system or in cases where immediate maximum braking force is needed for safety reasons.

These different operational modes of electric vehicles contribute to efficient power management, improved energy utilisation, and enhance the overall performance. The utilisation of battery and supercapacitor packs in various modes optimises power

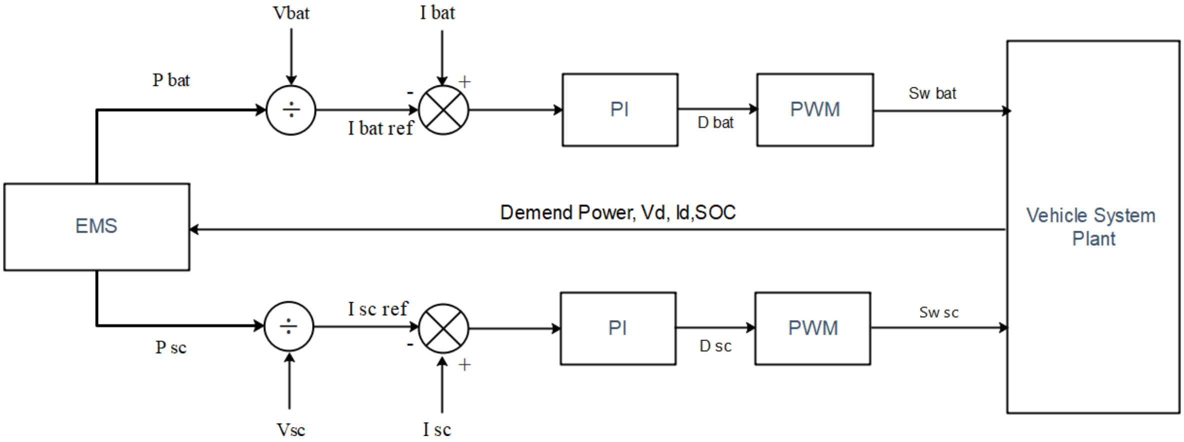


Figure 9. Block diagram of proposed controller.

distribution, ensuring smooth operation, and maximising the potential of regenerative energy recovery. In the initial phase of the research, the power demand of the vehicle under various driving conditions was extracted from the vehicle's system. This includes parameters such as power demand (P_d), current demand (I_d), and voltage demand (V_d), as illustrated in Figure 9. The real time data consists of power demand, bus voltage, motor current, and SOC and they are fed to the EMS where the based on rule rule-based algorithm allocates power to the battery and supercapacitor. The EMS divides the power demand into average power and peak power demand, as shown in the flowchart in Figure 8 [20]. Next, the individual power demands are processed together with the battery voltage to determine the current flow in the battery and supercapacitor during different vehicle operations. This process generates two current signals, namely I_{bat} and I_{sc}. These I_{bat} and I_{sc} are compared with the actual battery and supercapacitor currents, which generates current error signals. These signals are then fed into a PI controller, where signals are converted into appropriate duty cycles. After that, the PI controller output duty cycle is given to the PWM block to generate appropriate PWM switching signals to control the battery and supercapacitor converter depending upon the various operating modes. Specifically, S1 and S2 represent the IGBT switches of the battery-side DC/DC converter. These switches are controlled by PWM signals to discharge the battery during the average power demand. On the other hand, S3 and S4 correspond to the IGBT switches of the supercapacitor side DC/DC converter, which operates during the discharging mode during peak acceleration conditions. The controller design is described in detail in [22]. When regenerative braking is applied, the DC/DC converter switches to the charging mode to charge the supercapacitor depending on the regenerative power. The values of PI of the battery and SC controllers are $P = 0.13$ and $I = 65$ respectively, the control loop bandwidth is 10 kHz, and the sampling time is 5×10^{-6} sec.

4.2. Control and maintenance

To manage the increased system complexity of HESS for real-time maintenance and control, we developed a comprehensive strategy focused on real-time control efficiency and fast maintenance. The rule-based energy management gives a two-layer hierarchical control system approach designed to deliver fast and optimal energy management without depending on computationally intensive optimisation algorithms. The first layer sends hardware-triggered logic signals, which are based on the reference current, SOC of battery, and supercapacitor threshold in less than 10 milliseconds intervals. As a response, it makes immediate controlled switching decisions, which are very important to maintain HESS responsiveness during sudden and dynamic load changes, and regenerative braking. Following the primary layer, a second control layer runs at less than 15 Hz control thresholds based on the feedback signal from the BMS of the battery and supercapacitor modules health indicators, as well as driving scenarios [36]. This layered hierarchy structure ensures a fast response to any sudden acceleration, deceleration, and braking during real-time driving events while keeping the system functional with computation simplicity [46].

Maintenance is very important for such complex systems to ensure all subsystem components work properly without failing and affecting their performance. If one of the system failures happens, it may cause the whole system to stop working. For that, modular control and hardware architecture handle system complexity and enhance maintainability. In modular architecture energy management, speed control, and current control modules are designed as independent but synchronised and coordinated modules. This approach makes for easy implementation, troubleshooting and future scalability. For hardware ease of maintenance and to ensure minimal downtime modular design of battery, supercapacitor should be adopted, which is easy in case of faulty equipment replacement without opening the complete system. Real-time parameter data monitoring plays a very important role in the maintenance of such complex systems. HESS diagnostic algorithm continuously takes battery and SC current, voltage, SOC and equivalent series resistance (ESR). This real-time data monitoring and its computation through fault detection algorithms give preventive fault indications and locate faults in complex systems.

4.3. Real time optimization

The proposed EMS has been designed with real-time application in mind depending on various external factors. To validate the working performance of this EMS under realistic operating driving scenarios, we conducted tests using a real-time standard driving cycle simulation that mimics actual vehicle dynamics under different load conditions. This simulation environment allows for emulating a designed vehicle model in MATLAB with acceleration, deceleration, and other driving conditions. The energy management strategy periodically collects input data that is generated by various components, such as SOC, power demand from the motors, the DC bus voltage, and regenerative braking energy. Based on these real time data, the EMS rule-based algorithm allocate the high and low frequency power demand between the supercapacitor and the battery from which the PWM switching signal is generated through the PI controller with different loops are responsible for controlling the voltage and individual currents for the battery and supercapacitor modules [47]. During regenerative braking, this command signal is sent to the controller, which gives priority to the SC to recharge through the bidirectional converter. During this continuous operation, the EMS includes safety and fault-handling logic to limit overcharging and over-discharging of the energy storage sources. The decision-making capability that maintains the energy flow within the a safe operating range of the battery, SC, and converters, while ensuring optimal energy utilisation. The real-time performance of the proposed energy management strategy was tested in real-time simulation for standard drive cycles. This demonstrates the optimisation and effectiveness of the proposed real-time control approach under dynamic driving patterns [48].

4.4. Risk mitigation in dynamic and unpredictable driving environments

When proposed EMS is integrated with a hybrid energy storage system in a real world application, it can face some difficulties during unpredictable driving. The main risk is the delayed response of the EMS to sudden changes from the controller to the hardware components. Frequent fast changes of driving modes, such as high peak power demand to sudden emergency braking can limit the system's ability to respond and control the energy distribution properly without affecting its performance. Wrong predictions from the EMS or sudden dynamic changes can cause poor energy utilisation, which affects and reduces the performance and operational efficiency of the hybrid energy storage system. Without proper system design and advanced control, continuous peak power and dynamic demand on unpredictable road conditions cause stress to all components, resulting in a reduction in their operational lifespan. To avoid these risks preventive steps need to be taken for the safety of the whole integrated system. These include a continuous real-time computation of all parameters with defined safe limits that need to be implemented, which allows the system to respond to any sudden abnormal behaviour and take necessary action based on an adaptive fault mitigating algorithm [49].

To prevent possible incidents, the control algorithm and its hardware communication protocol time response must be optimised for any risks that can be introduced into the system. Predictive maintenance involves collecting operational data. The system is expected to detect equipment stress and issue maintenance alerts before a major issue occurs [37]. It is crucial to test these potential risks at a hardware test bench level, with all integrated components undergoing various load cycles. Extensive robustness operation tests must also be performed under additional environmental physical conditions to mitigate these risks and validate the functional response of the designed HESS with control strategy in the real world.

