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Developing a New Automatic Switching Mechanism for a Storage System that Combines Supercapacitor Bank with Battery

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Abstract: In this paper, basically a hybrid energy storage system (HESS) made up of a battery and a super capacitor (SC) is proposed for hybrid electric vehicles. A fully active converter topology is used for the packs of battery and super capacitor. Firstly, a MATLAB-developed Simulink model of the battery and super capacitor (SC) hybrid energy storage system is develop, and its performance is examined. The basic advantages of the recommended control approach is that it allows to reduce battery current while maintaining the super capacitor voltage fluctuations within a specified range. Secondly, the numerical results have been validated by developing an experimental setup of the proposed model consisting of integration of battery and a super capacitor in which two DC/DC converters are employed to regulate the flow of power between the two components. Lastly, the battery fade behavior is analyzed using a rectified battery fade model that precisely matches the examined battery. According to proposed model, it result show that by adopting a hybrid energy storage system (HESS), battery current is decreases by 38.47 % at the starting and by 20% during running conditions.

Index Terms-- *Battery, Super capacitor, Passive boost converter, BLDC Motor.*

NOMENCLATURE

V_{sc}	Super capacitor voltage
A_i	Interfacial area between the electrode
C	Molar concentration
I_{sc}	Super capacitor current
N_e	No. of layers of electrodes
N_s	Number of series super capacitors
N_p	Number of parallel super capacitors
Q_t	Electric charge
R_{sc}	Total resistance of super capacitors
R	Ideal gas constant
ϵ_0	Permittivity of free space
V_b	Battery voltage
E_b	Battery EMF
R_b	Battery internal resistance
SOC_b	State of charge for battery
Q	Electric charge

I_b	Battery current
P_b	Battery Power
C_{time}	Charging time
I_d	Discharging current
I_c	Charging current
R_p	Parallel resistance
R_s	Series resistance
SOC_s	State of charge for super capacitor
P_{in}	Input power
P_{out}	Output power
RSC	Resistance of super capacitor
iSC	Current of super capacitor
Abbreviations	
SCs	Super Capacitors
DOFs	Degrees of Freedom
EMS	Energy Management System
SOC	State of charge of battery
DC	Direct current
AC	Alternating current

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EVs	Electric Vehicles
PEVs	Purely Electric Vehicles
HEV	Hybrid electrical vehicle
DoD	Depth of discharge

OCV	Open circuit voltage
HESS	Hybrid energy storage system
BLDC	Brush less DC Motor
DP	Dynamic Programming

I. INTRODUCTION

The Electric vehicle (EVs) uses has increased dramatically over the past ten years as they don't pollute the environment and release grease pollutants. In the EVs battery packs is very essential part and also which is the more exclusive component of purely electric vehicles (PEVs), frequently costing more than 40% of the entire cost of the vehicle [1].Consequently large power required for charging and discharging of the battery.it can accelerate, aging and decreases lifespan [2] In divergence, super capacitors (SC) have a suggestively higher power density and increases life cycle compared to Li-ion batteries. Therefore, another key point are examined to increases the efficiency of the EV by using energy management system, to increases life of battery and decreases the electric vehicle cost by reducing the needs of battery replacement [3-4].However, the actual performance of hybrid system depend on its energy management strategy or switching of the system. Proper allocation of power management between energy storage components is necessary. By adding super capacitors to batteries, the load on the batteries decreases, increasing their lifespan and enhancing overall performance of the system [5–12].

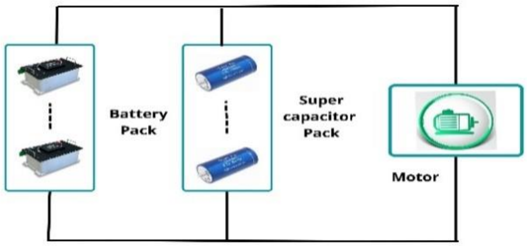
Li-ion batteries are generally employed in EVs, by comparing with SCs, SCs are an electrolytic capacitor type that has better power densities and capacitance values. SCs are able to deliver substantially more power in shorter amounts of time owing to their increased power density. Because of this, they are appropriate for handling the needs of EV motors in urban driving patterns where there are a lot of accelerations and decelerations and significant variations in power consumption [13]. The SC can provide this current when the load's current requirement is high in order to reduce thermal effect on the EV battery and increase its lifespan [14]. Due to a slower rate of EV battery deterioration and thus less frequent battery replacements, this enhances the performance of the EV EMS and smaller operating expenses. Smaller power losses are a result of a SC's internal resistance being substantially lower than Li-ion battery with a comparable energy storage capacity [15].

