Chapter 2
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Understanding Supercapacitor Performance: Voltage Dynamics and Internal Parameter Calculations with Validating Experiments

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ABSTRACT

Supercapacitors store electrical energy through the development of the double-layer capacitor structure at the interface between the anodes and the electrolyte. The modeling of the supercapacitor (SC) is crucial for its commercial application and can be represented by various models, including electrical, chemical, and electrochemical models. One of the models used to characterize the real-time operation characteristics of the supercapacitor is the equivalent circuit model. In addition to its mathematical complexity, the experiment's time-consuming nature poses a significant obstacle in acquiring the internal parameter values for the SC. The selection of test equipment, together with the experimental design structure, is a crucial factor that influences the correctness of the model. This project focuses on developing a systematic experimental strategy for SC (supercapacitor) modeling utilizing the Neware battery tester. The study describes and discusses the experimental procedure used to determine the internal properties of the SC. The experimental set-up was based on a Neware testing device with eight independent channels and an intermediate machine, host computer with the NEWARE software v7.5.6 and Matlab 2019a. The results were compared to an empirical model developed by earlier researchers. The terminal voltage of the superconductor (SC) was verified through experimentation, with a maximum relative inaccuracy of 0.045%. The proposed approach for parameter evaluation involves using two measurement points in the charge curve, as opposed to the four measurements typically utilized in the

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literature for both the charge and discharge phases. The model effectively replicates the dynamic behavior of the supercapacitor during the charge/discharge phase, demonstrating the accuracy of the suggested approach and model.

Keywords: Supercapacitor; charge/discharge behaviour parametric modeling; neware BTS4000; internal resistance terminal voltage.

1. INTRODUCTION

Many research cases are carried out to discover new sustainable power source answers for conventional power sources in various industrial applications. Energy storage systems (ESS) are considered one of those arrangements as sustainable power sources [1,2,3]. Electrical energy storage systems are today, very vital to the energy generation industry. This is because their performance determines the efficiency of the system, as well as its cost of operation. A supercapacitor is one of the main components in ESS which has the attributes of high-power density, and a long life span which can be charged and released in a couple of seconds [4,5,6]. SCs were invented in the middle of the 19th century and The first SCs for military application were developed by the Pinnacle Research Institute (PRI) in 1982, called PRI ultra-capacitors. The functionality and characteristics of the SC originate from the mutual effect of its electrode and electrolyte materials. The electrode material for EDL capacitors is usually activated carbon, carbon fibre cloth, aerogel, graphite, graphene, and carbon nanotubes in different appearances of carbon. One of the advanced power components in such a capacitor is the Electric Double-Layer Capacitors (EDLC) which stores the energy thousands of times compared with a typical regular capacitor [7]. It comprises two equal plates that have positive and negative charges isolated by a protector as appeared in Fig. 1 [8].

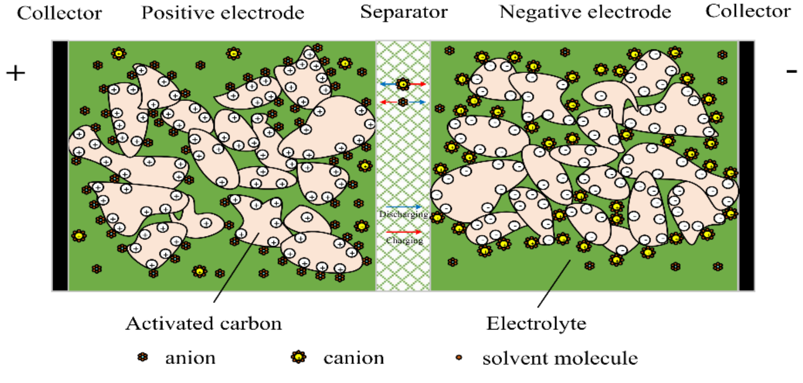

Fig. 1. Supercapacitor cell structure

The supercapacitor exhibits a remarkable ability to undergo rapid charging and discharging processes, making it well-suited for addressing short bursts of peak power demand. Its swift response during such scenarios positions it as a valuable buffer in power electronics or storage devices, particularly when dealing with pulse loads. The advantageous characteristics of the supercapacitor, illustrated in Fig. 2, contribute to its potential as an alternative and environmentally friendly solution for electric vehicles.

Despite these advantages, it is essential to note that supercapacitors come with certain limitations. Notably, they possess relatively low energy density, meaning they can store less energy per unit mass compared to traditional batteries. As a result, supercapacitors may not be suitable as standalone power sources in battery electric vehicles. However, their rapid charging and discharging capabilities make them valuable as power buffers, effectively managing peak power demands and instantaneous currents in conjunction with other energy storage systems. In this context, the supercapacitor serves as a complementary component within a broader energy storage strategy rather than functioning as the sole source of power in electric vehicles. This nuanced approach balances the strengths and limitations of supercapacitors, optimizing their role in enhancing the efficiency and performance of electric vehicle systems.

