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.
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](image)

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 $R_i$, $C_{i0}$ and $C_{i1}$ with a very short charging response. Delayed branch has components of $R_d$ and $C_d$ 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.

\[
R_i = \frac{V_1}{I_{ch}}
\]  

(1)

where $V_1$ is voltage at $t_1$ after charging current is supplied. Variable $I_{ch}$ 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, $\Delta V$ 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.

\[
C_{i0} = I_{ch} \frac{\Delta t}{\Delta V}
\]  

(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.

\[
C_{i1} = \frac{2}{V_4} \left( \frac{Q_{tot}}{V_4} - C_{i0} \right)
\]  

(3)

where $Q_{tot} = I_{ch} \times (t_4 - t_1)$ 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

$R_d$ and $C_d$ are calculated for delayed branch determination. In order to obtain $R_d$, discharging time for both battery and capacitor should be calculated which is $t_5$ for given voltage $V_5$, where $V_5 = V_4 - \Delta V$. $R_d$ is calculated by using:
\[ R_d = \frac{(V_4 - \Delta V) \cdot \Delta t}{C_{\text{diff}} \cdot \Delta V} \]  \hspace{1cm} (4)

where \( C_{\text{diff}} = C_{i0} + (C_{i1} \times V_3) \). Afterward, \( t_6 \) is calculated by using \( t_6 = t_5 + 3 \times (R_d \times C_{i0}) \), \( C_d \) is obtained by using Equation 5.

\[
C_d = \frac{Q_{\text{tot}}}{V_6} - \left( C_{i0} + \left( \frac{C_{i1}}{2} \times V_6 \right) \right)
\]  \hspace{1cm} (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, \( R_1 \) is calculated by using Equation 6.

\[
R_1 = \frac{(V_6 - \Delta V) \cdot \Delta t}{C_{\text{diff}} \cdot \Delta V}
\]  \hspace{1cm} (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.

\[
C_l = \frac{Q_{\text{tot}}}{V_8} - \left( C_{i0} + \left( \frac{C_{i1}}{2} \times V_8 \right) \right)
\]  \hspace{1cm} (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 replaced is a motor cycle battery: lead-acid 6.5Ah, 12 V with equivalent circuit depicted in Figure 2a and internal parameters in Figure 2b.

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].
where \( P \) is number of paralleled supercapacitor, \( S \) is number of serried supercapacitor, \( N_r \) and \( N_c \) 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 a single capacitor is depicted in Figure 3b, and the 6 series supercapacitor is depicted in Figure 3c.

\[
R_{\text{series}} = R_e(I) \times S^{n_r},
\]

(8)

\[
C_{\text{series}} = C_e(I) \times S^{n_c}.
\]

(9)

\[
R_{\text{parallel}} = R_e(I) \times P^{n_r},
\]

(10)

\[
C_{\text{parallel}} = C_e(I) \times P^{n_c}.
\]

(11)

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.

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.
5. Conclusion
This paper has shown that a lead-acid 12 volt, 6.5Ah battery with $R_{i1}=4.11\ \text{m}\Omega$, $R_d=3.3\ \Omega$, and $R_l=1.289\ \Omega$ $C_{i1}=393.65\ \text{F}$, and $C_l=16.469\ \text{F}$ 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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