Performance of a Battery - Capacitor Hybrid Power System under Pulse Loads

Ramakrishna Gundala a, Charles Holland a, John W. Weidner a, and Ralph E. White a*

a Center for Electrochemical Engineering
Department of Chemical Engineering
University of South Carolina, Columbia, SC 29208

*Phone: (803) 777-3270
*Fax: (803) 777-8265
*E-mail: white@engr.sc.edu

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* To whom correspondence should be addressed
ABSTRACT

The performance of a battery-capacitor hybrid power system under pulse load is studied. Simplified physics-based models of the battery and ultracapacitors are developed and model parameters are extracted from the experimental data collected from the individual components. Simulations of individual components and hybrid devices under constant current and pulse current loads also are performed and compared to the experimental data. The effects of component parameters (masses, capacitances, resistances) and load parameters (peak current, duty ratio, frequency) on hybrid performance are then studied via simulations. The results show that under pulse loads, hybrid systems not only increase the energy but they also decrease the load fluctuations on the battery. Guidance is given on how to choose a hybrid system to improve the energy density for a specific application.

Introduction

Battery-capacitor hybrid systems are of interest because they combine the high energy density of batteries and high power density of capacitors. They also lead to longer operating time and enhance battery life \(^1\). Miller \(^2\), discussed extending the energy-power performance envelop of a battery system when combined with a capacitor. He studied the performance of a digital phone for a fixed total volume. He varied the fraction of volume occupied by the capacitor and concluded the optimum battery capacitor volume ratio was 4:1. His analysis assumed that the two devices are electrically decoupled so that the capacitor could discharge through a different voltage window than the battery. Conway \(^3\)
compared and contrasted the shapes of Ragone plots of an individual ideal battery system (i.e. constant equilibrium voltage) and a supercapacitor. He characterized the Ragone plot of the battery system into ohmic and kinetic polarization parts and discussed the effect of each of these parts on its energy density – power density relationship. He also discussed the effects of capacitance and ohmic resistance of a supercapacitor on its Ragone plot and derived expressions for the maximum power that can be obtained from the capacitor.

In this work, we study the battery–capacitor hybrid systems without using any additional electronics for decoupling. The advantage of the approach is the elimination of additional electronics and the weight associated with them. The resistances of the battery and the capacitor serve as passive decouplers. We develop simple physics based models of the battery and the capacitors, where we neglect the spatial variations in the devices. The device models are fit to experimental voltage-time data obtained during constant current discharges. The models accurately reflect the experimental data for low to moderate currents. The models parameters are kept as few as possible without sacrificing the accuracy of the fits so that we can completely characterize the effect of each of these parameters on the hybrid performance. This also simplifies the modeling approach and drastically reduces the computational time.

**System Description**

The schematic of the battery-capacitor hybrid system under study is shown in Figure 1. Experimental data was collected on a system consisting of a 1.20 Ahr rated Polystor’s 8.8mm prismatic lithium-ion battery in parallel with a 5 F or 50 F ultracapacitor from Maxwell Technologies. In summary, the operating voltage range of
the lithium-ion battery was 4.2 V – 2.8 V. The peak operating voltage of the ultracapacitors was 2.7 V. Therefore, the nominal operating voltage of the battery was matched using either two 10 F or two 100 F ultracapacitors combined in series. No power electronics were used for decoupling the component voltages. Instead, the system voltage floated at the battery’s voltage. The internal resistances of the battery and the capacitors serve as the de-couplers. For a detailed description of the experimental set-up, data acquisition, charging and discharging regimes, the reader is referred to the paper by Holland et. al. 4.

For both experimental and simulation studies, the battery, capacitor and hybrid system were subjected to a pulse current load of varying amplitude (peak current), duty cycle and frequency. A typical system profile is shown in Figure 2 with a peak current of 2.50 A, a frequency of 1 Hz and a duty cycle of 0.50. The system current \( I_s \) is equal to the sum of the battery and the capacitor currents \( I_b + I_c \). During off pulse, the system current is equal to the leakage current in the experiments, which is measured at 19.8 mA 4. All the simulations are done between 4.2 V and 2.8 V unless indicated otherwise. The total energy density obtained during the discharge of an electrochemical system (individual component or a hybrid) is given by

\[
E_T = \frac{1}{M} \int_0^{t_c} V(t)I(t)dt
\]

