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Modeling, Simulation and Experimental Investigations for Hybridization of Lithium-Ion Battery and Supercapacitor in Electric Vehicle Applications

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Abstract: System modeling offers an expedited alternative to testing and evaluation of effects and relationships between input and output variables. Simulation approach helps to analyze the real world problems in safer and efficient way for easily verification and communication purpose. Moreover, it enables large-scale data analysis, which would be financially impractical in a testing scenario. The proposed work investigates the modeling of hybrid energy storage system of lithium-ion battery and EDLC supercapacitor which are connected in passive combination, to evaluate its charging and discharging characteristics as well to investigate integration of both energy storage devices for suitability in eV applications. Further simulation approach is used to evaluate the with circuit model designed MATLAB/Simulink for estimating effects of hybridization on working parameters of HESS like voltage, current and state of charge. The effects of battery model, supercapacitor model and its hybridization model circuit are evaluated for input and output variable's effects on hybrid system. The results are further validated with the experimental solution to get efficient, economical and reliable solution in the field of electric vehicles applications.

Keywords: *Simulation, Modeling, Li-ion battery, supercapacitor, hybrid system.*

1. Introduction

The current automobile sector diverting towards electric vehicle for major transportation and relevant applications. Among many energy storage systems, different chemistries of lithium ion battery found to be most efficient solution due to its high energy density, longer life cycles, and capability of comparatively fast charging and discharging. But eV applications with single energy storage device as battery, induces many mechanical, electrical and thermal stresses with reduced life. Therefore hybrid energy storage system with more than one seems to be better solution considering energy and power demands and controlling of limitations of lithium ion battery for sustainability of electric vehicles. As per Ragone plot combining lithium ion battery and supercapacitor offers a novel and promising solution to meet the aforesaid requirements. This study focused on inclusive mathematical modelling, simulation analysis and experimental validation of proposed HESS to evaluate input and output variables effects on performance parameters and to find efficient solution for eV applications. The works starts with detailed study of lithium ion battery cells model, supercapacitor cells model, battery management system and its effects on HESS system's model for voltage, current, state of charge, ageing effects and its relationship within the system for optimum design solution of hybridization. Further experimentation performed for charging and discharging parameter validation with hybridize system. Though, speculative models should scrupulously authenticated over actual investigation to confirm its reliability and suitability. This requires the building of somatic models symbolising the intended HESS arrangement, permitting experimental testing in numerous operative circumstances. Complete scrupulous statistics collection and examination, the investigational authentication intentions to validate the truthfulness and efficiency of the scientific models, confirming their arrangement with real-world consequences. This work attempt not only speaks about the methodological details of demonstrating and authentication but also steers concluded experiments like HESS complication, scalability, and safe keeping apprehensions. Eventually, the combination of these accurately constructed models with experimental authentications endeavours to under write applicably to the development of vigorous, well-organized, and consistent hybrid energy storage systems design for electric vehicles, nurturing progressions in justifiable conveyance technologies.

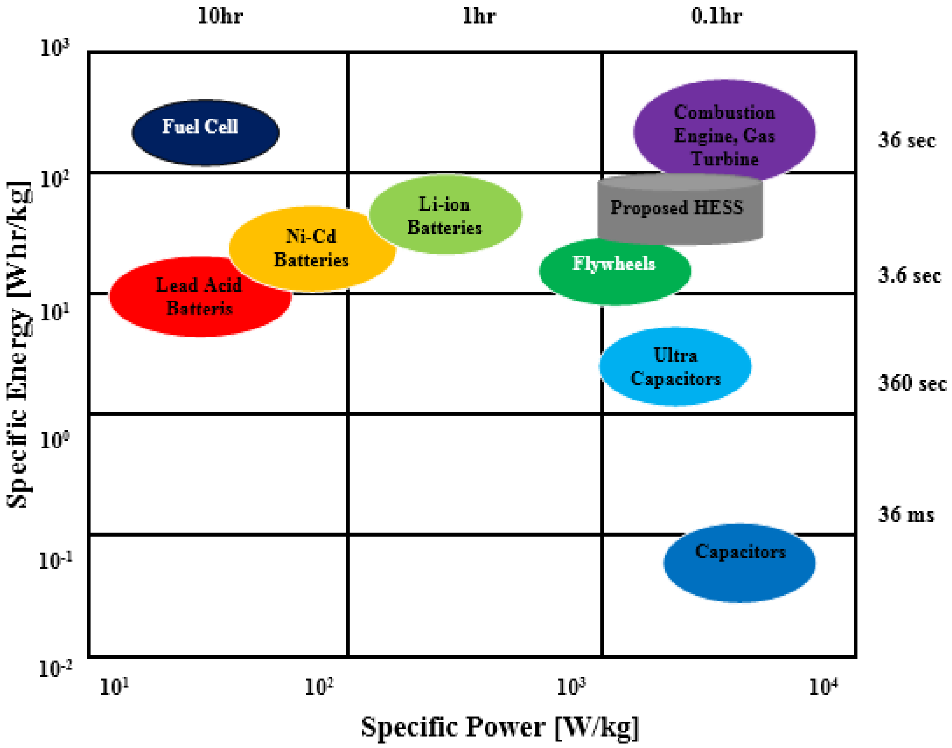

Figure 1: Ragone plot of different energy storage system.

