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Supercapacitor performance evaluation in replacing battery based on charging and discharging current characteristics

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Abstract. Supercapacitor is a new device of energy storage, which has much difference between ordinary capacitors and batteries. Supercapacitor have higher capacitance and energy density than regular capacitors. The supercapacitor also has a fast charging time, as well as a long life. To be used as a battery replacement please note the internal parameters of the battery to be replaced. In this paper conducted a simulation study to utilize supercapacitor as a replacement battery. The internal parameters of the battery and the supercapacitor are obtained based on the characteristics of charging and discharging current using a predefined equivalent circuit model. The battery to be replaced is a 12-volt lead-acid type, 6.5 Ah which is used on motorcycles with 6A charging and discharging currents. Super capacitor replacement capacitor is a capacity of 1600F, 2.7V which is connected in series as many as 6 pieces with 16.2 volt terminal voltage and charging current 12A. To obtain the same supercapacitor characteristic as the battery characteristic to be replaced, modification of its internal parameters is made. The results show that the super-capacitor can replace the battery function for 1000 seconds.

1. Introduction

Various energy storage technologies have been developed for various application, including supercapacitor. Basically, supercapacitor is modeled and analyzed as regular capacitor. However, its physical size and capacity are larger. This makes supercapacitor has higher energy density than the regular one and higher charge density than battery. Furthermore, its charging and discharging time are faster with longer lifetime [1]. As results, supercapacitor can be used as energy storage for various applications.

In order to use supercapacitor as a battery replacement, internal parameters should match with the equivalent battery. This parameters are approximated based on a predetermined equivalent circuit. If necessary, these parameters are modified accordingly [2]. This paper employs a simulation approach to determine the energy supply duration based on charging and discharging current characteristics.

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2. Internal Parameters Modelling

In order to obtain the internal parameters of a supercapacitor, an equivalent circuit model is employed [3] as depicted in Figure 1.

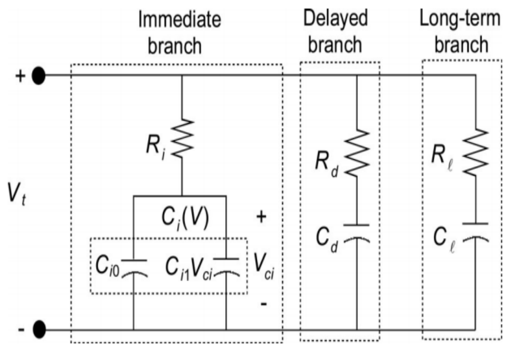


Figure 1. Equivalent Circuit for Battery and Supercapacitor

The model consists of three branches of RC circuits arranged in parallel manner [4]. Each branch has different time rate. Immediate branch has component of Ri, C_{i0} and C_{i1} with a very short charging response. Delayed branch has components of Rd and Cd with response time several minutes. Finally, long-term branch with R_l and C_l determines the characteristics of battery and supercapacitor with response time longer than 10 minutes. In order to obtain equivalent parameters, each branch should be analysed one by one by consider that voltage is time-dependant [4].

2.1. Immediate Branch

Immediate branch parameters are identified by performing charging on both devices by using a constant current. The parameter is then calculated from current and voltage relation on the branch by using Equation 1.

$$Ri = \frac{V1}{Ich} \tag{1}$$

where V_1 is voltage at t1 after charging current is supplied. Variable Ich is the constant charging current. V_1 is the reference point to determine C_{i0} and C_{i1}. C_{i0} is calculated by using voltage difference, ΔV so that $V_2 = V_1 + \Delta V$. The charging time (t_2) is calculated to make the voltage across the battery or supercapacitor achieve V_2, then the time difference is $\Delta t = t_2 – t_1$. C_{i0} is calculated by using Equation 2.

$$Cio = Ich\frac{\Delta t}{\Delta V} \tag{2}$$

Charging time (t_3) is the time required to achieve fully charged voltage (V_3), so that C_{i1} be calculated using Equation 3.

$$C_{i1} = \frac{2}{V4}\left(\frac{Qtot}{V4} - Cio\right) \tag{3}$$

where $Q_{tot} = Ich \times (t_4 - t_1)$ and $t_4 = t_3 + t_1$. V_4 is the remaining voltage on battery or supercapacitor after discharging process for duration of t_1.

