# Battery-Ultracapacitor based Hybrid Energy System for Standalone power supply and Hybrid Electric Vehicles

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*Abstract*— **Electric Vehicles (EVs) require energy storage system that can address its fast changing load requirements such as sudden acceleration or quick regenerative braking by being able to supply or absorb high power as demanded. Lead Acid Batteries, commonly used in cheaper EVs (like electric tempo in Nepal), can properly supply these variable loads and get recharged but this mode of operation drastically reduces the life cycle of the battery. A solution to improve the life cycle of the battery and enhance the system's overall performance is to provide a secondary energy storage device, such as Ultracapacitor, having relatively high power density, to act as a buffer by supplying or absorbing the fast changes in load. This combination can reduce the power demand in battery and improves its life cycle. This paper proposes an approach to interface the Ultracapacitor with the battery using digital hysteresis current mode controlled bi-directional boost converter. This approach has the advantage of simplicity and lower cost compared to other topologies. The system was modeled in MATLAB® Simulink and was simulated for step changes in load and regenerative braking conditions. A prototype hardware system with DC Machine as a load has also been developed. The results show that the fast changing load requirements are supplied by the Ultracapacitor and the lead acid battery supplies the slow changing demand and steady state demand.**

Keywords— **Boost Converter, Electric vehicles, Ultracapacitor.**

## I. INTRODUCTION

Large numbers of electric vehicles are being produced nowadays, because of the environmental concerns and ever increasing price of the gasoline. The EVs as compared to gasoline based vehicles have better fuel economy and adherence to emission norms of modern world. [1]. However, EVs are not yet in wide use because of the high cost, limited availability of energy density and short life cycle of the battery when subjected to time-varying current demands like sudden acceleration and regenerative braking. Batteries operate with greatest efficiency and have a longer life time when discharged at a low, steady rate. However, the discharge rate of the battery is determined by the energy needs of the trip and depends on the driving techniques which cannot be controlled by manufacturer. [2].

One way to handle this uncertainty related to fast changing loads is to use secondary energy storage system that can instantly respond to the sudden changes in load. Ultracapacitors are promising to be used as such secondary energy storage systems due to its high power density, long life cycle and good charge/discharge efficiency. [3]. In addition to that, Ultracapacitor can instantly provide and consume large transient power which can help address the load requirements during sudden acceleration and regenerative braking. Several methods have been in practice to connect Ultracapacitor with the battery [4].

Fig. 1 shows a basic approach to connect the Ultracapacitor to the battery. In this configuration, the energy storage devices are connected in parallel with each other and the load. The same terminal voltage of the device causes the power distribution between the devices determined only by their internal resistance. This passive hybrid scheme is suitable for use in supply starter motors but ineffective for source of propulsion power for electric vehicles.
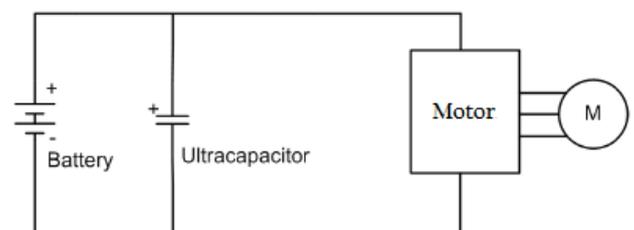


*Fig. 1 Passive Hybrid integration of Energy Storage Devices*

In [5] the Ultracapacitor is connected to the DC Bus through a bidirectional DC/DC buck converter. Fig. 2 shows the schematic scheme used for that system. The simulation result shows that this model can successfully divert the surge

