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Result on Effectiveness of Battery-Super Capacitor Combination in Electric Vehicles

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Abstract - Utilizing a super-capacitor bank, used as an influence buffer to tame sudden changes in power going into and coming out from electronics' battery of an electrical or hybrid electric vehicle is examined in this research. The study takes into account both the simple situation, in the bank of super-capacitors is linked directly in Along with the battery and the casing, in through a DC-DC converter, to which it is connected directly, it is essential for the best performance. Computer simulations that simulate vehicle acceleration and deceleration are used to illustrate the work. Additionally displayed is some data from an experimental circuit. It is anticipated that appropriate hybrid electrical energy storage system design will have a significant positive impact on that of the battery bank health.

KeyWords:*Super capacitors, deepcycle batteries, regenerative braking, power transients, and DC/DC converters are all related to electric and hybrid vehicles*

1.INTRODUCTION

When operating standard gasoline-powered automobiles in cities, where frequent cycles of acceleration and deceleration are necessary, a large amount of energy is lost through the brakes. Therefore, recovering energy from braking is a useful strategy for increasing a vehicle's range, and only electric or hybrid-electric vehicles are capable of doing so (HEV). By using the generator using a traction motor to apply brakes on the wheels and battery recharging, regenerative breaking in these vehicles is able to recover a portion in terms of kinetic energy contained inside the mass of the moving object.

The Associate Electric vehicle battery bank is built to handle peak power consumption, which frequently jeopardizes the necessary weight and area requirements. The auxiliary motor (API) of a degree HEV, on the other hand, is designed to supply the typical power needed by the vehicle, whereas the battery fits within to provide the power spikes necessary for acceleration and uphill climbs, and only permits brief power during braking. The electrical load profile of EVs and HEVs has a pattern of frequent acceleration and braking with high peaks and severe valleys, despite the fact that they are more economical than normal vehicles in metropolitan settings. As a result of the subsequent battery current fluctuating in and out, the battery tends to experience intense heat.

Once batteries are close to full state-of-charge (SOC), overheating of batteries is a concern, and capacity loss becomes much more significant because, at this point, they are unable to withstand large current bursts from regenerative breaking without degrading. The limitations of super-capacitors' higher power density and rapid charge and discharge times (also known as electrochemical capacitors or ultracapacitors) have many more advantages than the use of batteries, instead of using brief bursts of power Thus, by including a super-capacitor, the bank may assist the battery during vehicle and hill climbing. Acceleration Its quick recharging ability also helps the battery capture regenerative braking energy. In recent years, attention has been drawn to this important benefit of battery-super-capacitor energy storage/supply systems in transportation, in addition to in various applications. Additionally, using super-capacitors enables a reduced battery size and virtually unlimited charge-discharge cycles (because there are no internal resistances) (chemical processes that make up their energy storage system). In addition, these gadgets don't employ toxic substances and require no upkeep.

To achieve the best performance, special considerations should be made if the integration of a hybrid energy storage system has begun. The most efficient method of utilization Using an influence converter, the super-capacitor bank may regulate the amount of energy it contains. Even if there is no direct association of the Placing the super-capacitor over the terminals of the battery will reduce the battery's transient current going in and out. The direct super capacitor-battery shunt connection is reviewed in the paper, followed by a brief discussion of the issues with element modeling..

2. COMPONENT REQUIRED:

This part discusses the modeling of these three of the most important system components of an electric vehicle: the electrical load, battery bank, and supercapacitor bank. All the components are explained below.

A. BATTERY BANK

It's not easy to model batteries because they provide adequate energy while tolerating temperature-dependent molecular chemistry processes. Therefore, a battery's electrical behaviour may be a nonlinear performance of multiple regularly changing parameters, including internal temperature, charge status, charge/discharge rate, etc. The two factors that affect a battery's capacity are temperature and discharge rate. This relationship is described by the Peuket equation, I = $\sqrt[\alpha]{\beta/t}$ which links I (A) to the discharge current and discharge time t (hr), where α and β are constants. Given the battery capacity C_{T0} at temperature T_0 the capacity at some other temperature is computed by $C_T = C_{T0}(1 + \sigma(T - T_0))$. σ is a temperature constant.

An approximate model that is often used for batteries is a Thevenin equivalent circuit that consists of the open circuit voltage in series with an effective internal resistance. Both voltage and resistance values are functions of the battery SOC, and these relations are generally supplied the manufacturer. SOC is defined the percentage of energy left in a battery (after supplying a certain amount of amp-hours) relative to its full capacity.

The open-circuit voltage is often approximated by a linear function of the SOC: Voc = $a_1 + a_2$ **SOC,** at some specific temperature (e.g., 80^0 F). The battery internal resistance has static and dynamic values that depend of battery SOC, whether the battery is being charged or discharged and rate of charge/discharge. In short duration studies, however, the amount of amp-hours in and out of the battery **is a** small fraction of the battery capacity. Hence it is fair to assume that battery internal voltage is constant during such periods, and a quasi-steady state model with fixed open-circuit voltage and internal resistance constitutes an acceptable battery model. Note that two resistance values are used in this case, one during charging and another during discharging.

B. SUPERCAPACITOR BANK

The super-capacitors' resistance, as well as the inductance of their electrodes, a series R-L circuit is used to represent the terminal wires and wires, much like in regular capacitors. The insulation between the electrodes of the device is also deficient. This causes a leak current, which is shown by excessive shunt resistance. Super-capacitors differ from conventional capacitors in that they are significantly more cost-effective, meaning that their series resistance may be much lower and their shunt resistance may be much more valuable. Super-capacitors have a self-discharge time constant that is hundreds of times bigger than that of regular capacitors. The official contains many sophisticated models that are suitable for dynamic analysis units. The study under investigation tries to find out if a brief analysis of the power (or current) flow during acceleration and between the super-capacitor bank and the battery during acceleration and quickness is possible. As a result, the leak resistance won't be noticeable because of the small amount of inaccuracy, and the super-capacitor bank will be represented merely by a series R-C circuit.

