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Original Article

Investigations of Lithium-Ion Battery and Supercapacitor Hybridization on Relative Effectiveness and Energy Performance of E-Bicycle with Regenerative Braking

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Abstract *- This study investigates the integration of lithium-ion batteries and supercapacitors along with regenerative braking mechanisms for electric bicycles using microcontroller based switching smart switching mechanisms. The research focused on balancing the energy and power demands during driving a bicycle on uneven or elevated road surfaces in order to reduce the stress induced by lithium-ion batteries as a single energy storage system. The study includes modeling, simulation, and experimental analysis. It investigates the efficiency of hybrid systems to maximize vehicle dynamics and electrical performance, focusing on regenerative braking conditions. The theoretical analysis focused on the electrical behavior of individual lithium-ion batteries and supercapacitors. Simulation extends by analyzing the dynamic behavior of an e-bicycle integrating a hybrid system during real-world applications. The simulation investigates the effect of energy regeneration through applied brakes on the vehicle's dynamics, considering the ride performance, with active braking four-quarter BLDC motor mechanism. Experimental studies include a prototype e-bike using a proposed HESS system by simulating real-world conditions and monitoring e-bike performance using theoretical and mathematical predictions of the system's strength. Experimental data provide important insights into hybrid systems' efficiency and effectiveness, especially in regenerative braking. In addition, the study investigates the interaction between lithium-ion batteries and supercapacitor optimization to improve energy density, power density, and overall system efficiency in the case of e-bikes with regenerative braking.*

Keywords *- Lithium-ion battery, EDLC supercapacitor, Microcontroller, Regenerative breaking, e-bicycle, Simulation.*

1. Introduction

E-mobility or electromobility states a vehicle driven by electrical energy for transportation and relevant applications. This changeover from conventional petroleum fuel-based IC engine vehicles to electric and hybrid vehicles has gained significant momentum due to environmental concerns, energy efficiency, and improvements in energy storage technologies [1]. The significance of lithium-ion batteries and supercapacitors in e-mobility is important, and their flattering concern leads to the inclusive effectiveness and performance of electric vehicles. Because of their high power density combined with high energy density, lithium-ion batteries serve as the standard power source for electric vehicles [2]. This allows massive amounts of energy to be stored in compact form, providing the power needed to drive long distances on a single charge [3]. The high capacity of lithium-ion batteries gets electric vehicles directly influences impacts range and endurance. As battery technology improves, EVs with lithium-ion batteries can travel longer distances, making them more practical for everyday use [4]. Lithium-ion batteries are capable of delivering high power, allowing electric vehicles to run more efficiently and overall perform better. This is vital for meeting the demands of various driving conditions. The compatibility of lithium-ion batteries with current charging infrastructure facilitates the adoption of electric vehicles [5]. Rapid charging abilities are continuously enhancing, lowering charging times and increasing the ease of EV possession. Supercapacitors excel in excessive strength density requirements. It has a speedy discharge frequency, making it suitable for regenerative braking operation and imparting bursts of energy during acceleration, which is valuable in begin-forestall traffic situations [6]. Supercapacitors have a longer cycle existence in comparison to standard batteries. Their capability to bear an excessive range of rate-discharge cycles makes them properly perfect for applications wherein common, fast charging and discharging are required [7]. Supercapacitors play a vital function in regenerative braking structures, shooting and storing energy all through braking events.

This electricity can then be speedily launched for the duration of acceleration, enhancing ordinary power performance and lengthening the variety of electric vehicles [8]. This is in line with Ragone's plot, which combines supercapacitors with lithium-ion batteries in a hybrid electricity garage device, allowing for the benefits of both technologies. Supercapacitors handle high-electricity demands, even as lithium-ion batteries provide the essential electricity for sustained use [9]. The importance of lithium-ion batteries and supercapacitors in e-mobility lies in their complementary roles in addressing the demanding situations related to energy garages and electricity delivery.

Combining that technology can cause extra green, excessive-performance electric motors with improved variety, acceleration skills, and normal sustainability [10]. HESS integrates a Li-ion battery with a supercapacitor, as presented in Figure 1, which offers great power density, quick charge and discharge capabilities, and enhanced lifecycle [11]. The proposed hybridization faced issues of quick charging and discharging of supercapacitors. Therefore, a microcontroller-based smart switching mechanism is provided for activating and charging the supercapacitor through energy recovered by the regenerative braking mechanism described in further chapters. This smart system not only controls the charging and discharging of energy storage systems but also navigates e-bicycle electrical parameters per road conditions, reducing the stresses on the battery and improving its lifecycle.

Regenerative braking for supercapacitors uses supercapacitors to achieve and restore energy produced during brake or deceleration [10]. The storage device known as a supercapacitor exhibits two operating variants designated as Pseudo and electric double-layer discharge. The devices function together for rapid energy storage when combined with electric vehicles that use regenerative braking technology to transform vehicle movement into electrical power [12]. Regenerative braking systems convert this electric energy to supercapacitors Instead of dissipating it to the environment. During charging, supercapacitors absorb energy faster, making them well-suited to satisfy the fast bursts of energy generated during braking. Also, as supercapacitors can charge and discharge faster, they make higher voltage requirements more effective in capturing and releasing energy during short bursts, such as during acceleration or when extra energy is needed [13]. When a rider needs extra speed or energy, the overall demand for primary energy can be reduced if stored systematically.

Devices equipped with supercapacitors handle strong power fluctuations during braking and acceleration, thus minimizing the core energy storage component such as lithium-ion batteries [14]. This can contribute to energy storage, in particular, which has been around for a long time. Using regenerative braking with supercapacitors in electric bikes can lead to energy-efficient design, extended battery life, and improved overall performance [15]. This technology best matches the characteristics of supercapacitors and contributes to energy transport systems if it is an enduring and far-reaching paper.

2. Literature Survey

Mahdi Soltani et al.'s research used the Matlab / Simulink PLECS toolbox to simulate energy recovery through regenerative braking [16]. Researchers Jian Cao et al. [17] HESS used PSAT software to evaluate a compact DC/DC converter, which acted as a power amplifier to improve ultracapacitor voltage retention compared to battery levels. Rebecca Carter et al. [18] developed a novel lead acid battery-supercapacitor hybrid energy system through regenerative braking. They applied it to study supercapacitor behavior and energy efficiency from regenerative breakdown techniques.

Researchers discovered that supercapacitors enable current flow when operating voltage increases alongside equivalent series resistance reduction. A. A series of publications on battery and supercapacitor hybrid energy systems appeared in the work of Ostadi et al. [19] to meet vehicle demands for power and energy along with addressing energy management issues. Results confirmed the improved performance of disconnecting configurations when supercapacitors received power from the DC bus directly. The unit demonstrates both proper EV/HEV application knowledge and organizational capability. The lithium-ion batteries and ultracapacitors developed by Seyed Hamidi et al. [20] contained different cathode anode and lithium-ion battery compositions that produced varying performance characteristics from identical power circuits.

The system addressed lithium-ion and ultracapacitor power capacities targeted at high energy density storage to mitigate challenges from lithium-ion batteries, such as high manufacturing costs and thermal sensitivity issues. The researchers at Clemente Capasso et al. [21] built a HESS system based on Na-Cl batteries and EDLCs connected to an automatic bi-directional power Converter for control. The forthcoming research will focus on both simulation and experimental studies involving lithium-ion and ultracapacitor devices in HESS. Wenhua Zuo et al. [22] performed research in 2017 that investigated different HESS configurations that combined high capacitive batteries with rated capacitive electrodes. At BSH, researchers combined high-potential fluid windows with three-dimensional electrode and electrolyte structure architecture. In 2018, Anuradha Herath et al. developed charging and discharging protocols that track the performance of batteries alongside supercapacitors, which depend on speed and acceleration.

The new system demonstrates improved battery handling compared to standard battery electric vehicles through efficient strain reduction on the drivetrain span. Lithium-ion capacitor research by Mahdi Soltani et al. [24] developed systems with high energy storage capability for driving cycles under MLTB conditions. The development of lithium batteries will continue with the goal of building a high-performance system that combines better cost efficiency with stability at reduced size requirements. Lip Sawa et al. [25] Analysed driving cycles through a lithium-ion battery combined with an ultracapacitor model to measure electrical and thermal performance metrics. The improved dynamic stress and optimized battery performance for peak power operation require validating simulation results while establishing test platforms for electric propulsion components to integrate intelligent energy systems. Md. To analyze HESS with supercapacitors and new battery cells, Arman Arefin and his team ran simulations [26].

