Modelling and Simulation of Supercapacitor for Energy Storage Applications

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Abstract: ***Energy storage remains a key component in sustainable energy systems. Supercapacitors are gaining widespread use as a form of energy harvesters to store harvested energy. In this paper, both mathematical and electrical models of the supercapacitor are obtained and used to simulate the voltage charge/discharge cycle of the supercapacitor. Matlab Simulink was used for the implementation of the model. It is found from results obtained that the model correlates well with practical simulation results obtained.***

Keywords: Supercapacitors, charge cycle, discharge cycle, Matlab-Simulink.

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1. Introduction

A supercapacitor is an electrochemical double-layer capacitor (EDLC) which are widely used for energy storage in many applications, such as UPS, hybrid electrical vehicles etc. As an energy storage device, the supercapacitor is an energy has a unique property that makes it a component of choice in some applications. This property is its high power density which ensures it is able to handle fast fluctuations in energy level. A comparison between supercapacitors and batteries shows that the main difference is in the energy and power density. The theory on which the supercapacitor was based was first described by Hermann von Helmholtz in 1853. He opined that the interaction between a conductor and the electrolyte inside a capacitor is determined by electrostatic relations and that there are no chemical reactions involved in the process [1]. The electrodes of a supercapacitor basically consist of a porous microstructure made of carbon material and around which the electrolyte is deposited. This structure gives the superconductor a significantly larger surface area. The electrolyte of a supercapacitor contains free charges in the form of ions with the behaviour of the ions determined by diffusion and electrostatic relation. With the supercapacitor completely discharged, the ions in the electrolyte become evenly distributed due to the diffusion. As the supercapacitor is charged, the ions are attracted by the electric field which is formed between the electrodes and separation of ions is started as a result of the field. The self-discharge of the supercapacitor is mainly caused by the diffusion   Supercapacitors have a significantly lower energy and higher power density when compared to conventional batteries. They also exhibit unique performance characteristics - such as fast charge and discharge capability, and high recycleability – as it can relieve the battery of narrow and repeated transient charging and discharging, ensuring longer battery life, enabling higher system peak power performance and improve system efficiency. Conventional batteries have a limitation to their maximum deliverable power because of the slow chemical process required to release their energy [2]. Supercapacitors can act as a good supplement for batteries in the operation of renewable energy storage systems by connecting in parallel with the battery for the purpose of charging or discharging high power in a short period of time. A major benefit of using supercapacitors is that they have a long lifetime, about 10^6 charging cycles compared to some battery types that last for about 10^3 cycles [3]. Another benefit of the supercapacitor is that the number of charging cycles is not greatly affected by the variation of its state of charge (SOC) compared to batteries as batteries have a significantly shorter lifetime when they are used in cycles with large SOC variation compared with low SOC variation cycles. Hence, the need to understand and determine the voltage and energy responses characteristics of the supercapacitor especially during charging and discharging.

2. Supercapacitor Double Layer Structure and Related Work

Unlike conventional capacitors, a supercapacitor has two solid electrodes (in contact with a terminal plate) each with a liquid electrolyte [4]. The area between the solid electrode material and its electrolyte solution, as shown in Fig. 2, forms the ‘double layer’.

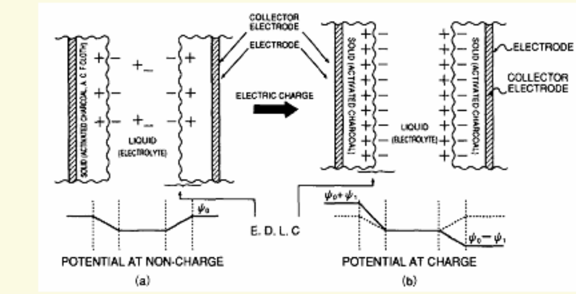

Figure1:Supercapacitor structure with positive and negative ions

When the supercapacitor is charged, the electrons at the cathode attract positive ions and onthe anode the vacancies of electrons attract negative ions in order to locally obtain a charged balance. This attraction of ions leads to a capacitance being formed between the ions and the surface of the electrode. The name dual layer comes from the two layers of ions at each electrode. The layer closest to the electrode acts as a dielectric and the layer outside the first layer holds the charges [5]. This occurs at both electrodes in the supercapacitor and the total capacitance consists of these two capacitances connected in series. When charges attract ions, they are gathered at the electrode surface. This is shown in Figure 2 which is an ideal case. In the picture that describes the charged state, all the ions are at the respective electrodes. In reality the diffusion causes some ions to be located at varying distances around the electrodes [6]. The intensity of the electric field determines the concentration of ions at the electrodes, which means that an increased voltage results in an increased capacitance.

