Energy conversion efficiency of carbon black-phosphoric acid ultracapacitor

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Abstract

The energy conversion efficiency of a carbon black-phosphoric acid composite ultracapacitor was determined. A typical ultracapacitor had a maximum energy storage capacity of 24.32J. It had a specific energy of 8.11 J/g of which, during discharge, 36% was dissipated internally in the ultracapacitor, in two resistances of 2.66Ω and 54.01Ω, where the latter resistor was in parallel with the charge storage capacitor of 18.53F. In discharge mode its energy conversion efficiency was 64% thereby delivering 15.56J to a 10Ω load resistor.

Keywords

Supercapacitor, ultracapacitor characterization, energy storage, composite electrode, energy efficiency

Introduction

The purpose of the work was to fabricate and characterize a composite ultracapacitor. These are high capacitance electrical devices due to their high surface area of the nano particular component of the composite material. They are used for energy storage and as high power density sources in electric vehicles, emergency power supplies, flash photography, elevators and mining excavation machines.[1-5] The device was fabricated by using a carbon black-phosphoric acid electrolyte composite. The electrical components of the model representing the device, and the efficiency with which the energy stored in the composite was converted into useful energy, were determined. Methods have been developed to characterize the electrical properties of such devices.[6-9] The experimental approach used here was based on acquiring the charge-discharge curve. The values of the two resistors and the capacitor, that represent the ultracapacitor, were then extracted from the charge-discharge plot using equations based on the boundary analysis method .[9] This enabled the determination of the qualitative and quantitative relationships between absorbed, generated and dissipated energies involved in the charge-discharge process.

Experimental

The ultracapacitor had the plate/composite/separator/composite/plate structure. The composite material was made up of a mixture of 0.1 to 1 by weight of carbon black to 10% electrolyte solution of phosphoric acid. It consisted of a two composite regions separated by an ion permeable membrane, and with graphite for the plates. The total weight of this structure was 3.5g. The transmission electron microscopy of the carbon black showed that it consists of particles of 56nm average diameter.[10]

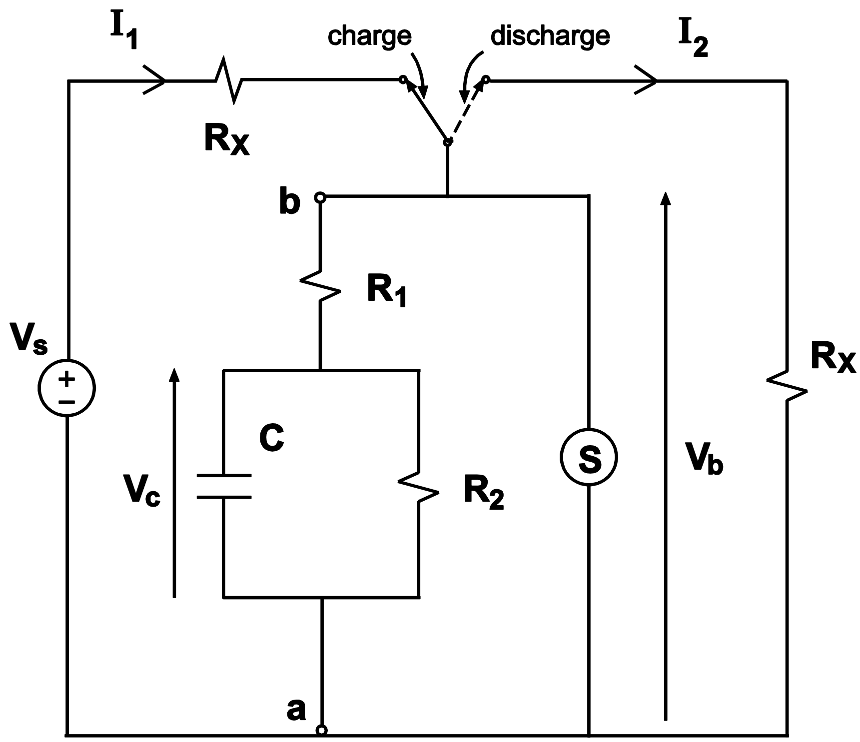

Fig. 1 Circuit for acquiring the temporal variation of ultracapacitor voltage V_b in charge and discharge phases where Vs=2V, Rx=10Ω, S=the storage oscilloscope.