5. Simulation and analysis of the proposed hybrid energy storage system

When designing a model of an electric vehicle using MATLAB Simulink, it is crucial to consider various parameters that impact the vehicle's performance. Both electrical and mechanical parameters must be taken into account to accurately simulate the system. Creating a validated working prototype model requires a comprehensive understanding of the necessary elements and block parameters involved in the simulation process. Modeling of an electric vehicle poses additional challenges as it necessitates the consideration of physical parameters specific to the vehicle. Moreover, predefined system specifications must be incorporated into the model to meet the desired requirements and objectives. This ensures that the resulting model accurately represents the behaviour and performance of the electric vehicle in the simulation environment.

The Electric Vehicle was simulated using MATLAB Simulink, using specifications of the TATA Nexon Electric Vehicle used to represent the vehicle body and tires. The schematic block diagram of the MATLAB Simulink model is shown in Figure 10. The battery current demand for different driving scenarios are recorded by running the model. The model also investigates how the use of a Hybrid Electric Vehicle (HEV) or a pure EV affects the battery current demand. To supply the necessary power from the energy storage system, a DC/DC buck-boost chopper is used.

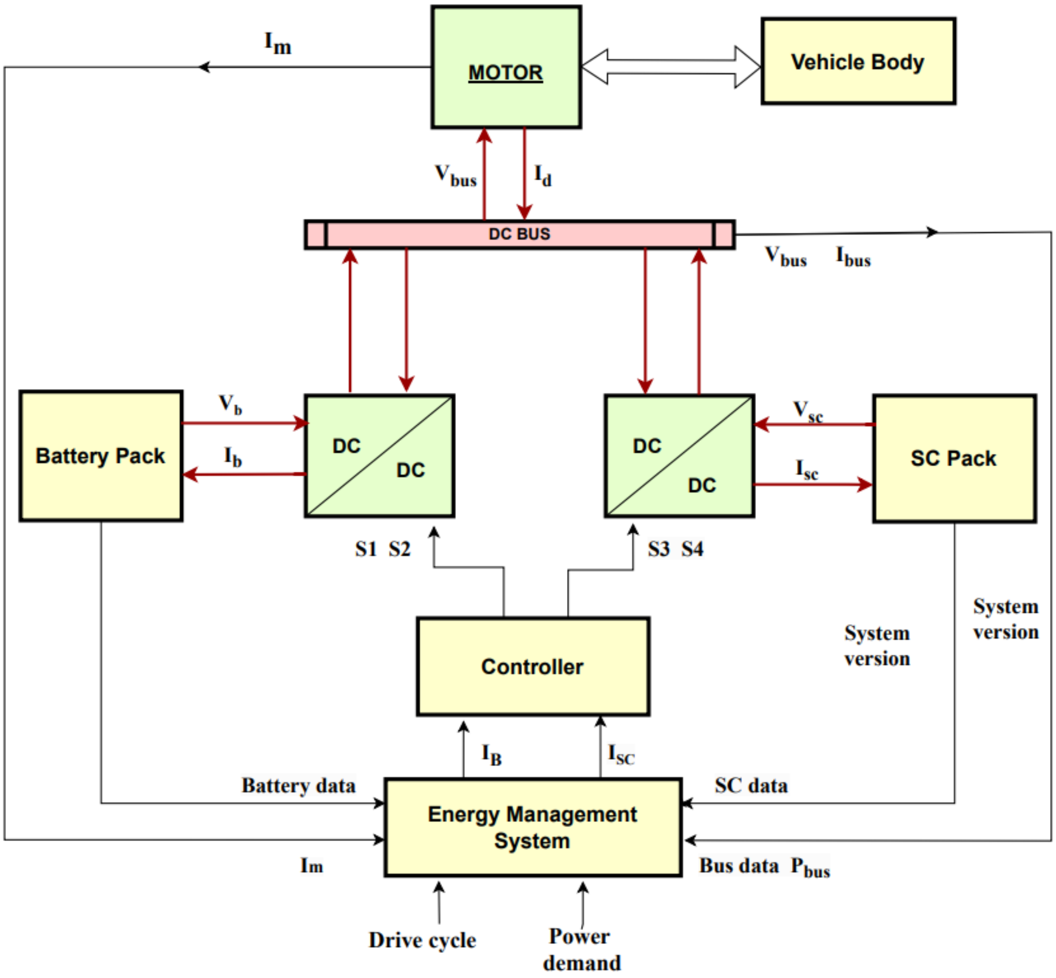


Figure 10. Block diagram of the HESS used for MATLAB simulations.

The output voltage of the chopper is controlled using a PWM control technique, and a PI controller is used to regulate the vehicle speed [24].

To validate the efficiency and durability of the suggested controller, a simulation is conducted using MATLAB Simulink models, as can be seen in Figure 10. The key parameters of the HESS model, specified in Tables 1–4 are determined through measurements of the HESS components. Consequently, the simulation accurately represents the actual system.

The load is simulated using a controlled current source with different current values depending the load demand P_d of electric vehicles in different driving conditions for acceleration and braking modes [12]. The aim of the rule-based controller is to create continuous control strategies that ensure robust tracking of the I_b(battery) and I_{sc}(supercapacitor) currents. On the other hand, the objective of the rule-based controller is to maintain the bus voltage at the desired level under varying load conditions. First, the DC bus voltage reference was initially established at 125 V, taking into account the configuration of the electric vehicle model. The battery and supercapacitor SOC was set to 100 %, while the supercapacitor voltage was set to at 130 V. To test how well the system can han-

Parameters	Value	Units
Total mass	1 500	kg
Tire radius	0.3	m
Front area	2.91	m^2
Drag coefficient (Cd)	0.19	–
Rolling resistance coefficient (r)	0.022	–

Table 1. Vehicle parameters.

Parameters	Value	Units
Li-ion battery capacity	20	Ah
Battery pack voltage	120	V
Battery voltage range	90 to 140	V
Internal resistance min	0.06	Ω
Battery pack	2.4	kW

Table 2. Li-ion battery parameters.

Parameters	Value	Units
Pack capacitance	200	F
Pack voltage	130	V
Internal resistance min	0.20	Ω

Table 3. Supercapacitor parameters.

Components	**Value**	**Components**	**Value**
C0	940 µF	Csc	200 F
Rbat	0.06 Ω	Rsc	0.20 Ω
C1	470 µF	C2	470 µF
L1	1.7 mH	L2	1.2 mH
RL1	700 mΩ	RL2	300 mΩ

TABLE 4. DC/DC converters parameters.

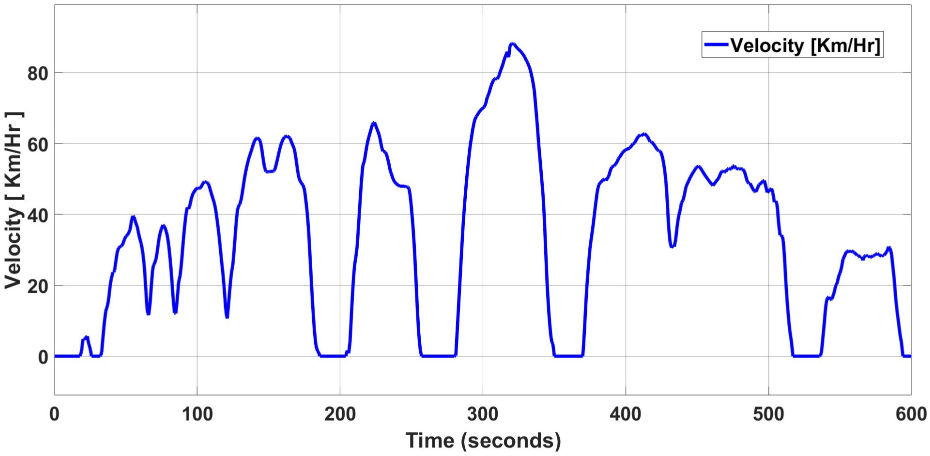


FIGURE 11. SC03 city drive cycle vehicle speed.

dle different situations, the load profile used for the validation includes frequent changes and noticeable ups and downs, as shown in Figure 11. When P_{demand} is negative, it indicates the regenerative braking condition, whereas in traction mode, P_d varies between 500 W and 8 kW for the SC03 driving cycle.

