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Investigations of Regenerative Braking and Vibration Energy Conservation for Efficient Charging of Lithium-Ion Battery and Supercapacitor Hybrid System in Electric Vehicle Applications

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Abstract: - This study aims to determine new methods of making electric vehicles more energy efficient by focusing on regenerative braking and vibration energy conservation in a hybrid energy storage system integrating lithium-ion batteries and supercapacitors. The first part of the research identifies the regenerative braking system, evaluates its effectiveness, and proposes enhancements for capturing and storing braking energy. Additionally, an investigation is made into whether it would be possible to conserve vibrating energies through creative integration with energetic harvesting technologies. The purpose is to capture and convert vibrational power produced when a car moves into an electrical charge using piezoelectric device for hybrid power storage. More energy efficiency is achieved through this method while also trying to overcome the shortcomings of regenerative braking in some driving situations. This experiments involve Modeling, Simulation and development and testing of prototype systems under different driving and vibrating conditions as well as real-world performance evaluation. It will help to determine how effective the hybrid system that has been suggested enhances energy recovery and storage efficiency in electric vehicles.

Keywords: Lithium-Ion Battery, Supercapacitor, Hybrid Energy Storage System, Regenerative Braking, Vibration Energy Harvesting.

I. INTRODUCTION

The electrification of transportation has prompted intensive research into innovative energy storage solutions to power electric vehicles (EVs) efficiently. Among the technologies under scrutiny, the hybridization of Lithium-Ion batteries and supercapacitors in a hybrid energy storage system (HESS) has emerged as a promising avenue. This combination seeks to harness the strengths of both Li-ion batteries and supercapacitors, addressing the limitations of each technology and creating a synergistic energy storage solution for electric vehicles. [1] The integration of Li-ion batteries and supercapacitors in a hybrid energy storage system combines the high energy density of batteries with the rapid charge and discharge capabilities of supercapacitors. The basic objectives of implementing a Li-ion and EDLC supercapacitor-based HESS in electric vehicles include Improved Power Delivery, Extended Battery Lifespan, Enhanced Energy Efficiency, and Environmental Sustainability and control the Challenges such as voltage matching, complex control systems, thermal management, and cost considerations need to be addressed to ensure the seamless integration and optimal performance of the hybrid system.[2] The main issue encountered in this hybridization is the quick charging and discharging capacity of the supercapacitor as well reduce the battery stress by utilizing supercapacitor as auxiliary energy storage device for peak power demands. The proposed work as shown in Figure 1, focused on conventional regenerative braking along with the conversion of vehicle vibration energy for charging of supercapacitor when it required else storing it in the battery system for its effective charging.

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The work starts with fabricating small prototype model for experimental analysis considering four wheeler headlights as an application. The set up consists of lithium ion battery pack and supercapacitor pack combined in passive mode to analysis and verify the required results, along with motor of 250 watts. The setup is fixed in vehicle system and run it on high hill and uneven road surfaces for approximately 1 hour to calculate the results of regenerative braking energy capturing mechanism. During the same vibrations induced in the system were also evaluated for analyzing the system's reliability under vibrating conditions along with piezoelectric device to capture vibration energy into usable electric energy either to store it in lithium ion battery pack or use it for charging the supercapacitor when it is required [3].

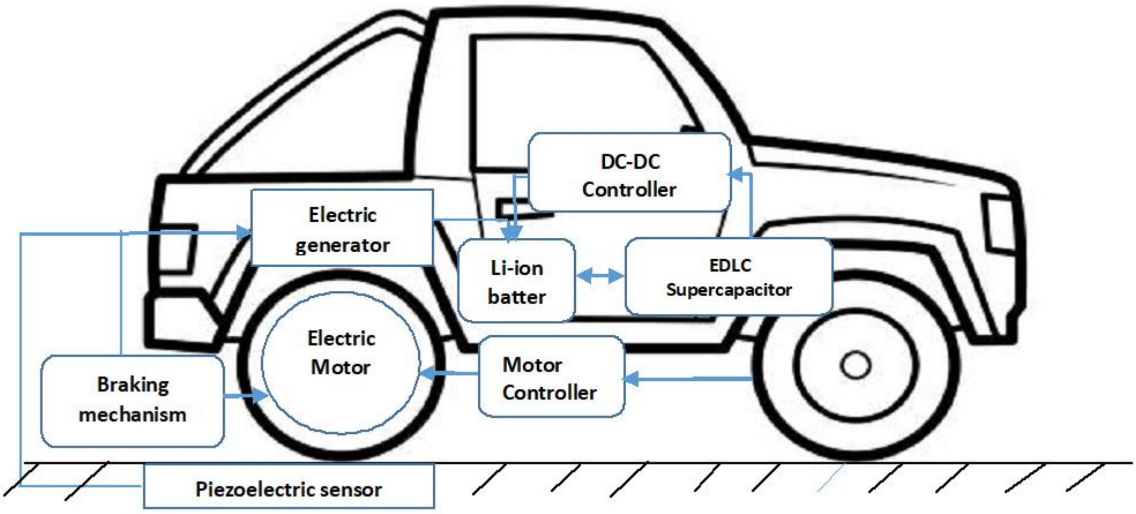


Figure 1: Block diagram of the proposed system

A. *Conversion of Kinetic Energy into Electrical Energy*

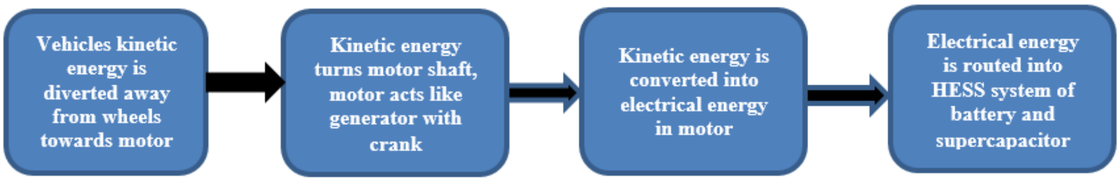


Figure 2: Regenerative braking mechanism in electric vehicles

Figure 2 shows, Regenerative braking mechanism that converts the kinetic energy of a moving vehicle into electrical energy. An electric motor works as a generator to store captured energy in the battery which is normally lost in the environment during braking. In an electric car, electric motors provide power to drive the wheels. When you take your foot off the accelerator pedal to the brake pedal, the electric motor stops to energize the wheels to work electric motor is reversed direction and acts like a generator. When this process begins, the vehicle slows down and the wheels transmit the kinetic energy across the driveway to the generator. [4] This kinetic energy is converted into electricity and stored in batteries that can be used later. As shown in Figure 2, during regenerative braking vehicle kinetic energy is diverted away from the wheels towards the motor, to turn the motor shaft. The motor acts like a generator with further movement of wheels to convert vehicle kinetic energy into electrical energy. This electrical energy is then further used for charging the hybrid energy storage system, especially the supercapacitor. [5]