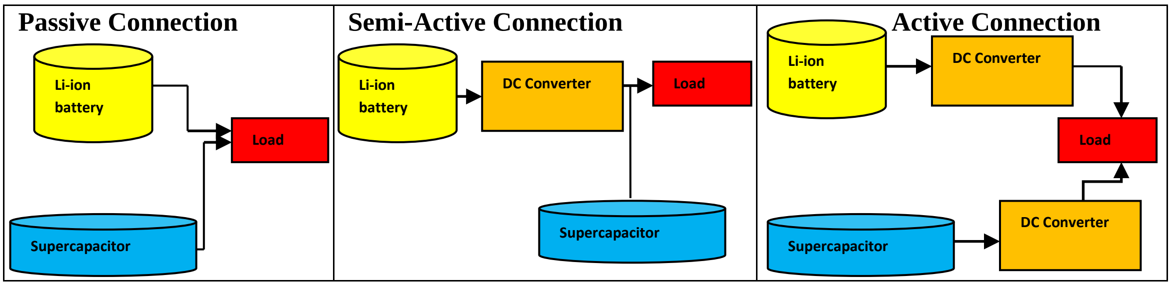

Figure 2: types of connections for HESS of li-ion battery and supercapacitor

MarekMichalczuk et.al.[1] In 2012 has worked on Energy recovery through regenerative braking and the results are simulated using Matlab / Simulink PLECS toolbox. Jian Cao et.al.[2] In 2012 experimented on HESS with PSAT (The Power System Analysis Toolbox) with a compact dc/dc converter that acts as a restrained energy pump for maintaining an inflated amount of ultracapacitor compared to the battery at driving conditions. Rebecca Carter et.al.[3] Worked on novel HESS of lead acid battery and supercapacitor using regenerative breaking. It worked on supercapacitor characteristics and energy recovery through regenerative breaking. Modifications can be done by increasing the supercapacitor operating voltages to enable energy content to be maintained while reducing equivalent series resistance. A. Ostadi et.al. [4] 2013 worked on various literature related to HESS of battery and supercapacitor by connecting it to DC sources to meet energy and power demands of the vehicle including energy management issues. Experimentation showed that the dissociate configuration with the supercapacitor unit connected directly to the DC bus and battery unit connected via a bidirectional DC-DC converter is and efficient associating organised in EV/HEV applications. SeyedHamidi et.al. [5] In 2015 worked on Lithium-ion batteries and Ultracapacitor for network applications with variant materials for cathode, anode and lithium-ion battery that results in a variety of output performance characteristics along with equivalent electrical circuit. Their work relates Lithium-ion and ultracapacitor for high power density with extensive discharge demand application to improve issues encountered in Lithium-ion batteries like high production cost, high sensitivity for thermal runaway. Clemente Capasso et.al. [6] 2016 worked on HESS with Na-Cl batteries & EDLC using a Controlled DC/DC bi-directional power Converter.

Further work proposed on Simulation & experimental study with HESS having lithium-ion and ultracapacitor. WenhuaZuo et.al. [7] 2017 worked on various combinations of HESS with a high capacitive battery and rated capacitive electrode. Further works remained on BSH with aqueous high voltage window and integrated 3D electrodes /electrolyte architecture. AnuradhaHerathet. al. [8] 2018 worked on charging and discharging algorithm of battery and supercapacitor as per its acceleration and deceleration conditions. The novel system is capable of reducing the strain on the batteries while extending the range of the vehicle compared to the conventional battery electric vehicle. Mahdi Soltani et.al. [9] 2018 worked on Lithium-ion capacitors that can be used as a high-power storage unit for MLTB (Millbrook London Transport Bus) driving cycle. Further work remained to optimize the li-ion battery and capacitor unit for optimized cost, size with a higher energy and power density. Lip Sawa et.al. [10] 2018 worked on HESS with Lithium-ion batteries and ultracapacitor model to evaluate the thermal and electrical performance parameters for different driving cycles. The simulation results in improved dynamic stress, better thermal performance for peak power demand the better life span of battery and reliability of HESS. The remained work is set up formation for electric propulsion system test bench to validate the simulation results and to incorporate the intelligent energy management system in the model. Md. Arman Arefin et.al. [11] 2018 worked on Simulations of HESS with battery and supercapacitor new and half-used battery cells. The results showed inverse proportionality between the temperature and the hybrid system efficiency. Hybridization with regenerative breaking increases the efficiency of the energy storage system with improvement in the power train efficiency and the battery lifespan. This HESS gives advantages of reduction in battery aging, peak battery current and more number of executed cycles with increase in power preserving capacity of the system that increases the battery maintenance interval. LiaKouchachvili et.al. [12] 2018 worked on battery and supercapacitor HESS by coupling the battery with a supercapacitor, which is basically an electrochemical cell with a similar architecture, but with a better capability rate and cyclability. Basic principal was supply of excess energy by supercapacitor when battery won't be able to so. Configurations, design, and performance of HESS had been discussed with active, semi active and passive types of HESS. Various applications area of HESS like mobile charging stations, racing cars, has been discussed with different batteries and supercapacitor combinations, related issues and future aspects. Immanuel N. et.al. [13] 2019 proposed a well organised hybridization of battery, supercapacitor and hybrid capacitor for efficient energy consumption in electric vehicles. The work remit the issue of deficiency in autonomy between two recharge points for supercapacitor. Experimentation involved analysis of multiple inputs for DC-DC convertor and obtaining eV profiles for proposed HESS. This work can further extended for various load profile with peak crest factors. S Devi Vidhya et.al. [14] 2019 worked on modelling, design and power management of hybrid energy storage system of li-ion battery and supercapacitor which combined bi-directional convertor for a light electric vehicle under Indian driving conditions to get optimized working parameters to improve the life of both energy storage systems. Simulation and experimental analyses were carried out to verify the effectiveness of the proposed control strategy with modelled prototype system components of light electric vehicle. A.BharathiSankar et.al. [15] 2019 worked on smart power converter for electric bicycle, powered by hybridization of lead acid battery and supercapacitor. The supercapacitor were connected in parallel to the battery pack via Arduino controller-based power converter that adjudge power between both energy storage systems. Experimental results showed an enhancement in the ascending speed w.r.to time of the bicycle as a direct result of the power converter sensitive to harvest the remaining current from the high power compatible supercapacitor neglecting deep discharges from the battery to improve its life with unchanged maximum speed. The main battery pack was protected from high discharge currents to enhance its life cycle. Walvekar, A. et.al. [16] 2020 worked on hybridization of li-ion battery and supercapaciter for two wheeler electric vehicle. In this paper, the effect of different combinations of hybrid energy storage systems and effect of degree of hybridization is analysed w.r.t. current, voltage and State of Charge (SOC). Results showed that use of HESS for pure battery based Electric two wheeler, decreases the higher value of Current of the battery with corresponding improvement in battery life. Renato Marialto et.al. Worked on parallel hybrid combination system of two electric motors, IC engine and battery energy storage system for propulsion system in naval applications through simulation and experimental approach. [20] Ghoulam Yasser et.al. Presented modeling, parameter estimation, identification and validation of lithium battery and supercapacitor including bidirectional dc/dc power converters for hybridization in eV applications. [21]

2. Methods And Materials

Simulations of energy storage systems and its hybridizationscan be used to accommodate performance, improved optimized design and safer operative processes for increasing system reliability and endurance. [22] Here simulation study is implemented to analyze the charging/discharging characteristics of lithium ion battery, EDLC supercapacitor and its hybrid combination in passive connection using MATLAB/Simulink software.

Figure 3 and 4 shows charging and dischargingcircuit for supercapacitor whereas figure 5 and 6 indicates charging and dischargingcircuit for battery respectively.