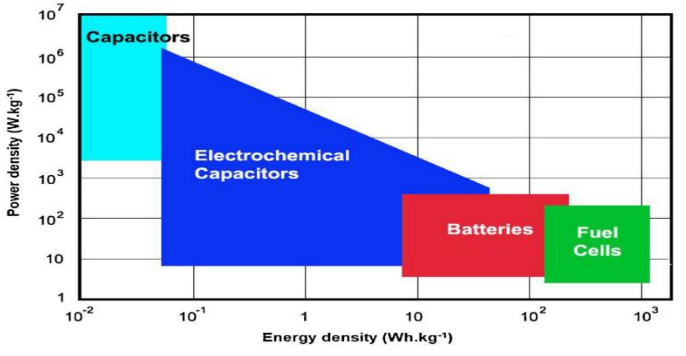

Fig. 2. Power density energy storage

Fundamentally, SCs store electrical energy through the development of the double-layer capacitor structure at the interface between the anodes and the electrolyte [9]. This vitality stockpiling instrument includes no synthetic stage or organization changes, aside from quick and reversible Faradaic responses existing on the cathode surface, which likewise add to the absolute capacitance. The trait of electrostatic charge movement brings about a serious extent of recyclability [10]. The uses of supercapacitors can be varied between electric vehicles (EVs), solar/wind power applications remote sensor nodes and hybrid electrical vehicles [11]. Supercapacitors have an essentially lower energy density and higher power density when compared with traditional batteries [12,13] and [14]. The combination of the battery and supercapacitor has integral characteristics and gives an astounding arrangement that can cover a wide scope of intensity and vitality necessities[15,16].

Accordingly, an upgrade of intensity quality utilizing batteries and supercapacitors is effectively sought after in the field of sustainable power sources and it was shown that this hybridization has lower battery costs, an overall increment in battery life and higher efficiency which may not be fulfilled by the single storage device [17,18] hence the hybridization was grown effectively in numerous applications like battery electric vehicle, hybrid electric vehicle and uninterruptible power supply as presented in [19,20,21]. In ESS applications, they ordinarily use SC terminal voltage as the criticism of regulator to accomplish constant control for the SC [22]. Nonetheless, the SC terminal voltage would be influenced by numerous elements, To viably assess the SCs terminal voltage and accomplish the exact control for the SCs in the ESSs, it is pivotal to build up a precise model for the SC [23]. Displaying of SCs has the greatest significance when planning and dimensioning SC establishments since it is the best approach to know ahead of time about the conduct and execution of the vitality energy storage devices when applied to specific hybridization [24].

Control systems of supercapacitors or operational boundaries and cutoff points can be acquired from a model, amplifying the lifetime of the capacity and hence accomplishing a more significant level of unwavering quality and competitiveness [25]. Numerous SC models have been distributed in the literature for various purposes, including describing electrical unique behavior, which is the most extreme significance for industrial applications [26,27,28]. The models that describe the electrical behavior of SCs can be characterized into three primary classes: electrochemical models, intelligent models and equivalent circuit models. The proposed models vary based on the specific application that has been addressed and intended for convenience in that application [29]. The model should likewise avoid complexity so that it tends to be effortlessly joined into real-time controllers [26]. Equivalent circuit models impersonate the electrical behavior of SCs with parametrized capacitors, inductances, and resistors (RLC). They focus on effortlessness, subbing PDEs with customary differential equations (ODEs), which tremendously encourage their usage and make them especially appropriate for industry application investigation and studies [30].

Three subcategories can be considered for equivalent circuit models: RC models, transmission line models, and dynamic models. model power under transient and differing conditions is of the most extreme significance [31]. Nevertheless, the different models of supercapacitors studied in the literature, choosing the model depending on the application of the model. In this paper, the two branches model was used for electrical behavior applications since it is considered one of the most widespread models . Even though the chosen model was studied previously, there are many hardware tools used for parameters identification and the method of identifying the internal parameter of the supercapacitor is mathematically complex using the least square method. However, in this research case, an efficient tool for testing devices (Neware) will be used with proposed simple and fast empirical equations for parameter identifications for modeling purposes.

This work emphasises the terminal voltage dynamics and the calculation of the internal parameters of SC. Not only that but also the experiments (pulse relaxation) for validation purposes were designed structurally. The robustness tests of the model have been benchmarked with the Matlab model and Error analysis validation. The following sections of this paper are organized; materials and methods, model structure, identification of model parameters, simulation model, results with discussion and conclusion.

2. MATERIALS AND METHODOLOGY

2.1 Model Structure

The model was built based on two branches circuit which has the following structure precisely displayed in Fig. 3.