C. .ELECTRICAL LOAD

The electrical load in electric vehicles consists mainly of an inverter-fed induction motor for motive power. During regenerative breaking, the motor is turned into a generator by reducing the frequency of its terminal voltage, thus reversing power flow and producing braking torque. Detailed modelling **of** inverter-fed motor drives is found in standard power electronics and drive textbooks. **As far** as the power source is concerned, power demand is sufficient for analysis. Since the DC bus voltage is not allowed to vary significantly from its nominal value, current demand gives a good approximation of power demand. Thus, the load can be modelled simply by a time-varying current source that reverses direction as the vehicle switches from coasting or acceleration to regenerative braking.

3. DIRECT SUPER CAPACITOR CONNECTION:

After attempts are made to maximise the functionality of this additional sub-system, it will be difficult to combine the super-capacitor with the battery-load circuit. The only way to connect is to directly connect a after precharging it to the voltage of the battery terminals, connect the super-capacitor in parallel with the battery bank. When the load current, denoted by iL in Figure 1, is shown to be flowing downhill, such a connection is indicated (i.e., positive throughout acceleration breaking and coasting, and negative throughout regenerative braking).

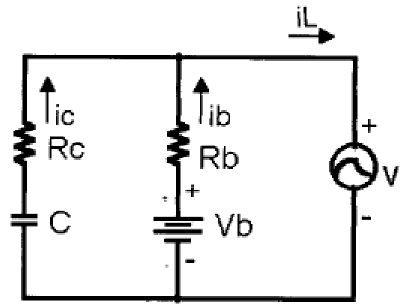

Fig. 1. Parallel connection of supercapacitor bank, battery bank, and electrical load.

Given a precise load current profile associated with a brief driving cycle, Kirchoff's voltage and current laws can be used to compute the super-capacitor current and battery current (I).

$$i_c + i_b = i_L$$

$$V = V_c - i_c R_c = v_b - i_b R_b$$

$$i_c = -C * \frac{d}{dt} v_c$$

where vc and vb stand for, respectively, voltages of the battery and internal capacitor. The vc equation of first order is produced when (1) and (3) are substituted in (2):

$$\frac{dV_c}{dt} + \alpha V_c = \alpha V_b + \beta i_L$$

Where,

$$\propto = \frac{1}{C(R_b + R_c)}$$

$$\beta = -\frac{R_b}{C(R_b + R_c)}$$

The answer to (5) can be expressed as in the following equation, Eqn. (6):

$$V_c = Ke^{-\alpha t} + V_b + \beta e^{-\alpha t} \int i_L * e^{\alpha t} dt$$

where K is established by changing v, from its initial value to vb. It should be noted that the bank of super-capacitors in the previous circuit cannot have its power flow controlled since the voltage at its terminals must always must match the voltage at the battery terminals.. The both internal voltages and resistances of the two branches alone dictate how much current is divided between the super-capacitor and battery banks.

CONNECTION OF A SUPERCAPACITOR THROUGH A POWER CONTROLLER

The above straight connection clearly indicates that optimal use of the super-capacitor bank requires a power flow controller between the two energy storage subsystems. The objective is to maintain the battery current as constant as possible with a slow transition from low to high current during transients to limit battery stress. On the other hand, the super-capacitor ought to charge as fast as possible without exceeding the maximum current from regenerative breaking and to discharge most of its stored energy during acceleration.

Energy flow in and out of the super-capacitor can be controlled with a pulse-with-modulated (PWM) DC/DC converter with a simple topology as shown in Fig. 2 [7], [8]. The super-capacitor is discharged during acceleration at a rate controlled by modulating switch S1. In this boost mode, energy is delivered to inductor Lf when S1 is turned ON (State 1), then transferred to the load through diode D2 when SI is turned OFF (State 2). During deceleration, the super-capacitor is charged at a rate controlled by modelling switch S2. Here, energy is transferred to Lf when S2 is turned ON (State 3), then to the super-capacitor through diode D1 when S2 is turned OFF (State 4). The analytical expression of the super-capacitor current can be determined by the second order differential equation.

$$\frac{d^2 i_c}{dt^2} + \frac{R_c}{L_f} * \frac{di_c}{dt} + \frac{1}{CL_f} i_c = f(t)$$

Where f(t)=0 in state 1 and 4, and

$$f(t) = \frac{R_b}{L_f} * \frac{di_L}{dt}$$

When the power demand changes in States 2 and 3, the power controller alone controls the energy The power controller governs the flow of energy in and out of the super-capacitor only during fluctuations in power demand. Consequently, quasi-steady state relations between the converter input and output parameters do not exist in this case, and one has to resort to circuit simulation software such as PSpice.

The basic controls for the static power converter in Fig. 2 can be summarised as follows. The super-capacitor must be charged by the battery bank or by an off board power supply prior to vehicle use. During the initial stages of vehicle acceleration, power flow out of the super-capacitor should be matched to that of the load demand as long as the device current rating is not exceeded. This requires the controller to adjust the ON state pulse of S1 accordingly. As the capacitor continues to discharge, the battery current should gradually increase and ultimately reach the load current when the energy stored in the capacitor reaches low levels. During regenerative breaking, the super-capacitor should be charged at the maximum possible rate (by modulating switch S2) so that a small fraction of the load current flows into the battery bank. The current injected by the load is then diverted slowly into the battery as the capacitor approaches full charge.