B. *Conversion of Vehicle Vibration into Electrical Energy*

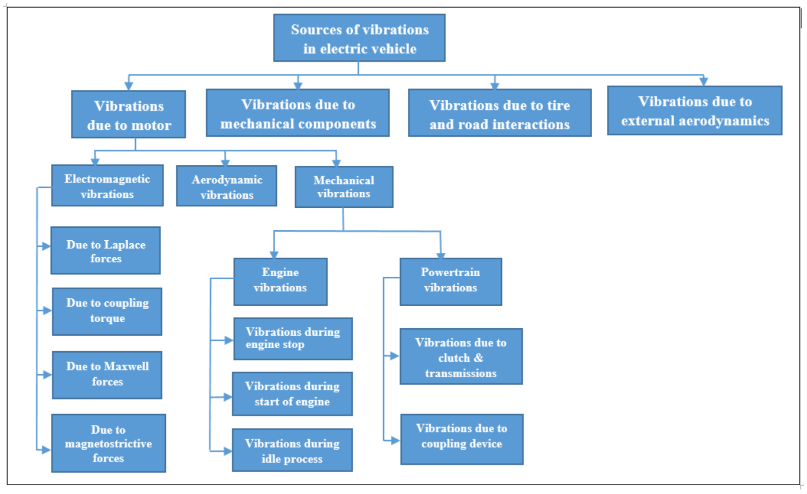


Figure 3. Vibration source identification methods

Theoretically, all vibrational energy can be converted into electricity; however, certain vibrations with definite pulse and control frequency are desirable when the intention is to energize a sensor or monitoring system. Vibrational energy harvesting is a process by which heat, light, vibration, and other external sources release small amounts of energy that would otherwise be lost to the immediate surroundings. [6] Figure 3 shows different sources of vibrations in electric vehicle. In the event of battery failure, the replacement costs can be reinvested to provide continuous power to batteries or supercapacitors. The energy collected by vibrations is used by sensors or measuring devices to supply it as per requirement; where conventional energy sources such as batteries are simply too expensive or inefficient to control the fast charging and discharging of supercapacitors using vibration-driven generators. [7]

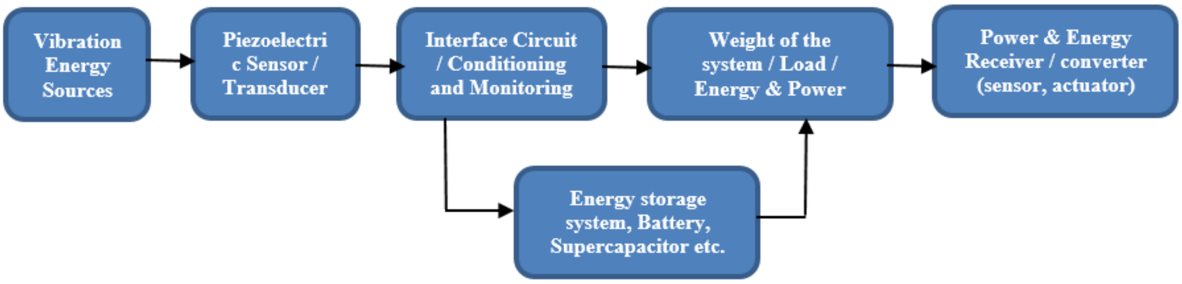


Figure 4: Block diagram of Vibration Energy harvesting system

Figure 4 indicates energy conversion mechanism of vibration energy into electrical energy. It consists of a resonator to amplify the vibration source, and a transducer device to convert the energy from the vibration to electricity. [8]The transducer is usually a magnetic coil or piezoelectric crystal. Many crystals can discharge electricity when pressed or change shape when electrically applied. When the crystal hardens by vibrating energy, it generates a small force due to the piezoelectric effect, these systems tend to be simple with few moving parts and have a very long lifetime, making them a common instrument used to harvest energy from vibration. [9] Vibration energy harvesting can provide sufficient energy to enable the system to communicate and communicate on a standalone basis using regular GPS and GSM or similar protocols. The vibration generated by the trailer converts it into electricity to ensure that there is always enough power for the monitoring systems. [9] The investigation has examined the mechanical performance of battery percentage systems exposed to dynamic loading and random vibrations. [10] Further work is done on the association amongst vibrations and the decreased electric performance of battery cells. When vibration through springs is generated by mechanical pressure on piezoelectric materials like loads from cars, people's feet, railways, dance floors etc. positive and negative charge centers transfer resulting in external electric field shoulders so in response to use mechanical pressure an accumulation of electronic charge occurs. [11]When pressure is applied to some crystals, polarization occurs and the degree of polarization is directly proportional to the applied pressure. Piezoelectric crystals were used to harvest energy from the vibrations of road traffic or vehicles moving on highways and expressways. [12] When a vehicle/vehicle passes through a selected area, it sometimes draws on the streams placed on the road just below the road (high sensitivity and longevity (05-1.5 m) can be stored Then when the car moves, the spring continues to expand and contract, which is in constant contact with the piezoelectric crystals causing pressure on the crystals. [13] When pressure is applied it causes distortion and movement of positive and negative charges causing lightning a force field is generated and finally an electrical transformer or half-wave or full-wave rectifier can be used for this. [14] Also, the microcontroller shows the lifetime status of the battery i.e. what percentage of battery is charged each time the vehicle will pass the level of the piezoelectric transducer. The output is then sent to the inverter. The output of the piezoelectric crystal is in the millivolt range. [15] So, we arrange several piezoelectric crystals in series to get high voltage, and the energy obtained is stored in a lithium battery.

