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Calculation of Internal Parameters of Super Capacitor to Replace Battery by Using Charging and Discharging Characteristics

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Abstract*— Various energy storage technologies have been developed in the market for various applications. Batteries flywheels, fuel cells are a few which are much common. The Super capacitor is an emerging technology, which is used to replace the battery with the help of internal parameters. Super capacitors are governed by the same fundamental equations as conventional capacitors, but utilize higher surface area electrodes and thinner dielectrics to achieve greater capacitances. This allows for energy densities greater than those of conventional capacitors and power densities greater than those of batteries. As a result, Super capacitors may become an attractive power solution for an increasing number of applications. A simple resistive capacitive equivalent circuit is sufficient to characterize its terminal behavior. The equivalent model consists of three RC branches. A method to identify the circuit parameters is presented in this paper. Measurements of carbon-based super capacitor for power applications are presented, analyzed, and the equivalent circuit response is compared with experimental results. This gives the behavior of the super capacitor which will help in any replacement of battery with super capacitor. In order to obtain the same characteristics of battery with the help of super capacitor the modification in internal parameters is required. Which modifications required are explained in this paper.

***Keywords*—Super Capacitor, Electrochemical Double Layer Capacitor, Charging and Discharging Of Super Capacitor, Battery, MATLAB/SIMULINK.**

I. INTRODUCTION

Super capacitor is a new device of stored energy; it is fulfill the gap between capacitor and battery. It has large capacitance and excellent charge-discharge performance of the instantaneous, to compare with normal battery it has the higher power density and the longer useful life; to compare with normal capacitor it has the bigger capacitor density and more advantages as maintenance-free, high reliability. The features are short charge-time, long service life, good temperature characteristics, energy conservation, and green environmental protection. Super capacitor is also known as ultra capacitor, electro-chemical double layer capacitor. It utilizes the high surface area electrode materials and thin electrolytic dielectrics to achieve capacitances several orders of magnitude larger than conventional capacitors (Fig.1). Super capacitor can store much more energy than conventional capacitors and offer much higher power density than battery. Super capacitor works on the principle of double-layer capacitance at the electrode/electrolyte interface where electric charges are accumulated on the electrode surfaces and ions of opposite charge are arranged on the electrolyte side.

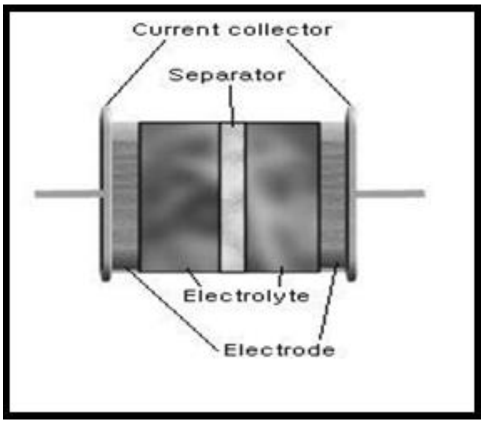

Fig.1 Conceptual Diagram of Super Capacitor Construction

Like a battery a super capacitor has an electrolyte (electrically active chemical) inside it, separating its plates, which is more like the electrolyte in a battery than the dielectric in a conventional capacitor (which might just be a piece of plastic or even air).

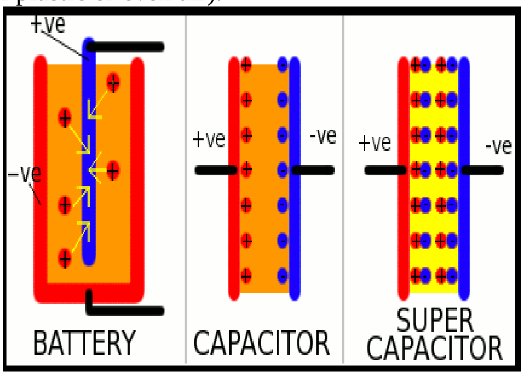

Fig.2 Construction Comparison between Battery, Capacitor and Super Capacitor

In a conventional capacitor, positive charges form on one plate and negative charges on the other with the dielectric sitting in between them, keeping the charges safely apart but otherwise not doing very much (Fig.2). In a super capacitor, the electrolyte is electrically active and adds another dimension: the charged plates polarize the electrolyte, making positive ions inside it move one way and negative ions the other, and causing a second set of charges to form. This makes what's called an electric double-layer that allows the plates to store more charge. Unlike in a battery, the positive and negative charges in a super capacitor are produced entirely by static electricity; no chemical reactions are involved. Batteries store electricity using chemical

