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Analysis and modeling a cost effective and range reassurance hybrid energy storage system for electrical vehicle

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ABSTRACT

Electric Vehicles (EVs) represent one of the key technologies to reduce CO2 emissions; their effective potential in real world driving conditions strongly depends on the performance of their Energy Management System (EMS). Range anxiety is an obstacle to the acceptance of electric vehicles (EVs), caused by drivers uncertainty regarding their vehicle's state of charge (SOC) and the energy required to reach their destination. Another one of the shortcomings of Electric Vehicle technologies is the high cost of batteries. Any enhancement in such points will make EV's a well built competitor for IC engines. The material cost for the Zebra battery is much lower compared with lithium batteries. In addition the cycle life better than 1000 cycles in zebra battery. Supercapacitors are one of the major components which play vital role in energy storage area. It also reduces the stress to batteries. The Multiple sources are modeled and analyzed by connecting the supercapacitor in parallel with ZEBRA battery. The combination shown was much cost effectives and range reassurance with addition battery maximum power demand will be reduced and also the internal power losses get minimized. The model is done by MATLAB®/Simulink® environment. In the designed model, by applying various input velocity the performance was evaluate. The performance which studied from the Hybrid EVs model was summarized in term of SOC and range covered. The paper will act as stand by reference about the Hybrid EVs in the point of design as well as application oriented.

KEYWORDS: ZEBRA, SOC, Hybrid, MATLAB, Supercapacitor

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INTRODUCTION

In Asian Zone for past few years the rate of raise of electric cars are get escalated. The Fig 1 had shown the trend chart of the EVs sales.

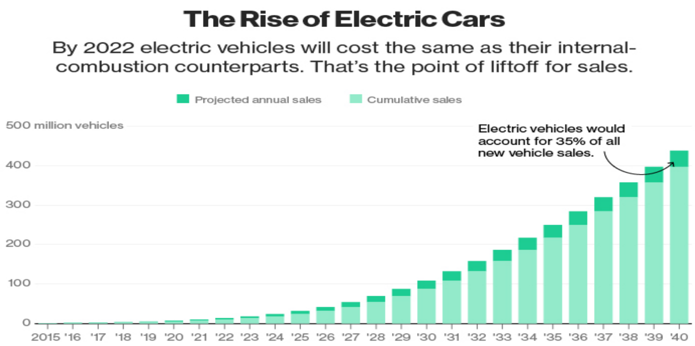

Fig. 1 The Rise of Electric Cars

With the increasing interest in electrically powered vehicles, there has been a great deal of attention paid to improving batteries and producing new types of batteries with higher energy density than lead acid. Additionally, there has been great interest in using peak power buffers to mitigate against the high battery current transients encountered during urban driving. Overall, the electric vehicle is more energy efficient, environmentally friendly, and cleaner than the vehicle that relies on fossil fuels, especially when smart grids have become omnipresent. By popularizing the electric vehicle, the environmental and economic costs of vehicles can be significantly reduced. Hence, the electric vehicle has attracted the attention of academia as well as industry in the recent decades. With the development of the electric vehicle, the techniques of charging piles- which are an essential component in the electric transportation system- have rapidly progressed as well.

Most of the automobile manufacturers around the world have paid a large amount of financial resource to the research of charging piles, since the charging technique is, to some extent, key to the success of the electric vehicle. The rest of this paper is organized as follows. In Section II, the technical fundamentals, including the technical background, theoretical principles, and mathematical models of zebra battery are given. It then reviews about the super capacitors and their pros and cons in Section III. Most importantly, the potential research directions for electric vehicle technology, especially analyzing and modeling of the hybrid EMS, are pointed out in Section IV. Finally, this paper is concluded in Section V.

MODELING OF EVs

By using the technical specification the analytical calculation was performed and the model is derived on the MATLAB / Simulink environment. The implemented vehicle model which gives raises the perceptive result.

