Modelling of Supercapacitors Based on Simplified Equivalent Circuit

Mustafa Ergin ŞAHİN, Frede BLAABJERG, and Ariya SANGWONGWANİCH

***Abstract*—The need for energy storage devices especially in renewable energy applications has increased the use of supercapacitors. Accordingly, several supercapacitor models have been proposed in previous researches. Nevertheless, most of them require an intensive test to obtain the model parameters. These may not be suitable for an initial simulation study, where a simple model based on the datasheet is required to evaluate the system performance before building the hardware prototype. A simplified electrical circuit model for a supercapacitor (SC) based on the voltage-current equation is proposed in this paper to address this issue. This model doesn't need an intensive test for accuracy. The structural simplicity and decent modelling accuracy make the equivalent electrical circuit model very suitable for power electronic applications and real-time energy management simulations. The parameters of the proposed model can be obtained from the datasheets value with a minimum test requirement. The experimental method to provide the parameters of the supercapacitor equivalent circuit is described. Based on the proposed method, the supercapacitor model is built in Matlab/Simulink, and the characteristics of equivalent series resistance (ESR) measurement and cycle life are compared with datasheets. The simulation results have verified that the proposed model can be applied to simulate the behaviour of the supercapacitor in most energy and power applications for a short time of energy storage. A supercapacitor test circuit is given to test the charge and discharge of supercapacitor modules. The experimental results are suitable for simulation results.**

***Index Terms*—Energy storage systems, Matlab/Simulink, Supercapacitors, Supercapacitor modelling.**

I. Introduction

THERE is a strong demand to reduce the use of fossil fuel and move toward more sustainable energy sources. Accordingly, several efforts have been made to increase the penetration level of Renewable Energy Sources (RES) such as photovoltaics and wind turbines [1]. Nevertheless, the intermittency nature of the power production from RES have risen a concern regarding the grid-integration. Energy storage systems are one of the promising solutions to ensure high power quality and stability of the electrical network.

Traditional energy storage devices such as batteries have some limitations as slow charging and limited lifetime. Some other storage technologies, such as mechanical, electrochemical, and electromagnetic, which store the energy in another form, are more expensive and complexes [2]. The fluctuation in the power production of renewable energy sources raises some requirements for the stability of the energy network. The need for instantaneous energy storage devices increases the use of SCs as an alternating storage device, especially in renewable energy applications and electrical vehicles [47], [48]. By employing the SCs, it is possible to smooth out an exact power fluctuation in the renewable energy systems. On the other side, energy storage systems play a significant role in a diverse range of industrial applications [2], [3].

For instance, the increased installation of grid-connected photovoltaic (PV) systems and building integrated PV systems have made rapid advances around the world over the last years. Photovoltaic panels are intermittent sustainable energy sources whose power generation capability varies with the environmental conditions. Thus, energy storage such as SCs can be used to smooth out the power fluctuation due to its high power density [4].

In general, rechargeable batteries and SCs have a similar chemical structure and work process to store and convert through diffusion and migration of ions. However, the SCs present some advantages which will be useful for the storage systems. An SC is a double-layer electrochemical capacitor that can store thousands of times more energy than a typical capacitor. Moreover, they have almost negligible losses and long lifespan [5]. They can process a large number of charge and discharge cycles compared to only a few thousand cycles for lead-acid batteries and can supply much higher currents than batteries [6], [7].

It is possible to find some primary studies in the literature where the chemical, mathematical and electrical characteristics and the dynamic structure of SCs were simulated and investigated [8]−[15]. Also, a simple electrical model of SCs has been designed to describe the behavior of SCs as a function of frequency, voltage, and temperature [16]. However, the

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simplified model is inadequate to demonstrate the SCs dynamics under different operating conditions. On the other hand, the structural simplicity and decent modelling accuracy make the equivalent electrical circuit model designed by Zubieta and Faranda for simulations very suitable for power electronic applications and real-time energy management simulations [22], [23]. The SCs module simulation was based on two branches' electrical circuit model, which included the module structure and its mathematical equation simulation in the previous studies [5], [15], [16]. An experimental method has been discussed in the literature used to determine some of the SC equivalent circuit parameters [15], [17]. Therefore, a simplified SC module model to be used in real-time simulations and to adjust and modified for some parameters is required.

In this paper, the chemical structure of SCs, physical and electrical characteristics, working principles, advantages, and drawbacks are investigated in detail. The chemical, mathematical and electrical and the other developed models in the literature are investigated. Using the equivalent circuit model of the SCs, which is suitable for power electronic practics the mathematical equation of SCs was derived. The procedure to obtain of SCs coefficients experimentally is given. Using this equation and coefficients of the SCs the Matlab/Simulink model was simulated, and the characteristics of ESR measurement and cycle life are simulated and compared with data sheets for different supercapacitors. Also, charge and discharge characteristics of SCs for different values were simulated to compare the power and energy density of SCs different values. A supercapacitor test circuit is given to test the charge and discharge of SC and modules.