2.2. Delayed Branch

Rd and Cd are calculated for delayed branch determination. In order to obtain Rd, discharging time for both battery and capacitor should be calculated which is t_5 for given voltage V_5, where $V_5 = V_4 - \Delta V$. Rd is calculated by using:

$$Rd = \frac{(V4 - \frac{\Delta V}{2})*\Delta t}{Cdiff * \Delta V} \quad (4)$$

where $C_{diff} = C_{i0} + (C_{i1} \times V_3)$. Afterward, t_6 is calculated by using $t_6 = t_5 + 3\ (Rd \times C_{il})$, Cd is obtained by using Equation 5.

$$Cd = \frac{Qtot}{V6} - \left(Ci0 + \left(\frac{Ci1}{2} * V6\right)\right) \quad (5)$$

2.3. Long-term Branch

For *long-term branch* with $V_7 = V_6 - \Delta V$, and t_7 is capacitor or battery discharging time where the voltage decreases to V_7, then, R1 is calculated by using Equation 6.

$$Rl = \frac{\left(V6 - \frac{\Delta V}{2}\right)*\Delta t}{Cdiff * \Delta V} \quad (6)$$

where $\Delta t = t_7 - t_6$.

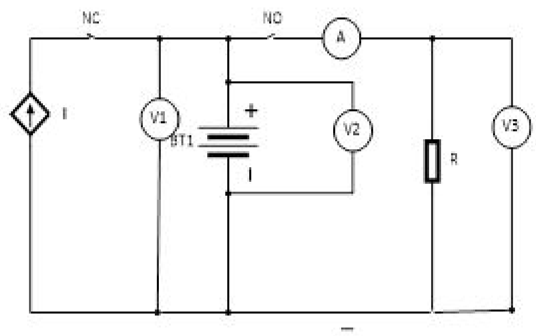
At the end of measurement stage, C_l is calculated by charging the capacitor for 30 minutes. C_l is calculated by using Equation 7.

$$Cl = \frac{Qtot}{V8} - \left(Ci0 + \frac{Ci1}{2} * V8 \right) \quad (7)$$

where V_8 is the capacitor voltage after being recharged for 30 minutes.

3. Method

In order to evaluate the supercapacitor performance, this paper employs Matlab by developing the replacement circuit to replace charging discharging branch circuits. The battery intended to be replaces is a motor cycle battery: lead-acid 6.5Ah, 12 V with equivalent circuit depicted in Figure 2a and internal parameters in Figure 2b.



(a) Battery circuit

Parameter	Battery, *lead-acid* 6.5Ah, 12 V
R_i	3,609 m?
C_{i1}	405.612 F
Rd	2,55 ?
Cd	52.86 F
R_1	0,84 ?
C_1	24.24 F

(b) Battery parameters

Figure 2. The battery circuit and parameters

Discharging circuit uses 4 rectifiers to ensure that charging current is DC. There are 6 series supercapacitors to achieve similar or larger voltage across the terminal of supercapacitor as the replaced battery. The parameters are calculated using Equation 8 to 11 [4].

