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Modeling and Analysis of Hybrid Energy Storage Systems Used in Electric Vehicles

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***Abstract*— This paper deals with the design and modelling aspects of hybrid energy storage system (HESS) used in Electric vehicles. Modelling of HESS includes modelling of battery, Ultra-capacitor and the vehicle load modelling for Light electric vehicle used in the work. A detailed analysis for vehicle load is carried out to find out capacity of motor, battery and ultra-capacitor in both acceleration and in regenerative braking. This paper also discusses different types of converters used in HESS for electric vehicle application along with its suitability to the light electric vehicles. The HESS in this work uses a bidirectional dc/dc converter along with battery and ultra-capacitor. A simple power sharing algorithm based on heuristic approach is presented to ensure the different modes of operation of electric vehicles. From the performance analysis at different speeds and at different gradients it is concluded that HESS reduces the size of the battery, weight of the system. Due to this the range of the vehicle can be improved in a single charge.**

Keywords—battery,electric vehicle, enerey storage, hybrid energy storage system, plug-in electric vehicle, PM BLDC motor, ultracapacitor, vehicle load modelling, power sharing.

I. INTRODUCTION

Due to the environmental pollution and increase in oil prices the electric vehicle (EV) is the obvious choice for the transportation [1], [2]. In battery operated EV, battery is the only source for energy and these batteries are facing problems like less number of charging and recharging cycles, poor transient response and less driving range. Above mentioned problems are overcome by hybridizing battery with any of the Energy source shown in Fig. 1.

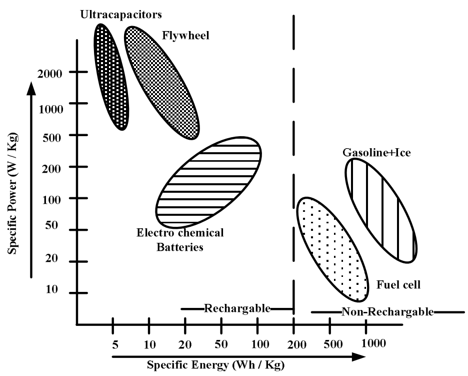

Figure 1. Characteristics various Energy sources

Fuel cells and internal combustion engines are having high energy density and low power density and theses are non-rechargeable. Electro chemical batteries, ultra-capacitors and flywheels are rechargeable and each one is having its own merits and de-merits. Batteries are having very low power density and high energy density compared to the ultra-capacitors and the fly wheels [3], [4]. Electric vehicles require high power density during accerlation or in starting and high energy density to travel more distance in single charge [5], [6]. So no single source can supply both energy and power demands in electric vehicles. In rail, road transport and in aerospace, hybridization of electric sources can be done in many ways. Hybrid energy storage systems (HESS) used in pure EV contains battery as a main source and ultracapacitor or flywheels as auxiliary sources. In fuel cell EVs fuel cell is hybridized with ultra-capacitor and battery [7].

Fig. 2 to Fig. 5 represents different HESS topologies. Fig. 2 represents fuel-cell based hybrid storage system. In this topology, since fuel cell is having very slow response time it should be hybridized with battery and ultra-capacitor [8], [9]. In this topology each source uses one bi-directional converter and control of each converter is independent so it is not suitable to use in light electric vehicles.

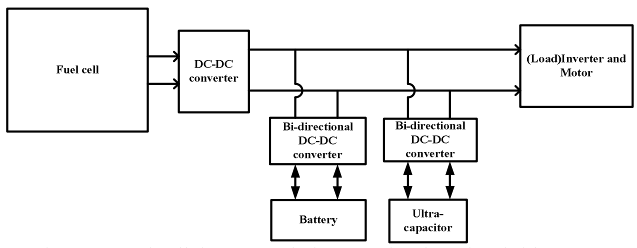

Figure 2. Fuel cell, battery and ultracapacitor based Hybrid system.

