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Hybrid Energy Management System Consisting of Battery and Supercapacitor for Electric Vehicle

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Abstract: This paper is mainly focused on Hybrid Energy Management System (HEMS) consisting of Battery (BT) and Super capacitor (SC). Two energy sources connected in with same DC link in parallel manner with the help of Bidirectional DC-DC converter, which is used to separate control of power flow of each source. Here Permanent magnet dc motor (PMDC) motor used as a load and speed control of PMDC motor can be done by PWM method for this purpose chopper circuit is used. Input of chopper circuit is DC link and output of the chopper is given to PMDC motor. This method of energy management gives power splitting between two sources based on State of Charge (SOC) of each individual source during different state of vehicle such as acceleration, constant running and deceleration. Improved filter-based power splitting techniques is implemented. Three acceleration reference points were taken for power splinting at different SOC levels of both energy sources. Objective of this proposed method is best use of both the sources i.e. battery and supercapacitor and maximum use of supercapacitor energy at the time of transient conditions. Battery supply energy during normal running condition or very less load condition. Hence during transient condition SC directly react with system and gives peak power requirement, so stress on battery is reduces hence lifetime of battery is increase, also power available during braking is store in SC and battery, so independence of Electric Vehicle (EV) is increases. Because of less peak power requirement, batteries with less peak output power is used so it is reduced size and cost of batteries. Matlab-Simulink software is used for simulation and also small scale hardware is also implemented of proposed method.

Keywords: Electric vehicle (EV), Hybrid energy management system (HEMS), Battery (BT), Super capacitor (SC), State of charge (SOC), topology, DC-DC bidirectional converter

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1. Introduction

Sustainable transportation is a vital component for maintaining an environmental and ecological balance. According to an international agency, the concentration of CO2 has increased by 45 to 50% in 2020 compared to the previous year and will continue to rise. The high carbon emission from the transportation sector has prompted various authorities to focus on zero-emission vehicles. Electric vehicles are an essential component for achieving zero-emission vehicles. Many energy sources, such as batteries, fuel cells, ultracapacitors, and flywheels, have been reported. The selection of a proper energy storage system should satisfy the vehicle's dynamic characteristics. The vehicle characteristics comprise mainly two areas: peak and average power requirements. The presently available energy sources do not meet both high energy and power requirements by prompting hybridization of energy sources. The system developed by this hybridization is referred to as Hybrid Energy Storage System (HESS)[1-3]. In this paper, a combination of ultracapacitor and battery is considered as HESS. The peak power requirements of the vehicle will be managed with the aid of the ultracapacitor because of its high-power density characteristics, and the average power requirement will be met with the aid of the battery because of its high energy density characteristics.

At present time demand of electric vehicle (EV) is increases very rapidly because of problem of environmental pollution and continuously increasing prize of fuel, so interest in EV is constantly increases. EVs are recommended solutions given by vehicle manufacturers and research organization to replace with convention vehicle. Main challenge in EV is energy storage issue and low driving range as compared to conventional vehicle. So increase driving range, improve efficiency and decrease cost become necessary to make EV competitive with conventional vehicle [4-5]. Thus, development of EV with well-defined control strategy has become very necessary. Control strategy of EV is that the solution between performance of vehicle and fuel economy. There are many reliable energy sources available in market, such as Super capacitor (SC), battery, fuel cell. But any source alone is not sufficient to meet all the requirements of electric vehicle (EV), like fuel cell able to provide clean energy with high energy density but it has very poor time response to sudden power demands, and it is also very costly and not able to absorb energy during braking of EV [6]. Battery consists of anode and cathode system which is takes part in electrochemical reaction and because of this battery has less power density and high energy density. Where in case of Super capacitor (SC) there is not any electrochemical reaction it is consistent with movement of ions in electrolyte medium. Supercapacitor is very high value of capacitor which has capacity is 10 to 100 times more than normal capacitors. Which can be able to sustain a greater number of charging and discharging cycle as compared to battery. SC has able to provide peak power requirement in very short interval of time [7]. SC has a high-power density and low energy density. So, we can say that available any energy source is alone not sufficient to provide high energy density and high-power density at same time, in EV we need both qualities, they are not found in single energy source. In EV high energy density require for entire driving range and high-power density allows to rapid acceleration and hill climbing. Hence, we need to use combination different type of energy source for proper energy management (EMS) [8], combination of more than two energy source is called Hybrid energy management system (HEMS). In this paper we focus on combination battery and Supercapacitor. Power splitting between SC and battery is solution for improve system performance because very fast dynamic behavior of SC and their long-life cycle is help to reducing battery burden and improve lifetime of the battery. Kinetic energies are available during braking period which can be converted into electrical energy and supply back to energy storage system, thus independence of EV is increase.

Many types of research have been carried out with basic rule-based energy management for sizing the HESS. It helps to provide a common energy management strategies platform for comparison of all sizing strategies. The previous chapter covers basic rule-based EMS, which decomposes the energy requirement or power splitting with fixed frequency component or time constant τ of the low pass filter (LPF) of demand power for a given drive cycle. It mainly depends on acceleration function, which leads to low and medium frequency current components stress on the battery. Improved rule-based energy management is proposed in this chapter to overcome this problem. Improved rule-based energy management strategy provides more than one value of τ for decomposing power and energy for battery and ultracapacitor. This helps to reduce the current stress on the battery as optimized energy management compared to basic rule-based energy management. It also provides fast switching between battery and ultracapacitor converters which helps to reduce the transition period from one source to another.

Low and medium frequency current is drawn from energy sources as the vehicle accelerates; also, speed fluctuations are experienced in traffic. Filter-based EMS only applied one acceleration point for reference, responsible for the sudden rise in source current and considered a high-frequency current. And average speed correction variation takes nearly average current, which is considered in low-frequency current. Improved filter-based EMS considers three filter frequency as acceleration variation, which help to distinguish three levels of current spike or sudden current rise. Supercapacitor supplies or absorbs all current fluctuations without giving more current stress to the battery. Overall current fluctuations experienced by batteries can be reduced using proposed method and more regeneration and peak power supply are given by supercapacitors.