II. Overview of Supercapacitors Technology

In this section, an overview of SCs technology including the chemical structure, the physical and electrical characteristics will be discussed in detail. The performance comparison of SCs with the other energy storage technologies will also be provided.

A. Chemical Structure

A typical SC is shown in Fig. 1(a) where the chemical structure is illustrated in Fig. 1(b) [19], [20]. The capacity of the SCs, which are also called ultra-capacitors or double-layer capacitors, can reach more than a thousand Farads, although the voltage value is only 2.7 V in most products.

Unlike the ceramic or electrolytic capacitors, SCs do not have dielectric material between positive and negative electrodes. Instead of an electrolyte which has positive ions and negative ions is filled between the two electrodes, it uses the electrical double layer (EDL) that is formed at the interface of the solid electrode and liquid electrolyte. A typical SC is composed of solid electrodes and liquid electrolytes which including electrolyte salt, and a separator to prevent direct contact between the positive and negative electrodes. The electrodes are positioned on the electricity collectors and

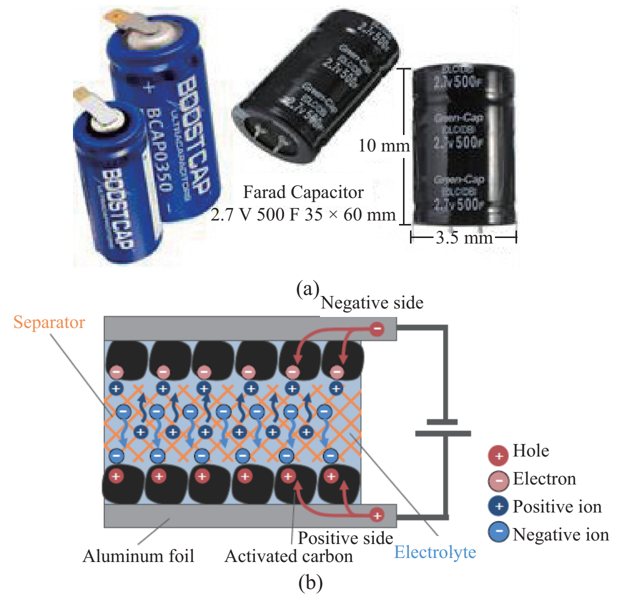

Fig. 1. (a) Some SCs to be obtained in the market. (b) The structure of SCs [19], [20].

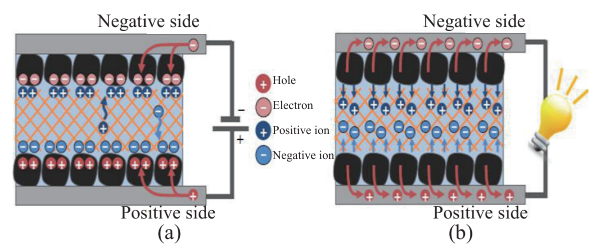

Fig. 2. (a) Charge. (b) Discharge state in SCs [20].

coated with activated carbon powder. An electrical double layer is formed at each interface where the active carbon powder contacts the electrolyte as shown in Fig. 1(b) [20]. The Stern layer accounts for the specific absorption of the ions on the electrode surface. The diffuse layer incorporates the Gouy-Chapman model, and their combination is called a Gouy - Chapman - Stern model [22].

When the SC is charged, the negative ions and vacancies on the positive electrode side and the positive ions and the electrons on the negative electrode side are aligned across the interface as shown in Fig. 2(a). This state of alignment of ions and electrons is called an electrical double-layer capacitor (EDLC) [20]. The capacitance value of SCs is depended on the surface area, and a large surface area has powdered activated carbons, which are used as an electrode material [21]. The SCs are charged by ions moving through the carbon surface and discharged by reverse moving away of ions is shown in Fig. 2(a) and (b) respectively [20].

B. Performance Comparison With Other Energy Storage Technologies

The main advantages and drawbacks of SCs are given in this section. The SCs have a high power density, but low energy density. The SCs are quick charging and discharging, but they

TABLE I
COMPARISON BETWEEN THE BATTERY, SC, AND ELECTROLYTIC CAPACITOR PERFORMANCES [16]

Storage devises characteristics	Battery	Supercapacitor	Electrolytic capacitor
Charging time	$1 < t < 5$ h	1 − 30 s	$10^{-3} < t < 10^{-6}$
Discharging time	$t > 0.3$ h	1 − 30 s	$10^{-3} < t < 10^{-6}$
The energy density (Wh/kg)	10 − 100	1 − 10	< 0.1
Lifetime (cycle number)	1000	10^6	10^6
Power density (W/kg)	< 1000	10,000	> 1,000,000
Charge/discharge efficiency	0.7 − 0.85	0.85 − 0.98	> 0.95

have a very high self-discharge rate. It does not blow up in case of accidental direct short connection and stops accepting energy when it becomes fully charged. SCs have extended the lifetime and long shelf life and them environmentally safe and no gas emissions [4]. Table I presents a numerical comparison between the battery, SC, and electrolytic capacitor characteristics. Compared with the other commercially available energy storage technologies, the SCs usually offer a high-power density, high efficiency, fast charging and discharging speed, and long cycle lifetime [16]. On the other hand, the energy density of SC is limited compared to batteries. Accordingly, a combination of SCs and batteries may be required in some applications [49].