1.1 Related to work

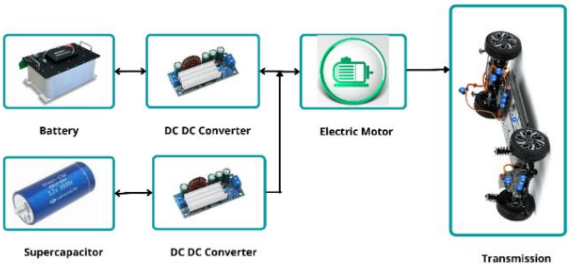
1.1.1 Connection of Battery- super capacitor

According to literature survey, various type of SC connectivity are proposed to increases the operating efficiency and also to maintained constant supply voltages competences with electric vehicle (EV) related to energy storage system [16]. These are illustrated in Figure 1. Based on the quantity of degrees of freedom (DOFs) under control, may be categorized into three categories: passive, semi-active, and fully active [17]. In this paper active and passive topology are discussed. Figure 1a illustrates the passive paralleling battery-SC connection setup that is suggested in Ref. [18]. Every power source has certain discharge resistance and charge values that determine how the discharge and charge controls are actually employed. In this configuration, the super capacitor cannot be utilized effectively. The passive topology is economical and has an easy-to-assemble structure, but its performance typically falls short of expectations. Due to the lack of power electronic circuits in this way of hybridization formation, the SC drains much more quickly than the Li-ion battery. In order to get around this problem, the SC is associated with the battery in Refs [19] using a DC/DC converter.

The fundamental block diagram of HESS, which has a completely active architecture, is shown in Figure 1. (b). A bi-facial DC/DC converter links with the Li-ion battery and super capacitor are coupled in parallel with the DC connection, for improving the HESS's dynamic responsiveness during periods of transient high power demand [20]. The power converters have extensive usage in several fields, such as computer power supply, office equipment, aviation, communications, and motor drives [21-22]. The primary purpose of a DC/DC converter is to produce a variable DC output from a constant DC input that may be used for buck, boost, or buck-boost operations. In electric vehicle design, the most common architecture is the power converter, where the output voltage is upper than the incoming voltage. The bi-directional DC/DC converter in the HESS has the dual purpose of transferring the energy and keeping the DC bus voltage steady. Additionally, the converter must offer two way power flow because the grid and the energy storage system both needs to exchange energy [23].



(a) Passive topology structure



(b) Fully active topology

Fig. 1. Schematic block diagram of HESS

1.2 Energy management system for HESS

To create effective EMS for integrated battery-SC HESSs in EVs, an abundant deal of research has been done. Refs. [24–25] present the deterministic rule-based approach as if-else paradigms that develop from heuristic human experience. The author of these papers have established a limit scale for the current in EV motor requires. When the current demand surpasses the threshold, the SC is triggered to provide the necessary power, while the EV battery functions below the threshold. Another rule-based for HESS in energy management algorithms are put forth in Refs. [26,27], where the power provided to the motor rather than its present demand is used as the threshold. In this method, the motor's needs for voltage and current are acknowledged.

The projected power requirement for pre-known drive cycles is used earlier discussed in rule-based algorithms to establish the current. In Ref. [28], an adaptive power split approach is proposed to overcome this constraint. This technique watches the real-time motor load profile to ascertain the degree of change in the power response and divides the power in between battery and super capacitor correspondingly. Ref. [29] employs a different real-time power split technique that uses fuzzy logic controls to determine the frequency of load variations. In Ref. [30], to accurately identify the power thresholds, a fuzzy rule-based HESS energy management system (EMS) with an optimized fuzzy membership function is discussed. Furthermore, Ref. [31] uses real-time current monitoring to limit higher current in the battery may supply to the electric vehicle (EV) motor and avoid excessive battery drain.Efficient power splitting in HESSs may also be achieved by integrating various optimization approaches with a rule-based algorithm. Another real-time optimization method is model predictive control (MPC) that is suggested in Refs. [32] to find the ideal power divided between the EV battery and SC bank during ambiguous driving cycles. On the other hand, offline, worldwide optimum EMSs are suggested in Refs. [33] Employing dynamic programming (DP); nonetheless, they necessitate a high level of computing power from the EMS controller in addition to prior driving cycle knowledge.

In this paper, a DC/DC converter supplied by a brushless DC motor has been developed and its performance analysis has been performed in the Simulink/MATLAB environment [34]. A hardware implementation of the BLDC motor supplied by the boost converter has also been performed. This paper's primary contribution is summarized as follows:

- Developing a new automatic switching mechanism for a storage system that combines super capacitor bank with battery.
- Developing the simulation model and analyzing the performance of the hybrid energy storage system design.
- Validating the simulation results by developing an experimental setup.