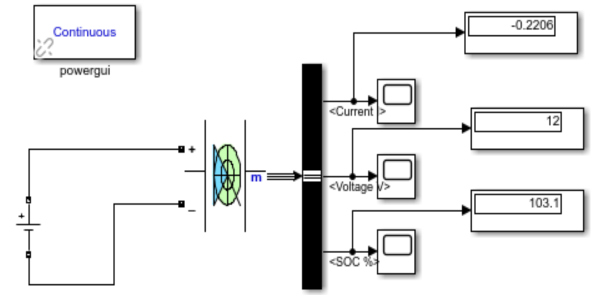

Figure 3: Charging Circuit for supercapacitor

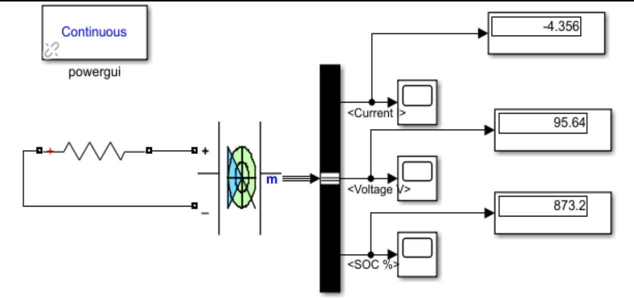

Figure 4: Discharging Circuit for supercapacitor

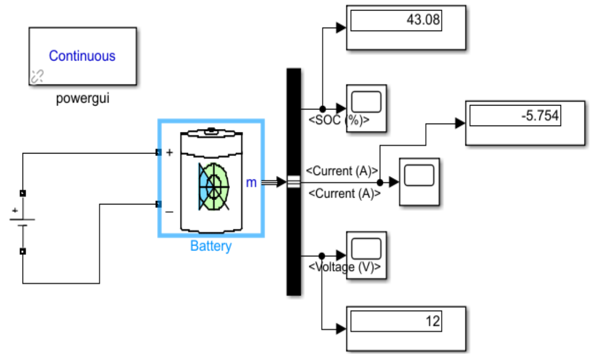

Figure 5: Charging Circuit for Lithium ion Battery

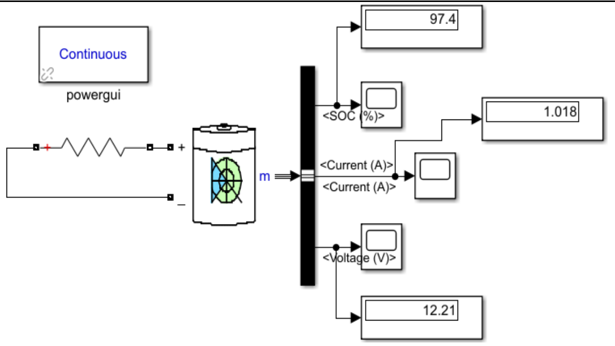

Figure 6: Discharging Circuit for Li- ion Battery

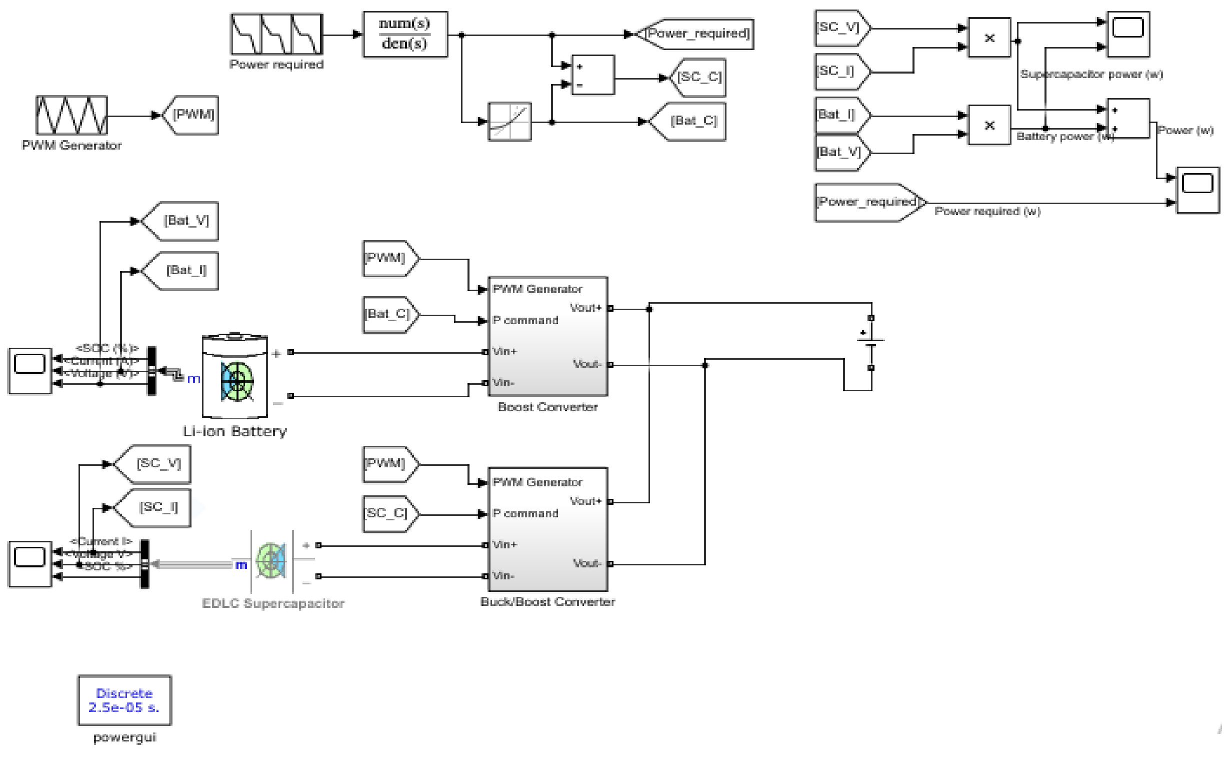

Figure 7: Charging /Discharging Circuit for HESS of battery and supercapacitor

Figure 7 indicated the HESS circuit designed for evaluating variation of performance parameter w.r.to loading conditions and its suitability for eV applications. The circuit demonstrates a hybrid energy storage system of li-ion battery and supercapacitor.The supercapacitor is coupled to a Buck/Boost converter and the battery is connected to a Boost converter. Power of the battery is controlled by a proportion regulator, therefore the momentary power is delivered to the DC bus by the supercapacitor. The model run for 2474 seconds following FTP 75 drive cycle. [22]Further the results are verified and validated with experimental set up at actual.Experimental set up consists of, hybrid connections of Lithium ion battery pack of 11.1V and 20A, and supercapacitor pack 13.5V and 100 faraday. HESS is supplied and electric power through Switched Mode Power Supply of 12V & 10 A. two shunt resistors are connected to control the current and voltage supply and to get correct input and output reading on display devices. Three Separate switches are connected to battery pack; supercapacitor pack and HESS of both to operate it individually and in HESS mode during experimental analysis. Here experimentation is performed taking two four wheeler headlights of 120 watt each for different drive cycle for individual energy storage device load as well as combine load on their hybridization. Figure 8 shows the block diagram of connections done for experimental investigation. Whereas figure 9 indicates actual experimental set up for hybrid energy storage system in which lithium ion battery pack and supercapacitor pack are connected in passive connections. Which is monitored by switch mode power supply to control the amount of current and voltage supplied to it while charging. Vibration isolators are connected with shunt resistors to control the induced vibrations on the system and effective readings on display devices. A light bulb of 220watt considering as a load for the system is connected to HESS pack through different switches to operate energy storage device at individual and hybrid conditions.Table 1 shows the Component Specifications for the experimental set up.