A number of simulations are performed based on the proposed rule-based energy management system with a battery-supercapacitor hybrid system, In these simulations, the initial SOC values of battery and the supercapacitor at the start of the driving cycle are set 100 % and 101 %. The proposed hybrid model is tested for city, urban, and highway driving conditions and include chassis dynamometer test cycle (SC03), high acceleration aggressive driving cycle (US06), and Highway Fuel Economy Test (HWFET) cycle. Vehicle body parameters required for modeling are given in Table 1. The simulation parameters used in MATLAB modeling of battery pack are voltage, capacity, and internal resistance and are given in Table 2.

The parameters used for modeling supercapacitors in MATLAB are given in Table 3, DC/DC bidirectional converter, which are the resistance, inductance, and capacitance values are given in Table 4.

The performance of the energy management strategy is analysed for different drive cycles, which include city and highway driving cycles. Braking and acceleration depend on road conditions, so the power demand and regenerative braking power differ. The proposed energy management strategy is tested for SC03, US06, HWFET, and BCD drive cycles.

6. SIMULATION RESULTS AND DISCUSSIONS

The proposed energy management strategy is analysed for different driving cycles using the MATLAB simulink platform to evaluate the effectiveness of the proposed strategy and the response of the battery and the supercapacitor in different operating modes of the vehicles. The simulation test is carried out for two different cases: the first one is a pure EV with no regenerative braking implemented, and the second case is an EV with HESS, which consists of a battery and supercapacitor, and implemented regenerative braking.

6.1. SC03 DRIVE CYCLE RESULTS

Figure 11 shows the SC03 driving cycle, a 5.8-kilometer test route, with a maximum speed of 88.2 km h^{-1}. The first test case data of the SC03 drive cycle is shown in Figure 12, where only a battery is used to power the vehicle and regenerative braking is not implemented. From the waveform of the motor load current, we can see that the maximum current was 80 A and the average continuous current was around 40 A when the speed is lower than 60 km h^{-1}. As the vehicle suddenly accelerated, the peak power demand was very high, around 8 kW, for a short period of time, when the vehicle accelerated from 0 to 90 km h^{-1} speed. The SOC of the battery was continuously depleting from 100 % to 86.44 % at the end of the drive cycle.

The second test case results of the SC03 drive cycle with a hybrid system operating in average power

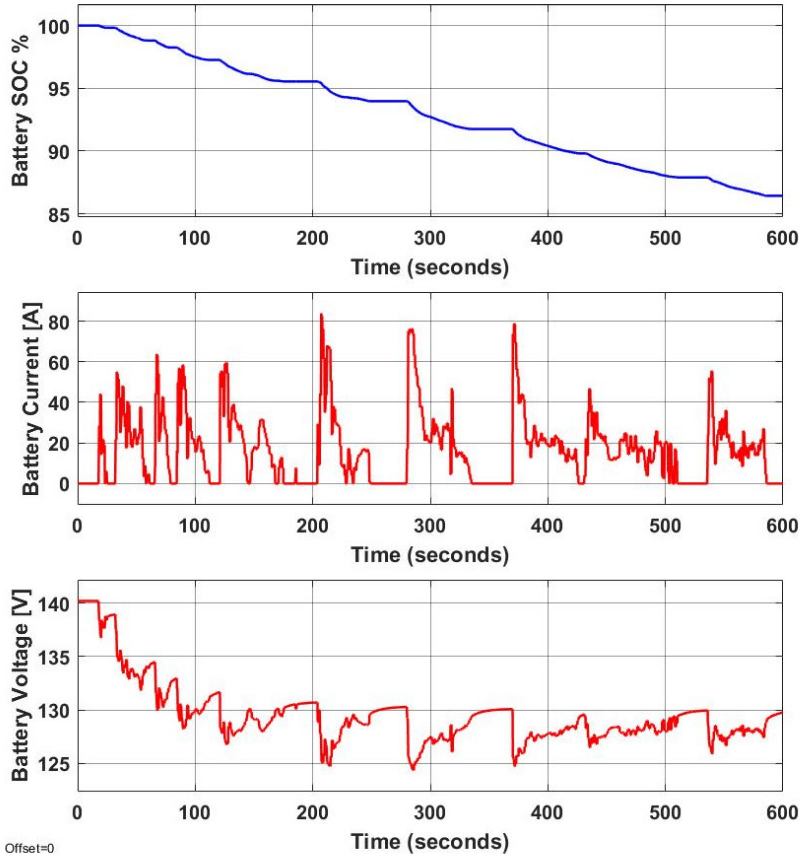


Figure 12. Battery SOC, current, and voltage of normal system without regenerative braking for SCO3 drive cycle.

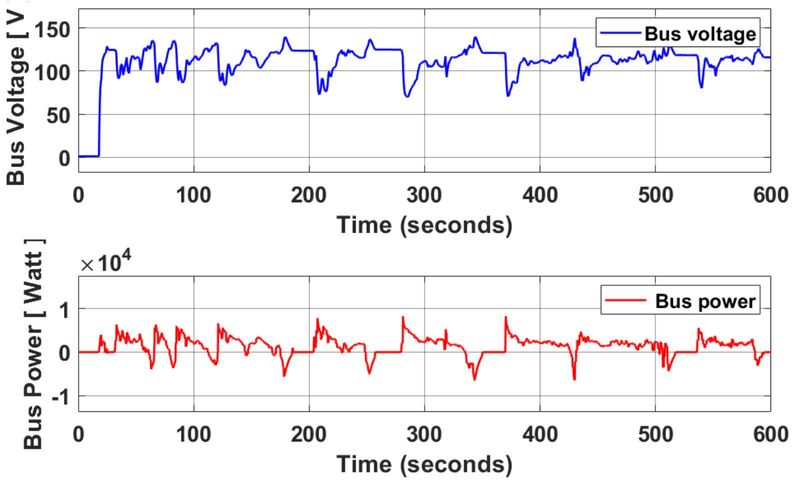


Figure 13. Bus voltage, and power of hybrid system for SCO3 drive cycle.

mode M1. The battery plays a crucial role in delivering the required average power for a vehicle speed below 60 km h^{-1}. Figure 13 demonstrates how the presence of a supercapacitor reduces the power demand on the battery and its charging-discharging current. Figure 12 shows that without a supercapacitor, the battery experiences numerous significant peaks in its charge and discharge current cycles.

Figure 14 shows the battery and supercapacitor currents for different modes and speed of the vehicle. The blue curve should is the battery current I_b in average power mode M3 and the current was below 40 A, the positive red curve shows the SC current in peak power mode M1 and the negative red curve shows the SC charging current in regenerative braking mode M4. During the peak power mode, the current can reach as high as 80 A, while during regenerative braking, the charging currents can go up to negative 45 A. The voltage of the supercapacitor pack starts at 125 V and momentarily decreases to around 100 V. From the waveform of the current, it can be seen that when the speed reaches 25 km h^{-1}, the regeneration stops and the regenerative part shows that the energy is generated during a sudden braking situation, during

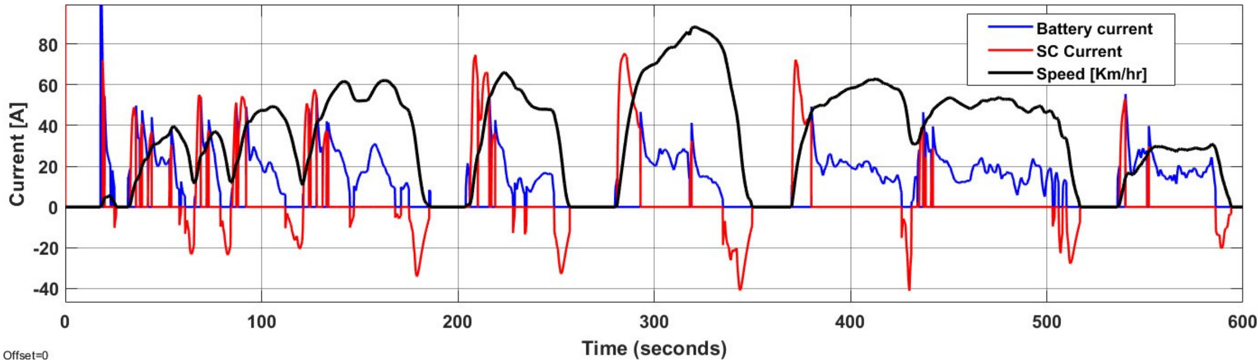


Figure 14. Battery and supercapacitor currents and vehicle speed of hybrid system for SCO3 drive cycle.