The ultracapacitor equivalent circuit is shown between nodes *a* and *b* in Fig. 1. It consists of a resistor R_1, in series with the parallel combination of a resistor R_2 and a capacitor C. Fig. 1 shows the schematic diagram of the circuit that was used to record the experimental data necessary for the analysis of the ultracapacitor. The experiment consisted of first charging, and then discharging the ultracapacitor. V_s is the charging voltage source. Throwing the switch to the left charges the capacitor through the current limiter resistor R_x, and throwing it to the right discharges it through the load resistor R_x. The oscilloscope S recorded the temporal variation of the voltage V_b, across the ultracapacitor, during the charge and then the discharge phase.

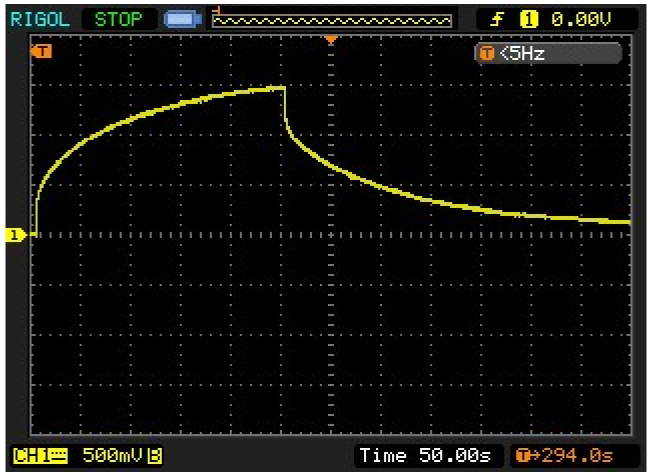

Fig. 2 The temporal variation of the ultracapacitor voltage V_b in the charge and discharge phases

Fig. 2 is a charge-discharge curve showing the variation in V_b against time, for an ultracapacitor that was uncharged prior to the start of charging. The curve shows two abrupt changes in V_b; one at the start of charging, and the second at the boundary between the end of the charging phase and the beginning of the discharge phase. For the latter, choosing the origin at time t=0 at the charge-to-discharge transition, the ultracapacitor parameters are described in terms of voltages and currents at time $t=0^-$ just before, and at $t=0^+$ just after, the switch is thrown from the charge to the discharge phase. For an experiment where the charging phase was maintained long enough to attain a steady state voltage across the ultracapacitor, $Vb(0^-)$ was 1.70V, and just after the transition at $t=0^+$ it was $V_b(0^+)$=1.28V.

The equation for the decaying exponential across the ultracapacitor as a function of time in the discharge phase is

$$V_b(t) = V_b(0^+)e^{-t/\tau} \qquad (1)$$

and the voltage across the capacitor C is

$$V_c(t) = \left(\frac{R_1 + R_x}{R_x}\right)V_b(0^+)e^{-t/\tau} \qquad (2)$$

where τ =190 seconds was the time constant of the decaying exponential.
If R_{equ} is the equivalent resistance seen by the capacitor C in the discharge circuit, then

$$\tau = R_{equ}C \qquad (3)$$

$$C = \tau\left(\frac{R_1 + R_2 + R_x}{R_2(R_1 + R_x)}\right) \qquad (4)$$

The values of R_1 and R_2 were determined by applying the transient-boundary circuit analysis method at boundaries between transient phases that appear in the temporal variation of voltages associated with energy storage devices.[9] This gave R_1=2.65Ω and R_2=54Ω., and with R_x=10Ω, Equ. 4 gave C= 18.53F.

Also, since

$$V_c(0^+) = V_b(0^-) - I_1(0^-)R_1 \tag{5}$$

$$V_c(0^+) = 1.62 \text{ V} \tag{6}$$

A summary of the above results appears in Table 1.

$V_b(0^-)$	$V_b(0^+)$	$V_c(0^+)$	τ	R_1	R_2	Rx	C
1.7V	1.28V	1.62V	190 sec	2.66Ω	54.01Ω	10Ω	18.53F.