[1]
where, $M$ is the mass of the electrochemical system and $t_c$ is the time taken to reach the cut-off voltage. The pulsed energy density is the energy obtained only during the pulse on time and is given by

$$E_p = \frac{1}{M} \int_0^{t_c} [V(t)I(t)]_p dt$$  \hspace{1cm} [2]

where the subscript $p$ is used to indicate the energy obtained only when the pulse is on. The total energy density is slightly more than the pulsed energy density because of the presence of the small leakage current during the pulse off time of the experiments. The pulsed power density is the power obtained only when the pulse is on and can be calculated from the pulsed energy density,

$$P_p = \frac{E_p}{t_c D}$$  \hspace{1cm} [3]

where $D$ stands for the duty cycle of the pulse and is defined as $D = t_{on} / (t_{on} + t_{off})$.

**Model Development**

*Li-Ion Battery Model*

We assume that concentration and potential variations in the porous electrode are negligible so that the electrochemical reactions are uniform throughout each electrode. Further, the cell is assumed to operate isothermally. Therefore, if we consider only an overall state of charge ($\theta$), the charge balance reduces to the following differential equation.
\[ \frac{d\theta(t)}{dt} = -\frac{I_b(t)}{Q_b} \]  

where \( I_b(t) > 0 \) for discharge process.

The equilibrium potential of the battery as a function of the state of charge \( \theta \) is unknown and assumed to follow the following equation,

\[ U_b = \sum_{k=1}^{10} a_k \theta^{k-1} \]  

Finally, the voltage across the battery after the ohmic losses is given by

\[ V_b(t) = U_b(\theta) - R_b I_b(t) \]  

where \( R_b \) is the overall resistance of the battery, and is assumed to be independent of current. Equations 4-6 are solved numerically and combined with Equations 1-3 to construct Ragone plots (i.e. power density versus energy density) of the battery. However, an analytical solution to the energy-power density can be obtained if one assumes the battery has a constant equilibrium potential denoted by \( U^*_b \). If we assume a completely flat discharge profile of the battery, the energy density and power density of the battery for a constant current discharge are given by,

\[ E^*_{T,b} = \frac{[U^*_b I_b t_c - I^2_b R_b t_c]}{M_b} \]  

\[ P^*_{T,b} = \frac{E^*_{T,b}}{t_c} = \frac{[U^*_b I_b - I^2_b R_b]}{M} \]  

where \( t_c \) is the time taken until the cut-off.
The maximum energy density is obtained from equation 7 by letting $I_b \rightarrow 0$. The maximum power density of the battery can be obtained from equation 8 by solving

$$\frac{dP_{T,b}^*}{dI_b} = 0$$

for $I_b$ and given as,

$$E_{T,b,\text{max}}^* = \frac{U_b^* Q_b}{M_b}$$

Equations 9, 10 will guide the parametric studies.

**Ultracapacitor Model**

Again assuming that the reactions are uniform throughout the electrode, the charge balance on the capacitor gives,

$$I_c(t) = -C_c \frac{dV_{c,q}}{dt}$$

where $I_c(t) > 0$ for discharge, and the capacitance, $C_c$, is assumed constant. The voltage across the capacitor is given by,

$$V_c(t) = V_{c,q} - R_c I_c(t)$$

Analytical solutions for the energy and power density of a capacitor can be obtained for a constant current discharge without any further simplifications. The power density can be given in terms of the energy density as,

$$E_{T,c} = \frac{V_{\text{max}} I_c t_c - \frac{I_c^2 t_c^2}{2 C_c} - \frac{I_c^2 R_c t_c}{2}}{M_c}$$

[13]
where \( t_c = \frac{[V_{\text{max}} - V_{\text{min}} - I_cR_c]C_c}{I_c} \) is the time taken to reach the cut-off voltage.

The maximum energy density of the capacitor can be obtained from equation 13, after plugging the expression for \( t_c \) and letting \( I_c \to 0 \).

\[
E_{T,c,\text{max}} = \frac{1}{2} \frac{C_c (V_{c,\text{max}}^2 - V_{c,\text{min}}^2)}{M_c}
\]  

[15]

The maximum power density of the capacitor can be obtained from equation 14 by solving \( \frac{dP_{T,c}}{dI_c} = 0 \) for \( I_c \) and is given as,

\[
P_{T,c,\text{max}} = \frac{1}{8} \frac{(V_o + V_c)^2}{R_c M_c}
\]  

[16]

where \( V_o \) is the initial voltage and \( V_c \) is the cut-off voltage.