Section II presents the various energy storage devices and converters used in the HEVs. Section III introduces the proposed scheme and the experimental setup. The experimental results are presented in section IV, Subsequent to the final observations in Section V.

II. Different Energy storage Devices & Converters

There are various sources such as battery, super capacitor, fuel cell and flywheel that are employed in hybrid electric vehicles. Hybridization is known as the arrangement of more than one sources with complementary properties. In this study, a 12 V, 7 Amp Li Ion battery is considered as the important source of energy for the HESS. However, a super capacitor cell commercialized by 500 F, 3 V is selected as an auxiliary power source. The integration of these two sources are presented as the HESS.

A. Battery

Every electronic device has a battery, which is a remarkable and often utilized energy source. It act as a major power source in the HEV system. A DC/DC converter connects the battery of a hybrid electric vehicle (HEV) to a DC bus, and the voltage of the battery & DC bus are same. The state of charge (SOC) of battery proves a significant concept that regulates the operation of the hybrid vehicle system. When the vehicle accelerates quickly, the battery provides maximum power and when it decelerates like SC, it replenishes the power. Batteries are employed in vehicles for a variety of purposes because of their beneficial qualities, including high energy density, compact size, and durability [35]. Lead acid batteries are the first rechargeable batteries, and they have been widely used for more than a century [36]. There has been several studies were conducted to enhance the battery performance, and as a result, different types of batteries are commercially accessible. The batteries has unique specific power and specific energy. Lead batteries have a lifespan of approximately six to fifteen years, with a cycle life of about 2000 and an 80-90 % depth of discharge (DoD) [37]. Fig. 2. Represents the commonly used batteries in the EVs. In this study, 12V Li Ion battery is used for the simulation and hardware implementation purposes.

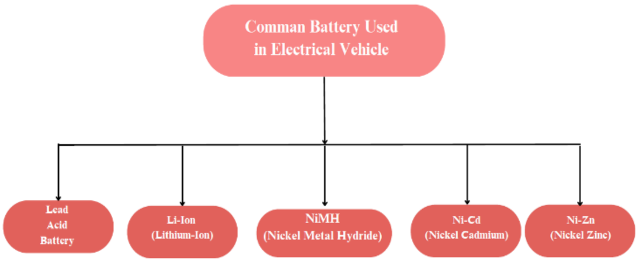


Fig. 2. Commonly used batteries in EV

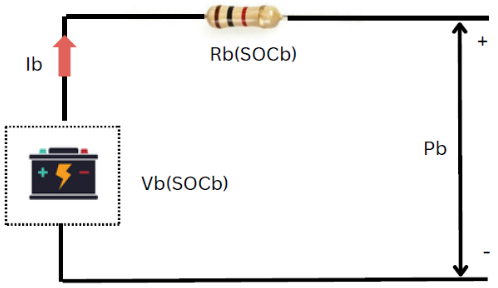


Fig. 3. Analogous circuit of the battery internal resistance model [38]

The optimum battery for a certain application is selected by taking into account a number of parameters, such as specific energy, power, cost, cycle life, and safety. An analogues circuit of the battery internal resistance model is used in EV represent in Fig. 3. This model has been frequently used to assess the energy management techniques of EVs and HEVs. The internal resistance, open circuit voltage (OCV) depend upon the battery SOC in this model and the battery characteristics are defined as follows:

$$V_b = E_b - R_b . I_b \tag{1}$$

$$SOC_b = -\frac{I_b}{Q} \tag{2}$$

$$I_b = \frac{V_b\,(SOC_b) - \sqrt{(V_b\,(SOC_b)^2} - 4\,R_b\,(SOC_b).\,P_b)}{2R_b\,(SOC_b)} \tag{3}$$

The various parameters of the battery are mentioned in Table I.

TABLE I EQUATION OF BATTERY

Specification	Formula
Charging Time	$C_{time} = \frac{\text{Battery Capacity (Ah)}}{\text{Charging current (A)}}$
Battery SOC	$SOC = \frac{\text{Remaining Capacity of Battery}}{\text{Total Capacity of Battery}}$
Charging Current	I_c = 30 % of capacity of battery in Ah
Discharge Current (I_d)	$Id = \frac{\text{Load in watts}}{\text{Battery Voltage}}$
Backup Time	$\text{Backhours} = \frac{\text{Battery Capacity (Ah)}}{\text{Discharging Current (A)}}$

Table II represents battery specifications used for simulation purpose. Fig. 4 shows the hardware module for checking battery voltage with digital oscilloscope.