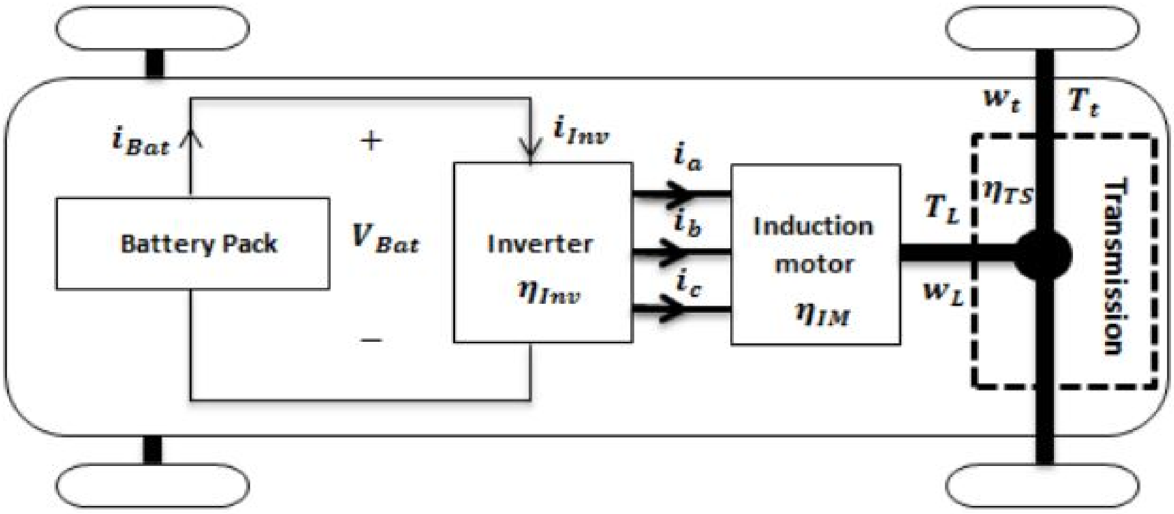

Fig. 2 Schematic view of a simple EV

Drag resistance (F_L)

The resistance offered by wind due to the forward movement of the vehicle.

$$F_L = 1/2 * \rho * A * v^2 * c_w \qquad (1)$$

Here,

v – Driving velocity of vehicle, A – Frontal area of vehicle, c_w – Drag coefficient and ρ – Air Density.

Rolling resistance (F_R)

Rolling resistance is due to the friction between the wheel and road surface .

$$F_R = m.\, g.\, f_r \qquad (2)$$

Here,

m – Mass of the vehicle, f_r – Coefficient of rolling friction and g – Acceleration due to gravity.

Bearing and Mechanical Friction (F_B)

Such resistance are due to the alignment of the parts such as bearing ,shaft and all at the point of manufacturing .It also includes loss due to improper lubrication.

$$F_B = m.\, g.\, k_B \qquad (3)$$

Here,

k_B – Constant for a vehicle which accounts for bearing and mechanical friction

Shaft Force (F_S)

$$F_S = F_L + F_R + F_B \qquad (4)$$

Shaft Power (P_S)

$$P_S = F_S * v \quad (5)$$

Shaft Speed (n_S)

$$n_S = 60 * v / \pi * D_{wheel} \quad (6)$$

Shaft torque (M_S)

$$M_S = F_S * R_{wheel} \quad (7)$$

Motor torque (M_m)

$$M_m = M_s / \eta_g * i \quad (8)$$

Motor Speed (n_m)

$$n_m = n_s * i \quad (9)$$

Motor Power (P_m)

$$P_m = \pi * n_m * M_m \quad (10)$$

The motor efficiency was calculated from the efficiency curve of the Asynchronous machine.

