Modeling of Supercapacitors as an Energy Buffer for Cyber-Physical Systems

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ABSTRACT

Supercapacitors have superior power density, 10x higher than that of the rechargeable batteries, while their energy density (i.e., charge storage capacity) is only one tenth that of comparable size rechargeable batteries. Despite this low energy density, supercapacitors have been the indispensable components of high-powered industrial applications, such as elevators, car starters, and brake energy regeneration systems in hybrid cars. One noticeable commonality in all of these applications is the irrelevance of the energy loss during the storage and consumption of energy. Since the energy is being stored and consumed at rates unmanageable by any other energy storage device, the loss of energy is tolerated. In this paper, we concentrate on a set of embedded systems that utilize supercapacitors for completely different reasons: In addition to their peak power output capability, supercapacitors also possess superior features such as environmental-friendliness, long operational lifetime (e.g., a million charge/discharge cycles, as opposed to a maximum of 5,000 as in the best commercially available rechargeable batteries), and energy-predictability. Our target embedded systems consume only 1–10 Watts of power, as opposed to the near-MW levels for the aforementioned industrial applications, and are nearly agnostic to the peak power capability. While these systems can significantly benefit from these superior features of the supercapacitors, one feature becomes the most important one: the energy storage and consumption efficiency. Through MATLAB-based simulations utilizing the existing supercapacitor models, we show that, at certain power consumption levels, supercapacitors are nearly 100% efficient, while their efficiency suffers dramatically when they are pushed outside their comfortable operating region. We demonstrate this using simulations on four different size (and type) supercapacitors and determine these efficient operation regions for each size supercapacitor.

Keywords: Supercapacitors; Cyber-physical Systems; Energy Buffering; Energy Harvesting;

INTRODUCTION

Supercapacitors are established as a compelling solution for high power buffering applications due to their ability to bank and supply power at levels an order of magnitude beyond the capabilities of electrochemical battery technologies per unit weight. This superior power density has been utilized for regenerative breaking (Rotenberg, Vahidi, & Kolmanovsky, 2011) elevator (Rufer & Barrade, 2002), and automating starting systems for combustion engines (Catherino, Burgel, Shi, Rusek, & Zou, 2006). Additionally, recent developments have also begun using supercapacitors for energy storage applications in order to take advantage of their excellent charge discharge efficiency as well as their power density capabilities. Energy efficiency is especially critical for self-sustaining environmentally powered systems, where efficient storage/use of a limited energy supply can prolong time of operation and improve quality of service. Another useful characteristic of supercapacitors is their relationship between terminal voltage and stored energy remaining. This relationship provides more accurate energy awareness for systems with dynamic supply and usage of power.

However, reliance on these efficiency, power density, and energy awareness benefits for design of supercapacitor-based systems must be tempered by the fact that supercapacitors do not operate as ideal devices. Classical concepts of capacitance apply much more closely to parallel plate or electrolytic devices. Observed supercapacitor behavior differs significantly from theoretical ideal capacitor performance. These operational differences between supercapacitors and their much weaker conventional cousins are a direct result of the physical phenomena governing supercapacitor behavior. Dynamic system and equivalent circuit models have been developed to characterize supercapacitor performance. However, focus has been on accurately predicting supercapacitor frequency response for power buffering applications using techniques such as EIS (electrochemical impedance spectroscopy) e.g. (Bertrand, Sabatier, Briat, & Vinassa, 2010) or characterizing long term storage efficiency for low power applications (Zhang & Yang, 2011).

	Conventional Capacitors	Supercapacitors	Electrochemical Batteries
Energy Density $\left(\frac{W*h}{kg}\right)$	$10^{-2}$to 10^{-1}	$10^{0}$to 10^{1}	$10^{1}$to 10^{2}
Power Density $(\frac{W}{kg})$	$10^{3}$to 10^{4}	$10^{3}$to 10^{4}	$10^{1}$to 10^{2}
Efficiency	≥95%	≥95%*	70% to 99%

*Table 1. Significant benefits are possible in supercapacitor-based systems. *efficiency performance can be jeopardized by naive disregard for non-ideal supercapacitor behavior.*

An emerging category of application, cyber-physical systems also hold potential to benefit from supercapacitor energy buffering. Cyber-physical systems have the ability to deploy significant computational resources into the field at the location the data is collected. For example, these computational resources can enable face recognition, without the need to transmit high bandwidth video streams back to a base station. While communication overheard and the need for infrastructure such as the base stations are reduced for cyber-physical systems, these systems can require much higher power to sustain their computational capabilities as opposed to wireless sensor nodes. Additionally these systems are many times remotely deployed, making maintenance costly. Supercapacitors can be an ideal fit for cyber physical systems due to their long operational lifetimes and peak power capabilities.

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This chapter begins by introducing an accepted model for supercapacitor behavior and then presents the analysis of this model relevant to supercapacitors used in energy buffering equations. Specifically, the analysis describes how the three branch model is implemented to provide energy awareness and track a system's remaining available energy. The model is also simulated to characterize energy storage efficiency trade-offs for supercapacitors. By implementing a simulated supercapacitor model which describes non-ideal behaviors this paper offers insight into the most significant factors affecting efficiency and the utility of supercapacitors for energy storage applications. Primary factors influencing storage efficiency are found to be supercapacitor size, stored energy level, and power at which energy must be delivered. A three branch equivalent circuit model (Zubieta & Bonert, 2000) based on the physical phenomena governing supercapacitor behavior is used to simulate these performance trade-offs. These simulations demonstrate how the exceptional charge-discharge efficiency benefits of supercapacitor-based storage can be severely degraded depending on power level, supercapacitor voltage, and supercapacitor size. These implications for energy efficiency must be considered in system design to realize the benefits of supercapacitor based energy storage over alternatives such as rechargeable batteries.

Our simulations, implementing the three branch equivalent circuit model for supercapacitor behavior with parameters both measured from physical devices and taken from literature demonstrate:

1) Superior charge-discharge efficiency for supercapacitor based energy storage.
2) The importance of power-awareness to maintain this superior charge-discharge supercapacitor performance.
3) The dependence between supercapacitor size and reasonable power level limits on the application within which near-ideal performance can be expected.
4) The dependence of the near-ideal operation power region limits on supercapacitor terminal voltage, as well as capacitor size.

