International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 20 (2017) pp. 10197-10204
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Comparative Performance Investigation of Battery and Ultracapacitor for Electric Vehicle Applications

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Abstract

Improving performance of Electric Vehicles (EV) has been trends of automobile market in recent time. The key to this improvement is the design of efficient energy management scheme for Hybrid Energy Storage System (HESS). The HESS may be form by taking Battery and Ultracapacitor (UC) together or Fuel Cell and Ultracapacitor together or all the three together. This paper investigates the performance of different types of rechargeable batteries such as Lithium Ion, Lead Acid, Nickel Cadmium and Nickel Metal Hydride types to be connected with Ultracapacitor to form our HESS. These different combinations are connected and applied in MATLAB/SIMULINK to check the performance of each combination to find out the optimal efficiency of battery and efficient energy management scheme when battery is connected with Ultracapacitor for electric vehicle applications. The selection of best battery and scheme is based on the performance analysis of the parameters like operating temperature, reliability, current and voltage of the battery, state of charge of battery and rate of charge/discharge. This investigation will lead to easy selection of type of battery in HESS which will also improve the life of the battery when connected with Ultracapacitor otherwise battery life is short when peak loads are handled.

Keywords: Ultracapacitor; Supercapacitor; Battery, Electric Vehicle.

INTRODUCTION

A. Battery:

The recent necessity of green world has led to green energy to check the Pollution problems and their environmental effects as long term goal. At present the automobile market is dominant with vehicles running on conventional fuel which pollutes the environment. Nowadays, research is more focused on minimization of the exhaust of carbon dioxide [1-2]. Hybrid Electric vehicle usage is a promising solution considering the environmental and its economic benefits. The batteries used by electric vehicles are easily damaged by extra high peak power and rapid charging/discharging cycles that are very much influenced by the repetitive actions of the acceleration and deceleration of the electric vehicles. This problem of peak current of battery can be solved if battery and Ultracapacitor combination is used as power supply where Ultracapacitor will act as buffer to fill the large magnitude of power and fluctuation demanded by load variation [3]. While designing an energy storage system for electric vehicle, its design, weight and volume must be considered for the vehicle to reach maximum acceleration and high performance to deliver enough power (kWh) for EV. This is dependent on the type of driveline the vehicle is equipping [4].

Rechargeable battery or storage battery or secondary cell or accumulator is kind of electric battery that can be charged and discharged through a load. It is recharged many times as unlike disposable battery and discarded after use. It is an electrochemical cell and also termed as accumulator as it accumulates and stores energy through a redox reaction. Rechargeable batteries are available in many forms of sizes and shapes (button cells to megawatt systems). The several types of electrode materials and electrolytes are combined in different ways to form different types of rechargeable batteries such Lead–Acid (Pb-Ac), Nickel–Cadmium (Ni-Cd), Nickel–Metal Hydride (Ni-MH), Lithium-Ion (Li-Ion) etc. These batteries initially are costlier than disposable batteries, but have the total cost of ownership and environmental impact is lower, as it easily recharges many times before they replaced. Disposable batteries may also be available in the same rating as the rechargeable batteries and can be used interchangeably sometimes. The positive active material is oxidized during charging which produces electrons while negative material is reduced by consuming electrons. The electron which moves constitutes the current flow in external circuit. The electrolyte will serve as a buffer for the ions to flow between the electrodes internally, as like in nickel-cadmium and lithium-ion cells whereas an active participant in the electrochemical reaction as in lead–acid cells.

A charger is used to supply energy to rechargeable battery through AC main electric supply which is to be maintained at higher potential so that current is forced to flow from charger towards the battery limiting to maximum current otherwise the battery will explode because of excessive input current rate. Since the input current to charge an electrochemical battery is limited, the charging time is very high to fully recharge a battery to charge without damaging. Recently new quick chargers have come with cooling fans to check the heating cells but still take hours to fully recharge a battery.