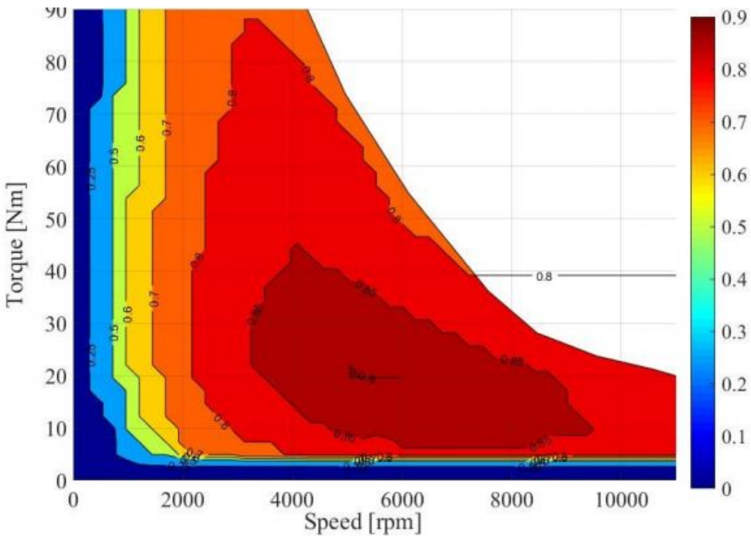

Fig. 3 Efficiency-Torque-Speed Curve of ASM

The graph was plotted between the motor rated torque and speed. The speed parameter was restrained by gearbox which is placed in between the shaft and wheel. The acceleration is calculated from the motor parameter.

$$M_{wheel} = i * M_m * \eta_g \quad (11)$$

Force on wheel (F_{wheel})

$$F_{wheel} = M_{wheel} / r_{wheel} \quad (12)$$

Acceleration (α)

$$\alpha = F_{wheel} / m * \lambda \quad (13)$$

BATTERY-SUPERCAPACITOR HYBRIDIZATION

Hybrid system were built by integrating two or more technologies into a single system. By this way the combination of zebra battery and supercapacitor were modelled having different advantage and characteristic are integrated to achieve the specified requirement. Moreover the power density, life cycle, duration of discharge and other parameter were not satisfied by single source. Battery having high energy density . On the other hand, batteries have high energy rates and long duration of storage, but limited power. Therefore, this hybridization provides high energy and power rating, fast response and both short and long discharge duration. Moreover, supercapacitors can reduce stress on batteries and increase the battery's life. There are many researchers who propose the use of batteries and supercapacitors together. This combination offers high storage capacity and a very fast response time. Some of them proposed the integration of battery supercapacitor storage into a wind power plant, in an electric vehicle or in a microgrid. Kanchev et al. proposed an energy management method in a building with PV system and battery-supercapacitor storage. Specifically, excess energy from photovoltaics is stored in batteries and the local real-time power control is achieved by supercapacitors. Therefore, it is necessary to choose an appropriate combination of energy storage systems to follow the system requirements.

ZEBRA BATTERY

Coetzer, in 1978 at CSIR devise the ZEBRA battery. MED-DEA, Stabio, Switzerland was the first industrialized production stated of the ZEBRA cell. In the ZEBRA technology, the electrode material is a nickel powder and plain salt, the electrolyte and separator is β - Al2O3 -ceramic that conductive for Na+ ions but insulator for electrons. The ZEBRA battery operates at temperature range of +270ºC to 350ºC.

In some systems these sources may be available through batteries or photovoltaic cells but in most drive systems transformer/rectifier sources are used for two stage conversion system. Combined in series, an effective switching state can be related to the switching states of the individual cells.

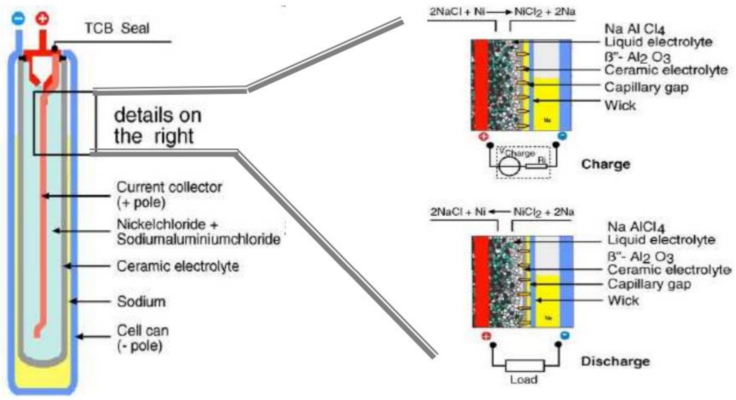

Fig. 4 The Cell of ZEBRA battery

The basic cell reaction is:

$$2NaCl+Ni \underset{\text{Discharging}}{\overset{\text{Charging}}{\longleftrightarrow}} NiCl_2+2Na \qquad (14)$$