2. Different Type of Topology

Figure 1 shows different type of topology

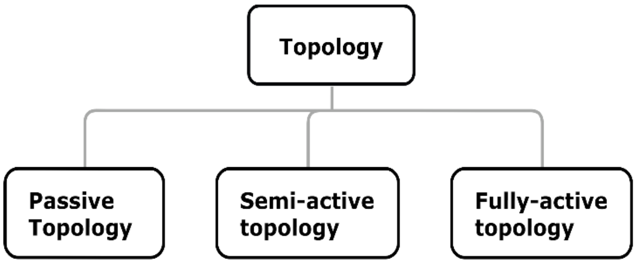

Fig. 1 - Different topology

2.1. Passive Topology

This type of topology is simplest structure with no control mechanism or control algorithm. This is shown in fig1. In this type of topology scheme charging and discharging control energy source achieved according to their internal resistance values. In this way SC cannot be effectively utilized. In this type of HESS, two energy sources that are battery and SC are directly connected in same DC link without any interfacing and without any power electronics converter (Fig.1).one of the main benefit of this type structure is less cost and less complexity. While design is quite simple and easy to implement, this type topology suffers from the lack of effective utilization of energy stored in supercapacitor, thus reducing its efficiency [9].

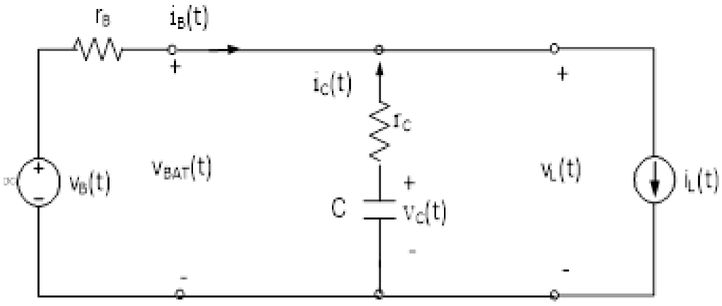

Fig. 2 - Passive topology

2.2. Semi Active Topology

According to connection of DC- DC converter Semi active topology can be classified into two types.

(1) DC- DC converter connected with battery and Supercapacitor is directly connected to the DC link.
(2) DC-DC converter connected with Supercapacitor and battery directly connected to the Dc link.

Detail discussion of both type of semi active topology given as under.

DC-DC Converter Connected with Battery and Supercapacitor Directly Connected to the DC Link

Circuit diagram of this type of topology is shown in fig 2.A, in this topology the DC/DC converter is used to connect the battery with DC link and SC is directly connected with DC link. In this structure, the power controlling is achieved by using controlling power supplied by the battery with a supervision of its voltage. However, disadvantage in this topology is that the voltage of the DC bus fluctuates in a wide range, which may become affected motor supply. The Supercapacitor is directly connected across the DC-link without any power electronic converter. This type of topology is used to improve the control of battery current irrespective of the fluctuation in load demand. Also, the appropriate size of battery pack can be reducing because battery voltage needs not to be same as DC link voltage. The linear charging and discharging characteristics of the SC causes sharp fluctuations in the DC-link voltage which causes reduction system performance. Thus, to maintain the dc-link voltage within limit, supercapacitor with higher capacity is required and hence the cost of the system is increased.

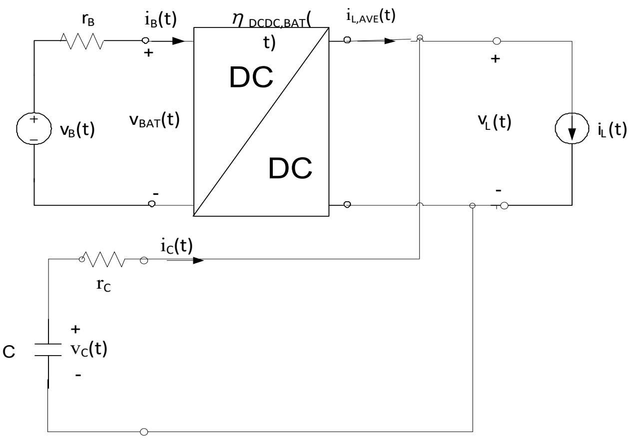

Fig. 2A - DC-DC converter connected with battery

DC-DC Converter Connected with Supercapacitor and Battery Directly Connected to the Dc Link

Circuit diagram of this type of topology is shown in Fig. 2.B In this type of topology the power electronics converter is used to connect the SC and battery is directly connected with the DC link. In this structure, the power splitting is achieved by controlling the current supplied by the supercapacitor with a supervision of its voltage. Since the SC is completely decoupled from the DC link, thus it can be effectively utilized. Fig.2. B. shows the semi-active structure where the SC interfaced with DC link by means of a bi-directional dc-dc converter while the battery is connected directly across the dc-link. Thus, a stable DC voltage can be obtained in this type of topology configuration. This topology also provides in the improvement of the efficiency of the SC [10].

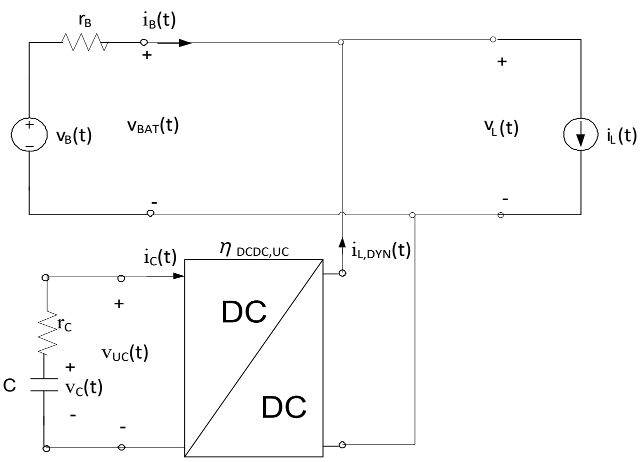

Fig. 2B - DC-DC converter connected with SC

2.3. Active Topology

Circuit diagram of active topology is shown in Fig-3, In this type of topology structure two bi directional DC/DC converters are used. Here both battery and SC can be controlled independently; therefore, it can be achieve best control performance. But in this type of control strategy cost is higher than that of the passive and semi- active topology because of the additional DC/DC converter cost. For better utilization of battery and SC in HESS, power electronic converters are usually employed for interfacing them with the DC bus. The control of these two energy sources enhances the system performance. It is also expected to considerable improvement in the life cycle of the battery. Power losses are more in this type of topology because of involvement of more power electronics devices [11].