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reactions happening between an electrolyte (orange), a positive electrode (blue), and a negative electrode (red). Capacitors store static electricity by building up opposite charges on two metal plates (blue and red) separated by an insulating material called a dielectric (orange). Super capacitors store more energy than ordinary capacitors by creating a double layer of separated charges between two plates made from porous, typically carbon-based materials. The plates create the double-layer by polarizing the electrolyte (yellow) in between them (Fig.2). The basic unit of electric charge is called the farad (F). Typical capacitors used in electronic circuits store only miniscule amounts of electricity (usually rated in units called microfarads or Pico farads, which are millionths and billionths of a farad). In marked contrast, a typical super capacitor can store a charge thousands, millions, or even billions of times bigger (rated in farads). The big advantage of a super capacitor is that it can store and release energy almost instantly much more quickly than a battery. That's because a super capacitor works by building up static electric charges on solids, while a battery relies on charges being produced slowly through chemical reactions, often involving liquids. Batteries and super capacitors compared in terms of their energy and power. Batteries have a higher energy density (they store more energy per unit mass) but super capacitors have a higher power density (they can release energy more quickly). That makes super capacitors particularly suitable for storing and releasing large amounts of power relatively quickly, but batteries are still king for storing large amounts of energy over long periods of time. Super capacitors work at relatively low voltages (maybe 2-3 volts), they can be connected in series (like batteries) to produce bigger voltages for use in more powerful equipment. Since super capacitors work electro statically, rather than through reversible chemical reactions, they can theoretically be charged and discharged any number of times. They have little or no internal resistance, which means they store and release energy without using much energy and work at very close to 100 percent efficiency (97-98 percent is typical).

II. PARAMETER CALCULATION OF SUPERCAPACITOR USING CHARGING AND DISCHARGING CHARACTERISTICS

To study the internal parameter, behavior of super capacitor is required. For this reason simple resistive capacitive model (series RC circuit) is used. In this paper carbon based super capacitor is used. These capacitors are low voltage device with a rated voltage of 2.4 V with capacitance value of 540 F. Higher voltages can be achieved by connecting many cells in series like batteries. An equivalent circuit describes the terminal behavior of a super capacitor. In this paper the measured voltage of a 540 F super capacitor charged up to the rated voltage with a constant current of 2 A, and discharged after some time with the same magnitude of constant current[2]. For a simple model and the experience from measurements, a model consisting of three RC branches is proposed. This provides three different time constants to model the different charge transfers, which provides sufficient accuracy to describe the terminal behavior of the super capacitor for the desired span of 30 minutes.

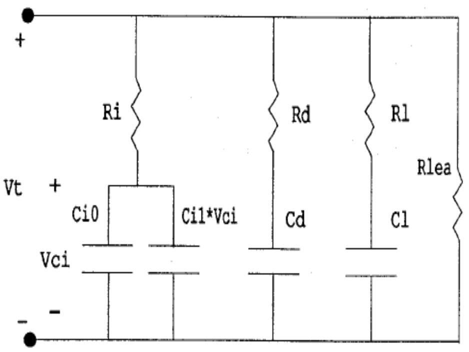

Fig.3 Equivalent Model of Super Capacitor

In this paper to show the voltage dependence of the capacitance, the first branch is modeled as a voltage dependent differential capacitor C_{dlff} explained in the next section. The differential capacitor consists of a fixed capacitance C_{i0} and a voltage dependent capacitor C_{il}* V. A resistor, parallel to the terminals, is added to represent the self discharge property. The proposed equivalent circuit is shown in Fig.3. The first or immediate branch, with the elements R_i, C_{i0} and the voltage dependent capacitance C_{il} in [F/V], dominates the immediate behavior of the super capacitor in the time range of seconds in response to a charge action. The second or delayed branch, with parameters R_d and C_d, dominates the behavior in the range of minutes. Finally, the third or long term branch, with parameters R_1 and C_l, determines the behavior for times longer than 10 minutes.

