Battery-Ultracapacitor based Hybrid Energy System for Standalone power supply and Hybrid Electric Vehicles - Part I: Simulation and Economic Analysis

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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. 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. Considering the average life of batteries in vehicular system as 15 months, the storage system is found to be economically feasible if the battery life is extended to 18 months.

Index Terms - 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 load 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

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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]

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]

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 Ultracapacitor thus allowing the battery to supply only the slow changing current.

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 the 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:
1. Single converter for charging and discharging for Ultracapacitor.
2. Simple and easy control
3. Deep discharge of Ultracapacitor possible.
4. Relatively low cost Ultracapacitor can be used as it 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 is designed 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 Ultracapacitor is determined by equation 1.

\[
\frac{1}{2} C \left( V_1^2 - V_2^2 \right) = \frac{1}{2} \text{ change in load } \times \text{ time} \quad \text{(1)}
\]

The capacitance is determined in such a way that the voltage of the capacitor may 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 16V, 58F Ultracapacitors 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 Ultracapacitor’s response is 10 s.

III. CONTROL STRATEGY

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

3.1 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 the load.
Fig. 6 Control Architecture for the proposed hybrid energy storage system

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 Ultracapacitor 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.

### 3.2 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 continuously 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 the 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 the current error. The output of the digital hysteresis comparator is then used as the gate signal for the DC/DC converter.

Fig. 7 MATLAB Simulink model of the power converter of the proposed scheme
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 the load current. The results show that after the step increase in the load current, the inductor current increases instantly absorbing the change in load current. The inductor current then decays as battery current starts supplying the load current slowly. As the load current stabilizes the Ultracapacitor starts drawing a small amount of current from the battery in order to maintain its voltage back to nominal value. Fig. 7 and 8 show the MATLAB Simulink model of the developed scheme.

The Simulink model of the proposed system was tested on the 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.

Fig. 9 Load Current, Battery Current and Converter Output Current at various loading conditions.
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.

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 only to slowly changing load current, and supplies only the fraction of the load current demand, the battery’s life is prolonged using this kind of energy storage system.

V. ECONOMIC ANALYSIS

The contribution of UC in enhancing the battery life is reported in many databases, specified as twice to 3 times. However, the exact number of extended time cannot be generalized here as it is specific to the motor drives, drive cycles and the road condition. Since there is no first hand observation of average life of UC-battery in Nepalese electric vehicle industry, the economic analysis is carried out on the basis of minimum number of extended months that would make the integration feasible. For this, a typical electric vehicle running in Kathmandu valley is assumed with parameters presented in Table I.

Table I: Data and assumption for the economic analysis

<table>
<thead>
<tr>
<th>SN</th>
<th>Items</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Drive system</td>
<td>DC motor and controller</td>
</tr>
<tr>
<td>2</td>
<td>Power rating</td>
<td>8 hp</td>
</tr>
<tr>
<td>3</td>
<td>Battery size</td>
<td>72 V, 120Ah</td>
</tr>
<tr>
<td>4</td>
<td>Battery life</td>
<td>15 month</td>
</tr>
<tr>
<td>5</td>
<td>UC Hybrid System</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>UC</td>
<td>200000</td>
</tr>
<tr>
<td>7</td>
<td>Controller</td>
<td>50000</td>
</tr>
<tr>
<td>8</td>
<td>Discount rate</td>
<td>10%</td>
</tr>
<tr>
<td>9</td>
<td>Inflation rate</td>
<td>8%</td>
</tr>
<tr>
<td>10</td>
<td>UC Life</td>
<td>12 years</td>
</tr>
<tr>
<td>11</td>
<td>Controller life</td>
<td>3 years</td>
</tr>
</tbody>
</table>

Under these data and assumption, an economic analysis is performed to determine the minimum amount of months to be extended so as to recover the additional cost of the UC and converter system. It has been found that the project is Feasible if battery’s life is extended to additional 2.5 months; that means to enhance battery life to 17.4 months.

Net 200000 136994.3 2434843.4
Min Month of Battery Replacement 17.4 months

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 the fast changing load and then get back to its nominal voltage slowly, after the load current reaches its new steady state. It has also been shown that the project would economically feasible if the hybrid topology enhance the battery life by 2.4 months, indicating its applicability in real system.

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