The organization of this paper begins by justifying the use of the three branch model as an equivalent circuit for the physical phenomena that govern supercapacitor operation, explained in the BACKGROUND AND THREE BRANCH MODEL sections. The next section then details the procedure for measuring the model's parameters from a physical supercapacitor device. The KALMAN FILTERING section then explains how this model can provide an accurate estimate of remaining energy to the system. The section titled ENERGY EFFICIENCY MODELING lays out the model parameters and the techniques used to simulate a varied collection of supercapacitors, and explore efficiency relationships for each. Results showing the significance of design considerations for supercapacitor-based systems are given in the evaluation section. To conclude, findings are summarized in the CONCLUSIONS AND FUTURE WORK section.

BACKGROUND

To motivate the significance of efficiency trade-offs inherent in supercapacitor energy storage we first outline the principles and construction of supercapacitors. Relevant supercapacitor properties include: 1) orders of magnitude greater energy storage capacity than conventional or electrolytic capacitors, 2) superior peak power performance in relation to electrochemical batteries, 3) long operational lifetime and low environmental impact, 4) internal charge redistribution among an array of internal time constants, 5) ESR (equivalent series resistance), and 6) self discharge leakage current.

In contrast to conventional capacitors in which opposing electric charge collects on electrode plates separated by a dielectric layer, supercapacitors physical design is shown in Figure 1. Instead of storing energy through the electric field created within a dielectric, supercapacitor electrodes are constructed of porous material such as activated carbon with extremely high surface area. Both mechanisms by which supercapacitors store charge, EDL (electric double layers) and pseudocapacitance (Conway, Birss, & Wojtowicz, 1997), contribute to energy storage proportional to electrodes' surface area. These phenomena, linking electrode surface area to capacitance, explain how such high capacitance is possible by using activated carbon electrodes with surface areas in the range of thousands of square meters per gram. The EDL and pseudocapacitance mechanisms also account for the relationships between power consumption, supercapacitor voltage level, and efficiency developed in later in this chapter.

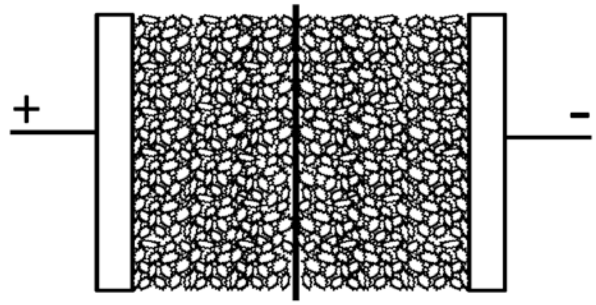

Figure 1. Typical supercapacitor construction includes two electrodes consisting of high surface area activated carbon immersed in an electrolyte. Positive and negative terminals of the supercapacitor are connected to distinct regions of the electrode material separated by a membrane. This membrane is only permeable to the electrolyte and allows charge carrying ions to pass through, but keeps the regions of electrode material isolated, preventing current from directly flowing between electrodes

The first charge storage mechanism, EDL, has been used to refer to supercapacitor devices as electric double layer capacitors and results from the accumulation of opposing charge on the surfaces of the two electrodes. This surface charge accumulates because the ion permeable membrane prevents the terminal voltage from driving direct current flow between the two regions of activated carbon electrode material connected to the opposite terminals. The EDL phenomena occurs because opposing electrode surface charges on either side of the membrane selectively attract charged ions of the opposite polarity from the electrolyte. As the electrolyte ions flow through the electrode material pores towards the opposing surface charges, concentration gradients build up resulting in Helmholtz layers. Helmholtz layers refer to the high concentrations of oppositely charged ions from the electrolyte that counteract the electrode surface charges by collecting along the porous electrode material surface. Supercapacitor charge storage by means of this EDL, relying on diffusion of ions, contrasts electrochemical batteries where re-dox (reduction oxidation) reactions store charge but limit charge and discharge power according to the speed of reaction kinetics. This EDL capacitance along the porous electrode material surface and flow of ions through electrode pores has motivated the use of RC transmission line elements to model the electrical behavior of the porous electrode supercapacitor design (Bertrand, Sabatier, Briat, & Vinassa, 2010) (Buller, Karden, Kok, & De Doncker, 2001). These models predict supercapacitor charge redistribution over a network of RC time constants. Another important effect of the torturous path ions must flow through to reach the electrode surfaces is significant supercapacitor ESR, resulting in wasted energy expended to support the ion currents.

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The second mechanism by which charge is stored in supercapacitors, pseudocapacitance, relies on charge transfer in re-dox reactions that occur at the electrolyte-electrode surface interface (Conway, Birss, & Wojtowicz, 1997). However, parasitic side reactions can also spontaneously dissipate stored energy (Niu, Pell, & Conway, 2006). This energy loss can be modeled as a leakage current and depends on many factors such as initial charge, storage duration, and temperature (Zhang & Yang, 2011) (Yang & Zhang, 2011). Another source of supercapacitor charge leakage is direct ohmic pathways by which current flows between terminals through the membrane.

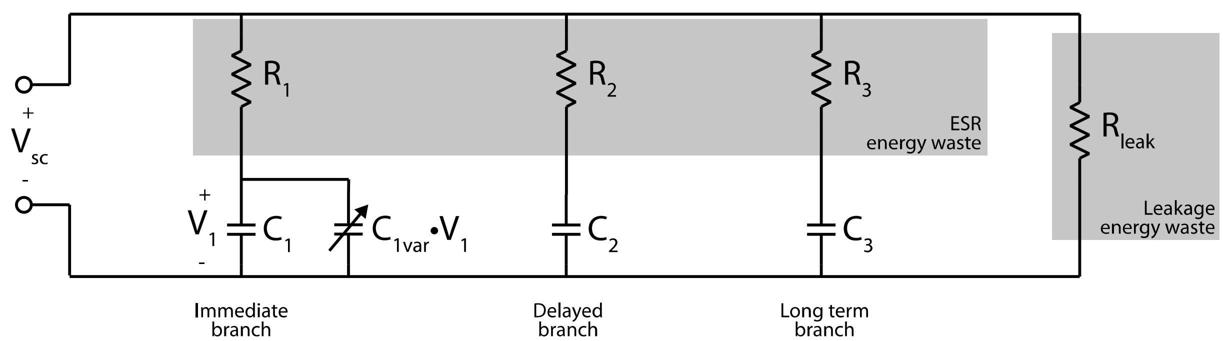

Figure 2. The three branch equivalent circuit supercapacitor model **(Zubieta & Bonert, 2000)** *accounts for charge redistribution between the immediate, delayed and long term capacitive branches of increasing time constant. Resistances in the three capacitive branches model internal supercapacitor ESR while the fourth purely resistive branch models supercapacitor charge leakage. The initial branch also models voltage dependent capacitance observed for supercapacitors.*