current to the Ultracapacitor during the sudden changes in load. However, one particular disadvantage of using such system is the use of higher voltage rating Ultracapacitor which is costlier than lower voltage Ultracapacitor. Another disadvantage is that the Ultracapacitor voltage cannot be decreased below the DC bus voltage, which prevents full utilization of the energy stored in Ultracapacitor.
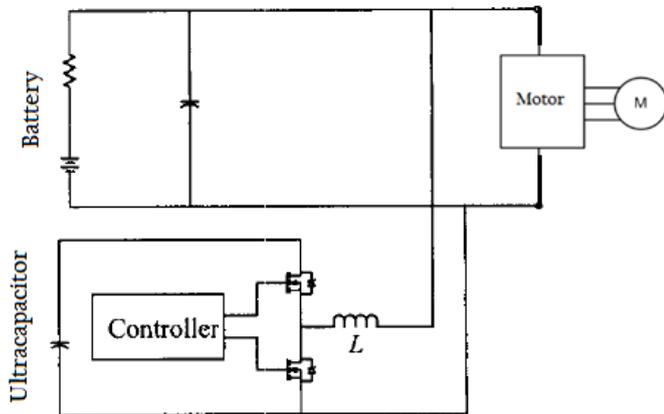


Fig. 2 Ultracapacitor interface topology using DC/DC buck converter

Another approach employs DC/DC converter to connect Battery to Ultracapacitor which is directly connected to the DC bus. Fig. 3 shows the schematic diagram of this type of system. However, in this approach, the power from the battery always needs to flow through the DC/DC converter, which results in poorer efficiency at normal loading condition and variations of the load voltage during capacitor charging/discharging. [4]
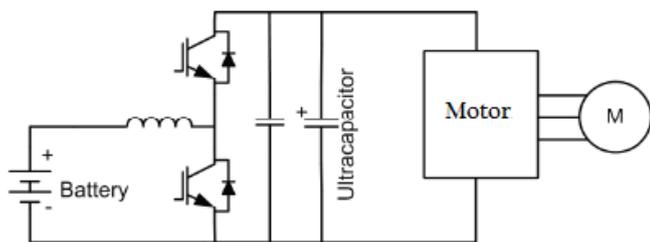


Fig. 3 Battery Ultracapacitor interface using DC/DC converter in battery side

Another approach uses DC/DC converter to connect both the Ultracapacitor and the battery to the DC bus. Fig. 4 shows an approach to use DC/DC converter on both battery and Ultracapacitor. Though this model provides greater control on power flow, the disadvantages are the complexity of the system, higher cost and higher switching losses. [4]
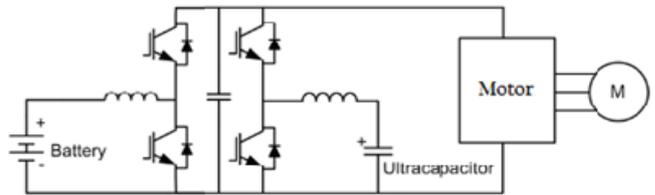


Fig. 4 Battery Ultracapacitor interface using DC/DC converter on both Battery and Ultracapacitor

In this paper, we present an approach of connecting Ultracapacitor to battery systems as shown in Fig. 5. The Ultracapacitor is connected to the DC bus through a bidirectional DC/DC boost converter with a digital hysteresis mode control. The battery is directly connected to the DC bus. This DC/DC converter ensures that the fast changing load requirements is supplied / absorbed by Ultra capacitor thus allowing the battery to supply only the slow changing current.
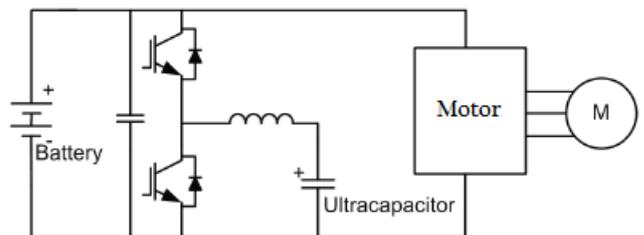


Fig. 5 Proposed Scheme of Battery Ultracapacitor using DC/DC boost converter on Ultracapacitor side

## II. PROPOSED HYBRID INTEGRATION SCHEME

A schematic diagram of the proposed method of interfacing an Ultracapacitor to the Lead Acid Battery is shown in Fig. 5.This is a bidirectional boost converter capable of charging and discharging the Ultracapacitor. Whenever there is a sudden increase in load current, the converter regulates power flow from the Ultracapacitor to the load such that the high frequency part of load current is supplied from Ultracapacitor and lower frequency part is supplied from the battery. Once the load current reaches its steady state value, the Ultracapacitor is recharged from battery using same converter. Likewise, when there is sudden decrease in load current, the high frequency part of the load rejection is absorbed by the Ultracapacitor and there is slow decrease in the battery current. And, after the load current reaches the steady state value the Ultracapacitor supplies back the excess charge to the load.