Srinivasan and Weidner 5 derived an analytical expression for the energy and power density for the constant current discharge of an electrochemical capacitor as a function of constant capacitor current. They accounted for the non-uniform discharge of the electrodes using porous electrode theory. For ionic resistance much larger than the electronic resistance, the dimensionless power density of the electrochemical capacitor model can be given in terms of its dimensionless energy density as
\[ E_{T,c} = \frac{2I_c V_0}{M_c \kappa^2} \left[ 1 - \frac{I_c L}{3\kappa V_0} - \frac{I_c t}{2aCL^2 V_0} - \frac{I_c L_s}{2\kappa_s V_0} \right] - \frac{4aC I_c^2 L^3}{M_c \kappa^2} \sum_{n=1}^{\infty} \frac{\exp\left(-\frac{n^2\pi^2 t}{aCL^2 \kappa}\right) - 1}{n^4 \pi^4} \]  

[17]

and

\[ P_{T,c} = \frac{E_{T,c}}{t_c} \]

[18]

where \( t_c \) is the time until cut-off. Equations 13, 14 approach equations 17 and 18 at low currents, with \( C_c = \frac{aCL}{2} \), \( R_c = \frac{2L}{3\kappa} + \frac{L_s}{\kappa_s} \). These functions will be compared in the next section using parameters obtained from the experimental data.

**Hybrid Model**

For current pulsing of the battery - capacitor hybrid system, Equations 6, 11 and 12 can be simultaneously solved during any small single on-pulse or single off-pulse (so that \( U_b \) can be assumed to be constant) to obtain the voltage and current profiles of the battery and the capacitor models during that pulse. An equation describing the charge on the capacitor during an on-pulse/off-pulse as a function of time can be given as

\[ Q_c(t) = (U_b - I_s R_b)C_c + (Q_c(0) - U_b C_c) \exp\left(-\frac{t}{C_c (R_b + R_c)}\right) \]

[19]

where \( t \) starts at the beginning of the on-pulse/off-pulse and \( Q_c(0) \) is the charge on the capacitor at \( t = 0 \). The time constant for discharging/charging the capacitor is seen to be \( C_c (R_b + R_c) \).
Results and Discussion

Comparison between Experimental Data and Simulation

There are totally 13 parameters ($a_1$, $a_{10}$ in equation 2, $R_b$, $Q_b$ and $M_b$) in the battery model. The mass was obtained by weighing the cell. The other 12 parameters are simultaneously estimated by fitting the model to the two lowest constant current experimental discharge curves (0.32 A and 0.62 A). The resultant parameters $R_b$, $Q_b$ and $M_b$ are given in Table 1. The discharge curves at various rates using these parameters are shown in Figure 3. It can be seen that the simple battery model predicts the discharge curves reasonably well over the discharge rate range used in the study.

There are 3 parameters ($C_c$, $R_c$ and $M_c$) in the capacitor model. The mass was obtained by weighing the capacitor. The other two parameters were simultaneously estimated by fitting the model to the experimental data obtained from pulse discharge of the capacitors. These three parameters are also shown in Table 1 for 5 F and 50 F capacitor models. Figure 4 shows the resulting voltage fit of the 5 F capacitor model to that of the experimental data for a pulse current discharge. The model does not track the transients very well since the charging current is assumed uniform. However, the model does track the voltage, which we will see late is the key to the hybrid for predicting the system level interaction of the hybrids.

The battery and capacitor models are further validated against the experimental data by comparing the component Ragone plots for constant current discharges. Figure 5 shows the Ragone plot for, (a) the battery discharged from 4.2 – 2.8 V, (b) the capacitors discharged from 4.2 – 2.8 V, and (c) the capacitors discharged from 5.4 – 0.1 V. As
expected, the capacitor supplies more energy when discharged over a larger voltage range. This is the advantage of decoupling the battery from a capacitor in a hybrid system as suggested by Miller. The disadvantage again is the need for extra controls, which adds weight to the system. It can be seen that the models agree well with the data and serve as simple and powerful tools for simulation of the Ragone plots. One reason for the good fit for these simple models is revealed when the simple capacitor model (Equation 13) was compared with the porous electrode model (Equations 17 and 18). As seen in Figure 5 the two models do not diverge until high currents (i.e. high power). At high currents, the reaction becomes highly non-uniform and the simple model fails. However, this occurs at a point where the device has lost most of its energy and is not operating under desired condition. Therefore, for practical currents, the models presented here reflect the performance of a hybrid device under desired operating conditions.