The relation between voltage and capacitance is described following:

$$C = \frac{Q}{V}$$

Where, Q is the stored charge and V the capacitor voltage. The same definition of C applies if the charge Q is the total charge in the device or an incremental charge ΔQ resulting from an incremental change ΔV in voltage. This definition is not valid for voltage dependent capacitance.

$$C_{diff}(V) = \frac{dQ}{dV}$$

Where, dQ an incremental change in charge at a certain capacitor voltage V that produces an incremental change in voltage dQ. The internal parameters of the super capacitor model with three RC branches that have heard time constants can be identified carrying out a single fast current controlled charge.

➢ **Calculation of immediate branch parameters:**

- n=0:
  At that time $V_0 = 0$ V.
  $Q_0 = 0$
  Current source is switched on ($I = I_{ch}$)
- n=1:
  $t_1 = 9$ sec
  t_1 is given at the at which current source is rises to the sat value I_{ch} in 9 sec,
  At that time measure V_1. V_1=1.29 V.
  After small time t_1

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$$Ri = \frac{V1}{Ich} = 0.645$$

- n=2:
  At when $V_2=V_1+\Delta V$
  ΔV chosen to be 500 mV. Measure t_2.
  t_2=62 sec,
  $\Delta t = t_2-t_1$ = 53 sec.

$$C_{io} = Ich\frac{\Delta t}{\Delta V} = 212\ F$$

- n=3:
  Reached when V_3 = V rated. V_3 = 2.4 V.
  Measure t_3. t_3 = 210 sec.
  Now current source is turned off (I_{ch} = 0)
- n=4:
  $t_4 = t_3$ + 9 sec.
  9 sec is given by fall time of the current.
  At that time measure V_4. V_4 = 1.828 V.
  Total charge supplied to the supercapacitor:
  $Q_{tot} = I_{ch} * (t_4 - t_1)$ = 420 coulomb.
  Now we calculate $C_q = Q_{tot}/V_4$ = 229.75 F.

$$Ci1 = \frac{2}{V4} * \left(\frac{Ich * (t4 - t1)}{V4} - Ci0\right) = 19.43\ F$$

➢ **Calculation of delayed branch parameters:**

- n=5:
  At when $V_5 = V_4 - \Delta V$.
  ΔV is chosen to be500 mV. V_5 = 1.328 V.
  Measure t_5. t_5 = 303 sec.
  $\Delta t = t_5-t_4$ = 84 sec.
  As ΔV is small and C_d is assumed discharged,
  $I_{tr} = (V_4-\Delta V/2)/R_d$.
  (R_i is neglected because $R_i << R_d$)
  Relating the transfer current $I_{tr} = C_{diff} * \Delta V/\Delta t$.
  Here, $C_{diff} = C_{i0} + (C_{i1}*V)$ = 258.63 F.

Now,

$$Rd = \frac{\left(V4 - \frac{\Delta V}{2} * \Delta t\right)}{Cdiff * \Delta V} = 1.025\Omega$$

- n=6:
  $t_6 = t_5 + 3(R_d * C_d)$
  Typically $R_d * C_d$ = 20 sec. t_6 = 303 sec
  Measure V_6. V_6 = 1.164 V.

$$Cd = \frac{Qtot}{V6} - \left(Ci0 + \frac{Ci1}{2} * V6\right) = 137.51\ F$$

➢ **Calculation of long term branch parameters:**

- n=7:
  At when $V_7 = V_6 - \Delta V$. V_7 = 0.664 V.
  Measure Δt = 73 sec.
  As ΔV is small and C_l is assumed discharge, I_{tr} is virtually constant and given by:
  $I_{tr} = (V_6-\Delta V/2)/R_l$.
  (R_i and R_d neglected because$R_i << R_d << R_l$).
  Because R_d is much larger than R_i, the transfer current I, at this initial instant is supplied mainly from the immediate branch:
  $I_{tr} = C_{diff}*\Delta V/\Delta t$.

$$Rl = \frac{\left(V6 - \frac{\Delta V}{2} * \Delta t\right)}{Cdiff * \Delta t} = 5.9\Omega$$

- n=8:
  t_8 = 30 min:
  At t, it is assumed that the charge redistribution to the long term branch has ended and the three equivalent capacitors have the same voltage.
  Measure V_8. V_8 = 0.60 V.
  The long term capacitor (C_l) is calculated using the charge balance:

$$Cl = \frac{Qtot}{V8} - \left(Ci0 + \frac{Ci1}{2} * V8\right) - Cd = 344.66\ F$$

With the clear definition of the procedure for the parameter calculation, the parameters values may now be measured. The below table summarizes the average results of the parameters measurements.

