Journal of Physics:
Conference Series

Supercapacitor’s Parameter Calculation based on Three Branch Equivalent Circuit Model under Different Constant Charging Current

To cite this article: M. Abdul Jabbar *et al* 2023 *J. Phys.: Conf. Ser.* **2550** 012019

ICE4CT-2022 IOP Publishing
Journal of Physics: Conference Series **2550** (2023) 012019 doi:10.1088/1742-6596/2550/1/012019

Supercapacitor's Parameter Calculation based on Three Branch Equivalent Circuit Model under Different Constant Charging Current

M. Abdul Jabbar[1], M. I. Fahmi[1], SB Yaakob[1], H F Liew[1], MDSA Khan[2]

[1] Faculty of Electrical Engineering & Technology, Universiti Malaysia Perlis (UniMAP), Perlis, Malaysia

[2] Department of Electrical & Electronic Engineering, Director, Centre for Research & Innovation Canadian University of Bangladesh

Email: mjabbar@studentmail.unimap.edu.my

Abstract. Supercapacitor is a type of energy storage with higher capacitance value compared to the normal capacitor. But it has lower voltage level compared to normal capacitor. However, it can be charged with high current and provide higher current to the load when needed when compared to the same size energy storage such as battery. The Three Branch Equivalent Circuit is one of the simple yet accurate model that has been proposed. The parameter of the Three Branch model included the capacitance, resistance and a unit of voltage dependent capacitance. The Parameter needed to be calculated accurately as it depends heavily on the terminal voltage of the supercapacitor at respective time which obtained through a charging and self-discharging experiment under constant current charging. The different constant charging current give effect toward the parameter calculation as it manipulates the rate of charging and self-discharging. This paper will calculate the parameter of supercapacitor based on the Three Branch model under different constant charging current and compared the result using the simulation to show the accuracy of the model. The parameter obtained throughout the study shows a high accuracy especially the parameters obtained using higher charging current.

1. Introduction

Energy storage is becoming a major factor in renewable energy application to stored electrical energy after the energy in harvest either from the solar panel or wind turbine. Thus, it led to the increase of demand toward the energy storage [1],[2]. Supercapacitor is amongst the current energy storage that is available on the market and some of it can be obtained commercially. With high power density, the supercapacitor can charge and discharge its energy rapidly [1]. The supercapacitor can accept high level of current during charging phase and provide high current to the load as it is not strictly bonded to any specific rated charging current such as common lithium-ion battery [2], [3]. Even with high charging capabilities, supercapacitor still have better life span before it is obsolete [4]. The use of supercapacitor in recent years has increase in multi-platform such as in an electric vehicles application, energy storage for photovoltaic, robotics and the use in elevator for the regenerative braking system [5]–[10].

Modelling a supercapacitor has been done through different type of equivalent circuit model as it is often used to shows the supercapacitor behaviour [11]. The equivalent circuit model of a supercapacitor contain the fundamental electrical component such as the resistor and the capacitor which either can exist as a single component or multiple component which is either connected in series or parallel [12]. The examples of the equivalent circuit model are the two-branch equivalent circuit model, three branch equivalent circuit model, ladder model, transmission line model, multi-branch model and dynamic model [13]. Different equivalent circuit models resulting in different numbers of parameter available that needed to be extract through various type of experiment. The Parameter extraction of the three branch equivalent circuit model for supercapacitor are based on the calculation that heavily depend on the experiment of self-discharge measurement or the charging and discharging measurement [11], [14]–[17]. The parameter identification for the supercapacitor is crucial as it reflect the modelling of the supercapacitor. Modelling of supercapacitor is important in simulating the supercapacitor for estimating the state-of-charge as it will help in increasing the accuracy of the estimation itself [24],[25]. Hence, the extracted parameter should be able to reflect the behaviour of the supercapacitor in real life application when modelled or simulate.

Thus, this paper will study the parameter extraction of the supercapacitor under different constant charging current based on the three branch equivalent circuit model and compared the results between the simulation and the experiment collected. Each supercapacitor will be charge with different constant charging current while the charging voltage and the self-discharge voltage will be measured and recorded for the calculation. The simulation will be done to every parameter extracted to show the accuracy of the parameter. The same parameter from a constant charging current will be used to simulate the supercapacitor self-discharge terminal voltage at different constant charging current configuration.

2. Methodology

There will be two major parts in the method use for this study which is the experimental part and the simulation. The experimental section will include the experimental results of the terminal voltage along with the parameter calculation.