II. LITERATURE SURVEY

Global warming has made renewable energies popular. Thus, notable attempts are being made to develop advanced technologies that can capture energy from such sources as wind, solar, ocean waves, mechanical vibration, and others thereby generating electrical power. Of all these renewable energies, mechanical vibration is the utmost striking alternative because it is available in plenty of the natural world. The generators based on mechanical vibrations have the advantages of higher potential, relatively high power density, and longer lifespan. Therefore, several strategies such as electromagnetic mechanism; piezoelectric mechanism, and electrostatic mechanism have been suggested to construct a generator that would harvest mechanical-vibration-based energy. The piezoelectric generator works on the principle of piezoelectricity that has been extensively studied over time about mechanical–electrical energy conversion. Zheng et. al. presented a drilling energy harvesting device using longitudinal vibration of the drill pipes. The developed harvesting system was applied as an uninterrupted power supply for downhole devices while drilling. The designed device presents an optimum energy harvest performance with a peak voltage between 15-40V when the thickness of the piezoelectric patches varies from 1.2-1.4mm. [16] In order to gather energy from random vibrations in railroads, Yang et. al. used effective rail borne piezoelectric energy harvester that collected vibration energies randomly generated on railways. The output powers at initial two resonance frequencies were 1036.9 and 8mW/Hz respectively. With the same excitation conditions, it was shown that there is a 194% increase in terms of amount of power produced from multiple frequency response piecewise linear PEH compared to linear design. Harvesting vibrational energy from the backpack can generate electricity, and power harvesting backpacks have been developed. [17] Thus, to improve human comfort, Liu et al. explored the dynamic interface amongst the human body and energy storage packs. An inclusive study examined the effect of tunable electrical boundaries on the electromechanical generator reaction. As key components of piezoelectric generators, piezoelectric smart materials, typically PZT, are widely used in energy-harvesting applications with the advantages of compactness, fast operation and high efficiency, and large numbers of generators have been developed some based on PZT. A piezoelectric generator constructed on vortex tempted vibration was projected to change inundated energy flow into electricity. This generator contains a piezoelectric cantilever beam, a linking device, springs, a loud body, and a movement sensor. The output voltage is obtained from the flow–solid electrode connection equations. [18] Dagdeviren et al. reported a piezoelectric generator to harvest the mechanical energy produced by the engagements of the heart, lungs, and diaphragm. The invented piezoelectric generator was founded on PZT and PI film, with PI acting as a supple matrix and outline layer, while PZT had a structure of ribbons sandwiched among gold and platinum electrodes between the Piezoelectric generator with an energy density of 1.2 μW/ cm^2. The results displayed that the maximum output of the intended piezoelectric generator might reach 4.82 MW. Additionally, simulation studies of continuous excitation voltage and power were also carried out and presented decent agreement with the experimental results, when the load resistances were labeled as 20 kΩ and 25 kΩ, respectively. [19] Xia Hua et.al. Focused on the progress made on the effects of dynamic loads and vibrations on lithium-ion batteries to improve the understanding of lithium-ion batteries the effects of dynamic loads and random vibrations were investigated obtain on mechanical behavior of battery systems.[20] Xibiao Yan, et.al. Introduced vibration test standards and common test methods for electric vehicle motor control units. A new vibration test scenario is proposed based on the vibration data collected during the actual vehicle testing. [21] Aniruddha Ghosh, et al. presented an overview of noise and vibration analysis of electric vehicles. The first relates to the growing demand for electric vehicles and the rapid growth of the market and electric vehicles. The second involves the identification of EV noise and vibration sources and a review of the supporting literature. In the third category, various methods for vibration sources range from traditional to innovative methods. [22] Xia Hua et.al. Focused on recent advances in BEV NVH analysis were focused on to improve BEV systems in the future. Also the critical dynamic response of the drivetrain was investigated, including dynamic forces acting on gear teeth, dynamic loads acting on bearings, torsional changes of tires or loads as it is subject to major vibration excitations, such as motor torque variation, and spiral bevel gear mesh excitation. [23] Jia-Shiun Chen, et al. focused on rapid acceleration/deceleration and vehicle vibrations caused by electric drive in electric vehicles under gear shifting. This work presented a new effective control concept that reduces the vibrations of the power line system. This system controls an electric motor to limit the driveline twisting vibration to the driver's seat, effectively reducing vertical vibration and increasing driver comfort. [24] Chenghao Deng, et al. presented a vibration and noise simulation method for the electrical system of vehicles under different speed conditions. [25] Kirthan Krishna, et. al. worked on the main noise and vibration issues in EVs and the efforts of researchers to find solutions to such problems. [26] Vincent M. Macharia, worked on the components and advances in different technologies used in electric vehicles to improve motion efficiency and improve energy efficiency in electric vehicles. [27] Bharti Sankar, et al. discussed supercapacitor-powered power applications in various areas such as flexible, portable, wearable electronics, implantable healthcare and biomedical sensors Using piezoelectric generators, they convert strong vibrations into electricity, if used though has stored low-power devices such as radios and could include frequency identification tags (RFIDs), wireless, global positioning system (GPS) and sensors.[28] Jia Wang, et al. Considered a low vibration generator to generate electricity under the operating conditions of multi-frequency microwave oscillators. [29] Toshiyuki Ueno, et al. proposed a new vibration power generator based on magnet-enhancer material (Fe–Ga alloy) for battery-free Internet of Things (IoT) applications. [30] S. P. Beebe, et al. described a microscale electromagnetic vibration generator that stores kinetic energy and provides local energy for wireless applications. [31] Raghu Chandra Garimella, et.al. Proposed an alternative to generating electricity using piezo sensors from unwanted earthquakes that may affect nearby buildings or cause noise pollution. [32] Seong Jin Cho et al. proposed a linear electromagnetic generator to collect the pulse energy from the transformer and transfer energy to the monitoring system. [33] So-Yeon Lim, et al. covered the characteristics of vibration energy harvesters and the interface between vibration energy harvesters and supercapacitors. [34] P.S., et al. Glynn-Jones, and others. Described the design of small generators that can convert ambient vibration energy into electricity for use in power supply in smart sensor systems [35] Pasis, M.C. et.al. It attempts to generate information on potential sources of renewable energy, exploiting the energy dissipation generated by the collision of the power grid [36] Ashwin S Babu, et al. A new regenerative braking system (RBS) with HESS topology was proposed to drive the BLDC motor, which provides benefits such as more efficient regenerative braking, battery safety, and improved vehicle speed [37]