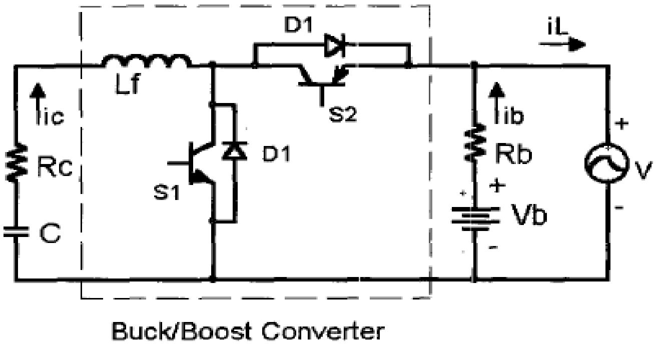

Fig. 2. Supercapacitor integration through power flow controller.

4. NUMERICAL ILLUSTRATION

The performance of the series hybrid-electric bus system as an installed part of the energy storage for freshly built supercapacitor banks is being studied to highlight the analysis in the sections above. The internal combustion engine in this hybrid vehicle's APU burns hydrogen. When the battery bank has reached or is very near to reaching full capacity, the study duplicates the APU and the vehicle power circuit turned off, mimicking the vehicle engine standing once. For the purpose of simplicity, this is done. The battery system consists of two batteries. Figure 3 shows one of the parallel-connected banks next to the supercapacitor bank. Here, a basic description of both the battery and supercapacitor subsystems is provided. Deep-cycle valve-regulated lead-acid (VRLA) battery modules totaling 28 . Figure 3 shows one of the parallel-connected banks next to the bank of supercapacitors. Here is a brief explanation of the battery and supercapacitor subsystems. 28 VRLA (valve-regulated lead-acid) battery modules for deep-cycle use. One of the parallel-connected banks is shown adjacent to the supercapacitor bank in Figure 3. Here is a brief explanation of the battery and supercapacitor subsystems. The twenty-eight deep-cycle valve-regulated lead-acid (VRLA) battery modules that make up each of the two battery banks are linked in series. Each unit can deliver and has a 12 V rating. C_T0= 85 Ah @ C/3 (at To = 80° F).

Below is a description of these varied battery specifications :-

- internal static resistance during charging: 4mΩ for SOC 5 80%, and 10 mΩ at SOC = 90% recharge current limit: 400 A,
- Peukert's equation constants: **α= 1.33** and **β= 256,**
- capacity-temp. dependence parameter: **σ=** 0.004,
- V,, vs. SOC parameters: a_1 = 11.80, a_2 = 1.32,
- battery subsystem rating: 336 VDC, 170 Ah@C/3.

The 150 cells that make up the supercapacitor are strung together. Each cell is rated at 2.5 V and 2,500 F. Here are some further details :

- cell series resistance = 1 mΩ,
- cell leakage resistance: 30052,
- cell peak voltage: 2.7 V,
- cell rated current: 400 A,
- supecapacitor subsystem rating - rated voltage: 375 V, peak voltage: 405 V, capacitance: 16.67 Farads, energy storage capability: 1.2 MJ

It is necessary to balance capacitor cells since no two are exactly alike and because internal parallel resistance and cell capacitance have an impact on how voltage is delivered. To distribute the total stack voltage over the capacitor bank uniformly, bypass resistor s are connected in parallel with each cell and scaled to be dominant. A charge equalisation is missing from the battery pack, though. Monitoring the battery's state is done through a data collection system. The user gets alerted if any voltages are unexpectedly high or low. Additionally, the terminal voltage and internal cell temperatures are noted.

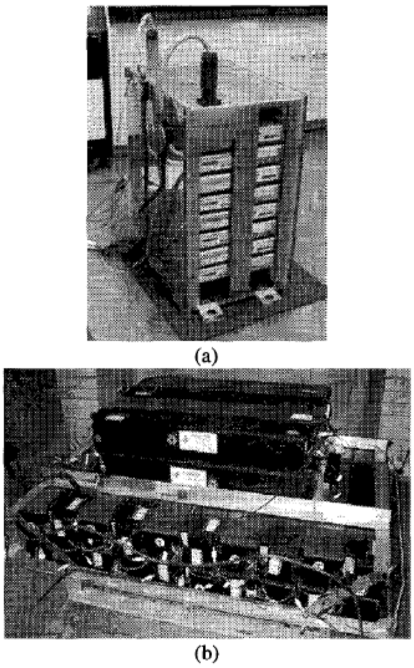

Fig. 3. (a) Supercapacitor bank, (b) battery bank.

A prototype has been made using a specialized device that simulates realistic current patterns by accelerating and decelerating while producing and absorbing current. A single 12 V battery cell was connected in parallel to a string of six super-capacitor cells of the same brand and type in order to evaluate how well the super-capacitor-battery combination worked both during charge and discharge. The following test strategy was finished:

1. Super-capacitor strings are pre-charged and connected in parallel with battery units.
2. 200 A of steady current should be injected until the voltage reaches 14.2 V, the maximum permitted value, and then the current should be reduced to keep the voltage there for 10 seconds.
3. For 30 seconds, turn off the load.

Connect a 200A load for 10 seconds, then turn off the electricity.

Using a customized tool that accelerates and decelerates while creating and absorbing electricity, a prototype of the system has been created. In order to assess how effectively the super-capacitor-battery combination functioned both during charge and discharge, a single 12 V battery cell was linked in parallel to a string of six super-capacitor cells of the same brand and kind.