Both significant sources of energy waste which degrade supercapacitor efficiency, ESR and leakage, are accounted for in the three branch model equivalent circuit (Zubieta & Bonert, 2000), shown inFigure 2. Supercapacitor charge redistribution is modeled by the three resistive capacitive branches, each with progressively greater time constant. Supercapacitor ESR is modeled by the series resistors: R_1, R_2, and R_3; and self discharge leakage is modeled by the parallel resistor R_{leak}. Using this three branch model, results show how *instantaneous* supercapacitor efficiency depends on both application power and supercapacitor voltage levels. This work builds on our previous study of how *net* supercapacitor efficiency and effective capacity vary for charge-discharge profiles of varying speed. Supercapacitor efficiency and capacity have been shown to depend on the different distributions of charge that result from different charging and discharging speeds. By using the same measured parameters for the supercapacitor model previously validated against experimental results, this work uses the three branch model to simulate how instantaneous supercapacitor efficiency changes with power and voltage level, controlling for charge redistribution by fixing equal voltage levels across all capacitive branches of the three branch model to remove the effects of charge redistribution.

EQUAL SERIES RESISTANCE (ESR)

For electrical current to charge or discharge a supercapacitor, ions must diffuse through the electrolyte into the torturous pathways in the porous electrode material. Any movement of theses ions results in waste heat just as electrical current flowing through a resistance. In a double layer supercapacitor, the resistivity of carbon particles within the electrode materials also contribute to the supercapacitor's equivalent series resistance (ESR) (Zubieta & Bonert, 2000). The equivalent series resistance plays an important role in applications where the power density is a major concern (Hassanalieragh, Soyata, Nadeau, & Sharma, 2014). Examples of such applications are elevators and electric vehicles. In such cases, a large amount of energy must be supplied in a very short amount of time which in turn leads to a high current. High current across the series resistance leads to a voltage drop which decreases the energy delivery efficiency. This problem can be mitigated by having several supercapacitors in parallel.

LEAKAGE AND CHARGE REDISTRIBUTION

High leakage, also known as self-discharge, is the loss of energy stored in a device and is frequently cited as a major drawback of supercapacitors. It is widely reported that leakage increases exponentially with a device's terminal voltage, however research has shown that real leakage is not as significant a problem as was previously believed and that most of the observed leakage effects are actually due to charge redistribution within the supercapacitor. This process is illuminated by models of supercacpitors such as the three branch model. Charge redistribution occurs when a supercapacitor has stopped charging and one of the capacitors in the model had significantly more charge put into it than the others; it can be thought of as similar to battery relaxation. This occurs frequently because of the large difference in time constants of the three branches leads each branch to take in energy at widely different time frames, with the first branch getting charged up in seconds, while the third branch can take hours. In other words, once charging stops, the branches with larger time constants, continue to charge, taking their energy from the branches with lower time constants.

Consequently, it has been shown that the longer a supercapacitor charges for, the slower its exhibited leakage. The redistribution of charge leads to a reduction in the terminal voltage of the super capacitor and has therefore been perceived as leakage instead of redistribution. The redistribution is not without energy loss, however; as the charge redistributes itself, energy is lost in each branch's resistance. Energy loss in supercapacitors therefore has two sources: leakage and redistribution loss. Research has shown that supercapacitors charged for a very short time, for example 0.1 hours, lose the majority of their energy through redistribution, while supercapacitors charged for a long time, for example 10 hours, lose the majority of their energy through leakage. Increased energy loss due to leakage in supercapacitors that have been charged for a long time can be attributed to the fact that they maintain high voltage longer. Meanwhile the quickly charged supercapacitors redistribute their charge very quickly, thus lowering their voltage and minimizing leakage. Thus, in situations that require a minimum voltage it should be kept in mind that the more time a supercapacitor is given to charge, the longer it is able to maintain a high voltage (Merrett & Weddell, 2012).

Leakage is only relevant in applications that use supercapacitors as long term storage, such as field systems that need supercapacitors as a long-term energy buffer (Fahad, et al., 2012) (Hassanalieragh, Soyata, Nadeau, & Sharma, 2014). Alternatively, other usage scenarios are nearly agnostic to leakage. For example, for data centers running intensive applications (Kocabas & Soyata, 2014) (Kocabas, et al., 2013) (Kwon, et al., 2014) (Li, Ding, Hu, & Soyata, 2014) (Page, Kocabas, Soyata, Aktas, & Couderc) (Wang, Liu, & Soyata, 2014) (Soyata, Friedman, & Mulligan, 1995) (Soyata, Ba, Heinzelman, Kwon, & Shi, 2013) (Guo, Ipek, & Soyata, 2010) (Soyata, et al., 2012), supercapacitors are used as a temporary energy buffer. Each computer on the data center racks could have a peak power demand, which is supplied from a supercapacitor block. In this case, the energy is stored and buffered within less than a minute, leaving no time for the leakage to take effect. Typically, the leakage time constant is in the order of hours. Therefore, any application that uses the stored energy in a supercapacitor (or a block of supercapacitors) will not be affected from leakage. Leakage can be thought of as being an Eqauivalent Parallel Resistor (EPR), connected in parallel, to the three branches.

Three Branch Model

Researchers at the University of Toronto set out to develop a simple model that accurately illustrates a supercapacitor's behavior in the first 30 minutes of a charge or discharge cycle. Additionally, they desired for their model to require only parameters that could be measured at the terminals of the supercapacitor. An RC circuit is used to best model the behavior of supercapacitors, however more than one, each with a unique time constant, is necessary due to the different time frames over which supercapacitors respond (Zubieta & Bonert, 2000). This range in response time is due to the same feature of supercapacitors that allows them to have such high capacitance: the incredible porousness of the materials they are made form. This is because the charge has to navigate through the caverns of the material, which result in many different paths of varying length to be taken. The result is an uneven charging for rapid charge cycles, which in turn brings about charge redistribution effects. Charge redistribution, it should be noted, is also responsible for drop in terminal voltage and is part of the reason energy estimation in super capacitors should not be based off of their terminal voltage (Nadeau, Sharma, & Soyata, 2014).