$$R_{\text{series}} = R_x(I) \times S^{n_r} \tag{8}$$

$$C_{\text{series}} = C_x(I) \times S^{n_c}. \tag{9}$$

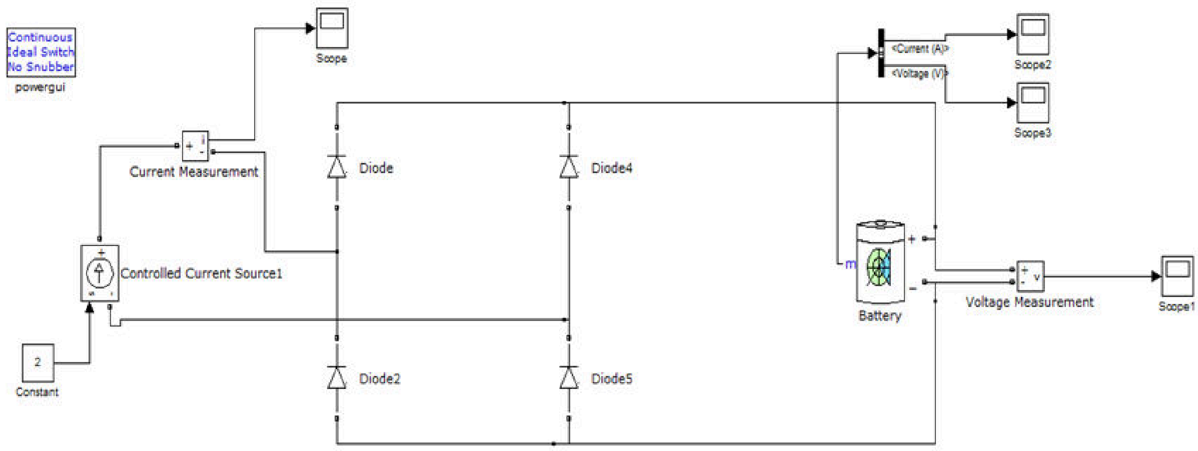
$$R_{\text{parallel}} = R_x(I) \times P^{n_r} \tag{10}$$

$$C_{\text{parallel}} = C_x(I) \times P^{n_c} \tag{11}$$

where P is number of paralleled supercapacitor, S is number of serried supercapacitor, Nr and Nc are resistor and capacitor correction factors.

4. Result and Discussions

The modelled analysed circuit is on Figure 3a. After carefully consider the internal parameters of the battery, NessCap 1600 F capacitor is chosen. The internal parameters of asingle capacitor is depicted in Figure 3b, and the 6 series supercapacitor is depicted in Figure 3c.



(a) Simulated charging circuit

Parameter	Baterai (6.5 Ah, 12 V)
Ri	4,11 m?
Ci1	101,53F
Rd	3,3 ?
Cd	393,65 F
Rl	1,289 ?
Cl	16,469 F

(b) single supercapacitor

Parameter	Super kapasitor (NessCap1600F, 2.7V)
Ri	0,94 m?
Ci1	4049 F
Rd	0,37 ?
Cd	254,8 F
Rl	0,09 ?
Cl	182,7 F

(c) series supercapacitor

Figure 3. The evaluation model and supercapacitor internal parameters

Increasing series resistor within capacitors changes discharging characteristic where supercapacitor discharging time getting slower. As result, the capacitance of series capacitor is larger.

In order to obtain supercapacitor performance in replacing battery, the discharging simulations are performed by using a model depicted in Figure 4.

