# Improvement in Storage System by Battery-Supercapacitor Combination in Electric Vehicles

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*Abstract*— **The paper is basically a review of development of power unit for electrical transportation vehicle. This paper critically analyses the challenges which can be faced in EV's effective and efficient power unit. It also throws light on application of supercapacitor application as power buffer in electrical vehicles. It also describes design and control requirements of supercapacitor power buffer. Two cases for simulation are presented where supercapacitor and battery are connected in shunt as well as trough power converter for optimum utilization of supercapacitor. Finally, simulation results are presented and analysed.**

***Keywords— VRLA (Valve Regulated Lead Acid Batteries), ESR (Equivalent Series Resistance), Supercapacitors, DC-DC Converter, NEMMP (National Electric Mobility Mission Plan***

## I. Introduction

There has been some radical changes in an automobile industry which has accelerated human civilization. Even though it comes with so many advantages it has some problems associated with it. A total transition to EVs and zero carbon vehicles has been needs of the hour. Hence we are accelerating way from fossil fueled cars.

Today almost 90-95% of transportation uses conventional energy sources. This conventional energy sources are limited as well as pollutant in nature which leads to many climate problems. In last few years' successive work has been done in an alternative technology for conventional source in automobiles such as electric vehicle and hybrid electric vehicles in India. In urban areas, periodic acceleration and deceleration is required, in such cases significant part of energy gets dissipated into breaks.

Recovering this energy and improve vehicle driving range can only be accomplished by EVs and HEVs. EVs and HEVs are more efficient than conventional vehicles, the electric load profile of them consists of high peaks and steep valleys which results in large current surges in and out of the battery. Surges tend to generate extensive heat inside the battery, which leads to increased battery internal resistance thus lower efficiency and ultimately premature failure. The problem of battery overheating and loss of capacity is more since they cannot accept large busts of current from regenerative breaking without degradation in its SOC. Since there is no any chemical reaction is involved in storage mechanism of supercapacitors, it has no limits for its charge cycle. Supercapacitors have much greater advantage over batteries as they don't require any maintenance.

India has announced 'National Electric Mobility Mission Plan (NEMMP) 2020' in 2013 to throw some light on the issues of National energy security, vehicular pollution. The grail of the National Mission for Electric Mobility (NMEM) are National energy security, reduction of bad impact of vehicles the environment and unfold domestic manufacturing capabilities in automotive sectors. The NEMMP 2020 mission has set new vision in automotive sectors strikingly for EVs and HEVs.

Industries have realized the huge potential that prevails for efficient and environmentally friendly electric and hybrid vehicles. This report is made to review direct shunt connection of supercapacitor and battery as well as by using DC-DC power converter in buck and boost mode while charging and discharging respectively.

## II. Paper Layout

In first chapter introduction about current transportation scenario and problems associated with it are described. Government plans and policies about Electric and Hybrid Mobility are also stated. In prosper chapters' system description and mathematical modelling is stated. After modelling system simulation is done and some results are exhibited and compared. Finally, conclusion is made that supercapacitors can be used to improve effectiveness in EVs and HEVs, it also reduces size and cost of battery.

## III. Component Modelling

Main components of our system are Battery, Supercapacitors, DC-DC Buck Boost Converter and Load that changes its direction while regenerative breaking.

*A. Battery*

Batteries stores charge by undergoing chemical processes as well as they are thermal dependent so they are difficult to model. Internal resistance, temperature, rate of charge-discharge, etc. affects the capacity of battery. Indefinite model that is commonly used for batteries is Thevenin's equivalent circuit that consists of the open circuit voltage in series with an effective resistance. Both resistance and voltage together represents battery SOC. SOC is nothing but amount of charge left in battery after serving load for specific time with respect to its full capacity. Battery voltage is represented by function of SOC: $V_{oc(t)} = a_{1\,+}\, a_2{*}SOC(t)$.

*B. Supercapacitor*

Supercapacitors can be modelled similarly to simple capacitors. They are represented by series R-L circuit, leakage resistance due to insulation is represented by shunt resistance. The difference between conventional capacitor and supercapacitor is self-discharge time constant. Our study is for short duration hence leakage resistance can be ignored and supercapacitor is modelled simply by series R-C circuit. For dynamic studies detailed models are found in Ref. [14].