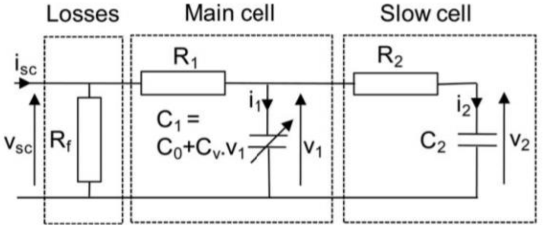

Fig. 3. Supercapacitor two branches model [14]

In Fig. 3, the primary pathway depicts the instantaneous behavior of the supercapacitor during charge or discharge events occurring within a range of minutes. Within this pathway, R1 denotes the series resistance, symbolizing the dissipated power responsible for internal heating during both the charging and discharging processes (measured in ohms, Ω). The voltage of the supercapacitor module, along with fundamental correlations outlined in references [6] and [7], can be mathematically expressed through equations (1-8) as detailed below:

$$V_{sc} = N_s \left(V_1 + R_1 \frac{Isc}{N_P} \right) \tag{1}$$

Where N_s is the number of cells in series, N_p is the number of cells in parallel, and *Isc* is the charge/discharge current. Since only one single cell was modeled the number of cells in parallel and series was set to one.

The voltage (V_1) across the capacitor C_1 on the main cell can be described as:

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

The capacitor C1 depends on the voltage ν_1 and can be expressed as:

$$C_1 = C_0 + Cv\, v_1 \quad (3)$$

Where C_0 is the constant capacitance in Farads (F) and Cv is the constant parameter (F/V).

Where Q_1 is the instantaneous charge of C_1 and can be calculated by:

$$Q_1 = C_0V_1 + \frac{1}{2}C_VV_1^2 \quad (4)$$

The slow branch determines the internal energy distribution at the end of the charge or discharge cycle in the time range of minutes. The parallel resistance R describes the leakage current that can be neglected for fast charge and discharge cycles.

Concerning the slow cell, the voltage v_2 in the secondary capacity *C*₂ can be expressed by:

$$v_2 = {}^1\!/_{C_2} \int i_2\, dt = {}^1\!/_{C_2} \int \frac{1}{R_2}(v_1 - v_2)\, dt \quad (5)$$

Let $Q_2$the instantaneous charge of C_2, we have

$$Q_2 = \int i_2\, dt \quad (6)$$

The current i_2 going in the secondary capacitor C_2 is represented by:

$$i_2 = Is_C - i_1 \quad (7)$$

The current i_1 going in the main capacitor C_2 is expressed as:

$$i_1 = C_1\frac{dv_1}{dt} = \frac{dQ_1}{dt} = (C_0 + C_vV_1)\frac{dv_1}{dt}. \quad (8)$$

2.2 Paramteric Experimental Strcuture

The internal characteristics of the supercapacitor crucial for understanding its transient response are the resistance and capacitance, yet their specific values remain undefined. To unravel these parameters and gain insights into the transient behavior, a comprehensive experiment has been meticulously designed, depicted in Fig. 4. This experimental setup aims to provide a systematic exploration, allowing for the precise identification of the resistance and capacitance associated with the supercapacitor's transient response. The outcomes of this experiment are anticipated to enhance our comprehension of the underlying dynamics and facilitate a more accurate modeling of the supercapacitor's behavior during dynamic events such as charge and discharge cycles.

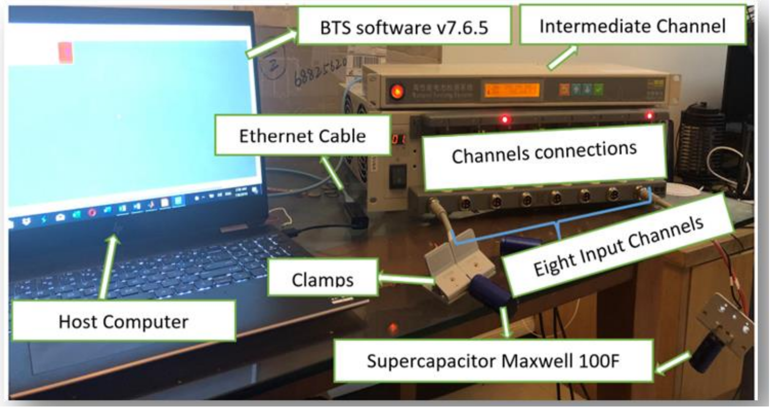

Fig. 4. Experimental set-up

The experimental set-up was based on a Neware testing device with eight independent channels and intermediate machine, host computer with the NEWARE softwarev7.5.6 and Matlab 2019a. The tester has the function of charge and discharge by applying certain software coding algorithms to the Neware software installed in the host computer as in Fig. 3. The Neware internal tester has two switches to operate in either charge or discharge based on the data collected from the current and voltage sensor circuits through DAQ, so transmits the control commands through the software to the SC connected to it as shown in Fig. 5.