Fig. 3 represents battery operated EV and in this topology batteries are hybridized with Ultra-capacitor. In this type of hybrid system hybridization can be done in many ways. Battery and ultracapacitor can be connected in series or in parallel and Fig. 3 is the most suitable topology for light electric vehicles. In this topology, the batteries are directly connected to dc link and the ultracapacitor is connected through bidirectional dc/dc converter [9]-[12]. Both fuel cell and battery operated EVs uses bidirectional dc/dc converters to interface with dc link. Due to this proper power sharing between the sources is possible. Hybridizing battery or Fuel cell with a converter is called active combination. In this type auxiliary source power can be controlled and the optimal power sharing takes place based on the type of power management strategy used in the HESS.

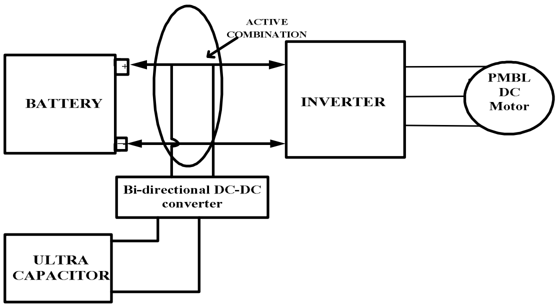

Figure 3. Battery and ultra capacitor based Hybrid system

In Fig. 4 the multiple converters are used to interface with the dc link. In this configuration more than two sources are used to maintain the power sharing and there is no centralized control. Each converter is separately controlled to obtain the power transfer between the power source and the load, it needs a common dc bus and the power management is difficult and become slow. So this type is also not suitable for light EV applications.

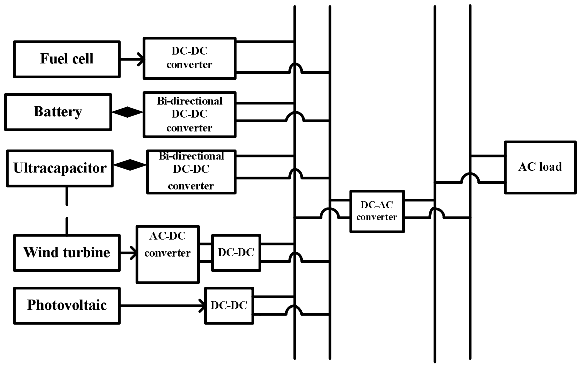

Figure 4. Conventional Hybrid storage system

In Fig. 5 multiport converters are used to interface with the dc link. All disadvantages mentioned above can be avoided in this structure. Moreover the voltage rating of the energy sources can be different. In this paper battery and ultracapacitor combination with bi-directional converter is used.

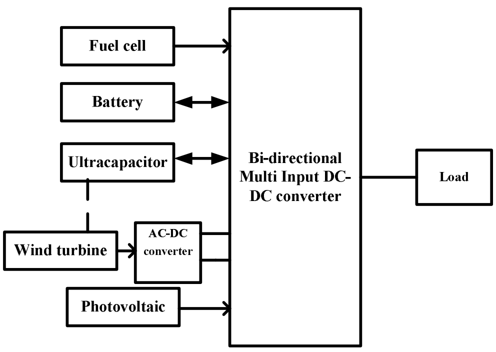

Figure 5. Multi-Port Hybrid Storage system

II. Hybrid Energy Storage Systems

In this section, different HESS topologies, modelling of vehicle load, design and modelling of battery, design and modelling of ultracapacitors are presented.

A. Modeling of Vehicle Load

The road load (Frl) consists of rolling resistance (Frr), aerodynamic drag (Frw) and climbing resistance (Frc).

1) Rolling Resistance

The rolling resistance , $Frr = (fr * M * G)$

fr - rolling friction co-efficient= ($M * G * \cos\alpha$)

M - Vehicle mass and G - gravitational acceleration constant.