TABLE.II

BATTERY PARAMETERS

Parameters	Values
Battery voltage	12 V
Rated capacity	7 A
Total no of battery	1

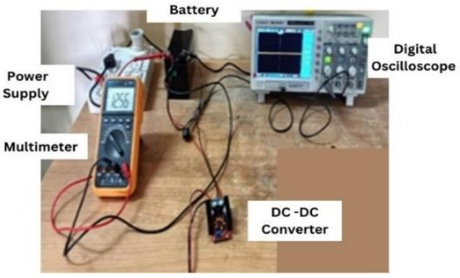


Fig. 4. Hardware module for checking of Battery voltage

B. *Supercapacitor*

In terms of energy storage and delivery, super capacitors work similar to secondary batteries [39]. When compared to batteries, the charge storage methods of super capacitors are extremely different. Batteries use chemical processes to generate electric charge, whereas super capacitors use static charge to store energy. Super capacitors provide quicker charging and discharging rates than batteries of equivalent capacity. Because energy is stored in the same form as it is consumed. However, the energy densities of super capacitors are 10 to 20 times lower than those of batteries. As such, super capacitor cannot be considered as a replacement for secondary batteries, but rather a complementing power delivery technology. Fig. 5 represents the physical model of a super capacitor, and its specifications are shown in Table III. A capacitor's stored energy (E) is expressed as follows:

$$E = \frac{1}{2} C V^2 \quad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_} 4)$$

Where, C is the capacitance of capacitor in Farad and V is the applied voltage in volts.

Fig. 5. Super capacitor module

Super capacitor models have been applied in a variety of vehicle applications [40-46]. The basic internal resistance model is one of them is considered due its simplicity and sufficient accuracy, in which an EV or HEV's capacitor is coupled to a series resistance (R_s) is frequently used when creating energy management approaches [47]. To account for total leakage as well as the resistance against discharging and charging, a parallel resistance (R_p) is included in addition to the series resistance (R_s) in this research. Fig. 6 illustrates the equivalent model of super capacitor employed in this study, which has previously been widely used.

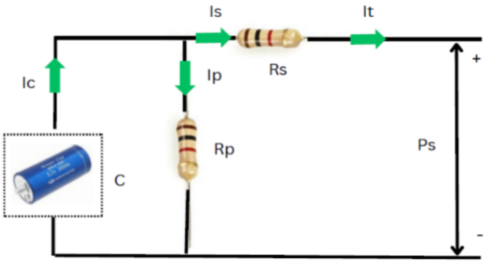


Fig. 6. Equivalent circuit diagram of supercapacitor

$$I_t = I_c - I_p \ \text{(Discharging)} \qquad (5)$$

$$I_t = I_c + I_p \ \text{(Charging)} \qquad (6)$$

Where, the capacitance current is I_c, leakage current is I_p, and the output current of the supercapacitor is I_t.

TABLE.III

SUPER CAPACITOR PARAMETERS

Parameters	Values
Voltage per cell	3 V
Capacity	500 F
Total no of SC	4

The relationships between the super capacitor specifications are shown in Fig. 5 as follows:

$$SOC_s = -\frac{1}{C} * ((\frac{1}{2R_s} \pm \frac{1}{R_p}) * SOC_s - \frac{1}{2R_s}\sqrt{SOC_s^{\,2}} - \frac{4R_s}{V_s Max^2} * P_s$$

(7)

The super capacitor output voltage is represented as [48]:

$$V_{sc} = \frac{N_s\, Q_\tau\, d}{N_p\, N_e \in\in_0\, A_i} + \frac{2\, N_e\, N_s\, R\, T}{F} \sinh^{-1} * $$

$$(\frac{Q_\tau}{N_s\, N_e^2\, A_i \sqrt{8R \in\in_0\, c}} C) - R_{SC}.\, I_{SC}$$

(8)

The super capacitor self-discharging formula is as follows:

$$Q\tau = \int i_{\text{dis}}^{\text{self}}\, dt \qquad (9)$$

The super capacitor’s SOC is as follows:

$$SOC = \frac{A - \int_0^t i(\tau)\, d\tau}{Q_\tau} \times 100$$

(10)

C. DC/DC converter used in HESS system

To integrate various energy storage devices into a HESS that can control current flows, more power electronics are needed. As a result, a DC-DC converter was develop for all purposes. The output and the high-energy battery are separated by the DC/DC converter unit. In this design, the DC/DC converter for the high-energy component can be sized lower since peak loads will be handled by the high-power storage device, which is linked directly to the output. [33]. A boost converter is called as a step up converter. Fig. 7 shows the hardware module of converter, where the output voltage is higher than the input voltage.