Table 1: List of components required for Experimental Analysis

Particulars	**Specifications**
A switched-mode power supply (SMPS)	12V, 10A
Li-ion Battery Pack	11.1V, 20A
Supercapacitor Pack	13.5V, 500F
Voltage display unit	0-200 V
Current display unit	0-75A
Resistor for supercapacitor connections	470KΩ, 2W
Shunt resistor (2nos)	75mV
Switches	3
Load	200W
Other miscellaneous accessories	As per requirement

2.1 Experimental set up for Hybrid energy storage system

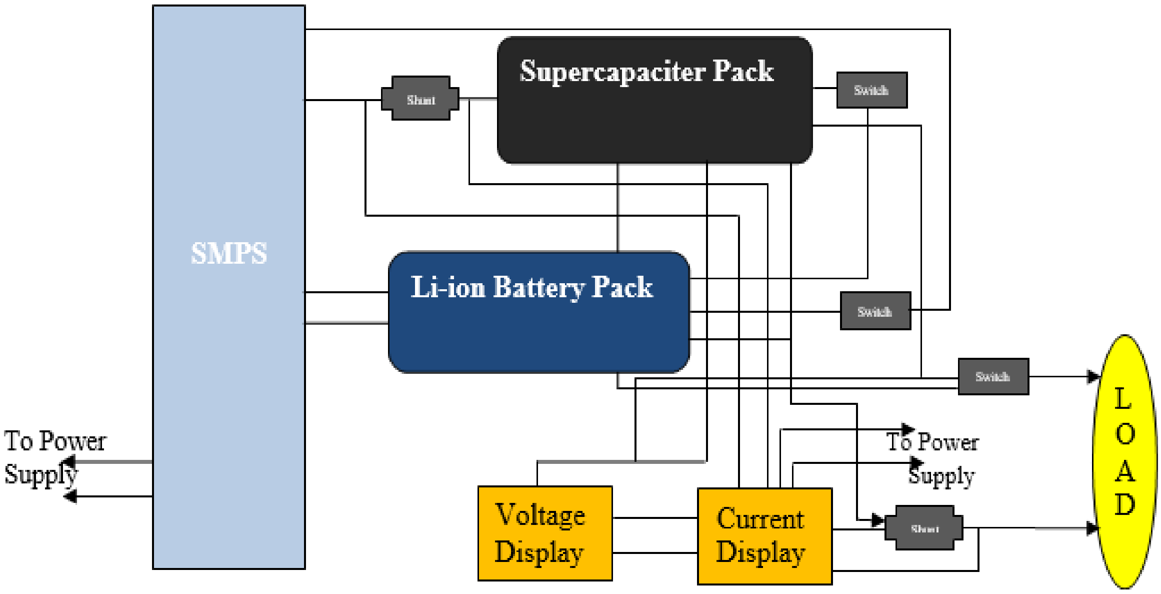

Figure 8: Block diagram of set up

2.1.1 Calculations of the battery pack for generating approx.100-watt energy for approx. two hours.

- Single lithium ion battery with 3.7 V and 2500mAh capacity.
- Using formulae (assuming 80% efficiency of the battery)

$$time(t) = \frac{Efficiency \times Battery\ voltage \times Battery\ capacity}{Total\ required\ power} = \frac{0.8 \times 11.1 \times 20}{100} = 1.776 \cong 2 Hours$$

Therefore 24 cells of batteries with a pack of three (3.7 x 3 = 11.1) pairs in parallel and eight (2500mAh x 8 = 20Ah) in series combination.

- 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 watt.

2.1.2 Calculations for Supercapacitor pack,

- We have taken 5 nos of Green cap EDLC (DB) supercapacitor with 2.7 V and 500 faradays, having size 35 mm x 60mm and connected in series for experimental analysis.
- Input current limit –1mΩ, Discharge limit – 470kΩ,
- Total voltage 2.7 x 5 = 13.5 V
- Total capacitance (CT) = $\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \frac{1}{C_4} + \frac{1}{C_5} = \frac{1}{500} + \frac{1}{500} + \frac{1}{500} + \frac{1}{500} + \frac{1}{500} = \frac{5}{500}$

  $C_T = 500/5 = 100 Faraday$
- Energy calculation € = $\frac{1}{2} C_T V^2 = \frac{1}{2} \times 100 \times 13.5^2 = 9112.5 joules = 2.53125 w/h$
- Power generated = E/ (t_2-t_1) = (2.53125 / 3) = 843.75 watt.

2.1.3 Calculations for hybridization ratio,

The connections made in experimental set up is parallel hybrid in which degree of hybridization needs to be 10% to 50 %. Using above calculations the degree of hybridization for proposed experiential set up is calculated as below,

Degree of hybridization

$$= \frac{Battery\ Power}{Battery\ power + supercapcitor\ power} = \frac{222}{222 + 843.75} = 20.83\%$$