2) Aerodynamic Drag

The aero-dynamic drag is given by

$$Frw = 0.5\rho_a C_d A_f (V + Vo)^2$$

ρ_a - Air density, C_d - Aero dynamic drag co-efficient

A_f - Vehicle frontal area, Vo - wind velocity

3) Climbing Resistance

The climbing force = $Frc = (M * G * \sin\alpha)$

α - Road angle

Total road load = $Frl = (Frr + Frw + Frc)$

The motive force available from the propulsion system (F) is partially consumed in overcoming the road load Frl , the net force, ($F - Frl$), accelerates the vehicle (or decelerates when Frl exceeds F . δ - Rotational inertia coefficient

The acceleration is given by = $\left(\dfrac{F - Frl}{\delta * M}\right)$

In specific drive cycle, the total tractive effort of the vehicle can be given by equation

$$F_t = (Mg\, frr \cos\alpha + 0.5\rho_a C_d A_f (V + Vo)^2) + M\delta \frac{dv}{dt}) \quad (1)$$

The tractive effort developed by the traction motor on driven wheels is given by

$$Ft = \frac{Tm * i_g * i_o * \eta_t}{r_d} \quad (2)$$

Where

i_g - Gear ratio of transmission, i_o - gear ratio of final drive

Tm - Torque output of the motor, r_d -radius of the driven wheels, η_t - efficiency of whole driveline.

Total driving power required on the vehicle wheels for road angle α=0 is

$$P_{t_{ot}} = \frac{V}{1000}(Mgf_{rr} \cos\alpha + 0.5\rho_a C_d A_f V^2 + M\delta \frac{dv}{dt})KW \quad (3)$$

B. *Modelling of Battery*

The battery is modeled using a simple controlled Voltage source in series with a constant resistance as represented in this model assumes the same characteristics for the charge and the discharge cycles. The open voltage source value is calculated with a non-linear equation based on the actual SOC of the battery. The Fig. 7 shows the discharge characteristics of the battery. In the HESS, the battery power is calculated using (4) and (5).

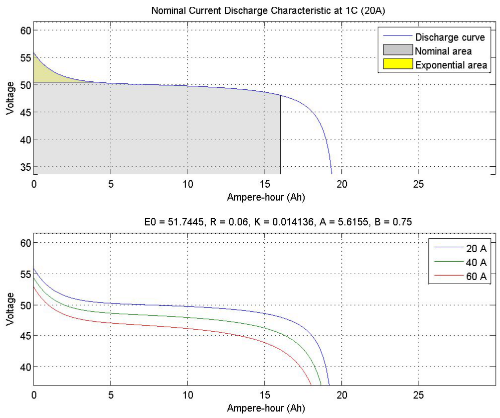

Figure 6. Battery discharging characteristics

1) *Design of Battery Power Capacity*

At constant speed and on a flat road, the power output from the battery can be expressed as

$$P_{batt}=\frac{V}{1000*\eta_t*\eta_m}(Mg\,f+0.5\rho_a C_d A_f V^2+Mg\alpha)KW \qquad (4)$$

For flat road, α=0

$$P_{batt}=\frac{V}{1000*\eta_t*\eta_m}(M*g*f+0.5\rho_a C_d A_f V^2)KW \qquad (5)$$

When regenerative braking is applied, braking power at the battery terminals can be expressed as

$$P_{batt}=\frac{\beta V}{1000*\eta_t*\eta_m}\left(\begin{array}{r}Mg\,f+0.5\rho_a C_d A_f V^2\\ +Mg\alpha+M\delta\frac{dv}{dt}\end{array}\right)KW \qquad (6)$$

In (6) the road angle (α) or acceleration or both can be negative. The β is the percentage of the total braking energy that can be regenerated by the electric motor and it varies from 0 and 1.

The net energy consumption from the battery is given by

$$E_{batt}=\underbrace{\int P_{bout}dt}_{Traction}+\underbrace{\int P_{bin}dt}_{Re\,generation} \qquad (7)$$

C. *Modelling of Ultracapacitor*

1) *Physical Model of Ultracapacitor*

Fig .8(a) gives physical model of ultracapacitor [13], [14]. The model is constituted of an infinite number of RC branches with voltage-dependent capacitances to mimic the activated carbon fibers in the positive and negative electrodes, and resistances corresponding to the electrode material, the electrolyte material, the membrane material and the various sizes of pores.