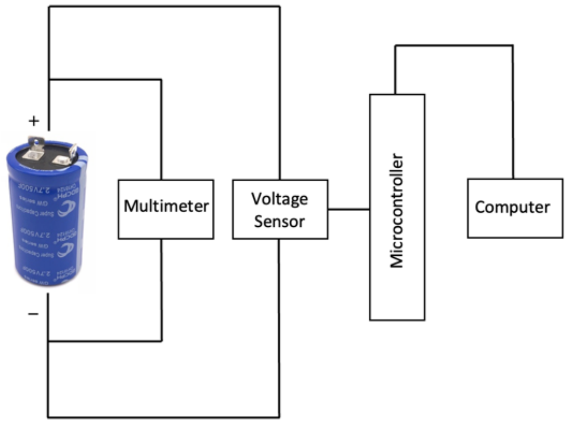

Figure 1 Experiment Setup

2.1. Experimental setup and parameter calculation

The supercapacitor that will be used in this experiment is the 650F supercapacitor rated at 2.7V. The constant charging current will be supplied through the GW DC power supply model GPR-6060D. there are three different constant charging current that will be used in this experiment, which is 1A, 3A, and 6A. The terminals voltage of the supercapacitor will be recorded during charging phase until its rated voltage and 30 minutes after the power supply is disconnected. The setup for the experiment can be seen in Figure 1.

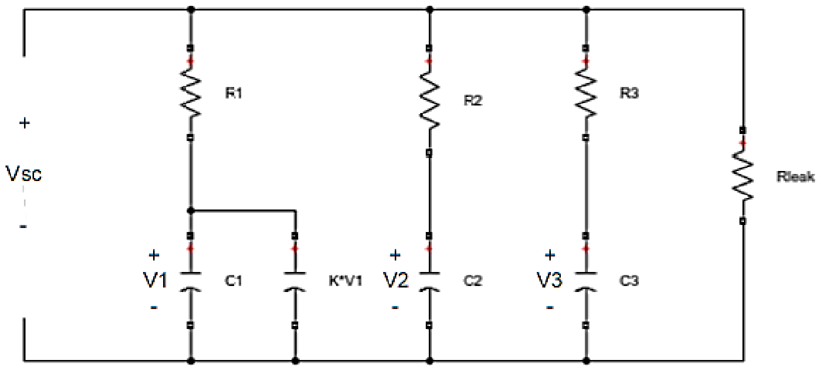

Figure 2 Three branch equivalent circuit model

Figure 2 shows the three branch equivalent circuit model along with the parameters needed to be calculated. Each branch has a resistor where resistor, R1 is for the first branch and resistor, R2 and Resistor R3 are for the second branch and third branch, respectively. The first branch has another two parameter which is capacitor, C1 and the voltage dependent capacitor, Cvar. Second branch and third branch both have a capacitor which is capacitor, C2 and capacitor, C3, respectively. The calculation will heavily depend on the result from the terminal voltage of the supercapacitor during charging and self-discharging phase with respect to the time. The three branch equivalent circuit model is choose in this study as it comes with simple circuit analysis for its parameter calculation.

For the first branch or also known as immediate branch, the parameters needed to be calculated are the resistor, R_1, capacitor, C_1 and voltage dependant capacitor, C_{var}.

$$R_1 = \frac{V_1}{I_{ch}} \tag{1}$$

$$C_1 = \frac{I_{ch}(t_2 - t_1)}{\Delta V} \tag{2}$$

Equation (1) will be used to obtain the resistor, R_1 while equation (2) will be used to get the capacitance, C_1. The resistor, R_1 can be obtained by using a simple Ohm's Law where the voltage, V_1 value is obtained at time, t_1 which at the early moment of the charging phase with constant current charging, I_{ch} where it is taken typically less than 5 second after the power supply is turned on. The ΔV in equation (2) is the voltage obtain from $V_2 = V_1 + \Delta V$ and the value is set at 50mV and time, t_2 is obtained at the calculated V_2.

$$C_{var} = \frac{2}{V_4} * \left(\frac{I_{ch}(t_4 - t_1)}{V_4} - C_1\right) \tag{3}$$

$$t_4 = t_3 + 20ms \tag{4}$$

For the voltage dependant capacitor, C_{var}, the power supply needed to be turned off and voltage, V_3 at time, t_3 is recorded. Then, C_{var} is calculated by using equation (3). Voltage, V_4 will be obtained at time, t_4 as in equation (4).

$$R_2 = \frac{(V_4 - \frac{\Delta V}{2})(t_5 - t_4)}{\left[C_1 + C_{var}\left(V_4 - \frac{\Delta V}{2}\right)\right]\Delta V} \tag{5}$$

$$C_2 = \frac{I_{ch}(t_4 - t_1)}{V_6} - \left(C_1 + \frac{C_{var}}{2} \cdot V_6\right) \tag{6}$$

Next, resistor, R_2 and capacitor C_2 will be calculated for the medium or delayed branch. The resistor, R_2 can be calculated through equation (5) with time, t_5 can be obtained at the point of voltage, $V_5 = V_4 - \Delta V$. Capacitor, C_2 can be calculated using equation (6). the voltage, V_6 is taken at time, $t_6 = t_5 + 3R_2C_2$ with R_2C_2 can be assumed as 100s.

$$R_3 = \frac{\left(V_6 - \frac{\Delta V}{2}\right)(t_7 - t_6)}{\left[C_1 + C_{var}\left(V_6 - \frac{\Delta V}{2}\right)\right]\Delta V} \tag{7}$$

$$C_3 = \frac{I_{ch}(t_4 - t_1)}{V_8} - \left(C_1 + \frac{C_{var}}{2} \cdot V_8\right) \tag{8}$$

Final branch parameter can be calculated using equation (7) and equation (8) for resistor, R_3 and capacitor, C_3 respectively. The time, t_7 is obtained right at $V_7 = V_6 - \Delta V$ and voltage, V_8 is obtained at time, t_8 set at 30 min.

