Indonesian Journal of Electrical Engineering and Computer Science
Vol. 37, No. 2, February 2025, pp. 730~739
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v37.i2.pp730-739

Two RC model and parameter estimation of lithium-ion battery

Girisha Joshi[1], Lakshmi Narayana Valluru[2], Amol Prakash Khade[2]
[1]Department of Electrical and Electronics Engineering, NMAM Institute of Technology, Nitte (Deemed to be University), Nitte, Karnataka, India
[2]L&T Technology Services, Bangaluru, India

Article Info

Article history:

Received Jul 2, 2024
Revised Sep 17, 2024
Accepted Sep 30, 2024

Keywords:

Battery management system
C rate
Electric vehicles
Hybrid pulse power characterization test
MATLAB
State of charge

ABSTRACT

Electric vehicles are the trend of this decade. Frequent high-power requirements of electric vehicles, make the batteries discharge at higher C rate. Discharging at a higher C rate will lead to higher heat production leading to destruction and explosion of the battery. To optimize the charging and discharging C rates considering both safety and performance factors, battery management system (BMS) is used as an eternal component of power source. To estimate the state of charge (SOC), which is an essential component of BMS, accurate battery modelling is required. Two RC model is one of the most used lithium-ion battery model, due to its simplicity and accuracy. The equivalent circuit parameters, resistances and capacitance do change with SOC and temperatures. This paper focuses on estimation of equivalent circuit parameters for a wide range of temperatures and SOCs ranging from -20 degree celsius to +25 degree celsius and 100 to 0 respectively. We have developed two RC model for Panasonic 18650PF and estimated the parameters of the model using hybrid pulse power characterization (HPPC) data. MATLAB based parameter estimator is used in determining the equivalent circuit parameters.

Corresponding Author:

Girisha Joshi
Department of Electrical and Electronics Engineering, NMAM Institute of Technology
Nitte (Deemed to be University)
Nitte, Karnataka-574110, India
Email: girishjoshi85@nitte.edu.in

1. INTRODUCTION

One of the challenges in achieving the transition from IC engine-based technology to electric vehicles (EV) is batteries. The conventional lead-acid batteries used as an auxiliary power source in IC engine-based vehicles are not suitable for electric vehicles. This is due to their low power to weight and power to size ratio [1], [2]. Due to the advantages such as high energy density, long lifespan, light in weight, lower self-discharge and less charging time, lithium-ion batteries have become the first choice for electric vehicle power source [3], [4]. High charging and discharging C rates cause thermal runaway in these batteries. This has raised major concerns with respect to the safety of the passengers and electric vehicles. There are two approaches in modeling of lithium-ion batteries namely physics based modelling and equivalent circuit model. Physics based modelling is a complex and involved method. This approach employs mathematical formulas based on chemical and physical principles to describe the events that take place inside the battery. Compared to this equivalent circuit models are simple and robust [5]–[7]. Most of the battery management systems (BMS) use an equivalent circuit model of the battery [8]–[10]. Even though the equivalent circuit model is less accurate and do not have all the features of physics-based models they are preferred in battery management systems of majority of the batteries because of the simplicity and adequate model accuracy.