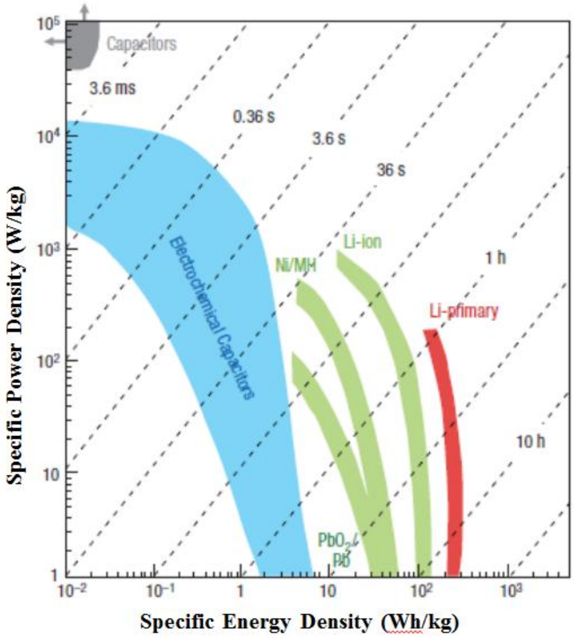


Figure 1: Performance Characteristics of various electrical energy storage devices [5]

B. Ultracapacitor:

Another energy storage device that has become popular because of its high power and high energy density is Ultracapacitor. Ultracapacitor uses the same principle as the conventional capacitor but has the ability to store more energy and release more power quickly than electrochemical battery. Ultracapacitor is also known by other names like, Supercapacitor, Electrochemical Capacitor or Electrochemical Double Layer Capacitor (EDLC). It stores electric charge electrostatically using reversible adsorption of ions of the electrolyte on the interface of the materials that are stable electrochemically with high accessible specific surface area. Polarization takes place at the electrode-electrolyte interface for charge separation producing Helmholtz proposed in 1853 as double layer capacitance.

This particular capacitance model was refined later by Gouy and Chapman, and Stern and Geary, who went on to suggest the presence of a diffuse layer due to the accumulation of ions close to the surface of electrode in the electrolyte [5]. The charge storage is electrostatic at EDLC electrodes so there is no faradic (redox) reaction. An Ultracapacitor electrode is considered as blocking electrode from the point of electrochemical view. The limitation caused by electrochemical kinetics through a polarizing resistance as what is the case in battery is not there in EDLC which makes the storage of charge on the surface mechanism very fast uptake and giving better power delivery performance. The absence of redox reactions eliminates the swelling in the active material shown in batteries during charging/discharging cycles so EDLC can go on millions of cycles while batteries can sustain a few thousands.

The solvent of the battery contributes to charge storage mechanism at solid electrolyte interphase if graphite anodes are used or very high potential cathodes. As a result of surface charge storage mechanism, there is limitation in energy density in EDLC which is why research is more focused on their energy density and increasing temperature limits in the ranges where batteries cannot work [6]. Figure 1 shows the Ragone plot of power density against energy density for the most important energy storage systems [7].

MODELING OF BATTERY, ULTRACAPACITOR AND HESS

A. Battery Modeling:

The simplest equivalent model of a battery consist of an independent voltage source in series internal resistance or which can be considered as Thevenin circuit is shown in figure 2. This model does not account the varying internal impedance and state of charge.

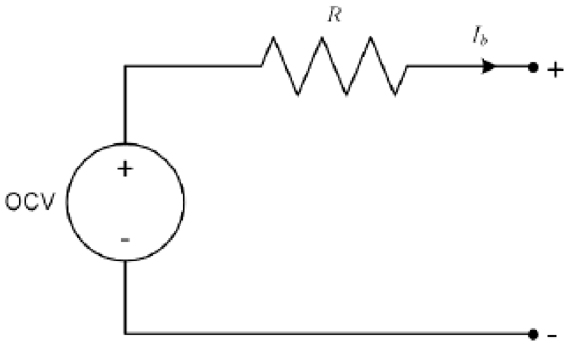


Figure 2: Equivalent Circuit of Battery

Different types of battery models are available commercially but the batteries to be investigated are considered which accounts into its state of charge with discharging and charging effect. The model which is used here is the modified Shepherd model which considers the dynamics of voltage during the variation of current with accounting the open circuit voltage that is taken as function of state of charge (SOC) [8]. Typical discharge plot of the battery is shown in figure 3 which describes the nature of discharging of battery to indicate the SOC. The block diagram representation of the charging model and discharging model used in the investigation of batteries is shown in figure 4 which can give information of the terminal voltage as per the state of charge of the battery.