*C. Electrical Load*

Load for electrical vehicles is generally an induction motor fed from inverter which will act as generator during coasting or regenerative breaking. Direction of current can be changed by reducing frequency of its terminals i.e., reversing power flow and producing breaking torque as well.

Modelling of an inverter fed induction motor is available in electronics text books. But as far as study is considered power demanding circuit is sufficient. As DC bus voltage is constant, load can be modelled as time varying current source which reverses its direction while regenerative breaking.

*D. DC-CD Converter*

Voltage at the terminals of supercapacitor varies over wide range hence DC-DC converter is needed to arrogate output voltage of supercapacitor as per load demand. Simple converter topology is used in which two solid-state switches are used to control the current as shown in Fig.1. During acceleration converter operates in boost mode and while during deceleration it will be in buck mode. Initially, the supercapacitors are kept as full as possible to be ready for supporting acceleration and at high speeds, the supercapacitors are kept at a low charge in order to be ready to accept energy when the vehicle decelerates in regenerative braking. [7]

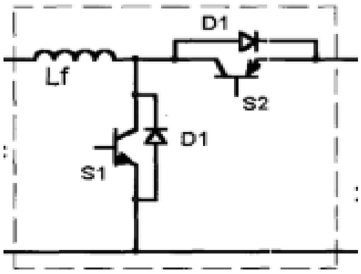



Fig.1 - DC-DC Converter Topology

## IV. SYSTEM DISCRIPTION

*A. Battery*

The battery system consists of two banks connected in parallel. Each of the two battery banks consists of 28 deep-cycle valve-regulated-lead-acid (VRLA) battery units connected in series.

Table No.1 – Battery unit Specifications

| | |
|---|---|
| Rated voltage | 12 V |
| Capacity | 85Ah |
| Recharge current limit | 400A |
| Internal resistance | 4mΩ (SOC≤80%)<br>10mΩ (SCOC=90%) |

Total battery subsystem ratings:336VDC,170Ah

*B. Supercapacitor*

Super capacitor sub system consists of string of 150 cells connected in series. Capacitors are connected in series to increase its energy. Supercapacitors have very high power density and low energy density.

Table No.2 – Supercapacitor Cell Specifications

| | |
|---|---|
| Rated voltage | 2.5 V |
| Capacitance | 2500 F |
| Peak voltage | 2.7 V |
| Series resistance | 1 mΩ |
| Leakage resistance | 300Ω |
| a1, a2 | 11.80, 1.32 |

Total Supercapacitor subsystem rating:
Rated voltage= 375 V
Capacitance = 16.66667 F
Energy stored = 1.17 MJ

*C. Electrical load*

Electrical load can be modelled as a vehicle acceleration cycle. Acceleration can be simulated by wave shape that increases from 0 to 300A in 1o seconds, decreases exponentially for 1.5 seconds up to 66A, then stays constant at 66 A for succeeding 9.5 seconds.

*D. DC/DC Converter:*

The size of the solid-state switches and freewheeling diodes is effected by the maximum power requirement of the converter and the system's cooling abilities.

Table No.3 - Converter Specifications

| | |
|---|---|
| Switching frequency | 1 KHz |
| Inductance | 100 mH |
| Resistance | 10 mΩ |
| Capacitance | 100 |

## V. Parallel Connecion Of Batter and Supercapacitor

For connecting super capacitor in shunt with battery as shown in Fig. 2, Supercapacitor is pre-charged. Where $i_c$, $i_b$ & $i_l$ are supercapacitor current, battery current and load current respectively. Load current flows in downward direction for acceleration cycle and vice-versa for deceleration