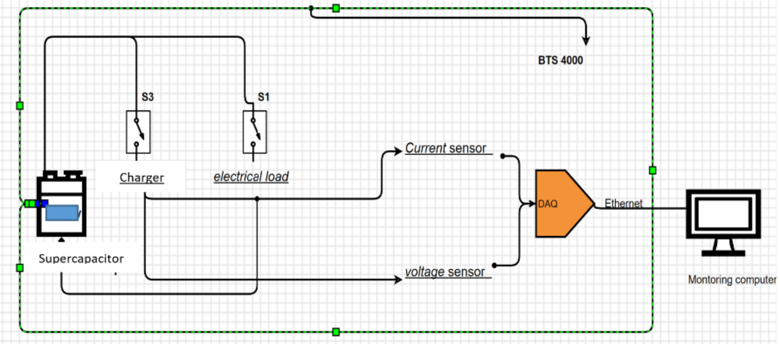

Fig. 5. Neware battery testing system BTS4000

The tester works on the range of (0-10V) and current of (0-6A), with a sampling frequency of 1 Hz and measuring errors of less than 0.5%.The middle machine has the functions of the following; network connections, receiving the control commands from the host computer, controlling the battery cycler and uploading the acquired data from the real-time experiment. The computer has the function of controlling the cycler through the Ethernet cables and storing the data in the software from voltage and current sensors. The SC used in this experiment is MaxwellBCP100F and its important parameters are summarized in Table 1.

Table 1. Supercapacitor parameters

Rated Voltage V	Rated Capacitance F	Typical ESRDC, Mω	Maximum Leakage Current mA	Maximum Peak Current A
2.7	100	8	0.26	61

2.3 The Proposed Method of Parameter Identification

The internal parameters of the supercapacitor represent the resistance and capacitance in charge and discharge phases as two branch elements. The basic nonlinear relationship between charge, current and voltage can be expressed [6] as follows:

$$i = \frac{dq}{dt} * \frac{dv}{dt} = (C_O + K_V v)\frac{dv}{dt} \quad (9)$$

Integrating equation with respect to time;

$$\int_0^t i\,dt = \int_0^t (C_O + K_V v)\frac{dv}{dt}dt \quad (10)$$

Since the current is constant yields;

$$t = f(v) = \frac{C_O}{I_c}v + \frac{1}{2}K_V\frac{1}{I_c}v^2 \quad (11)$$

Since the two-branch model have two capacitances in equation 11 we can assume that the values of those constants represented from equation 11 by:

$$\mathrm{C}_1 = \frac{C_O}{I_c} \quad (12)$$

$$\mathrm{C}_2 = \frac{K_v}{2*I_c} \quad (13)$$

So rearranging equation11-13 yields the following;

$$t = \mathrm{C}_1 v + \mathrm{C}_2 v^2 \quad (14)$$

Based on equation 14 the voltage during the charging phase has two unknown coefficients C1 and C2. Based on voltage data obtained experimentally the values of these two coefficients C1 and C2 can be compared with equation 14 as displayed in Fig. 6.

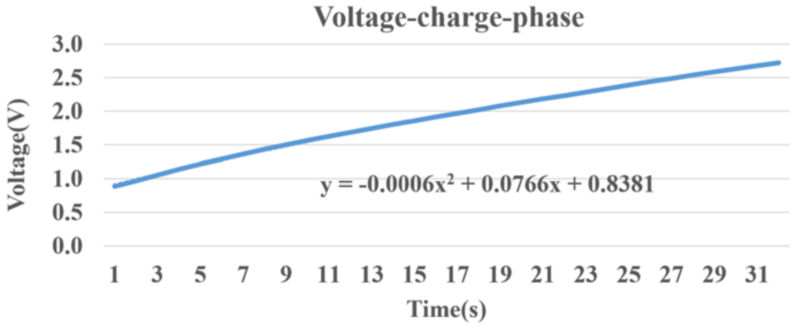

Fig. 6. Experimental charging phase data

From the figure , there is a minus sign on the displayed equation in Fig. 6 and the capacitance cannot be negative rather than confirm the relationship physically so the two points have been selected for obtaining the values of C1 and C2 as in Fig. 7.