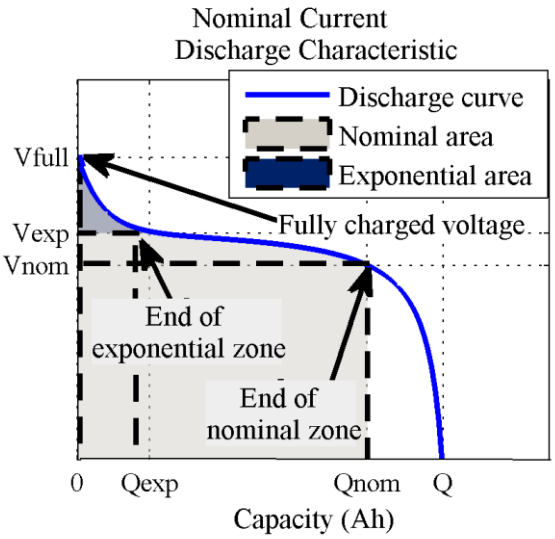


Figure 3: Typical Discharge Plot of Battery [8]

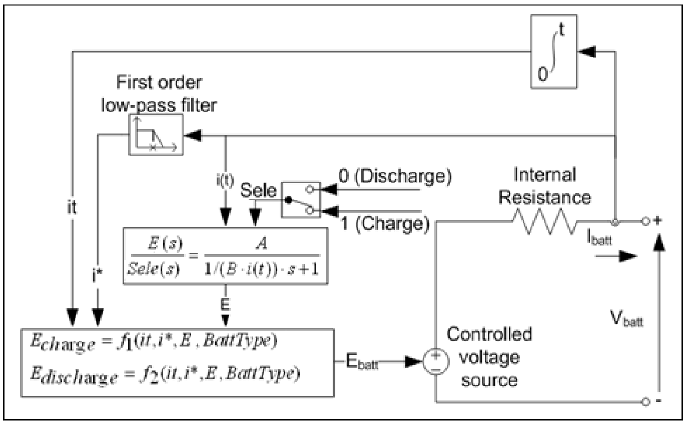


Figure 4: Charge/Discharge Model of Battery

Typical expressions used for different types of batteries as per this model is given as follows:

The equation used by the Lead-Acid (Pb-Ac) battery type:

- Discharge Model (i* > 0):

$$f_1(it,i^*,i,E) = E_o - K.\frac{Q}{Q-it}.i^* - K.\frac{Q}{Q-it}.it + Laplace^{-1}\left(\frac{E(s)}{Sele(s)}.0\right)$$

- Charge Model (i* < 0):

$$f_2(it,i^*,i,E) = E_o - K.\frac{Q}{it+0.1\,Q}.i^* - K.\frac{Q}{Q-it}.it + Laplace^{-1}\left(\frac{E(s)}{Sele(s)}.\frac{1}{s}\right)$$

The equation used by the Lithium-Ion (Li-Ion) battery type:

- Discharge Model (i* > 0):

$$f_1(it,i^*,i) = E_o - K.\frac{Q}{Q-it}.i^* - K.\frac{Q}{Q-it}.it + A.E(-B.it)$$

- Charge Model (i* < 0):

$$f_2(it,i^*,i) = E_o - K.\frac{Q}{it+0.1\,Q}.i^* - K.\frac{Q}{Q-it}.it + A.E(-B.it)$$

The equation used by the Nickel-Cadmium (Ni-Cd) and Nickel-Metal-Hydride Ni-MH) battery types:

- Discharge Model (i* > 0):

$$f_1(it,i^*,i,E) = E_o - K.\frac{Q}{Q-it}.i^* - K.\frac{Q}{Q-it}.it + Laplace^{-1}\left(\frac{E(s)}{Sele(s)}.0\right)$$