Figure 6 compares the voltage and current profiles of battery - 50 F capacitor hybrid at the specified conditions. Initially, both the components have same open circuit voltage, but the resistance of the 50 F capacitor is one-third the battery resistance. Hence, the capacitor current is 3 times the battery current. Figure 6 also shows that the hybrid model, which contains the simple device models, accurately reflects the load sharing of the two devices. Figure 7 compares the voltage and current profiles of battery - 5 F capacitor hybrid at the specified pulse conditions. Initially, both the components have the same open circuit voltage and the resistance of the 5 F capacitor is slightly greater than the battery resistance. Hence, its contribution to the load is slightly less than that of the battery. Since the 5 F capacitor cannot store much charge, its open circuit voltage drops rapidly as it discharges. Hence, its contribution decreases during the on pulse. During off
pulse, the battery recharges the 5 F capacitor, increasing its open circuit voltage. This enables the 5 F capacitor to increase its contribution to the load during the next on pulse. Another benefit of a hybrid device under pulse load is that the voltage fluctuations on the battery are dampened by the presence of the capacitor. This would increase the operating life of the battery. Again, a good agreement is seen between the data and model simulations.

Along with the system interactions seen in Figures 6 and 7, the hybrid models should also be able to predict the experimental Ragone data with sufficient accuracy if the usefulness of the models is to be realized in performing optimization studies. Figure 8 shows the Ragone plots of battery - 50 F capacitor hybrid and battery - 5 F capacitor hybrid capacitor hybrids at pulse frequency of 1 Hz and different duty cycles. Ragone plots at different duty cycles converge at low power density because all the energy present in the hybrids can be obtained at low currents, regardless of the pulse profile.

Effect of Parameters on hybrid Ragone plots

Simulated pulse discharges were performed on the hybrid system containing (a) battery and a 50 F capacitor, and (b) battery and a 5 F capacitor. These simulations are done at different frequencies, duty cycles and current rates. This simulated data is then used in constructing Ragone plots for the hybrid systems. Initially, all these simulations were done using the model parameters that were obtained from fitting the experimental data and listed in Table 1. The power density of the hybrid models still remains inferior to that of the battery because of the small power density difference between the battery and the capacitors. Hence, for the given devices, a battery alone is a better choice than the
hybrid system since it has higher energy and power densities. Therefore, in order to choose a battery and an ultracapacitor that would give rise to a hybrid system that performs better than the battery and the ultracapacitor, a parametric study was performed. To study their influence, the above simulations are repeated for different parameter values (i.e. mass, resistance, capacitance), frequencies and duty cycles.

Figure 9 shows the Ragone plots of the battery - 50 F capacitor at 1 Hz frequency and for D = 0.05, 0.25 and 0.75. The Ragone plots of the individual devices are for constant current discharges. The dashed lines represent the performance of the hybrids and the solid lines represent the performance of the individual devices. The darker lines show the Ragone plots of the battery, the 50 F capacitor and the battery - 50 F capacitor hybrid for the parameters listed in Table 1. It can be seen that the hybrid performance is worse than that of the battery in this case. The lighter lines show the Ragone plots of the ultracapacitor and the hybrid when the mass of the ultracapacitor is reduced to 1/5 of its initial mass, keeping its resistance and capacitance constant. As a result, there is a five-fold increase in the energy and power density of the ultracapacitor. Also, at this capacitor mass, for D = 0.05 and 0.25, the hybrid outperforms the battery. This is because, the capacitor now has much higher power density than the battery and therefore, the hybrid also has higher power density than the battery. However, at D = 0.75, it can be seen that the hybrid performance is still bad compared to the battery. This is because the hybrid performance deteriorates as duty ratio increases, as there is less time to recharge the capacitor. Therefore the capacitor contribution becomes negligible due to the low charge on it and it just adds weight to the battery without improving system performance.
Figure 10 shows the Ragone plots for the battery, 5 F ultracapacitor and the battery – 5 F capacitor hybrid when the capacitor mass is 1/5 of its initial mass listed in Table 1 and at D = 0.25 and at pulse frequencies of 1 Hz and 0.02 Hz. The parameters of the battery were unchanged. The dashed lines represent the performance of the hybrid and the solid lines represent the performance of the individual devices for constant current discharges. At 1 Hz pulse frequency, it can be seen that the hybrid performance is better than the battery where as at a frequency of 0.02 Hz, the hybrid performance is worse than that of the battery. This is because, in the later case, the width of the on-pulse is too big during which the open circuit voltage of the capacitor drops, decreasing its contribution. According to Equation 18, the time constant for battery - 5 F capacitor hybrid can be computed to be 3.58 s. When the frequency is 1 Hz, the width of a single on-pulse is 0.25 s. When the frequency is .02 Hz, the width of a single on-pulse is 0.25/0.02 = 12.5 s. It can be seen that in the former case, the on-pulse width is much smaller than the time constant and in the later case, the on-pulse width is at least 3 times bigger than the time constant. Therefore, for a fixed duty cycle, as frequency decreases, the on-pulse width increases and the capacitor’s charge and contribution to the load decrease. Therefore the pulse frequency should be high enough to keep the pulse width small.