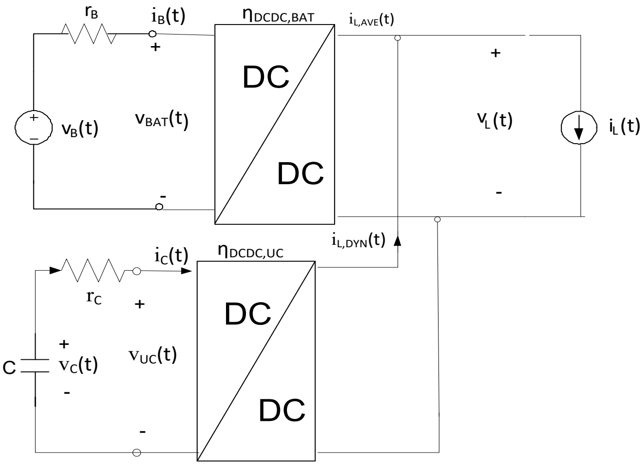

Fig. 3 - Fully Active topology

3. Methodology

The proposed method of Hybrid energy management system (HEMS) shown in fig. 4. in block diagram form, It consist of battery, supercapacitor, two DC-DC bidirectional converter, PMDC motor and chopper for motor speed control. Here battery and supercapacitor connected with same DC link through DC-DC converter. Here bidirectional DC-DC converter is used for power flow in either direction i.e., source to load and load to source. When power flow from source to load converter increases output voltage i.e., boost operation and during braking period power flow from load to source converter decreases its output voltage i.e., buck operation [12]. One bidirectional converter is used between DC link and PMDC motor for speed control of motor. In many electrical applications PMDC motor is used because its speed torque characteristics are superior to AC motor. Unlike DC shunt motor PMDC motor is free from interaction between main magnetic field and armature magnetic field, so it can develop high momentary starting and acceleration torque. This makes PMDC motor suitable and acceleration torque. This makes PMDC motor suitable in application required high starting torque. In this work PWM method is used for motor speed control [13].

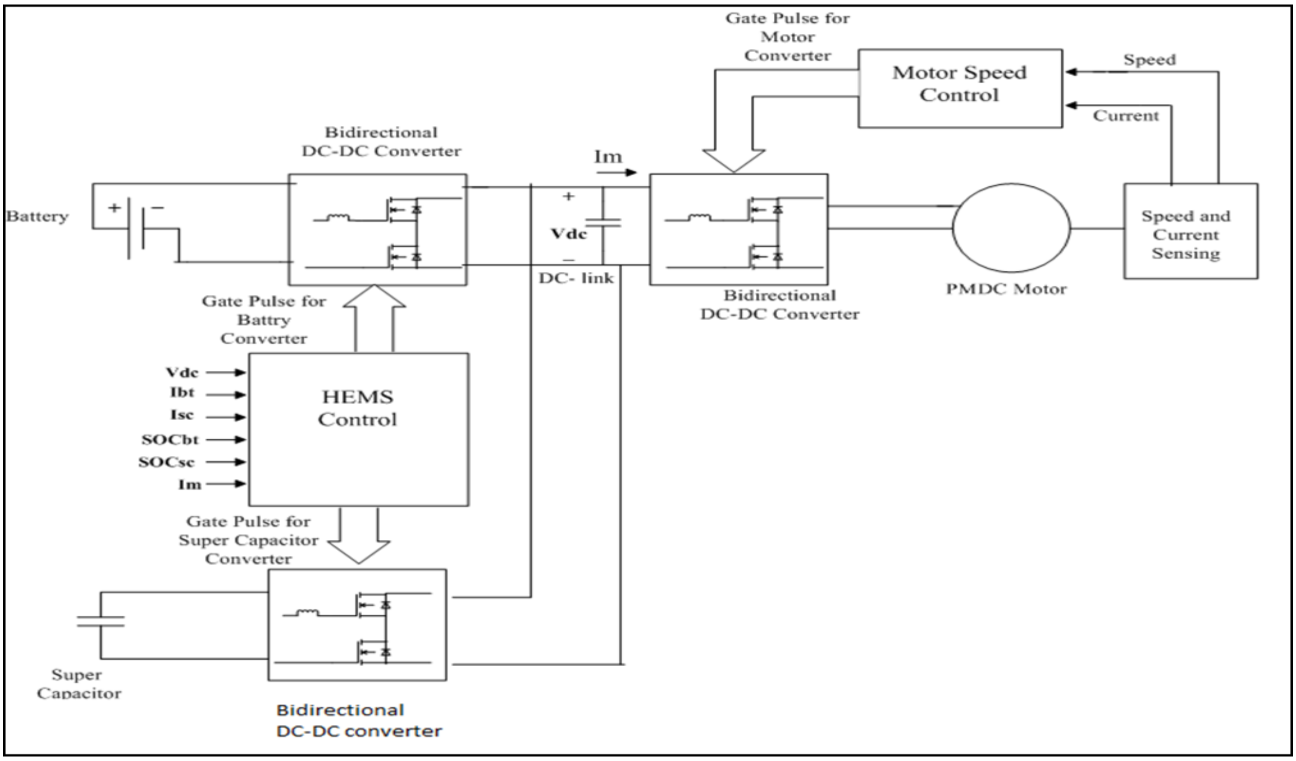

Fig. 4 - Block Diagram of Proposed HEMS system

4. MATLAB Simulation of Battery and Supercapacitor Hybrid System

Simulation of Battery and Supercapacitor Hybrid energy management system (HEMS) is done in MATLAB/SIMULINK 2016 version. To maintain DC link voltage 42 V constant, 24 V. Battery and 24V supercapacitor is interfaced to DC link through bidirectional DC-DC converter. PMDC motor is connected to DC link through bidirectional converter. Closed loop PWM method is used for motor speed control.

