Analysis and Simulation of Hybrid Energy Storage System for Electric Vehicle

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Abstract - **The continuous increase in demand of efficient energy storage for automobile sector and with controlling mechanism to rise in environmental issues leads to adoption of hybrid energy storage system. This hybridization can be battery and internal combustion engine or battery with supercapacitor to meet the energy and power requirement demands. Electric mobility deals with use of electric energy in automobile sector but problem lies in using pure electric battery-based vehicle are less power density at higher torque requirement as well thermal runaway for longer run. Many renewable energy sources like wind, wave and solar energy which can be used to generate electricity for charging electric vehicle batteries. Some conventional batteries like lead acid have drawbacks of increased in weight and size optimization for efficient energy storage system. Also, by using hybridization of internal combustion engine with battery, still dependency on petroleum fuel and its environmental effects will not be controlled. Therefore, selecting option of hybrid energy storage system of lithium-ion battery and supercapacitor can be an efficient option to meet the requirement of energy and power during working cycle. The structural design of battery and supercapacitor hybrid system consists of high-capacity battery-type electrode and a high-rate capacitive electrode; its proper design will provide improvement in performance, reduction in cost, safer working conditions and environmental friendliness. The proposed work basically focuses on hybrid energy storage system for light vehicle. A comparative analysis of various hybridization is studied in this paper with case study involving simulation using MATLAB / Simulink software. Main idea in this work is use of convertor to be worked as a controlled energy system for maintaining the high voltage of the supercapacitor when it exceeds the battery voltage for at most of driving conditions. At smooth running conditions battery will provide the necessary amount of energy to propel the vehicle, when requirement of power density is less and energy density is more. At starting phase and inclination road when power requirement is more compared to energy density supercapacitor will work. This system will increase the life of the battery and reduction in weight of vehicle as the batteries are sized to ensure many constraints like start up, acceleration, braking and energy recovery.**

***Index Terms* - Electric vehicles, lithium-ion batteries, Supercapacitor, Hybrid Energy Storage System, Simulink.**

I.INTRODUCTION

Electric mobility is the field in which all street vehicles that is powered by an electric motor and primarily gets their energy from the power grid. This includes purely electric vehicles, vehicles with a combination of electric motor and a small combustion engine and hybrid vehicles that can be recharge via the power grid. The basic source of fuel supply to electric Vehicle is Electrical Energy which significantly reduces CO2 emission. This electricity can be generated from many non- conventional energy resources which help to decrease in use of fossil fuels. Various rechargeable batteries can be an efficient option for replacing conventional energy sources and to reduce its unwanted effects. Among all Lithium battery is a type of rechargeable battery that have metallic lithium as an anode. The batteries have a high energy density, no memory effect and low self-discharge but with drawback, of a flammable electrolyte, and if damaged or incorrectly charged can lead to explosions and fires.

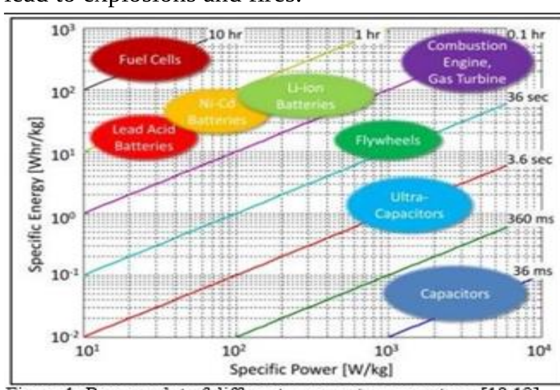

Figure 1: Ragone plot of different energy storage system. [18,19]

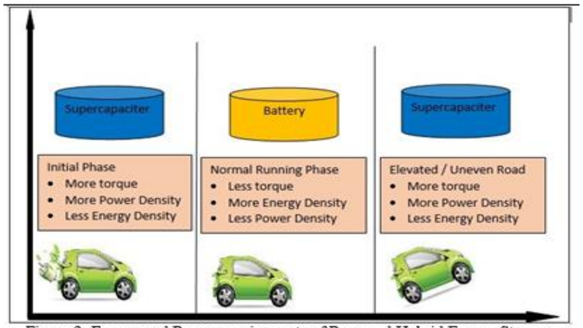

Figure 2: Energy and Power requirements of Proposed Hybrid Energy Storage system for electric vehicle.