The experimental outcomes indicated that temperature affects the operational efficiency of hybrid systems. The power train efficiency, together with battery lifespan, improves due to hybridization and regenerative fracturing, which boost the efficiency of energy storage systems while extending the system's power maintenance capacity. Lia Kouchachvili et al. [27] Developed battery-supercapacitor HESS through electrochemical cell design that features supercapacitor power rates and battery-cycle capability. The complementary supercapacitor adds supplementary power to maintain the system operation if the battery exhibits power limitations.

The authors examined passive HESSs together with active and semi-active HESSs from a structural and operational perspective. The paper investigates HESS applications starting from mobile charging stations up to race cars and explains several supercapacitor battery combinations together with their related content and forecasted developments.

Emerging proposals from Emmanuel N. et al. [28] conduct systematic research on batteries and supercapacitors, and hybrid capacitor combinations are supposed to enhance energy efficiency in electric transportation. Within the reported work, researchers replicated the problem, where two recharge points generated an independent charging state for the supercapacitor. The DC-DC converter receives various input signals followed by eV profile collection for the proposed HESS during experimentation. This methodology demonstrates the potential for expansion through additional studies involving load systems with peak crest factors. The modeling design and power structure of a Li-ion battery compatible with a supercapacitor hybrid energy system was developed by S Devi Vidya et al. [29] to enhance the operational life through a bi-directional converter for light electric cars in Indian driving scenes.

Experimental and simulation investigations analyzed the effectiveness of control management through modeled light electric vehicle A prototype system components conducted by Sankar Bharti A et al. [30]. A parallel connection unit combining battery and supercapacitor packs existed within a power converter controller operating with an Arduino to make power judgments between storage components. The main battery received protection against sudden surges, which extended its operational lifespan. The authors Walvekar, A. et al. [31] Studied Li-ion battery and supercapacitor hybrid systems for 2020 two-wheeled electric vehicles. The study examines how hybrid energy storage systems interact with the degree of hybridization concerning current usage along with voltage distribution and State of Charge (SOC) regulation.

Tests revealed that implementing HESS systems into clean battery-based two-wheeled electric vehicles reduced battery Current expenses while extending overall battery life. Using both simulation and experimental approaches, Renato Marialto et al. [32] developed a parallel hybrid system that combined two electric motors powering the navy propulsion alongside an IC engine battery storage unit. The paper by Ghoulam Yasser et al. [33] shows the modeling, parameter estimation, identification, and validation of lithium batteries and supercapacitors with bidirectional DC/DC power converters for hybridization in eV applications.

3. Proposed System

The proposed system is based on the novelty of efficiently resolving the energy and power density requirement for lightweight vehicles and reducing stresses induced on a single energy storage device, i.e., the battery in this case, with the extra device as a supercapacitor. Also, the involvement of simulation and experimental approach of regenerative braking for energy recovery mechanism is an innovative approach applied here using BLDC motor.

In the proposed system of e-bicycles, experimental analysis for energy recovery for battery charging is done by implementing a dynamometer, which is further improved by a microcontroller-based system for reducing losses and efficiency. A hybrid lithium battery-supercapacitor system appears in Figure 1 on the Ragone plot for experimental testing at the centre location.

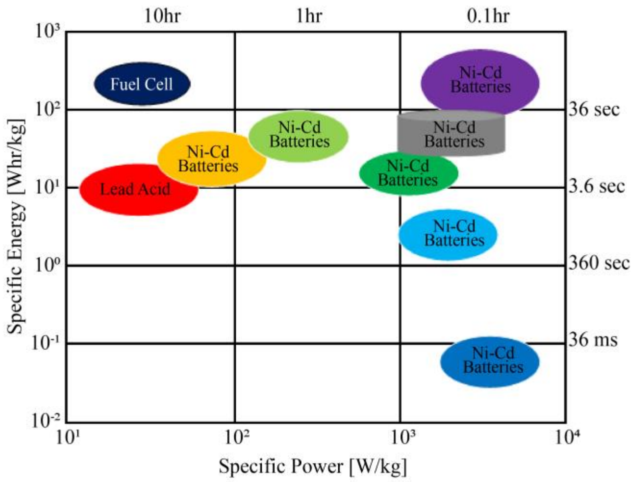

Fig. 1 Ragone plot for proposed HESS system

Fig. 2 The proposed electric bicycle with regenerative breaking

Figure 2 shows the proposed electric bicycle CAD model using solid works with regenerative breaking using a BLDC hub motor fixed at the rear axle with a regenerative braking mechanism. The display unit and controller system are connected via the proper sensory mechanism connecting the HESS system and motor.

3.1. HESS System Calculations

3.1.1. Battery Pack Calculations

As shown in Table 1, we have used 18650 li-ion batteries assuming 80% efficiency, each of 3.7Volts and 2.5 Ampere, to generate 100 watts of energy to run the application for 2 hours.

$$\text{Time} = \frac{Battery\ efficiency(\%)\times Battery\ voltage(V)\times Battery\ current(A)}{Energy\ required\ in\ (watt)}$$

$$\text{Time} = \frac{0.80\times 11.1\times 20}{100} = 1.776 \text{ Hrs.} \cong 2 \text{ Hrs.}$$

As per calculations, it is found that three pairs of cells need to connect in series and 8 in parallel combination, i.e., a total of 24 cells will be required.

$$\text{Calculated energy} = \frac{Total\ battery\ voltage \times Total\ battery\ current}{100}$$

$$a = \frac{11.1\times 20}{1000} = 0.222\text{Kw/h} = 222\text{watt/hr}$$

$$\therefore Calculated\ power = 222\ watts$$

3.1.2. Supercapacitor Pack Calculations

Experimental analysis for this work included the serial connection of five Green cap EDLC (DB) supercapacitor units with 2.7 Volts battery capability at 500 faradays, which measured 35 mm x 60mm each having Input current limit – 1mΩ and discharge limit – 470kΩ, analysis.

- Supercapacitor pack voltage 2.7 x 5 = 13.5 V
- Supercpacitor pack capacitance (CT)

$$CT = \frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \frac{1}{C_4} + \frac{1}{C_5}$$

$$CT = \frac{1}{500} + \frac{1}{500} + \frac{1}{500} + \frac{1}{500} + \frac{1}{500} = \frac{5}{500}$$

- CT=500/5 = 100 Faraday.
- Energy calculation € =9112.5J=2.53125Watt/hr.

$$\frac{1}{2}C_T V^2 = \frac{1}{2}\times 100\times 13.5^2$$

- Power generated = E/ (t2-t1) = (2.53125 / 3) = 843.75 Watts.

3.2. Regenerative Breaking

The four-quadrant principle operation of a Brushless DC (BLDC) motor provides a regenerative braking method that collects the energy during deceleration.

The BLDC motor works like a generator for the braking quadrants II (Forward Braking - Quadrant II) and IV (Reverse Braking Quadrant IV). The transforming process begins when vehicle kinetic energy transitions into electricity at this point.

The system routes the energy to the main battery together with an ESS through an inverter under BMS control, which stops forward battery charging. As a four-quadrant device, it allows for seamless transitions between motoring and braking modes, fine-tuned control and energy efficiency. This mechanism decreases the dependence on mechanical brakes, increases battery life, and enhances the performance of electric and hybrid vehicles.

When the driver drives the vehicle, kinetic energy is generated between the human body and the vehicle. This kinetic energy vanishes in space as the driver stops the vehicle or applies the brakes. With a regenerative mechanism, this kinetic energy can be recovered to generate electrical energy for charging a battery, supercapacitor, or both.

As shown in Figure 3, when the driver moves on an elevated or uneven road surface or high hill mountain road conditions, the motor supplies power to the wheel, and due to a sudden brake, the kinetic energy is converted to potential energy.

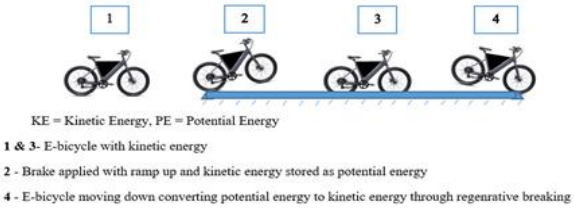

Fig. 3 Regenerative breaking mechanism for e-bicycle

In this case, the motor also stops supplying power for that period, and the vehicle will stop at a certain distance due to the vehicle's inertia force. At this distance, the vehicle wheel will supply power to the motor. The same condition is created when the vehicle moves down from a high-altitude elevated road, where the motor or battery can be kept idle, and power to move the vehicle is supplied by the wheel's rotary motion only. Therefore, in both braking and slope situations, the battery is in working condition for other vehicle devices, and power is received from the wheel and the motor. The motor turns a generator and converts the power into electrical energy to keep it stored in energy storage devices like batteries or supercapacitors to increase its state of charge. That's the basic theme of regenerating brakes. In the case of lightweight electric vehicles like the e-bicycle proposed in this work, the regenerative braking won't be that effective compared to heavy vehicles on hill stations or sloping roads. Therefore, a good portion of the energy that would have vanished through braking goes back into the battery and can be reused when you restart the vehicle, charge the discharge energy storage devices, or keep it stored in the battery. Therefore, the proposed e-bicycle BLDC hub motor with a 12 V DC regenerative motor controller is selected due to its significant features compared to conventional DC motors.