This interface has the following advantages:

- Single converter for charging and discharging for Ultracapacitor.
- Simple and easy control
- Deep discharge of Ultracapacitor possible.
- Relatively low cost Ultracapacitor can be used as Ultracapacitor is used in low voltage side.

The capacitance C of Ultracapacitor is determined by the increase in the instant load (watt) that the Ultracapacitor has to provide during the transient period of T until the load current reaches up to 95% of its steady state value. We have designed the system such that at maximum the Ultracapacitor is able to supply half the amount of the change in load for the transient period until the load stabilizes. With that, the capacitance C of Ultra capacitor is determined by equation 1.

$$\frac{1}{2}*C*(V_1^2 - V_2^2) = \frac{1}{2} * change\ in\ load * time \qquad (1)$$

The capacitance is determined in such a way that the voltage of the capacitor can fluctuate from its nominal value of 24V to 16V when supplying to the load and up to 32V when absorbing the load rejection.

The inductance L of the converter is decided based upon the acceptable ripple of the current supplied from the Ultracapacitor. The system was tested on two nos. of 16V, 58F Ultracapacitor connected in series and operated at reference voltage of 24V. The system was tested on 48V system, with maximum change of load of 300W and the time constant of the response of the Ultracapacitor is 10 s.

## III. CONTROL STRATEGY

This section details the design of the controller for the bidirectional converter.

### A. Control Architecture

A single controller is designed to control both the current to be supplied by the Ultracapacitor and maintain the voltage of the Ultracapacitor after it addresses the changes in load. Fig. 6 shows the control loop implemented in the proposed system. There are two control loops in the control architecture:

1. The innermost loop is the current controller that controls the inductor current $i_L$ which is the current to be supplied by the Ultracapacitor. This loop is designed to be very fast so that inductor current changes instantly for a change in load, hence enabling the Ultracapacitor to respond instantly to load changes.

2. The outer Ultra capacitor voltage control loop stabilizes Ultracapacitor voltage after the load current reaches its steady state value. This loop implements a PI controller which is fed the voltage deviation from the steady state voltage and provides the current required to flow in/out of Ultracapacitor in order to return back to the steady state voltage of the Ultracapacitor.

### B. Controller Design

The objective of energy storage device is to stabilize the current supplied by the battery during sudden changes in load current. The controller consists of a digital high pass filter, a digital hysteresis comparator and a PI controller for voltage regulation of Ultracapacitor. The digital high pass filter constantly monitors the load current and outputs the high frequency component of the load current. As the voltage level at which the load changes has occurred is not same as the Ultracapacitor voltage, this high frequency component of load current is then scaled by the ratio of Battery Voltage to Ultracapacitor Voltage. Also, to consider the losses in the DC/DC converter a loss factor has been used to scale the high frequency component of load current. The PI controller is used to maintain the Ultracapacitor voltage at its nominal level. The output of the PI controller is subtracted from the scaled high frequency part of load current, the result of which is the reference current that is to be supplied / taken by the Ultracapacitor. This reference current is then compared with the actual current flowing from the Ultracapacitor using the digital hysteresis comparator. The band of the hysteresis comparator is determined based on the tolerated value of current error. The output of the digital hysteresis comparator is then used as the gate signal for the DC/DC converter.