The input power must match the output power in accordance with the rule of conservation of energy (Negligible power losses in the circuit).

$$P_{in} = P_{out} \qquad (11)$$

Since in a step up converter:

$$V_{in} < V_{out} \tag{12}$$

As a result, the output current is less than the incoming current. Therefore ,in a boost converter:

$V_{in} < V_{out}$ and $I_{in} > I_{out}$

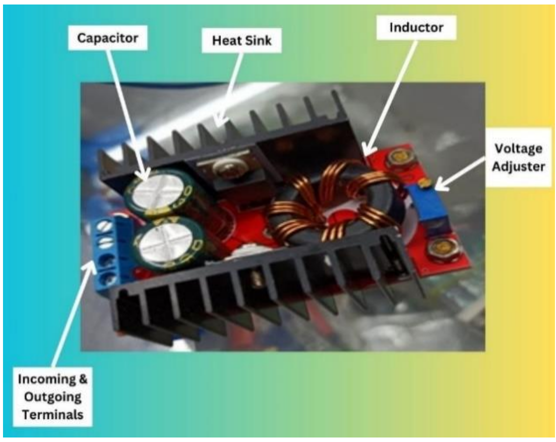


Fig. 7. Hardware module of boost converter

A DC/DC converter's primary purpose is to prevent sudden changes in input current from entering the input circuit. When the primary switching device is turned on and energy is stored in it, the inductor current rises to its maximum value. The generated induces emf polarity of inductor flips when the switching device is off since it is unable to quickly alter the direction of the current, so freewheeling diode is conduct in one direction. The inductor discharges as a result, transferring its stored energy to the load and causing the inductor current to drop. As a result, the voltage across the load will be the same as the total of the supply voltage and the inductor voltage. Therefore, this converter performs boosting action by producing an output that is greater than the input voltage. Output voltage stability is ensured by a large time constant in relation to switching period. The following mentions the boost converter's conversion gain:

$$\frac{V_0}{V_{in}} = \frac{1}{1 - D} \tag{13}$$

Where V_o is the output voltage, V_{in} is the input voltage and D is the duty ratio of boost converter. Table IV presents the specifications for the boost converter simulation. The simulation circuit of boost converter is also shown in Fig. 8.

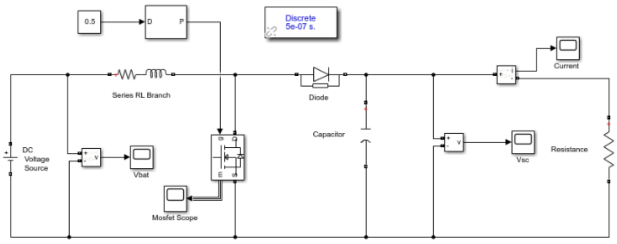


Fig. 8. Simulation model for boost converter

TABLE.IV

BOOST CONVERTER PARAMETERS

Specifications	Values
Inductor	12.5 mH
Capacitor	20 µF
Resistor	100 Ω
Duty Cycle	50 %
Input voltage (Vin)	12 V
Switching Frequency	10 kHz
Inductor	12.5mH

III. PROPOSED SCHEME

Power semiconductor switches, like metal oxide field effect transistors (MOSFETs), insulated gate bipolar transistors (IGBTs), and power diodes, are used and controlled in the proposed scheme. Fig. 10 illustrates the schematic arrangement of proposed scheme that consists of a battery as an input voltage source, switches, filtering circuit and control circuit.

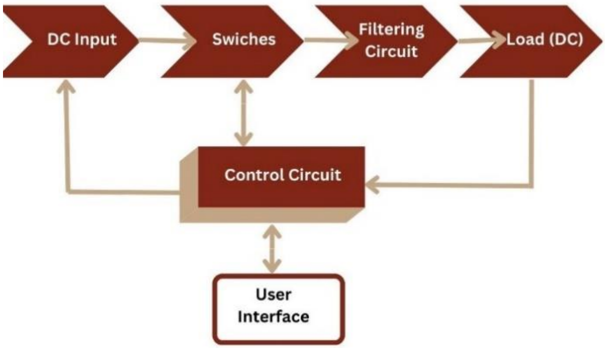


Fig. 9. Proposed scheme

Fig. 10 shows MATLAB simulation of super capacitor joined in shunt with battery. Battery output voltage is connected to the boost converter that increases the voltage to a chosen level. The output voltage of the boost converter is connected to the brush less DC motor (BLDC motor). Super capacitor is linked in parallel via a boost converter. Diode is coupled in between the battery and super capacitor, so that it does not allow reverse voltage in the system.