- Charge Model (i* < 0):

$$f_2(it,i^*,i,E) = E_o - K.\frac{Q}{|it|+0.1\,Q}.i^* - K.\frac{Q}{Q-it}.it + Laplace^{-1}\left(\frac{E(s)}{Sele(s)}.\frac{1}{s}\right)$$

Where the terminologies used in equations are:

E_{Batt} is the nonlinear voltage, in V; E_0 is the constant voltage, in V; E(s) is the exponential zone dynamics, in V; Sele(s) represents battery mode where Sele(s) = 0, for battery discharge, and Sele(s) = 1 for battery charging; K is the polarization constant, in Ah^{-1}; i* is the low frequency current dynamics, in A; i is the battery current, in A; |it| is extracted capacity, in Ah; Q is the maximum battery capacity, in Ah; A is the exponential voltage, in V; B is the exponential capacity, in Ah^{-1}.

B. Ultracapacitor Modeling:

The simple model of Ultracapacitor is quite similar to an equivalent model of battery as both are used for storing energy is shown in figure 5. It has an equivalent series resistance (R_S) in series with a parallel combination of capacitance (C) and leakage resistance (R_P).

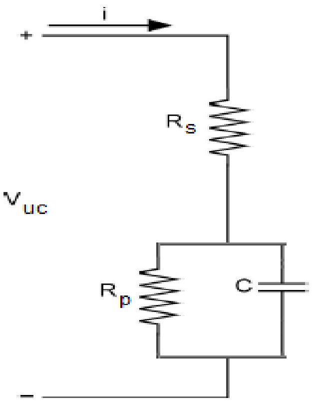


Figure 5: Equivalent Circuit of Ultracapacitor

The energy stored by the Ultracapacitor and calculation of capacitance uses the following equations which is are derived using the basic concept of electrostatic charge storage of conventional capacitor.

$$C_{UC} = \frac{Q}{V};\ C_{UC} = \varepsilon\frac{A}{D} = \varepsilon_o\varepsilon_r\frac{A}{D}\ \ \&\ \ E = \frac{1}{2}C_{UC}V^2$$

Where, C is the capacitance; Q is the charge; V is the voltage; ε is the permittivity; A is the area; D is the distance and E is the energy.

There are other models available which are first order linear type or non-linear model type. The equation for the presented model is as follows:

The voltage output of the Ultracapacitor is:

$$V_{UC} = V_C - I_{UC}R_S$$

The rate of change of capacitance voltage is:

$$\frac{dV_C}{dt} = -\left(\frac{I_{UC}}{C} + \frac{V_C}{CR_P}\right)$$

Where, V_{UC} is terminal voltage; I_{UC} is UC current; R_S is series resistance; V_C is capacitance voltage; C is capacitance; R_P is resistance in parallel.

C. Hybrid Energy Storage System Modeling:

The main aim of this investigation is to find the best and efficient hybridization of energy sources by combining Battery and Ultracapacitor. The energy sources are connected such that the Ultracapacitor complements the battery to deliver high peak load as when demanded by the load. The normal power demand is handled by the battery thereby keeping a check on the delivery of high power by battery thus the life cycle of the battery is controlled. The power sharing of the battery and Ultracapacitor is done using the Parallel Active Hybrid (PAH) model of HESS topology. In this topology, the battery and Ultracapacitor is connected in parallel along with one dc/dc converter in each path to be connected to the load and supply power whenever demanded forming a dc bus which allows power sharing efficiently [11-12]. The topology used is shown in figure 6 and power sharing is completed using the equations to provide power supply to the load from the Ultracapacitor and battery:

$$P_{UC} = P_{Battery} + P_{Load} - \text{Power from UC to Battery}$$

$$P_{Battery} = P_{UC} + P_{Load} + \text{Power from Battery to UC}$$

The above equations provide efficient power sharing scheme with the help of dc/dc converters connected each to the battery and Ultracapacitor in series. The current supplied by the Ultracapacitor is calculated using the equation:

$$I_{UC} = \frac{P_{UC}}{V_{UC}}$$

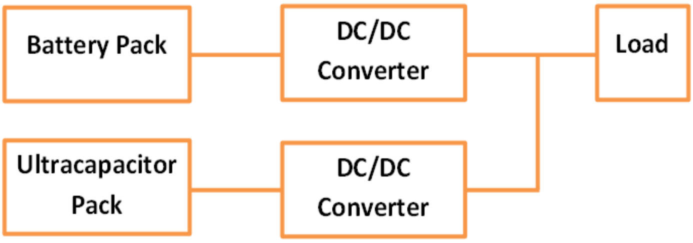


Figure 6: Parallel Active Hybrid Topology

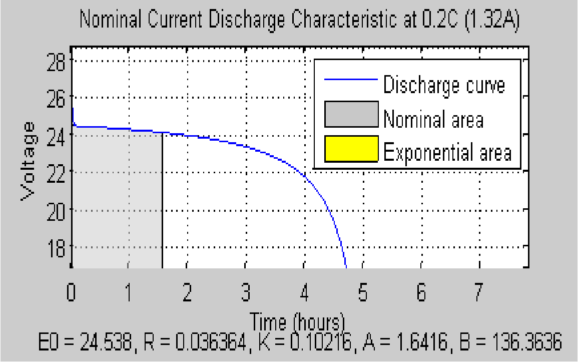
The Ultracapacitor considered assumes constant internal resistance during charging/discharging cycles without temperature effect on the electrolyte material where continuous current flows throughout life cycle.

SIMULATIONS RESULTS

The investigation of the battery is made by connecting different batteries with Ultracapacitor in the PAH topology one by one considering for the same ratings of battery. The simulation of this investigation is completed using battery and Supercapacitor model available in MATLAB/SIMULINK tool. The simulation is done with 24 V and 48 V for battery nominal voltage taking Lithium Ion, Lead Acid, Nickel Cadmium and Nickel Metal Hydride types available in MATLAB as per the given data in table 1 to obtain the discharge behaviour curve and plot showing the power shared by battery and Ultracapacitor to supply the power demand by the load. HESS is simulated for two cycles of varied load with time duration of 20 seconds simulation time and takes about one minute to give simulation result.

Table 1: Data of Battery and Ultracapacitor Specifications

Battery Properties			
Nominal Terminal Voltage (V)	**Nominal Energy Capacity (Ah)**	**Initial State of Charge (%)**	**Response Time (s)**
24	6.6	100	50
48	6.6	100	50
Ultracapacitors Properties			
Initial Voltage (V)	**Nominal Capacity (F)**	**Operating Temperature (°C)**	**Response Time (s)**
16	500	25	50



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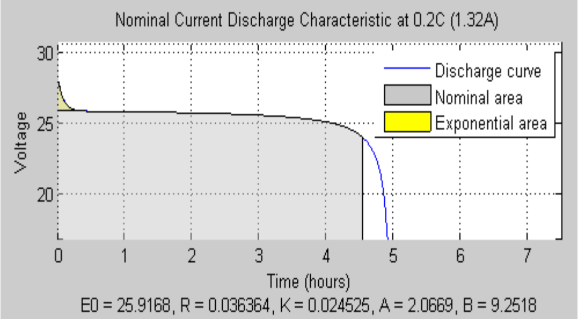

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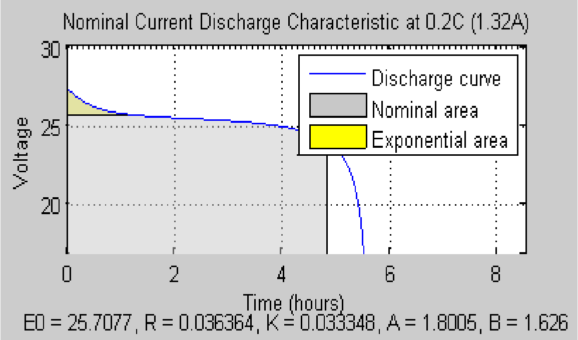