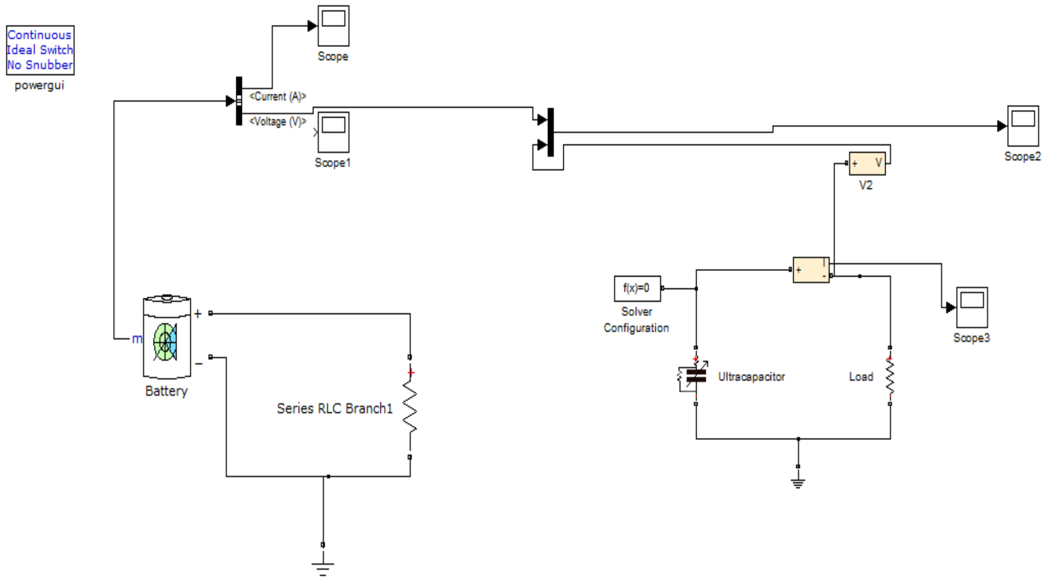


Figure 4. Simulated charging circuit

The discharging voltages are shown in Figure 5. Battery sustains 1800 second with 6 A constant current when connected to a motorcycle starter circuit. On the other hand, supercapacitor experiences rapid discharging and sustain only about 1000 s to supply at least 12 Volt.

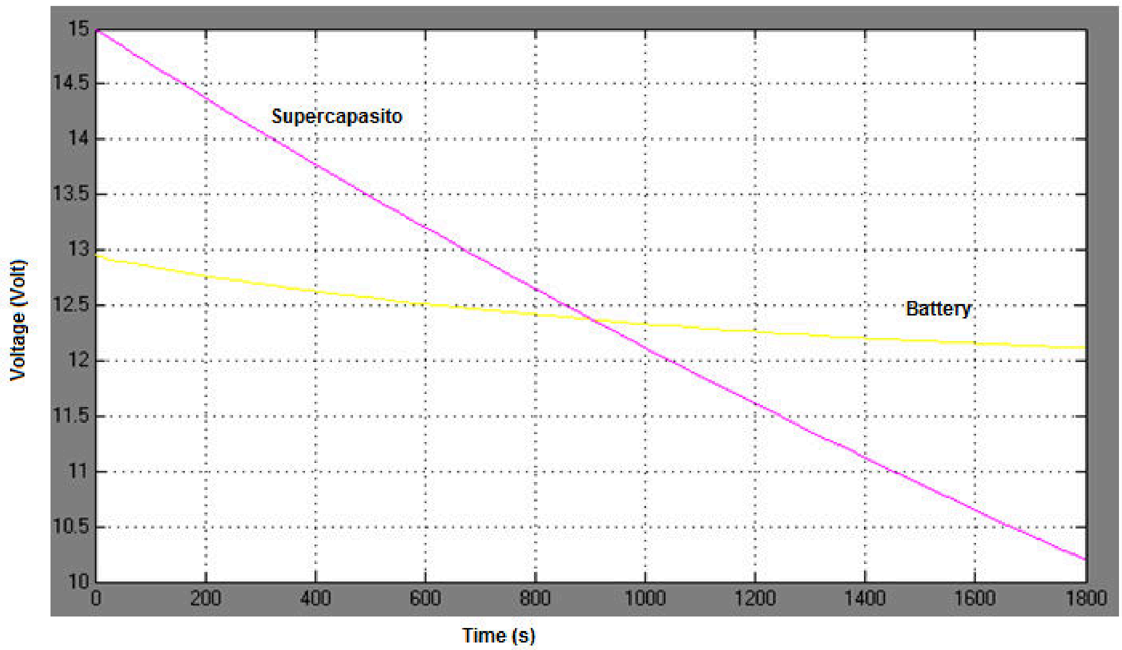


Figure 5. Discharging graph

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5. Conclusion

This paper has shown that a *lead-acid* 12 volt, 6.5Ah battery with R_{i1} 4,11 mΩ, Rd 3,3 Ω, and R_l 1.289 Ω C_{i1} =Cd = 393,65 F, and C_l 16,469 F can be replaced by using 6 series capacitor NessCap 1600F. The 6 series 1600F, 2.7V capacitor sustains 1000 s supplying a 6 A, 12 Volt motor cycle starter. The battery itself supplies the same current and voltage for about 1800 s. Supercapacitor discharging time is more rapidly than the battery discharging time. Future works may deal with solutions to enlarge discharging time of supercapacitor.

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