An arbitrary number of branches can be used for the model however, three has been suggested as it is the least required to obtain a reasonably accurate model of supercapacitor behavior over a time period of thirty minutes. Each branch consists of a resistor to model the energy lost in the materials that form the double layer charge distribution, and a capacitor to model the capacitance between the electrode and electrolyte. Each branch's time constants should vary widely, ideally being at least one order of magnitude apart from each other, so that only the behavior of a single branch is dominating the overall behavior of the model at any given time. This in turn makes it significantly easier to determine the parameters of each branch that allows the model to be simpler to use as well as more accurate. The first branch, the immediate branch, has the smallest time constant and models the immediate response, in the first seconds, to charging. The second branch, which the authors call the delayed branch, models the bulk of what occurs in the first minutes of charging. The final branch, the long-term, branch models what occurs past 10 minutes. The first branch contains an additional, voltage dependent capacitor, in order to simulate the voltage dependency behavior exhibited by supercapacitors. Out of interest for simplicity, the other two branches do not contain this additional capacitor. Finally, in addition to the three RC branches in the model, a parallel resistor is included to simulate leakage and self-discharge effects in the supercapacitor (Zubieta & Bonert, 2000).

The three branch model is just one of many proposed to model the behavior of supercapacitors, however it has been shown to be the one to most adequately addresses long term behavior. That being said the three branch model is not without its drawbacks: it was developed to model larger supercapacitors and loses some accuracy when applied to smaller ones that might be used in cyber physical systems or wireless sensor networks. Additionally, it takes each branch to be completely independent, which research has shown, is not an accurate reflection of supercapacitor behavior. Despite this, the three branch model remains the most accurate, even for small supercapacitors, due mainly to the fact that the majority of the research and literature concerns larger supercapacitors and there is not as thorough an understanding of smaller supercapacitors (Weddell, Merrett, Kazmierski, & Al-Hashimi, 2011).

MEASURING THE THREE BRANCH MODEL PARAMETERS

In this section we elaborate on measuring the three branch model parameters based on the approach which was originally introduced in (Zubieta & Bonert, 2000) . A precisely timed and controllable current source is needed for conducting the experiment in order to be able to keep track of the injected charge. This method presumes distinct time constant of three branches. Initially the supercapacitor is charged to the rated voltage in a very short amount of time. The charging period must be short enough to make sure the initial charge is placed only on the first branch. Observing the terminal voltage in this period leads to identifying the first branch parameters. After that, the current source is turned off and analyzing the terminal voltage over a longer period of time will lead to measuring other two branches parameters. The supercapacitor must be completely discharged prior to conducting the experiment which needs the supercapacitor to be in short circuit state for a long time.

Throughout this section we refer to 'instantaneous capacitance' many times. The usual definition of capacitance is actually the relation between supplied charge and the voltage of the capacitor which is $= \frac{Q}{V}$. When working with variable capacitance this definition must be revisited: If we inject a small amount of charge (dQ) into the capacitor , there will be ΔV voltage change. The instantaneous capacitance at this specific voltage determines the relation between the injected charge and the voltage difference. Specifically we have:

$$C_{inst}(V') = \frac{dQ}{dV}|_{V'} .$$

A. First Branch Parameter Measurement

If we denote the supercapacitor terminal voltage shortly after turning on the current source by V_1 (taking into account the rise time of the current source) and the charging current by I_{ch} we have:

$$R_1 = \frac{V_1}{I_{ch}}.$$

We can use the instantaneous capacitance of the supercapacitor during charging to the rated voltage to determine $C_1$and C_{1Var} . Instantaneous capacitance (C_{inst})is defined by:

$$C_{inst} = I_{ch}\frac{\Delta t}{\Delta V}.$$

in which ΔV is the supercapacitor voltage change during small time periodΔt. After finding the instantaneous capacitance in rated operating voltage range using a high current, we can determine C_1 and C_{1Var} by the use of a simple least square line fitting method.

B. Second Branch Parameter Measurement

After turning off the current source there is an immediate voltage decrease due to R_1. We denote the terminal voltage by V_1at this time stamp. As in the case of turning on the current source, the fall time of the current source must also be taken into account. We continue monitoring the terminal voltage afterwards. The voltage starts decreasing because of charge redistribution. If there is ΔV voltage change in

Δt amount of time we can assume there is a virtually constant current from first to second branch (I_{tr}) given by:

$$I_{tr} = \frac{V_1 - \frac{\Delta V}{2}}{R_2}.$$

ΔV must be small enough so that this holds true. ΔV is commonly chosen to be 50 mV. Choosing a smaller voltage difference will lead to better approximation of the constant current, but the precision of the measurement device (both sampling frequency and voltage measurement precision) prevents us from choosing a very small voltage difference.

We can relate $I_{tr}$to the first branch instantaneous capacitance (C_{inst}) which is measured at $V_1 - \Delta V/2$ by $I_{tr} = C_{inst} * \Delta V/\Delta t$. Using the two derived equations for I_{tr} we have:

$$R_2 = \frac{\left(V_1 - \frac{\Delta V}{2}\right) * \Delta t}{C_{inst} * \Delta V}.$$

For measuring the second branch capacitanceC_2, we need to wait long enough so that charge redistribution from first to second branch has already taken place. Typically the time constant of the second in a double layer supercapacitor is of order 100 seconds. Waiting for three times the time constant will be adequate. C_2can be easily calculated by taking into account the charge conservation fact, specifically we have: $Q_{total} = Q_1 + Q_2$, where Q_{total} is the total charge supplied to the supercapacitor and Q_1 and Q_2 are the amount of charge present in first and second branch respectively.$Q_{total}$is easily determined by considering the charging period and the charging current.

If the terminal voltage is V_2 at the end of this period we can write:

$$Q_1 = \int_0^{V_2} (C_1 + C_{1var} * V)dV = V_2\left(C_1 + \frac{C_{1var}}{2} * V_2\right),$$

$$Q_2 = V_2 * C_2 .$$

So we can easily derive:

$$C_2 = \frac{Q_{total}}{V_2} - \left(C_1 + \frac{C_{1var}}{2} * V_2\right).$$

C. Third Branch Parameter Measurement

When charge redistribution between first and second branch has taken place, there is still no charge on the third branch due to its very long time constant.

For determining R_3 , we will wait Δt amount of time until the terminal voltage reaches $V_3 = V_2 - \Delta V$ where ΔV is a small value e.g. 50 mV as it was chosen for calculating R_2. Since ΔV is pretty small there is a virtually constant transfer current to the third branch given by: $I_{tr} = (V_2 - \frac{\Delta V}{2})/R_3$ while holding the assumption $R_1 \ll R_2 \ll R_3$. Since time constant of the first branch is quite shorter compared to the second branch, I_{tr} is mostly supplied by the first branch for this time period. If C_{inst} is the first branch capacitance at $V_2 - \frac{\Delta V}{2}$, we can write:

$$R_3 = \frac{\left(V_2 - \frac{\Delta V}{2}\right) * \Delta t}{C_{inst} * \Delta V}.$$

For calculating C_3, we have to wait long enough so that the charge redistribution between three branches has finished. If we assume the terminal voltage is V_4 at the end of this period, we can calculate C_3 by taking advantage of charge conservation fact:

$$C_3 = \frac{Q_{total}}{V_4} - \left(C_1 + \frac{C_{1var}}{2} * V_8\right) - C_2.$$

Measurement of the parameters must be conducted on several test units in order to mitigate the possibility of measurement errors and variation in supercapacitor parameters.