In equivalent circuit model approach, phenomenological approximation of battery is done using the electrical components [11]. The equivalent circuit parameters do not have any direct mapping with battery chemistry. One equivalent circuit parameter, for example R1 alone will not represent any chemical process in the battery. But using all the equivalent circuit parameters one will be able to model the complete behavior of the given lithium-ion battery at different temperatures and state of charge. Equivalent circuit models use basic electrical circuit components in such a way that it will be able to represent battery voltage for different current stimuli applied to the battery cell. Due to nonlinear relationship between voltage and SOC of lithium-ion batteries, voltage alone cannot be used to calculate the SOC. To reduce the ambiguity about the distance that could be travelled with available charge in batteries correct estimation of state of charge (SOC) is needed. To estimate SOC, having the parameters of the equivalent circuit is very much essential. When SOC is estimated in real time by BMS at any given drive cycle, values of the circuit parameters is needed. The circuit parameters do change with temperature and state of charge of the battery which makes the model complex. Understanding the characteristics of the battery with respect to change in SOC and temperature is essential factor for the success of BMS [12]. Very few researchers have published their work in this line and reported the parameter estimation at different SOC and temperatures [13]. Zhang *et al.* [14] estimated SOC considering only the data for three temperatures. Work carried by Khanum *et al.* [15] estimates values of internal resistance R0 for different temperatures and SOC. In the work carried out by Jung and Tullu [16] developed expressions for Thevenin equivalent circuit model as a function of SOC but effect of temperature on equivalent circuit parameters is not analyzed. Since the battery temperature depends on ambient temperature and C-rate at which it is discharged, parameters need to be estimated for wide range of temperatures. Work related to, impact of temperature and SOC on the equivalent circuit parameters is not significantly reported in the literature. Present work addresses this issue and estimates the parameters for temperatures ranging from -20 to +25-degree Celsius for SOC changing from zero to one. This work is significant considering the fact that during the operation of the battery, both during charging and discharging, temperature do change and for accurate SOC estimation, having equivalent circuit parameters for the entire range of operating temperature is very important.