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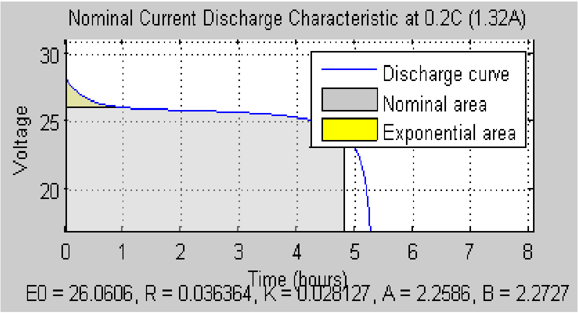

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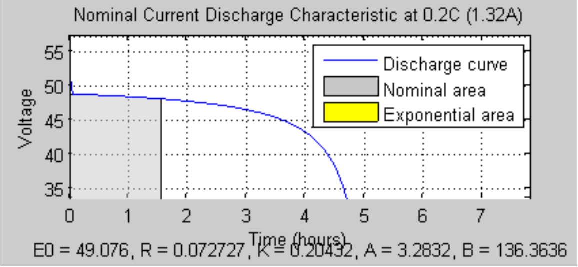

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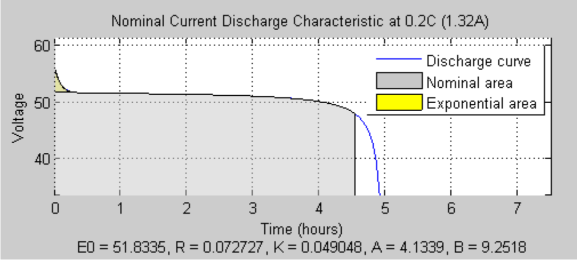

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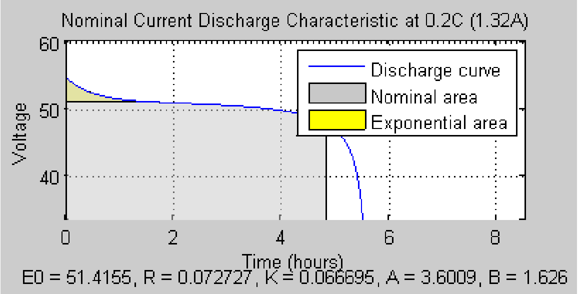

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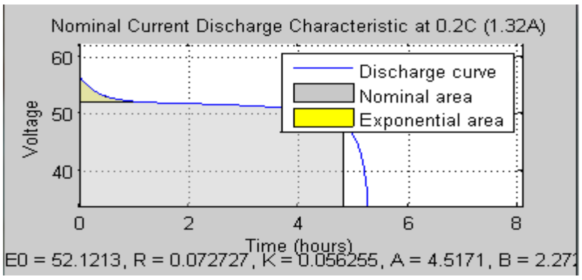
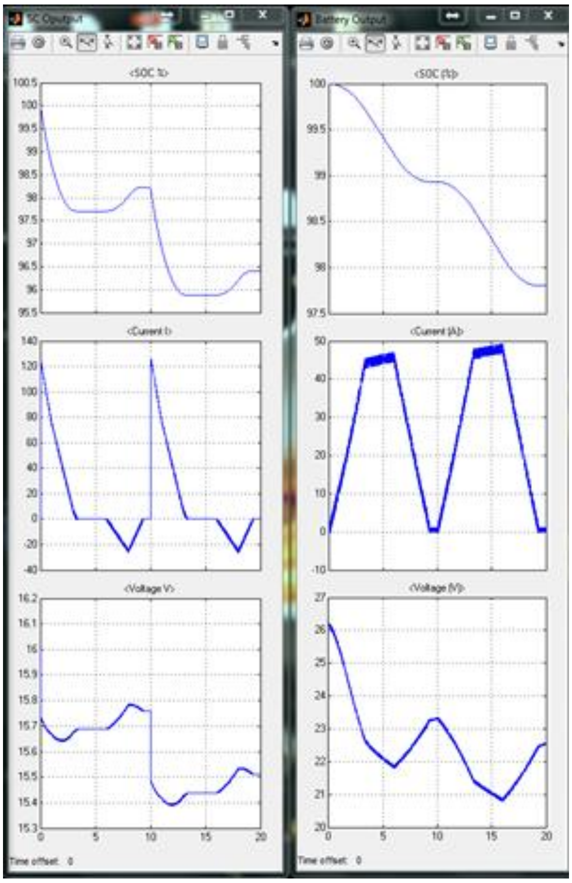