2) *Different Mathematical Models of Ultracapacitor*

Single branch and two branch models of ultracapacitor are shown in Fig. 8(b) and Fig. 8(c). A series resistor RESR which simulates energy loss during capacitor charging and discharging and a parallel resistor REPR which simulates energy loss due to capacitor self-discharge. In this work ultracapacitor is modeled using SIMULINK and single-branch model is used in the simulation.

3) *Design of Ultracapacitor Power Capacity*

The following voltage definitions [15] are used for design of ultracapacitor as shown in Fig. 7.

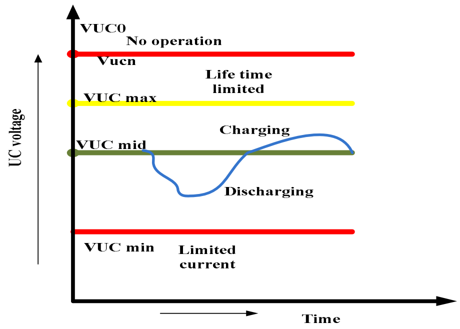

Figure 7: Ultracapacitor voltage definitions.

a) *Maximum Operating Voltage*

The maximum operating voltage ($V_{uc\,\max}$) of the ultracapacitor module depends on the type of HESS and type power converter used. In this work battery and ultracapacitor are connected parallel and ultracapacitor is connected with a non-isolated bi-directional converter.

$$V_{uc\,\max}\le V_{dcbus} \qquad (8)$$

b) *Minimum Operating Voltage*

The minimum operating voltage ($V_{uc\,\min}$) of the ultracapacitor is determined by the dc-dc converter current capability (Icm) and the conversion power (Po).

$$V_{uc\,\min}\ge\frac{p_0}{Icm} \qquad (9)$$

c) *Intermediate Operating Voltage*

The intermediate voltage (V_{ucmid}) is long-term average voltage defined as

$$V_{ucmid}=\sqrt{\frac{E_{discharge}*V_{uc\,\max}^{\;2}+E_{charge}*V_{uc\,\min}^2}{E_{discharge}+E_{charge}}} \qquad (10)$$

The major function of the ultracapacitor is to supply the peaking power to the drive train. In the ultracapacitor power design, acceleration performance and peak load power in typical drive cycles are the major concerns. Ultra capacitor power is calculated using equations (3) to (5)

$$P_{total} = P_{batt} + P_{ucap} \quad (11)$$

$$P_{ucap} = P_{total} - P_{batt} \quad (12)$$

The minimum capacitor CUC min is calculated using (13)

$$0.5 * C_{uc\min}(V_{ucnom}^2 - V_{uc\min}^2) = P_{uc} * t_d \quad (13)$$

Generally, $V_{uc\min}$ is chosen as $V_{uc\max/2}$ and $V_{uc\max}$ is equal to V_{dc}. When the ultracapacitor's voltage reaches the bottom limit $V_{uc\min}$, the ultracapacitor should stop working and get charged to maintain the state of charge and to avoid too much stress on itself. From (13),

$$C_{uc\min} = \frac{2 * P_{uc} * t_d}{(V_{ucnom}^2 - V_{uc\min}^2)} \quad (14)$$