A major application of supercapacitor is in hybrid electric vehicles (HEV). The author in [7] has proposed design of supercapacitor energy storage system for a Metro-vehicle where the kinetic energy of the vehicle is conserved during breaking. Regenerative breaking is then used to store the energy into a super capacitor for later use. This method helps in saving energy voltage. In [8], the authors discuss the selection of the size for a supercapacitor for a hybrid battery–supercapacitor and the advantages of this arrangement are outlined. The authors in [9] also propose a novel control system for a hybrid electric vehicle which utilizes the supercapacitor energy storage system. The systemwas tested throughsimulation using MATLAB/Simulink. In [10], the authors used an equivalent mathematical model to simulate the voltage response of the supercapacitor. The model was implemented using MATLAB/Simulink.

3. Supercapacitor Modelling

A simple model for a double-layer capacitor can be represented by acapacitance (C) with an equivalent series resistance (ESR) and an equivalent parallel resistance (EPR). The ESR models power losses that may result from internal heating, which will be of importance during charging and discharging. The EPR models current leakage, and influences long-term energy storage. By determining these threeparameters, one is able to develop a first order approximation of EDLC behaviour.While the simple model provides a first approximation of a double layer capacitor's behaviour, it is observed there is a large error when compared with experimental results [11]. Therefore, a simplified model of the supercapacitor is proposed. The Faranda model [12] proposes a simplified model of the supercapacitor as shown in Figure 2 below.

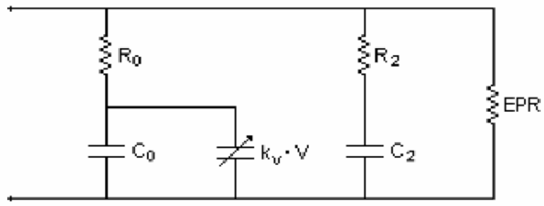

Figure2:A simplified Faranda model of the supercapacitor [11]

The equivalent capacitance is given by

$$C_{cell} = C_o + K_v V_c$$

The total capacitance for n cells in series for the model is given by;

$$C_{total} \frac{1}{{}^{1}/_{C_{cell1}} + {}^{1}/_{C_{cell2}} + {}^{1}/_{C_{cell3}} + \dots {}^{1}/_{C_{celln}}}$$

(1)$C_{total} = \frac{1}{n} C_{cell} = \frac{1}{n}(C_o + K_v V_c)$ (2)

Applying Kirchoff Voltage law to Figure 2:

$i(R_0 + R_2) + \frac{1}{C_{total}} \int i dt = V$(3)

$$\frac{dq}{dt}(R_0 + R_2) + \frac{1}{C_{total}} q = \quad (4)$$

$$(C_o + K_v V_c)(R_0 + R_2) + \frac{dv_c(t)}{dt} + V_c(t) = V \quad (5)$$

$$\frac{dV_c}{dt} = \frac{V - V_c}{(R_0 + R_2)(C_o + K_v V_c)} \quad (6)$$

Voltage across internal resistance is given by

$$R_{ESR}\, i(t) + \frac{1}{C_{total}} \int i(t) dt = V \quad (7)$$

At t = 0

$$R_{ESR}\, i(t) + \frac{1}{C_{total}} \int i(t) dt = V_0 \quad (8)$$

Therfore

$$R_{ESR} C_{total} \frac{di(t)}{dt} - i(t) = 0 \quad (9)$$

Figure 4: BMOD0165 Supercapacitor

Where $V_r\ (t)$ is a solution to the equation and is given by

$$V_r(t) = K e^{{}^{1}/_{R_{ESR} C_{total}} t} \quad (10)$$

The equation for a supercapacitor discharge is given by

$$\frac{dV_c}{dt} = \frac{-V_c}{(R_0 + R_2)(C_o + K_v V_c)} \quad (11)$$

Terminal voltage is

$$V_c = V_c - V_r(t) \tag{12}$$

3.1 BMDO165 Supercapacitor Module

The supercapacitor considered here is the BMOD0165 manufactured by Maxwell Technologies, shown in Figure 3.