3.3. Vehicle Dynamics

Here, the power calculation is done for fabricating the lithium-ion battery and supercapacitor system-based e-bicycle using the following data in Table 1.

Table 1. E-bicycle parameters for calculation of applied forces

Sr. No.	Particulars	Specifications
1	Target average speed of e-bicycle	25 km/hr
2	Target average distance of e-bicycle	20 km
3	Load (e-bicycle + driver)	100 kg
4	e-bicycle rim radius with tire (r)	0.35m
5	Coefficient of friction of road surface for static load (μs)	0.3
6	Coefficient of friction of road surface for dynamic load(μf)	0.004

- The maximum normal reaction of the tire (Nr)
  = 50 x 9.81 = 490.5N on each tire.
- The static frictional force on the tire (Sf) = (μs) x (Nr)
  = 490.5 x 0.3 = 147.15 N.
- Dynamic frictional force (Df) = 0.004 x 490.5 = 1.96 N.
- The torque acting on the tire (T) = (Sf + Df) x r
  = (147.15 + 1.96) x 0.35 = 52.1885 N.m
- Angular velocity of shaft of e-bicycle (ω)
  $$= \frac{v}{r} = \frac{25\times1000}{0.35\times3600} = 19.8412 \text{ rad/sec.}$$
- Speed of cycle wheel (N) = $\frac{60\omega}{2\pi} = \frac{60\times19.8412}{2\times\pi} = 189.56\text{RPM}$
- Motor power required (P)
  $$= \frac{2\pi\pi N}{60} = \frac{2\pi\times189.56\times52.1885}{60} = 1035.45\text{Watt}$$

A motor with a power of 1KW is selected for an e-bicycle, provided by the hybrid system.

3.4. Power Switching Mechanism

A control algorithm, as shown in Figure 4, is established using an Arduino microcontroller to regulate the system's optimum situation, considering the voltage levels, current flow, and other applicable parameters. During voltage monitoring, the voltage levels of the battery and supercapacitors are periodically measured by voltage sensors.

Depending on the voltage level and other parameters, such as the state of charge, the microcontroller decides whether to store energy in the battery, supercapacitor, or both. When load power is required, the microcontroller activates a switching mechanism to connect the battery, supercapacitor, or both.

Based on the power consumption parameters and power requirements of the system, balancing mechanisms are used to serve to recharge the supercapacitor cells to ensure longevity and efficiency. A fault detection system detects and controls any abnormality, such as overvoltage, undervoltage, or excessive current.

User interfaces such as LCDs or LED indicators are incorporated to provide real-time information about the status of these energy storage units. A low-power mode is used to reduce standby power consumption when the system is inactive. The software implementation is done by a control algorithm written in the microcontroller programming language "C".

The communication protocol is used to switch between battery and supercapacitor. It works if the system needs an external device or communication from a central control system. The system is then tested under various conditions to ensure it behaves as expected to optimize control algorithms for efficiency and responsiveness.

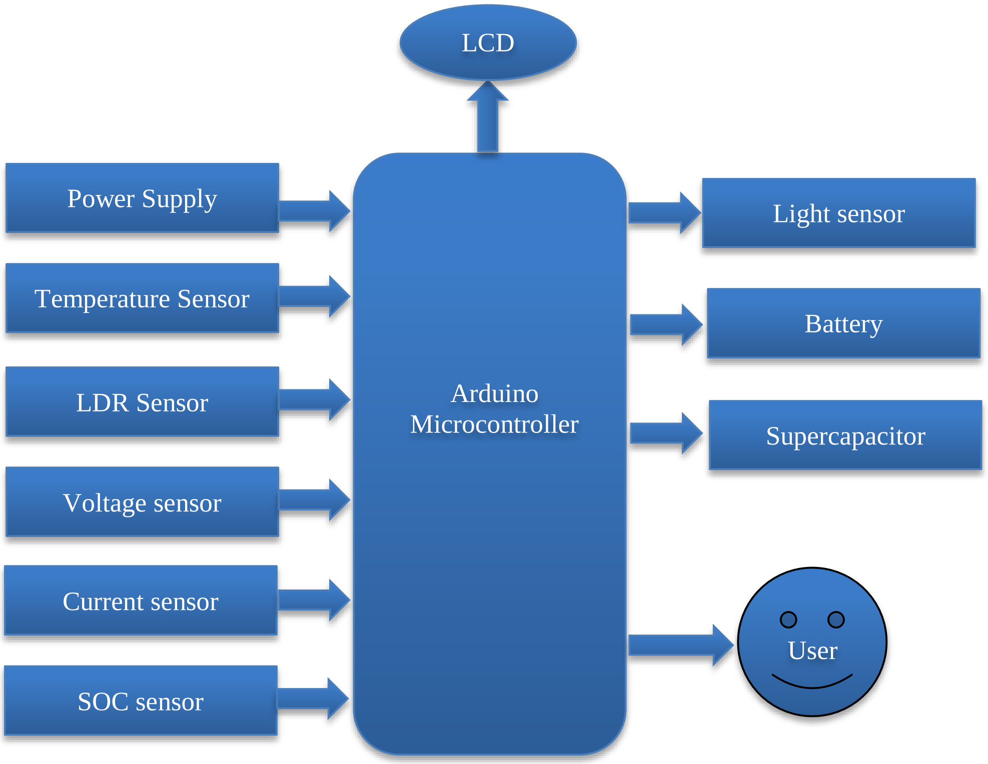

Fig. 4 Switching mechanism for power in the proposed HESS system

4. HESS System Simulation and Experimentation

4.1. HESS Simulation

Here for the simulation of a bicycle, Matlab/Simulink software is used to verify the results of the hybridization of lithium-ion batteries and EDLC supercapacitors. The EV design process requires EV development to use Simulink since this MATLAB-based simulation tool stands as a key component. Engineers optimize complex systems through Simulink's dynamic modeling capabilities and use them to analyze EV components such as batteries, electric motors, and power electronics. Engineers can use the block diagram approach to build complete EV systems to test their control strategies while evaluating system energy efficiency across different operating environments. Through its hardware-in-the-loop capability, Simulink gives developers the ability to validate systems in real time while decreasing development timescales and associated costs.

The tool serves as a necessary component for improvements in EV technological development. The switching mechanism is designed to activate the supercapacitor when it is the requirement higher power demands. The vehicle body includes the parameters of the bicycle as per its dynamics parameters. It is connected to the DC motor through differential and gear blocks per the power requirement and assumes negligible meshing, viscous, and inertia losses. Further, the longitudinal driver block is connected to the DC motor through the H-bridge motor drive block, which acts as a controller for the simulation circuit. The results are verified using the FTP 75 drive cycle, which defines the variation of bicycle speed in km/hr. w.r.to time for different loads and environmental conditions. Figure 5 shows the standard FTP 75 drive cycle with its different phases and applicability for the given system simulation.

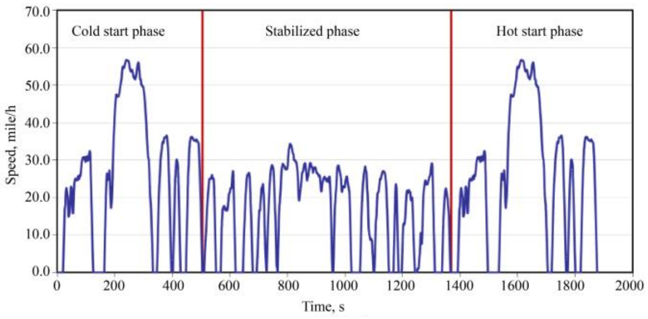

Fig. 5 FTP 75 drive cycle [14]

Table 2 indicates the vehicle dynamics parameters required for designing the simulation structure for the proposed e-bicycle.

Figure 6 shows the simulation model of the e-bicycle for evaluating and verifying the results for changes in the hybrid energy storage system's current, voltage, and state of charge as per the load conditions and HESS mechanism considering the FTP drive cycle.