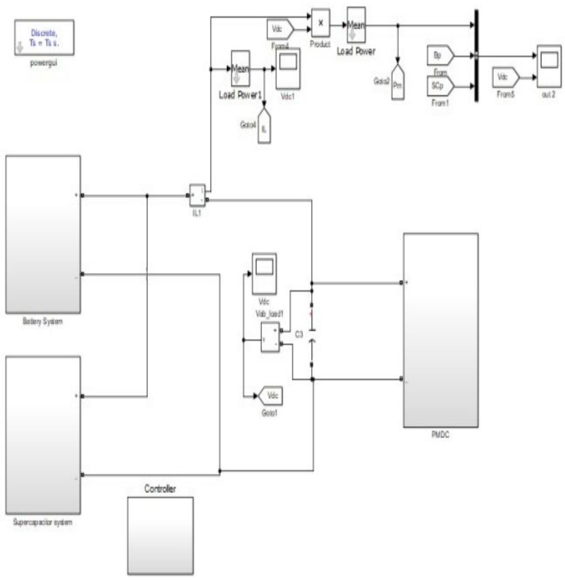

Fig. 5 - Matlab Simulation of Battery and Supercapacitor Hybrid System

Battery and Supercapacitor specification is given below table 1 and 2.

Table 1- Battery Specification

Battery Type	Nickel- Metal - Hydride
Nominal Voltage (V)	24
Rated Capacity (Ah)	400
Initial State of Charge (%)	80

Table 2 - Supercapacitor specification

Rated capacitance (F)	30
Rated Voltage (V)	26
Initial Voltage (V)	24

4. 1 DC-DC Converter

Bidirectional DC-DC converter is used to interface battery and Supercapacitor with DC link. Converter transfers power from source to load and load to source.

Fig. 6 shows battery and Dc-Dc converter system. Switching pulses (S1 and S2) is given from HEMS control. When Q2 is ON, converter acts as a boost converter and transfer power from battery to DC link. When Q1 is ON, converter acts as a buck mode and transfer power from DC link to battery (Charging of battery). For controlling converter and generate switch pulse (S1 and S2) PI controller with hysteresis current controller is used. Actual DC link voltage (Vdc) is compared with 42 V constant DC bus voltage and generated error is given to PI controller. Output of PI controller and battery current is compared and given to Hysteresis current controller. Based on values of comparison Hysteresis current controller generate switching pulse S1 and S2.

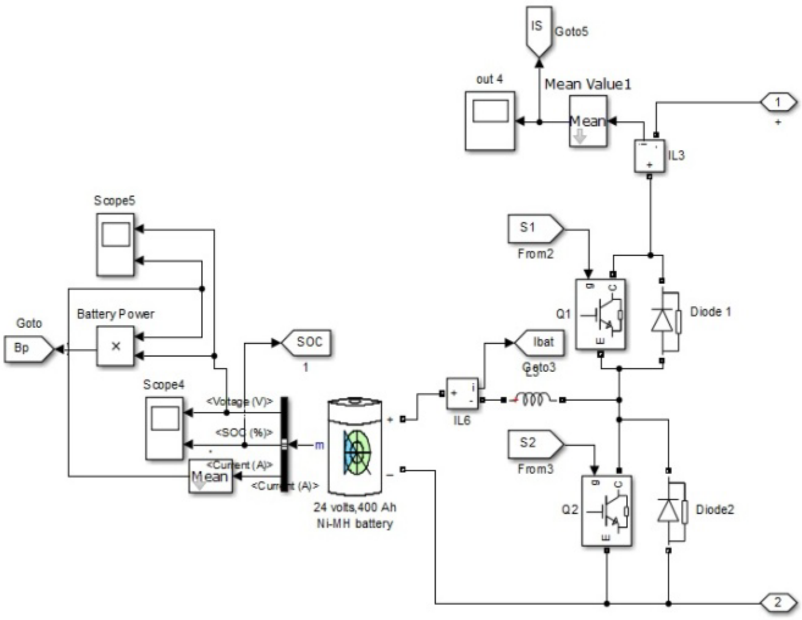

Fig. 6 - Battery and DC-DC converter system

Fig. 7 shows supercapacitor and DC-DC converter system. Switching Pulse S3 and S4 given from HEMS control. When Q4 is ON, converter acts as boost converter and transfer power from SC to DC link. When Q3 is ON, converter acts as a buck mode and transfer power from DC link to SC (Charging of SC). For controlling converter and generate switch pulse (S3 and S4) PI controller with hysteresis current controller is used. Actual DC link voltage (Vdc) is compared with 42 V constant DC bus voltage and generated error is given to PI controller. Output of PI controller is given to saturation to limit oscillation and produced PI output within limit. Output of saturator and supercapacitor current is compared and given Hysteresis current controller. Based on values of comparison Hysteresis current controller generate switching pulse S3 and S4.