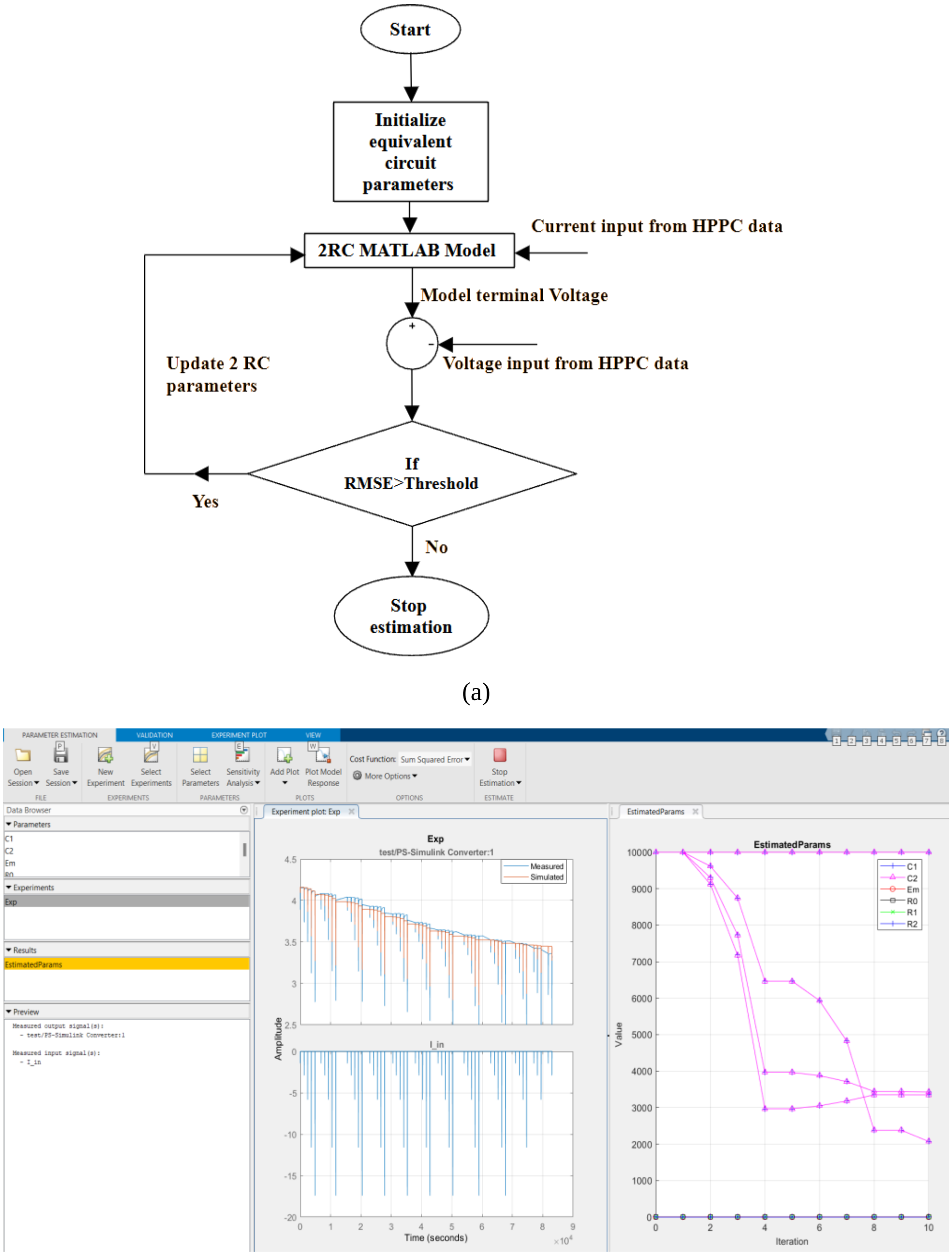
2. METHOD

In this section information about different state of the art equivalent circuits and the process in Figure 1 of parameter estimation is explained. Figure 1(a) shows the flow chart of parameter estimation. Figure 1(b) shows the parameter estimation window of MATLAB used in the work, for estimation of parameters.

Lithium-ion battery is modeled using 2 RC equivalent circuit. The equivalent circuit is developed in MATLAB Simulink platform. Parameter estimator application of MATLAB is used in this work. Data generated from hybrid pulse power characterization (HPPC) tests performed at the University of Wisconsin-Madison by Kollmeyer [17] has been used in our work. HPPC test data consists of information of voltage, current, time, battery temperature, Ampere hour, Watt hour and power. The brief process followed in MATLAB parameter estimation is as follows. Equivalent circuit parameters are given some initial value. For a given current impulse data from HPPC test, the model terminal voltage is compared with HPPC experiment terminal voltage data. The parameters are adjusted till RMSE value of this terminal voltage error reduces to the acceptable level set in the application. The process is explained in detail in following subsections.

2.1. Development of equivalent circuit model of lithium-ion battery

First Element of equivalent circuit model is selected such that the predominant behavior of the battery cell must be represented. Any difference in characteristics between cell model and actual cell is the modelling error. The equivalent circuit model is improved by adding one more element such that the modelling error reduces significantly. Adding the elements to equivalent circuit model continues till the error reduces significantly and the corresponding battery cell model is called as “good enough” model of the battery cell [18]. The fundamental observed behavior of the battery cell is voltage at the terminals of the battery cell. To start with, a battery cell is represented by an ideal voltage source. Figure 2 to Figure 6 shows various stages of 2 RC equivalent circuit model development. Figure 2 shows the representation of the battery cell using ideal voltage source. The representation shown in Figure 2, is valid only during the initial phase where the battery is just connected to the load. The ideal voltage source alone is not able to represent the behavior of battery as battery terminal voltage is dependent on the load current. After the initial phase the terminal voltage depends on the amount of current drawn from the battery, recent usage, and many other aspects of the battery.



(a)

(b)

Figure 1. Parameter estimation (a) Flow chart of parameter estimation and (b) MATLAB parameter estimation Window