Table 1

Energy Equations

The power delivered to the load R_x at time t is

$$P_L(t) = \frac{V_b^2(0^+)e^{\frac{-2t}{\tau}}}{R_x} \tag{7}$$

Therefore, the total energy consumed by the load between time 0 and t is

$$E_L(t) = \int_0^t \frac{V_b^2(0^+)e^{-2t/\tau}}{R_x}dt \tag{8}$$

$$E_L(t) = \frac{\tau V_b^2(0^+)}{2R_x}(1 - e^{-2t/\tau}) \tag{9}$$

Similarly, the energies dissipated in R_1 and R_2 during this time are

$$E_{R1}(t) = \frac{\tau R_1 V_b^2(0^+)}{2R_x^2}(1 - e^{-2t/\tau}) \tag{10}$$

$$E_{R2}(t) = \frac{\tau V_b^2(0^+)}{2R_2}\left(\frac{R_1 + R_x}{R_x}\right)^2 (1 - e^{-2t/\tau}) \tag{11}$$

Calculations and results

The ultracapacitor acts as an absorber of energy, during charging, when the energy is stored in capacitor C. The stored energy is at its maximum at $t=0^+$ and given by

$$E_c(0^+) = \frac{1}{2}CV_c^2(0^+) = 24.32 \text{ J} \tag{12}$$

This gives the ultracapacitor an energy density of 8.11 J/g.

During discharge the capacitor is a generator of energy. The total energy $E_c(t)$ generated by the capacitor C from t=0 to time t, is

$$E_c(t) = \frac{1}{2}CV_c^2(0^+) - \frac{1}{2}C\left[\left(\frac{R_1+R_x}{R_x}\right)^2 V_b^{\,2}(0^+)e^{\frac{-2t}{\tau}}\right] \qquad (13)$$

$$E_c(t) = 24.32(1-e^{-2t/\tau}) \qquad (15)$$

Of this energy $E_L(t)$ is delivered to the load Rx , and $E_{R1}(t)$ and $E_{R2}(t)$ to R1 and R2, respectively. Substituting values from Table 1 into Equs. 9 to11 gives the dissipated energies as

$$E_L(t) = 15.56(1-e^{-2t/\tau}) \qquad (16)$$

$$E_{R1}(t) = 4.14(1-e^{-2t/\tau}) \qquad (17)$$

$$E_{R2}(t) = 4.62(`1-e^{-2t/\tau}) \qquad (18)$$

Time t/s	$E_L(t)$ /J dissipated	$E_{R1}(t)$ /J dissipated	$E_{R2}(t)$ /J dissipated	$E_c(t)$/J generated
0	0	0	0	0
50	6.37	1.70	1.89	9.95
100	10.13	2.70	3.01	15.83
150	12.35	3.29,	3.67,	19.31
200	13.66	3.64	4.06	21.36
250	14.44	3.84	4.29	22.57
300	14.90	3.96	4.42	23.29
350	15.17	4.04	4.50	23.71
400	15.33	4.08	4.55	23.96
450	15.42	4.10	4.58	24.11
500	15.48	4.12	4.60	24.19
550	15.51	4.13	4.61	24.25
600	15.53	4.13	4.61	24.28
800	15.56	4.14	4.62	24.32
1000	15.56	4.14	4.62	24.32
1200	15.56	4.14	4.62	24.32

Table 2

Table 2 shows the energy supplied to the circuit by the ultracapacitor, and the energy dissipated in the load resistor and the ultracapacitor resistors R_1 and R_2, as a function of discharge time. It shows that at 200 seconds into the discharge 88% of the energy stored in the capacitor has been expended. At all times the generated energy equals the sum of the dissipated energies. At any time t the percentage of the generated energy that is dissipated in the load resistance R_L and the internal resistors R_1 and R_2 are 64%, 17% and 19% respectively. Although there is an order of magnitude difference between R_1 and R_2, the energies dissipated in these two resistors are quite close in value. This is because R_2 is in parallel with C while R_1 is in series. In consequence, the power delivered to each of these resistors is also close; at $t=0^+$, for instance, 0.043W and 0.049W for R_1 and R_2, respectively.

Conclusions

The ultracapacitor had a specific energy of 8.11 J/g of which 36% was dissipated internally in two resistances of 2.66Ω and 54.01Ω, where the latter resistor was in parallel with the charge storage capacitor of 18.53F. Its maximum energy storage capacity was 24.32J in a 3.5g composite of carbon black and phosphoric acid. In discharge mode its energy conversion efficiency was 64% thereby delivering 15.56J to a 10Ω load resistor within a period of 20 minutes. The specific energy of the device was over 20 times that of a conventional capacitor and a hundredth of that of an alkaline battery.

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