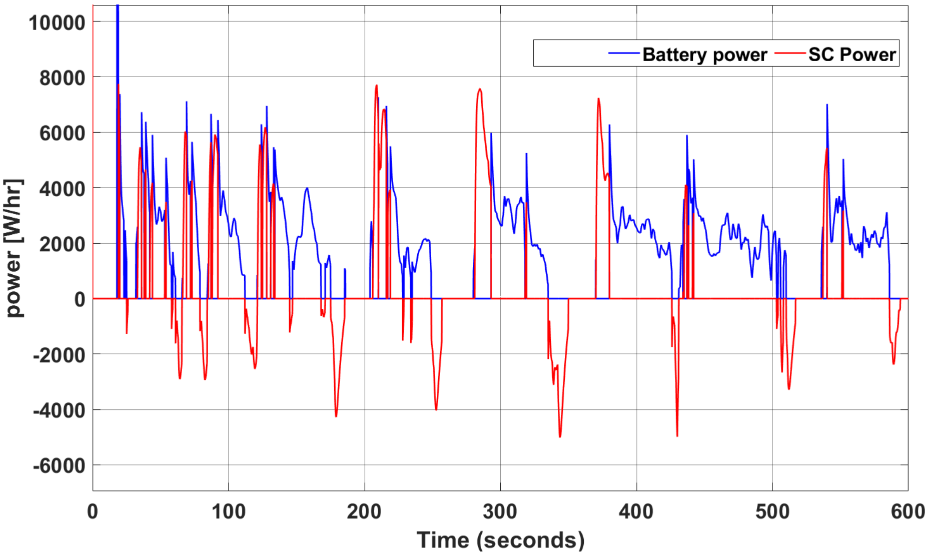


Figure 15. Battery, and supercapacitor power of hybrid system for SCO3 drive cycle.

which the speed drastically decreases for a short period of time.

Figure 13 shows the variations of the bus voltage and bus power for both the battery and supercapacitor of the proposed hybrid system. I_d represents the current demand and V_{bus}, exhibits a dynamic oscillating range between 140 and 80 V. The bus voltage decreases in specified intervals while the bus current incrementally increases in response to a rapid acceleration of the vehicle. As a result, as the vehicle slows down during the regenerative braking mode, the bus voltage increases, indicating the activation of the supercapacitor's charging mode.

Figure 15 shows the power demand and regeneration of battery and supercapacitor of the hybrid system during different vehicle scenarios for the SC03 drive cycle. In mode M1 and M4, the supercapacitor plays a crucial role by providing peak power to the vehicle and absorbing regenerative power during regenerative braking, this behaviour is a consequence of the supercapacitor's frequent charging and discharging cycles, which aim to maintain its SOC and prevent continuous depletion. The voltage of the battery at the start is 140 V, and then ranges between 125 and to 135 V.

From Figure 16, it is seen that the SOC of the hybrid system battery is decreasing slower than that of the normal system battery because the battery in HESS only supplies power in average power demand mode M3 not in peak power demand. The SOC of the supercapacitor is decreasing in peak power demand mode M1 and increasing in regenerative braking mode M4, and it also increases due to regenerative braking energy recovery. At the end of the drive cycle, SOC of the battery in HESS is 90.59 % and the normal system battery SOC is 86.44 % which shows that less energy is used to drive the vehicle.

Figure 17 shows the Energy consumption for test cases, red curve shows the energy consumption from the battery in the case where no regeneration is implemented and only the battery supplies the power to the vehicle and the consumed energy is 347.8 W h^{-1} while the second case, the blue curve, shows the total energy consumption for HESS with regenerative braking, which is 285.15 W h^{-1}. Therefore, 62.65 W h^{-1}, 18.01 % of the total energy, is regenerated during regenerative braking and the SOC of both the battery and the supercapacitor is decreasing at a slower rates as compared to the single-battery EV.

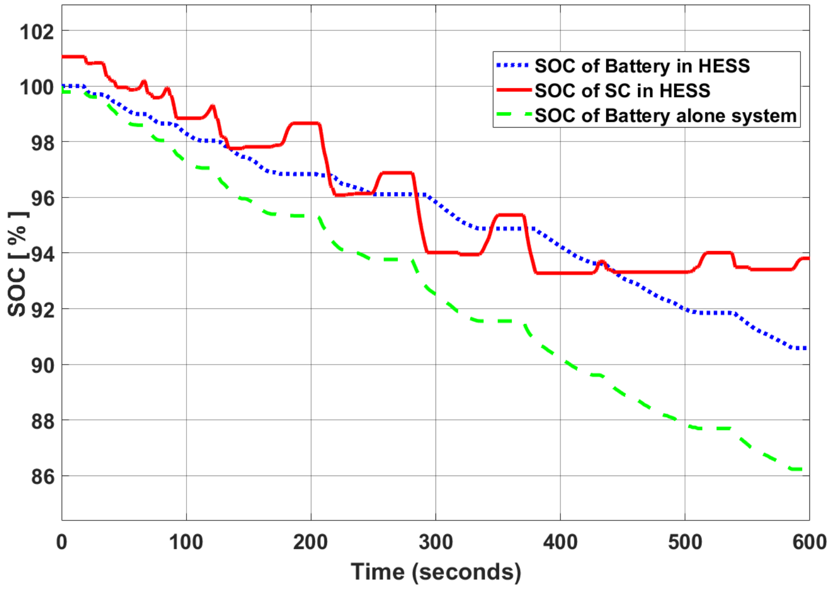


Figure 16. SOC of battery and supercapacitor of normal and hybrid systems for SCO3 (city) drive cycle.

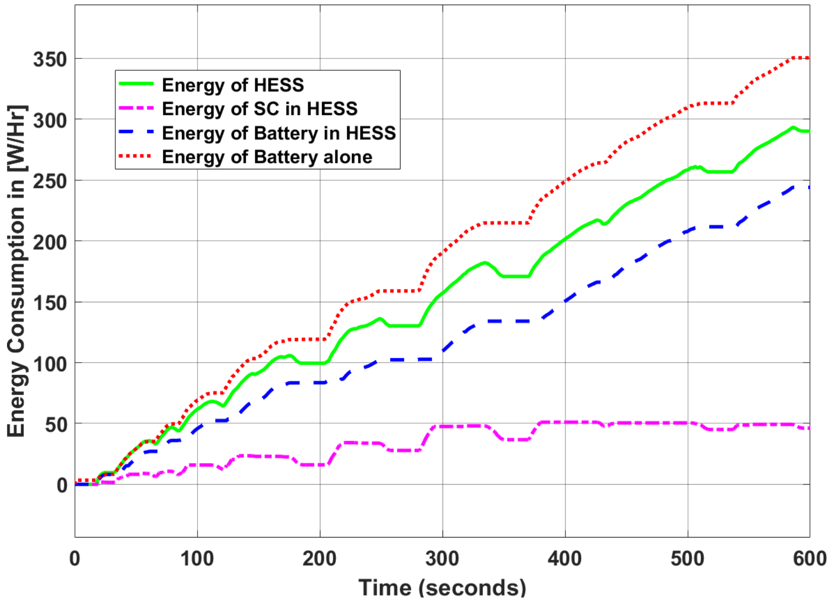


Figure 17. Energy consumption for normal and hybrid systems for SCO3 (city) drive cycle.

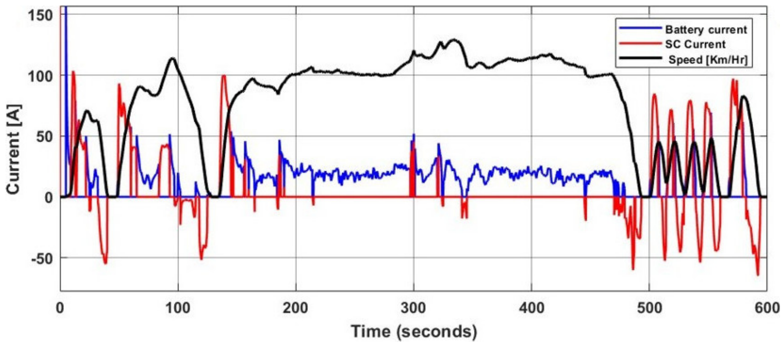
6.2. US06 drive cycle results

The US06 is a high acceleration aggressive driving cycle. The average speed during the cycle was 77.9 km h^{-1}, and the maximum speed was 129.2 km h^{-1}. In this cycle, the average current drawn during a constant speed from the battery pack is 35 A. In transient situations such as sudden acceleration from a stationary position, the supercapacitor provides a peak current of $I_{sc} = 100$ A, the charge and discharge currents of the supercapacitor have high peaks for short time instants. During regenerative braking, the current can reach up to −50 A.