## IV. SIMULATION RESULTS

The performance of the proposed system along with the controller was simulated in MATLAB Simulink for a step change in load current. The model consists of a standard battery and Ultracapacitor model along with a high pass filter and a controlled current source to model the changes in load current. The results show that after the step increase in load current, the inductor current increases instantly taking up the change in load current. The inductor current then decays as battery current takes on the load current slowly. As the load current stabilizes the Ultracapacitor takes on small amount of current from the battery in order to maintain the voltage of Ultracapacitor back to nominal value. Fig.7 and 8 shows the MATLAB Simulink model of the developed scheme.
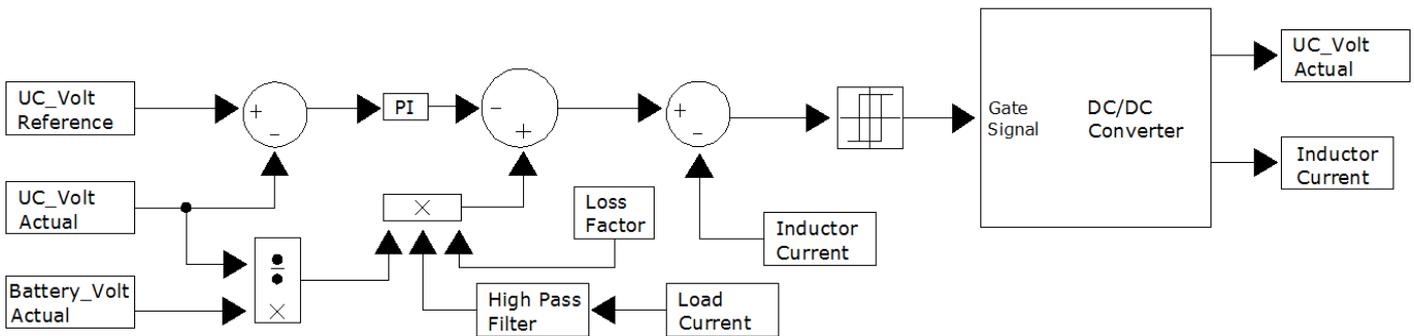