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Fig. 4 displays the system voltage, battery current, capacitor current, and measured load current (a). Be aware that the super-capacitor's presence significantly reduced battery current, particularly during the first few imposing load current for seconds. The related current and voltage profiles derived using Eqn are displayed in Fig. 4(b). (1)-(7) where the load current is approximated by **iL** = $\mathbf{320(e^{-1.25t} - e^{-0.16t})A}$ for $0 < t \leq 10$ **sec.,** and **iL** = -205 A for $40 < t \leq 50$ sec.

Both figures' graphs are practically exact replicas of one another.

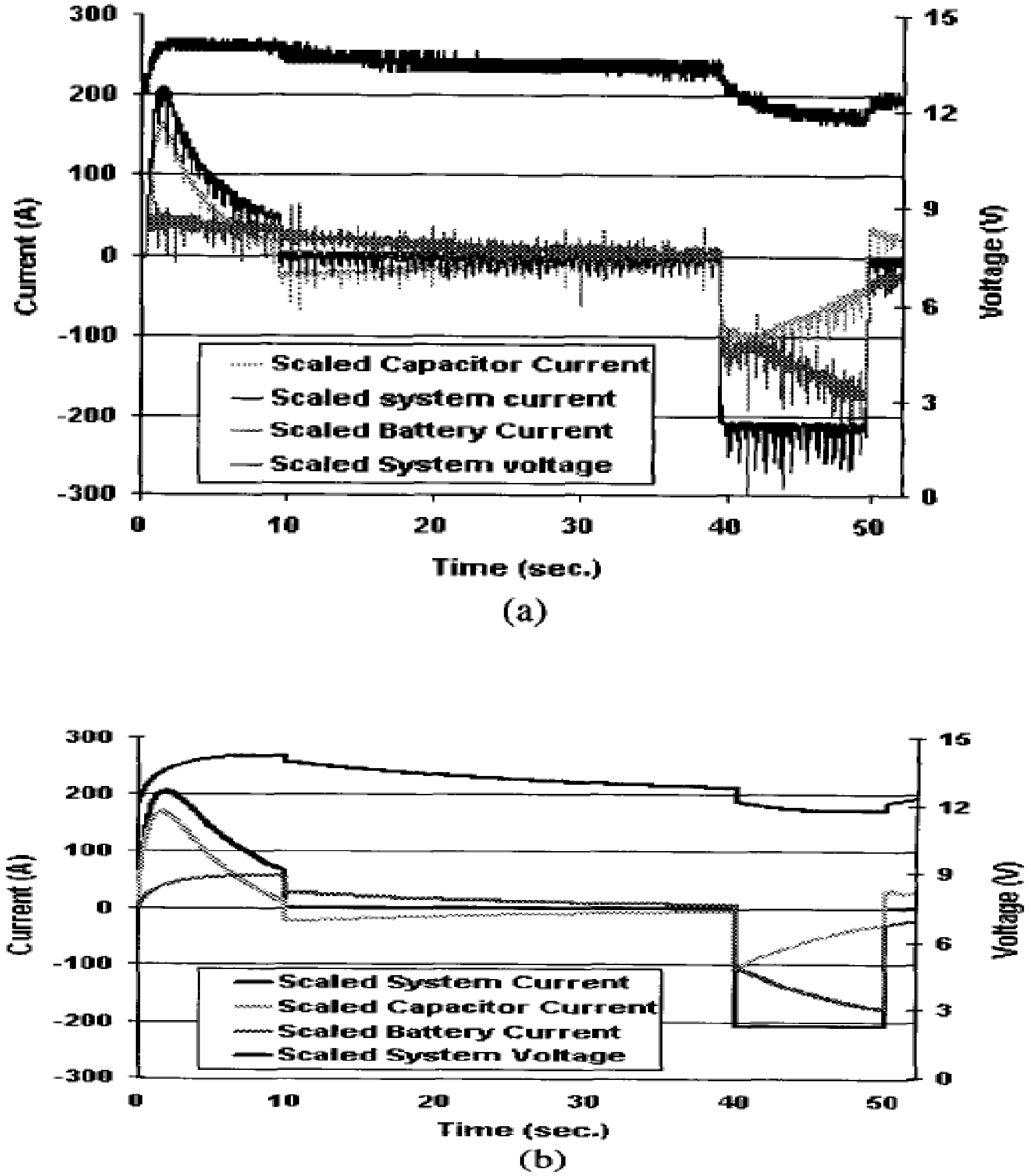


Fig. 4. Battery and supercapacitor currents during charging and discharging, (a) experimental data, (b) calculated data.