III. LITERATURE REVIEW FOCUS ON SUPERCAPACITOR CIRCUIT MODELS

For SCs systems, modeling is essential for the system dimensioning, condition monitoring, and controller design. Several SC models are available in the literature based on chemical, mathematical and electrical characteristics, aging, artificially intelligent, and the dynamic structure of SCs models [8]–[15], [22]. A simple electrical model of SCs for describing the behavior of SCs as a function of frequency, voltage, and temperature has also been discussed in [16]. Electrochemical models offer high accuracy but increase the calculation complexity. As an alternative, an equivalent circuit model derived from empirical and experimental data can also be used. These make them inadequate to demonstrate the SCs dynamics under different conditions. However, structural simplicity and decent modeling accuracy make the equivalent electrical circuit model suitable for real-time energy management simulations [22], [23].

The electrochemical model is known as a double-layer model since the structure of the SC has a double layer at the junction of a metal with an electrolyte solution, and the layer has two elements as shown in Fig. 1(b). The inner component, known as the "compact layer" or "Helmholtz layer" discovered by Helmholtz [24] and described the EDL phenomenon it using a model where all the charges were assumed to be absorbed in the electrode surface. The outer element, the "diffuse layer" or "Gouy–Chapman layer", is semi-infinite in extent and contains anions and cations distributed unequally. Gouy [25] and

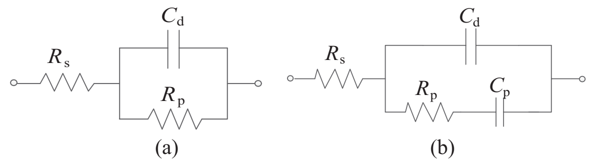

Fig. 3. (a) Classical SC model. (b) SC model using a Debye polarization.

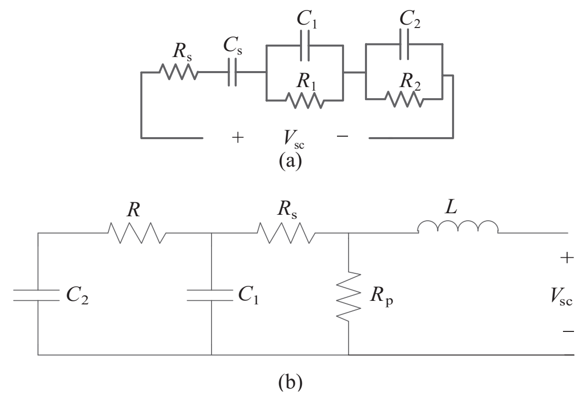

Fig. 4. (a) Conventional equivalent circuit model. (b) A dynamic model for SCs [34].

Chapman [26] further modified the Helmholtz model to account for the ion mobility in the electrolyte solutions as a result of diffusion and electrostatic forces. The model to describe the (metal)/(electrolyte solution) double layer was modified by Stern [27], [28].

Several circuit models have been proposed for SCs. The most often applied being the classical capacitor model [31], [32], where the simplified equivalent circuit is considered as actual capacitor behavior in a slow discharge as illustrated in Fig. 3(a). This circuit consists of a capacitance (C_d), the equivalent series resistance (R_s), which occurs during charging and discharging internal resistance, and an equivalent parallel resistance (R_p) to represent the path of leakage charge of SCs in a long-term effect [30]. Also, Nelms *et al.* described another approach where the SC characteristics are modeled using a Debye polarization cell, which is shown in Fig. 3(b) [33].

The conventional equivalent circuit model employs elementary electrical circuit elements to represent the SC dynamics is shown in Fig. 4(a) [23]. The basic model has a limitation since the capacitance of an SC is strongly dependent on terminal voltage in general [16], [34]. Therefore, a more effective model for SCs has been proposed in [34] based on the circuit diagram in Fig. 4(b). A more complex equivalent circuit model that represents the physical mechanisms in the SC has also been discussed in the literature. Such a model is known as a transmission line network model where the resistances and non-linear capacitances represent the distributed ESRs and electrostatic double-layer capacitance intrinsic to each pole in the electrode material. There are also additional resistances in the electrode material and a diffusion resistance in the membrane [35], [36].