*Fig. 6 Control Architecture for the proposed hybrid energy storage system*
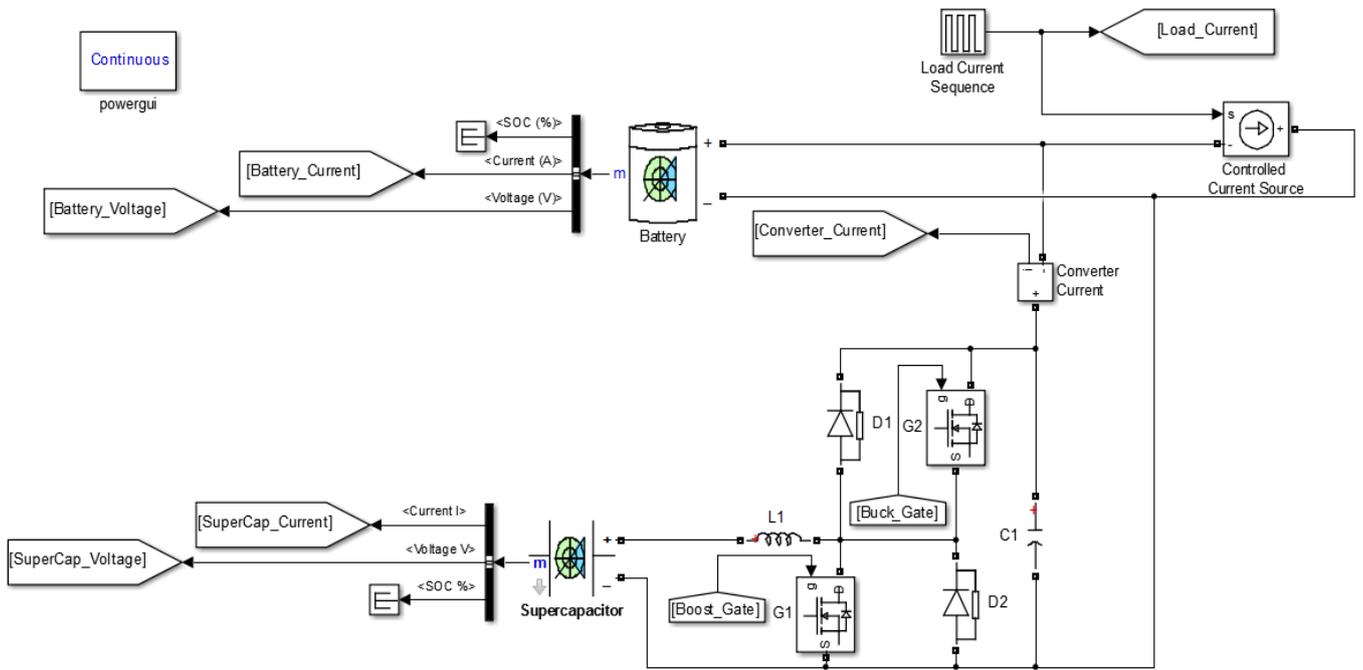
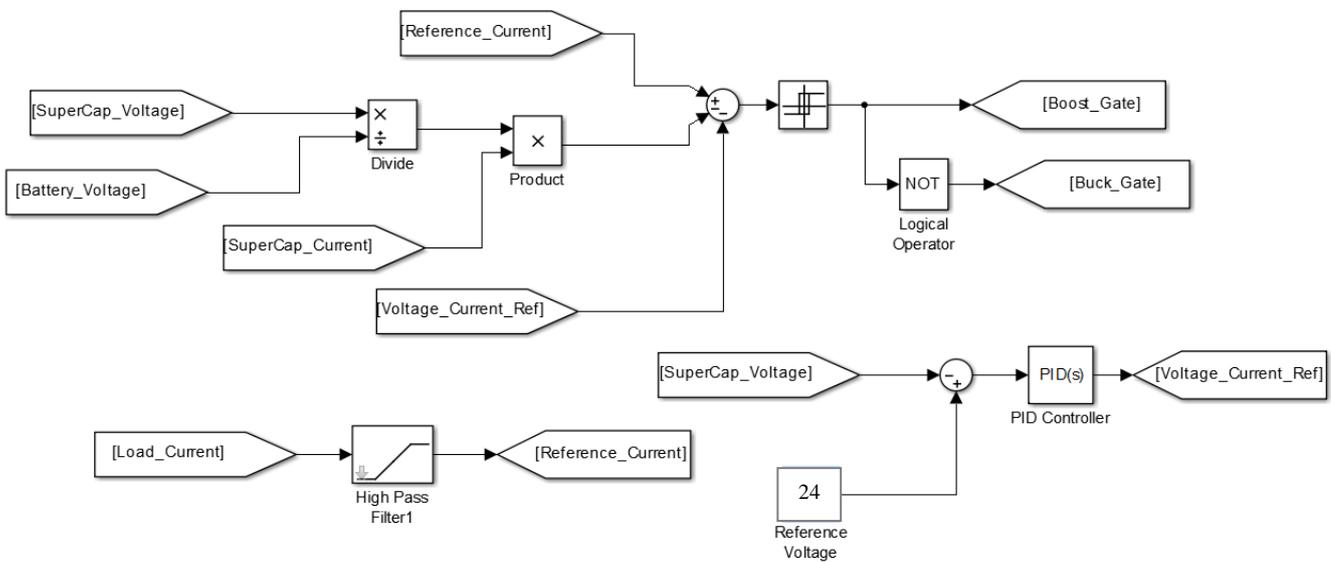*Fig. 7 MATLAB Simulink model of the power converter of the proposed scheme*



*Fig. 8 MATLAB Simulink model of control architecture of the proposed scheme*

The Simulink model of the proposed system was tested on following load conditions:

a. At time t = 10 seconds, a step load of 50A was turned on.
b. At time t = 75 seconds, the load was turned off.
c. At time t = 100 seconds, a step load of 100 A was turned on.
d. At time t = 110 seconds, the step load of 100A was turned off.
e. At time t = 175 seconds, a negative step load of 50 A was turned on.
f. At time t = 200 seconds, the negative load was turned off.