Table 2. HESS system parameters for simulation using Matlab/Simulink

Particulars	Specifications
Mass of vehicle with driver	100kg
Distance from the front axle to CG	1.4m
Distance from the rear axle to CG	1.6m
CG height above ground	0.5m
Gravitation acceleration constant	9.81m/s^2
Frontal drag area	2m^2
Drag coefficient	0.25
Air density	1.18kg/m^3
vertical load for peak force on tire	3000N
The rolling radius of the tire	0.6
Velocity threshold	0.1m/s
BLDC motor power and voltage	20 W & 24 V
Rated speed of motor	3000 rpm
Rolling resistance coefficient	0.003
Air drag coefficient	1.0
Rotational inertia coefficient	1.05
Reference area	0.3 m^2
Static-loaded wheel radius	0.33 m
Air density	1.1 kg/m^3
Brake disc radius	0.07 m
Area brake piston	346.36 mm^2
Friction factor brake	0.7

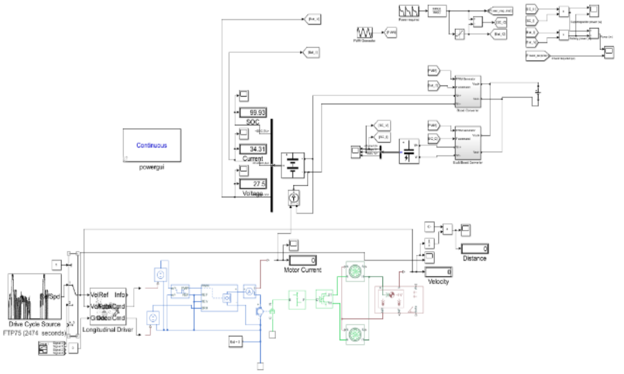

Fig. 6 Simulation model of an e-bicycle with proposed HESS system

Figure 7 shows the simulation model of regenerative breaking designed for the proposed HESS system. This example illustrates the role of a kinetic energy recovery system in the regenerative breakdown of the proposed system.

The HESS uses lithium-ion batteries together with ultracapacitors to store energy during braking operations. A 60KW extreme output can provide up to 400KJ of power during a single cycle according to predictions. The battery weight, the EDLC supercapacitor weight and the BLDC motor weight represent the system limitations. When all these boundary conditions are fixed to an initial value of 0.01kg, one drive's acceleration and deceleration time is 95 seconds, which resembles an e-bicycle without a regenerative braking system.

Implementing kinetic energy recovery systems only on selected parts requires a large supercapacitor to demonstrate any significant benefit; therefore, it runs for all corner conditions to get efficient results. By using the tools from Simulink and Simscape, researchers can act as support for system-level design activities.

System performance in kinetic energy recovery depends on the weight balance between three essential components while maintaining proper energy management protocols. Kinetic energy recovery drives the system's weight along with reduced speed due to the engine. The electricity collected from braking must exceed this.

The efficiency rating of lithium-ion batteries per unit mass reaches high levels that create a negative operating environment. The specific application requires ultracapacitors which provide high efficiency amounts per unit mass while maintaining lower overall efficiency per unit mass when compared to lithium-ion batteries.

Table 3. Specifications of kinetic energy recovery model

Components	Specifications
Weight of BLDC motor	3.8 kg
Weight of battery and supercapacitor HESS	6.2 kg
Specification of Li-ion battery pack	11.1V and 20 A
Specification of supercapacitor pack	13.5 V and 100 faraday

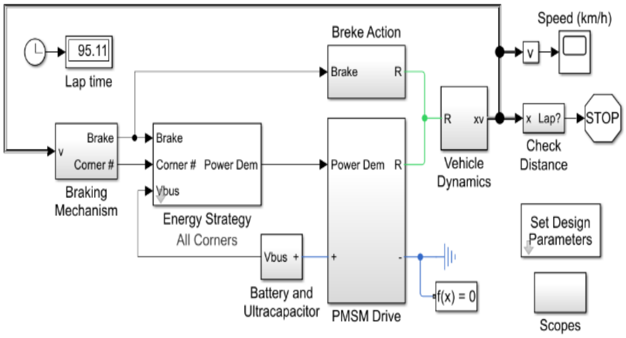

Fig. 7 Simulink model for regenerative braking of HESS system

The simulation-based energy recovery data for individual components appears in Table 4. The data collected revealed system-generated and recovered energy along with recorded braking times and distances.

Table 4. Kinetic energy recovery through simulation

Speed (Km/h)	Braking Time(sec)	Braking Distance (meter)	Total Energy(watt)	Recovered Energy(watt)	Absorbed Energy (watt)	Supercapacitor Capacity (Faraday)
10	12	18	45.18	46.76	44.35	6.7676
20	15	27	56.32	58.98	57.56	7.3454
30	17	38	60.37	59.38	42.71	8.7372
40	19	55	97.88	96.16	70.52	15.8151
50	21	80	138.6	144.23	99.38	24.595
60	24	160	178.22	177.14	125.71	34.835
70	26	165.5	217.61	237.29	149.83	46.2791
80	29	225	255.85	263.54	170.83	58.6145
90	32	300	293.06	293.07	186.45	70.6939

4.2. HESS Investigational Set-Up

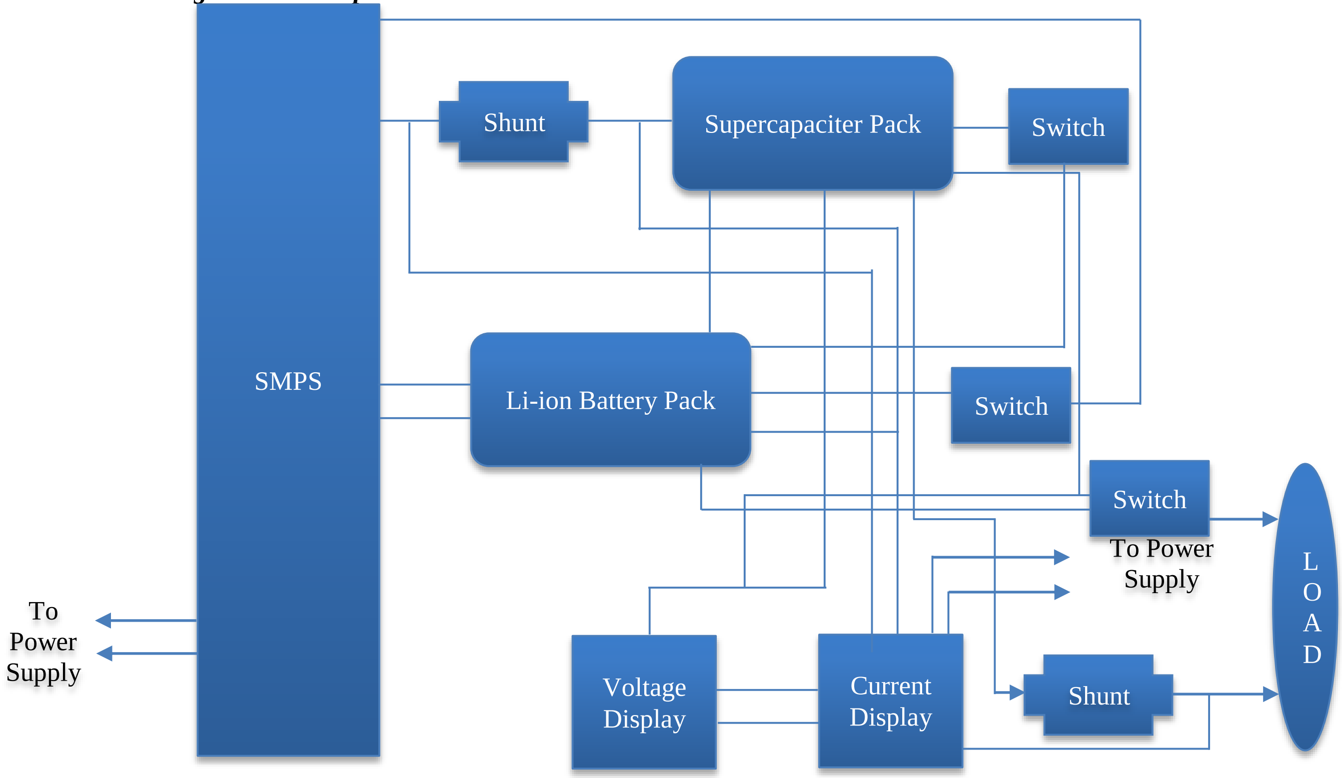

Fig. 8 HESS experimental set-up block diagram

A Lithium-ion battery pack combining 11.1V and 20A with a supercapacitor pack providing 13.5V and 100 Faraday serves as the experimental configuration. Electric power, together with the HESS, receives its supply from a Switched Mode Power Supply that provides 12V at 10A.