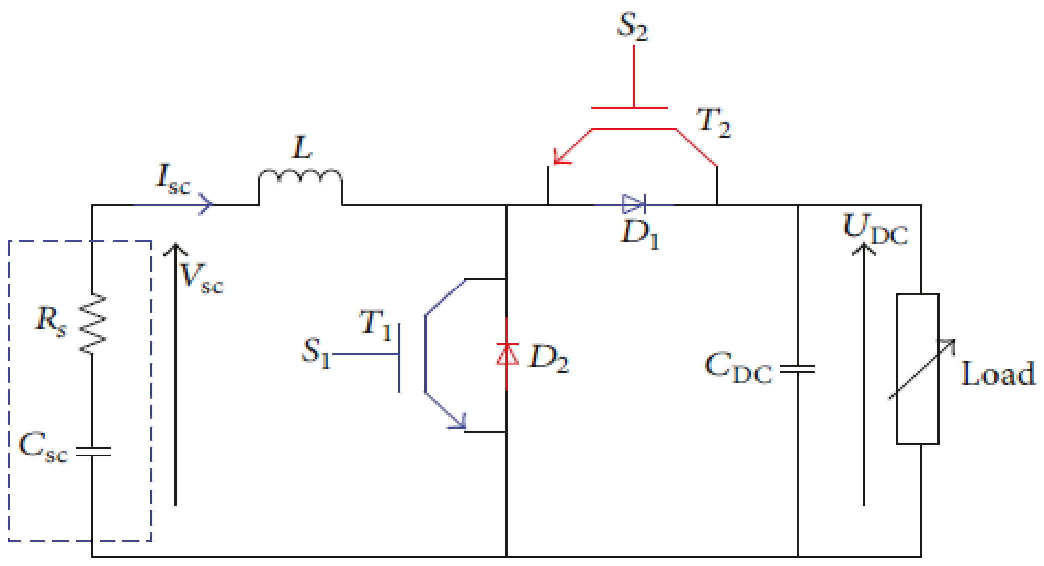
The use of a power controller to manage the energy flow via the super-capacitor was not tested since there were no converters available; instead, only PSpice-based computer simulations are presently being employed. With a load current whose waveform increases from 0 to 300 A in 10 seconds, then exponentially decreases for 1.5 seconds, and finally stays constant at 66 A for 9.5 seconds, the performance of a hybrid system under the direction of a DC/DC controller is shown.

*- These are the conversion settings: It is intended for the switch duty ratio to grow discretely in phases for as long as the load current is increasing every 1.5 seconds **(L_f= 100 mH, R_f= 10 &,f_{sw} = 1 kHz, C_f = 100 mF).**

It makes sense to add a super-capacitor bank to an electric or fuel cell car since the benefits much exceed the drawbacks. While a straight parallel connection can assist minimize battery stress by taking into account transitory currents when moving swiftly and slowly, it will not fully use a true power buffer, the super-capacitor. A filter capacitor, two power diodes, two inductors, and two static power switches are all that are required for the power manager to maximize the utilization of the super-capacitor. The best control strategy hasn't yet been fully identified, though. realized as a result of challenging control issues. The development of the power converter, which is presently in the design phase, as well as experimental data from actual automobile driving cycles will be the subject of future study.

5.Results By Connecting The Controller

a) A 40% reduction in battery peak current is made.
b) A 30% increase in DC bus voltage regulation has been made.
c) After acceleration, the power controller reduces the super-capacitor's SOC by 3.5 times compared to no power controller.



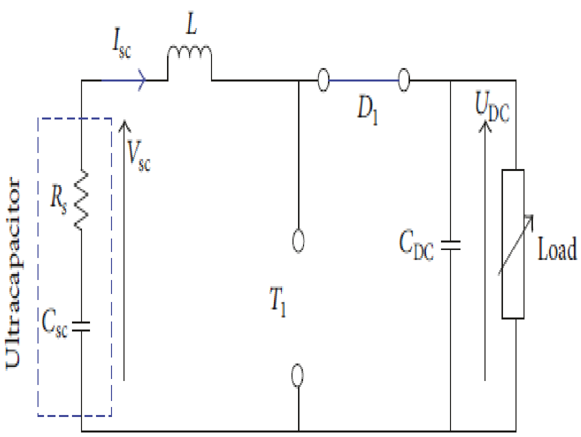
There are many possible topologies of DC-DC converters which interface the ultracapacitor and the DC link. The DC/DC converters can be divided into two categories depending on using the galvanic insulation or not: nonisolated converter or isolated converter. The proposed converter has two basic operating modes: the buck and the boost mode. In this context, many papers have been elaborated. Above fig.5 shows the converter topology. The chosen DC-DC converter is composed of two IGBTs, two diodes, inductor, and capacitor.

Table :-

Switch	Charging mode
T_1	0
T_2	$[0 \quad d_2T_s]$
D_1	0
D_2	$[d_2T_s \quad T_s]$

❖ Topology of Converter

There are two modes. (a) Charging mode: in this case, the load delivers the energy to the capacitor through the IGBT



($T2$),the diode ($D2$), and the inductor L. (b) Discharging mode: in this case, the supercapacitor delivers the energy to the load through the IGBT ($T1$), the diode $D1$, and the inductor L. Table 1 shows the state of any switch for two modes, where Ts, $d1$,and $d2$ denote, respectively, the switching period, the duty cycle in charging mode, and the duty cycle in discharging mode.

The key factors that determine the parameters of the circuit include the limit ripple of the supercapacitor current ($\delta(I\mathrm{sc})$) and the ripple of the output voltage ($\delta(V\mathrm{DC})$), the switching period (Ts), and the output power (Pout).In discharging mode the inductor and the output capacitor are described by the following equation:

$$L \geq \frac{V_{sc} d_2 T_s}{I_{sc} \delta\left(I_{sc}\right)}$$

$$C \geq \frac{d_2 \left(1 - d_2\right)^2 T_s I_{sc}}{V_{sc} \delta\left(V_{DC}\right)}.$$

To model the boost converter, we used the average method. In this case, it is assumed that all components are ideal; that is, there is no internal resistance in the circuit and the circuit components do not consume any energy. We choose two state variables including output voltage and inductor current. The system state space representation is

$$x^{\cdot} = Ax + B \cdot u$$

$$y = C \cdot x,$$

where u is the vector of inputs, y is the outputs, and x is the status variables vector.

$$x = \left[i_{sc}(t), v_{DC}(t)\right]^T,$$

$$y(t) = v_{DC}(t),$$

$$u(t) = v_{sc}(t).$$

During the switching period, the topology converter can be divided into two equivalent circuits.