III. SIMULATION AND EXPERIMENTAL ANALYSIS

A. Simulation For Vibration Energy Recovery

Here a simulated approach is studied in Matlab/Simulink software, using piezo blender for analysing the energy harvesting through vibration energy. This conserved energy is utilised for charging the battery and supercapacitor HESS. The vibration source through which energy is collected is considered to be sinusoidal and linear increasing frequency. The system consists of a piezo blender, a rectifier and a DC-DC converter. One side of piezobinder is connected to the vibrating objects, causes it to move whereas the rights side is connected to the other components of the system. Both side movements are independent to each other due to dynamics, size and inertia of piezo bender. Any types of distortions / vibrations generates a charge and voltage in piezo bender's cables. Further rectifier converts this AC voltage into DC voltage which is controlled by buck converter to maintain unidirectional power transfer. This example illustrate the pulse generator controllers that converts static interchanging frequency and duty cycle. A closed loop controller can be designed to optimized power transfer and increase in power harvesting s for constant frequency and harmonics to charge the batteries and work on constant energy load. Piezoelectric benders are malleable ropes with a natural fundamental frequency of vibration. When it oscillates at resonant frequency, it produces maximum power. The basis frequency is close to the resonance frequency, thus providing approximately the maximum possible energy for power limit. Table 1 shows the parameter specifications of components used for simulation model as shown in figure 5, which is run for evaluating the energy recovery mechanism. The results were evaluated for sinusoidal as well as variable frequency conditions as shown in figure.

Table 1: Specifications of Simulation for Vibration Energy Recovery Model

Sr. No.	Particulars	Specifications	Sr. No.	Particulars	Specifications
1	Nominal voltage of HESS	13 V	9	Piezo bender total beam length	3.175E-2 m
2	Internal resistance	2 ohm	10	Piezo bender total beam	1.27E-2 m
3	Cell capacity	2.5 hrA	11	Piezo bender total beam	5.0E-4 m
4	Initial voltage	6 V	12	Amplitude for sinewave	0.25m/s
5	Initial Cell capacity	1.5hrA	13	Frequency for sinewave	185Hz
6	Load type	DC	14	Initial frequency for	150Hz
7	Power consumed	100 mW	15	Target frequency for	250Hz
8	Minimum supply	0.6V	16	Mass	5kg

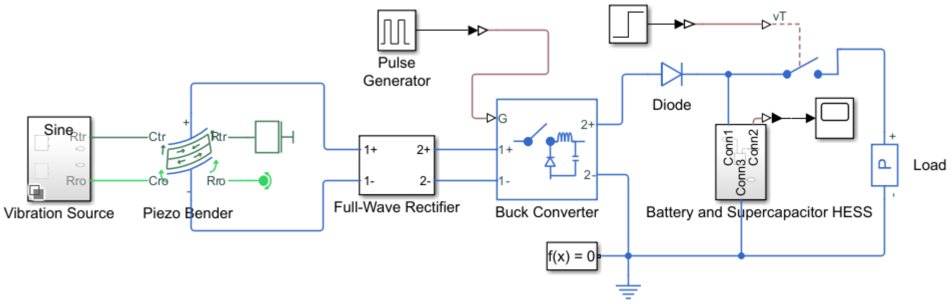


Figure 5: Vibration Harvesting Mechanism in Matlab/Simulink

B. Simulation For Kinetic Energy Recovery

This example shows the kinetic energy recovered by four wheeler automobile system and during braking or vehicle moving on uneven surface road or hill area road surface, the energy stored in hybrid system of lithium ion battery and supercapacitor. The system worked on initial assumption of delivering 400KJ of power with maximum output of 60KW in a single cycle. The constraints are the masses of the battery, supercapacitor, and motor generator. Lithium-ion batteries have very high efficiency per unit mass but negative efficiency per unit mass. In contrast, ultracapacitors have very low efficiencies per unit mass, but very high efficiencies per unit mass suitable for this particular application. Table 2 specifies the different component specification of Simulink model modeled in Matlab/Simulink software. Figure 6 shows the Simulink model for analyzing the effects of braking and kinetic energy recovery system.

Table 2: Specifications of Kinetic Energy Recovery Model

Particulars	Specifications
Mass of BLDC hub motor	3.8 kg
Mass of Hybrid pack of Lithium ion battery and supercapacitor	6.2 kg
battery pack specification	11.1V and 20 A
Specification of supercapacitor pack	13.5 V and 100 faraday

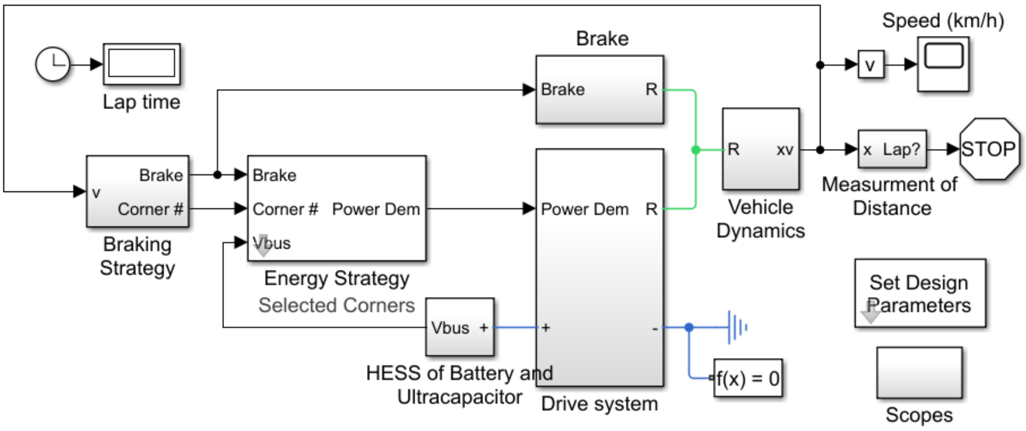


Figure 6: Kinetic Energy Recovery Mechanism in Matlab/Simulink

Table 3 indicates the energy recovered by simulating the model w.r.to to specified components parameters. The results tabulated the braking time and distance, according to which total energy generated and recovered by the system.