(h)

Figure 7: Discharge Characteristic of Batteries (a) Pb-Ac, 24V (b) Li-Ion, 24V (c) Ni-Cd, 24V (d) Ni-MH, 24V (e) Pb-Ac, 48V (f)Li-Ion, 48V (g) Ni-Cd, 48V (h) Ni-MH, 48V



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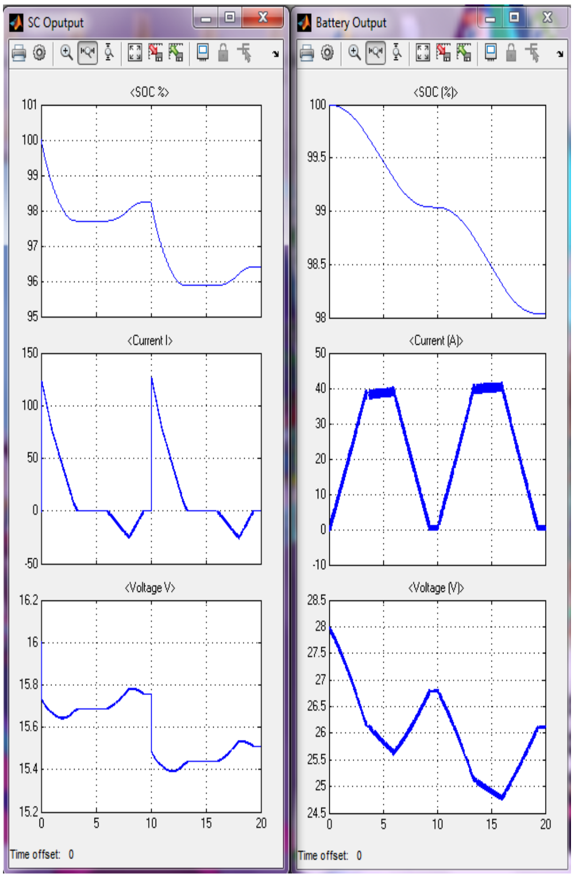

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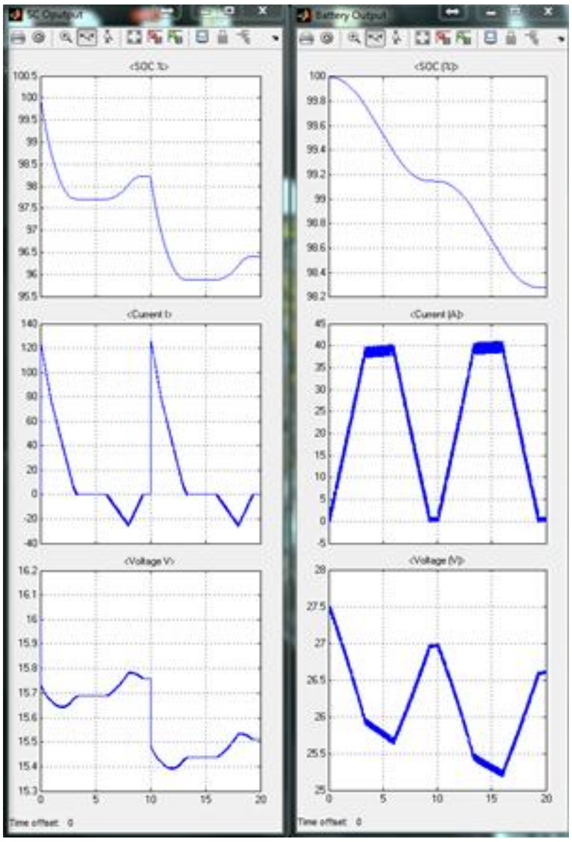