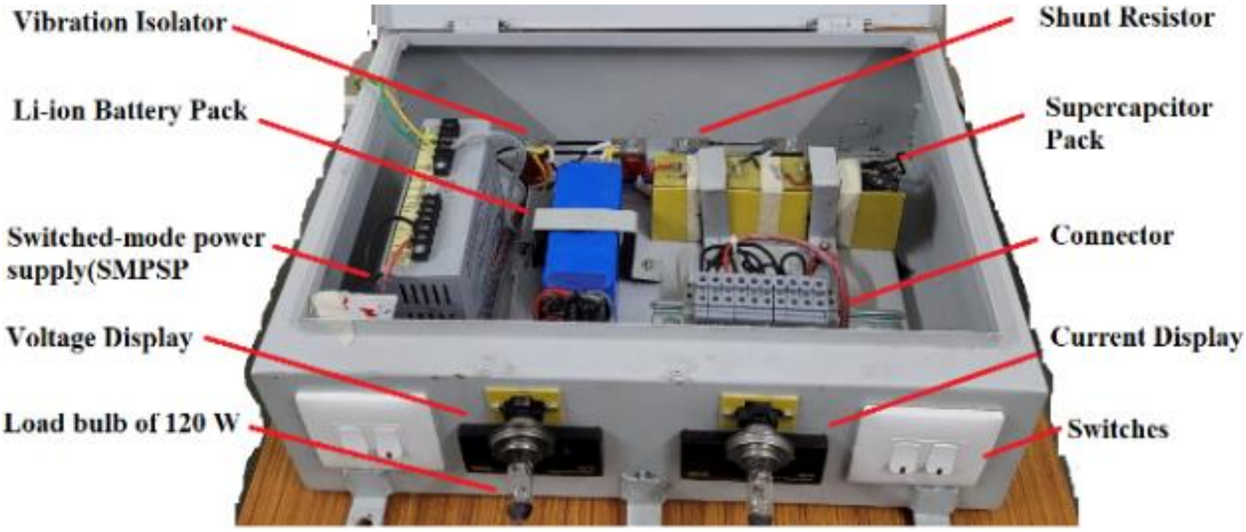

Figure 9: Experimental setup for HESS test

3. Result And Discussion

3.1 Simulation results

As discussed above in hybridized circuit for energy storage systems, the simulation is run for 300 seconds considering maximum discharge time of supercapacitor pack so that its hybridization with battery pack give effective results using MATLAB/Simulink. Figure 10 and 11 indicates variation of state of charge w.r.to time, which shows smooth decrement in state of charge for battery from 100 to 78 % due applied load with negligible deviation whereas in case of supercapacitor abrupt deviation till it get completely discharge in 100 seconds.

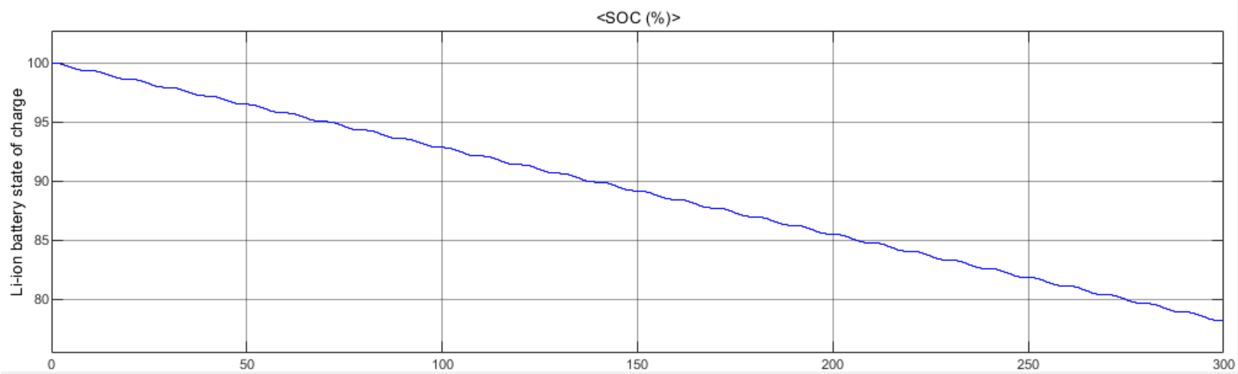

Figure 10: variation of li-ion battery state of charge vs. time in seconds

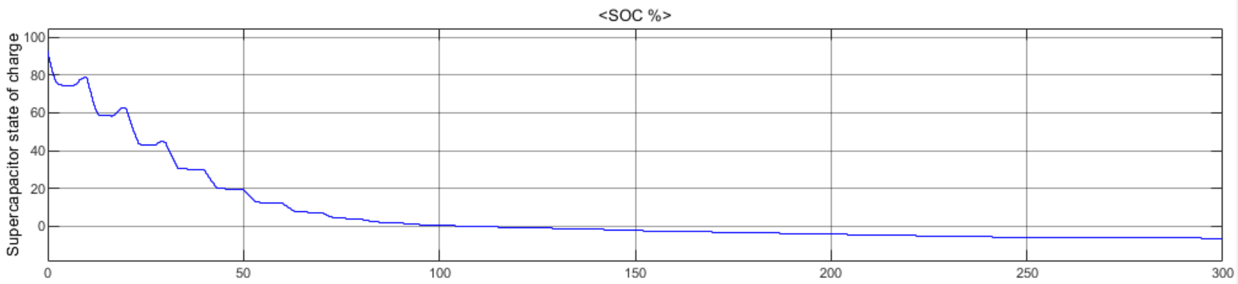

Figure 11: variation of supercapacitorstate of charge vs. time in seconds

Figure 12 and 13 indicates variation of lithium ion battery current and supercapacitor current w.r.to time which shows stepwise variation in continuous fashion with maximum magnitude 80 Ampere. But supercapacitor discharge current variation is abrupt with drop at equal intervals from maximum magnitude of 120 ampere with complete discharge in 100 seconds.

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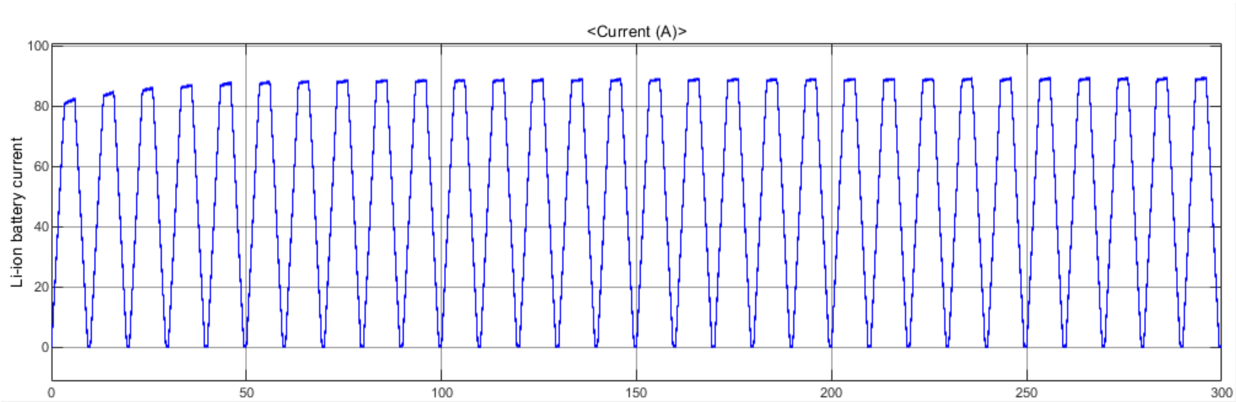