Unfortunately, the equivalent circuits used in the detailed modeling of SCs mentioned above are not very suitable for

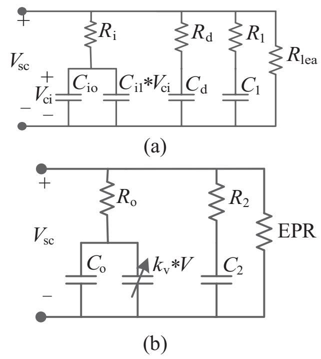

Fig. 5. The equivalent circuits of SCs. (a) Zubieta model. (b) Faranda model.

a power electronic simulation environment. Most of them require an intensive test to obtain the model parameters. These may not be suitable for an initial simulation study. Therefore, a simplified equivalent circuit that can capture the characteristic behavior of SCs under different operating conditions has been developed. Such a model implementing the variable capacitance feature is described by Zubieta *et al*. [15]. The model uses three separate RC time constants in three parallel branch networks, and a high resistance element to model cell leakage is illustrated in Fig. 5(a). The third or delayed branch parameters are R_d and C_d. An improved version of the Zubieta model was proposed by Rafik [16], where the frequency-dependent parameters in the capacitor are taken into consideration. Faranda [10] is proposed a simplified version of the Zubieta model [15] with one RC-branch less than as shown in Fig. 5(b). According to [10], this model simplifies the estimation of parameters, reduces the number and complexity of measurements, and decreases the possibility of errors. Faranda also proposes a method of determining the parameters in the model based on measurements. The complexity of the parameters determined in the Zubieta model makes it difficult to be implemented. Therefore, using the simplified Faranda model gives adequate relevance with the measurements besides good accuracy.

The fractional-order equivalent circuit's model of SCs has also been developed in the previous research [23]. To further improve the model accuracy, a fractional-order calculus has been introduced for SC modeling applications [22]. When the SCs operate under high rate cycling, they may generate high heat depend on low internal resistance. This operation affects the performance and lifetime of SCs, which are very sensitive to temperature change. Therefore, several studies focused on the temperature model of SCs [16], [37]−[40]. Intelligent modeling techniques such as an artificial neural network (ANN) and fuzzy logic have been successfully utilized to predict the performance of energy storage systems include batteries and SCs [41], [42]. Temperature, voltage, and current are the parameters of the accelerating aging of SCs and define the lifetime. A simplified thermal model of the SC to estimate the core temperature and the case temperature of the components is proposed [43], [44].

Although all these models include more details and different applications, this paper focused on the equivalent circuit model designed by Zubieta and Faranda for simulations, which will

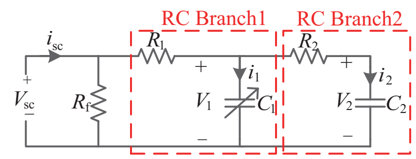

Fig. 6. SC two branches circuit model.

be very suitable for power electronic applications. This model doesn't need an intensive test for accuracy. Moreover, the structural simplicity and decent modelling accuracy make the equivalent electrical circuit model very suitable for power electronic applications and real-time energy management simulations [51].

IV. Proposed Supercapacitor Circuit Model

Several studies in the literature investigate the chemical, mathematical, and electrical stimulation model of SCs [8]−[15]. The SCs module simulation was based on two RC branches' electrical circuit models as shown in Fig. 6, which includes the module structure and its mathematical equation simulation in this study [5], [15], [16]. This circuit is simplified by neglecting the leakage current of SC as given in (1). The U_{SC} and I_{SC} are the SC module voltage and currents respectively. The v_{SC}, i_{SC}, N_{S_SC}, and N_{P_SC} are the SC primary voltage and current, series elements, and parallel branches respectively. The first capacitance C_1 depends on the voltage v_1 and consists of a constant capacity C_0 and a fixed parameter C_V, and it is written as $C_1 = C_0 + C_V v_1$. The R_1C_1 branch determines the immediate behavior of the SC during rapid charge and discharge cycles in a few seconds. The R_2C_2 cell is the slow branch and completes the first cell in the longtime range and describes the internal energy distribution at the end of the charge. The equivalent parallel resistance R_f represents the leakage current and can be neglected during fast charge/discharge applications [5].

$$U_{SC} = N_{S\_SC} v_{SC} = N_{S\_SC}(v_1 + R_1 i_{SC}) = N_{S\_SC}\left(v_1 + R_1 \frac{I_{SC}}{N_{P\_SC}}\right) \tag{1}$$

The relationship between quick charge (Q_1) and voltage (v_1) is shown in (2) depend on current (i_1). The charge (Q_1) is shown in (3). The inverse relationship between v_1 and Q_1 the equation can be obtained as in (4), which considers the equivalent electric circuit with two RC branches proposed by Zubieta and Bonert [36], Rafik *et al*. [37] to obtain this equation.

$$i_1 = C_1 \frac{dv_1}{dt} = \frac{dQ_1}{dt} = (C_0 + C_V v_1)\frac{dv_1}{dt} \tag{2}$$

$$Q_1 = C_0 v_1 + \frac{1}{2} C_V v_1^2 \tag{3}$$

$$v_1 = \frac{-C_0 + \sqrt{C_0^2 + 2C_V Q_1}}{C_V} \tag{4}$$

(1) and (4) are combined as in (5).