Table.1 Internal Parameters of Super Capacitor

Parameters	540 F Super capacitor
R_i	0.645 Ω
C_{i0}	212 F
C_{i1}	19.43 F
R_d	1.025 Ω
C_d	137.51 F
R_l	5.9 Ω
C_l	344.66 F
R_{leak}	1.6 KΩ

Above calculation is calculated from following charging and discharging graph. The experimental graph voltage verses time for Charging and discharging (at constant current applying 2 A) are given below. This is clearly mention that voltage is increasing with time and capacitor is charge and voltage is decreasing with time when capacitor is discharge. Figure 4 shows the terminal voltage during the charge action with constant current and the first minutes of the internal charge distribution process. This graphic presents the first three minutes of the capacitor response to a charge action.

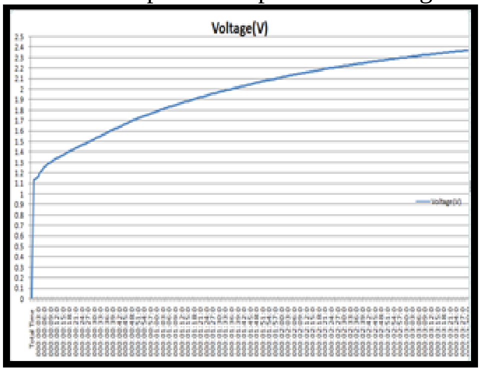

Fig. 4 . Charging Of Super Capacitor with Constant Current 2A.

Figure 5 shows terminal voltage during recharge action with constant current. After that, the capacitor is discharged until the voltage across the immediate and delayed branches are at approximately equal. Finally, the current is turned off

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again and the change in terminal voltage thereafter is very low since that change is given only by the long term branch.

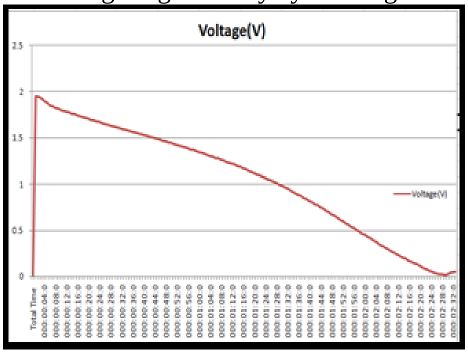

Fig. 5. Discharging Of Super capacitor With Constant Current 2A.

III. REPLACEMENT OF BATTERY WITH SUPERCAPACITOR

Batteries have many advantages like high self-discharge rate, long life nearly 5 years, good reversibility, easily available, low cost, simple charging method. Over several advantages batteries have many disadvantages like bulky, not eco-friendly, failure rate is high; charging time is high, lead-acid batteries requires acid which is harmful to the human beings etc. So, it is require overcoming these disadvantages and finding the better replacement of batteries. The relative energy storage device is capacitor but the main disadvantages of capacitors are low energy storage capacity. This disadvantage can be overcome with the help of super capacitors. In order to obtain the same characteristics of battery with the help of super capacitor the modification in internal parameters is required. The internal parameters require obtaining the same characteristics of battery the following procedure has been adopted.

- Obtain the charging and discharging characteristics of battery by using MATLAB Simulink,
- Use these charging and discharging characteristics as the characteristics of super capacitor,
- Calculate the internal parameters for obtained characteristics,
- State the require modification to be done in super capacitor in order to obtain the require internal parameters.

For getting charging characteristics of battery, MATLAB Simulation tool is used. Its initial state of charge is 0% in the starting. For getting charging characteristics constant current of 2 A is applied (Fig.6).

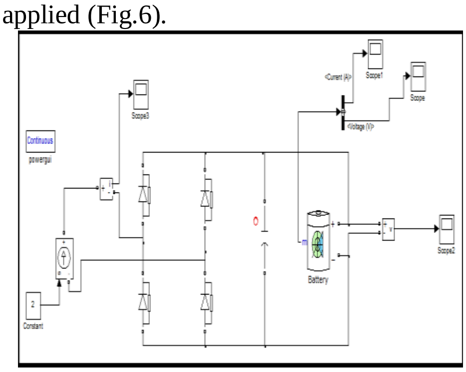

Fig.6 MATLAB Simulink Model for Battery Charging

Following charging characteristic is obtained from the MATLAB Simulink model for battery charging (Fig.7).