Various hybrid combinations are used in electric vehicles like, pure battery based electric vehicle, hybrid electric vehicle, plug in hybrid electric vehicle. Etc. the design of efficient energy storage system and its thermal management is critical issue. In battery-based energy storage system, battery with higher power density is required to meet the power demands. As a solution for this, the size of battery can be increase but it will raise the issue of increase in cost and thermal management in high power load as well as cold temperature conditions. In addition to that some issues related to the balancing of cells of battery as without balancing system, the individual cell voltages tend to drift apart over time. This tends to decrease the capacity of the total pack during operation results in failure of the total battery system during high rate of charge and discharge conditions. In addition to these issues, the application where instantaneous power input and output is required i.e. the applications where batteries suffering from frequent charge and discharge operations adversely affect the life of battery. All of above problems can be resolved by Hybrid energy storage system in which Supercapacitor is to combine with batteries to achieve better overall performance. As shown in figure 1, this is because, supercapacitor has more power density but lower energy density compared to batteries.

Table 1: Comparison of Li-ion supercapacitor with other Energy storage system [5]

Energy Storage Device	Energy Density	Power Density	Cycle life
HESS of Li-ion	10-20	900-9000	>100000
Li-ion Battery	100-265	100-265	300-500
EDLC (Supercapaciter)	2-8	500-5000	>100000
Li-acid battery	30-50	100-200	200-300
Ni-MH battery	60-120	250-1000	300-500
Zinc-bromide battery	85-90	300-600	2000

Therefore during higher power requirements i.e. start and peak power phase supercapaciter will work and during smooth running conditions batteries will work for supplying energy requirements which will surely increase the life of battery. Therefore, the basic idea, in this work is to use best features of both devices. The high life cycle and power density of supercapaciter will be use to improve the battery life and optimize use of energy density so that there will be significant reduction in cost of battery as well CO_2 emission. This hybridization should be such that it should be equipped with high power as well as high energy density. Basically, there are two ways for this hybridization as shown in figure.

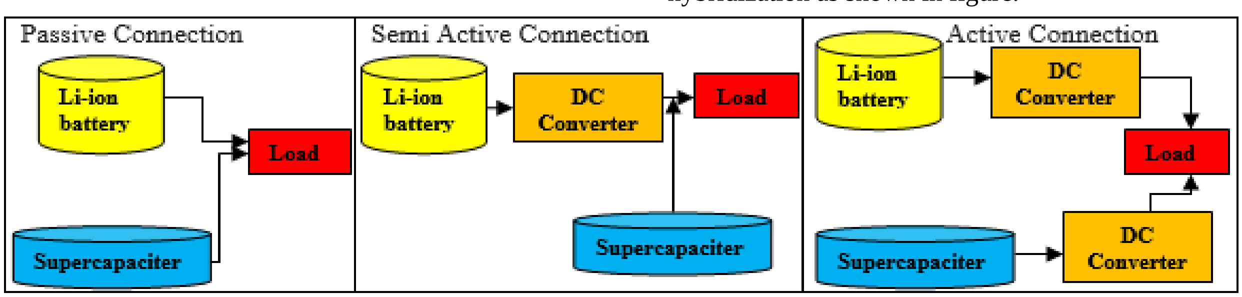

Figure 3: Types of hybridization for battery and supercapaciter. [16]

First is passive type in which battery and supercapacitor is directly connected to DC bus. It has advantages like, high peak power capability, higher efficiency and longer battery life cycle etc. but has a drawback of unachievable system optimization as there is no power management mechanism to govern the power sharing between battery and super capacitor. Whereas in active type, battery and super capacitor are connected to DC-bus via DC-DC converter. It has advantages of design flexibility, acquiring higher power capacity, less voltage variation and reduction in weight but with disadvantage of increase in cost of DC- DC converter. Other possible hybridization can be other types of batteries as mentioned above with either supercapacitor or internal combustion engine. Other type of energy storage can be fuel cell which can be future aspect in automobile field. The proposed works is based on analysing different hybrid combination specifically for light weight applications like two-wheeler. Various types of earlier work related to this is explained in literature survey.