2.2. *Simulation*

The simulation will be run to monitor the accuracy of the model by showing the terminal voltage of the supercapacitor after the power supply is turned off. The simulation will be using the MATLAB Simulink software and the help of Microsoft Excel to compare the results from both experiment and simulation.

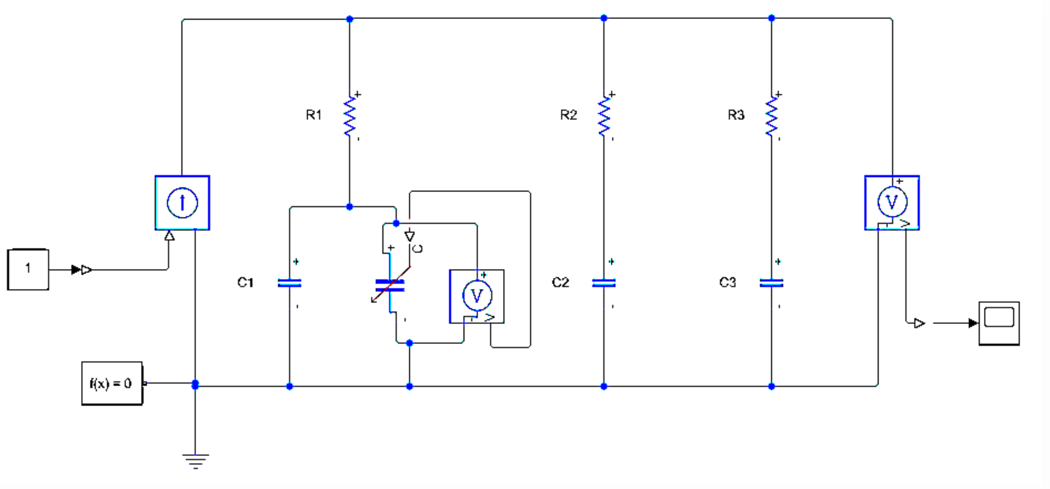

Figure 3 The three branch equivalent circuit model configuration in MATLAB Simulink

Figure 3 shows the configuration of the three branch equivalent circuit model using MATLAB Simulink that will be used to simulate the supercapacitor behaviour.

3. Results and Discussion

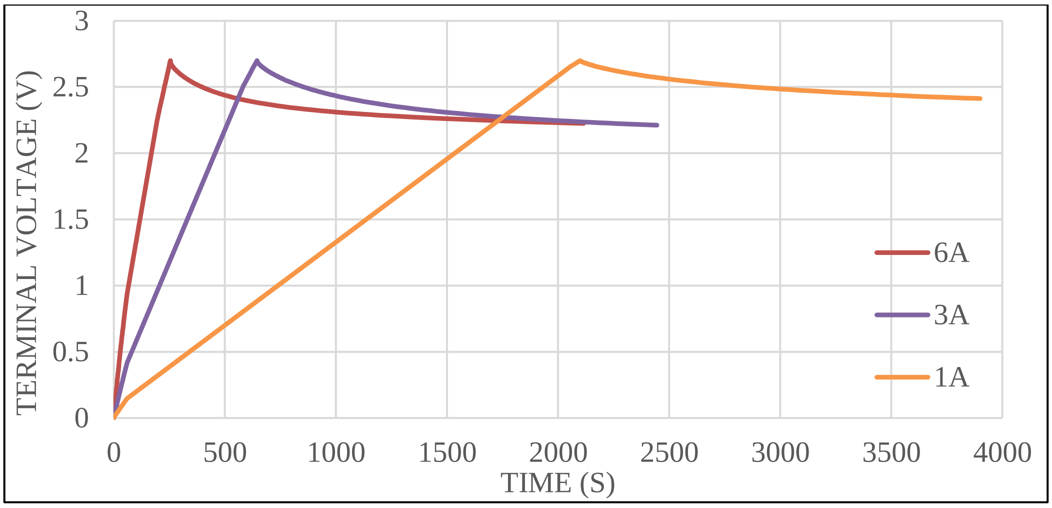

Figure 4 Terminal voltage of supercapacitor during charging and self-discharging phase under different constant charging current