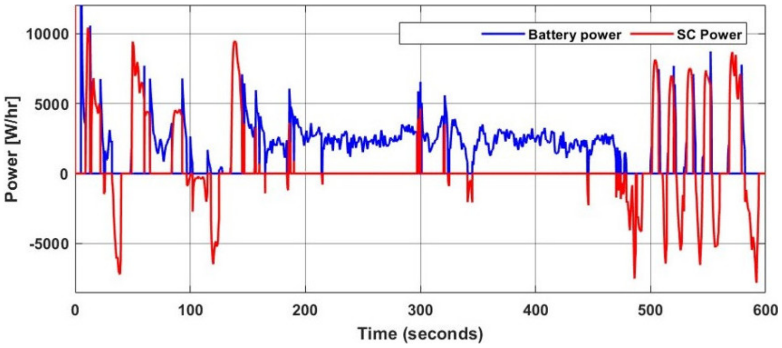
Figure 18a shows the vehicle speed for the US06 drive cycle with the current demand for batteries and supercapacitors. It can be seen that the proposed EMS supplies peak and average currents according to the current demand at various speeds of the vehicle.

From the Figure 18b, it can be seen, that the peak power of 9 kW is required for a short time when the vehicle is accelerating from zero speed in M1 mode. At that instant, the supercapacitor effectively provides the starting peak power and then the battery provides the average power of 3 kW during mode M3. During mode M4 operation, regenerative energy is stored in the supercapacitor, as shown by the negative power displayed in the graph during sudden braking. Most of the regenerative braking energy is stored during sudden braking.

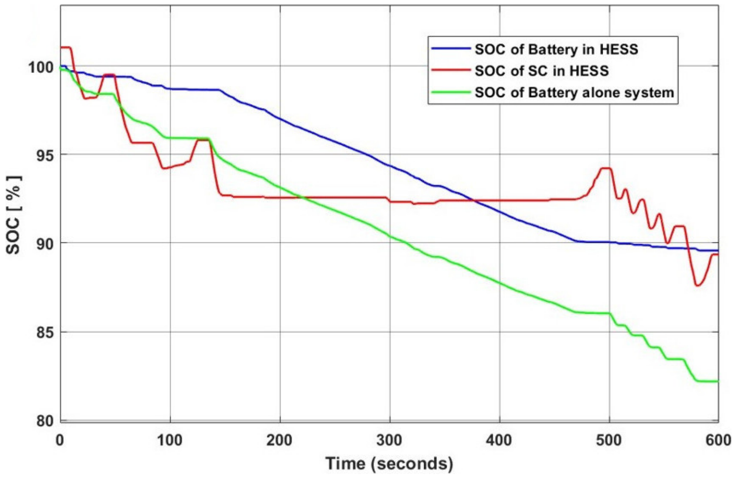
Figure 18c shows the SOC of a 20-Ah normal system battery. The starting value is 100 %, and it slowly decreases during to cycle to 82.38 %. While for the HESS system, the SOC of the battery at the end is 86.36 %.



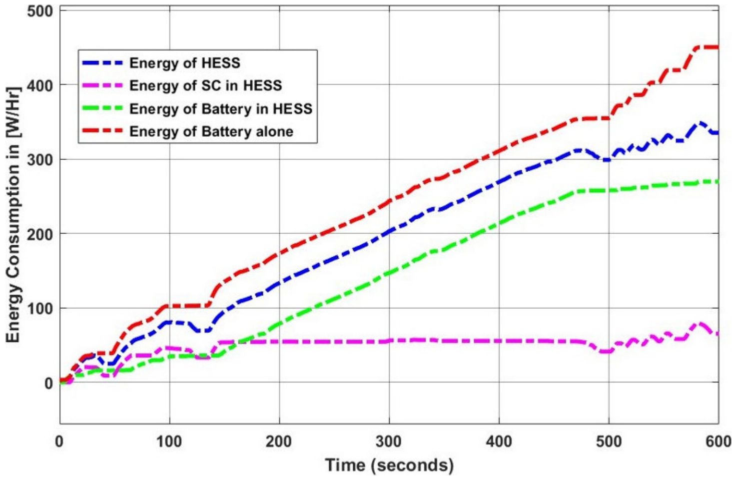
(A). Battery and supercapacitor currents and vehicle speed.



(B). Battery and supercapacitor power.



(C). State of charge (SOC) of battery and supercapacitor.



(D). Energy consumption for normal and hybrid systems.

FIGURE 18. Simulation results for US06 (urban) drive cycle.

Figure 18d shows the energy consumption from the battery and supercapacitor in two test cases, red curve shows the energy consumption from the battery for the first case, in which no regeneration is implemented and only the battery supplies and power to the vehicle and the consumed energy is 447.6 $\mathrm{W\,h^{-1}}$, while the second case, the blue curve, shows the total energy consumption of HESS with regenerative braking which is 335.21 $\mathrm{W\,h^{-1}}$. Therefore, 112.39 $\mathrm{W\,h^{-1}}$, 25.1 % energy is regenerated during regenerative braking and the SOC of both the battery and the supercapacitor is decreasing at a slower rate as compared to the single-battery EV. The battery contributes 80.48 % and the supercapacitor 19.51 %.

6.3. HWFET drive cycle results

Figure 19a shows the vehicle speed for the HWFET drive cycle with the current demand on batteries and supercapacitors. In this cycle, the vehicle is drawing an average current of $I_b = 25\,\mathrm{A}$. The supercapacitor supplies a peak current when sudden acceleration is required to reach a speed of 95 $\mathrm{km\,h^{-1}}$ from 40 $\mathrm{km\,h^{-1}}$, which in this case was a total of 300 sec. In this highway cycle, speed decreases for short instances but there is no sudden braking. Regenerative energy is captured effectively at the end of the drive cycle when braking is applied at a speed of 80 $\mathrm{km\,h^{-1}}$ and the vehicle comes to a stop.

Figure 19b shows the power supplied by the battery and supercapacitor during the HWFET drive cycle and shows the expected outcome of the proposed energy management strategy, which is designed based on the rule-based controller by splitting the high and low-frequency components of the battery and the supercapacitor. The highest power supplied by the supercapacitor during M1 mode is 4.5 kW at $t = 300\,\mathrm{sec}$. During the highway drive cycle, vehicles there are only small power fluctuations and the average power in M3 mode is 4 kW.

From Figure 19c it can be seen that during the HWFET drive cycle, the regenerative energy does not have a significant impact, as the SOC of the normal system battery at the end of the cycle is 80.64 % and 81.53 % for the hybrid system battery, which means an improvement of only 1 %. As there are no high power demand fluctuations, the single battery system is sufficient to provide power to the vehicle on a highway.

Figure 19d shows the energy consumption from the battery and the supercapacitor, only 2 % of the energy required to run a vehicle is recovered during regenerative braking. The total energy consumed by the single battery system is 498.2 $\mathrm{W\,h^{-1}}$, and the total energy consumed by the hybrid system is 488.45 $\mathrm{W\,h^{-1}}$. The battery contributes 97.43 % of the energy, while the supercapacitor contributes 2.5 %.

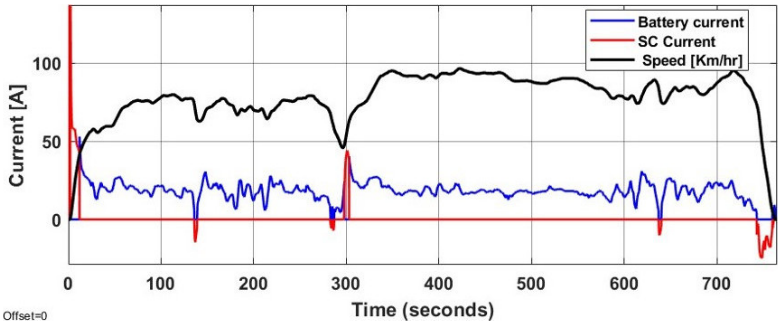
These results, obtained from different drive cycles, clearly show that different driving patterns significantly affect the regenerative braking energy recovery performance of electric vehicles, as well as the efficiency, cost, and performance of energy storage devices, and most importantly, the driving range of the vehicle on a single charge of the on-board energy storage system.