The ceramic electrolyte in the zebra cell has zero side reaction due to that the charge and discharge cycle is carried out 100%. The cathode is porous in structure which has 50:50 ratios of nickel (Ni) and salt (NaCl). The essential to the ZEBRA battery are:

- Sodium-ion conductivity inside the cathode: Cells are produced in a discharge state. The liquid salt ($NaAlCl_4$) is vacuum-impregnated into the porous Nickel-salt mixture which forms the cathode. The Sodium-ions are conducted between the ceramic surface and the reaction zone inside the cathode bulk during charge and discharge and makes all cathode material available for energy storage.
- Low resistive cell failure mode: The cell having ceramic substance, in which is in brittle nature at the time of production it may cause small crack. When it developed as a larger one , the liquid salt ($NaAlCl_4$) becomes in contact with the liquid Sodium, the reaction is described as follows:

$$NaAlCl_4 \longrightarrow 4NaCl + Al \qquad (15)$$

The zebra battery has cell failure tolerance in which the salt and aluminum close the small crack in the cell. The above reaction shorts the current conduction between positive and negative. It has been established by Beta R&D that 5-10% of cells a series string may fail before the battery can no longer be used.

- Over-charge reaction: The quantity of salt NaCl at cathode decided the charge capacity of ZEBRA cell. By applying the voltage continuously in the time of fully charged state, the liquid salt (NaAlCl4) supplies a sodium reserve the reversible reaction as follows:

$$2NaAlCl_4 + Ni \longleftrightarrow 2Na + 2AlCl_3 + NiCl_2 \qquad (16)$$

ZEBRA BATTERY MODEL

In electric vehicles, the battery model is the strong candidate which plays a vital role as an energy source. Many researchers and published were done in the field models. An ultimate battery model is the key point for the successes of total system. The battery model must be robust and the chemical phenomena such as the diffusion effects, ohmic resistance, self discharging and mass transport limitations are to be predict accurate battery voltage, current, and state-of-charge (SOC). There are several battery models, reported in the literature, aimed to reflect the battery characteristics. The simplest battery model is shown in Fig. 5 consisting of an ideal voltage source (EO) and a constant equivalent internal series resistance (ESR).

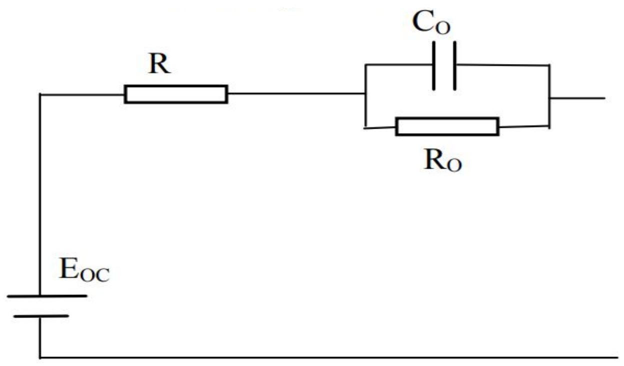

Fig. 5 Simple equivalent circuit battery model

Calculation of Battery Parameters

By considering the constant auxiliary consumption Paux, battery power is calculated as

$$P_B = P_{aux} + P_m / \eta_m \qquad (17)$$

From the discharge curves provided by the battery manufacturer, battery no-load voltage U_{BO} and internal Resistance R_{BI} can be calculated. The battery current I_B can be calculated,

$$I_B = U_{BO} / 2R_{BI} - \sqrt{((U_{BO} / 2R_{BI})^2 - P_B / R_{BI})} \qquad (18)$$

SOC of the battery

$$SOC = (Q_N - Q) / Q_N \qquad (19)$$

SUPERCAPACITOR

A supercapacitor is an electrochemical double layer capacitor (EDLC) which is widely used in electric vehicle and Energy storage systems. Energy storage capability of the supercapacitor has unique feature, by which the component has been made choice by some application where the high power density is required.