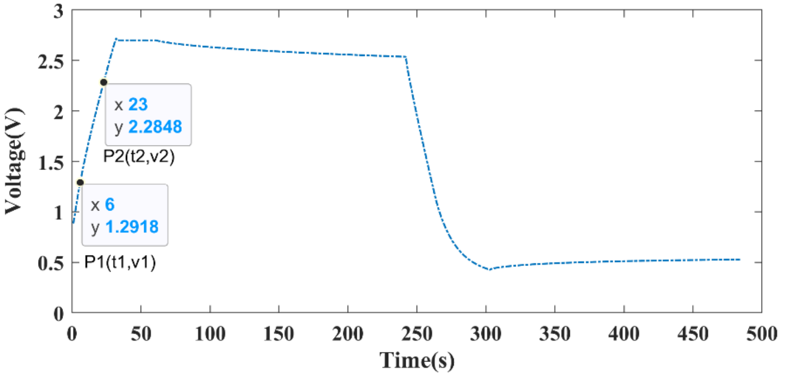

Fig. 7. Experimental terminal voltage data of supercapacitor

Based on Fig. 7, two points of the charging phase were selected to calculate the values of the immediate branch during the charging phase. The selected points were based on the characteristics of SC specified on the data sheet that the presentation of capacitances can be picked at 0.5, 0.95 of SC rated voltage or 0.4, 0.8 of rated voltage. Based on equation 14, the two points in Fig. 5 must be equal since they are in the same charging phase as follows;

$$t_1 = C_1 v1 + C_2 v1^2 \quad (15)$$

$$t_2 = C_1 v2 + C_2 v2^2 \quad (16)$$

By solving equations 15 and 16 yields;

$$C_1 = \left[\frac{v_1 * t_2 - v_2 * t_1}{v_1 * {v_2}^2 - v_2 * {v_1}^2}\right] * I_{charge} \quad (17)$$

$$C_2 = \left[\frac{v_1 * t_2 - v_1 * t_1}{v_1 * {v_2}^2 - v_2 * {v_1}^2}\right] * I_{charge} \quad (18)$$

So based on the two points obtained, the values of C_1 is 32.7604 F and C_2 is 44.9576 F.

The resistance R1 is calculated based on;

$$\mathrm{R_1} = \frac{\mathrm{D_v}}{\mathrm{I_{charge}}} \quad (19)$$

$\mathrm{D_v}$ is the discharge drop voltage in the first 10 ms of the voltage discharge represented as follows:

$$\mathrm{D_v} = \frac{\mathrm{V_{1-}V_2}}{\mathrm{t_{1-}t_2}} \quad (20)$$

$\mathrm{R_1}$ obtained as 0.0097 Ohm, so that the only parameter left is R_2 by applying a fitting curve application in Matlab for terminal voltage during rest the exponential function can be expressed as follows;

$$OCV = a_* e^{-\frac{t}{\tau}} \quad (21)$$

The open circuit voltage (OCV) during discharge in the second phase is displayed in Fig. 8.

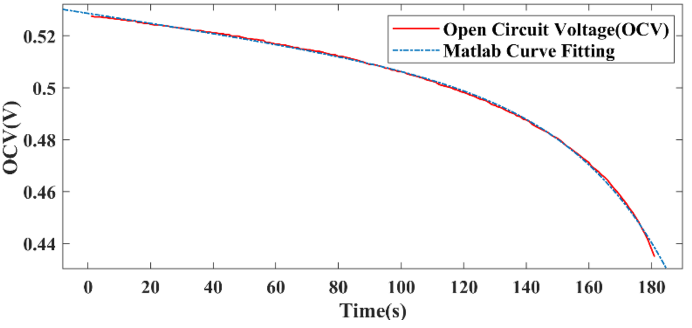

Fig. 8. Terminal voltage during discharge curve

From Fig. 6 the Matlab fitting curve equation with an RMSE error of 0.008204V is represented as;

$$OCV = 0.5017_{*}e^{-0.04139t} \tag{22}$$

So that the model was obtained and and time constant (τ_2) obtained by comparing equations (22) and (21), so R_2 can be calculated based on the following equations;

$$\tau_2 = C_{2*}R_2 \tag{23}$$

$$R_2 = \frac{\tau_2}{c_2} \tag{24}$$

All the obtained internal parameters are calculated and tabulated in Table 2.

Table 2. Identification results of the two-branch equivalent circuit model

R_1 Ohm	C_1 F	C_2 F	R_2 Ohm	Kv
0.0097	32.7604	44.9576	0.0008	10.9201

2.4 Simulation Model

Once the indicated parameters were obtained using the test processes, the simulation model was constructed using Matlab Simulink. The line transmission model was employed for comparison with the model developed in this paper, and ultimately, the validity of the results was confirmed using experimental terminal voltage data of the SC. Fig. 9 displays the two-branch models, namely the line transmission model and the observed voltage. Various tests employing different current profiles were utilized in the simulation to authenticate the two-branch model. The intricate representation of the dual-branch model utilized in the simulation is accurately depicted in Fig. 10.