Case 1 :-

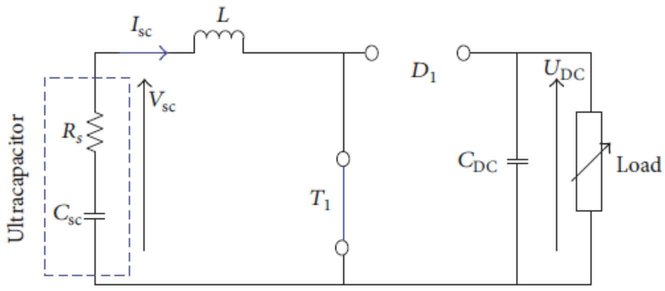


Fig.6

($t \in [0\ d1Ts]$). The switch $T1$ is ON; the equivalent circuit can be simplified as shown in above fig.6

We can write the state space by the following equation:

$$x^{\cdot} = A_1 x + B_1 \cdot u$$

$$y = C_1 \cdot x.$$

The matrices $A1$, $B1$, and $C1$ can be expressed as follows:

$$A_1 = \begin{bmatrix} 0 & 0 \\ 0 & \dfrac{-1}{R_{Load} C_{DC}} \end{bmatrix},$$

$$B_1 = \begin{bmatrix} \dfrac{1}{L} \\ 0 \end{bmatrix},$$

$$C_1 = \begin{bmatrix} 0 & 1 \end{bmatrix}.$$

Case 2 :-

($t \in [d1Ts\ Ts]$). In this case, the switch $T1$ is OFF; the supercapacitor delivers the energy to the load through the inductor and the diode $D1$. The equivalent circuit can be simplified as shown in Figure 7 . Using Kirchhoff law, the state space model is the following:

$$x^{\cdot} = A_2 x + B_2 \cdot u$$

$$y = C_2 \cdot x.$$

The matrices $A2$, $B2$, and $C2$ can be expressed as follows:

$$A_2 = \begin{bmatrix} 0 & 0 \\ \dfrac{1}{C_{DC}} & \dfrac{-1}{R_{Load}C_{DC}} \end{bmatrix},$$