This unique property will made the component to ensure it is ability to handle a fast fluctuation in energy level. Theory about the supercapacitor was first released by Hermann Von Helmholtz. In supercapacitor there is no chemical reaction involved in it, only having interaction between the conductor and the electrolyte inside the capacitor. The electrodes of a supercapacitor are porous in structure made of carbon material. Electrolyte is deposited around the electrode of the supercapacitor. The above arranged structure which gives the larger conduction area to the supercapacitor. The electrolyte present inside the supercapacitor will have free charge carrier which termed as ions and the behavior of ions is determined by the diffusion and electrostatic relative.

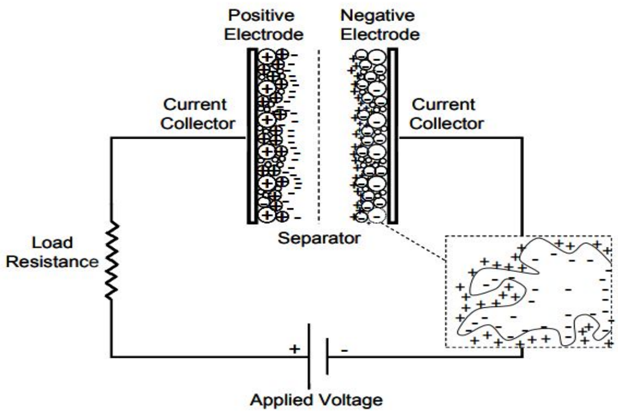

Fig. 6 Schematic of an electrochemical double-layer capacitor

With the supercapacitor due to the diffusion reaction the ions which present in the electrolyte are evenly distributed the time of completely discharge state. While supercapacitor gets charged, Electric field is created in between the electrodes of the supercapacitor. The evenly distributed ions are get attracted toward that field as result of the field the ions started to separate. Thus the supercapacitor has high power density and lower energy density compared to any other energy storage device. Supercpacitor have a distinctive character such as faster charge and discharge rate and high recyclability which take over the battery performance. By alleviate the battery it will gives space for the longer life of battery, narrow charging and discharging and also improve the system efficiency by boosting the peak power of the system. Supercapacitor can act as greater substitute for battery by connecting parallel with battery for charging and discharging high power in short time. This leads the battery for longer life. The state of charge variation in case of battery will affect the life of the battery. But in supercapacitor whatever the SOC the charging cycle will not affect that much greater.

MODELING OF SUPERCAPACITOR

Supercapacitors are considered as a promising technology with favorable characteristics.

They are also known as ultra capacitors or as electrochemical double layer capacitors. The energy storage is in the form of an electric field between their two electrodes, without any chemical reaction. During charge process, the electrically charged ions are moved from the electrolyte towards the electrode of opposite polarity. Supercapacitors have complementary features, such as high energy efficiency (85–98%), long life cycle (> 100000 cycles), high power density (500–5000 W/kg) and very fast response time (< 5 ms). Moreover, they do not get affected so much from deep discharges. However, they have short charge and discharge duration and low energy density (0.1–5Wh/kg). Supercapacitors have low cell voltage resistance between their terminals (up to 3 V) and hence they are built up with modules of single cells connected in series or in a combination of series and parallel connections. The equivalent circuit of the supercapacitor cell is shown in Fig. 7. We examine the two branches model, which consists of the main branch and the slow branch.

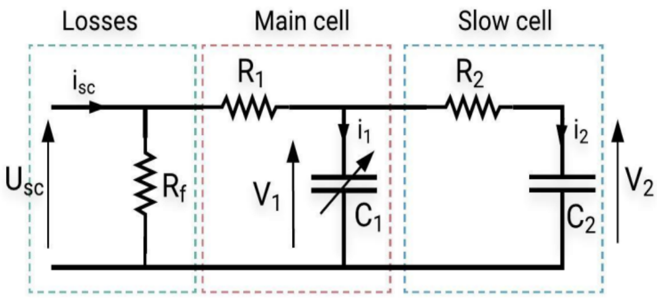

Fig.7. Two branches equivalent circuit of a supercapacitor cell

The main branch corresponds to the immediate response of the supercapacitor during the charge or discharge event in the time range of seconds. In the main branch, R_1 is the series resistance and represents the waste power for internal heating on charging and discharging (mΩ). The capacitor C_1 depends on the voltage V_1 as expressed in (20), where C_0 is the constant capacitance in Farads (F) and C_v is the constant parameter (F/V).