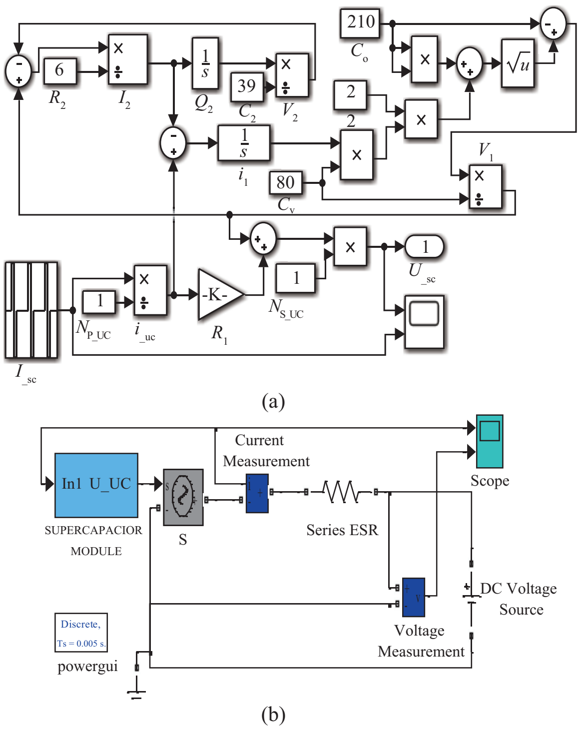

Fig. 7. (a) Module model. (b) Electrical model of an SC in Matlab/Simulink.

$$U_{SC} = N_{S\_SC} v_{SC} = N_{S\_SC}(v_1 + R_1 i_{SC}) = N_{S\_SC}\left(\frac{-C_0 + \sqrt{C_0^2 + 2C_V Q_1}}{C_V} + R_1 \frac{I_{SC}}{N_{P\ SC}}\right) \quad (5)$$

The voltage (v_2) in the secondary capacity (C_2) is described in (6).

$$v_2 = \frac{Q_2}{C_2} = \frac{1}{C_2}\int i_2 dt = \frac{1}{C_2}\int \frac{1}{R_2}(v_1 - v_2)dt \quad (6)$$

These equations are designed in Matlab/Simulink as an SC module model as shown in Fig. 7(a). The (5) and (6) are modified for 310 F capacitor coefficients in the simulation. These coefficients are obtained and calculated in previous studies experimental values and datasheets [45], [50]. This values are R_1 = 5.5 mΩ, R_2 = 6 Ω, C_0 = 210 F, C_V = 80 F/V, C_2 = 39 F for 310 F SCs. Identification of coefficients of different capacitors is given in the next section more detailed. An SC electrical model for simulations of power systems is shown in Fig. 7(b).

To identify the parameters of the proposed model a charge and discharge test at constant current have been carried out. The experimental method which determines the coefficient of the SC equivalent circuit is described firstly by Zubieta and Bonert [5]. In the proposed model, the parameters are identified by charging the DLC from zero to rated voltage and by observing the terminal voltage during the internal charge redistribution over the time of 30 min. The process to identify the parameters assumes that this condition of zero charges is present at the beginning. The approach to determine the different equivalent circuit model parameters is based on the fact that the three equivalent branches: the immediate branch, delayed branch, and long-term branch have distinctly different time constants considering the coefficient identifications. Table II shows the average of the equivalent model parameter values measured for the two types of double-layer capacitors. [15].

TABLE II
THE PARAMERERS AND THEIR COEFFICIENTS FOR DIFFERENT SC MEASUREMENTS [5], [10]

Parameters	Zubieta and Bonert		Faranda *et al*			
Capacitor Value	470 F	1500 F	110 F	200 F	350 F	600 F
R_i, R_o (mΩ)	2.5	1.5	10	8.8	4.8	2.8
C_{io}, C_o (F)	270	900	89	158	232	454
C_{i1} (F/V)	190	600	29	56	90	176
R_d, R_2 (Ω)	0.9	0.4	17.5	8.8	5.5	3.1
C_d, C_2 (F)	100	200	13.7	27.5	43.2	77.4
R_1 (Ω)	5.2	3.2	-	-	-	-
C_1 (F)	220	330	-	-	-	-
R_{lea}, EPR (kΩ)	9	4	5	5	2.5	2.5

The other experimental method to define the coefficients is described in [10]. In the first step, the values of the parameters of the immediate branch are determined. The R_0 resistance is calculated by measuring the potential difference ΔV between the two terminals during the first charge moment and subdividing it for the total charge current, assuming all the capacitances are still discharged. The two components of the total capacitance of the short-term branch are determined through a unique procedure. To validate the proposed model, seven models of SCs and their coefficients are tested as shown in Table II. According to the results, it can be noticed that capacitors of the same type and size can have different parameter values of the equivalent circuit [10].

V. THE TEST OF SUPERCAPACITOR MODEL AND SIMULATIONS IN MATLAB/SIMULINK

The SC model is simulated and compared with the capacitance/ESR measurements and cycle life waveforms from the datasheet of 310 F SCs [46]. The ideal Capacitance/ESR measurements waveforms for data sheets are given in Fig. 8 (a), and cycle life waveform measurements for data sheets are given in Fig. 8(b).