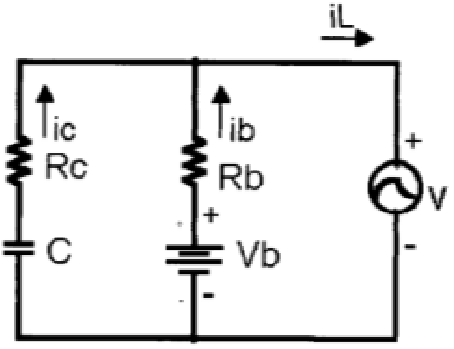



Fig. 2 – Supercapacitor and Battery in Parallel

$$i_c + i_b = i_l \quad (1)$$

$$v = v_c - i_cR_c = v_b - i_bR_b \quad (2)$$

$$i_c = -C\frac{dVc}{dt} \quad (3)$$

$$V_C + R_C.C\frac{dVc}{dt} = V_b - R_b\left(I_l + C\frac{dVc}{dt}\right)$$

$$V_C + R_C.C\frac{dVc}{dt} = V_b - I_lR_b - C.R_b\frac{dVc}{dt}$$

$$V_C + C\frac{dVc}{dt}(R_c + R_b) = V_b - I_lR_b$$

$$\frac{dVc}{dt} + \frac{Vc}{C(Rc+Rb)} = \frac{Vb-Il.Rb}{C(Rc+Rb)}$$

$$\frac{dVc}{dt} + \alpha V_c = \alpha V_b + \beta I_l$$

Where,

$$\alpha = \frac{1}{C(Rc+Rb)}, \quad \beta = -\frac{Rb}{C(Rc+Rb)} \quad (4)$$

$$\frac{dVc}{dt} + \alpha V_c = \alpha V_b + \beta I_l \quad (5)$$

Solving this differential equation

$$V_c = K.e^{-\alpha t} + V_b + \beta e^{-\alpha t}\int e^{\alpha t}.I_l.dt \quad (6)$$

Without power converter it is impossible to control charge flow in supercapacitor bank hence it is forced to maintain its voltage constant equal to battery terminal voltage. Shunt connection of supercapacitor and battery is simplest way but we can't utilize supercapacitor bank optimally hence we require some power modulating device to interface between battery and supercapacitor.

## VI. Supercapacitor Integration Through DC-DC Power Flow Controller

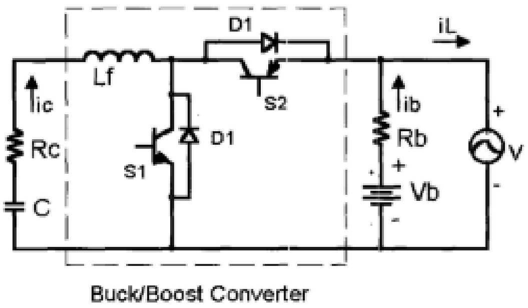



Fig. 3 – Supercapacitor and Battery Through DC-DC Buck Boost Converter

The analytical expression of the supercapacitor current can be determined by the second order differential equation for RLC circuit.

$$\frac{d^2ic}{dt^2} + \frac{Rc}{Lf}\frac{dic}{dt} + \frac{1}{c_f}ic = f(t) \quad (7)$$

There are total four states of bidirectional operation from which, f(t) is zero first and fourth stage. As in first stage supercapacitor is transferring its energy to inductor and vice versa in fourth state.

A. *State 1***:** Switch s1 is on and switch s2 is off. Recharged supercapacitor will transfer its energy to inductor.
B. *State 2:* Switch S1 & S2 both are off. Energy stored in capacitor and inductor is together delivered to the load through diode D2.
C. *State 3:* Switch s2 is on and switch s1 is off. Regenerated energy is transferred to the inductor.
D. *State 4:* Switch S1 & S2 both are off. Inductor gets discharged in supercapacitor through diode D1.

Current through switches and diodes can be given by

$$I_{Sw1} = \delta_1 I_{SC} \quad (8)$$

$$I_{D2} = (1-\delta_1)\, I_{SC} \quad (9)$$

$$I_{Sw2} = \delta_2 I_{SC} \quad (10)$$

$$I_{D1} = (1-\delta_2)\, I_{SC} \tag{11}$$

Equation (9), (10) represents condition for acceleration i.e., boost mode whereas equation (11), (12) represents condition for deceleration i.e., buck mode. It can be seen that, in buck mode, the stress of the switch $D_1$ is constant and given by the power flowing through the converter. The diode's average current, depends on the duty ratio. At 50% duty ratio switch and diode both currents are equal. For lower duty cycles the average diode current exceeds the average current in the switch. In boost mode the average diode current is always constant, while the average current in the switch increases as per the duty cycle.