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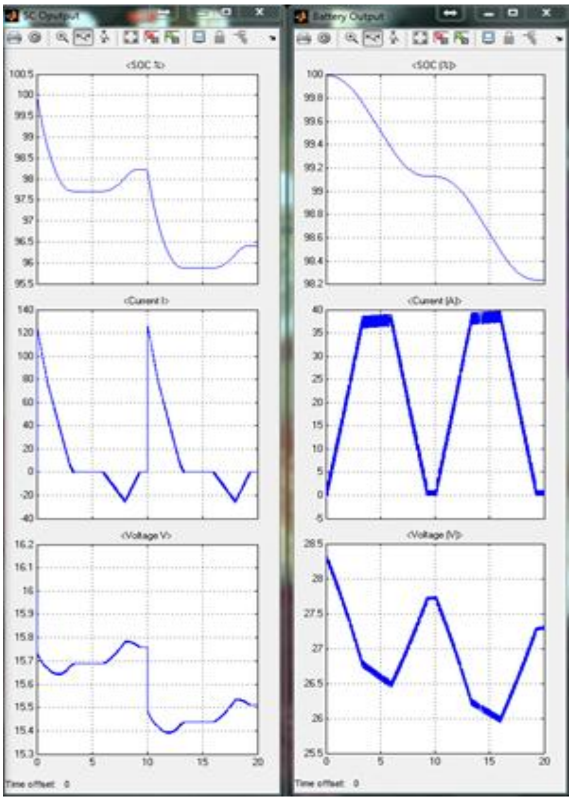

(d)

Figure 8: Load Sharing of Batteries and Ultracapacitor (a) Pb-Ac, 24V (b) Li-Ion, 24V (c) Ni-Cd, 24V (d) Ni-MH, 24V

The batteries performance are simulated as shown in figure 7, with nominal self-discharge current of 1.32A and also set the forced discharged current behaviour for 5A, 15A and 25A values to check the performance of each battery. The values of constant voltage (E_O), internal resistance (R), polarization constant (K), exponential voltage (A) of the corresponding batteries gets doubled as the nominal voltage of operation gets double while the exponential capacity (B), dependent on the type of battery, remains same irrespective of the operating voltage. As seen from the characteristics of discharge, Li-Ion and Ni-MH have larger area of section (nominal area) indicating better SOC performance as compared to other batteries. After the nominal area, the discharge will be rapid till complete discharge. Li-Ion, although it has been operated to discharge at 1.32A, its nominal discharge capability is 2.8696A meaning that it can deliver higher value of current (at peak power demand) which is required in electric vehicular applications [13-14]. So, the current handling performance for Li-Ion battery type can be considered better that Ni-NM battery type.

The output plot shown in figure 8, gives the result of simulation of HESS which shows the power sharing between battery and Ultracapacitor. The peak load during the transient is handled by the Ultracapacitor and then the normal continuous energy is supplied by the battery. Thereby, the complete discharge of battery is checked which in turn increases the life cycle of battery [15-16]. The terminal voltage for the Ni-MH battery type is at the highest than others followed by Li-Ion. The other type which is in competition is Ni-Cd, has mature technology and cost effective because of bulk production which is following both Li-Ion and Ni-MH type battery in performance. The cell voltage of Ni-Cd and Ni-MH type battery is almost one-third of the cell voltage of Li-Ion type battery. Self-discharge which occurs in all the batteries is highly dependent on temperature which determines the Shelf Life of battery; in here Li-Ion has the least self-discharge, making it better in temperature handling performance.

CONCLUSION

The energy supplied to the electric vehicle can be concluded as best solution with the hybrid energy storage system with better efficiency and better performance in depth of discharge of battery. The efficient power management scheme makes it possible to share power demand by load between battery and Ultracapacitor. As per the simulation results, Li-Ion and Ni-MH are the leading type of batteries that can be used in electric vehicular applications with high SOC, constant voltage and terminal voltage. When more delivery of current is required for high peak load, Li-Ion battery can be used in HESS for better power sharing performance. Besides these batteries, Ni-Cd can also be used in applications where cost is a concern but the efficiency is of less demand. The HESS technology is a new one and a lot of scope is there for research. Further research can be done using Fuel Cell, Photovoltaic system and Ultracapacitor combinations for hybrid power source for different high power applications.

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