In datasheet $V_1 = V_{rated}$ = 2.7 V, $V_3 = 0.5xV_{rated}$ = 1.35 V, t_2–t_1 = 15 s, t_4–t_3 = 5 s are given for Fig. 8 (a). The t_3–t_2 value is calculated from capacitance (7). T_{charge} is calculated as a 26 second for 0 to t_1.

$$\text{Capacitance} = I\frac{\Delta t}{\Delta V} \rightarrow \Delta t = \frac{CV}{I} \rightarrow t_3 - t_2 = \frac{C(V_2 - V_3)}{I} = \frac{310(2.7 - 1.3)}{31} = 14\ \text{s} \quad (7)$$

$V_1 = V_{rated}$ = 2.7 V, $V_2 = 0.5V_{rated}$ = 1.35 V, $t_2 - t_1$ = 5 s, $t_4 - t_3$ = 15 s are given for Fig. 8(b) in data sheets.

For these tests, a constant current source is used in charging, discharging, and zero current modes, and voltage variations are observed. The simulation result for the capacitor/ESR

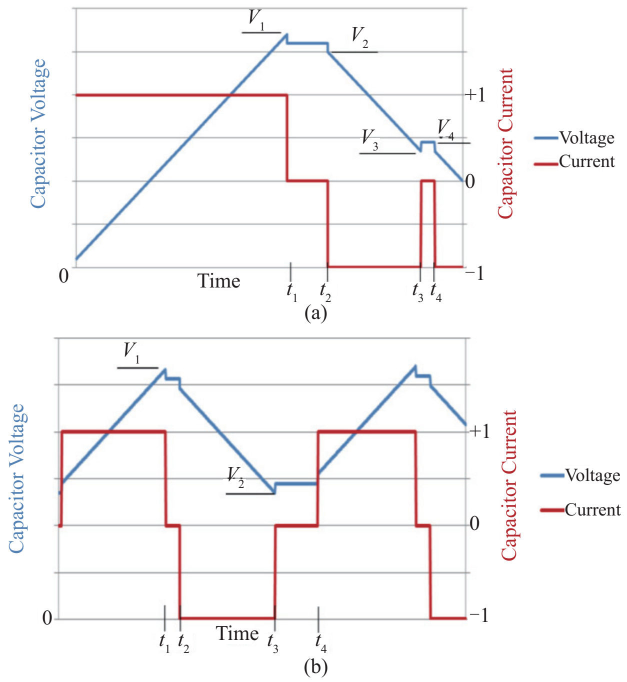

Fig. 8. (a) Capacitance/ESR. (b) Cycle life waveform measurements in datasheet [46].

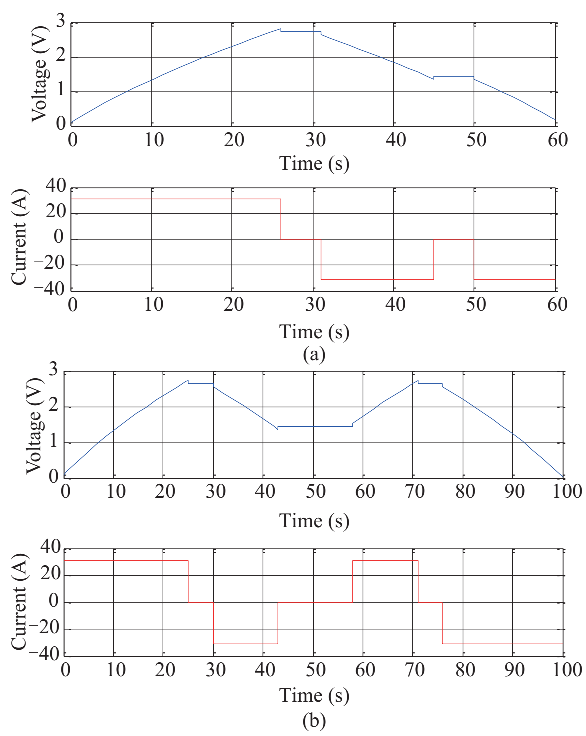

Fig. 9. (a) CAP/ESR. (b) Cycle life waveforms simulation results for 310 F SCs.

measurement waveform is shown in Fig. 9(a), and the cycle life waveform is shown in Fig. 9(b) for 310 F SCs. The simulation results are seen suitable for the experimental results and calculations in Fig. 8 manufacturer datasheets, and this shows the SC model works correctly. The simulation result for