The load current, battery current and converter output current at the given load conditions are shown in fig. 9. Fig. 10 shows the battery voltage and Ultracapacitor voltage at the same load conditions.
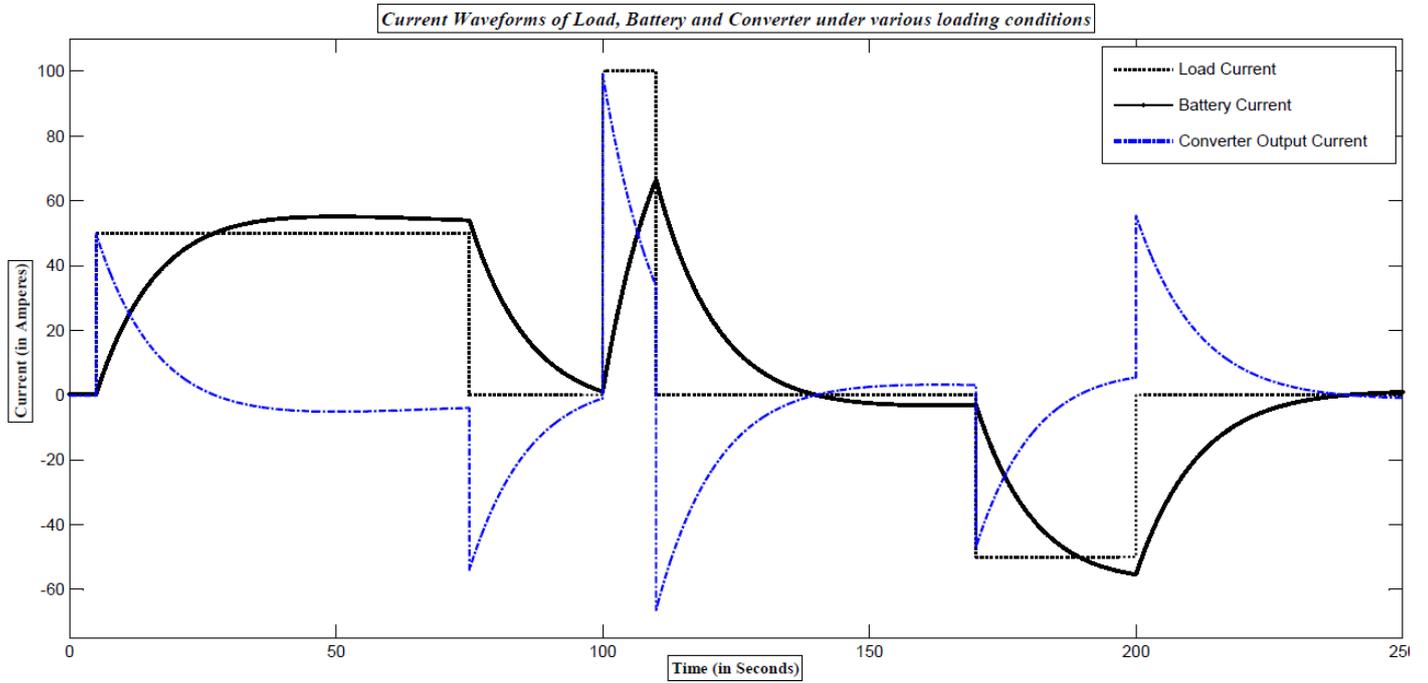
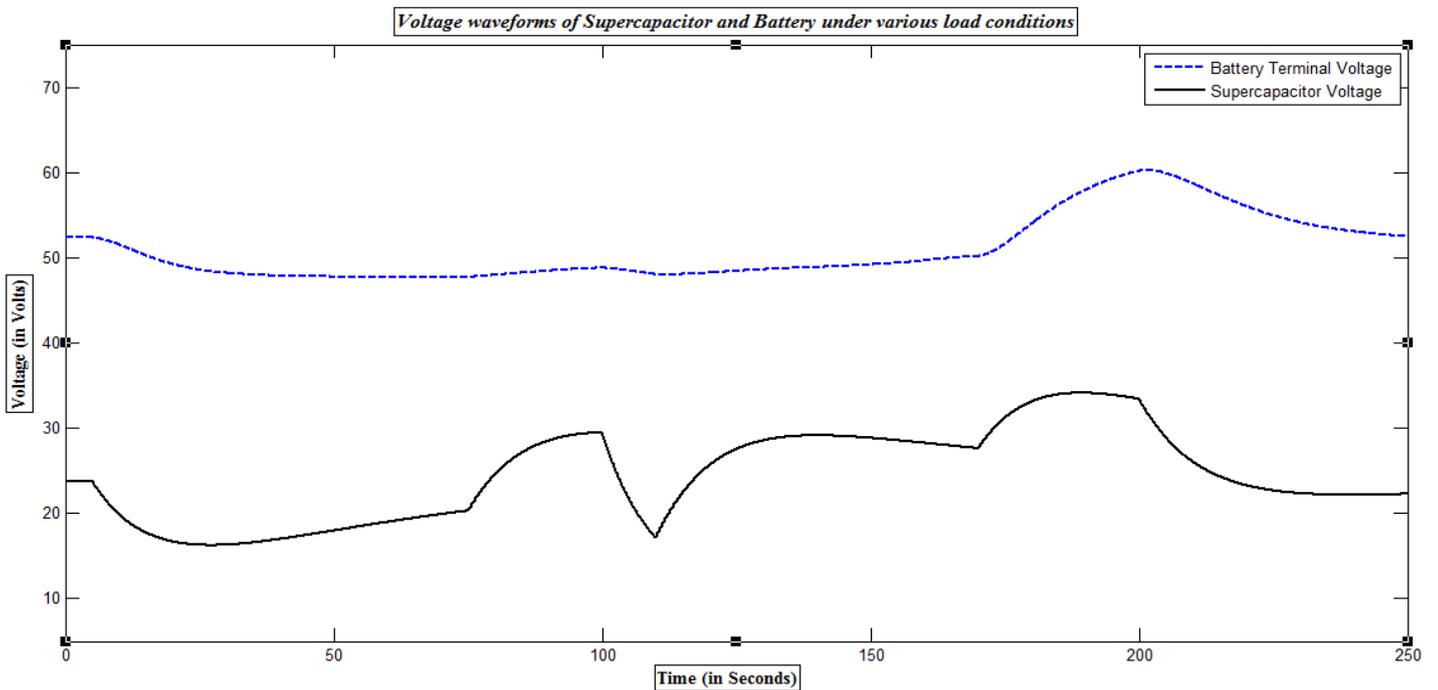*Fig. 9 Load Current, Battery Current and Converter Output Current at various loading conditions*