II. LITERATURE REVIEW

Marek Michalczuk et.al. [1] In 2012 has presented HESS for a small urban electric car with lithium batteries and Ultracapacitors. They 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 smaller dc/dc converter which acts as a controlled energy pump for maintaining an inflated amount of ultracapacitor compared to the battery at driving conditions. Further work proposed on the analysis of the HESS efficiency parameters at high- voltage conditions and Sizing of the dc/dc converter versus the Ultracapacitors. Rebecca Carter et.al. [3] Worked on novel HESS of lead acid battery and supercapacitor using regenerative breaking. The availability of energy from regenerative braking and the characteristics of the supercapacitor were considered as impact factors. With decreasing peak battery current supercapacitor were found to be effective. Further 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. Qualitative analysis through literature review reveals that the partially decoupled configuration with the ultra-capacitor unit directly connected to the DC bus and battery unit connected via a bidirectional DC-DC converter is the most promising interfacing topology in EV/HEV applications. Seyed Hamidi 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 proposed 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. Wenhua Zuo 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. Anuradha Herath et. al. [8] 2018 worked on charging and discharging algorithm of battery and supercapacitors 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 which can be used as a high-power storage unit for MLTB (Millbrook London Transport Bus) driving cycle. Further work remained to optimize the LiC and LiB unit for a lower cost, size, 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 supercapaciter taking two basic scenarios into consideration: fresh cells and half-used battery cells. The simulations showed that the lower the temperature is, the higher the hybrid system efficiency becomes. Hybridization with regenerative breaking not only increases the efficiency of the energy storage system but it also increases the power train efficiency and the battery lifespan. This HESS gives advantages of reduction in battery aging, maximum battery current and the number of executed cycles and increase in power preserving capacity of the system with increase in battery maintenance interval. Lia Kouchachvili et.al. [12]

2018 worked on battery and supercapaciter HESS by coupling the battery with a supercapaciter, 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 supercapaciter 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 supercapaciter combinations, related issues and future aspects. Immanuel N. et.al. [13] 2019 proposed a novel topology of hybridizing battery, supercapaciter and hybrid capacitor for optimum utilization of energy in electric vehicles. This paper deals with the combination of both supercapaciter and hybrid capacitor with the battery thus addressing the problem of the lack of autonomy between two recharge points in supercapaciter. The prospects of using a multiple-input DC-DC converter was also analysed. Electric vehicle profile obtained by experimental analysis were used for verification with the proposed ides of the project. The application of the novel hybridization of the three energy storage devices can be extended to other applications having a load profile with high crest factors. S Devi Vidhya et.al. [14] 2019 presented the modelling, design and power management of HESS for a three wheeled light electric vehicle under Indian driving conditions. The HESS includes Li-ion battery and Ultracapacitor combined with a bi-directional converter in order to get efficiency parameters. The HESS in this project work shows efficient results towards improving the life of battery and supercapaciter. Simulations were carried out in MATLAB/Simulink environment to verify the effectiveness of the proposed control strategy with modelled system components of three-wheeled light electric vehicle. The power split validation in this work were done experimental prototypes of HESS. A.Bharathi Sankar et.al. [15] 2019 presented a smart power converter to for electric bicycle which is powered by a battery and super capacitor hybrid combination. In this work an assembly of a rear hub motor onto a normal geared bike powered by a lead acid battery pack is introduced. A super capacitor module was connected in parallel to the battery pack via a custom-made Arduino controller-based power converter which arbitrates power between the battery and super capacitor. Experimental results show an improvement in the up-hill acceleration of the bicycle as a direct result of the power converter being responsive enough to harvest the extra current from the high power complementary super capacitor module avoiding deep discharges from the battery to improve the battery life. The maximum speed remained unchanged. The main battery pack was shielded 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 topologies of HESS and effect of degree of hybridization is analysed w.r.t. current profile, voltage profile and State of Charge (SOC). Results show that use of HESS for Electric two-wheeler in place of only battery decreases, the Peak/RMS Current experienced by the battery with corresponding improvement in battery life.

III.PROPOSED MODEL

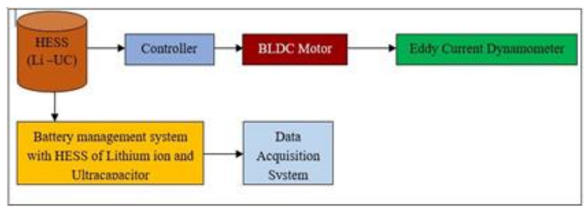

Figure 4: Proposed model of hybridization of lithium ion battery and supercapacitor

Dynamics of Motorcycle:
Here, the motion of motorcycle and their components due to applied forces in running conditions are discussed. This includes balancing, steering, braking, acceleration, suspension and induced vibration on the vehicle body. The various forces acting on two-wheeler bike including the driver, has been categorised into external and internal. The external forces are due to gravity, inertia, ground contact and atmospheric conditions whereas internal forces are caused due to bike rider and interaction between the components of the vehicle body. The mathematical modelling of electric vehicle's mechanical behaviour is studies considering it as two-wheeler and the performance limiting parameters viz. state of charge, variation of current and voltage according to battery parameters. Finally, the Simulink model of the e-vehicle is performed using Matlab/Simulink. The

mechanical model performed here on assumptions that motorcycle as a rigid body with rider to be static on motorcycle, so that centre of gravity is constant during driving conditions. The motorcycle body is subjected to aerodynamic drag force, rolling resistance and the component of the weight force caused by the angle of inclination to the road surface (Fp). Considering all these forces the free body diagram of two-wheeler is as shown in figure.