Shunt resistors serve both to act as voltage and current controllers and to provide accurate measurements on display equipment. The experimental setup uses three independent switches that activate both the battery pack and supercapacitors and allow HESS combinations for separate testing conditions. Experimental work utilizes two four-wheeler headlights totaling 240 watts to evaluate individual drive cycles on energy storage devices before moving to combined HESS hybridization testing.

The experimental implementation of hybrid energy storage illustrated in Figure 9 shows lithium-ion batteries and supercapacitor packs that remain connected through passive pathways [34]. The charging process requires a switch mode power supply monitoring to control current and voltage flow through it. Shunt resistors within vibration isolators help manage system vibration responses and display device readouts.

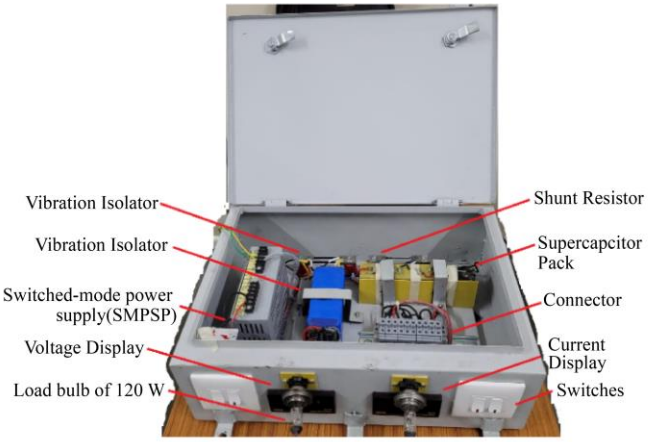

Fig. 9 Experimental setup for a hybrid energy storage system

The system uses a 220-watt light bulb and the weight of the cycle as the load to operate the mechanical energy storage system using various connecting switches.

$$\text{Degree of hybridization} = \frac{Motor\ power}{Motor\ power + HESS\ power} \times 100$$
$$= \frac{353.878}{353.878 + (222 + 843.75)} \times 100$$
$$= 24.92\%.$$

This shows the proposed hybridization is suitable for parallel hybrid vehicles. Table 5 shows the list of other components required for fabricating a hybrid energy storage system configured for the e-bicycle.

Table 5. List of components required for experimental setup

Components	Specifications
HESS Charger (SMPS)	12V, 10A
Pack of Li-ion Battery	11.1V, 20A
Pack of Supercapacitor	13.5V, 500F
Voltage display unit	0-200 V
Current display unit	0-75A
Resistor for supercapacitor	470KΩ, 2W
Shunt resistor (2nos)	75mV
Switches	3
Load	200W
Other Accessories, i.e. solder gun,	-

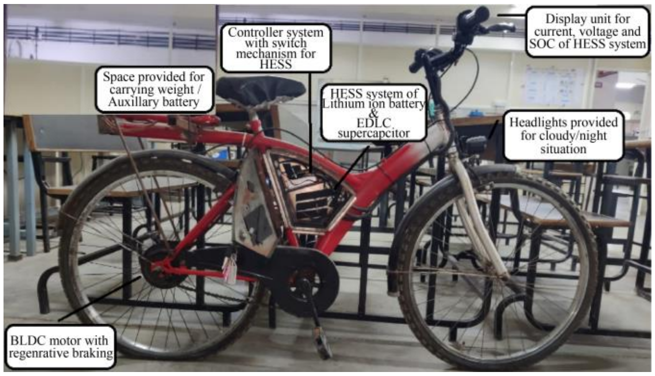

Fig. 10 Final e-bicycle with HESS system

5. Results and Discussion

Figure 10 shows the final set-up of the e-bicycle equipped with a HESS system of Li-ion battery pack and supercapacitor pack at a central position along with controller and other accessories connected as per the requirement.

5.1. Results

5.1.1. Simulation Results with Pure Battery-Based Vehicle

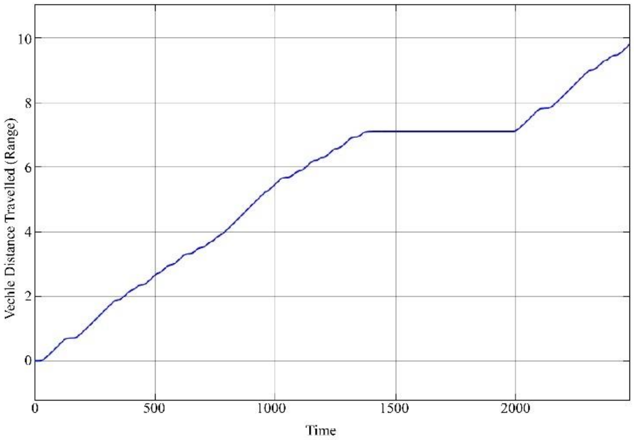

Fig. 11 Variation of vehicle distance traveled (Km) vs time (sec)

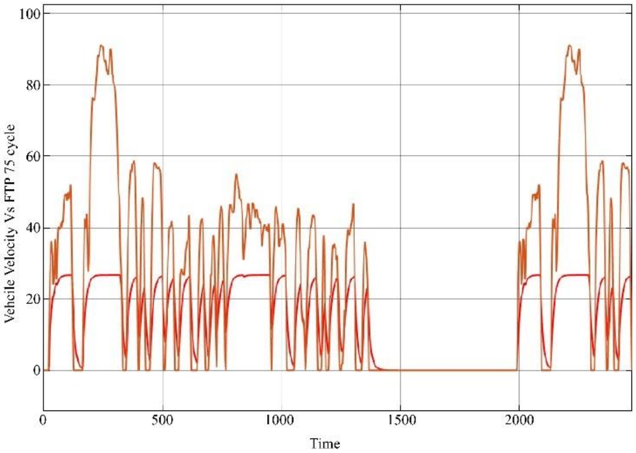

Fig. 12 Variation of vehicle velocity traveled (Km/hr) vs time (sec) in comparison with FTP 75 drive cycle

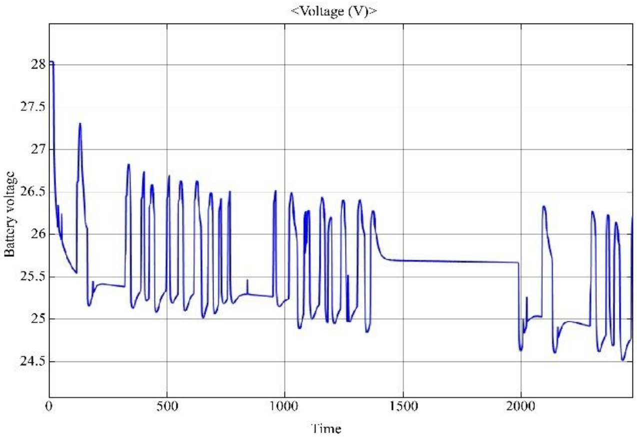

Fig. 13 Variation of battery voltage (V) vs time (sec)

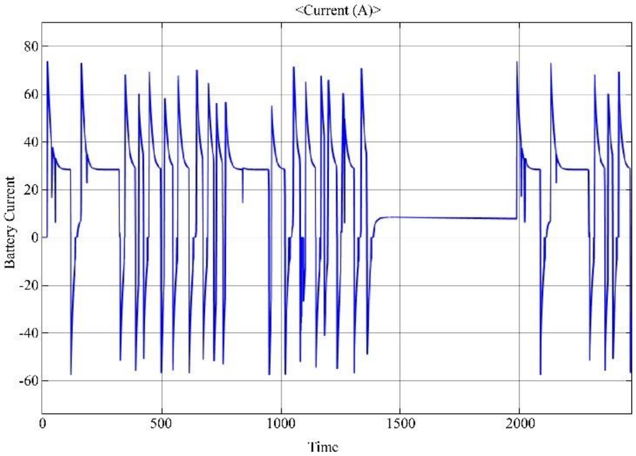

Fig. 14 Variation of battery current (A) vs time (sec)

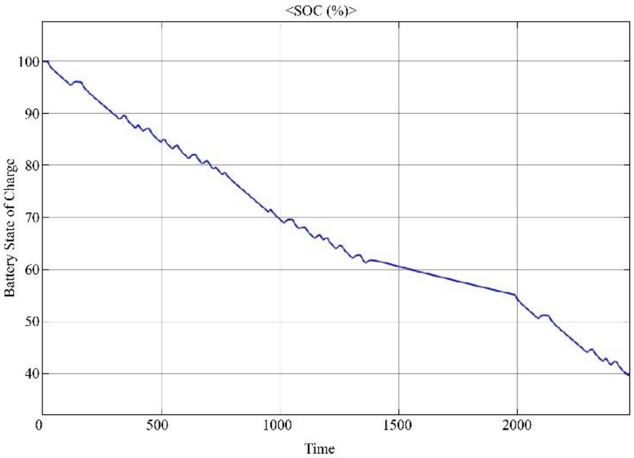

Fig. 15 Variation of battery state of charge (%) vs time (sec)