Figure3: BMOD0165 Supercapacitor

This supercapacitor module has an operating voltage of 48V with a rated capacitance of 165F.It has 18 eighteen supercapacitor cells with an operating voltage of 2.7V per cell Table 4.1 gives the product specification of this module.

I.**Table1**:Product Specifications of BMD0165 supercapacitor module

Rated Capacitance	165F	Short circuit current (max)	4800A
ESR(DC)	6.0m Ω	Energy Density(max)	3.81Wh/Kg
ESR(1KHz)	6.3m Ω	Power Density (max)	6600W/Kg
Leakage current(max)	5.2m A	PowerDensity (DC)(max)	2600W/Kg
Thermal Resistance	0.25^0 C/W	Mass Module	13.7Kg
Rated Voltage	48V	Volume Module	12.6L
Max/Min Operating temperature	65^0C/ -40^0C	Max/Min Storage Temperature temperature	70^0C /-40^0C
Stored Energy	53Wh	Number of cells	18

4. MATLAB/Simulink Model

Simulink is a software package that is part of MATLAB. Modelling and analysis of dynamic systems is simplified as compared to performing the same operations using code in MATLAB programming. The equivalent Simulink Faranda model is given in Figure 5 below with constant capacitance value *C*0 integrated into the variable capacitance's look-up table.

Simpower does not contain a variable capacitor component, the variablecapacitance in the model is created as a sub block build around a variable voltage source. The incoming current is measured, then multiplied by the inverse of the variable capacitance and then integrated over time to give the voltage output. The voltage output is fed back to a look up table where a function is defined describing the capacitance voltage dependence.The output from the look up table is the capacitance at the instantaneous voltage level.

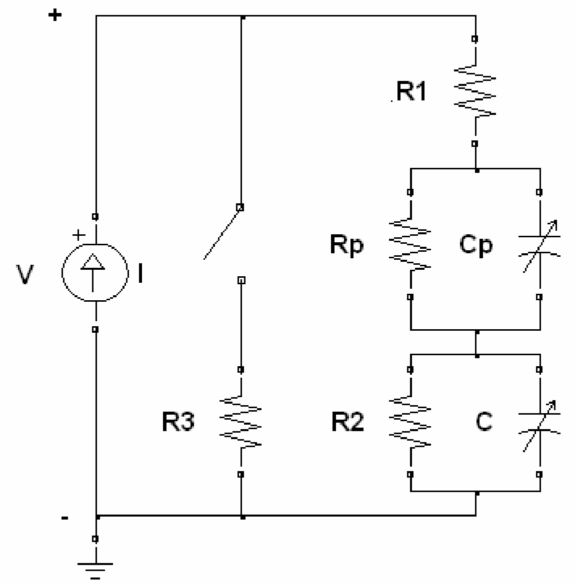

Figure 4: Basic Supercapacitor Model

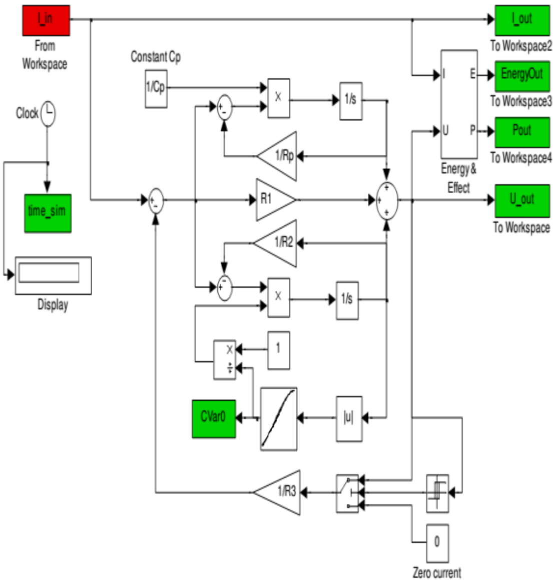

Figure 5: Simulink model of the Supercapacitor

5. Simulation Methodology

Figure 6 shows a basic circuit for the simulink model with a variable capacitance value. The switch that connects the balancing resistance R3 to the circuit is controlled by the relay block. It is that part of the circuit that keep the voltage of the supercapacitor from rising too high, it is set to be connected whenever the voltage goes beyond a certain value of 24.05V. The supercapacitor gets disconnected when the voltage goes below 24.02V.