KALMAN FILTERING

The three branch model is used by cyber-physical systems and energy buffering applications to predict a supercapacitor's behavior. One of the most important aims is to provide a measure of the amount of energy buffered within a supercapacitor that is available to the system. However, predictions and measurements that use the three branch model require knowledge of the internal voltages across the capacitors in the equivalent circuit's three branches. These three branch voltages are referred to as the supercapacitor's internal state, and cannot be directly observed from a single measurement of the supercapacitor's terminal voltage. For example, if a supercapacitor is left at rest after is has been charged up, charge redistribution will cause current to flow to any branch with a lower voltage than the others. All three branches will settle to an equilibrium at the terminal voltage. In this equilibrium case, the state is directly observable. However, the same observed terminal voltage could also be produced by rapidly charging the supercapacitor such that most of the charge is stored in the first branch. Knowledge of the internal state distinguishes this rapid charging case from the supercapacitor at equilibrium even when the terminal voltages observed in both cases are identical. Tracking the internal state is important because while both cases are identical to an observer, the energy buffered in the supercapacitor is significantly greater for the first case because the long term branches store more energyat equilibrium.

It has been shown that tracking a supercapacitor's internal state provides much greater accuracy than treating a supercapacitor as an ideal device of capacitance, C for which buffered energy, E is directly observable from the terminal voltage, V_{sc} as

$$E = {}^{1}/_{2}\, C V_{sc}^2 .$$

Simulations show that this simple observation-only energy awareness scheme underestimates the buffered energy in a supercapacitor by a root mean square error of 31% over a test profile including charging and discharging at various current levels (Nadeau, Sharma, & Soyata, 2014).Stored energy is underestimated because approximating the supercapacitor as an ideal device neglects the long term branches that store additional energy when the supercapacitor is charged slowly. A supercapacitor's rated capacitance normally represents the device's average instantaneous capacitance measured while it is quickly charged. The ideal model can be adjusted for applications that operate within a narrow power range by increasing C in proportion to the extra energy stored on the longer term branches at that specific power level. This strategy of fitting a supercapacitor with a single constant capacitance value that is dependent on the operating power fails for applications with variable power supply and demand such as cyber-physical systems that rely on solar power. Solar power can vary day to day, hour to hour, and even minute to minute in the case of variable cloud cover, causing varying portions of charge to be stored in the three branches, depending on how the supercapacitor is charged and discharged.

An alternative to modeling the supercapacitor as simple ideal capacitor is to treat the supercapacitor as a black box and integrate the net power into and out of the supercapacitor without the need for any modeling. Buffered energy is found as the difference between the energy inputted, determined by the current into the supercapacitor over time, $I_{in}(t)$ and the energy outputted to the application, determined by the current out of the supercapacitor over time, $I_{out}(t)$,

$$E = \int I_{in}(t)V_{sc}(t)\,dt - \int I_{out}(t)V_{sc}(t)\,dt\,.$$

Because the above equation does not rely on any model for the supercapacitor it is easily implemented without the need to set any parameters such as the capacitance, C. However, neglecting internal loss treats the supercapacitor as perfect energy storage and overestimates E in the long term. In the short term supercapacitors can operate at an efficiency close to 100% because of their small equivalent series resistance (Maxwell Technologies, Inc., 2012). However, over the long term leakage and series resistance losses accumulate and degrade the accuracy of this technique. Additionally the measured quantities $I(t)$and $V(t)$are always subject to measurement noise. This noise accumulates over time in this model resulting in significant inaccuracy. For the simulation profile mentioned, this energy awareness scheme is found to produce a root mean square error of 79.3%, due to the long duration of the simulation which allows error due to internal losses to accumulate (Nadeau, Sharma, & Soyata, 2014).

As opposed to the two energy awareness schemes described prior, best results are produced by using the three branch model to determine the energy buffered in a supercapacitor. Assuming that the supercapacitor's internal state,$x = [V_1 \quad V_2 \quad V_3]^T$is known, the contribution of each branch to the total buffered energy is calculated as,

$$E = {}^1\!/_2\, C_1 V_1^2 + {}^1\!/_3\, C_{1var} V_1^3 + {}^1\!/_2\, C_2 V_2^2 + {}^1\!/_2\, C_3 V_3^2\,.$$

A simple technique to track the state, x is to recursively predict x each time step according to the dynamics the equivalent circuit. This method provides acceptable root mean square error of 4.8% in the simulation because it is only subject to the accumulation of measurement error which is set to be small and zero mean (Nadeau, Sharma, & Soyata, 2014). However, outside of simulation, modeling error is also present, and estimates of circuit parameters are imperfect. These inaccuracies introducing systematic error that accumulates in E over time and would cause greater error in the energy estimate. This prediction-only method also fails to utilize information in the observed supercapacitor voltage.

To use both the observed input current into the supercapacitor and the observed terminal voltage to estimate$x$ the Kalman filter is used.The discrete Kalman filter provides an optimal estimate of the supercapacitor's state, $\hat{x}$ taking into account all observations including the present and previous values of $V_{sc}(t)$.Given that the three branch equivalent circuit is a linear system of the form,

$$\dot{x}(t) = F \cdot x(t) + \ B \cdot I_{sc}(t) \ ,$$

$$V_{sc}(t) = H \cdot x(t) + D \cdot I_{sc}(t) \ ,$$

The prediction for the supercapacitor's internal state, $\tilde{x}$ over any discrete time step can be found by matrix exponentiation of F:

$$\tilde{x}(t + \Delta t) = e^{F \cdot \Delta t} \cdot \hat{x}(t) + F \backslash (e^{F \cdot \Delta t} - I) B \cdot I_{sc}(t) \ ,$$

$$\tilde{V}_{sc}(t + \Delta t) = H \cdot \tilde{x}(t + \Delta t) + D \cdot I_{sc}(t + \Delta t) \ .$$

The Kalman filter is an efficient iterative solution that uses an update step to incorporate the information of each new voltage observation into the next estimate of the internal state, $\hat{x}(t + \Delta t)$.Each new observation is incorporated by distributing the error residual between the predicted terminal voltage and the actual observation into the predicted state according to the Kalman gain, K:

$$\tilde{x}(t + \Delta t) = \tilde{x}(t + \Delta t) + K \cdot \{V_{sc}(t + \Delta t) - \tilde{V}_{sc}(t + \Delta t)\} \ .$$

The Kalman gain can be calculated analytically for the discrete linear system of the three branch model, but many times it is approximated using a sigma-point Kalman filter. Alternatively, more complex models can besimplified by using a linear approximation as in the extended Kalman filter. Of all the energy awareness techniques mentioned, Kalman filtering provides the lowest root mean squared error at less than 1% (Nadeau, Sharma, & Soyata, 2014), and is best suited for energy awareness in cyber-physical systems.