Above equations can also be expressed as a function of power **P** or bus current $I_{bus}$

$$I_{Sw2} = \frac{P}{Vbus} = I_{bus} \tag{12}$$

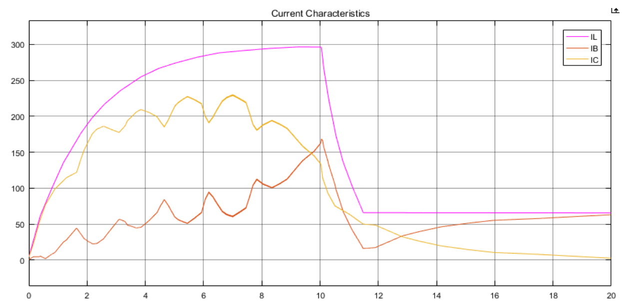
$$I_{D1} = \frac{P}{Vbus}\left(\frac{1-\delta 1}{\delta 1}\right) = I_{bus}\left(\frac{1-\delta 1}{\delta 1}\right) \tag{13}$$

$$I_{D2} = \frac{P}{Vbus} = I_{bus} \tag{14}$$

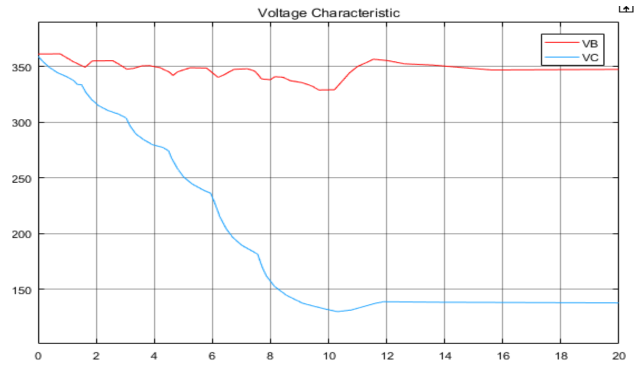
$$I_{Sw1} = \frac{P}{Vbus}\left(\frac{1-\delta 1}{\delta 1}\right) = I_{bus}\left(\frac{1-\delta 1}{\delta 1}\right) \tag{15}$$

In a supercapacitor application the DC-to-DC converter runs at very low duty cycles. Therefore, it is important to select the semiconductor switches according to the worst case duty cycle.

When models were developed in software and simulated then current and voltage characteristics of both cases were as shown in figure.

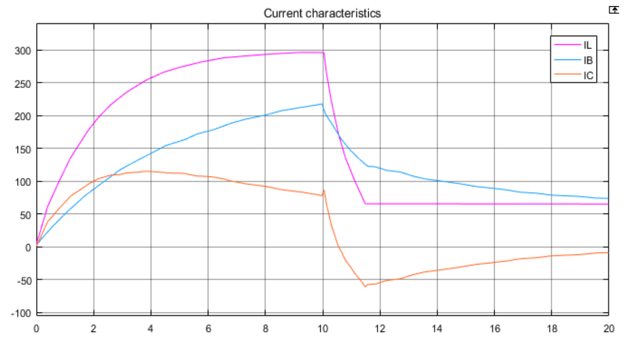



(a)

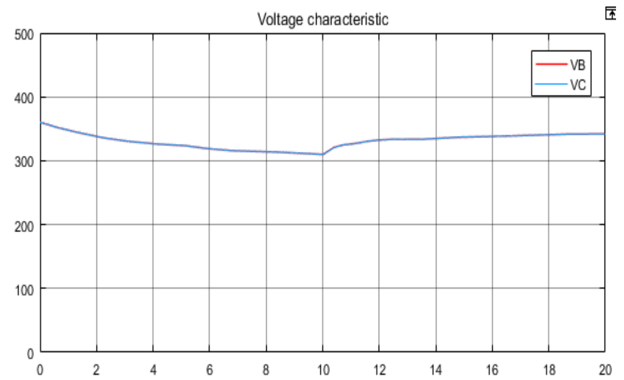



(b)

Fig. 4 – Simulated Battery and Supercapacitor (a) Current and (b) Coltage Without Power Converter




(a)




(b)

Fig. 5 – Simulated battery and Supercapacitor (a) current and (b) voltage With Power Converter

Both models are simulated for comparison purpose only, when both figures are compared it is observed that:

A. The battery peak current demand is reduced approximately by 40%.
B. The DC bus voltage regulation is improved with power converter.
C. The supercapacitor's SOC is also improved with power controller after acceleration.