The voltage peak occurs at 24.02V and is usually selected after studying the measured voltage curve as a major derivative change occurs beyond a voltage peak of 24.02V. This derivative change can be interpreted to occur because of the connection of the extra resistance since the increased load means that the voltage increase is slower.

6. Experimental Methodology

An experimental system was developed which allowed the supercapacitor to be normalized and subjected to controlled-current tests which then enable the equivalent circuit parameters to be calculated.

The supercapacitor under test was subjected to controlled-current charge and discharge. It has been developed to deliver a range of voltages and currents and hence is capable of characterizing the range of supercapacitors. It is able to charge or discharge at up to 300mA in 2mA increments and current values are stable within 3ms. Simulations were ran on a charge and discharge using the proposed model and the ideal which were then compared against the behavior of the BMOD0165 Supercapacitor. The ideal model is obtained using MATLAB -Simulink while the proposed model is obtained from experiments carried out. Firstly, to remove any residual charge from the supercapacitor, the supercapacitor was normalized for 24 hours and then rapidly charged at 100mA. This charging current allowed the verification of both the 'fast' and 'slow' effects of the supercapacitor behavior to be verified, and is consistent with the charging rate of the supercapacitor. After charging, the supercapacitor was rested for one minute before entering a pulsed discharge test for one hour.

The device was subjected to a pulsed discharge of 70mA with a 2% duty cycle (70mA discharge current for 1s). There is a good correlation between the real (solid black line) and proposed (solid gray line) model performance, indicating that the generated model and parameters are correct.

7. Simulation Results

As the supercapacitor is charged from almost empty to full charge, measurement points are taken at several places during the test cycle. The voltage drop occurring over the series resistance is constant during charging and so does not affect the voltage difference measurement. Since the capacitance varies with the voltage, this relation is included into the model than to simply have a constant C-value all the time a lookup table is added, so the correct capacitance value can be used in the simulations. The capacitance curve that is the result of the input voltage to the lookup table is shown in Figure 7.

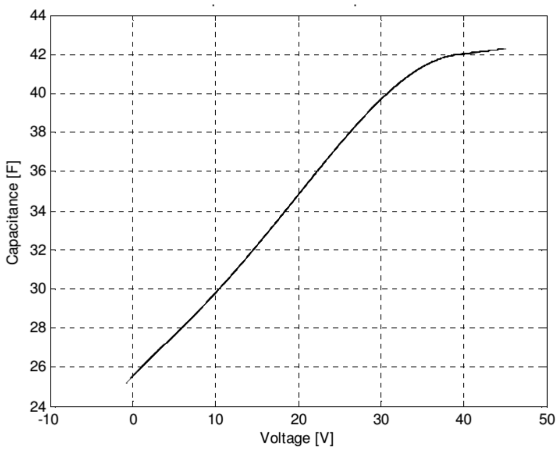

Figure 6: Capacitance Lookup Table

Figure 8 shows the charge profile of the supercacitor at supply current of 20 Amperes where dashed and solid curve are represented as simulation and experimental results respectively.

Figure 9 shows the discharge profile of the supercacitor at load currents of 20A, 40A and 60A where dotted and solid curves are simulation and experimental results respectively which shows a good correlation between simulation and experimental results However, the minor difference observed can be attributed to the effect of the approximated electrical model. Although the derived equivalent model is not a perfect model, it gives a good approximation of the supercapacitor characteristics when compared to a real device in slow discharge applications. Using this model, it can be estimated by how much time the supercapacitor can be fully charge at high levels of supply current.