ENERGY EFFICIENCY MODELING

One reason supercapacitors are a good choice for energy buffering, especially in cyber-physical systems, is that supercapacitors provide high charge-discharge efficiency over a wide range of power levels without the need for more complex battery management techniques required for electro-chemical batteries. However, the three branch model includes series resistors and leakage that consume power and result in less than 100% efficiency. This sections applies the three branch model to determine a power range that a supercapacitor can comfortably operate within with near 100% efficiency. For example, cyber-physical systems commonly rely on solar energy harvesting and experience large fluctuations in the input power. A supercapacitor must efficiently buffer the energy that is harvested regardless of whether the weather is sunny and provides high power, or the weather is cloudyand energy harvesting is much slower. The operating efficiency of a supercapacitor is determined by the two sources of internal energy loss: series resistance in each capacitive branch, and current loss through the parallel resistor in the leakage branch. At high power, high currents flow in and out of the supercapacitor and make power lost in the series resistancesa more significant source of loss. At low power losses in the series resistances are

	Illinois Capacitor 10F-2.7V-DCNQ	Maxwell BCAP0050	DLC (Zubieta & Bonert, 2000) 470F	DLC (Zubieta & Bonert, 2000) 1500F
C_{Rated}	10F	50F	470F	1500F
C_1	2.05F	42.5F	270F	900F
C_{1var}	$6.03 F/V$	$5.1\ F/V$	$190\ F/V$	$600\ F/V$
R_1	56mΩ	205mΩ	2.5mΩ	1.5mΩ
C_2	9.43F	10.5F	100F	200F
R_2	4.0Ω	112Ω	.9Ω	.4Ω
C_3	6.76F	4F	220F	330F
R_3	77.5Ω	628Ω	5.2Ω	3.2Ω
R_{leak}	90kΩ	36kΩ	9kΩ	4kΩ

Table 2: Three branch model parameters found for 10F Illinois Capacitor and 50F Maxwell supercapacitor. Parameters for 470F DLC and 1500F DLC supercapacitor from **(Zubieta & Bonert, 2000)** *also used to test efficiency.*

less significant, but leakage consumes a more significant portion of the power transferred to or from the supercapacitor.

To test a supercapacitor's efficiency limits, the three branch model is simulated using various equivalent circuit parameters. Circuit parameters are measured from an Illinois Capacitor 10F-2.7V-DCNQ (Illinois Capacitor, Inc., 2012) and Maxwell BCAP0050 (Maxwell Technologies, Inc., 2012), and also simulated from literature (Zubieta & Bonert, 2000) for the 470F and 1500F DLC (double layer capacitors). These parameters are listed in Table 2.

Supercapacitor efficiencyis tested over a wide range of power by simulating the three branch model charged to voltage, V. Efficiency is then measured by discharging the model through a range of different load resistances, R.For each different R the supercapacitor's efficiency, η is the ratio between the useful power delivered to the load, P and the total power including the internally wasted power, P_W within the three branch model:

$$\eta = \frac{P}{P + P_w} \times 100\% \,.$$

Depending on a how a supercapacitor is charged, the distribution of charge storage represented in the three branch model by the voltages across the three capacitances can vary significantly from the terminal voltage, V. Simulations remove any ambiguity in the supercapacitor's internal state by assuming an equilibrium where the voltage across all capacitors in the three branch model is the same as V. This assumption gives intermediate results for efficiency: if the supercapacitor's internal state is distributed with more charge stored in the long term branches leakage losses are reduced, but series resistance losses become worse. If the supercapacitor's internal state is distributed towards short term storage, series and leakage losses are skewed in the opposite directions. As the supercapacitor discharges its terminal voltage, V_{sc} is lower than the internal branch voltages, V. Total wasted power P_W across all branches is:

$$P_w = \frac{(V - V_{sc})^2}{R_1} + \frac{(V - V_{sc})^2}{R_2} + \frac{(V - V_{sc})^2}{R_3} + \frac{V_{sc}^2}{R_{leak}} ,$$

And power delivered to the load is:

$$P = \frac{V_{sc}^2}{R}.$$

The terminal voltage, V_{SC} is determined by solving the node equation for the currents in all of the model's branches in addition to current to the load,

$$\frac{V - V_{sc}}{R_1} + \frac{V - V_{sc}}{R_2} + \frac{V - V_{sc}}{R_3} - \frac{V_{sc}}{R_{leak}} = \frac{V_{sc}}{R}.$$

EVALUATION

Energy buffering efficiency, η for the 10F, 50F, 470F, and 1500F supercapacitors is evaluated using the equations given in the previous section and shown in Figure 3,Figure 4, Figure 5 and Figure 6. Each figure plots percent efficiency in relation to power delivered to the load as resistance value, R for the load varies. For example, a large load resistance is used to test supercapacitor efficiency at low power. The large load resistance prevents the flow of high current and limits the power delivered to the load. As load resistance is decreased, more current is drawn from the supercapacitor and power increases as $P = I_{sc}^2 R$. For each sequence of load resistances there is an inflection point of maximum power that can be drawn from the supercapacitor. Beyond this maximum power, further decreasing the load resistance no longer delivers greater power.This inflection point happens because such small R draws very high current from the supercapacitors, and a large amount of wasted power is consumed by the supercapacitors' ESR. The efficiency of this maximum power operating point is below the range of efficiencies shown in Figure 3, Figure 4, Figure 5, and Figure 6. Due to the low efficiency of drawing maximum power and because the simulated current significantly exceeds the maximum rating of physical devices, these casesdo not occur in typical energy aware operation.

As power delivered to the load increases, efficiency initially increases due to diminishing leakage: a greater portion of the power flows to the load rather than to the parallel leakage branch in three branch model. As in Table 2, leakage resistance is shown to be inversely proportional to supercapacitor size resulting in more severe inefficiency for larger supercapacitors at low power. Inefficiency due to leakage is also influenced by the voltage of the supercapacitor. Because leakage is modeled as current through a resistor, the waste power is V_{sc}^2/R_{leak}. Consequently, leakage waste increases with the square of voltage.