5.1.2. Simulation Results with HESS of Battery and EDLC Supercapacitor

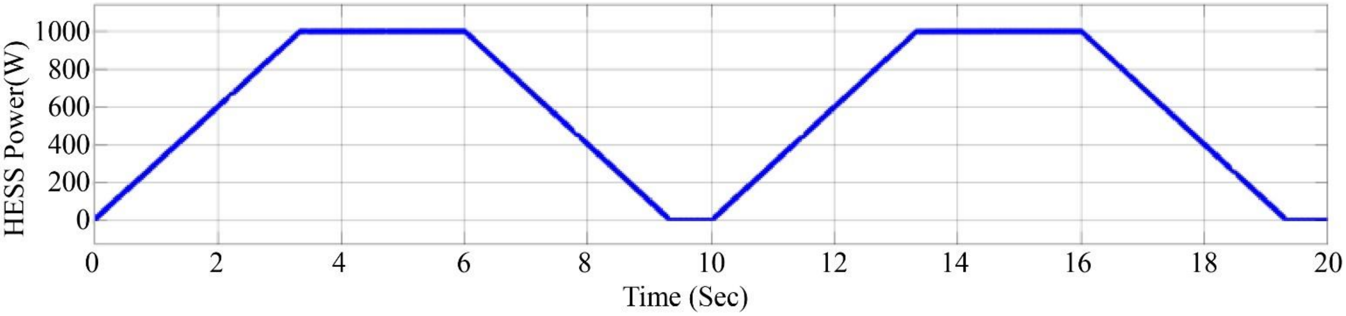

Fig. 16 Variation of HESS power (W) vs time (sec)

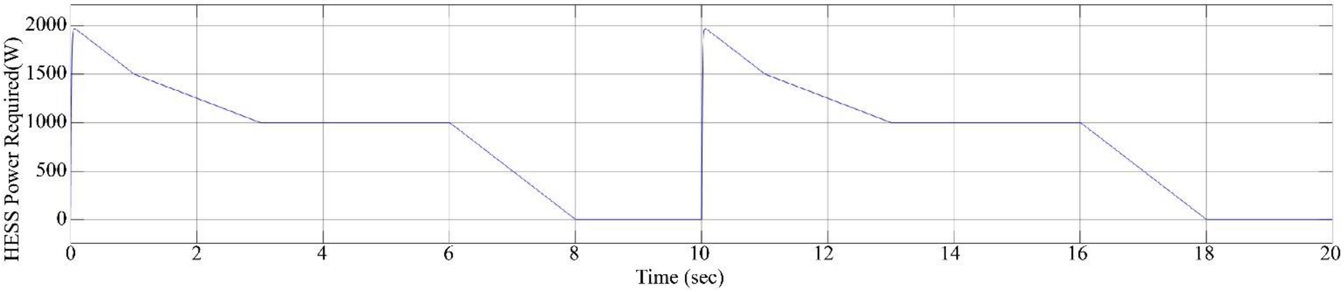

Fig. 17 Variation of HESS power required (W) vs time (sec)

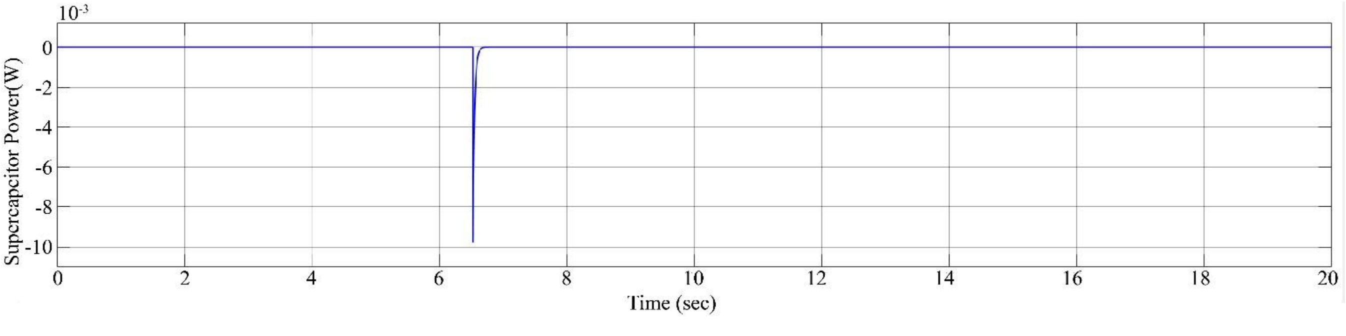

Fig. 18 Variation of supercapacitor power(W) vs time (sec)

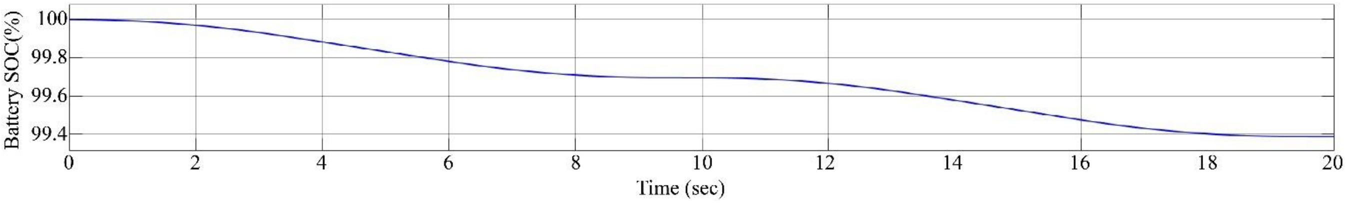

Fig. 19 Variation of battery SOC(%) vs time (sec)

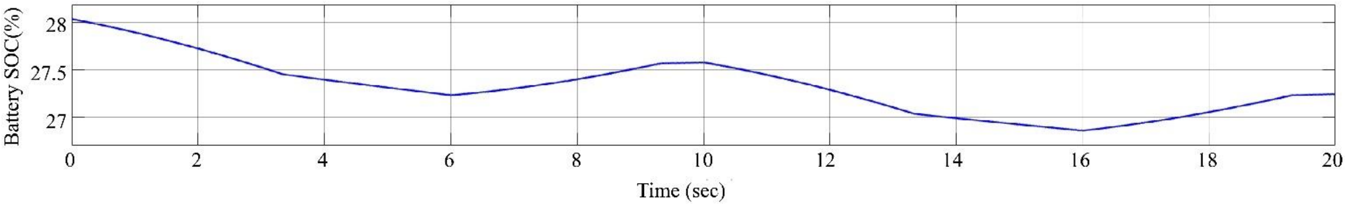

Fig. 20 Variation of battery voltage(V) vs time (sec)

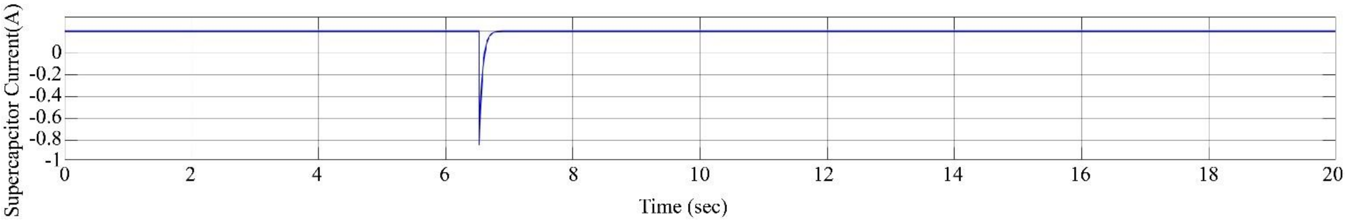

Fig. 21 Variation of supercapacitor current (A) vs time (sec)

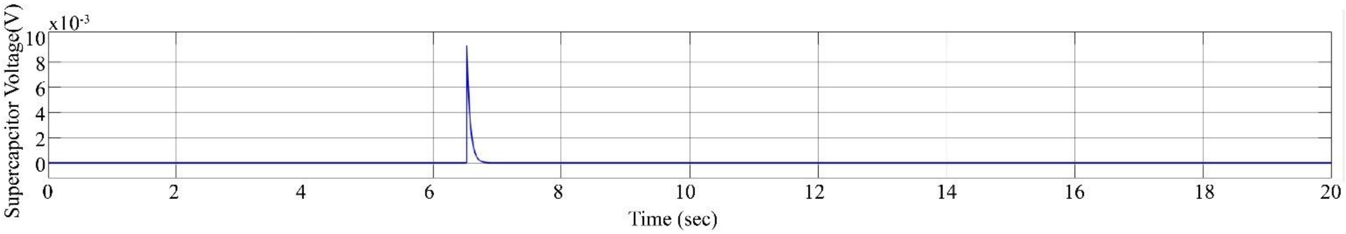

Fig. 22 Variation of supercapacitor voltage (V) vs time (sec)