Figure 12: variation of li-ion battery current vs. time in seconds

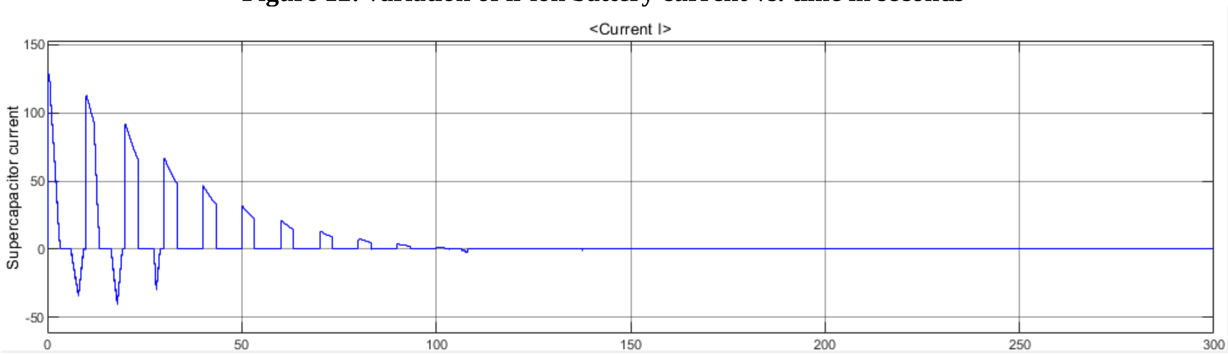


Figure 13: variation of supercapacitorcurrent vs. time in seconds

Figure 14 and 15 indicates variation of lithium ion battery voltage and supercapacitor voltage w.r.to time which shows triangular stepwise variation in continuous fashion with crest of 13 volt to down of 11 volte but supercapacitor discharge voltage variation is abrupt with drop from maximum magnitude of 14 volt till it gets completely discharge in 100 seconds.

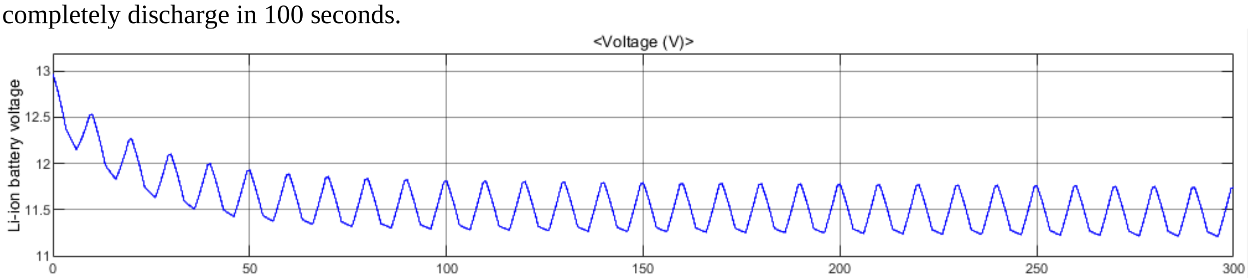


Figure 14: variation of li-ion battery voltage vs. time in seconds

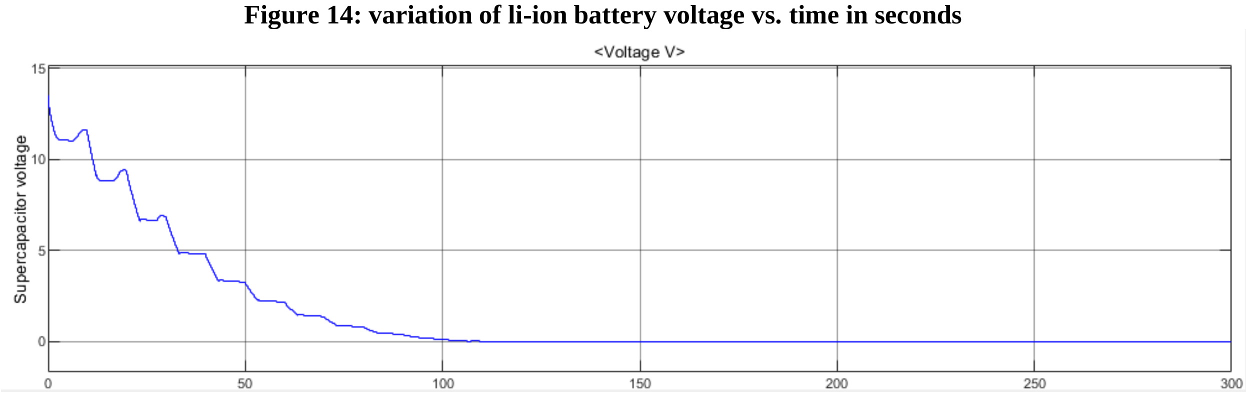


Figure 15: variation of supercapacitorvoltage vs. time in seconds

Figure 16 and 17 indicates variation of lithium ion battery power and supercapacitor power w.r.to time which shows triangular stepwise variation in continuous fashion with maximum magnitude of 1000 watt and supercapacitor power variation is abrupt with drop from maximum magnitude of more than 1500 watt till it gets completely discharge in 100 seconds.