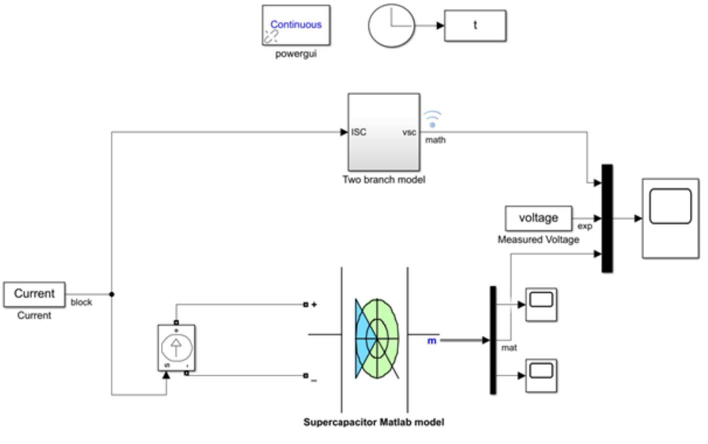

Fig. 9. Matlab model and two branch model simulation

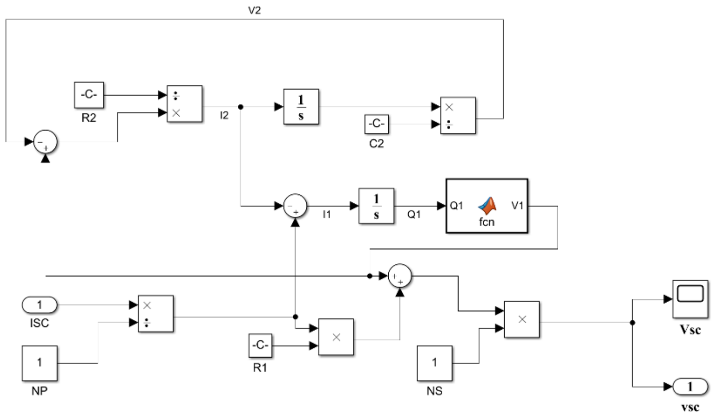

Fig. 10. Subsystem simulink for supercapacitor two branch model

The two-branch model was derived from the fundamental principles of Kirchhoff's laws, which are represented by equations (1-8). The number of cells connected in parallel and series was fixed to one in order to investigate the cell model. The terminal voltage of the supercapacitor model was calculated using equations (1-8), which serve as the primary parameters in the mathematical representation. The simulation incorporated the current profile data obtained from Neware's experimental data. The terminal voltage data obtained from trials is exported to the Matlab workspace for use in Matlab Simulink. This data will be employed for model validation and comparison of the supercapacitor. The simulation model in Figs. 9 and 10 employed distinct profiles for various validation purposes, which will be emphasized and examined in the findings and discussion section.

3. RESULTS

The model validation primarily concentrated on the terminal voltage of the supercapacitor as a regulatory parameter for the design of the controller. A variety of current profiles were employed to assess the validity of the model, comparing it to both the built-in Matlab model and the measured voltage data. The initial test was the process of charging and discharging the supercapacitors for two consecutive cycles of rest, charge, and discharge, as seen in Fig. 11.

The current profile in Fig. 11a was set in a Neware device with complete cycles of (rest-charge /discharge–rest) for the purpose of supercapacitor terminal voltage validation. The simulation started with a period rest of 50 seconds to check the self-discharge of the supercapacitor with initial voltage measurement. Then, followed by 30 seconds of constant charging phase until it reached the rated voltage of 2.7V. After that, the SC was at rest for 30 seconds followed by a one-minute constant discharge phase. Furthermore, the same time frame and phases for the first cycle were repeated. In Fig. 11b the terminal voltage of supercapacitor (during rest -charging /discharging) phases for two cycles was compared with experimental curve data. The initial voltage was about 0.4427V since the supercapacitor cannot reach zero voltage which confirms the self-discharge property of the supercapacitor. In Fig. 9b, by looking at the dotted red, blue and black lines which represent experimental data, two branch simulation models respectively, it is clear that all models have similarities in trend but different precision. The relative error is shown in Fig. 9c. for measured and simulated terminal voltage of two branches and and line transimision (Matlab) model. Of supercapacitor. The two branch models studied in this paper have a maximum relative error of 0.08 V while the line transmission (Matlab) model reached up to 0.1 V. Based on relative error values, the two branch models have better terminal voltage response and followed measured data. Another parameter of charge/discharge validation of supercapacitor is load fluctuation for fast charge and discharge as displayed in Fig. 11.