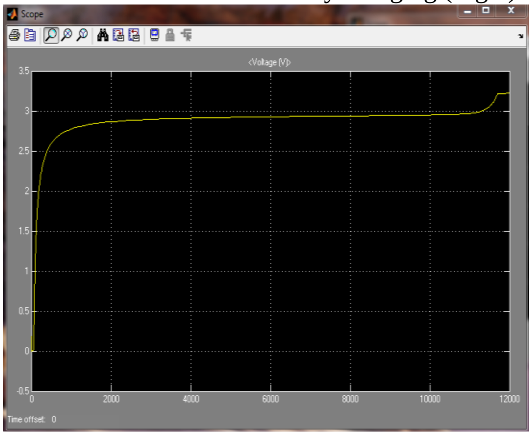

Fig.7. Charging characteristic of battery

For getting discharging characteristics of battery, MATLAB Simulation tool is used. Its initial state of charge is 100% in the starting. For getting discharging characteristics constant current of 2 A is applied (Fig.8).

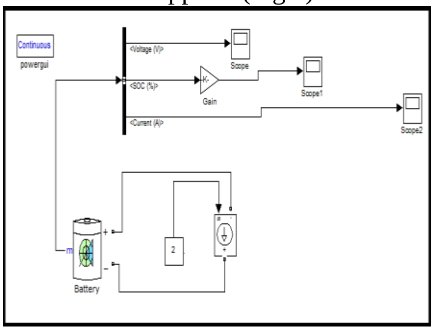

Fig.8. MATLAB Simulink model for battery discharging

Following discharging characteristics is obtained from the MATLAB Simulink model for battery discharging (Fig.9).

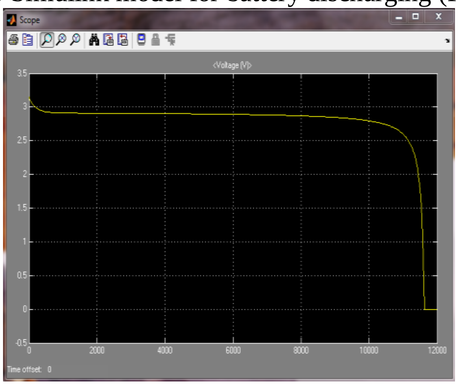

Fig.9 Discharging characteristics of battery

The total discharging time of the battery can be found from its discharging characteristics. This discharging time is used for calculating of internal parameters. In order to obtain same characteristics with the help of super capacitor modification in internal parameters have to be done and it is explained below. Use above charging and discharging characteristics as an super capacitor characteristics and calculate its internal parameters. The above test procedure is used to calculate the internal parameters. With the clear definition of the procedure for the parameter calculation, the parameters values can be calculated. The following table summarizes the results of the parameters measurements. From the obtained results, in order to replace battery with super capacitor internal parameters required for super capacitor is shown in table 2.

Table.2 Internal Parameters Required to Replace Battery with Super capacitor

Parameters	Battery (6.5 Ah, 2.7 V)	Supercapacitor (560 F, 2.7 V)
R_i	0.835	0.645
C_{i0}	356 F	212 F
C_{i1}	99.22 F	19.43 F
R_d	87.659	1.025
C_d	209.93 F	137.51 F
R_l	12.44	5.9
C_l	60 F	344.66 F

By implementing the internal parameters of battery in super capacitor, charging and discharging characteristics of battery can be obtained with the help of super capacitor. And hence by varying the internal parameters of super capacitor the required characteristics can be obtained. To change the internal parameters of super capacitor some modification in design and material is required. By changing the material used in super capacitor the internal parameters variation is to be found.

IV. CONCLUSION

The charging time of super capacitor is quite less compare to conventional capacitor and also the power density is very high. So, from the knowledge of different branch parameter of super capacitor the exact behavior and response can be predicted. From the charging and discharging time, the internal parameter has been calculated and which will be helpful for designing the charging and discharging circuit. In order to replace battery with super capacitor, it is require changing internal parameters of super capacitor. and by changing the internal parameters of super capacitor the exact charging discharging characteristics of battery can be achieved.

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