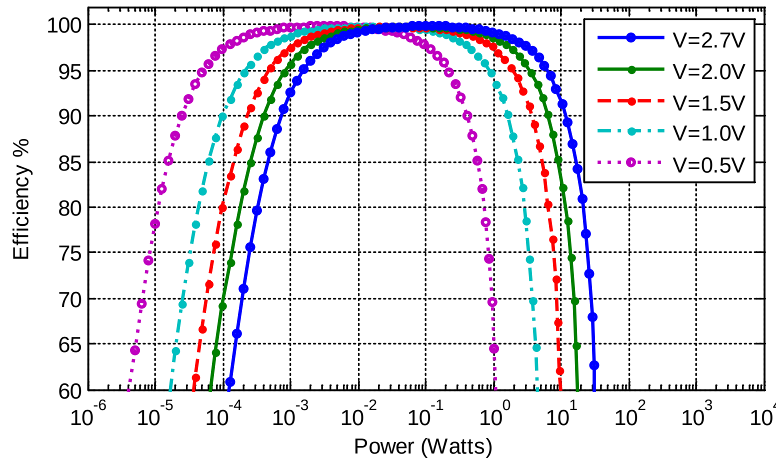

Figure 4. Predicted efficiency for discharging a 10F supercapacitor is modeled by the three branch model.

The second important relationship between efficiency and power is the inefficiency of supercapacitors while delivering high power to load resistances. Inefficiency at high power results from high current flowing through the ESR of the supercapacitor. Consequently as current increases to deliver more power at a certain voltage or to maintain power at a lower *V* efficiency suffers. It can be seen that larger supercapacitors perform better at high power due to their smaller internal ESR, represented by the R_1 parameter in the three branch model.

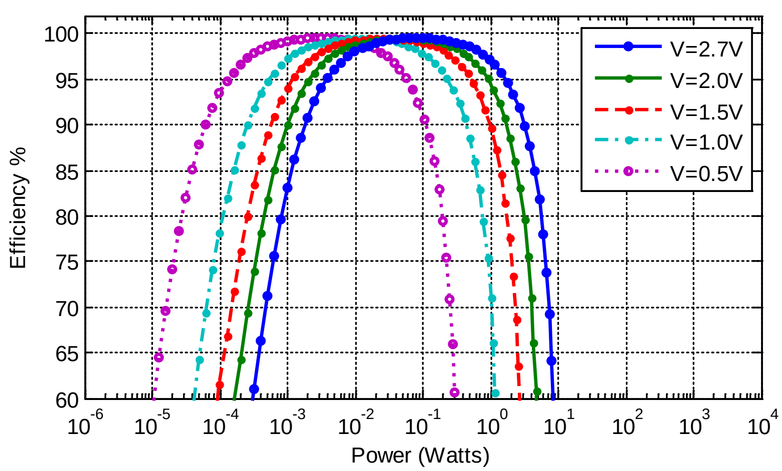

Figure 3. Predicted efficiency for discharging a 50F supercapacitor is modeled by the three branch model. Note that large R_1 was measured, resulting in inefficiency at high power.

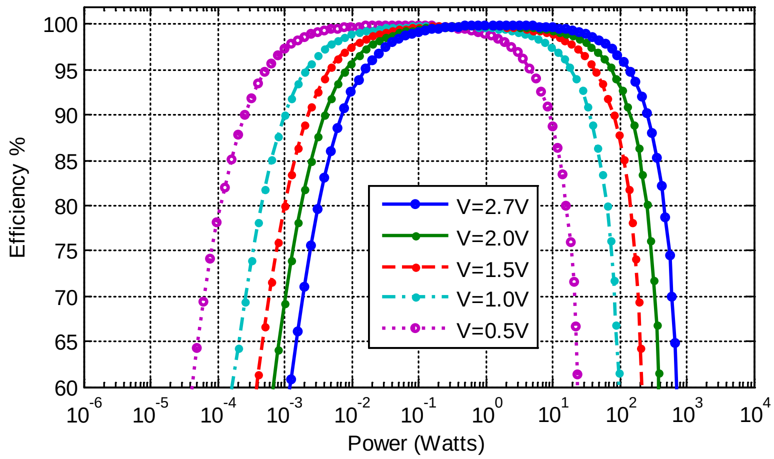

Figure 6. Predicted efficiency for discharging a 470F supercapacitor is modeled by the three branch model.

CONCLUSIONS AND FUTURE WORK

This paper demonstrated design considerations that can jeopardize the charge-discharge energy efficiency benefits of supercapacitors over electrochemical batteries. Demonstrations use a three branch model equivalent circuit with parameters taken from previous measurements of two different physical devices and two supercapacitor modeled in literature to give a wide range of capacitances from various manufacturers. Results show the importance of limiting supercapacitor operation to within suitable power limits. These power limits for comfortable operation are found to be dependent on both supercapacitor size and voltage level.

In this paper, a method for measuring the already proposed three branch model is elaborated on. A precisely timed controlled current source which is capable of supplying large amount of current is needed for conducting the experiment.

Three branch model is able to characterize supercapacitor behavior over a wide operating range power. For specific applications, a simplified model could be used where some of the parameters play an important role. For example, in elevators where there is a need to supply a large amount of energy in a very short time, series resistance of the first branch plays an important role. In field systems, the field processor needs to have an estimate of the remaining energy based on supercapacitor voltage. The dynamics in incoming and outgoing power to super capacitor is limited in such systems, thus the charge redistribution between branches may be neglected. In wireless sensor networks, supercapacitors are mainly used as the energy buffer for an extended period of time. Thus the leakage resistor is mostly emphasized.

Operation at both low and high power outside these limits result in severely degraded supercapacitor efficiency. For example, while a 1500F capacitor fully charged to 2.7V may be

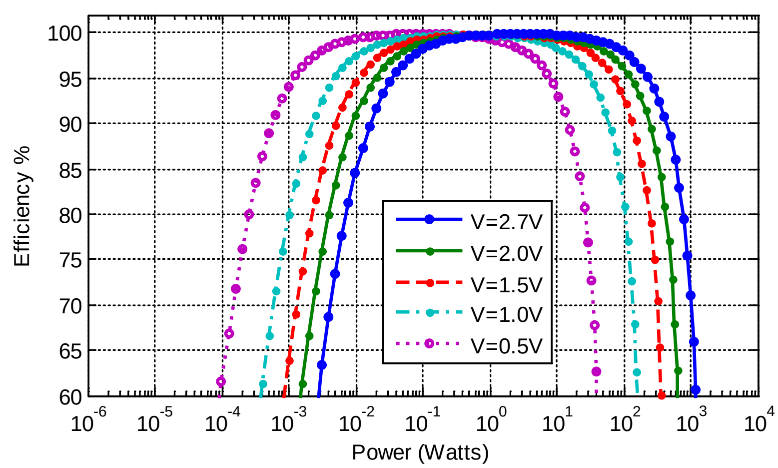

Figure 5. Predicted efficiency for discharging a 1500F supercapacitor is modeled by the three branch model.