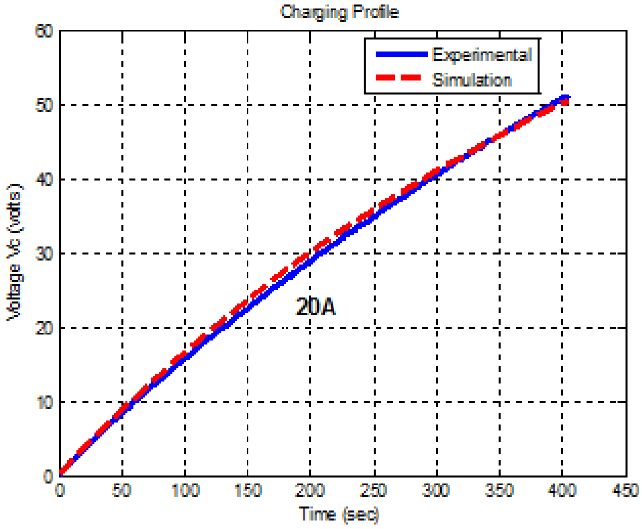

Figure 7:Charging profile of BMOD0165 Supercapacitor

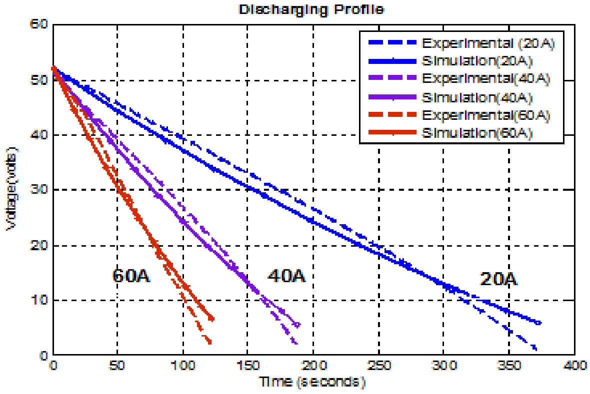

Figure8:Discharging profile of Supercapacitor

8. Temperature Variations Of Supercapacitor

The supercapacitor temperature during operation was also observed and monitored since it is very important to determine how the temperature behaves when the supercapacitor is operated at different level of operating current so that it will be protected from damage. Modeling of the temperature of the supercapacitor was not considered in this study but results of the temperature variations during experiments are presented. When the supercapacitor was charged for the first time at 20A supply current, the temperature was initially at a constant of 12°C for approximately 180 seconds and it started to increase exponentially until it became fully charged. Figure 16 shows the curves of temperature when the supercapacitor was charged at different initial temperature at 20 amperes charging. In all cases the supercapacitor temperature was initially constant and then it increases exponentially. Figure 17 shows the curves of the temperatures of the supercapacitor as a function of the discharge time for different constant load currents. The temperature varies sinusoidally as a function of discharge time as load current increases. When the load current was 20 A, the temperature operates at the range of 17.0°C to 21.67°C, and when it was discharged at 80 amperes, the temperature range increased and became 30°C to 34.8°C.

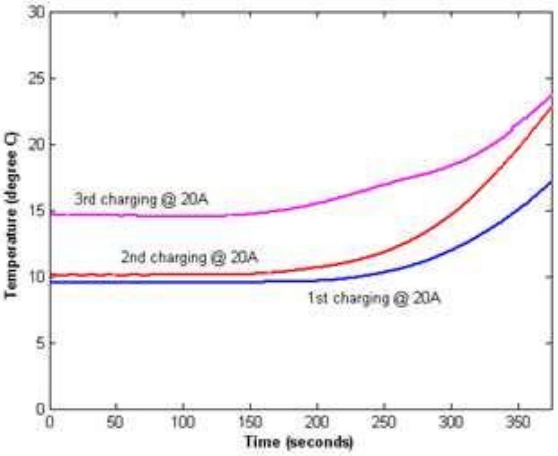

Figure 9: Temperature variation during charging

7. Conclusion

The simulation of the charge/discharge characteristics of a model supercapacitors was carried out using the mathematical model derived from the electrical model. The charge and discharge voltage behavior of the supercapacitor was simulated. It is was observed that that the model is well capable of simulating the voltage behavior and can predict the time of charge/discharge voltage of the supercapacitor. Although the derived equivalent model is not a perfect model, it gives a good approximation of the supercapacitor characteristics when compared to experimental models.

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