Table 1 The calculated parameter for the supercapacitor three branch model

Parameter	Charging Current		
	1A	**3A**	**6A**
Resistor, R1	0.013 Ω	0.008 Ω	0.012 Ω
Capacitor, C1	430 F	390 F	320 F
Voltage dependent Capacitor, Cvar	258.03 F	242.67 F	184.35 F
Resistor, R2	4.49 Ω	1.75 Ω	1.61 Ω
Capacitor, C2	58.42 F	102.42 F	88.11 F
Resistor, R3	13.85 Ω	7.18 Ω	7.60 Ω
Capacitor, C3	127.74 F	197.05 F	155.15 F

The main purpose of the experiment is to obtain the terminal voltage of the supercapacitor when supplied with constant current during charging until its rated voltage. Also, the experiment needs to measure the terminal voltage of the supercapacitor during self-discharging phase for 30 minutes after the power supply is disconnected. This is because the three branch equivalent circuit model has more reliable in accuracy for the first 30 minutes in reflecting the supercapacitor behaviour [18]. The results can be seen in Figure 4 where all the supercapacitor's terminal voltage under different constant charging current is shown. The higher charging current resulting in higher charging rate which help the supercapacitor to achieve its rated voltage faster compared to lower charging current. However, the higher charging current resulting in faster voltage drop during open circuit condition. The purposes of the results obtained as in Figure 4 is for the parameter estimation of the supercapacitor. The results for the parameter can be seen in Table 1. Since the waveform of the supercapacitor is different due to the different of constant charging current, the huge different between each parameter to each constant charging current use is expected.

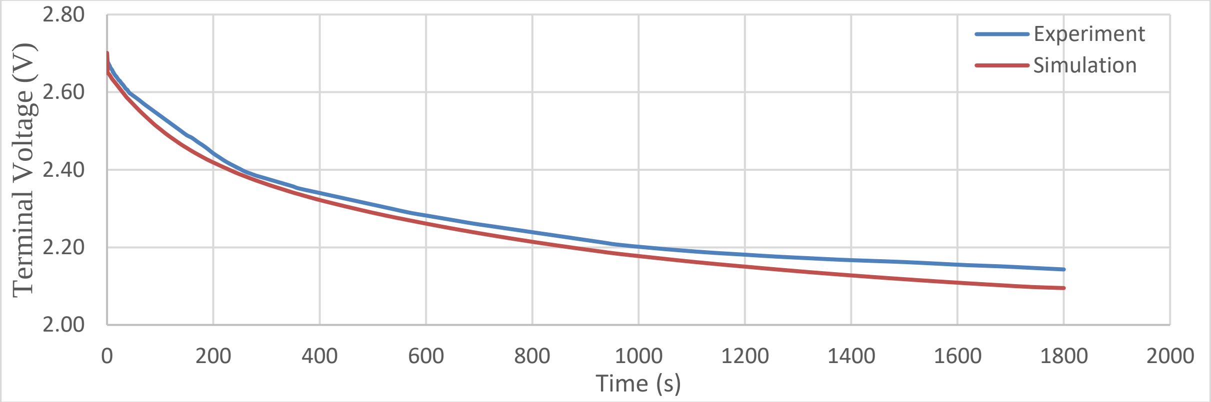

Figure 5 The experiment and simulation result of the supercapacitor's terminal voltage with 6A constant charging current

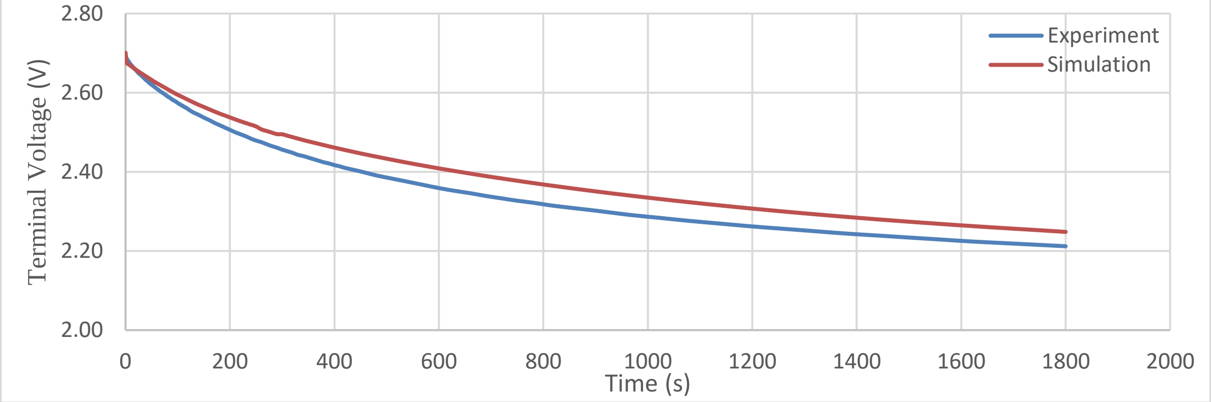

Figure 6 The experiment and simulation result of the supercapacitor's terminal voltage with 3A constant charging current