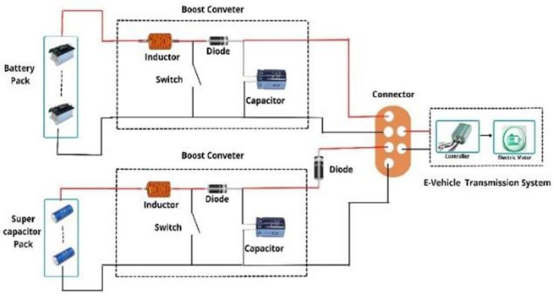


Fig. 10. Simulation diagram in MATLAB for parallel combination of battery with supercapacitor

Fig. 11 represents the hardware model of the proposed system. Lead acid battery of 12 V, 7 A is connected to the BLDC motor through boost converter. Four supercapacitors, each having capacity of 3 V, 500 F, are connected in series and pack of this supercapacitor are allied in parallel with main supply via boost converter. Two manual switches are used to on/off the two sources.

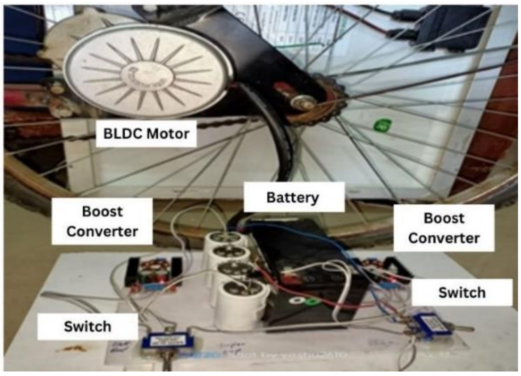


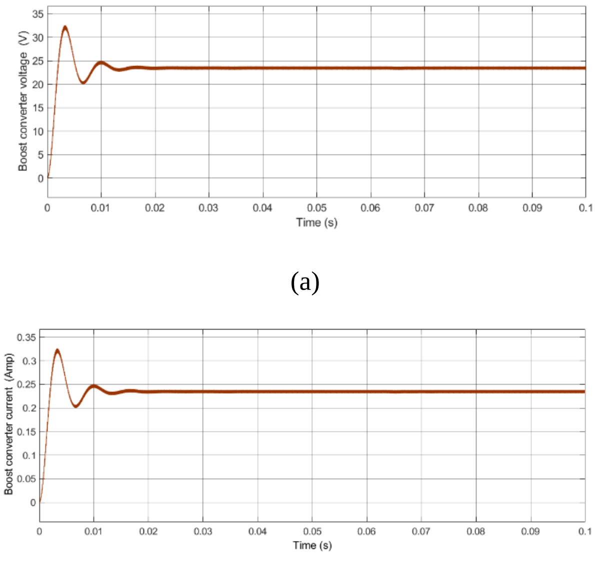
Fig. 11. Hardware model of proposed system

IV. SIMULATION & EXPERIMENTAL RESULTS

In this study, two sources are integrated and the simulation method has been carried out using MATLAB Simulink along with its hardware model has also been implemented.

A. Simulation Results

Fig. 12a and Fig. 12b show the simulated transient output voltage and current of the boost converter correspondingly. When the boost converter input is connected to the battery output, battery provides 12 V voltage to the power converter. At the starting, the boost converter voltage increases to 32 V till 0.005 s, and then decreases. At 0.015 s, the boost converter output voltage becomes stable and it provides a constant voltage to system. Initially, the boost converter takes higher current of almost 0.32 A, but after 0.015 s, its output current becomes stable and it provides a constant current of 0.24 A to the load.



(a)

(b)

Fig. 12 Transient output (a) voltage and (b) current of boost converter

Fig. 13 represents the transient output voltages of battery and super capacitor. Initially, the battery supplies a steady voltage of 12 V to the motor. In this study, four supercapacitors are connected in series so that they maintain a steady voltage of 12 V during startup, but when the power to a load, their voltage drops to 11.18 V and then rises to 11.58 V when they are fully charged, and finally providing a continuous voltage. The supercapacitors start to deliver continuous voltage after 0.025 s.

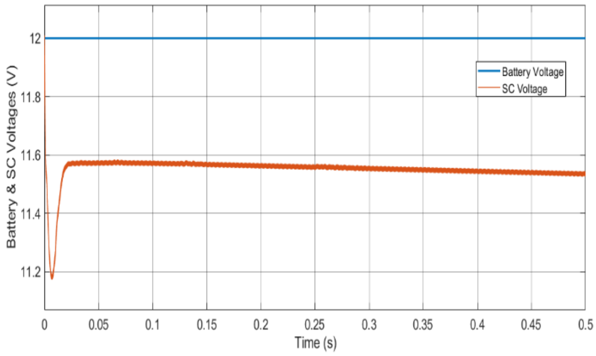


Fig. 13. Battery and supercapacitor output voltage

Fig. 14 presents the transient output voltage of the boost converter when super capacitor is linked in shunt with the battery. The battery and super capacitor work in parallel while coupled to a boost converter, raising the voltage up to a required point where the boost converter voltage reaches 28 V. At startup, the motor draws more current and the boosted voltage falls. After 0.01 s, the motor voltage rises to 35 V during the next 0.05 seconds. The battery and supercapacitor output voltages start supplying the motor with steady voltage after 0.05 s. Fig. 15 indicates that both energy storage devices share a voltage of 35 V.