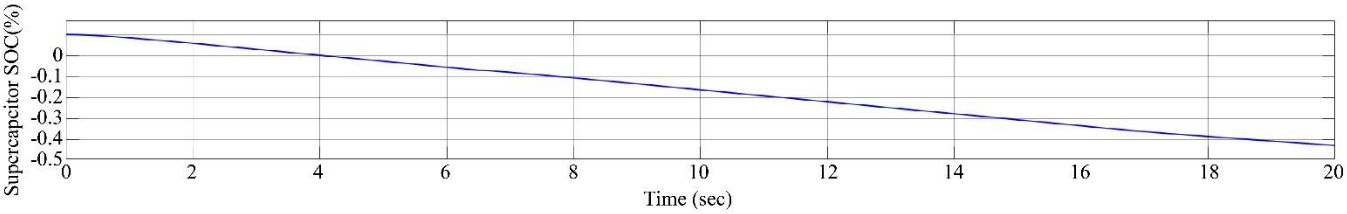

Fig. 23 Variation of supercapacitor SOC (%) vs time (sec)

5.1.3. Simulation Results for HESS of Battery and EDLCSupercapacitor with Regenerative Braking

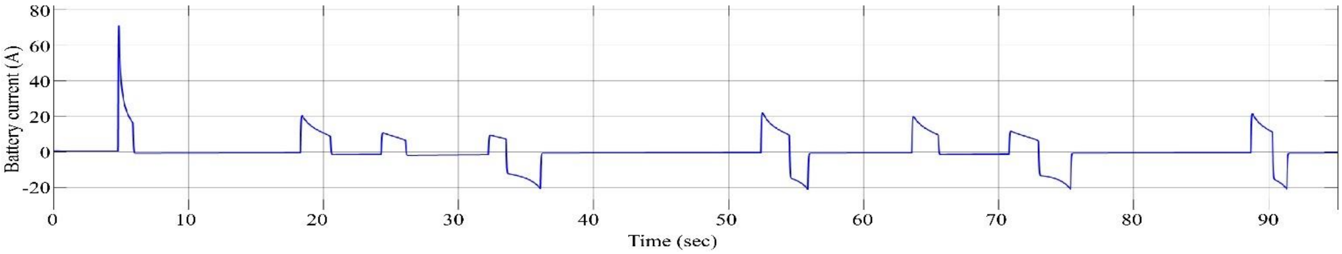

Fig. 24 Variation of battery current vs time (sec)

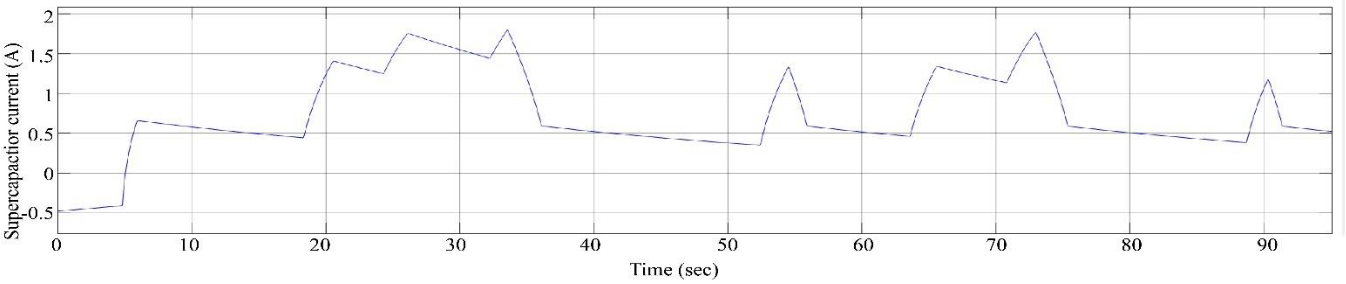

Fig. 25 Variation of supercapacitor current vs time (sec)

The plot below indicates the vehicle speed during one round of acceleration and deceleration. The vehicle would be traveling at the corners of the prescribed path, and the driver would apply the brakes to attain that maximum speed in the corner.

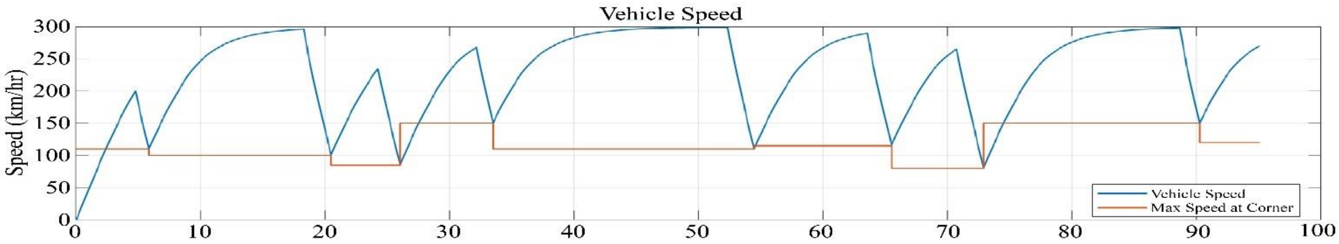

Fig. 26 Variation of HESS speed vs time (sec)

Two acceleration strategies for using electrical systems exist, as shown in the Figure below. The first strategy powers all wheels using electricity, while the second strategy powers select wheels as indicated by specific circles.

Selected corners enable the motor to deliver zero torque output while the vehicle executes rapid deceleration functionalities along several corners.

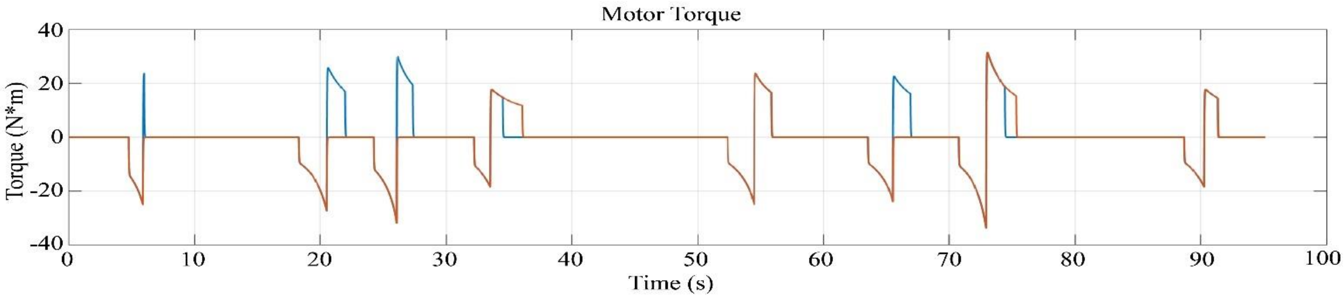

Fig. 27 Variation of HESS system torque vs time (sec)