As shown in Table 5, MATLAB simulation data for the comparison of energy consumption of vehicles for different drive cycles are recorded at the end of each cycle. It can be seen that in the case of the US06 drive cycle with a single battery system, the energy consumption rate was 447.9 $\mathrm{W\,h^{-1}}$, and in the case of an a supercapacitor, it was 335.21 $\mathrm{W\,h^{-1}}$, which is a 25.1 % lesser energy consumption. During regenerative braking, 112.39 $\mathrm{W\,h^{-1}}$ of energy is stored in the supercapacitor and then supplied to the drive unit in peak power demand mode. During the SC03 drive cycle, 62.65 $\mathrm{W\,h^{-1}}$ of energy is stored in the supercapacitor through regeneration, and a total energy consumption reduction of 18 % is reached for the hybrid storage system proposed in this paper.

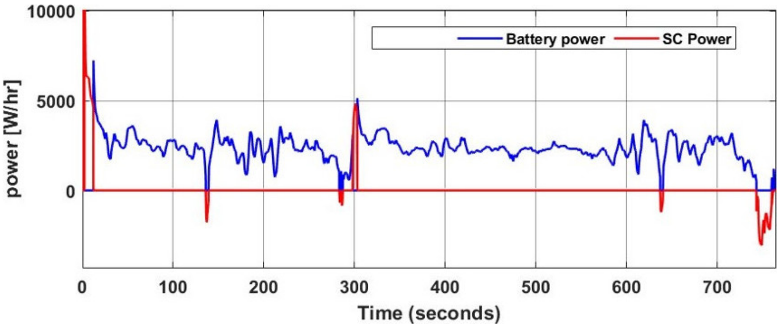
Table 6 shows the observed SOC data for different MATLAB simulations tested for each drive cycle for the normal and hybrid systems. The SOC of the battery and supercapacitor is recorded at the start and end of each drive cycle for the same energy management strategy. At the start of each drive cycle, the SOC for both the battery and the supercapacitor is 100 %. As can be seen in Table 6, the SOC of the battery changes differently in normal and hybrid systems. The SOC for the hybrid system is higher than that of the normal system for every drive cycle. This means that the battery of the hybrid system depletes at a slower rate, which in turn means a longer range. In the SC03 drive cycle, the battery supplied 85.56 % of the energy and the supercapacitor supplied 14.43 %. For the US06 drive cycle, the battery supplied 80.48 % and the supercapacitor supplied 19.51 %. For the HWFET drive cycle, the battery supplied 97.43 % and the supercapacitor supplied only 2.5 %. During the highway cycle, the supercapacitor supplied just 2.5 %, showing a very small contribution. The energy shared by the battery and the supercapacitor is shown in the second column in Table 6 which only shows the SOC of the battery. The hybrid system SOC is shown in columns 3 and 4. The energy contributed by the battery and the supercapacitor, i.e. HESS, is shown in columns 5 and 6. For example, in the SC03 drive cycle, the battery contributed 85.56 % of the energy and the supercapacitor contributed 14.43 %. From this individual energy contribution percentage, we can determine the optimal battery and supercapacitor ratings for short drive cycles.

6.4. Result summary

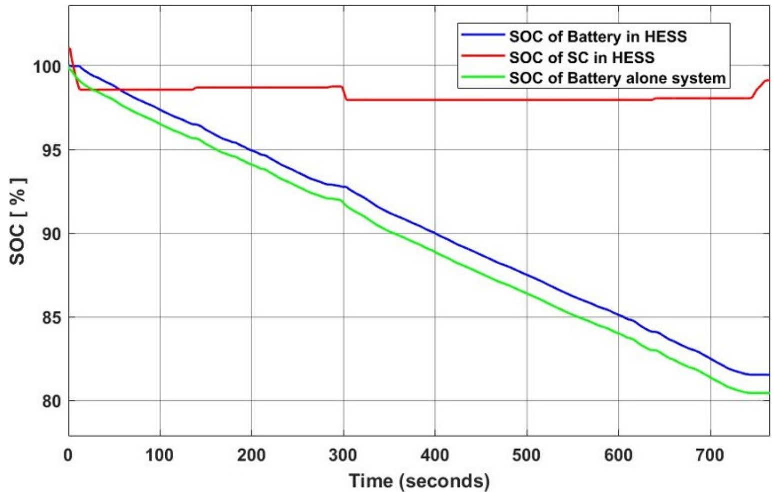
The effectiveness of the hybrid system varies depending on the driving cycles. The main objectives of the proposed system are to reduce the peak current of the battery pack using a supercapacitor pack, thereby reducing stress on the battery pack and increasing



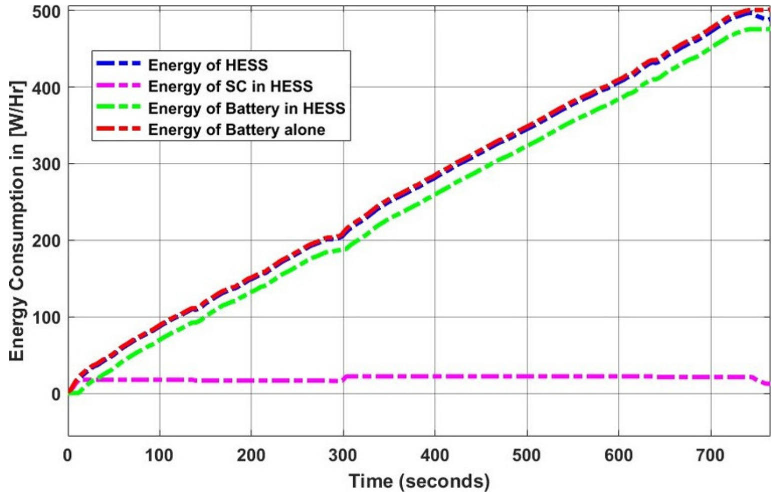
(a). Battery and supercapacitor currents and vehicle speed.



(b). Battery and supercapacitor power.



(c). State of charge (SOC) of battery and supercapacitor.



(d). Energy consumption for normal and hybrid systems.

Figure 19. Simulation results for HWFET (highway) drive cycle.

Drive cycles	Normal system energy [Watt/Hr]	HESS Bat energy [Watt/Hr]	HESS SC energy [Watt/Hr]	HESS total energy [Watt/Hr]	Energy saving [Watt/Hr]	Energy saving [%]
SCO3 (city)	347.8	244	41.15	285.15	62.65	18.0118
US06 (urban)	447.6	269.8	65.41	335.21	112.39	25.1
HWFET(highway)	498.2	475.9	12.55	488.45	9.75	1.95
BCD (city)	980.3	642.4	123.1	765.5	214.8	21

Table 5. Energy consumption table for different driving cycle.

Drive cycle	Normal system SOC [%]	HESS SOC [%]	HESS SOC [%]	HESS energy share [%]	
	Battery	Battery	Supercapacitor	Battery	SC
SCO3	86.44	90.59	93.81	85.56	14.43
US06	82.38	86.36	89.58	80.48	19.51
HWFET	80.64	81.53	99.13	97.43	2.5
BCD	61.44	74.98	79.47	83.91	16.08

Table 6. State of charge SOC and energy contribution in hybrid system.

its life. Another main objective is to effectively store regenerative braking energy using the fast-charging characteristics of the SC, which overcome the limitations of the battery. To implement and validate our energy management strategy, we created a vehicle model which we tested in the MATLAB Simulink environment using standard system parameters to mimic vehicle dynamics and all integrated HESS components. The model is tested using standard city, urban, and highway drive cycles. The benefits of regenerative braking can be seen in the city drive cycle due to the frequent braking. In real-world scenarios, vehicle driving patterns and road conditions are continuously change, combining city, urban, and highway driving, including uphill and downhill driving in hilly areas. While we generate more energy during the city drive cycle, we also utilise the benefits of the hybrid energy storage system during sudden acceleration and uphill driving on the highway, using the stored regenerative braking energy.