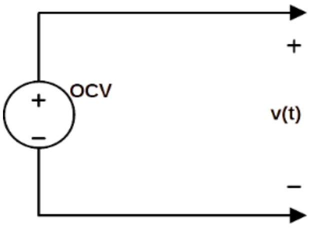


Figure 2. Constant output voltage cell model

An independent source voltage representation of the battery cell alone is incomplete. Battery voltage will be greater in fully charged cells compared to a discharged cell. This fact inspires change in the open circuit voltage (OCV) representation from independent voltage source to dependent voltage source of state of charge. This modification is justified because terminal voltage of fully charged cells is different from partially discharged cells. SOC is measure of amount of charge available in the battery at a given instant compared to total charge holding capacity of the battery. SOC, which is a unitless parameter, varies from zero to one. The symbol used for SOC is “z” When the battery is fully discharged, the SOC value is zero and when the battery is fully charged, corresponding SOC value is one. Total charge holding capacity or total capacity could be defined as total amount of charge removed from the battery when state of charge is varied from one to zero. It is measured in either ampere-hours or milli ampere hours depending on the battery rating. It is represented by the symbol Q. The total capacity is a parameter of equivalent circuit model, which does not change with current and temperature. This may change from cell to cell. However, the value of Q reduces gradually with ageing of the battery. The (1) provides the model of SOC.

$$\dot{z}(t) = \frac{-\eta(t)i(t)}{Q} \tag{1}$$

Sign of the current is positive while discharging and negative during charging. The symbol η used in (1) is coulombic efficiency which is defined as the ratio of charge out to charge in and the SOC value is retained to the value before discharging and charging cycle. The value of η is one during discharging and it is less than one during charging. Due to higher coulombic efficiencies of lithium-ion battery, the approximation of η to one during both charging and discharging phases leads to reliable model representation. By integrating (1) we can have expression for the state of charge. The (2) represents the continuous time model.

$$z(t) = z(t_0) - \frac{1}{Q}\int_{t_0}^{t} \eta(\tau)i(\tau)d(\tau) \tag{2}$$

The discrete time state of charge expression is represented in the (3).

$$z[k+1] = z[k] - \frac{\Delta t}{Q}\eta[k]i[k] \tag{3}$$

Improved circuit model where OCV is a function of state of charge is shown in Figure 3.

Models represented in Figures 2 and 3 describes the static models and does not incorporate the effects of charging and discharging on the terminal voltage. In any battery, it is observed fact that terminal voltage is less than the open circuit voltage during discharging and terminal voltage is greater than open circuit voltage during discharging. This characteristic can be embedded in the model by connecting a resistance in series with the controlled voltage source. The resistance is named as equivalent circuit resistance (ESR). The improved model is represented in Figure 4.

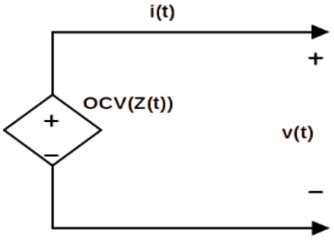


Figure 3. SOC dependent voltage source Cell model

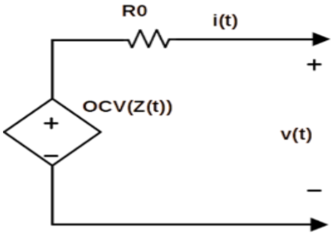


Figure 4. Equivalent circuit resistance model

Mathematical equations governing the model shown in Figure 4 are as follows. For continuous time domain, equation for state of charge is same as (2). Terminal voltage is expressed as,

$$v(t) = OCV\big(z(t)\big) - i(t)R_0 \tag{4}$$
$$v(t) > OCV\big(z(t)\big)\ for\ i(t) < 0\ i.e\ during\ charging$$
$$v(t) < OCV\big(z(t)\big)\ for\ i(t) > 0\ \text{ i.e during discharging}$$

For discrete time domain. Equation for SOC is same as (3), Battery terminal voltage is expressed as,

$$v(k) = OCV\big(z(k)\big) - i(k)R_0 \tag{5}$$

Any change in the terminal voltage with respect to open circuit voltage due to current flowing in the battery cell is termed as polarization [18]. In the model discussed above as shown in Figure 4, polarization effect is modelled as voltage drop taking place across the equivalent circuit resistor Ro. In a battery cell the polarization effect is different from this. This develops slowly with time when current is demanded from the battery cell. The polarization voltage decays when the battery is at rest. This slowly changing voltage due to polarization effect is called diffusion voltage. The diffusion voltage is modelled by connecting one or more resistor capacitor parallel sub circuits in series with the equivalent series resistor. Figure 5 shows the equivalent circuit including the effect of diffusion voltage. The state of charge equation is same as represented in (2) and (3). The terminal voltage equations for continuous and discrete domain are as expressed in (6) and (7).