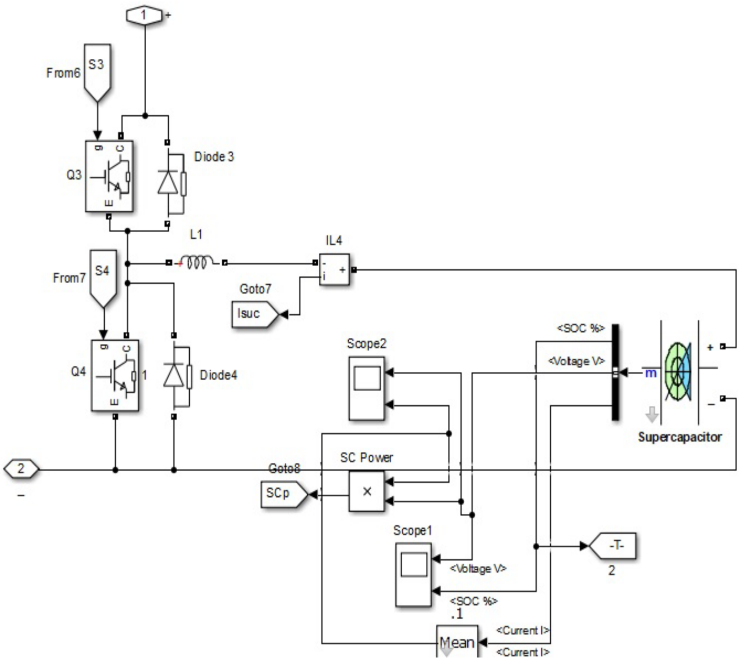

Fig. 7 - Supercapacitor and DC-DC converter system

4.2 PMDC Speed Control

Supply of PMDC motor is feed by Bidirectional DC- DC converter. Pulse width modulation (PWM) technique is used for motor speed control. PWM method for speed control of motor has advantage is that the amplitude of motor voltage is remain constant, so motor is always at rated supply. Also switching power loss in this method is very less because switch fully ON of fully OFF, thus high efficiency can be achieved.

Fig.7. shows PMDC motor with DC-DC converter. Switching pulse S1 and S2 is given by PWM controller which is shown in fig. 8. When switch S4 is ON converter operate in boost mode and switch S3 is ON converter operate in buck mode. In fig.8. Reference speed and actual speed of motor is compared. Reference speed is given like a drive cycle of vehicle i.e., different time instant different value of speed in RPM is given in this block. Comparison result is given to PI controller. PI controllers minimize error and output of PI controller is further compare with motor current (Im), comparison results are further given to PI controller and after minimizing error by PI controller output of PI controller is given to Saturation block. Saturation block output and carrier signal is compared and switch pulses S1 and S2 is generate. Here frequency of carrier wave is taken 10 KHz.

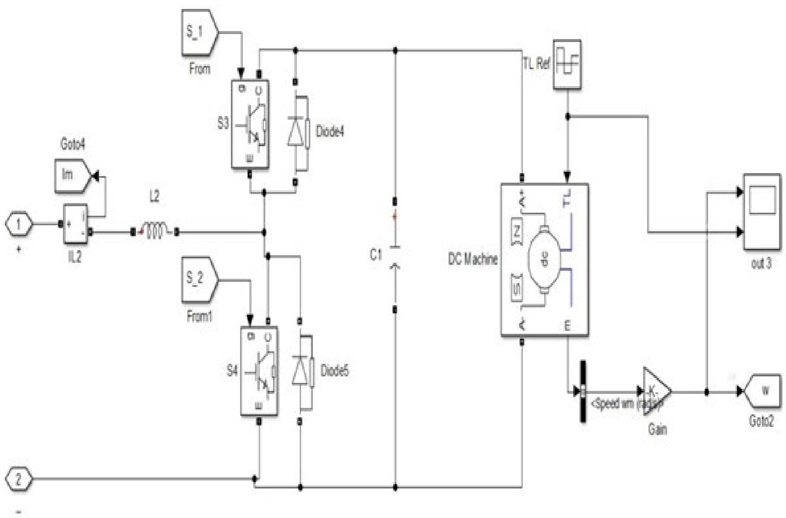

Fig. 8 - Motor and DC-DC converter system

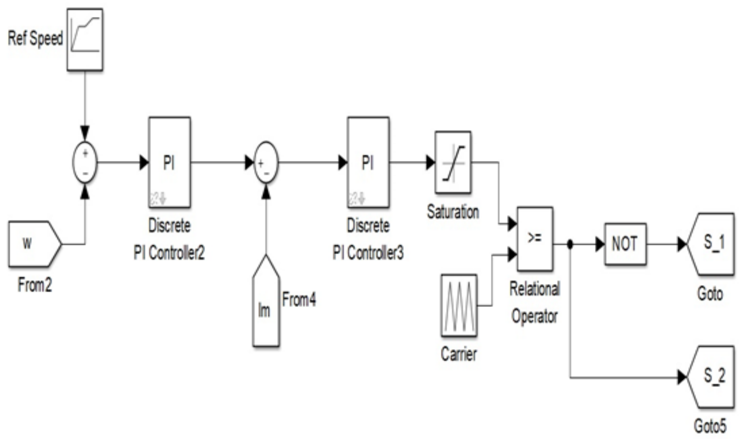

Fig. 9 - Motor PWM speed control

4. 3 Control Strategy

In EMS Energy conservation low is used for control strategy. It is assumed that there is no loss in system than total load power is equal to source power. I.e. load power is equal to battery power plus supercapacitor power.

$$Pload = Pbt + Psc \quad (1)$$

Different operation of motor is depending on load. If acceleration and load torque is positive, vehicle is in motoring mode. If deceleration or negative load toque, vehicle operates in braking mode. During motoring mode battery and SC supply power to the load. Very fast dynamic behaviour of SC, at the time of any transient condition SC react fast and gives necessary power demand in very less instant of time. Power splitting between SC and battery decide based on their SOCs [13,14]. Battery will provide power if SOCbt > 20%, Otherwise battery will not supply power and vehicle is stop. Similarly for supercapacitor will supply power if SOCsc > 20%. During braking period SC react fast with system and charge from load power. If SOCsc >95 % SC cannot charge. Otherwise, Supercapacitor become overcharge and reduces their life and efficiency. Similarly, battery will not charge if SOCbt > 95%. Otherwise, battery become overcharge and life and efficiency of battery become reduced.