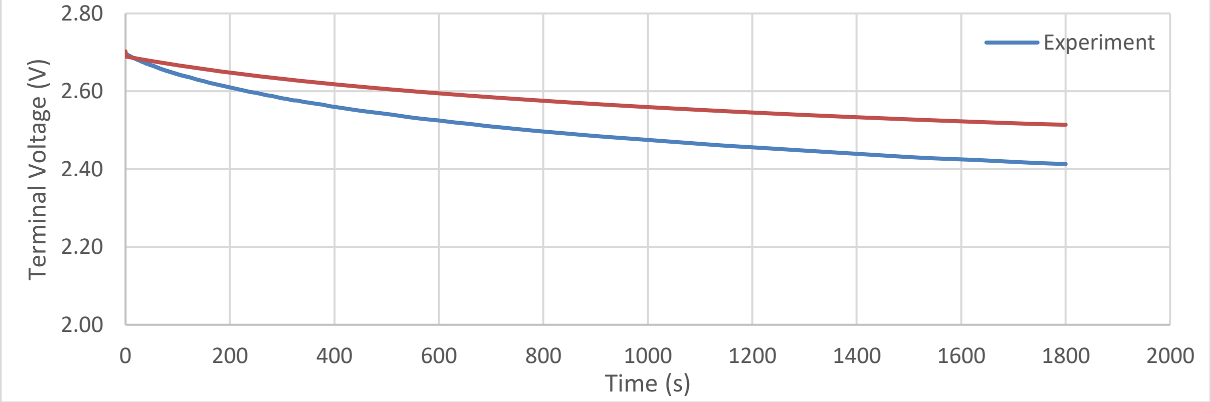

Figure 7 The experiment and simulation result of the supercapacitor's terminal voltage with 1A constant charging current

The purpose of the simulation done is to validate the calculated parameter done based on the supercapacitor's three branch equivalent circuit model. Hence, the result of the simulation will be compared with the experimental result during self-discharging phase for 30 minutes and the results is closely monitored. Figure 5 until Figure 7 shows the comparison result of simulation and experiment at different constant charging current of 6A, 3A and 1A, respectively. In Figure 5, the high voltage drop during the early moment is due to self-discharge phenomenon of the supercapacitor at the early phase. This phenomenon shows the nonlinear behaviour of the supercapacitor. In Figure 7, the supercapacitor that has been charge with 1A current has the lowest voltage drop since the slow charging current create more uniform charge build up along the surface of electrode which led to balance electric field. Hence, lower voltage drops. Compared to higher charging current, build up charge around the electrode is high which cause gradient in the electrical field [19]. The self-discharge happens at the early phase of open circuit condition as to reflect the charge redistribution that happen to the supercapacitor.

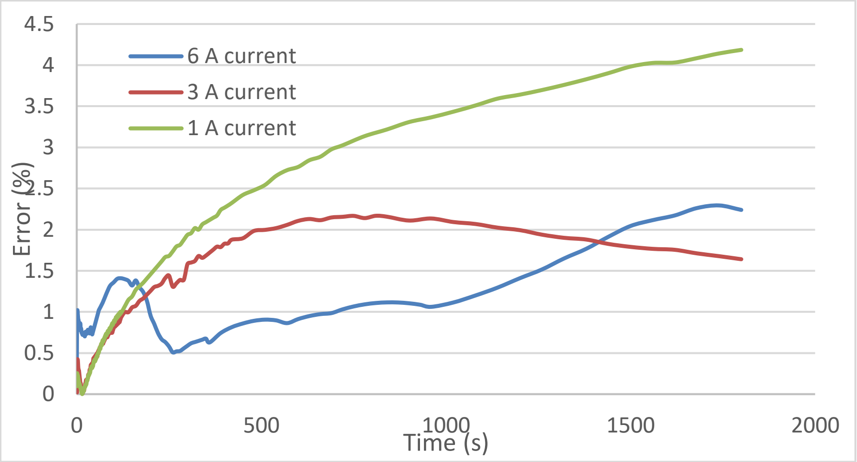

Figure 8 The percentage error between experiment and simulation results

Table 2 The different of charging time between experiment and simulation

Charging current (A)	**Charging time (s)**		
	Experiment	Simulation	Different
1	2100	2138	38
3	645	673	28
6	255	252	3

Both experiment and simulation results have a close similarity in term of its value. However, need to be noted that the different between simulation and experiment result for supercapacitor with 1A constant charging current in Figure 7 is higher compared to the supercapacitor with higher constant charging current. The error trend for the self-discharge behaviour between the simulation and the experimental results can be seen in Figure 8. The increase of error for the 1A constant charging current parameter compared to the experiment is relatively high compared to the other two results. For the 6A and 3A error based on respective parameter tend to increase after at one point. However, the three branch model or also called as Zubieta's model only reliable to show the supercapacitor behaviour for the first 30 minutes. All the three parameters able to simulate the supercapacitor behaviour with percentage error less than 5%. In the perspective of charging time as seen in Table 2, the different between the simulation and experiment decrease when the simulation run using parameter obtained from higher constant charging current data. Also, the charging time is faster for the simulation that use parameter from 6A constant charging current experiment.