$$v(t) = OCV\big(z(t)\big) - R_1 i_{R_1}(t) - R_0\, i(t) \tag{6}$$

$$v(k) = OCV\big(z(k)\big) - R_1 i_{R_1}(k) - R_0\, i(k) \tag{7}$$

To represent the diffusion voltage more accurately the number of parallel RC branches could be increased [19]. As the number of RC branches increases, the model becomes complex. Considering these two contradictory factors an optimal number of RC branches are selected. In most of the applications 2 RC equivalent circuit is used. Figure 6 shows the equivalent circuit, representing the diffusion voltage more effectively by two parallel RC branches [20].

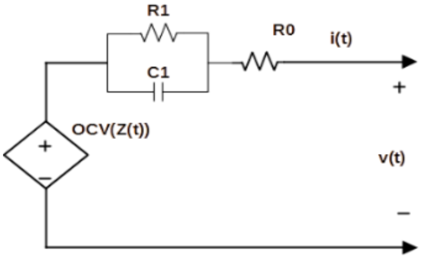


Figure 5. One RC equivalent circuit

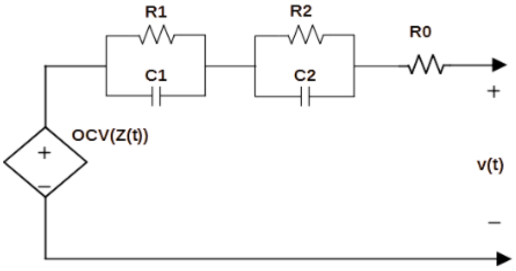


Figure 6. Two RC equivalent circuit

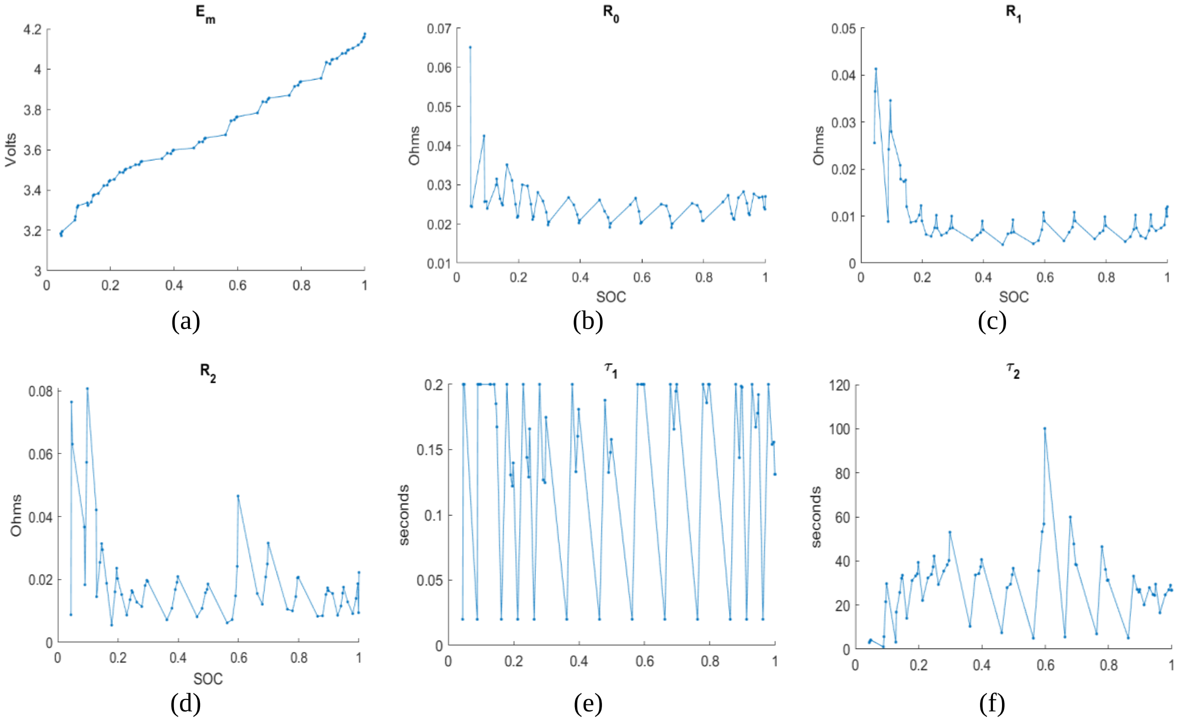
2.2. Determination of equivalent circuit parameters of lithium-ion battery