$$C_1 = C_0 + C_v V_1 \qquad (20)$$

The slow branch determines the internal energy distribution at the end of the charge or discharge cycle in the time range of minutes. The parallel resistance R_f describes the leakage current when the supercapacitor is in standby mode (kΩ×10^2). This self-discharge property can be neglected for fast charge and discharge cycles. Equation (21) represents the voltage V_{sc} of the supercapacitor module,

$$V_{sc} = N_s U_{sc} = N_s\left(V_1 + R_1 \frac{I_{sc}}{N_p}\right) \qquad (21)$$

Where N_s and N_p are the number of supercapacitor cells in series and parallel connection, respectively. Also, U_{sc} is the cell voltage and I_{sc} is the current of the supercapacitor module. Concerning the slow cell, the voltage V_2 can be expressed by:

$$V_2 = \frac{1}{C_2}\int i_2 dt = \frac{1}{C_2}\int \frac{1}{R_2}(V_1 - V_2)dt \quad (22)$$

The voltage V_1 across the capacitor C_1 on the main cell is given by:

$$V_1 = \frac{-C_0 + \sqrt{C_0^2 + 2C_v Q_1}}{C_V} \quad (23)$$

Where Q_1 is the instantaneous charge of C_1 and can be calculated by:

$$Q_1 = C_0 V_1 + \frac{1}{2} C_v V_1^2 \quad (24)$$

SIMULATION USING SIMULINK

Simulation results of terminal voltages of both energy sources are shown in Fig.8, while Fig.9 shows the demand current, ZEBRA battery and super capacitor currents. The terminal voltage variation is very important on the battery life as well as inverter design. The variation of the voltage defined as the dip voltage that occurs regarding to discharging current.