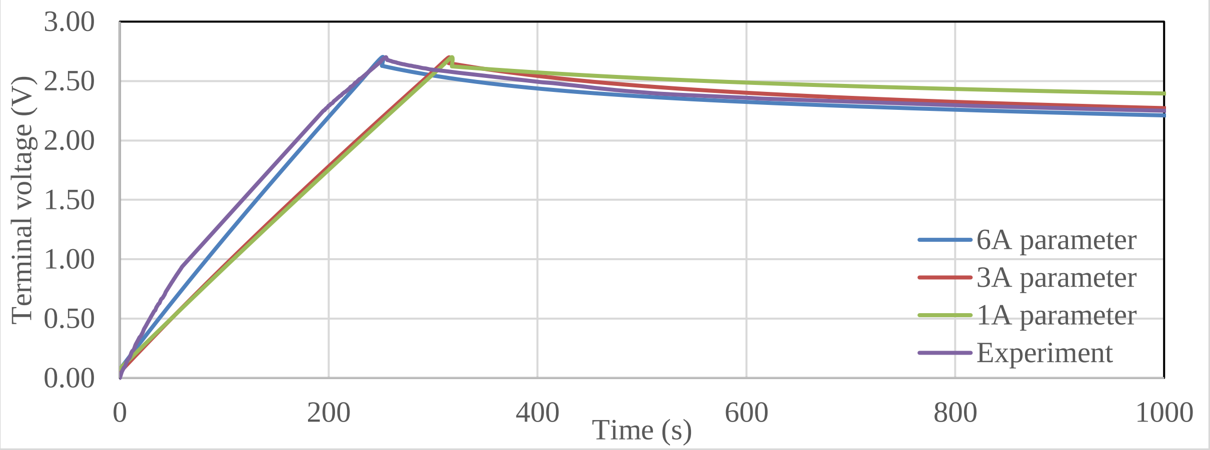

Figure 9 6A, 3A and 1A calculated parameter used to simulate the 6A charging current behaviour and compared with 6A experiment.

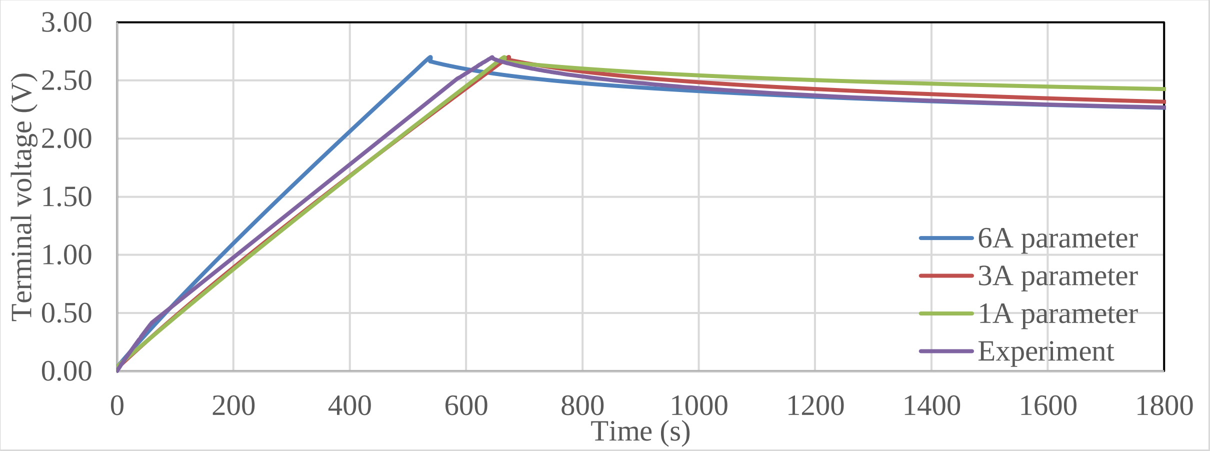

Figure 10 6A, 3A and 1A calculated parameter used to simulate the 3A charging current behaviour and compared with 3A experiment.