We are making use of two RC equivalent circuit to model battery behavior. It mainly consists of SOC dependent voltage source named as OCV, equivalent series resistance (R0), two parallel resistors and capacitor blocks to represent diffusion voltage. Two RC equivalent circuit model is implemented in MATLAB Simulink. Input to the battery model is a current controlled current source and outputs are terminal voltages and state of charge values.

As the equivalent circuit parameters are functions of state of charge [21]–[24] the range of the SOC and equivalent circuit parameters need to be broken down depending on the number of charging and discharging cycles performed in HPPC test [21]. To estimate the parameters of a Lithium-ion battery, it is essential that a HPPC test is conducted on the same battery at different charging and discharging rates. After every charging or discharging pulse in HPPC test, relaxation is provided so that terminal voltage at the end of relaxation period is considered as OCV [25]–[27]. In other standard drive cycles like LA92, HWFET, UDDS etc., the information of OCV cannot be derived since we cannot have regular relaxations when the battery supplying to load. Hence, we have used HPPC test data for parameter estimation.

A HPPC test was conducted on a brand-new Panasonic battery, 18650PF with a rating of 2.9 Ah and 4.2 V by Kollmeyer at the University of Wisconsin-Madison and this data is available open source [17]. The five-pulse discharge HPPC test was conducted at different discharge C-rates such as 0.5C, 1C, 2C, 4C and 6C for different state of charge levels. From this HPPC test, we made use of data with respect to input current impulse, output terminal voltage, temperature, Ampere-hour, time stamping. HPPC test conducted for a chamber temperature of zero degree Celsius has 54 pulses and SOC and equivalent circuit parameters have been divided into 55 breakpoints. The range of SOC is from zero to one. SOC and other circuit parameters range is divided into 54 equal intervals.

In this work an application by name parameter estimation, available in MATLAB as shown in Figure 1(b), is used to estimate the equivalent circuit parameters of the battery. Initial values and range of the parameters to be estimated are defined. During parameter estimation as indicated in Figure 1(a), showing the flowchart of parameter estimation, output of the two RC equivalent circuit model terminal voltage is compared with the terminal voltage observed during the HPPC test for a given charge or discharge current pulse, Terminal voltage value from the simulation is not same as terminal voltage of HPPC test. This is since the initial values of the equivalent circuit parameters are not actual equivalent circuit parameters. The difference between simulation terminal voltage and terminal voltage from HPPC test data is used to tune the equivalent circuit parameters of the two RC models. Cost function used is sum-squared error. After several iterations of updating the equivalent circuit parameters, terminal voltage error reduces. If the error cost function value comes below the permissible limit set, then parameters estimation stops. Figure 7 shows equivalent circuit parameters vs SOC at 25 degrees Celsius. Figures 7(a) to 7(f) show the plot of open circuit voltage, R0, R1, R2, τ1 and τ2 for the SOC varying from 0 to 1 for the chamber temperatures of +25 degrees Celsius. Where τ is a multiple of resistance and capacitance. We have estimated the parameters of the Panasonic 18650 PF 2.9 Ah 4.2 V battery using the above approach using the HPPC test results available for different chamber temperature such as -20-degree, -10-degree, 0-degree, 10-degree, 25-degrees Celsius [17]. When the simulation stops equivalent circuit parameters, SOC, Ro, R1, R2, τ1 and τ2 are saved in MATLAB workspace. The objective of the work is to understand the effect of temperature on equivalent circuit parameters of the battery.