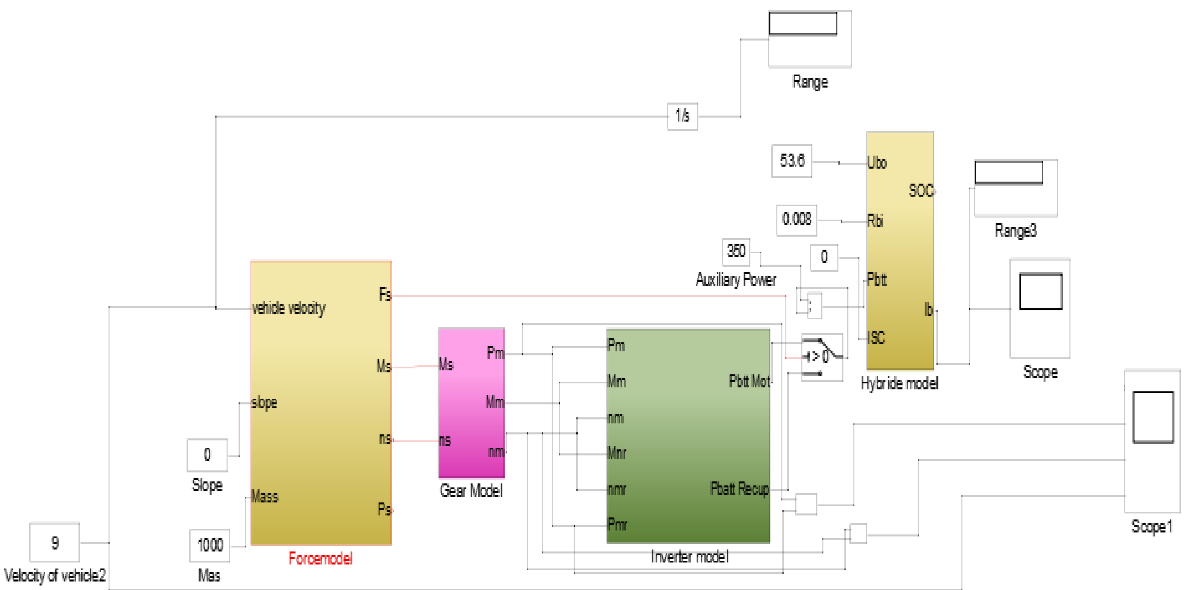

Fig.8 Simulink model of hybrid system

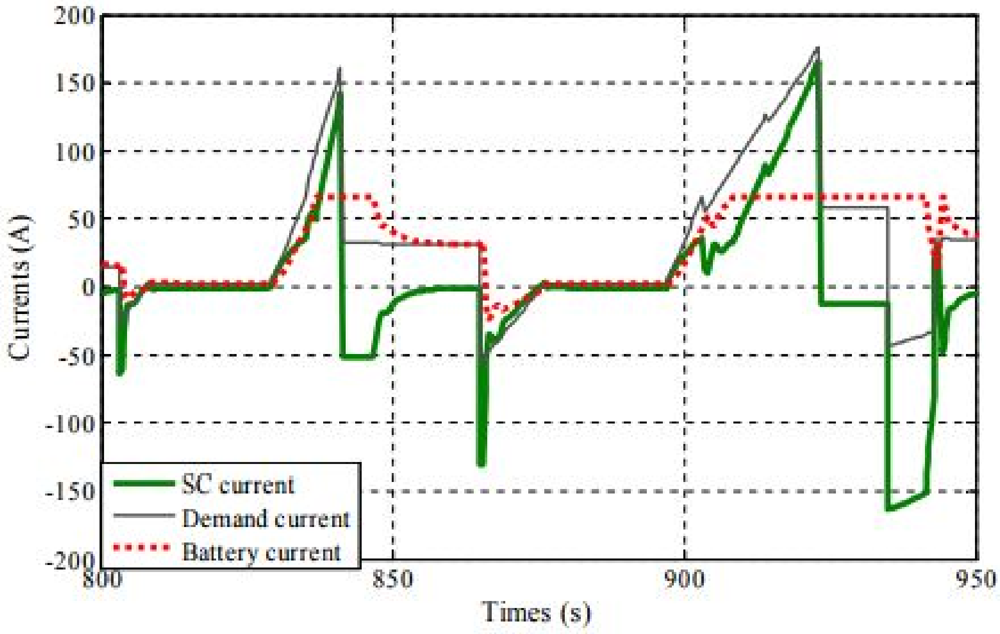

Fig.9 Currents of demand, battery, and supercapacitor

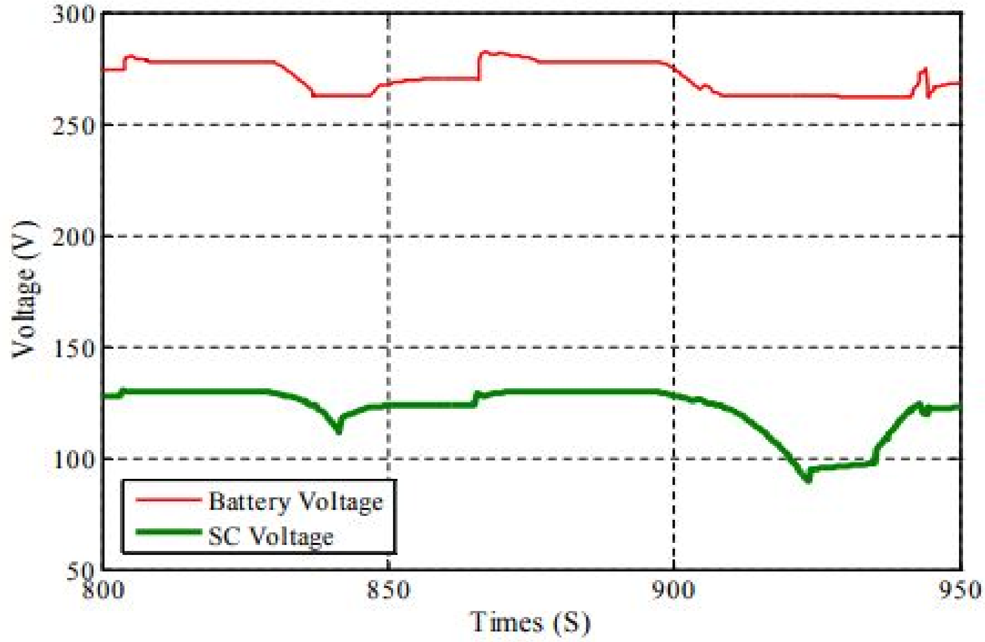

Fig.10 Terminal voltages of both energy sources

The range of considered EV can be evaluated by simulation for different inputs with parameters set of Table 1.