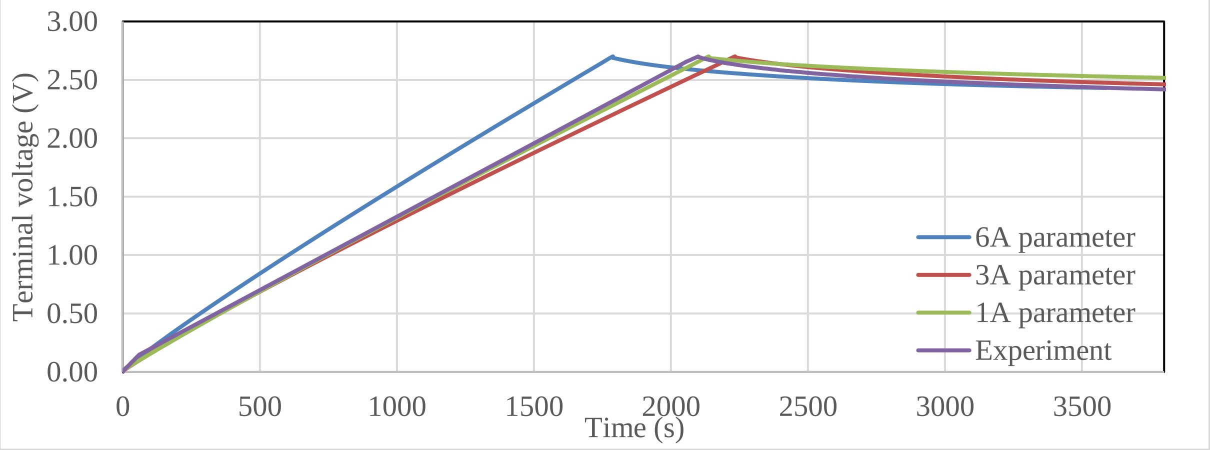

Figure 11 6A, 3A and 1A calculated parameter used to simulate the 1A charging current behaviour and compared with 1A experiment.

The results shown in Figure 9 until Figure 11 is the terminal voltage of supercapacitor to study the parameter accuracy when used to simulate different constant charging current. In Figure 9, all 3 parameter that has been calculated is used to simulate the supercapacitor behaviour during charging and self-discharging phase under 6A constant charging current. The result show that only its own parameter able to imitate the experiment data with the parameter obtain from 3A constant charging current experiment closely having the same results after the few minutes. For 3A results comparison in Figure 10, both of its own parameter and 1A parameter able to closely imitate the charging phase. In Figure 11 for the 1A simulation results, only its own parameter able to show the accuracy between the simulation and experiment during the charging phase. The parameter obtains using 6A experimental data has fastest charging time when implemented for the 3A simulation and 1A simulation as in Figure 10 and Figure 11, respectively.

4. Conclusion

The purpose of this paper is to study the parameter estimation of the supercapacitor's three branch equivalent circuit model under three (3) different constant charging current. The calculated parameter for each respective constant charging current also use to study its reliability and accuracy in simulating the terminal voltage of supercapacitor at different constant charging current. For example, the parameter calculated from 6A experiment is used to simulate the supercapacitor behaviour with 3A and 1A constant charging current. The parameter calculated for all three (3) condition able to show the accuracy when compared both simulation and experiment result which having less than 5% of percentage error following the THD error range. However, from this study it is advisable for researchers to simulate the supercapacitor behaviour using the same parameter based on the charging current use for the experiment to achieve better results before implementing the supercapacitor into any application. All the calculated parameter at the different experiment results in this study able to shows it reliability to be implemented in any supercapacitor modelling purposes if considering the use of three branch equivalent circuit as the supercapacitor's model.

References

[1] M. A. Jabbar, M. I. Fahmi, S. Yaakob, H. F. Liew, N. Nordin, and M. Z. Aihsan, "Self-discharge of Supercapacitor under Different Timeframe for Open Circuit Condition," in *IEEE ROMA*, Institute of Electrical and Electronics Engineers (IEEE), Oct. 2022, pp. 1–5. doi: 10.1109/roma55875.2022.9915666.

[2] N. Reema, G. Jagadan, N. Sasidharan, and M. P. Shreelakshmi, "Comparative Analysis of CC-CV/CC Charging and Charge Redistribution in Supercapacitors," in *Proceedings of 2021 31st Australasian Universities Power Engineering Conference, AUPEC 2021*, Institute of Electrical and Electronics Engineers Inc., 2021. doi: 10.1109/AUPEC52110.2021.9597829.

[3] Ryszard Kopka, "Discrepancy between derivative orders in fractional supercapacitor models for charging and discharging cycles," in *23rd International Conference on Methods & Models in Automation & Robotics (MMAR)*, 2018.

[4] M. Nikkhoo, E. Farjah, and T. Ghanbari, "A simple method for parameters identification of three branches model of supercapacitors," in *2016 24th Iranian Conference on Electrical Engineering, ICEE 2016*, Institute of Electrical and Electronics Engineers Inc., Oct. 2016, pp. 1586–1590. doi: 10.1109/IranianCEE.2016.7585774.

[5] C. Patnaik, M. M. Lokhande, and S. B. Pawar, "Hybrid Energy Storage System using supercapacitor for Electric Vehicles," *Innovations in Power and Advanced Computing Technologies* , pp. 1–5, 2019.