Table 3: 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

IV. EXPERIMENTAL ANALYSIS

All equipment was duly calibrated equipment under test (EUT) weighing 12.667 kg and dimensions of 300 mm x 500mm. tests were performed at Ambient Temperature / Humidity / Pressure 24.5°C, 58.4% as per AIS 156 standard. The system uses an electric material enabling power to be obtained by varying the amount of static electricity. If the vibration frequency is 30 Hz the generator delivers 100 microwatt. And acceleration of 0.15g if enough to generate power if the object doesn't appear to be moving. Figure 7 shows the actual experimental setup fabricated for the vibration test setup. The purpose of this test is to verify the safety performance of the REESS (Electrical Energy Storage System) under a vibration environment which the REESS will likely experience during the normal operation of the vehicle. The test is performed at a surrounding temperature of 22 ± 5 °C; here, test has been carried out by following AIS 038 and AIS 156 standards. The testing set up is exposed to a vibration with a sinusoidal waveform and a logarithmic sweep rate between 7 Hz and 50 Hz and back to 7 Hz crisscrossed in 15 minutes. This cycle is continual 12 times for a total of 3 hours in X, Y and Z direction. Here we have followed AIS 156 standard for conducting the test. Total weight of equipment under test were 12.5 kg. Table 4 shows a List of components required for experimental setup with its particulars and specifications for vibration analysis using an electrodynamic vibration shaker.

Table 4: List of components required for experimental setup

Particulars	**Specifications**
A switched-mode power supply (SMPS)	12V, 10Ah
Li-ion Battery Pack	11.1V, 20Ah
Supercapacitor Pack	13.5V, 100F
Voltage display unit	0-200 V
Current display unit	0-75Ah
Resistor for supercapacitor connections	470KΩ, 2W
Shunt resistor (2nos)	75mV
Switches	3 nos.
Load	200W
Other Accessories i.e. solder gun, wire	-
MS box	300 x 500 x 100
Metal Box	As per requirement

- Total Energy generated: VA/100 = (11.1 x 20) / 1000 = 0.222 Kwh = 222 w/h
- Total Power generated: VA = 11.1 x 20 = 222 watts.
- Energy calculation (E) = $\frac{1}{2}C_T V^2 = \frac{1}{2}\times 100\times 13.5^2$ =9112.5J = 2.53125w/h.
- Power generated = E/ (t_2-t_1) = (2.53125 / 3) = 843.75 watts.