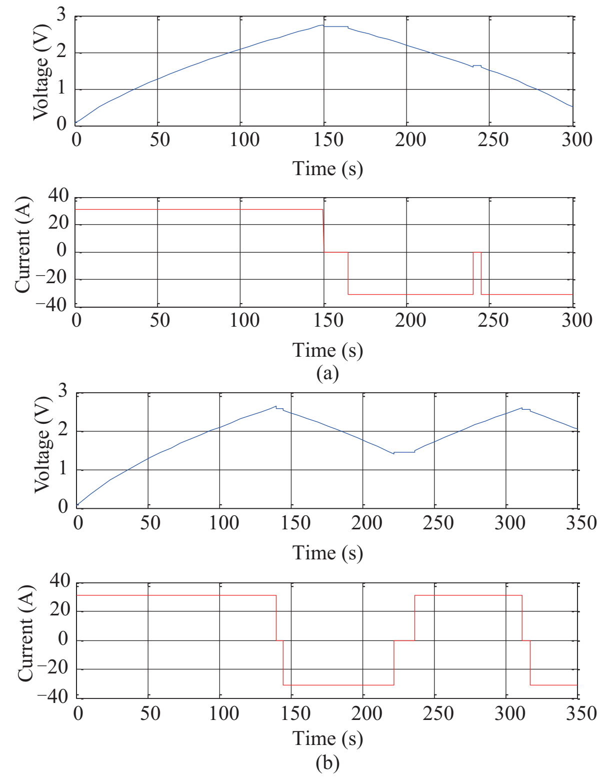

Fig. 10. (a) CAP/ESR. (b) Cycle life waveforms simulation results for 1500 F SCs.

the capacitor/ESR measurement waveform is shown in Fig. 10 (a) and cycle life waveform is shown in Fig. 10(b) for 1500 F SCs. The charge and discharge cycle time of this SC is longer than the first one as expected. Also, the charge and discharge times are compared with datasheet values quantitatively.

The simulation results of the SC charge and discharge test circuit are shown in Fig. 11(a) and (b) for a specific series charge ESR and discharge load resistance. The test circuit turns from charge mode to discharge mode at 600 s for the 310 F SC model, and at 1500 s for 1500 F SC model. The charge and discharge simulation results of a 310 F SC model are shown in Fig. 11(a). The SC voltage reaches 2.7 V and fixed its charge mode. The current and power go to zero with time. Adversely in the discharge mode, the SC voltage, current, and power go to zero with time. The SCs charged in 300 s and discharged 100 s depending on resistances. The charge and discharge simulation results of the 1500 F SC model are shown in Fig. 11(b). The SCs charged in 1000 s and discharged 500 s depending on the resistance. The maximum power in charge mode reaches 20 W, and in discharge mode reaches 70 W depend on ESR resistance and discharge load resistance. The ESR resistance is select 0.1 Ω, and the load resistance is selected 0.01 Ω for the simulation set up. These results are seen suitable with theoretical and experimental results in datasheets and with the other studied model results in the literature [5]–[16], [46].

The supercapacitor test circuit with an experimental setup is given in Fig. 12(a) and (b). A DC power supply and a variable load are used to charge the SC module. The designed supercapacitor module is consists of two blocks and five-piece 310 F, 2.7 V SCs. In the first step, the DC power supply is

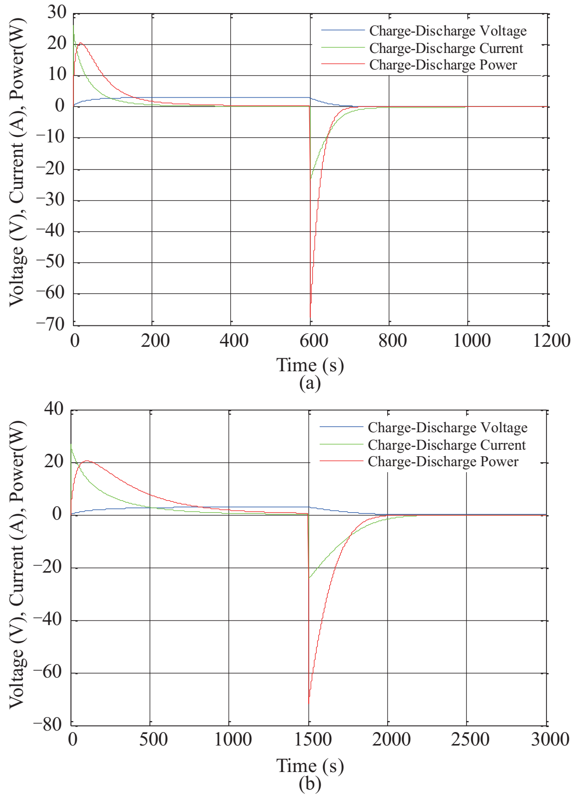

Fig. 11. The SC charge and discharge circuit simulation results for 310 F (a), and 3000 F (b).

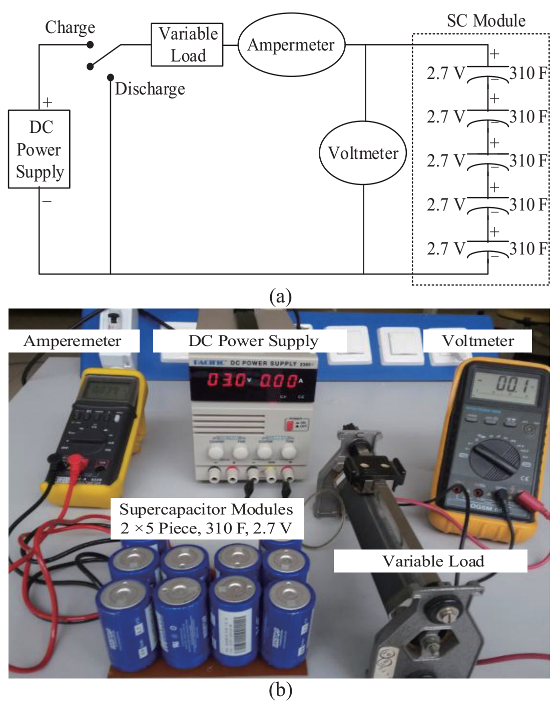

Fig. 12. SCs testing circuit diagram (a), Experimental setup (b).