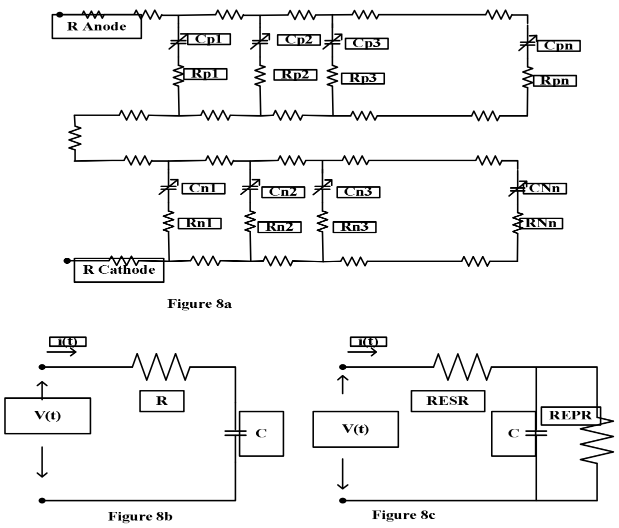

Figure 8: Ultracapacitor model (a) Physical model (b) one branch model (c)Two branch model.

D. Bi-directional DC/DC Converter

Many converters are used in literature for power sharing between battery and ultracapacitors [16], [17], [18].In this work bi-directional buck-boost converter is used .high voltage side battery is used and in low voltage side ultracapacitor is used.

When T1 is ON converter acts as boost converter and Inductor, Ls stores the energy. When T1 is OFF, the stored energy in inductor transfers to load through diode D2. When T2 is ON the converter acts in buck mode and it takes power from load and battery. When T2 is OFF, the current flows in ultracapacitor and inductor Ls. The topology of the converter is shown in Fig.9. Many power and energy sharing algorithms are proposed in literature. Since the work is based on light EV, a simple control algorithm is presented.

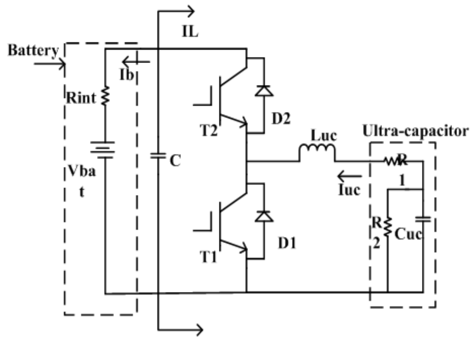

Figure 9: Bi-directional DC/DC Converter.

From Fig. 10, reference current to the ultracapacitor is generated based on battery voltage, load current, speed of the vehicle and based on battery Soc.

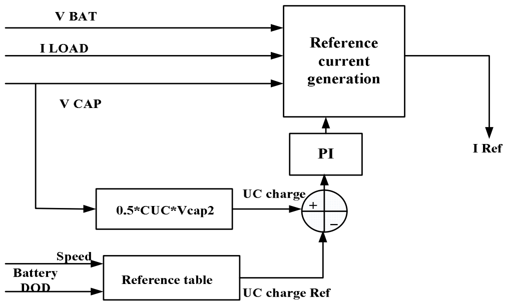

Figure 10: Ultracapacitor reference current generation.

Ultracapacitor charge reference is generated based on speed and battery SOC. A look-table method is used to maintain sufficient energy in ultracapacitor. Inductor current is controlled by multiplying reference current with the ratio of battery voltage to ultracapacitor voltage. The discriminator shown in Fig.11 will decide buck and boost modes of operation of converter.

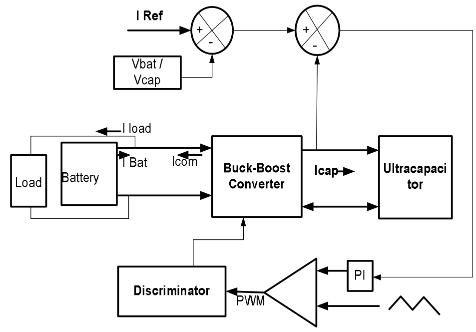

Figure 11: Basic control structure.

III. Calculation of Vehicle Performance

In above section, modelling of different components of HESS is presented. Vehicle load modelling is performed with the equations (1) to (3) and the parameters mentioned in Table I, are considered for vehicle load modeling.