[6] D. Mestriner, "Feasibility Study of Supercapacitors as Stand-Alone Storage Systems for Series Hybrid Electric Vehicles," *11th International Symposium on Advanced Topics in Electrical Engineering (ATEE),* pp. 1–5, 2019.

[7] T. Dey, K. Dey, G. Whelan, and A. Eroglu, "Supercapacitor Implementation for PV Power Generation System and Integration," in *International Applied Computational Electromagnetics Society Symposium (ACES),* 2018, pp. 1–2.

[8] T. C. Ting, Z. Rasin, and C. S. Ching, “Design and simulation of cascaded H-bridge multilevel inverter with energy storage,” *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 23, no. 3, pp. 1289–1298, Sep. 2021, doi: 10.11591/ijeecs.v23.i3.pp1289-1298.

[9] V. J. Nagarajah, H. J. Lee, K. G. Tan, and N. Khunprasit, “Performance analysis of supercapacitors for transportation industry,” *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 13, no. 3, pp. 1031–1038, Mar. 2019, doi: 10.11591/ijeecs.v13.i3.pp1031-1038.

[10] J. Gao and G. Yan, “A novel power management circuit using a super-capacitor array for wireless powered capsule robot,” *IEEE/ASME Transactions on Mechatronics*, vol. 22, no. 3, pp. 1444–1455, Jun. 2017, doi: 10.1109/TMECH.2016.2646859.

[11] L. E. Helseth, “Modelling supercapacitors using a dynamic equivalent circuit with a distribution of relaxation times,” *J Energy Storage*, vol. 25, Oct. 2019, doi: 10.1016/j.est.2019.100912.

[12] A. H. Abdul, N. Ramli, A. N. Nordin, and M. F. Abd. Wahab, “Supercapacitor performance with activated carbon and graphene nanoplatelets composite electrodes, and insights from the equivalent circuit model,” *Carbon Trends*, vol. 5, p. 100101, Oct. 2021, doi: 10.1016/J.CARTRE.2021.100101.

[13] M. A. Jabbar, M. I. Fahmi, S. B. Yaakob, L. H. Fang, and M. Z. Aihsan, “The different approach for supercapacitor modelling in the perspective of self-discharge study,” *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 28, no. 2. Institute of Advanced Engineering and Science, pp. 663–673, Nov. 01, 2022. doi: 10.11591/ijeecs.v28.i2.pp663-673.

[14] B. Bairwa, K. Pareek, M. Sarvagya, and U. R. Yaragatti, “Analysis of Leakage Current Mechanism in Supercapacitor with Experimental Approach,” in *2022 IEEE Fourth International Conference on Advances in Electronics, Computers and Communications (ICAECC)*, IEEE, Jan. 2022, pp. 1–6. doi: 10.1109/ICAECC54045.2022.9716664.

[15] Z. Cabrane and S. H. Lee, “Electrical and Mathematical Modeling of Supercapacitors: Comparison,” *Energies (Basel)*, vol. 15, no. 3, Feb. 2022, doi: 10.3390/en15030693.

[16] I. N. Jiya, N. Gurusinghe, and R. Gouws, “Electrical circuit modelling of double layer capacitors for power electronics and energy storage applications: A review,” *Electronics (Switzerland)*, vol. 7, no. 11. MDPI AG, Nov. 01, 2018. doi: 10.3390/electronics7110268.

[17] G. Marconi *et al.*, “MODELING AND MODEL VALIDATION OF SUPERCAPACITORS FOR REAL-TIME SIMULATIONS,” Alma Mater Studiorum-Universita Di Bologna, Italy, 2019.

[18] H. Pourkheirollah, J. Keskinen, M. Mäntysalo, and D. Lupo, “Simplified exponential equivalent circuit models for prediction of printed supercapacitor’s discharge behavior - Simulations and experiments,” *J Power Sources*, vol. 567, p. 232932, May 2023, doi: 10.1016/J.JPOWSOUR.2023.232932.

[19] H. Yang and Y. Zhang, “A study of supercapacitor charge redistribution for applications in environmentally powered wireless sensor nodes,” *J Power Sources*, vol. 273, pp. 223–236, Jan. 2015, doi: 10.1016/J.JPOWSOUR.2014.09.061.

Acknowledgments

The authors would like to acknowledge the support from the Fundamental Research Grant Scheme (FRGS) under a grant number of FRGS/1/2020/TK0/UNIMAP/02/81 from the Ministry of Higher Education Malaysia. Additionally, we want to thank Electric Vehicle Energy Storage System (eVess) Group, Centre of Excellence for Renewable Energy (CERE), Faculty of Electrical Engineering and Technology, Universiti Malaysia Perlis for providing the support, facilities, and equipment to produce our publication. The authors would like to thank the Faculty of Electrical Engineering & Technology, Universiti Malaysia Perlis (UniMAP) for providing the facilities and financial support under FKTE Research Activities Fund.