$$B_2 = \begin{bmatrix} \dfrac{1}{L} \\ 0 \end{bmatrix},$$

$$C_2 = \begin{bmatrix} 0 & 1 \end{bmatrix}.$$

The average state model is

$$x^{\cdot} = Ax + B \cdot u$$

$$y = C \cdot x,$$

Where,

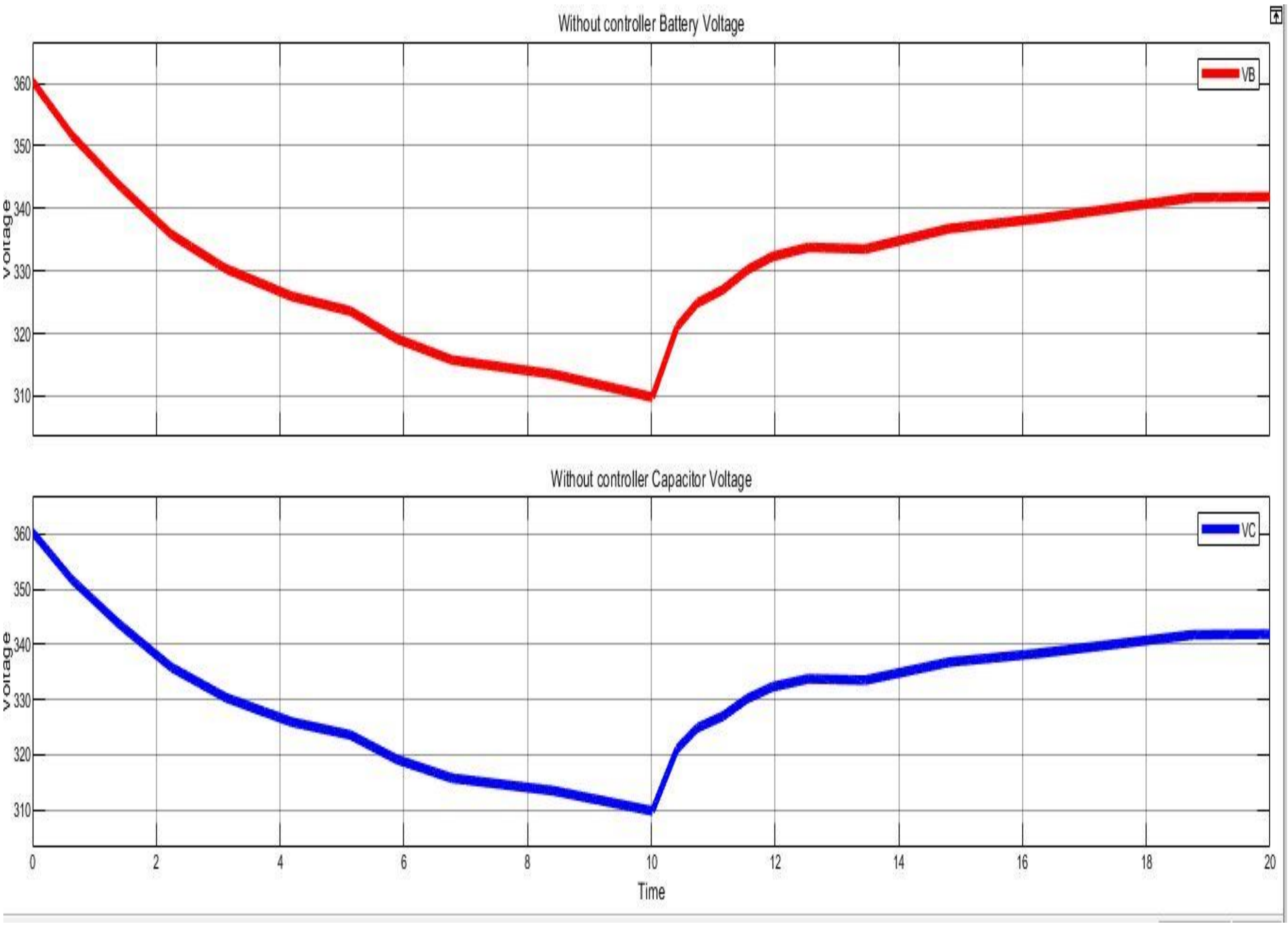
$$A = d_1 \cdot A_1 + (1 - d_1) A_2$$

$$B = d_1 B_1 + (1 - d_1) B_2$$

$$C = d_1 C_1 + (1 - d_1) C_2.$$

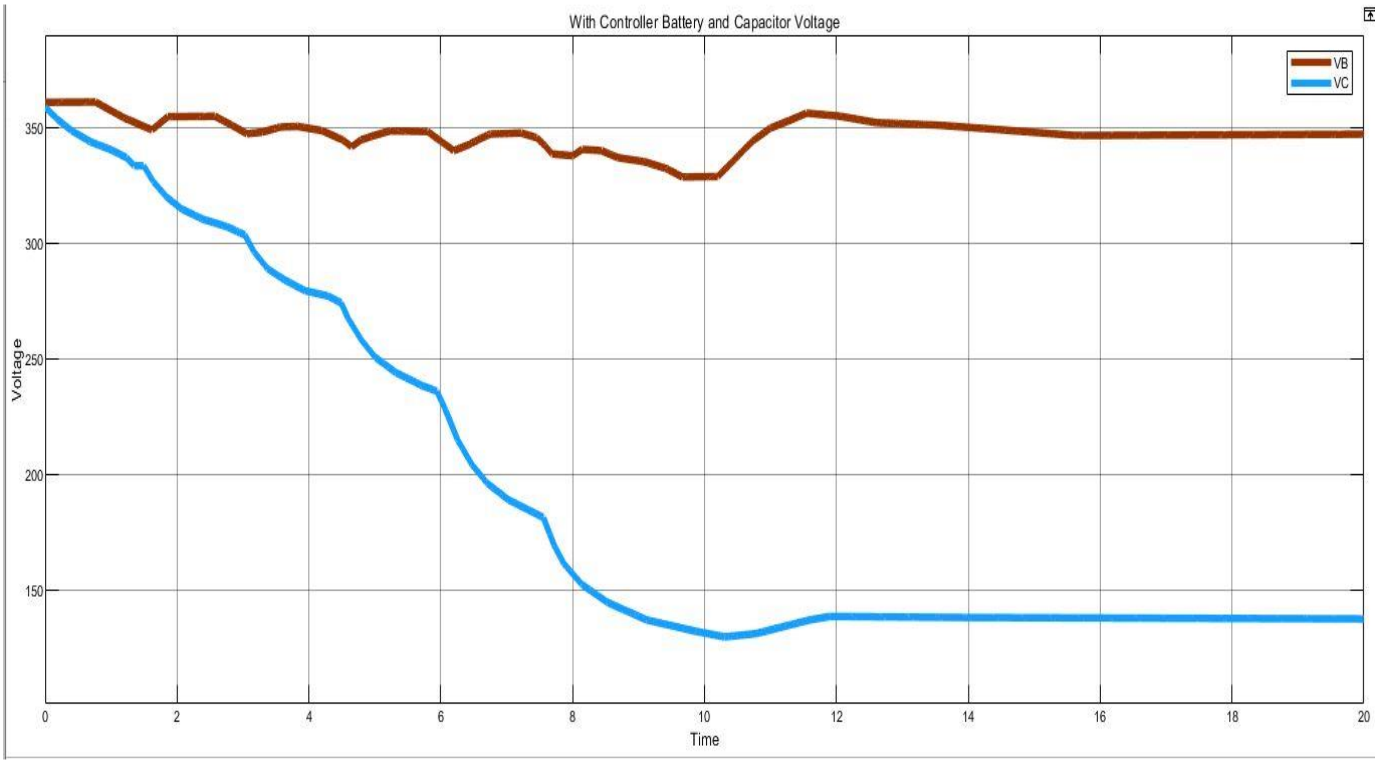
❖ Result with Explanation :-

1. **Without controller connection of battery and super-capacitor**
   Both the battery and the super capacitor discharge voltage equally when they are connected directly. It is not practical since it is exceedingly challenging to charge a battery once its voltage falls below the SOC.