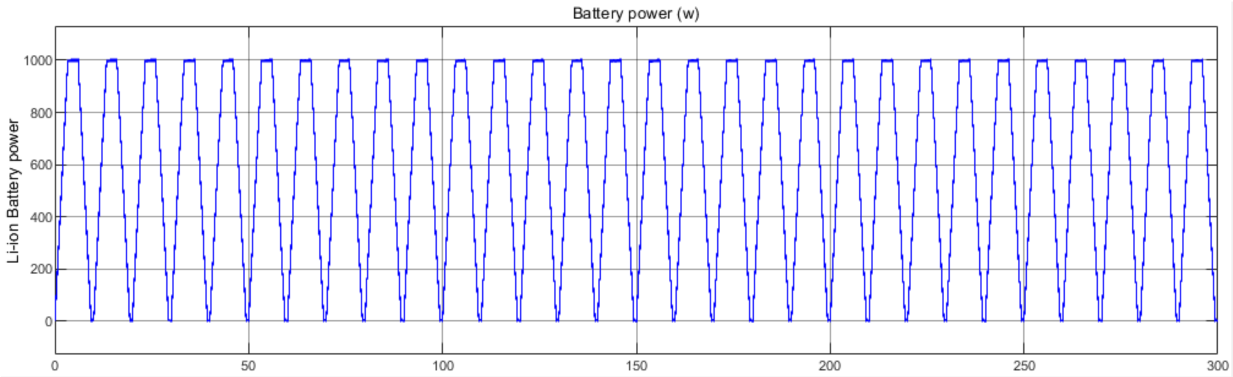


Figure 16: variation of Li-ion battery power vs. time in seconds

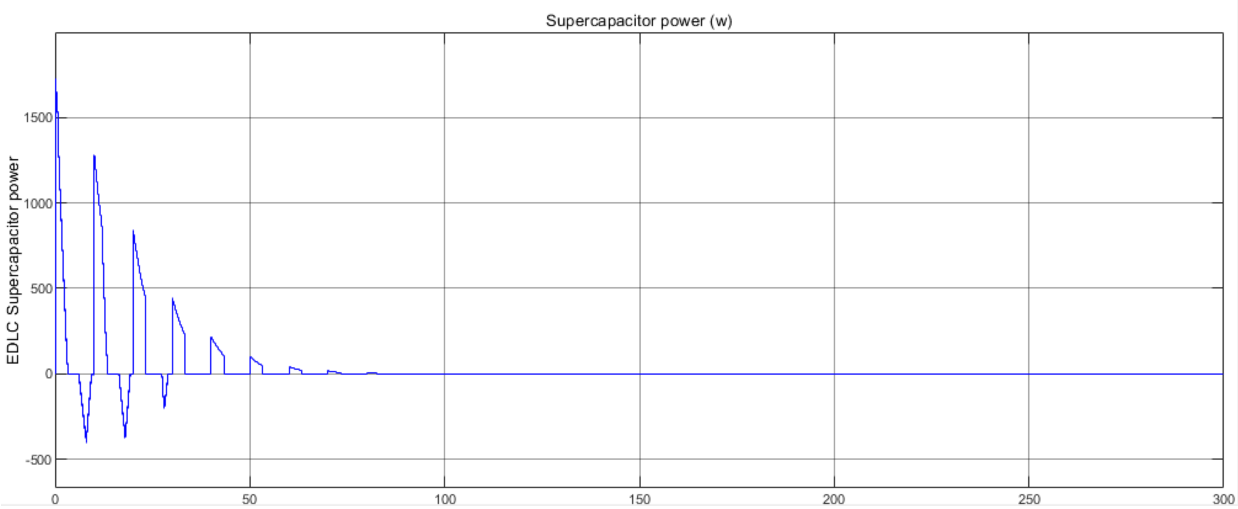


Figure 17: variation of EDLC supercapacitor power vs. time in seconds

Figure 18 indicates, variation of HESS power w.r.to time with variation from 1800 watt to 1000 watt, which shows supercapacitor power were used during high starting torque and due to that battery power remains constant. This shows effective hybridization of energy storage system that reduces battery stress and increase in its effective life of further applications.

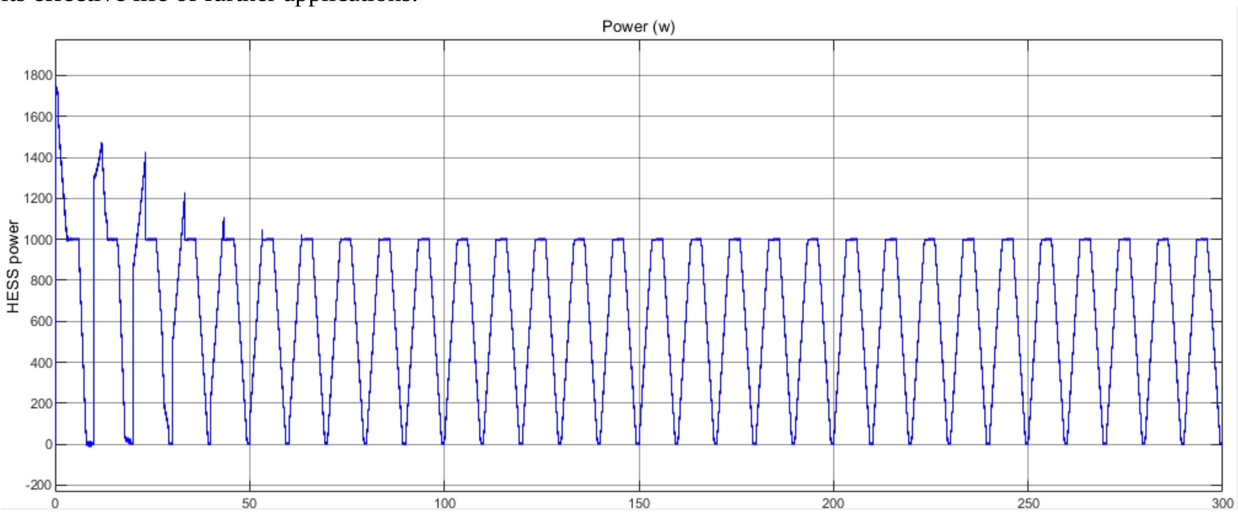


Figure 18: variation of simulated circuit HESS power vs. time in seconds

Figure 19 indicates the ideal variation of HESS power requirement w.r.to time, which shows constant variation of power vs. time. We can see from above figure that proposed hybridization meets the requirement of ideal power till 100 seconds later as supercapacitor discharges load again comes on battery. This indicates importance and implementation of regenerative breaking for charging the supercapacitor as it get discharge so that we can meet the ideal power graph and load on battery will again reduce with its improved effective life.