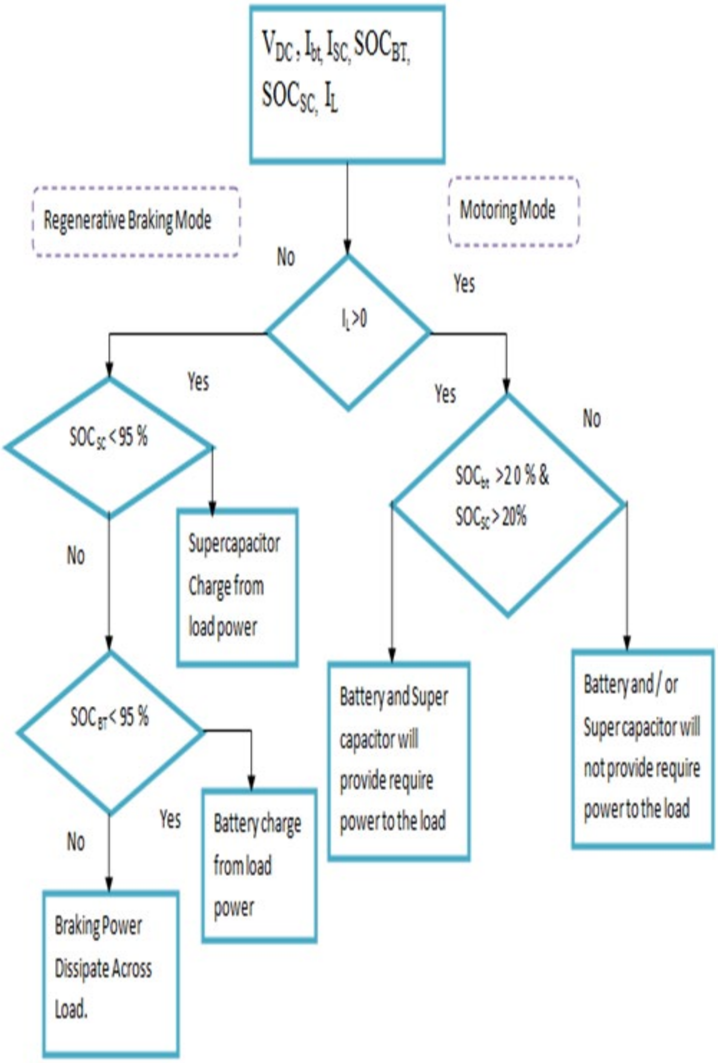

Fig. 10 - Flow chart of control strategy

5. Matlab Simulation Results and Interpretation

To verify control of the proposed method, a simulation model was developed in MATLAB/SIMULINK software. Simulation parameter and simulation circuit are also given in previous section.

Vehicle is passed by three phases namely acceleration phase, constant speed phase and deceleration phase [15-17]. Behaviour of battery and supercapacitor clearly analyse by wave form. At time t= 0 vehicle start accelerating. During t=0 to t=1second load torque is positive it is called acceleration phase. During this phase motor start taking power from source. Vehicle start from 0 rpm speed and reaches speed 600 RPM at 1 sec. At initially vehicle takes high power from source in very short time interval, from the wave from we can observe that at stating instant SC react very quickly and provide high power requirement in very short time interval and battery power is gradually increases, after transient period load power demand is gradually increases which supply by battery and supercapacitor power is nearly constant (Fig.13). From the load current wave form (Fig.11) it clear that during acceleration phase load current is positive which is indicate motoring mode of operation. During t= 0 to t= 1 sec. Load current increases. Battery SOC and Battery voltage wave form also shown in fig 14. At t= 0 battery become fully charge. Approx. battery initial voltage is 26.1V and initial SOC is 79.16 % during acceleration phase Battery Voltage and SOC start decreasing and end of the acceleration phase (at t= 1sec) battery voltage become 26.08V and battery SOC is 79.159%. SC voltage and SOC wave form is also shown in fig.15. At t=0 SC charge at 24V and initial SOC is 92.2 % , During acceleration phase SC voltage and SOC start decreasing fast as compare to battery and at the end of the phase SC voltage is 23.7V (approx) and SOC is 91.2% (approx.).

During t = 1 sec to t= 1.5 sec load power is constant, and speed become constant at 600 RPM. This phase is called constant speed phase in this phase load torque and load current constant and positive (Fig. 11 and Fig. 12). Load takes power from the source from the power comparison wave form (Fig.13) required load power demand supply by battery and Supercapacitor power become start decreasing and reaches to zero during constant speed phase. Hence during transient condition Supercapacitor will supply required load and during constant speed condition battery will supply required load power.

At time t = 1.5 sec load torque become negative till t = 3 sec. at t = 2 sec. speed become reduces to 250 RPM and goes to less than 600 RPM because of deceleration of vehicle. So at t= 1.5 sec to t =3 sec is called deceleration phase or braking period. At t= 1.5 sec load power become negative till 3 sec. from the fig.13. At t= 1.5 supercapacitor power become quickly goes to positive value to negative value. Hence supercapacitor absorbs power surges without affecting battery. It is also seen that at t = 1.5 sec. battery power start decreasing gradually and approx. t = 1.8 sec. it become negative. Negative power of battery and supercapacitor indicates charging of battery and supercapacitor, during this phase load current is also become negative (Fig.11.). This period is also called regenerative braking period because load gives power back to source. During this phase battery voltage goes from 26.08V to 26.105V(approx) and SOC goes from 79.158% to 79.1585% (fig.14) . At t= 1.5 sec SC voltage suddenly goes from 23.7V to 26V and finally reaches to 24V at the end of the phase and supercapacitor SOC increases from 91.2% to 92.4 %. after t= 3sec load torque and load current become positive and again motoring mode start and battery and supercapacitor start giving power to the load.

During all the three phases DC link voltage become maintain constant 42V, however there are some peaks during quick transition of the load power.