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able to comfortably supply power at 10W at near 100% efficiency, the efficiency of 50F capacitor discharging at that power level will be below 50%. Furthermore, once the voltage of the 1500F capacitor falls below 0.5V, it will also suffer from increasing energy waste as efficiency at 10 W will fall to 93%.

In addition to using the three branch model to measure the efficiency of supercapacitors, the three branch model is also used in a Kalman filtering implementation to accurately track and predict a supercapacitor's behavior. Kalman filtering is shown to have greater energy awareness accuracy than simpler methods, because Kalman filtering is able to optimally update a running prediction of the internal state of a supercapacitor. Tracking the internal state of a supercapacitor is important because the distribution of charge in the three branches of the supercapacitor model can significantly impact stored energy, but cannot be observed from the terminal voltage. While alternative energy awareness methods suffer from root mean square error ranging from 80% down to 5%, the Kalman filter implementation of the three branch model has error of less than 1%.

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KEY TERMS AND DEFINITIONS

Supercapacitor: A device used to store electrical energy through two processes: Double Layer Capacitance and Pseudocapacitance. They are made of highly porous materials such as activated carbon which allows them to achieve capacitance, energy density, and power density levels orders of magnitude higher than electrolytic capacitors. Compared to rechargeable batteries, supercapacitors have much lower energy density but much higher power density. Also known as Ultracapacitors and Electric Double-Layer Capacitors (ELDCs).

Rechargeable Battery: A type battery whose charge can be replenished by applying a charge in the reverse (charging) direction. This is the opposite direction from when the stored energy is being consumed.

Energy Density: The amount of energy stored per unit volume for a given energy buffering device (e.g., supercapacitor or rechargeable battery). Supercapacitors are known to have around 10 times lower energy density than rechargeable batteries. For example, while supercapacitors have an average 10 Wh/kg (Watt-hours per kilogram) energy density, a rechargeable battery typically has a 100 Wh/kg density.

Power Density: The amount of power that can be supplied to the load. Supercapacitors are known to have around 10 to 100 times better power density than rechargeable batteries. Primarily determined by their ESR, supercapacitors can supply a real high peak power to the load. This allows supercapacitors to be used in applications with very high power demand, such as hybrid electric cars and elevators. It is measured in W/kg (Watts per kilogram).

Pseudocapacitance: Electrochemical storage of energy in supercapacitors by means of redox reactions. Like, Double Layer Capacitance, it increases with the surface area of the electrode. It is one of two contributing factors to the overall capacitance of a supercapacitor.

Double Layer Capacitance: Capacitance at the interface of the electrode and electrolyte inside a supercapacitor. Due to the extremely high surface area of the materials used for electrodes in supercapacitors, Double Layer Capacitance can be very large. It is one of two contributing factors to the overall capacitance of a supercapacitor.

Leakage: Energy lost internally in the supercapacitor; increases exponentially with terminal voltage. Leakage is considered to be high in supercapacitors and is sometimes referred to as self-discharge.

Charge Redistribution: The evening out of charge across the supercapacitor that occurs most dramatically when a supercapacitor has been charged over a short period of time. Charge Redistribution leads to a reduction in terminal voltage, which is sometimes mistaken for voltage.

Three Branch Model: The most accurate model for supercapacitors that consists of three branches, each containing a resistor and a capacitor. The time constant in each branch is significantly different from that of the other branches so that only one branch dominates the supercapacitor behavior at any one time. The three branch model also consists of a parallel resistor to simulate leakage and a voltage dependent capacitor in the first branch to replicate supercapacitors' voltage dependent behavior.

State of Charge: The level of charge of each branch in the three branch model. There is no way to directly observe state of charge for each of the three branches.

Equivalent Parallel Resistance (EPR): The three branch model approximates the supercapacitor behavior as three parallel-connected RC pairs. The leakage aspect of supercapacitors is modeled as a resistor that is connected to these three branches in parallel, thereby continuously wasting energy. For this reason, the leakage resistor can be thought of as being an Equivalent Parallel Resistor (EPR).

Equivalent Series Resistance (ESR): The first branch of the three branch model has a very small resistor connecting to the main capacitor that is the dominant storage element in the entire supercapacitor. The resistance of this first branch is termed Equivalent Series Resistor (ESR) and limits the amount of current that can flow from the main terminals into this first branch capacitor. ESR is an important parameter in determining the power density of the supercapacitor.

Kalman Filter Formulation: A technique used to continuously track the state of charge of the capacitors in the three branch model. It utilizes recursive operations to continuously estimate the state of charge. This technique yields accuracy within 1%.

Observable Variables: These are the variables that can be measured and fed back into the Kalman filter. In the case of supercapacitor modeling, the only two observable variables are the terminal voltage of the supercapacitor and the terminal current (i.e., the current that is being fed into the supercapacitor).

Latent Variables: In the Kalman filtering, the latent variables are the ones that the model tries to estimate, since they cannot be directly measured. In the case of supercapacitor modeling using Kalman filtering, the latent variables are the individual voltages and currents of the three branches. When the voltages of three individual branches deviate, they have to eventually equalize in the long term. So, the primary advantage of using Kalman filtering is to estimate the latent variables during the iterative Kalman filtering process.

DC-DC Converter: A switching converter that takes energy from a power source and transfers it to another power source. Specifically, since both of these sources might have different DC voltage levels, the configuration of the DC-DC converter might have to be chosen specifically depending on the input/output voltage levels (i.e., Vin vs. Vout). A Boost converter transfer energy in the Vout > Vin case, whereas a Buck converter transfers energy in the opposite scenario (i.e., Vout < Vin). A SEPIC converter can transfer energy in both cases.

Energy Efficiency: Quantifies what percentage of the energy that is input into a DC-DC converter actually transferred to the output. For example, if 1 Watt is being applied to the input and a constant 0.85 Watt is being transferred to the output (e.g., to the supercapacitor storage), this system has an 85% efficiency. In other words, 15% of the incoming energy is wasted.