(a) (b) (c)

(d) (e) (f)

Figure 7. Equivalent circuit parameters vs SOC at 25 degrees celsius (a) no-load terminal voltage, (b) terminal resistance (R0), (c) diffusion resistance (R1), (d) diffusion resistance (R2), (e) time constant (τ1), and (f) time constant (τ2)

3. RESULTS AND DISCUSSION

As explained in the method section equivalent circuit parameters for wide temperature ranging from -20 degree Celsius to 25 degree Celsius at different SOCs 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% and 100% are noted down and tabulated in Tables 1 to 5. Table 1 shows the values of internal resistance R0, for different temperatures and SOC levels. It could be noticed that for a given SOC level the resistance decreases with an increase in temperature. At 100% SOC Ro value at minus 20 degree celsius is 0.05897444 Ω and at 25 degree celsius its value is 0.027014 Ω which is 45% of it is value at minus 20 degree celsius.

Table 2 shows Parallel branch-1 diffusion resistance R1, for different temperatures and SOC levels. It could be noticed that for a given SOC level the resistance decreases with an increase in temperature. At 100% SOC R1 value at minus 20 degree celsius is 0.252649 Ω and at 25 degrees celsius it is value is 0.011998 Ω which is 4.7 % of it is value at minus 20 degree celsius.

Table 3 shows Parallel branch-2 diffusion resistance R2, for different temperatures and SOC levels. It could be noticed that for a given SOC level the resistance decreases with an increase in temperature. At 100% SOC R2 value at minus 20 degree celsius is 0.499083 Ω and at 25 degrees celsius it is value is 0.022213 Ω which is 4.45 % of it is value at minus 20 degree celsius.

Table 1. R0 For different temperature and SOC

SOC	-20 Degree	-10 Degree	0 Degree	10 Degree	25 Degree
100	0.0590	0.0409	0.0438	0.0406	0.0270
90	0.0691	0.0560	0.0426	0.0302	0.0211
80	0.0703	0.0551	0.0388	0.0283	0.0208
70	0.0688	0.0528	0.0379	0.0274	0.0201
60	0.0716	0.0546	0.0364	0.0278	0.0204
50	0.0716	0.0532	0.0386	0.0270	0.0202
40	0.0719	0.0538	0.0401	0.0275	0.0209
30	0.0707	0.0521	0.0379	0.0292	0.0205
20		0.0518	0.0383	0.0303	0.0220

Table 2. R1 for different temperature and SOC

SOC	-20 Degree	-10 Degree	0 Degree	10 Degree	25 Degree
100	0.4991	0.1440	0.0497	0.0587	0.0222
90	0.1265	0.0793	0.0377	0.0298	0.0164
80	0.1384	0.0950	0.0564	0.0381	0.0207
70	0.1509	0.0697	0.0593	0.0495	0.0316
60	0.1488	0.0616	0.0559	0.0441	0.0465
50	0.1413	0.0806	0.0451	0.0321	0.0186
40	0.0724	0.0856	0.0448	0.0233	0.0209
30	0.1173	0.1213	0.0520	0.0332	0.0194
20		0.1916	0.0588	0.0579	0.0203