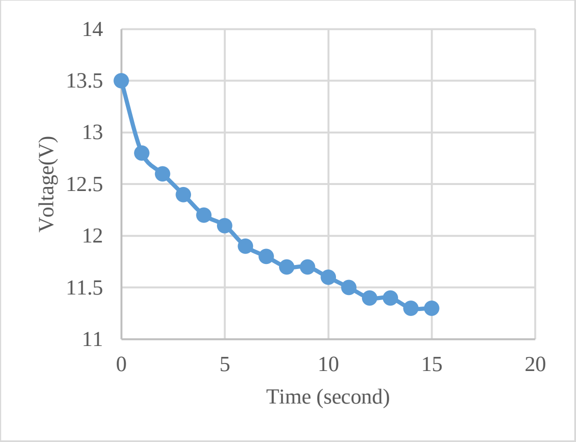

Fig. 28 Voltage deviation of HESS at no load condition

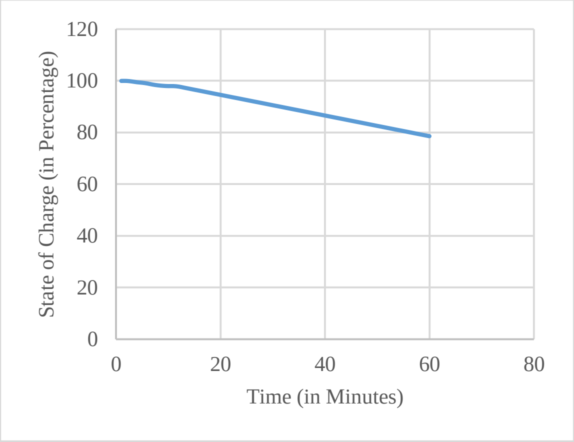

Fig. 29 HESS State of charge deviation w.r.to time

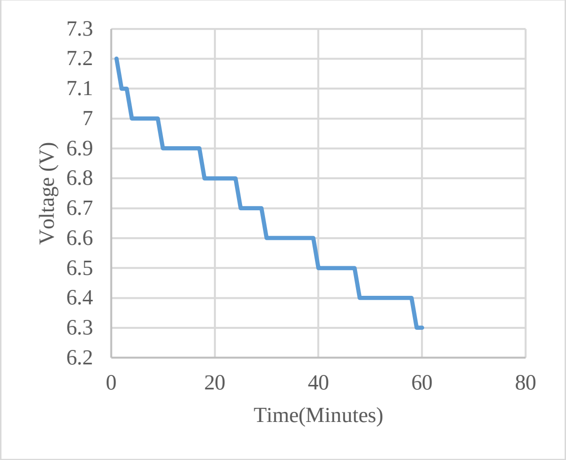

Fig. 30 HESS voltage deviation w.r.to time

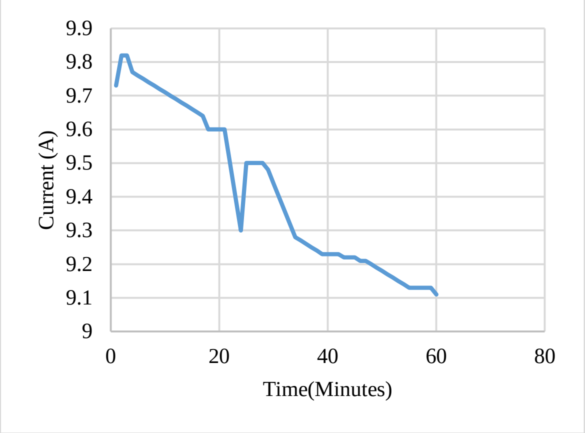

Fig. 31 HESS current deviation w.r.to time

5.2. Discussion

The research develops modeling techniques and simulation evaluation practices with experimental validation procedures for Li-ion battery working parameters as well as supercapacitors to benefit power electric vehicle systems. Again, our proposed hybrid lithium-ion battery / supercapacitor system shows this key structural behavior following the analysis: The Supercapacitor behaves as needed when extra power demand occurs. Hence, the battery works optimally while supercapacitor discharges are recharged through regenerative breaking processes that achieve the desired performance. The supercapacitor discharges automatically to collect power from the battery during times when the battery needs to remain idle for intense operational loads. The battery assumes operation duties after load reduction which maintains the supercapacitor in its optimal state. By implementing this approach, the battery avoids excessive power usage during demanding applications. The battery power requirements stay high because of this setup; therefore, implementing either regeneration braking systems or auxiliary energy storage systems provides an effective supercapacitor charging and battery replenishment solution. The completed e-bicycle implementation integrates both a lithium-ion battery and an EDLC supercapacitor hybrid energy storage system, as depicted in Figure 10.

5.2.1. Pure Battery-based E-Vehicle

- Figure 11 shows the simulation result of the distance covered (range) by a vehicle as per the specification of the proposed system vs. time for 2474 seconds following the standard FTP 75 cycle. The total distance is approximately 10 km.
- The voltage decreases to 24 volts (Figure 13) discretely till 1300 seconds; later, it was constant till 2000 seconds.
- The current variation is discrete stepwise and varies between +/- 60 ampere (Figure 14).
- The state of charge reaches 40 % in linear mode with small disruptions from 300 seconds to 700 seconds and 1100 to 1300 seconds.
- Figure 12 shows the speed variation is within acceptable limits, achieved at approximately 25 km/hr. Mating the proposed value of the HESS system. This indicates the simulation circuit designs are reliable for analyzing the system behavior under different loading conditions.

This shows that until the battery gets its nominal voltage, the behavior of its electrical parameters is discrete stepwise; this indicates that at the starting position, there is an increase in battery stresses due to an increase in power requirement that can affect its life cycle. Later, it is constant for further operation. To avoid this, an extra energy storage device needs to be implemented, which acts as a power storage device, and a battery will act when there are smooth road conditions with less energy but more power density.

5.2.2. E-vehicle with HESS System

This system is run for the first 20 seconds, considering the supercapacitor's quick charging and discharging time.

- Figures 16 and 17 show the power variation of the HESS system achieved (related to battery voltage) vs. the power required from the system (related to supercapacitor voltage), respectively. The power achieved is nearly 100 watts, which matches the motor's calculated power. The variation between the required value and the achieved value is due to the absence of an energy charging system for the supercapacitor. Figure 18 shows the decrease in supercapacitor power. Right now, it gets a charge from the battery, which is why the variation in the results is reflected in the figures. This can be avoided by implementing a regenerative braking system or an auxiliary battery to charge the supercapacitor only.
- Figures 19 and 20 show an increase in battery state of charge and voltage, respectively, due to the implementation of a supercapacitor after a certain equal interval of time. This shows a significant reduction in battery stresses and an efficient life cycle.

- Figures 21, 22, and 23 indicate supercapacitor electrical parameters, i.e. current, voltage, and state of charge, respectively, decrease continuously, showing its discharge at stating the position, at peak power demands, indicating the need for a suitable charging system, i.e. regenerative braking for its charging during instance of time.

5.2.3. E-Vehicle HESS System with Regenerative Braking

- These tests are performed for 100 seconds, considering the regenerative effects of supercapacitor charging. Figures 24 and 25 show a significant rise in current values for battery and supercapacitor. This shows both devices can work more than at the same voltage, and the battery can work faster with increased power.
- Figure 26 shows the relevant variation of e-bicycle speed and maximum speed at the corner, and it shows a smooth increase and decrease in the bicycle's speed due to regenerative braking. The maximum attainable speed is noted to be 300 km/hr.
- Figure 27 shows the torque and variation vs. time with the maximum attainable value of 30 N.m., which is quite near the calculated value needed to get a reliable simulated system solution.

5.2.4. HESS System with Experimentation

- Figure 28 shows the voltage variation of the supercapacitor without any load on the bicycle; this shows that the supercapacitor voltage is reduced significantly due to environmental temperature. A proper cooling system or case of suitable material to cover the supercapacitor pack must be designed to overcome this.
- Figure 29 indicates the important effect on the battery state of charge, which shows the battery SOC reduced to only 78% till 2000 seconds, Compared to Figure 15, which was 56 % without regenerative braking. This shows approximately a 22% rise in the charging state of the battery pack due to the implementation of a supercapacitor with a regenerative braking system, indicating a reliable and efficient solution for the electric vehicle field.
- Figure 30 shows the smooth stepwise variation of voltage w.r.to time compared to abrupt variation compared to Figure 13.
- Figure 31 shows quite a similar variation for the current of the HESS system compared to Figure 14 but with much smoother curves, which show a significant reduction in battery stresses and a rise in its life cycle.
- The smart switching mechanism works smoothly, as shown in Figures 16 and 31 of the simulation and experimental approach.

6. Conclusion and Future Scope

6.1. Conclusion

- The proposed HESS system delivers an effective hybridization to address current energy needs in the automobile market for lightweight electric vehicles as applied to e-bicycles.
- A controller-based switching mechanism inside the hybrid energy storage system enables interactions between batteries and supercapacitors, and this mechanism can be applied to the simulation circuit and test conditions to demonstrate enhanced eV applications and battery lifespan through power management.
- The e-bicycle with the proposed HESS system generates a significant amount of electrical energy through regenerative braking, which is required to charge the supercapacitor.
- The degree of hybridization of the proposed HESS system was found to be 25%, an acceptable value for a fully hybrid electric vehicle per standard specifications.
- Experimental data and simulated results demonstrated acceptable time-related deviations of electrical performance measurements, including current, voltage and state of charge.
- Regenerative braking and supercapacitor switching mechanisms work with reliable and efficient solutions in the field of electric vehicles.

6.2. Future Scope

- It is suggested here that with more braking effects for regenerative braking, the system will be able to generate more electrical energy sufficient to charge the lithium battery to a certain extent.
- Further work can be continued by incorporating lightweight solar panels to capture solar energy and charge batteries and supercapacitors.
- Also, at high hills and rough and uneven road conditions, this bicycle can be affected by some vibration. This vibration energy can also be harvested by converting it into electrical energy using a suitable vibration energy generator.

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