Table 1 Simulated range versus the velocity of vehicle

Velocity of Vehicle (m/s)	Type of Energy Source								
	Li Ion Battery			Pure Zebra Battery			Zebra Battery + Supercapacitor		
	I_b (A)	SOC %	Range (Km)	I_b (A)	SOC %	Range (Km)	I_b (A)	SOC %	Range (Km)
22.5	150	25	81	180	25	67	58	59	81
13.9	78	61	50	93	53	50	30	78	50
9	50	75	32	60	60	32	19	86	32

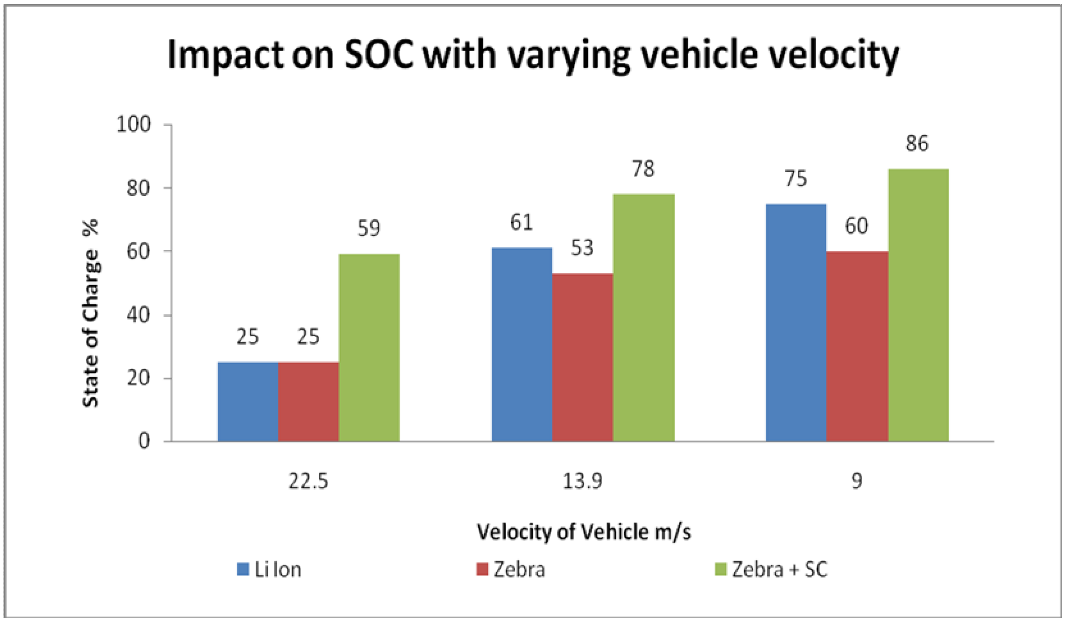

Fig.11 Impact on SOC with varying vehicle velocity

The result shown in Fig.11and Table 1 indicate that the combination of the zebra battery and supercapacitor will improve the state of charge of the battery. With the improvement on the SOC of battery we can overcome the range anxiety problem. The cost wise the zebra cells are cheaper compare to the lithium batteries. The model developed is much more cost effective. While using the zebra battery the failure of cell in multiple packages will not affect the system performance. By improving the SOC of battery the distance cover by the vehicle is improved. Thereby the overall performance and efficiency of the electric vehicle system is improved.

CONCLUSION

In this paper the combination of zebra battery with supercapacitor for electric vehicle energy storage system was described in detail. The individual component of the EV system was examined well in terms of mathematical expression and the effect of individual component in the system was analyzed. Based on the theoretical analysis the choice of the component was done and simulink model was created. The analysis which shows how the individual parameter was affects the overall performance of the system. The current draw by the battery was decreased so that the life of the battery gets improved. The SOC of battery was improved by 15%. The paper also presented a salient feature of Zebra battery and super capacitor. This paper will serve as a valuable resource to any future worker in this important area of research. This paper can further be extended by introducing the thermal model for zebra battery which would improve the overall model resolution.

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