Due to the integration of HESS and the energy management strategy, we can achieve an increased driving range, reduced operational costs, an improved battery lifespan, and high dynamic performance. These benefits justify the implementation of this system, despite them not being consistent across all driving conditions. In a highway driving cycle, there are fewer braking instances, so energy recovery is reduced. To improve the energy recovery on the highway, we can implement alternative strategies and system configurations to enhance energy recovery. Firstly, maximum priority should be given to the SC absorbing regenerative energy instead of using a mechanical friction brake. The highway road conditions are more predictable than urban conditions, therefore, predictive control can be used for highway braking, optimising the energy recovery. Using adaptive cruise control with smooth deceleration for HESS improves regenerative braking, especially in combination with specially designed PMSM machines, which give high output regenerative energy, and a motor that uses double stator winding or a separate generator set. Other ways to improve the efficiency include using mild regenerative braking to maintain speed and avoid sudden braking and using economic mode, which is designed to improve regeneration and reduce power consumption. In order to tailor the system to different user profiles or vehicle applications, we suggest a flexible and adaptive system design that is utilised for different user profiles and vehicle applications. To differentiate between users' driving cycles, a machine learning based approach for classifying city, highway, uphill, and downhill driving cycle patterns can be used, which automatically learns and optimally adapts the energy flow. This classification provides an optimal sizing ratio for the battery and SC system. Based on the identified driving profiles, the EMS can be adjusted to recognise driving patterns and achieve high performance by utilising a hybrid energy storage system.

7. Conclusion

This paper proposes an energy management system designed for a hybrid storage system combining batteries and supercapacitors, implemented in MATLAB Simulink modelling for various driving cycles. The modelling results show that the implemented rule-based energy management strategy effectively splits the peak and average power, and captures regenerative braking energy in the supercapacitors. Energy Management strategy plays a crucial role in hybrid energy storage systems used in different driving conditions. Regenerative braking energy recovery changes depending on the vehicle driver's behavior. Integration of supercapacitors reduces the charging-discharging cycles of the battery, so the life cycle and degradation rate of the lithium-ion battery reduces and the overall energy storage system works efficiently in long-term operation. SC improve the performance of EVs by overcoming problems faced by single-battery vehicles.

As per results obtained from the MATLAB Simulink model, the energy used in the hybrid system is reduced by up to 25 % during a US06 city drive cycle compared to normal single-battery system. This is due to continuous acceleration and deceleration driving patterns. The benefits from the battery/SC hybrid energy storage system include improving the lifespan of the energy storage system, recovering kinetic energy, and a better overall vehicle performance. With the proposed effective energy management control strategy, the performance of an EV is improved with the low energy consumption and extended driving range on a single charge. This hybridisation further reduces the necessity of a large battery pack.

In future work, we will implement an energy management strategy with a power blending feature based on the state of charge of the battery and supercapacitor to enhance the range and performance of the vehicle.

REFERENCES

[1] J. Armenta, C. Núñez, N. Visairo, I. Lázaro. An advanced energy management system for controlling the ultracapacitor discharge and improving the electric vehicle range. *Journal of Power Sources* **284**:452–458, 2015. `https://doi.org/10.1016/j.jpowsour.2015.03.056`

[2] L. Kouchachvili, W. Yaïci, E. Entchev. Hybrid battery/supercapacitor energy storage system for the electric vehicles. *Journal of Power Sources* **374**:237–248, 2018. `https://doi.org/10.1016/j.jpowsour.2017.11.040`

[3] N. M. Jamadar, A. Bhagat, S. Gaikwad, et al. Reliability assessment of supercapacitor for electric vehicle with hybrid energy storage. *Life Cycle Reliability and Safety Engineering* **11**(1):49–59, 2022. `https://doi.org/10.1007/s41872-022-00184-5`

[4] Z. Zou, J. Cao, B. Cao, W. Chen. Evaluation strategy of regenerative braking energy for supercapacitor vehicle. *ISA transactions* **55**:234–240, 2015. `https://doi.org/10.1016/j.isatra.2014.09.011`

[5] M. K. Hasan, M. Mahmud, A. K. M. A. Habib, et al. Review of electric vehicle energy storage and management system: Standards, issues, and challenges. *Journal of energy storage* **41**:102940, 2021. `https://doi.org/10.1016/j.est.2021.102940`

[6] W. Zhao, G. Wu, C. Wang, et al. Energy transfer and utilization efficiency of regenerative braking with hybrid energy storage system. *Journal of Power Sources* **427**:174–183, 2019. `https://doi.org/10.1016/j.jpowsour.2019.04.083`

[7] C. Capasso, D. Lauria, O. Veneri. Experimental evaluation of model-based control strategies of sodium-nickel chloride battery plus supercapacitor hybrid storage systems for urban electric vehicles. *Applied energy* **228**:2478–2489, 2018. `https://doi.org/10.1016/j.apenergy.2018.05.049`

[8] A. T. Hamada, M. F. Orhan. An overview of regenerative braking systems. *Journal of Energy Storage* **52**:105033, 2022. `https://doi.org/10.1016/j.est.2022.105033`

[9] K. Itani, A. De Bernardinis, Z. Khatir, A. Jammal. Comparative analysis of two hybrid energy storage systems used in a two front wheel driven electric vehicle during extreme start-up and regenerative braking operations. *Energy Conversion and Management* **144**:69–87, 2017. `https://doi.org/10.1016/j.enconman.2017.04.036`

[10] Z. Fu, Z. Li, P. Si, F. Tao. A hierarchical energy management strategy for fuel cell/battery/supercapacitor hybrid electric vehicles. *International Journal of Hydrogen Energy* **44**(39):22146–22159, 2019. `https://doi.org/10.1016/j.ijhydene.2019.06.158`

[11] N.-D. Nguyen, C. Yoon, Y. I. Lee. A standalone energy management system of battery/supercapacitor hybrid energy storage system for electric vehicles using model predictive control. *IEEE Transactions on Industrial Electronics* **70**(5):5104–5114, 2023. `https://doi.org/10.1109/TIE.2022.3186369`

[12] I. Shchur, I. Bilyakovskyy, V. Turkovskyi. Improvement of switched structure semi-active battery/supercapacitor hybrid energy storage system for electric vehicles. *IET Electrical Systems in Transportation* **11**(3):241–255, 2021. `https://doi.org/10.1049/els2.12017`

[13] Z. Song, J. Hou, H. Hofmann, et al. Sliding-mode and Lyapunov function-based control for battery/supercapacitor hybrid energy storage system used in electric vehicles. *Energy* **122**:601–612, 2017. `https://doi.org/10.1016/j.energy.2017.01.098`

[14] F. S. Garcia, A. A. Ferreira, J. A. Pomilio. Control strategy for battery-ultracapacitor hybrid energy storage system. In *2009 Twenty-Fourth Annual IEEE Applied Power Electronics Conference and Exposition*, pp. 826–832. IEEE, 2009. `https://doi.org/10.1109/APEC.2009.4802757`

[15] S. Tibude, G. Goyal, A. Ranjan, S. Bodkhe. Advanced energy management strategies for hybrid energy storage systems in electric vehicles: A comprehensive review. In *2025 Fourth International Conference on Power, Control and Computing Technologies (ICPC2T)*, pp. 855–860. IEEE, 2025. `https://doi.org/10.1109/ICPC2T63847.2025.10958756`

[16] S. Bansal, S. Dey, M. Khanra. Energy storage sizing in plug-in electric vehicles: Driving cycle uncertainty effect analysis and machine learning based sizing framework. *Journal of Energy Storage* **41**:102864, 2021. `https://doi.org/10.1016/j.est.2021.102864`

[17] F. Jin, M. Wang, C. Hu. A fuzzy logic based power management strategy for hybrid energy storage system in hybrid electric vehicles considering battery

degradation. In *2016 IEEE transportation electrification conference and expo (ITEC)*, pp. 1–7. IEEE, 2016. `https://doi.org/10.1109/ITEC.2016.7520207`

[18] J. Hu, D. Liu, C. Du, et al. Intelligent energy management strategy of hybrid energy storage system for electric vehicle based on driving pattern recognition. *Energy* **198**:117298, 2020. `https://doi.org/10.1016/j.energy.2020.117298`

[19] Y. Yang, Y. Xu, H. Zhang, et al. Research on the energy management strategy of extended range electric vehicles based on a hybrid energy storage system. *Energy Reports* **8**:6602–6623, 2022. `https://doi.org/10.1016/j.egyr.2022.05.013`