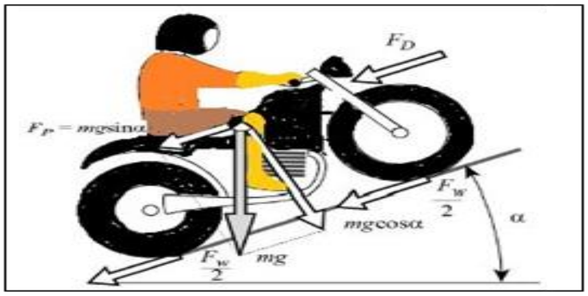

Figure 5: Drag forces acting on the motorcycle. [17]

The rolling resistance can be considered as 2% of the weight, which is considered as negligible for sum of resistance forces. If ρ is the air density coefficient, C_D is the drag coefficient, A is the frontal area of the motorcycle and V is the linear velocity, the drag force acting on the motorcycle centre is (F_d) can be calculated by,

$$F_d = \frac{1}{2}\rho C_D A V^2 \quad \text{…………………1)}$$

The resistive force caused by a slope of the road is given by,

$$F_R = m.g.\sin\alpha \quad \text{………………… (2)}$$

Where, m = 220 kg Approx. (considering racing bike two wheeler), g = acceleration due to gravity = 9.81m/s^2, α is the angle of inclination to the road surface. The effect of sum of resistive forces applied on the motor shaft is given by following equation where, Tm is total resistive force, r_w is the total radius of wheel and tire and N is the ratio of number of teeth of front and rear sprockets.

$$T_m = \frac{r_\omega}{N}[m_g \sin\alpha + \frac{1}{2}\rho C_D A V^2] \quad \text{… (3)}$$

The change in linear momentum of the motorcycle and pilot, given by following equation, can be seen as a linear force Fi being applied on the motorcycle centre of gravity.

$$F_i = m\ddot{x} \quad \text{…………………………. (4)}$$

The equivalent torque applied on the rotor shaft is given by,

$$T_{im}^{r} = \frac{\ddot{\theta}_r}{N}\frac{mr^2\omega}{N} = \frac{\ddot{\theta}_r\, mr^2\omega}{N^2} \quad \text{…... (5)}$$

Converting above equation in terms of the angular acceleration of the rotor shows that the equivalent moment of inertia of the motorcycle applied at the rotor shaft is,

$$J_m = \frac{mr^2\omega}{N} \quad \text{…………………... (6)}$$

The effect of both wheels' angular momentum is mathematically described as the concentration of both wheels momentum on the rear wheel. The torque resulting from the variation of the wheels' angular momentum is given by,

$$T_{im}^{\omega} = j_\omega \ddot{\theta}_\omega \quad \text{…………………… (7)}$$

In the rotor, this torque can be determined by following equation, where the equivalent inertia of the wheels applied on the motor shaft is,

$$T_{im}^{\omega} = \ddot{\theta}_r \frac{j_\omega}{N^2} \quad \text{………………….. (8)}$$

For simplification, the wheels are modelled as disks of homogeneous density, thus, the moment of inertia of each is determined with following equation, where the subscripts wf and wr are used to refer to the front and rear wheels. In this case, the radius of both wheels are equal, $r_{\omega f} = r_{\omega r} = r_\omega$

$$J_{\omega f} = \frac{1}{2} m_{\omega f} r_{\omega f}^2$$

$$J_{\omega r} = \frac{1}{2} m_{\omega r} r_{\omega r}^2 \quad \text{…………………… (9)}$$

The motorcycle geometry can be characterized by the wheelbase p, the height of the centre of gravity h and the distance between the centre of gravity and rear wheel axle b, see figure,

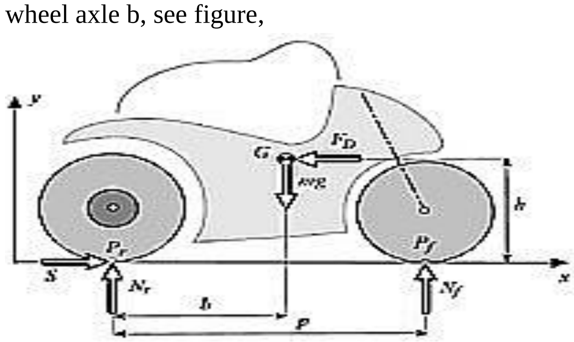

Figure 6: Motorcycle geometric parameters. [17]