Future work will be reported on experimental data from actual vehicle driving cycles in different conditions. A detailed analysis would be carried to improve effectiveness of combined storage system.

## VII. Conclusions

Direct connection of the supercapacitor across the battery terminals does partial reduction of transient currents in and out of the battery but the best way to utilize the supercapacitor bank optimally is to control energy content through it. Energy control is possible by introduction of Buck Boost bidirectional power converter.

## VIII. References


[1] Y. Gao, L. Chen and M. Ehsani, "Investigation of the effectiveness of regenerative braking of EV and HEV" *Proc. Society of Automotive Engineers,* 1999, paper No. 1999-01-2910.

[2] P.T. Moseley, "High-rate, valve-regulated lead-acid batteries – suitable for hybrid electric vehicles?' ***Journal of Power Sources,*** Vol. 84, 1999,pp. 237-242.

[3] Electrosource, ***Battery Handbook,*** Horizon C2M Batteries, 1999.

[4] E. Faggioli, P. Rena, V. Danel, X. Andrieu, R. mallant, and H. Kahlen."Supercapacitors for the energy management of electric vehicles", ***journal of Power Sources,*** Vol. 84, 1999, pp. 261-269.

[5] J.C. Brown, D.J. Eichenberg, W.K. Thompson, L.A. Viterna, and R.F. Soltis, "Ultracapacitors store energy in hybrid electric vehicles", NASA

[6] **Smith,** T.A.; Mars, J.P.; Turner, G.A., "Using supercapacitors to improve battery performance", ***Proc. IEEE 33rd annual Power*** Electronics Specialists Conference, pp. 124 -128.

[7] B.J. Amet and L.P. Haines, "Hig-power DC-to-DC converter for supercapacitors", ***Proc. IEEE Power Conversion Conference,*** Osaka,Japan, 2002, pp. 1160-1165.

[8] L. Bertoni, H. Gualous, D. Bouquain, D. Hissel, C. Pera, J.M. Kauffmann, "Hybrid auxiliary power unit (APU) for automotive applications", Proc. IEEE 5gh Vehicular Technology Conference, 2002, pp. 1840-1845.

[9] C. Chen, "High pulse system through engineering battery-capacitor combination," ***Proc.*** 2000 ***American Aeronautics*** & ***Astronautics, Inc.,*** Paper # AAA-2000.2935, pp. 752-755.

[10] Barrade, P.; Rufer, A, "Supercapacitors **as** energy buffers: a solution for elevators and for electric busses supply", ***Proc. Power Conversion Conference,*** 2002, pp. 1160 -1165.

[11] P.T. Krein, ***Elements of Power Electronics,*** Oxford University Press, 1998.

[12] M.A. Merkle, Variable Bus Voltage Modeling of Series Hybrid Electric Vehicles, M.S. Thesis, Virginia Tech University, 1997.

[13] Steven Pay, Hybrid Electric Vehicle Regenerative Braking Using Ultracapacitors, M.S. Thesis, University of Nevada, Las Vegas, Dec., 2000.

[14] **S.** Buller, E. Karden, D. **Kok** and R.W. **De** Donker, "Modeling the dynamic behavior of supercapacitors using impedance spectroscopy", ***IEEE Trans. Ind. Applications,*** Vol. 38, No. 6, 2002, pp. 1622-162.

[15] Y. Baghzouz, Y.J. Fiene, J. Van Dam, **L,.** Shi, E. Wilkenson, and R.F. Boehm, "Modifications to a hydrogedelectric hybrid bus", ***Proc. American Aeronautics and Astronautics Engineers,*** 2000, paper No. AAA-2000-2857