Performance Optimization of Battery-Super Capacitor Hybrid System

Electrochemical capacitors (ultracapacitors) offer high power density when compared to battery systems and also have a relatively large energy density compared to conventional capacitors. In the late nineties they have gained considerable attention because of their extensive use in power distribution systems, electronic devices, uninterrupted power supply and hybrid vehicles. Several research attempts have been made to understand the performance of super capacitors with batteries and fuel cells under specific loads. Despite the fact that Lithium-ion batteries are the superior most power sources as compared to other battery systems, the performance of the Li-ion battery is greatly affected when utilized under high current discharges. Lithium ion batteries have a high energy density of about $10^5$ J/kg; however the power density is very less, around 100W/kg. As a result, the Lithium-ion battery cannot yield to high power demands. The addition of ultra capacitors in parallel to the battery increases the utilization of the battery at higher rates of discharge because of the high power density of ultra capacitors ($\sim 10^6$ W/kg). To enhance the need for the ultracapacitors pulsed power loads are very frequently encountered in communication systems such as mobile phones, cellular devices and military applications in which the batteries alone cannot yield to intermittent high power demands.

In this work, the effect of operating parameters such as the duty ratio, the pulse frequency and design parameters (the capacitor configuration index) on a battery/hybrid system were studied in detail. It was observed that the performance improvement of the hybrid system over the battery system was maximum at a duty ratio of around 0.2 and shifts slightly to higher duty ratios at higher frequencies. The increase of the discharge capacity of the hybrid system was limited beyond a certain frequency, called the maximum Eigen frequency. From the experimental analysis it can also be seen that the hybrid systems suffer less internal ohmic losses when compared to the battery. Although higher power can be withdrawn from hybrid a system which has the same energy as that of the battery, when compared on a mass basis, the Ragone plots show a decreased value of power and energy densities for the hybrid system.

Figure 1 shows the fractional capacity increase $\beta$ as a function of duty ratio for various frequencies. The fractional capacity $\beta$ is defined as the ratio of increase in the discharge capacity obtained for the hybrid system over the discharge capacity of the battery system under the same discharge protocol. As shown in Figure 1, at lower frequencies the fractional capacity increase was maximum at low duty ratios and at higher frequencies the peak moves towards higher duty ratios. However at a duty ratio of 0.4 the fractional increase in the capacity goes to a minimum and it was found that at even higher duty ratios the fractional increase in the discharge capacity diminishes to zero. The results can be explained by taking into account the shift of the discharge curve in the case of the hybrid system observed at higher duty ratios which results in shorter run times. It can also be observed that the increase of the fractional capacity levels off beyond a particular frequency. The results indicated that above 1 Hz there is not much gain in the fractional capacity. This agrees with the maximum Eigen frequency given by $1/R_c C_c$ which is approximately 2.5 Hz.

![Figure 1](image-url)  
**Figure 1.** Fractional capacity increase as a function of duty ratio for various frequencies.
Optimization

The optimization of the operating conditions for a given system is based mainly on the application requirements. Some of the predominant features which most applications entail are: high power output, longer discharge period and a complete utilization of the active material. According to these studies in a case where higher discharge capacity is expected from the system, the hybrid system is obviously a better choice over the battery. The number of super capacitors in parallel with the battery or the configuration index \( m \) is the next parameter to be adjusted. It can be seen from the experiments (Figure 2) that the fractional capacity increase is very small between \( m=5 \) and \( m=10 \) however, the mass of the capacitor network is doubled for these configurations. Thus, it would be better to chose a capacitor network that would match with the battery voltage and with \( m=5 \).

For the optimization of the operating condition we can see from Figure 1 that the fractional capacity increase is maximum at duty ratios around 0.2-0.3 depending on the frequency of operation. The pulse frequency as observed in Figure 1 is optimized in the range between 1-10 Hz. Although the system can yield slightly higher capacity at higher frequencies it would be advisable to operate at the limiting frequency (~10 Hz) in order to avoid the use of a robust hardware power sources to deliver high frequency pulses. Also for light weighted applications it is disadvantageous to use a hybrid system as seen from the Ragone plots despite many obvious advantages. Similar optimization of operating conditions and design parameters for high power or energy requirements can be made from the presented experimental data.

![Figure 2. Plots showing the fractional increase in the capacity and the fractional increase in energy on the left axis as a function of the capacitor configuration index. The plot corresponding to the right axis shows the average power withdrawn from the system for various capacitor configuration indices.](image-url)