It is seen from Figure 9 that if the mass of the ultracapacitors can be decreased keeping their capacitance and resistance constant, it is possible to obtain a hybrid that is better than the battery. There is another way of obtaining a better hybrid performance. Figure 11 shows Ragone plots of the battery, 5 F capacitor and the battery – 5 F capacitor hybrid at D = 0.10 and at a frequency of 1 Hz. As before, the dash-dot lines represent the
performance of the hybrids under pulse discharges and the solid lines represent the performance of the individual devices under constant current discharges. The darker lines show the Ragone plots of the battery, the 5 F capacitor and their hybrid for the parameters given in Table 1 and the thinner lines show the Ragone plots of the 5 F capacitor and the hybrid when the resistance of the 5 F capacitor is reduced to 1/10 of its initial value. The battery parameters are not changed. The initial hybrid performance (darker lines) is slightly worse than that of the battery because of small difference in the power densities between the capacitor and the battery. But, once the capacitor resistance is decreased, the maximum power density of the capacitor increased by 10 times as given by equation 15. The resistance has no effect on the maximum energy density of the capacitor. As the capacitor with reduced resistance has much higher power density than the battery, the resultant hybrid performs better than the battery.

Finally, increasing the capacitance of the capacitors and the capacity of the battery increases the energy density of the hybrid when other parameters are constant.

Conclusions

Models of a commercial battery and ultracapacitors were developed with very few parameters and are shown to be simple and powerful tools to investigate and characterize hybrid performance. It was shown that capacitance and constant linear resistance of the models along with their masses are the main and important parameters that can be successfully used to gain insight into the system level interactions and the more quantitative Ragone information, which can be used for system optimization. Both the original hybrid systems considered in the experimental study have poorer performance than the battery. To be able to get a better hybrid performance, the capacitor should have
a much higher maximum power density than the battery and the battery should have much higher energy density than the capacitor. This can be done in two ways, either use capacitors that are much lighter and have the same capacitances and resistances or decrease the resistance of the capacitors keeping their mass and capacitance constant. The capacitor should be big enough to be at least able to single handedly supply the energy in one pulse. The frequency and duty cycle together determine the on pulse width. The pulse width should be less than one time constant to get good hybrid performance. At a fixed frequency, more energy from the system can be obtained at lower duty cycles but this increases the total operation time of the hybrid. The duty cycle should not exceed 0.50 to be able to get a good hybrid performance. At a fixed duty cycle, more specific energy and hence more average specific power can be obtained at higher frequencies. The components of a hybrid system that have a desired energy density, power density relationship can be chosen based on the above guide lines. An optimum hybrid system with least weight can be designed to meet given energy, power requirements.