*Fig. 10 Battery Terminal Voltage and Ultracapacitor voltage at various loading conditions*

The simulation result shows that whenever there is a change in load current the Ultracapacitor can respond instantaneously to the change in load current leaving the battery to slowly supply the load demand. As the battery is subjected to only slowly changing load current, and only supplies the fraction of the load current demand, the battery's life is prolonged using this kind of energy storage system.

## V. HARDWARE RESULTS

The hardware prototype of the proposed system has been developed for a 48V system. The load used was a DC motor

coupled with a synchronous generator. The change in mechanical load is simulated by changing the load in the synchronous generator side. The controller used is Microchip's dsPIC33FJ32MC202. The PI controller, hysteresis comparator and high pass filter has been implemented in the micro-controller. Fig. 11 shows the current delivered by the battery without the controller. Here, in this figure, it is seen that the changing current are sharp.
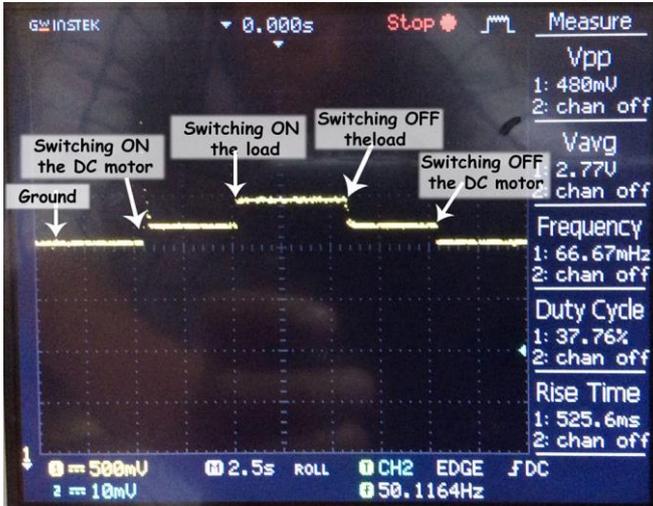