The weight of the motorcycle is shared between both wheels and the opposite force that the ground exerts on each wheel is called normal force Nr for the rear wheel and Nf for the front wheel. In steady state, the normal force acting on each wheel is given by,

$$N_f = mg\frac{b}{p}$$

$$N_r = mg\frac{(p-b)}{p} \quad \text{.................. (10)}$$

In transitory rectilinear motion, i.e. accelerating or braking, a load transfer occurs between wheels, which is proportional to the accelerating or braking force. During acceleration, the normal force acting on each wheel is given by,

$$N_f = mg\frac{b}{p} - S\frac{h}{p}$$

$$N_r = mg\frac{(p-b)}{p} + S\frac{h}{p} \quad \text{... .... (11)}$$

Where, $S = T_{em}^{r}\frac{N}{r_\omega}$

During braking, there is a load transfer from the rear wheel to the front wheel, characterized with by,

$$N_f = mg\frac{b}{p} + F_B\frac{h}{p}$$

$$N_r = mg\frac{(p-b)}{p} - F_B\frac{h}{p} \quad \text{................ (12)}$$

Where, $F_B = F_{BF} + F_{BR}$ is the braking force applied by the ground on the rear wheel, F_{BR}, and on the front wheel F_{BF}. Both when accelerating and braking the maximum linear force applied by one tire on the road is given by,

$F_{Bmax} = F_{BFmax} + F_{BRmax}$ .... (13)

$\leq \mu_f Nf + \mu_r Nr$..............................(14)

$S_{max} \leq \mu_r Nr$

Where μ_f and μ_r are the front and rear wheel traction coefficients. These are considered equal, $\mu_f = \mu_r = \mu$. The value of μ is not given by the tire manufacturers. For the case of the racing tires, the values ranged from μ = 1:1 to μ = 1:5. Hence, the value μ = 1:3 was considered a good approximation. For this value of the traction coefficient, the maximum braking and acceleration forces are given by F_{Bmax} = 2904:72 Nm and S_{max} = 2904:72 Nm

The maximum braking force applied by the tires on the road is limited to either the slip condition or the flip over condition (complete loss of rear tire traction). Considering the traction coefficients of slick tires on a racetrack, maximum braking is generally limited by the flip over of the motorcycle. Moreover, the braking force distribution among front and rear brakes varies with the traction coefficient and tends to increase on the front tire while decreasing on the rear tire as μ increases. This is due to the previously described load shift to the front of the motorcycle when braking. The distribution of braking force among the wheels can take values higher than 90% for the front wheel and less than 10% for the rear wheel in a case where μ≤ 1. The flip over of the motorcycle happens when the normal force on the rear tire becomes null and all the braking force is being applied on the front wheel. In this case, the braking force is given by,

$$F_B = mg\frac{(p-b)}{h} = 2255.63\text{Nm} \quad \text{......... (15)}$$

This value corroborates that for this particular motorcycle, braking is limited by the flip over of the motorcycle and not by the tire slippage.

Similarly to the braking limits, acceleration can also be limited either by the point at which the normal force on the front wheel is null (wheelie) or the point at which the rear tire slips. Again it is less common for rear tire slippage to happen on a race environment, nevertheless, both situations are considered. The traction force required to lift the front wheel is given by,

$$S = mg\frac{b}{h} = 2255.63\text{Nm} \quad \text{.................. (16)}$$

As with the case of braking situation, the maximum traction force is limited by the wheelie situation.

The dynamics involved in a motorcycle turning are highly complex. For the sake of simplicity, the simplifications used here are,

1. The motorcycle runs along a turn of constant radius at constant velocity (steady state conditions)
2. The gyroscopic effect is negligible
3. The cross section of the tires is null

The maximum velocity in a turn is given by,

$$V_{max} = \sqrt{\tan\varphi_i g R_c} \quad \text{........................(17)}$$

Where φ_i is the lean angle, R_c is the radius of the curve, g is the acceleration of gravity and V is the motorcycle linear speed. This demonstrates the fact that the maximum turn speed is not affected by the mass, but by the turn geometry and the maximum lean angle.

The actual lean angle is measured from the upright position, resulting in an approximate value of 52º. Even though this represents but a gross estimate of the real lean angles, it serves to prove that a maximum value of 50º of lean angle is be an adequate approximation.