[20] Z. Bai, Z. Yan, X. Wu, et al. H_∞ control for battery/supercapacitor hybrid energy storage system used in electric vehicles. *International Journal of Automotive Technology* **20**(6):1287–1296, 2019. `https://doi.org/10.1007/s12239-019-0120-x`

[21] C. Qiu, G. Wang, M. Meng, Y. Shen. A new strategy of controlling the regenerative braking system of electric vehicles in safety-critical road situations. *Energy* **149**:329–340, 2018. `https://doi.org/10.1016/j.energy.2018.02.046`

[22] P. Thounthong, P. Sethakul, S. Rael, B. Davat. Performance evaluation of fuel cell/battery/supercapacitor hybrid power source for vehicle applications. In *2009 IEEE Industry Applications Society Annual Meeting*, pp. 1–8. IEEE, 2009. `https://doi.org/10.1109/IAS.2009.5324894`

[23] K. Itani, A. De Bernardinis, Z. Khatir, et al. Regenerative braking modeling, control, and simulation of a hybrid energy storage system for an electric vehicle in extreme conditions. *IEEE Transactions on Transportation Electrification* **2**(4):465–479, 2016. `https://doi.org/10.1109/TTE.2016.2608763`

[24] C. S. Phutane, P. K. Katti, G. B. Shinde. Analysis of hybrid energy storage system for electric vehicles. In *2022 IEEE 3rd Global Conference for Advancement in Technology (GCAT)*, pp. 1–6. IEEE, 2022. `https://doi.org/10.1109/GCAT55367.2022.9972029`

[25] A. K. Podder, O. Chakraborty, S. Islam, et al. Control strategies of different hybrid energy storage systems for electric vehicles applications. *IEEE Access* **9**:51865–51895, 2021. `https://doi.org/10.1109/ACCESS.2021.3069593`

[26] M. B. F. Ahsan, S. Mekhilef, T. K. Soon, et al. Lithium-ion battery and supercapacitor-based hybrid energy storage system for electric vehicle applications: A review. *International Journal of Energy Research* **46**(14):19826–19854, 2022. `https://doi.org/10.1002/er.8439`

[27] L. Guo, P. Hu, H. Wei. Development of supercapacitor hybrid electric vehicle. *Journal of Energy Storage* **65**:107269, 2023. `https://doi.org/10.1016/j.est.2023.107269`

[28] Y. Li, X. Huang, D. Liu, et al. Hybrid energy storage system and energy distribution strategy for four-wheel independent-drive electric vehicles. *Journal of Cleaner Production* **220**:756–770, 2019. `https://doi.org/10.1016/j.jclepro.2019.01.257`

[29] V. Mounica, Y. P. Obulesu. Hybrid power management strategy with fuel cell, battery, and supercapacitor for fuel economy in hybrid electric vehicle application. *Energies* **15**(12):4185, 2022. `https://doi.org/10.3390/en15124185`

[30] B. Wang, J. Xu, B. Cao, X. Zhou. A novel multimode hybrid energy storage system and its energy management strategy for electric vehicles. *Journal of Power Sources* **281**:432–443, 2015. `https://doi.org/10.1016/j.jpowsour.2015.02.012`

[31] Y. Li, O. P. Adeleke, X. Xu. Methods and applications of energy saving control of in-wheel motor drive system in electric vehicles: A comprehensive review. *Journal of Renewable and Sustainable Energy* **11**(6):062701, 2019. `https://doi.org/10.1063/1.5129070`

[32] L. Hu, Q. Tian, C. Zou, et al. A study on energy distribution strategy of electric vehicle hybrid energy storage system considering driving style based on real urban driving data. *Renewable and Sustainable Energy Reviews* **162**:112416, 2022. `https://doi.org/10.1016/j.rser.2022.112416`

[33] M. A. Hannan, Z. Abd Ghani, A. Mohamed, et al. An enhanced inverter controller for PV applications using the dSPACE platform. *International Journal of Photoenergy* **2010**:457562, 2010. `https://doi.org/10.1155/2010/457562`

[34] B. G. Pollet, I. Staffell, J. L. Shang. Current status of hybrid, battery and fuel cell electric vehicles: From electrochemistry to market prospects. *Electrochimica Acta* **84**:235–249, 2012. `https://doi.org/10.1016/j.electacta.2012.03.172`

[35] M. A. Hannan, F. A. Azidin, A. Mohamed. Hybrid electric vehicles and their challenges: A review. *Renewable and Sustainable Energy Reviews* **29**:135–150, 2014. `https://doi.org/10.1016/j.rser.2013.08.097`

[36] H. Rezk, A. Fathy. Combining proportional integral and fuzzy logic control strategies to improve performance of energy management of fuel cell electric vehicles. *International Journal of Thermofluids* **26**:101076, 2025. `https://doi.org/10.1016/j.ijft.2025.101076`

[37] H. Maghfiroh, O. Wahyunggoro, A. I. Cahyadi. Energy management in hybrid electric and hybrid energy storage system vehicles: A fuzzy logic controller review. *IEEE Access* **12**:56097–56109, 2024. `https://doi.org/10.1109/ACCESS.2024.3390436`

[38] M. A. Hannan, A. Mohamed. PSCAD/EMTDC simulation of unified series-shunt compensator for power quality improvement. *IEEE Transactions on power delivery* **20**(2):1650–1656, 2005. `https://doi.org/10.1109/TPWRD.2004.833875`

[39] H. Jiang, Y. Zhao, S. Ma. Dual-layer energy management strategy for a hybrid energy storage system to enhance PHEV performance. *Energies* **18**(7):1667, 2025. `https://doi.org/10.3390/en18071667`

[40] M. A. Hannan, F. A. Azidin, A. Mohamed. Multi-sources model and control algorithm of an energy management system for light electric vehicles. *Energy Conversion and Management* **62**:123–130, 2012. `https://doi.org/10.1016/j.enconman.2012.04.001`

[41] R. S. Sankarkumar, R. Natarajan. Energy management techniques and topologies suitable for hybrid energy storage system powered electric vehicles: An overview. *International Transactions on Electrical Energy Systems* **31**(4):e12819, 2021. `https://doi.org/10.1002/2050-7038.12819`

[42] D. T. Tu. A novel concept of hybrid electric public bus with power management system in Vietnam's condition. *Journal of Advanced Manufacturing Technology (JAMT)* **17**(2):71–88, 2023. `https://jamt.utem.edu.my/jamt/article/view/6528`

[43] Y. Tong, I. Salhi, Q. Wang, et al. Bidirectional DC-DC converter topologies for hybrid energy storage systems in electric vehicles: A comprehensive review. *Energies* **18**(9):2312, 2025. `https://doi.org/10.3390/en18092312`

[44] H. Rezaei, S. E. Abdollahi, S. Abdollahi, S. Filizadeh. Energy management strategies of battery-ultracapacitor hybrid storage systems for electric vehicles: Review, challenges, and future trends. *Journal of Energy Storage* **53**:105045, 2022. `https://doi.org/10.1016/j.est.2022.105045`

[45] A. S. Veerendra, M. R. B. Mohamed, F. P. García Márquez. Energy management control strategies for energy storage systems of hybrid electric vehicle: A review. *Energy Storage* **6**(1):e573, 2024. `https://doi.org/10.1002/est2.573`

[46] N. Kumaresan, 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* **46**(3):146, 2024. `https://doi.org/10.1007/s40430-024-04736-x`

[47] M. S. Ramkumar, S. Muthukrishnan, J. Giri, et al. Optimizing battery and supercapacitor management in electric vehicles: A hybrid approach for enhanced performance and reduced harmonics. *Case Studies in Thermal Engineering* **68**:105815, 2025. `https://doi.org/10.1016/j.csite.2025.105815`

[48] I. Kranthikumar, C. H. Srinivas, T. V. Kiran, et al. A novel hybrid approach for efficient energy management in battery and supercapacitor based hybrid energy storage systems for electric vehicles. *Electrical Engineering* **107**(1):1–17, 2025. `https://doi.org/10.1007/s00202-024-02483-9`

[49] O. A. AlKawak, J. R. R. Kumar, S. S. Daniel, C. V. K. Reddy. Hybrid method based energy management of electric vehicles using battery-super capacitor energy storage. *Journal of Energy Storage* **77**:109835, 2024. `https://doi.org/10.1016/j.est.2023.109835`