**Acknowledgement**

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List of Symbols

\( a \)  interfacial area per unit volume, cm\(^2\)/cm\(^3\)
\( C \)  capacitance of each electrode, F/ cm\(^2\)
\( E \)  specific energy of device, Ws/kg
\( E_T \)  total specific energy of an electrochemical system, Ws/kg
\( E_P \)  pulsed specific energy of an electrochemical system, Ws/kg
\( f \)  frequency of current pulse, Hz
\( I \)  current through device \( d \), A
\( L \)  thickness of the electrode, cm
\( L_s \)  separator thickness, cm
\( M \)  mass of a device, kg
\( P \)  specific power of a device, W/kg
\( P_P \)  pulsed specific power of an electrochemical system, W/kg
\( Q_b \)  capacity of the battery, C
\( Q_c \)  charge on the capacitor, C
\( R \)  internal resistance of device \( d \), ohms
\( t_c \)  time taken to reach the cut-off voltage, s
\( T.C. \)  time constant for charging/discharging of capacitor in a hybrid, s
\( U_b \)  equilibrium potential of the battery, 4.2 V
\( U_{b^*} \)  flat equilibrium potential of the battery, 4.2 V
\( V \)  voltage of a device, V
\( V_{c,eq} \)  open circuit voltage on the capacitor due to the charge, \( \frac{Q_c}{C} \) V
Greek

$\kappa$ effective conductivity of the electrolyte in the electrode of the capacitor, $\Omega^{-1}cm^{-1}$

$k_s$ effective conductivity of the electrolyte in the separator of the capacitor, $\Omega^{-1}cm^{-1}$

$\sigma$ matrix phase conductivity of the capacitor, $\Omega^{-1}cm^{-1}$

$\theta$ state of charge of the battery

$\beta$ ratio of separator to electrode resistance in the capacitor $[L_3.k\sigma / k_s L(\kappa + \sigma)]$

Subscripts

$b$ battery

c capacitor

$max$ maximum

$min$ minimum

$s$ hybrid system

$5F$ 5 F capacitor

$50F$ 50 F capacitor
Parameters

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</table>

Table 1. Model Parameters obtained for the Li-ion battery and the Maxwell Ultracapacitors. These parameters are also the base case parameters for the parametric study.
References


4. C. Holland, J. W. Weidner, and R. E. White, submitted to *J. Power Sources*

Figure 1. Schematic of the Polystor’s 1.20 Ahr Li-Ion Battery- Maxwell’s 5 F/ 50 F Ultracapacitor hybrid power system.
Figure 2. A current pulse of 2.5 A peak current, 1 Hz frequency and D = 0.50.
Figure 3. Comparison of the constant current discharge curves of Li-Ion battery between the data and simulations.
Figure 4. (a) Comparison of Voltage profiles between data and simulation during a pulsed current charging and discharging of the 5 F capacitor, and (b) The pulse current load.
Figure 5. Ragone plots comparison between simulation (lines) and data (symbols) for Li-Ion battery (*), 5 F (□, □) and 50 F (O,O) ultracapacitors for 4.2-2.8 V (light symbols) and 5.4-0.1 V (dark symbols). All discharges were constant current (i.e. D =1.0). The broken lines for the capacitors discharged from 4.2 to 2.8 V represent equations 17 and 18 (i.e. porous electrode model).
Figure 6. Comparison of (a) Voltage profiles, and (b) Current profiles between data and simulations during a pulsed current discharge of battery-50 F capacitor hybrid system at 6 A 1 Hz frequency and D = 0.03.
Figure 7. Comparison of (a) Voltage profiles, and (b) Current profiles between data and simulations during pulsed current discharge of battery-5 F capacitor hybrid system at 1A 0.25 Hz frequency and D = 0.25.
Figure 8. Ragone plots comparison between data and simulations for pulsed current discharge of the two hybrid systems at 1 Hz frequency as a function of duty cycle. The points represent the data and the lines represent the model.
Figure 9. Ragone plots for constant current discharge of Li-Ion battery, 50 F capacitor and pulsed current discharge of the battery-50 F capacitor hybrid system at 1 Hz frequency at D = 0.05 and 0.75. The darker lines represent the Ragone plots for the capacitor mass as given in Table 1 and the lighter lines represent the Ragone plots with 1/5 the capacitor mass. The solid lines represent the individual devices and the broken lines represent the hybrid system.
Figure 10. Ragone plots for constant current discharge of Li-Ion battery, 5 F capacitor and pulsed current discharge of the battery-5 F capacitor hybrid system with 1/5 the capacitor mass and at 1 Hz and 0.02 Hz frequencies at D = 0.25. The solid lines represent individual devices and the broken lines represent the hybrid system.
Figure 11. Ragone plots for constant current discharge of Li-Ion battery, 5 F capacitor and pulsed current discharge of the two hybrid systems as a function of the capacitor resistance at 1 Hz frequency and D = 0.1. The solid lines represent individual devices and the broken lines represent the hybrid systems.