Experimental analysis

Simulation for electric vehicle to evaluate the battery parameters is proposed here. The simulation has been carried out using MATLAB / Simulink considering Hybridization of lithium ion battery which is initially charged 100% and Supercapaciter as an energy source and following input parameters,

Table 2: EV parameters for simulation

Nominal voltage of lithium ion battery	48 V	Mass of vehicle	220 kg
Rated Capacity	48Ah	No of wheels per axle	2
Rolling radius of tire	0.3 m	Horizontal distance from front axle to CG	1.4 m
Rated vertical load	3000 N	Horizontal distance from rear axle to CG	1.6 m
Peak longitudinal force at rated load	3000 N	CG distance above ground level	0.5 m
Slip at peak force at rated load	10%	Frontal area	$2m^2$
Carrier (C) to driveshaft (D) teeth ratio	4	Drag coefficient	0.25
Follower (F) to base (B) teeth ratio (NF/NB)	2	Air density	$1.18kg/m^3$
No-load speed	7500 RPM	Rated speed (at rated load)	5000 RPM
Rated load (mechanical power)	5KW	Rated DC supply voltage	50V

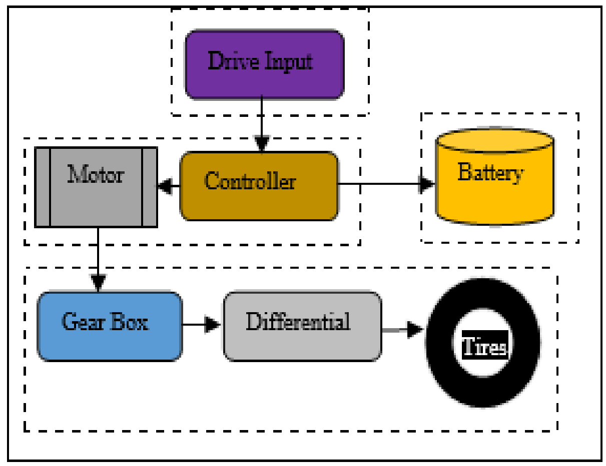

Figure 7: Block digram of the system

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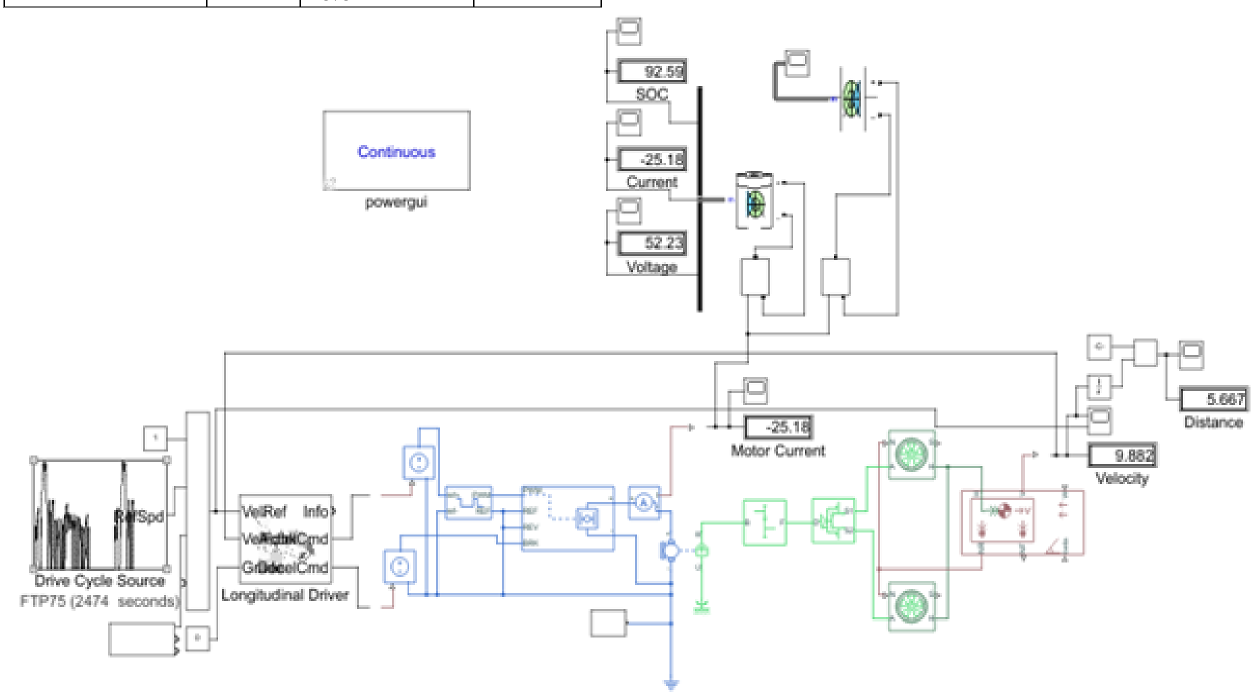

Figure 8: Simulink model of Electric Vehicle

Observation Results:

Initially battery was charges 100%. Comparing FTP 75 cycle of 2474 seconds, following results were obtained,

Battery state of charge – 85.17%

Current - -25.13 A
Voltage – 52.29 V
Velocity – 9.865 Km / hr
Distance Travelled – 5.664 Km.