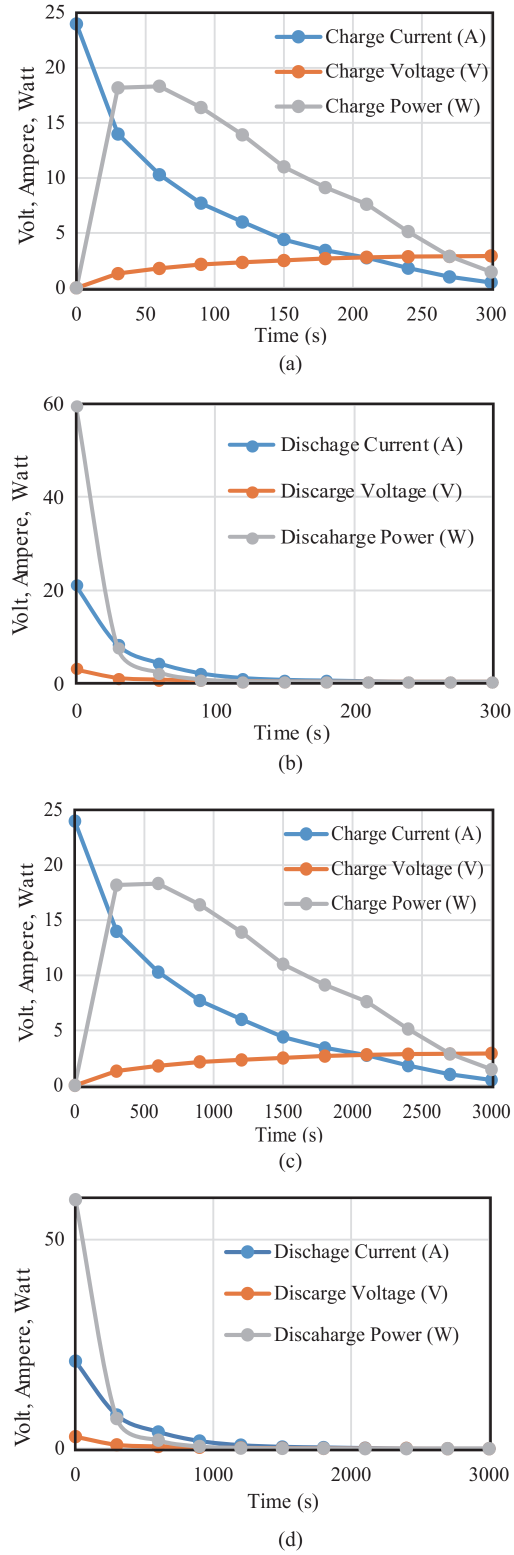

Fig. 13. The experimental results show for 310 F (a) charge, (b) discharge, and 3000 F (c) charge and (d) discharge voltage, current, and power variations.

used, and the variable load setting to 0.01 Ω as the same with simulations and charged the SC. In the second step, the SCs are discharged using the same variable load. The amperemeter precision is ±1.5 %, and the voltmeter precision is ±1 % is given in user manuals. Also, the results are compatible with the power supplies amperemeter and voltmeter. The power values are calculated from voltage and current measurements. The experimental measurement results are shown in Fig. 13(a)−(d) for the charge and discharge. The experimental results obtained for single 310 F SC is shown in Fig. 13(a) and (b), and for a 3000 F SC is shown in Fig. 13 (c) and (d) where the charge and discharge voltage, current, and power variations are demonstrated. The charge and discharge time is increased nearly ten times for 3000 F SC depending on the time constant. As a result, the experimental and simulation results are seen as suitable as expected.

VI. Conclusions

In this paper, the principle of SCs and their chemical structure, the advantages, and disadvantages of SCs, basic specifications, and performance comparison of SCs with the batteries and electrolytic capacitors are presented. Different SC models available in the literature are investigated in terms of their specifications and design applications. The voltage-current equation of the SC module using the SC simplified circuit model is proposed in this study. The experimental methods which determine the parameters of the SC equivalent circuit are provided for different capacitors, and the method to obtain the model parameters are presented. Using this parameter and voltage-current equations, the SC Matlab/Simulink model was designed and simulated. The characteristics curves of Capacitance-ESR measurement and cycle life are obtained and compared with datasheets. Also, charge and discharge characteristics of SCs for different capacitor values are simulated to compare the power and energy density of SC modules. Moreover, a supercapacitor test circuit is used to test the charge and discharge of SC modules. The results show a good agreement between the model and the datasheets, and the designed models can be used for different electrical applications as a storage system. The supercapacitors (SCs) model can be used as an alternating storage device, for instantaneous energy storage in renewable energy applications.

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