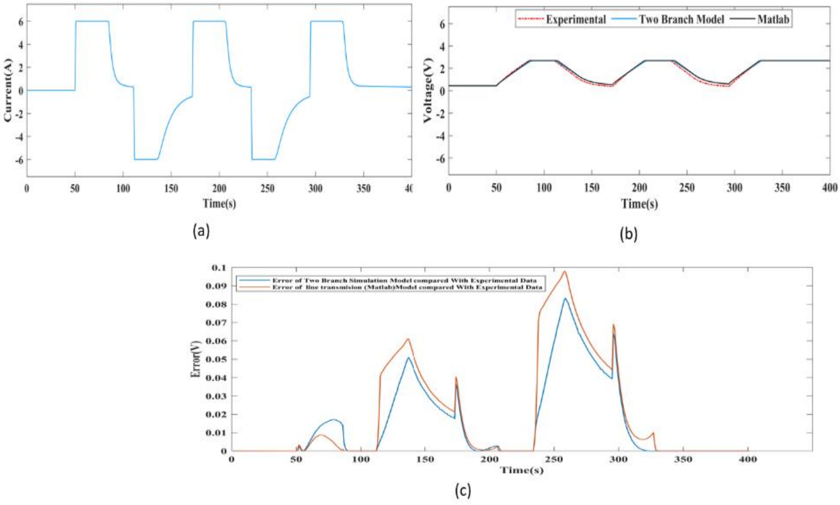

Fig. 11. (a) Current profile (b) supercapacitor Experimental terminal voltage data, simulation two branch model and simulation of Line Transmission model (c) Error between measured and simulated models

As shown in Fig. 12. a, the current profile used was by initiating the supercapacitor to rest for 20 seconds and then followed by charge and discharge for 30 seconds in each phase of charging and discharging. In Fig. 10. b it is clearly shown that during the charging and discharging phase, the terminal voltage compromised the measured voltage data of the terminal voltage of the supercapacitor. As in Fig. 10. c, the maximum relative error for the Matlab model was up to almost 0.075 V while the two-branch model investigated in this study was up to almost 0.04V. From the results obtained, the simulated two-branch model shows better accuracy for the terminal voltage response of the supercapacitor. Another method for self discharge checking of supercapacitors within a short period of time is displayed in Fig. 11.

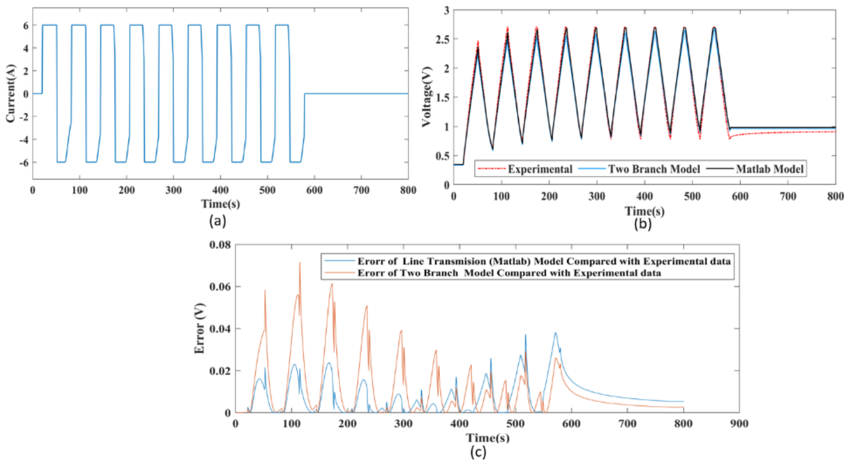

Fig. 12. (a) Current profile (b) supercapacitor Experimental terminal voltage data, simulation two branch model and simulation of Line Transmission model (c) Error between measured and simulated models

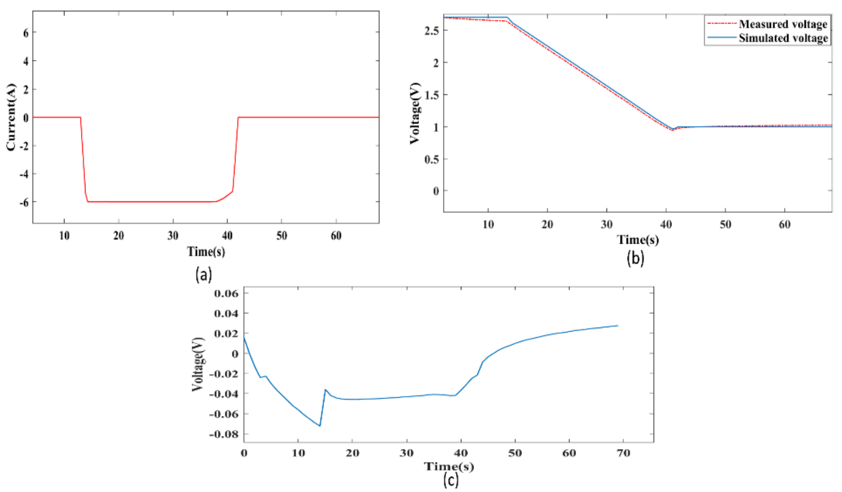

Fig. 13. (a) Current profile (b) Rest-discharging terminal voltage validation (c) Error for rest and discharge validation of supercapacitor voltage

The supercapacitor underwent a discharge process employing a continuous current profile of 6A, as illustrated in Fig. 13(a). Initially, the supercapacitor was in a quiescent state and fully charged. Subsequently, it was discharged for a duration of 30 seconds, followed by a period of rest for the remaining 30 seconds of the simulation. To validate and compare the terminal voltage of the supercapacitor, both the two-branch simulation model and experimental data were scrutinized, as displayed in Fig. 13(b). The analysis of the simulated two-branch model against the measured data revealed a maximum relative error value of approximately 0.02V, as indicated in Fig. 13(c). This minimal discrepancy underscores the accuracy and reliability of the simulation model in replicating the supercapacitor's behavior under the specified discharge conditions.