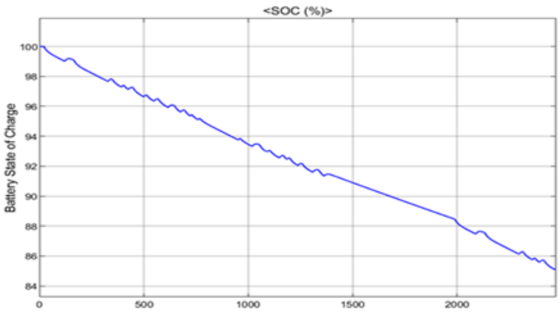

Figure 9: Battery SOC Vs time

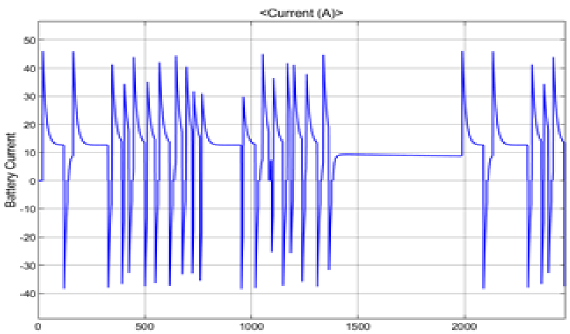

Figure 10: Battery current Vs time

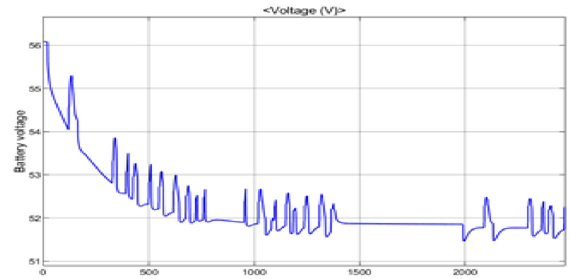

Figure 11: Battery Voltage Vs time

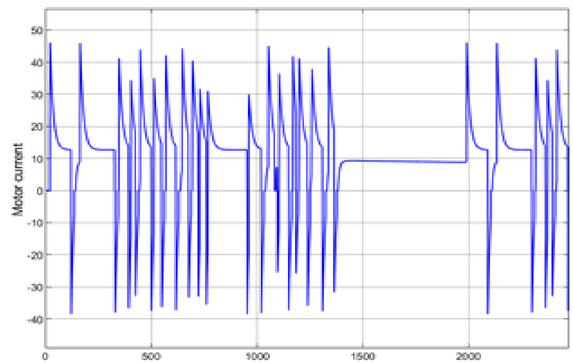

Figure 12: DC Motor current Vs time

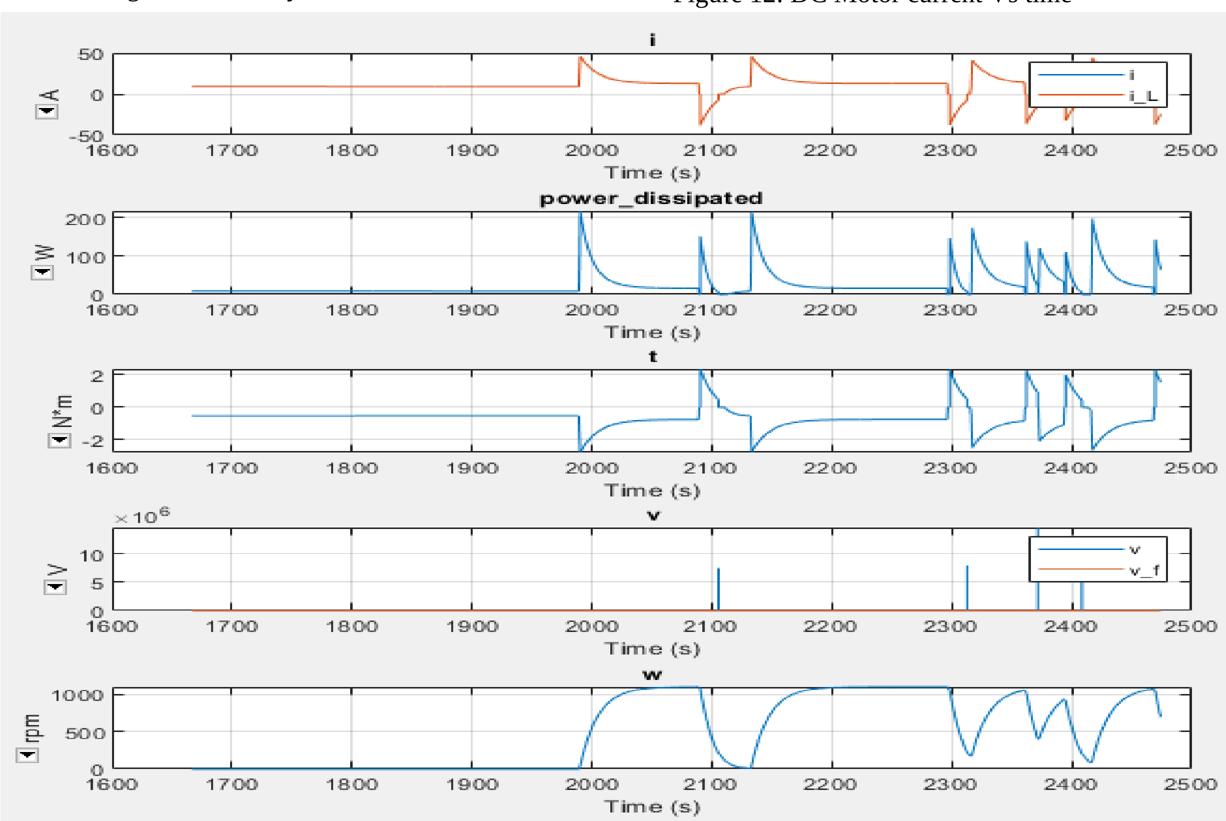

Figure 13: Variation of DC motor parameters Vs time

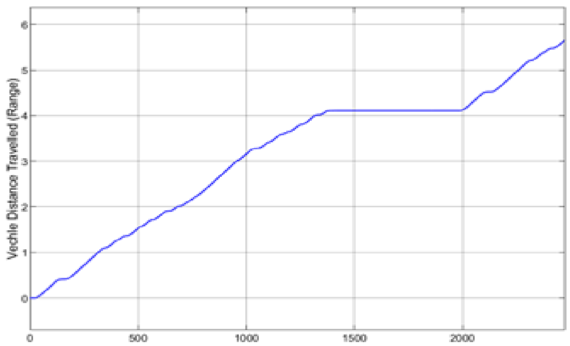

Figure 14: Distance covered by vehicle Vs time

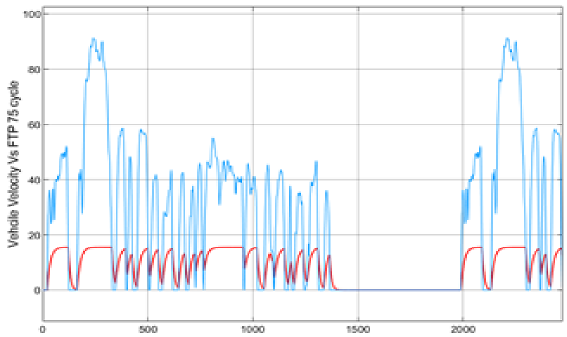

Figure 15: Distance covered by vehicle Vs time

V.CONCLUSION AND FUTURE SCOPE

Conclusions:

- Literature Survey showed much work needs to be performed on implementation of electric vehicle and its hybridization related to its structural and thermal investigations as per road and transportation conditions.
- Mechanism needs to analyse for activation of supercapaciter during high power density requirements and battery during high energy density requirements. Also the shorter discharging time of supercapaciter needs to work upon for effective hybridization.
- Proposed HESS can be worked on active as well as passive for getting effective structural optimized solution.
- Simulation of electric vehicle shows graphical representation of variation in different parameters of electric vehicle and it seems that, battery state of decreases linearly w.r.to. Time. Battery and DC motor current shows interrupted step response and voltage decreases interruptedly w.r.to time. Distance covered by vehicle shows increasing linear relation for first 1300 seconds, for next 700 seconds it is constant whereas again increase linearly further till completion of cycle.
- In this analysis FTP 75 cycle is considered for comparative analysis with proposed EV, the graphical representation of which shows necessity of modification in input parameters to match with the required cycle.

Future scope:

- Further analysis can be done for different motors and controllers performance.
- EV paraemters can be further modefied for paramters meting with the required FTP 75 cycle.
- Further comparative analysis can be done for different batteries and other energy sources.
- We can make hybridization of battery and solar panel, battery and supercapaciter, battery with internal combustion engine also for analysis the behaviour of different battery performance with its hybrdiaztion for getting effective energy storage system for electric vehicle.

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