*Fig. 11 Switching pattern of the load used to test the developed hardware prototype*
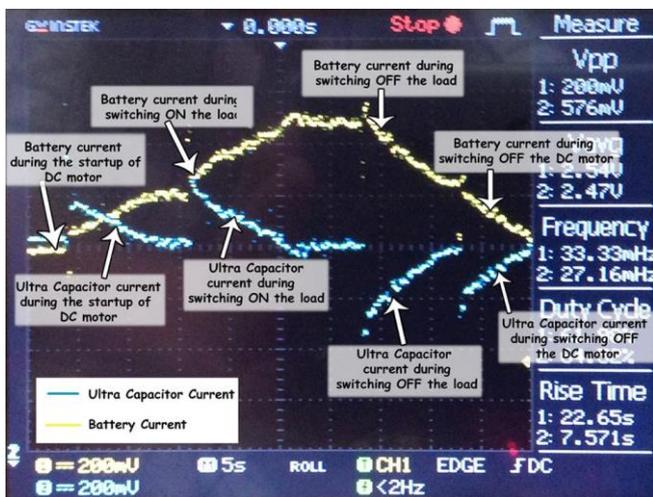


*Fig. 12 Battery Current and Ultra capacitor Current at various load switching instances*

Fig.12 shows the current delivered by the battery after the integration of the controller circuit and Ultra capacitor. Here, in this figure, it is seen that there is no sharp changes in battery current and all the high frequency component of the load current has been diverged to the Ultra capacitor. Fig. 13 shows the voltage profile of the battery and Ultra capacitor. Here, it is seen that the voltage of the battery is almost constant whereas the voltage of the Ultra capacitor is

changing with change in load. Its voltage drops while delivering power to the load and comes back to its nominal voltage after getting charged by the voltage loop of the controller.
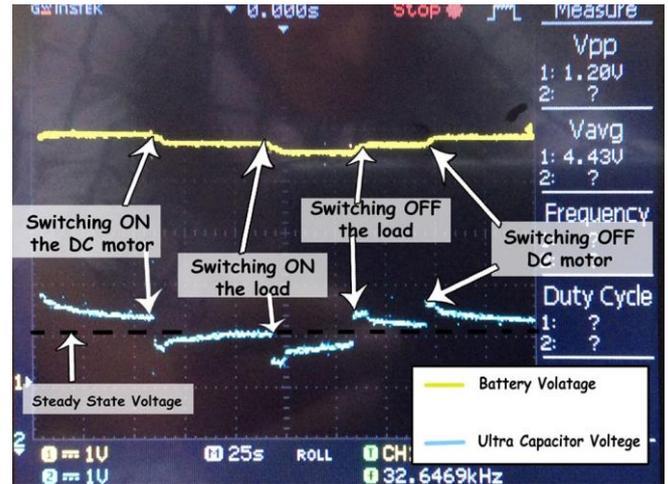


*Fig. 13 Voltage profile of Ultracapacitor and Battery as per the load switching instances*

## VI. CONCLUSION

The paper discusses a topology and control strategy for interfacing an energy storage device like an Ultracapacitor to a lead acid battery. Such interfacing improves the dynamic response of the system and helps the system to respond to the sudden change in load conditions in better manner. Also, the lead acid battery is subjected to lower frequency component of the change in load current which causes a smooth transition in battery current thus contributing to a prolonged life of the battery. The paper also shows that using a bi-directional boost converter as an interface between Ultracapacitor and lead acid battery gives better control of the current that is to be supplied by the Ultracapacitor. The controller designed allows the Ultracapacitor to respond to fast changing loads and then get back to its nominal voltage slowly, after the load current reaches its new steady state.

## ACKNOWLEDGEMENT

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