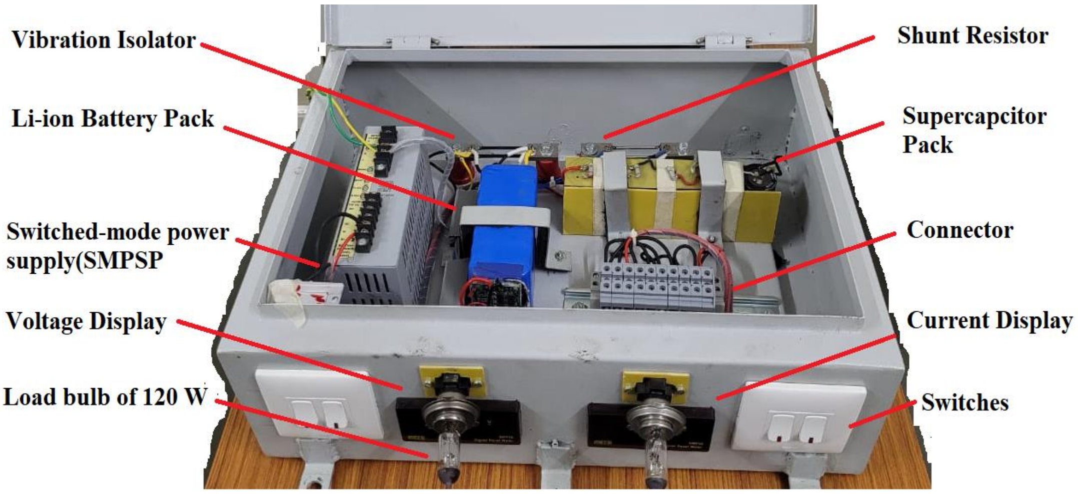


Figure 7: Experimental setup for vibration test

V. RESULTS AND DISCUSSION

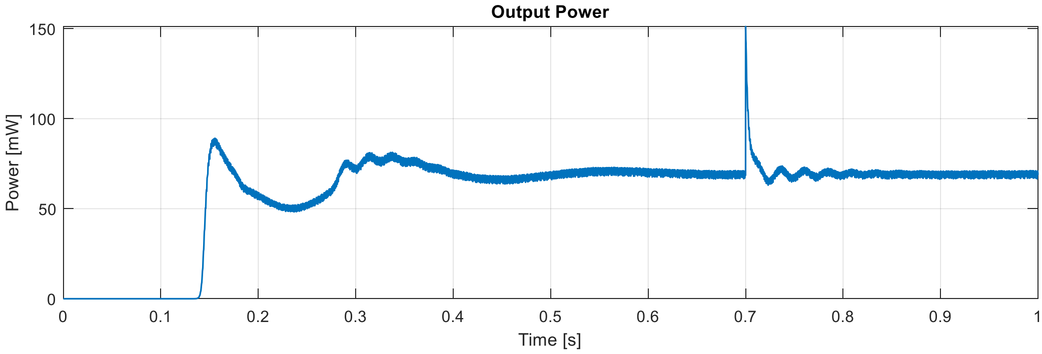


Figure 8: Plot Results for Sinusoidal Source for voltage and power respectively

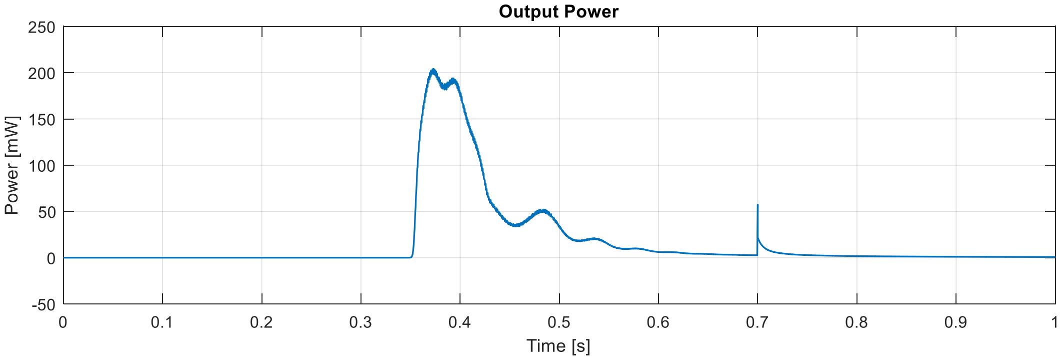
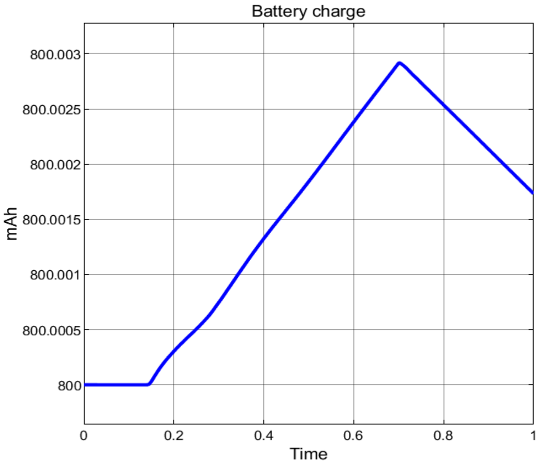


Figure 9: Plot Results for variable frequency Source for voltage and power respectively

The figure 8 shows the outcomes of a vibration source fluctuating at a continuous frequency, generating output power at final time = 68.7332 mW.

The figure 9 shows the outcomes of a vibration source with linearly increasing frequency, generating power output at the final instant = 0.71343 mW.

The yield power rises as the source is reaching the resonant frequency. Then, it reduces as the source surpasses the resonant frequency.



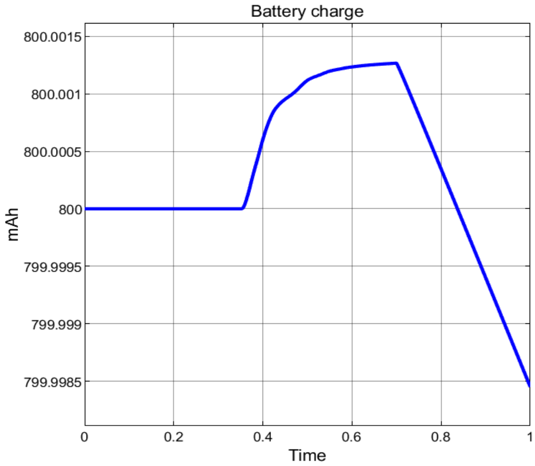


Figure 10: Plot Results for Sinusoidal Source

Figure 11: Plot Results for variable frequency Source

Figure 10 and 11 shows the battery charging status of the system through sinusoidal and variable frequency input respectively. Which shows a significant rise of conserving the energy through regenerative braking. Comparing to both of above, the variable frequency approach generates more energy compared to sinusoidal system.

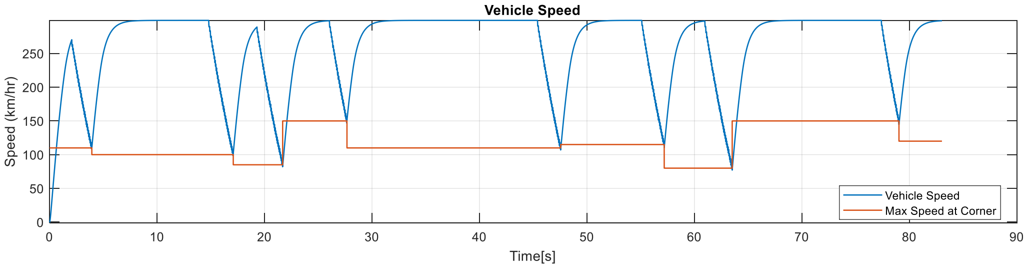


Figure 12: Comparison of vehicle speed vs. maximum speed at corner location

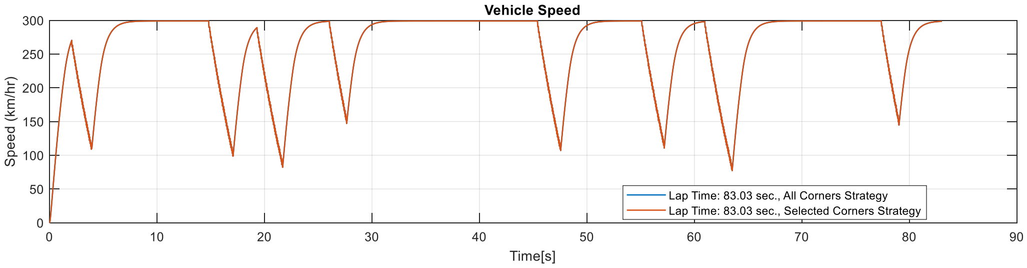


Figure 13: Comparison of vehicle speed at all corner vs. selected corner location

Figure 12 shows the comparison of vehicle speed and maximum speed at corner location w.r.to time. Whereas Figure 13, indicates the comparison of vehicle speed at all corner vs. selected corner location with lap time of 83.03 seconds. It indicates vehicle speed, exceeding the maximum corner speed and reaches up to 300 km/hr. compared to FTP drive cycle it shows controllable results, considering factors such as safety, performance and efficiency of the system. This comparison helps for encouraging road safety, enhancing vehicle performance, supervisory driver control, and notifying organization development and vehicle design. Further this graphical analysis helps for a complete methodology to road safety, planning of infrastructure and permits stakeholders to aim involvements where it is required to generate a safer and more efficient transportation environment. Figure 14 shows, Qualitative analysis of kinetic energy recovery through regenerative braking mechanism, considering mass, Inertia system and braking effect. It exposes the possibility to expressively recover energy effectiveness, reduction in emissivity, and improving vehicle enactment.