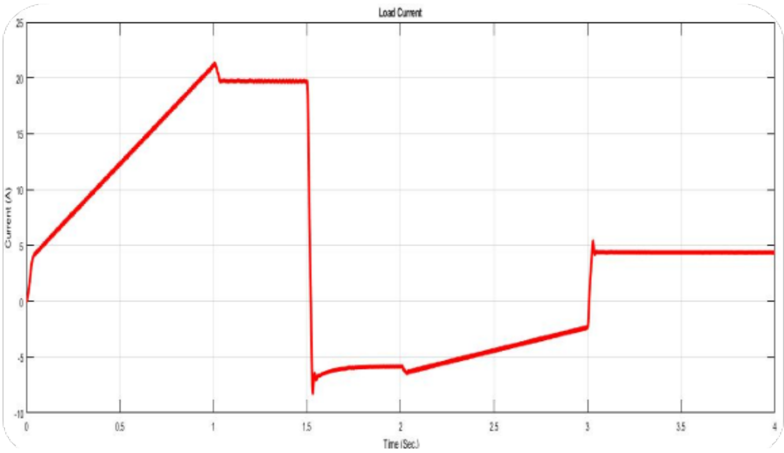

Fig. 11 - Load current waveform

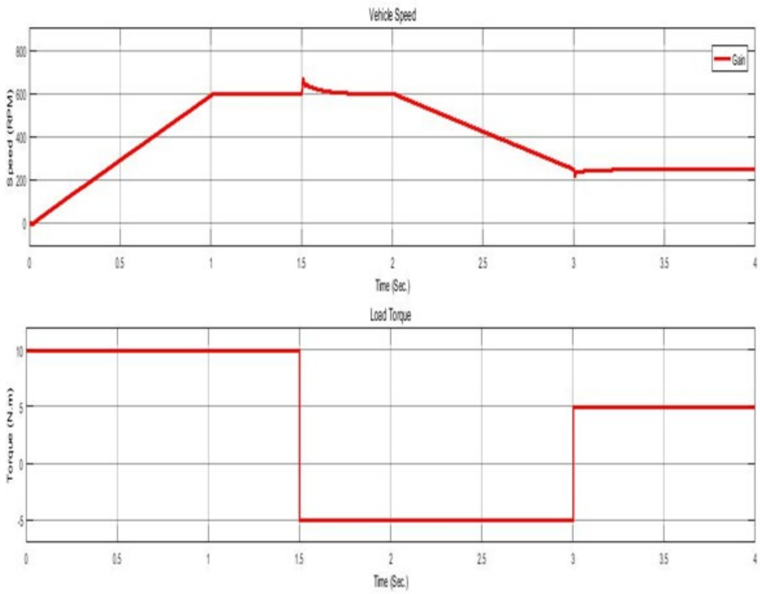

Fig. 12 - Speed and load torque waveform

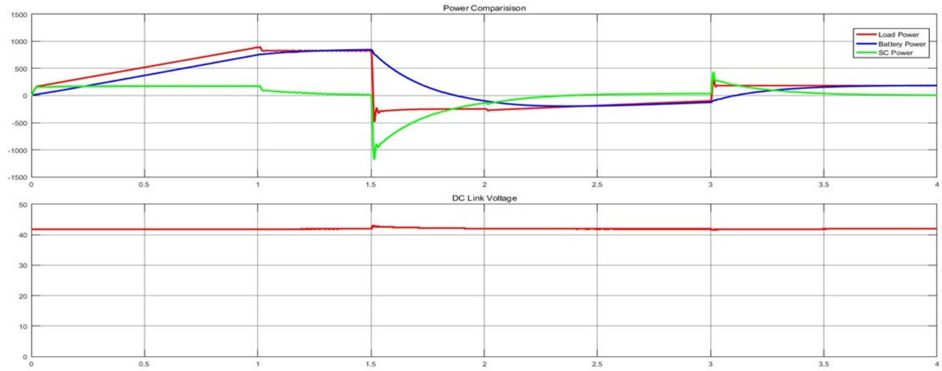

Fig. 13 - Power comparison wave form

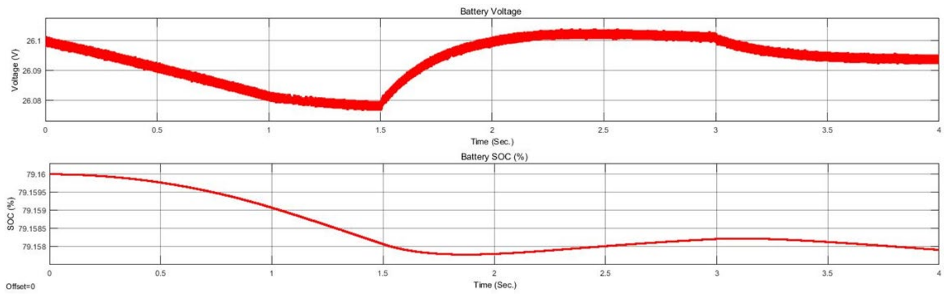

Fig. 14 - Battery voltage and battery SOC waveform

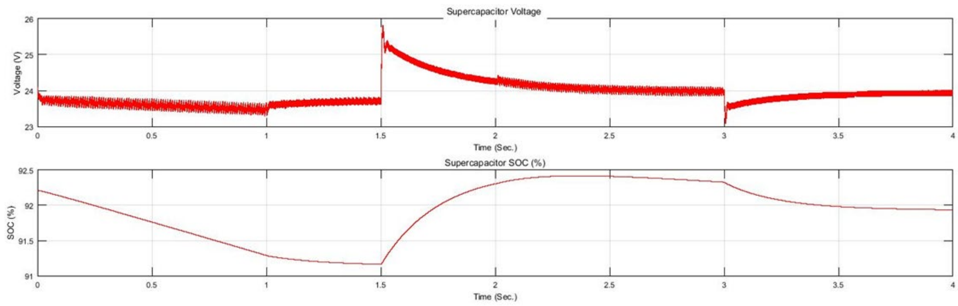

Fig. 15 - Supercapacitor voltage and SOC wave form

6. Hardware Implementation

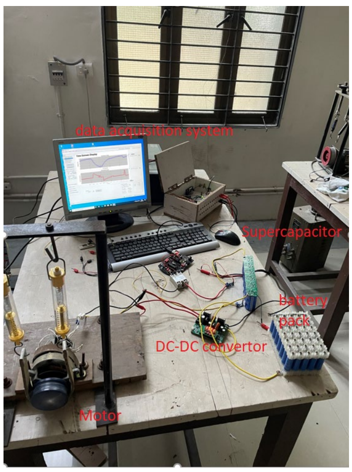

Fig. 16 - Small scale hardware implementation of HESS

Figure 16 shows the hardware Implementation of HESS with the 150-Watt universal motor. The system comprises of Battery of 24 V and an ultracapacitor of 16 V. The DC to DC converter for the battery will boost the voltage from 24 to 38 V and the DC to DC converter for the ultracapacitor will boost the voltage from 16 V to 38 V. The motor rating is of 150 W.