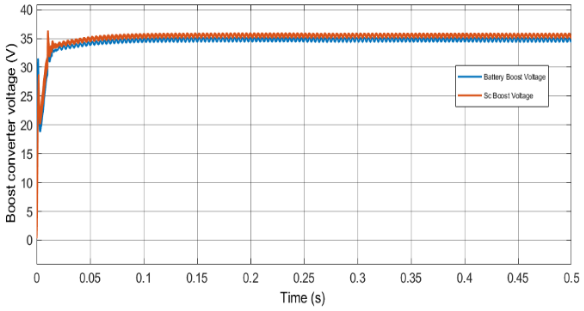


Fig. 14. Battery and supercapacitor boost voltage

Battery and supercapacitor transient current variations are shown in Fig. 15. The motor is initially supplied with a regular supply voltage. However, the motor requires a higher starting current of up to 65 A due to its inductive nature. It is assumed that the supercapacitor is initially completely charged so that it may deliver voltage to the motor in shunt connected with the battery as an energy source while the motor is extract current from the battery. When the super capacitor is attached in parallel, it also supplies the current to the motor at a rate of up to 25 A/s. Following that, the battery current and the supercapacitor currents both decrease when the motor winding's maximum flux is set up. After 0.02 s, the motor takes a standard rating current of 10 A and super capacitor also provides 2 A current.

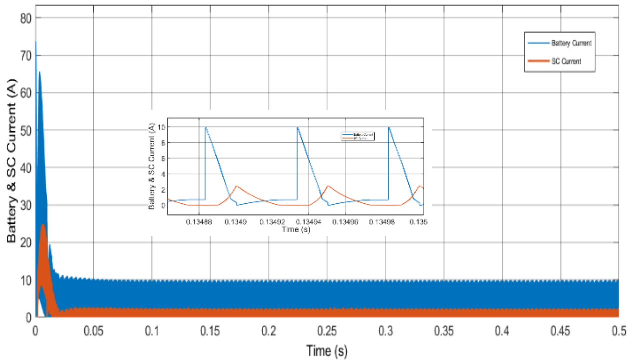


Fig. 15. Battery and supercapacitor current

With a battery serving as the primary source, Fig. 16 depicts the power-sharing between two energy storage devices with respect to time. Battery and supercapacitor together can supply the load's entire amount of power. In this case, the supercapacitor has been restored to supply the load with peak and starting power, whereas the battery is supplying the load with regular power throughout the operation. Battery and supercapacitor both give maximum power from 0 to 0.02 s, and then they switch to steady power of 350 W and 75 W, respectively. Both energy storage systems simultaneously supply electricity to the electric vehicle.

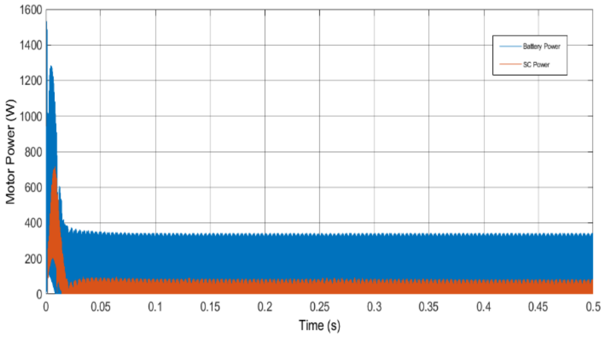


Fig. 16. Battery and supercapacitor Power

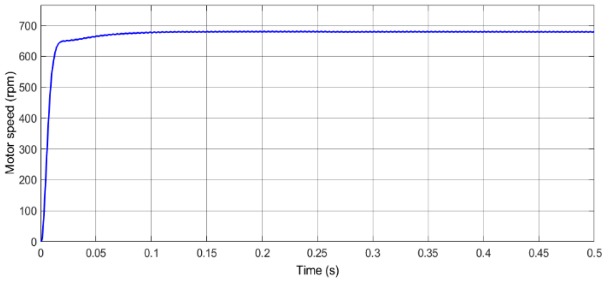


Fig. 17. Motor speed in rpm at no load

The transient motor speed at no load is shown in Fig. 17. Firstly, it is assumed that the motor is in a stationary state having zero speed. When an energy storage device is connected to a motor, the motor begins to run and its transient speed increases linearly till 0.015 s. Following the setting of the winding's maximum flux, the rotor's maximum speed is developed. The BLDC motor's speed reaches 700 rpm or close to it after 0.02 s and remains constant.