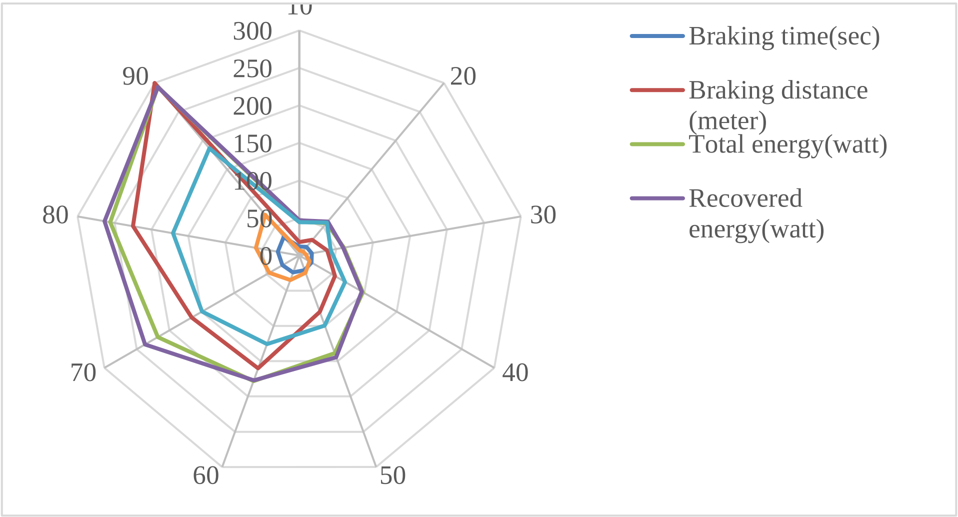


Figure 14: Qualitative analysis of kinetic energy recovery

Test were conducted for approx. 3hours as per standard procedure. Figure 15 shows, the variation of voltage and current w.r.to time while conducting the vibration test on given experimental set up. Which shows a negligible change or effects on working parameters of the HESS system.

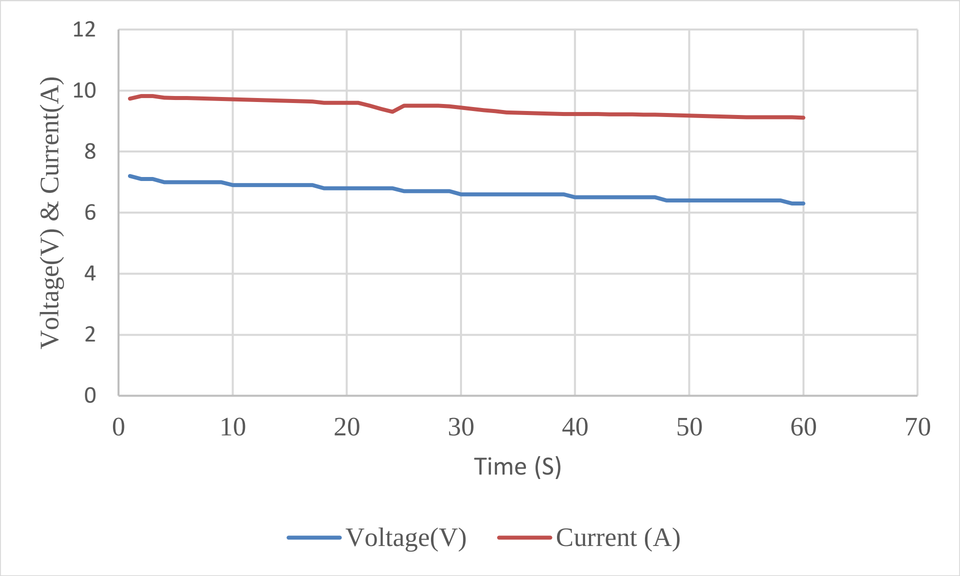


Figure 15: Voltage and Current variation of HESS w.r.t.to time during vibration test

Figure 16, indicates resonant vibration frequency w.r.to acceleration of the HESS system in X, Y, and Z directions using electrodynamic vibration shaker equipped with piezoelectric vibration energy generator device to the system. It indicates the HESS system is safer with 150 HZ of vibrating frequency. For X and Y direction the resonance occurs at 143 Hz whereas for Z direction it occur at 95Hz. It shows HESS system rigidity and robustness to sustain the vibrating conditions. Dwell tests were performed to check the safety of the system, with the resonance frequency of 143.66 Hz at an amplitude of 3g and sweep rate of 1 Oct/min, with resonance found at 20 minutes for X, Y, and Z directions. whereas with the resonance frequency of 72.37 Hz at 3g and sweep rate of 1 Oct/min, resonance was found at 20 minutes.