TABLE I. LIGHT ELECTRIC VEHICLE PARAMETERS

Structure Parameters	
Mass of the system (M)	175 Kg
Aerodynamic drag coefficient (C_d)	0.92
Rolling Friction(f_r)	0.018
Rotational Inertia Factor (δ)	1.1
Efficiency of transmission(η_t) and efficiency motor (η_m)	0.95
Vehicle Frontal Area(A_f)	0.6
Tire radius (r)	0.2m
Air density (ρ)	1.23m^3

Power capacity of the battery is calculated using (4) to (7). Battery is modeled in SIMULINK and its parameters are taken from light EV available in the laboratory. The parameters of the battery are shown in Table II.

TABLE II. LEAD ACID BATTERY PARAMETERS

Lead acid Battery Parameters	
Battery voltage	48 V
Battery Peak current	20 A
Battery resistance	0.056Ω
Battery nominal current	5A
Battery rating	20AH

Light EV in this work uses direct driven PM BLDC Motor and its load torque requirement is calculated using (2) and (3). The parameters of the PMBLDC motor are measured and are shown in Table III.

TABLE III. PM BLDC HUB MOTOR PARAMETERS

Motor parameters	
Stator resistance per phase	0.18 Ω
Moment of inertia	0.1324 kg-m^2
No. of poles	46
Back –EMF constant	133$V_{peak(L-L)}$/krpm
Viscous Friction co-efficient	0.0516N-m/s
Stator Phase Inductance	0.54mH

HESS used in this work uses battery ultracapacitor and bidirectional dc/dc converter. The size of the converter and ultracapacitor rating is obtained using (8) to (14). The parameters of ultracapacitor are taken from manufacturer datasheet. The parameters of ultracapacitor and dc/dc converter are shown in Table IV.

TABLE IV. ULTRACAPACITOR AND CONVERTER PARAMETERS

Maxwell Ultra-capacitor parameters	
BMOD0110-P016 B01 modules	2
V_{ucmax}	32V
I_{peak}	50A
ESR	0.0072Ω
V_{dc}	48V
V_{ucmin}	10V
Bi-directional DC/DC converter Parameters	
Switching Frequency	20kHz
Maximum Power rating	1kW
Current rating	50A

The performance of vehicle at different speeds and at different road angles is analyzed using the data obtained from Tables I to IV and the data is shown in Table V.

TABLE V. PERFORMANCE OF VEHICLE AT DIFFERENT SPEEDS AND AT DIFFERENT ROAD ANGLES

For Flat Road						
S. No.	Vehicle Speed (Km/ph)	P_{Steady} (W)	$P_{Acceleration}$ (W)	$P_{Transient}$ (W)	P_{Bat} (W)	T_L (N-m)
1.	15	179.3	93.89	273.2	273.2	13.11
2.	25	384	297.8	681.7	681.7	19.63
3.	45	1227	806.6	2034	2034	32.54
Grad=0.05 (5%)						
1.	10	387.8	123.9	511.6	511.6	36.84
2.	20	826.6	252.5	1079	1079	38.85
3.	40	2062	774.2	2836	2836	51.05

From Table V it is observed that as speed of the vehicle changes for fixed accerlation of 10 sec, the acceleration power required for the vehicle increases and it is almost 50% of the total power required by the vehicle. So if a HESS is designed in such a way that the battery can take steady state power and ultracapacitor can take transient power ,the total cost of the system and weight of the system will approximately reduces to approximately half of the actual system. Moreover, the regenerative braking is employed the vehicle range can be improved.

IV. Conclusion

The detailed modeling and design aspects of battery, ultracapacitor and vehicle load are presented. The parameters of the different components of the HESS are obtained from the rules specified in the modeling and design aspects .The performance analysis carried out for a Light

EV at different speeds and at different road angles. From the analysis it is observed the acceleration power is almost half the total power required for the vehicle to move on the road. So hybridizing the battery with any other source which can provide transient power will reduce the battery size, weight of the system. So effectively the range of the vehicle in a single charge will be improved. The suitability of different dc-dc converters for light electric vehicle is also presented. A simple power sharing algorithm is presented to control the power flow between the battery and ultracapacitor.

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