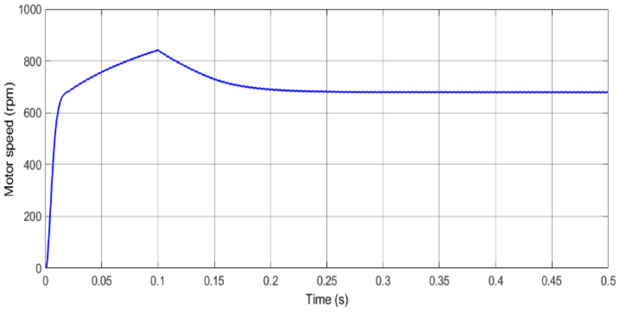


Fig. 18. Motor speed in rpm at load

It is assumed that the BLDC motor is supplied with a load of 0.1 N. Fig. 18 shows the BLDC motor transient speed under the load. Up to 0.02 s, the motor speed increases linearly. The BLDC motor speed rises to 820 rpm when, after 0.02 s, the maximum flux is built up in the motor coil. After applying a 0.1 N load, the motor's speed drops and only reaches 700 rpm.

B. Experimental Results

This segment builds an experimental testing platform to demonstrate the viability of the control strategy for simulated energy management. The hardware implementation of a super capacitor linked in parallel with the battery is shown in Figs. 19–21. Firstly, it appears that the lead acid battery is fully charged and its voltage is measured with the help of multi meter and DSO. When battery is fully charge, it shows a full voltage of 12.7 V as represent in Fig. 19.

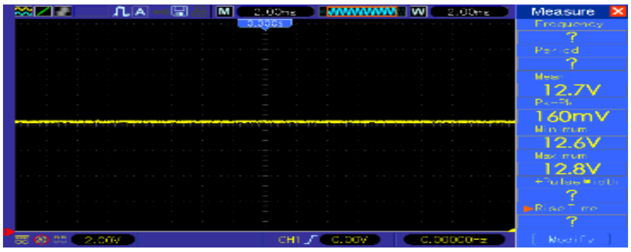


Fig. 19. Output voltage of battery with DSO

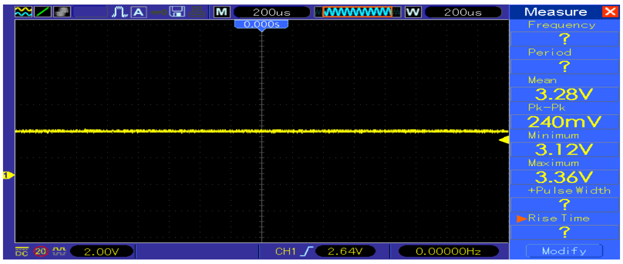


Fig. 20. Output voltage of single supercapacitor with DSO

While verifying the results, a single super capacitor is also tested and its output voltage is presented in Fig. 20. In the hardware model, 4 super capacitors are connected in series so that an equivalent voltage of 12 V is achieved. The battery and BLDC motor are linked in series with the power converter. The boost converter's output voltage is represents in Fig. 21. When battery is connected with BLDC motor, the motors runs and its speed is measured with the help of tachometer as shown in Fig. 22. The motor speed reaches nearer to 700 rpm and it is verified with the simulation model developed in MATLAB.

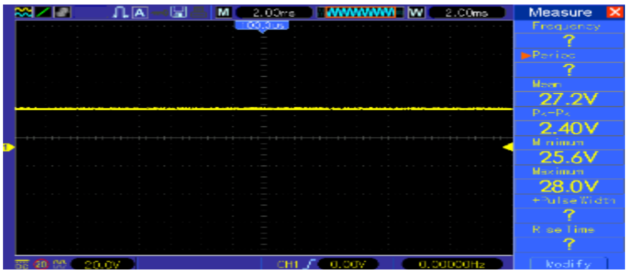


Fig. 21. Output voltage of boost converter with DSO

Fig. 22. Hardware model with motor speed in rpm

V. CONCLUSION

This study discusses adoption of electric vehicles to efficiently handle the problems of rising carbon emissions. Battery and super capacitor are considered as the hybrid energy storage system used in the electric vehicles. The proposed HESS's Simulink model battery & super capacitor are associated in parallel, is developed in MATLAB Simulink. Fully active converter topology is adopted for this study. Furthermore, The suggested model is created for hardware execution. The experimental design is verified with simulation model. According to the findings, the battery's peak current drops by 38.57% when it starts and 20% when it is operating in running condition. It has also been observed that the motor speed decreases by 4.41% when a load of 0.1 N is applied with reference to the no load conditions.

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