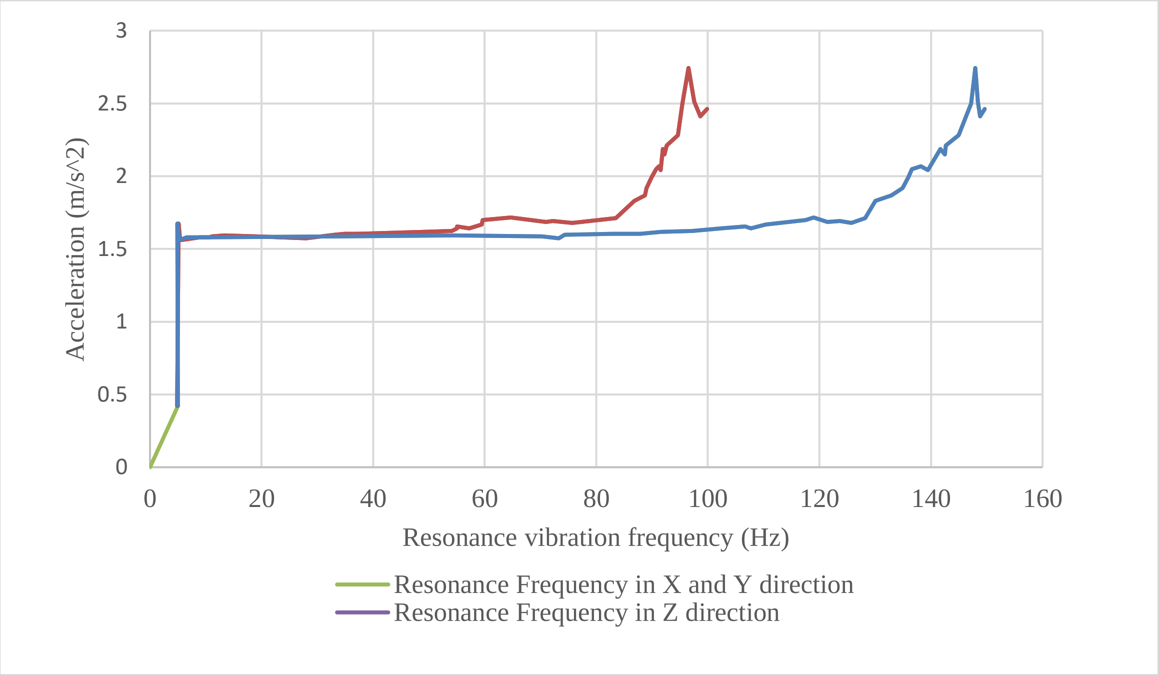


Figure 16: Resonant frequency of HESS pack vs. acceleration in X, Y and Z directions

The same HESS system is run with piezoelectric device till 150 Hz of vibrations to keeping acceleration 0.5 m/s^2, it shows a significant energy recovery up to 700µW. Figure 17 shows the energy harvesting through vibrations which is sufficient to charge the supercapacitor or to store energy in battery pack when it is required. .

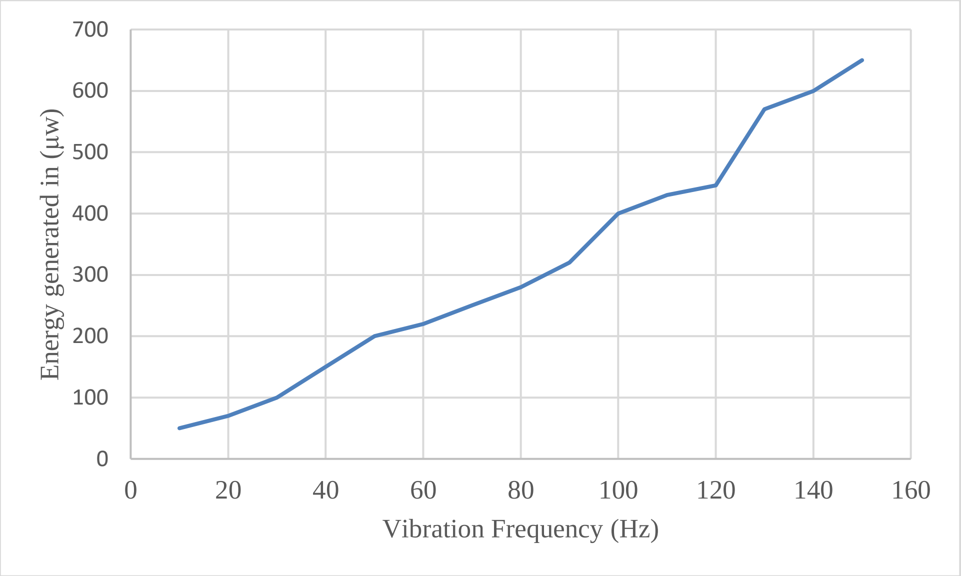


Figure 17: Energy generated w.r.to vibration frequency of HESS system

VI. CONCLUSION

In this work, the hybrid energy storage system of lithium ion battery and supercapacitor is analyzed considering efficient hybridization solution for electric vehicle. Energy recovery mechanism is proposed for controlling quick charging and discharging of supercapacitor and storing the extra energy in lithium ion battery pack when not require. The system considers two energy recovery approaches, first conservation of kinetic energy of moving vehicle and second harvesting induced vibrations during vehicle run on uneven road surface, due to environmental and internal vehicle dynamics. Kinetic energy recovery through regenerative braking is simulated using Matlab/Simulink, indicates a significant amount of energy recovery. Further vibration analysis of the HESS system on an electrodynamic vibration shaker, following AIS-038 and AIS-156 standard procedure shows comparatively good amount of energy can be harvested through vibrations considering all safety aspects. The following conclusions have been elaborated based on experimentation,

1) Negligible change in HESS electrical parameters were observed like current and during experimentation as well as simulation approach.

2) Significant amount of energy can be recovered through regenerating braking and vibration energy which is more than sufficient for charging the supercapacitor of HESS system.

3) This energy which would have been lost to environment can be utilized for controlling supercapacitor state of charge and utilizing its power capacity for higher torque requirement conditions. This directly reduces the battery stresses in high power demands.
4) The proposed energy recovery mechanism not only proved to be significant solution for effective hybridization of energy storage systems but also improving the life cycle of battery for electric vehicle applications.
5) The vibration study shows the HESS system reliability and rigidness for heavy vibration in extreme conditions and utilizing those for converting into electrical energy.
6) During experimentation, the proposed HESS was found to be safe as there was either no effect observed on battery or supercapacitor connections as well as wiring connectivity, solder joints, etc.
7) Noise occurs to be more, which can be controlled by modifying the design of the test box, clamping for the battery and supercapacitor pack, etc.

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