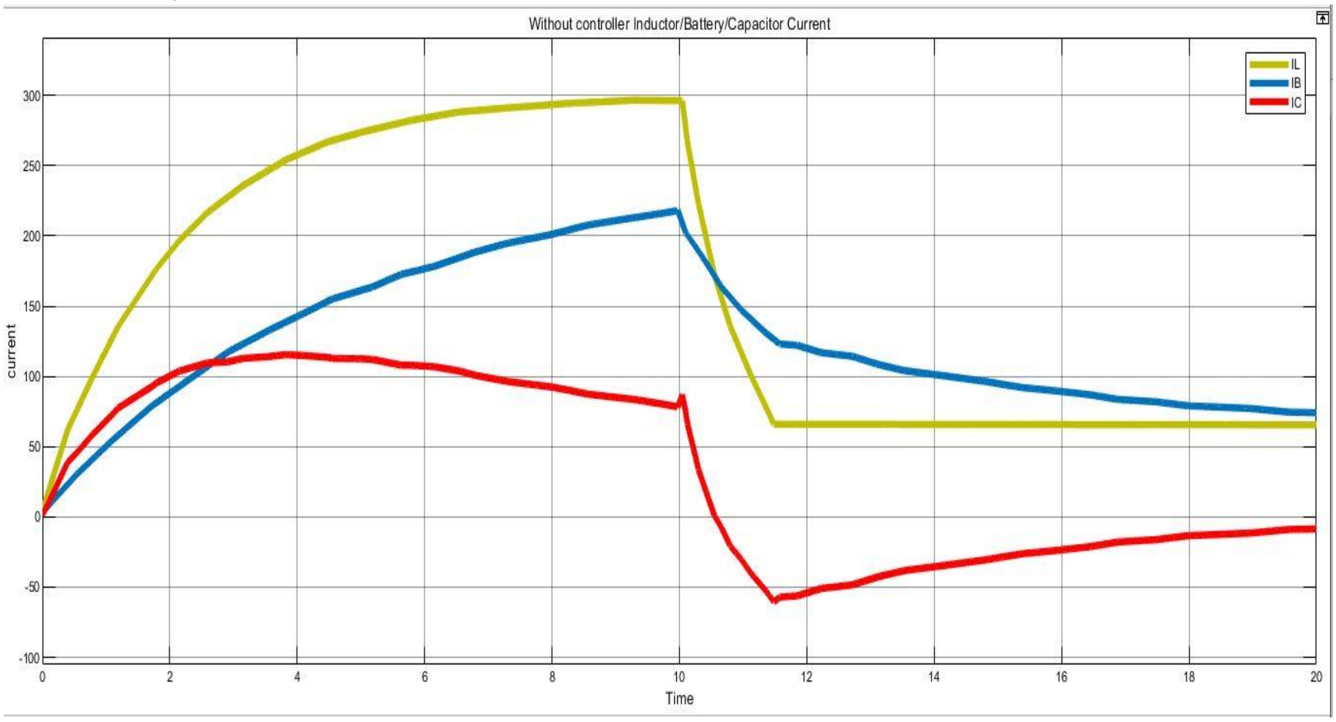
2. With controller connection of battery and super-capacitor

Because the battery voltage is constant and the supercapacitor supplies voltage during acceleration, this is the ideal outcome. After acceleration, the dynamo-powered super-capacitor begins to charge in regenerative mode.



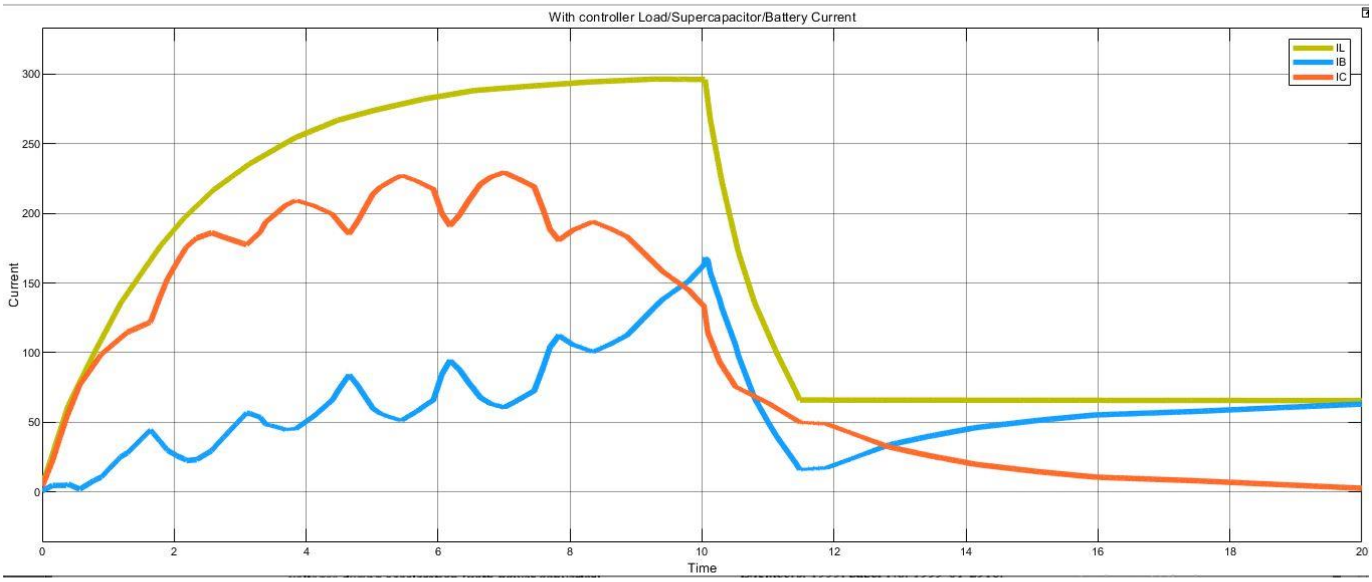
3. Without controller Load / Super-Capacitor / Battery current

The controller has the effect of causing the battery to achieve its peak current after 10 seconds, at which point the current begins to decline.



4. With controller Load/ Super-Capacitor /Battery current

Battery current is reduced by attaching the controller, which is excellent for the battery. This controls the battery and supercapacitor's power flow.



CONCLUSIONS

A direct parallel connection will reduce battery stress by accounting for stray currents that travel to and from the battery, but it will not fully use the super-capacitor as a real power buffer. To use the super-capacitor as efficiently as possible, the power manager only needs two power diodes, two inductors, and two static power switches. However, the ideal control method has not yet been thoroughly determined.

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