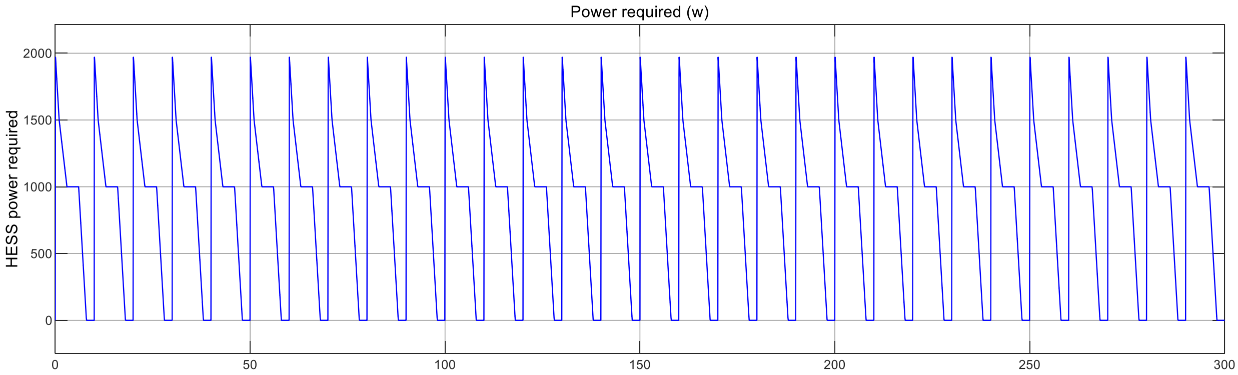


Figure 19: variation of simulated circuit HESS powerrequired vs. time in seconds

3.2 Experimental Results

1) Here experimental analysis is performed for approx. 3 hrs. to evaluate the effects of hybrid energy storage systems for given load conditions of 220 watt andfor validating above simulation results using AIS 34 and 158 standard procedure. As shown in figure 20 Initially HESS is tested for variation without any load, in steady conditions it shows considerablevoltage drop from 13.5 to 11.3, till 15 seconds, due to environmental temperature effects on supercapacitor.
2) Further the HESS is tested for a load of 220 watts (four-wheeler headlights) for approximately 3 hour, at loading conditions voltage of HESS decreased stepwise with the initial jerk for the first 2 minutes later with 7.7 volt to 6.3 volts. As shown in figure 22.
3) The current variation is discrete with an initial jerk for the first 2 minutes from 9.8 ampere to 9.7 ampere. Further it decrease linearly till 9.6 ampere for next 20 minutes. Later it is constant for the next 2 minutes. For the next 2 to 3 minutes it decreases drastically to 9.1 amperes. The current increases suddenly to 9.6 amperes to decrease in further steps. This is the point where the supercapacitor comes into working as shown in figure 23.
4) HESS state of charge varies linearly w.r.to time as shown in figure 21.
5) It is observed that the supercapacitor charge and discharge time is approximately 3 minutes for the given setup and that for the battery it is approximately 2.5 hrs.

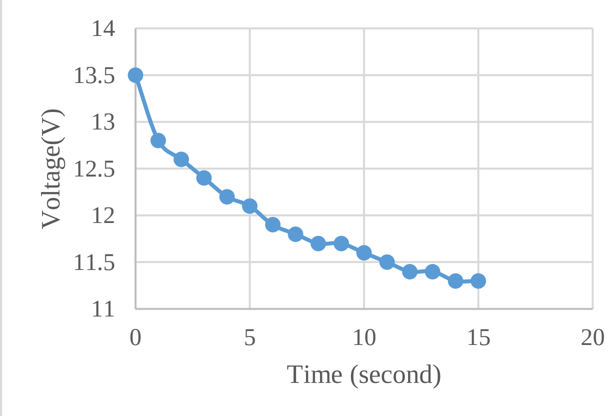


Figure 20:HESS voltage variation w.r.to time without load condition

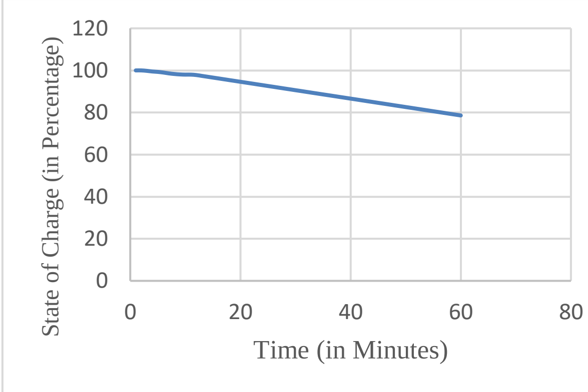
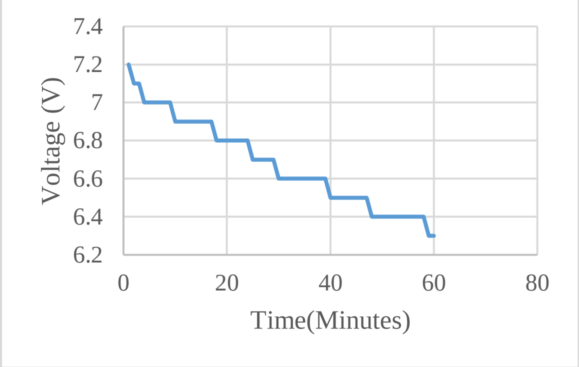
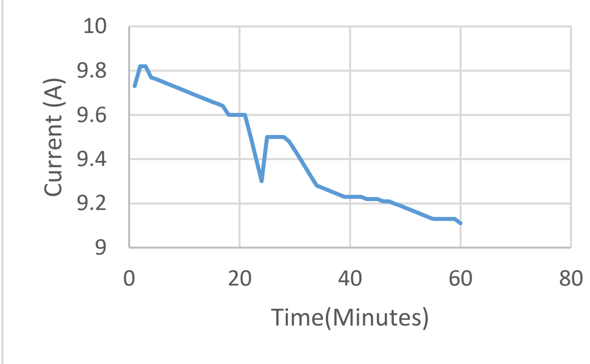


Figure 21:HESS SOC variation w.r.to time at load of 220W

 **Figure 22:HESS voltage variation w.r.to time at load of 220W**	 **Figure 23:HESS current variation w.r.to time at a load of 220W**

4. Conclusions

- A study of the modelling, evaluation of parameters through simulation and validation using experimentation for the behaviour of the working parameters of our Li-ion battery, supercapacitor and its hybridization has been proposed to meritoriously riven power electric vehicle applications.
- After structural analysis of the proposed hybridization of lithium-ion battery and supercapacitor, we can find that when the HESS is worked for given load considerable results show that The Supercapacitor acts only when there is more power requirement else is ideal.
- As soon as the supercapacitor is discharged it gets charged from the battery when the battery is not working for heavy loads. Further, as the load decrease battery acts for the next working and keeps the supercapacitor ideal. This effectively decreases the load on the battery for high power requirements. But it again increase the power demands on battery, therefore regenerative breaking or auxiliary energy storage system can be implemented to charge the supercapacitor.
- This shows a significant solution for automobiles for effective hybridization to meet current demands of energy and power in the energy and automobile sector.
- Switching mechanism of hybrid energy storage system for battery and supercapacitor simulation circuit shows the proposed hybridization is best suited to meet energy and power demands of eV applications and reducing the stresses on battery to improve its effective life.
- Comparative analysis of simulated and experimental results showed acceptable deflections in current, voltage, and state of charge w.r.to time.

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