4. DISCUSSION

Overall, the explored parameters of the supercapacitor model vary depending on the specific application. However, the accuracy of the model is still considered the major criterion for evaluating the model. In the field of electrical modeling, the accuracy of the model is contingent upon both the identification profile and the resilience of the supercapacitor's voltage response. The identification technique in this study relied on empirical equations that demonstrated the efficacy of accurately calculating the internal properties of the supercapacitor. The proposed approach for parameter evaluation involves using two measurement points in the charge curve, as opposed to the four measurements typically utilized in the literature for both the charge and discharge phases. These two points encompass the charging period and mathematically describe the equations for terminal voltage, capturing the link between resistance and capacitance. The precision of the computed internal parameters can be enhanced by examining the error assessed in the results section.

Furthermore, this research exclusively utilizes the Neware BTS4000 device for modeling operations. This device possesses the capability to gather a multitude of significant data while being employed for charging and discharging the supercapacitor, in contrast to conventional approaches. The conventional approach requires the utilization of an oscilloscope, voltmeter, shunt board, data collection device, and interface devices for the host computer. However, this can potentially introduce errors in the measurement of the terminal voltage of the supercapacitor.

A multitude of scholars have thoroughly investigated and analyzed the supercapacitor model in the existing body of literature. Nevertheless, the precision of the model is assessed by considering other factors. This study conducted a comparative evaluation of the investigated model, with a specific focus on the instruments used for modeling and the analysis of accuracy mistakes. Citing previous modeling studies, particularly the investigation carried out by [27], it was demonstrated that the highest relative error exceeded 2%.

Furthermore, another investigation conducted by [6] utilized numerous hardware tools, resulting in a maximum relative inaccuracy of 0.25V for the terminal voltage. In addition, the work conducted by [11] introduced a modified two-branch circuit model for modeling supercapacitors. This model incorporates a current-regulated source to enhance the self-discharge rate of the supercapacitor voltage. In this investigation, the Neware testing apparatus was utilized.

However, the greatest relative errors observed ranged from 0.19% to 2.35% for similar test profiles conducted in this research. Nevertheless, this paper reported a maximum relative error of merely 0.045V for the purpose of validating the terminal voltage of the supercapacitor.

Moreover [11] in their study the self-discharge rate was improved in their model but still, there are long and complex methods of the identification process of internal parameters by using filters and optimization algorithms. However, in this study, the self-discharge rate during rest was relatively low and better than the line transmission (Matlab) model with small variation error, so that, it is not modelled as the main parameters in this paper. In addition [28] stated in their study that it is difficult to have a unified standard to compare the self-discharge rates due to the different systems (including electrode materials, electrolytes, separators, and initial cell voltages) employed by researchers for self-discharge tests. However, due to the phenomenon of supercapacitor self-discharge in practical applications once the supercapacitor application requires being in rest for days and a long time without charge or discharge, it is recommended for modeling self-discharge accurately.

In summary, the examination of error analysis leads to the conclusion that the model under investigation exhibits a superior error value. This affirmation underscores the effectiveness of the tools and methodologies employed for the estimation and validation of internal parameters in supercapacitor modeling. It is evident that the selected methods are highly recommended, affirming their reliability and suitability for accurately capturing the intricacies of supercapacitor behavior in the modeled system.

5. CONCLUSION

The dynamic behavior of a supercapacitor was studied by examining the two-branch circuit model under various current profiles. The internal parameters of the model were determined and the simulation model was successfully constructed using Matlab Simulink. The simulation findings were compared to the measured voltage, and a compromise was reached. The discrepancy between the measured and simulated models was examined in each stated scenario. The largest relative error of the model was 0.04V, indicating its effectiveness and validity in comparison to the literature. Ultimately, the self-discharge rate of the supercapacitor was enhanced and aligned with the recorded voltage. For future research, it is advisable to investigate the impact of self-discharge rate over extended periods of inactivity in real-world scenarios while employing the two-branch circuit model. The Neware testing device is primarily designed for battery testing, but it may also be used for supercapacitor charge and discharge. However, it is advisable to purchase and utilize this device when multiple cells need to be modeled in order to save costs.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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