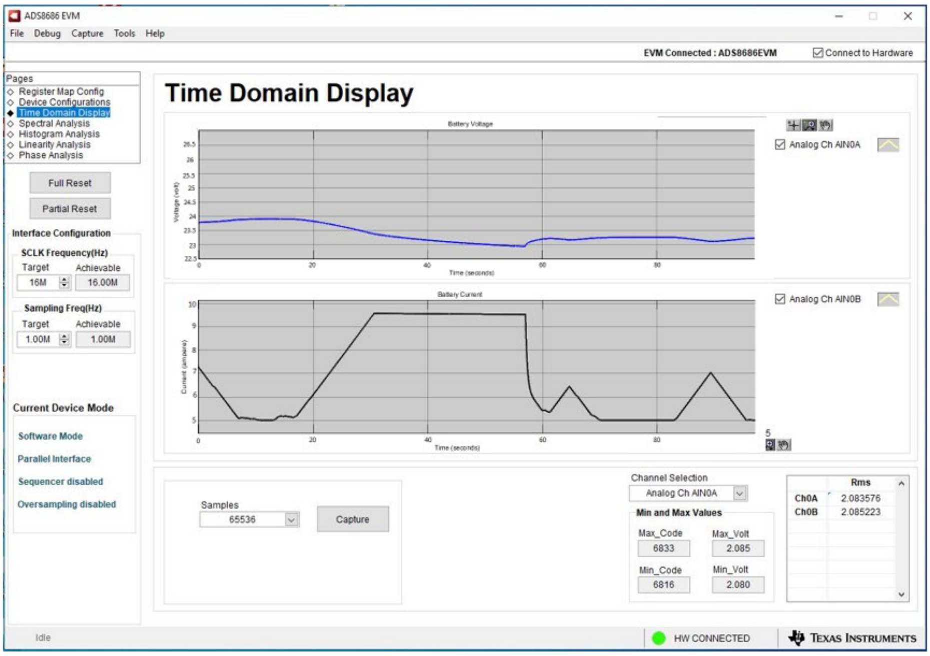

Fig. 17 - Voltage and current waveforms of battery pack

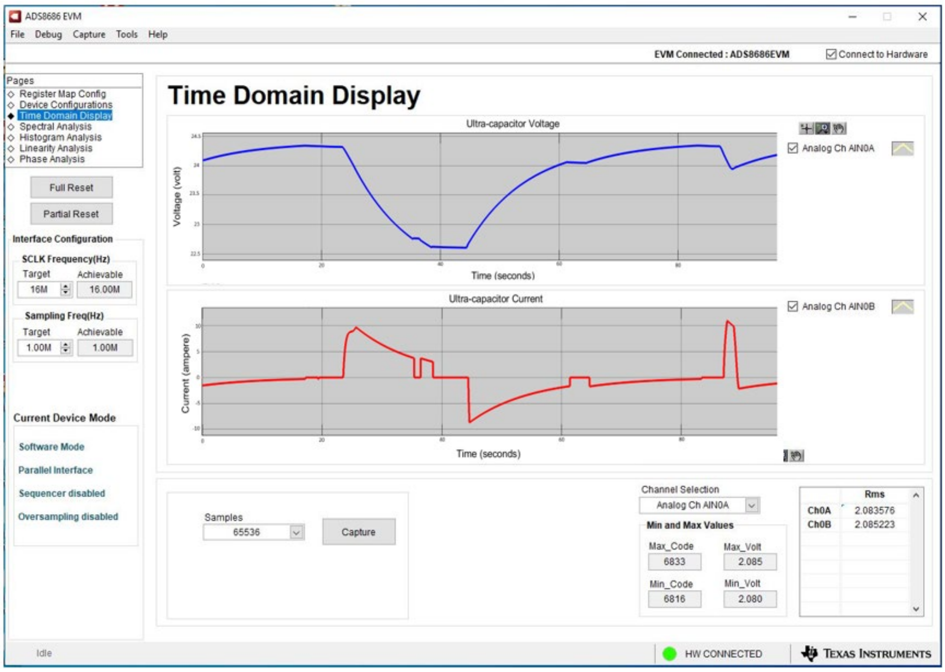

Fig. 18 - Voltage and current waveforms of ultracapacitor

Figure 17 and figure 18 show the voltage and current waveform of the battery and ultracapacitor, respectively. These waveforms are 50-60 second portions of the complete drive cycle. Drive cycle duration is much larger than the DSO time frame window, so the voltage and the current reading are taken in lab-developed computer-based DSO. This lab-based DSO is developed with Texas Instruments Chip ADS8686EVM with ten channel input and data logging with a continuous sampling DSO time frame window.

This low-scale lab setup is developed to demonstrate the energy-sharing capabilities of li-ion battery and ultracapacitor in conjunction with DC-DC converters. A pre-programmed speed profile is taken for estimating power requirements. Power-sharing between battery and ultracapacitor is also done by controlling DC-DC convertors with firing pulses as par required power which was pre-calculated from speed profile data. Switching of source for supplying power like battery supplies the power or ultracapacitor will have decided by improved filter-based EMS to demonstrate the effectiveness of the newly developed EMS scheme.

7. Conclusion

This work is mainly focused Hybrid energy management system (HEMS) consisting of battery and supercapacitor for electric vehicle. Objective of this work is that increase lifetime of battery by integration of supercapacitor with battery. During transitions of the load power, Supercapacitor quickly respond to the system by providing or absorbing power peaks. Thus, power stress of the battery is reducing, and lifetime of battery become increases. Other objective is that increase independence of electric vehicle recovering energy during phase of decelerations or regenerative braking period. Other advantage is requirements of high rated batteries are avoided. Less peak output power is required which is reduces bulkiness and cost of the battery. Small scale hardware implementation is developed to demonstrate prefix drive cycle as input and power sharing between battery and supercapacitor as total power demanded as output with newly developed EMS.

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