Table 3. R2 For different temperature and SOC

SOC	-20 Degree	-10 Degree	0 Degree	10 Degree	25 Degree
100	0.4991	0.1440	0.0497	0.0587	0.0222
90	0.1265	0.0793	0.0377	0.0298	0.0164
80	0.1384	0.0950	0.0564	0.0381	0.0207
70	0.1509	0.0697	0.0593	0.0495	0.0316
60	0.1488	0.0616	0.0559	0.0441	0.0465
50	0.1413	0.0806	0.0451	0.0321	0.0186
40	0.0724	0.0856	0.0448	0.0233	0.0209
30	0.1173	0.1213	0.0520	0.0332	0.0194
20		0.1916	0.0588	0.0579	0.0203

Table 4 shows Parallel branch-1 diffusion capacitance C1, for different temperatures and SOC levels. It could be noticed that for a given SOC level the capacitance increases with an increase in temperature. At 100% SOC C1 value at minus 20 degree celsius is 0.791612 F and at 25 degrees celsius it is value is 10.9254 F which is 13.8 times greater than its value at minus 20 degree celsius.

Table 5 shows Parallel branch-2 diffusion capacitance C2, for different temperatures and SOC levels. It could be noticed that for a given SOC level the capacitance increases with an increase in temperature. At 100% SOC C2 value at minus 20 degree celsius is 23.00274 F and at 25 degrees celsius it is value is 1202.983 F which is 52.29 times greater than its value at minus 20 degree celsius.

Table 4. C1 For different temperature and SOC

SOC	-20 Degree	-10 Degree	0 Degree	10 Degree	25 Degree
100	0.7916	1.0989	1.8011	4.0247	10.9254
90	2.1102	3.1879	5.9059	10.4728	26.4233
80	2.5039	4.2748	7.3261	14.5697	25.1078
70	2.5943	5.1563	7.8429	14.1518	22.3246
60	2.5716	5.6447	6.9984	17.0765	22.3333
50	2.5492	5.4635	7.4655	12.2675	23.8342
40	2.3538	4.1694	7.7753	13.7024	25.4510
30	2.0227	3.2761	6.8602	12.2015	23.2396
20		2.5013	3.5589	7.3975	15.5530

In Tables 1 to 5, cells corresponding to -20 degree celsius and 20% SOC are blank since in -20 degree celsius HPPC test was not performed at 20% SOC. While estimating the SOC of any lithium-ion battery during it is operation, using extended Kalman filter or any similar estimation method, equivalent circuit parameters for the entire range of SOC and operating temperature are required. It could be observed from Tables 1 to 5 that there is large change in the battery parameters, especially at low temperatures. Even though HPPC tests and parameter estimation process are time consuming, these play an important role in SOC estimation.

Table 5. C2 For different temperature and SOC

SOC	-20 Degree	-10 Degree	0 Degree	10 Degree	25 Degree
100	23.0027	34.6550	79.2340	684.0839	1202.9830
90	184.2341	401.8412	986.3841	1103.7880	1644.0580
80	306.2986	834.6045	799.3554	924.8798	1511.1540
70	347.4454	943.1140	1677.0860	959.2829	1209.4480
60	400.7212	1269.1130	1070.6460	1528.7060	2151.5470
50	312.6745	997.9258	1313.5460	1424.6850	1977.6650
40	85.4718	991.9034	1505.0610	2279.4150	1941.3870
30	48.8230	267.6034	1702.2780	2090.4370	2736.3170
20		39.3184	59.4807	635.9643	1937.1630

Even though parameter estimation of Lithium-ion batteries is found in the literature [3], [19], [20], [22], [24]–[27] comparison of battery parameters for a wide range of temperatures is not much focused. To make the product globally acceptable, for all temperatures, manufacturers of the lithium-ion battery are required to furnish the details of their battery equivalent circuit parameters so that SOC estimation will be accurate and makes the applications powered by these batteries like electric vehicles will be reliable and safe.

4. CONCLUSION

In this work we have estimated two RC equivalent circuit parameters of Panasonic 18650 PF 2.9 Ah 4.2 V battery at different temperatures like -20, -10, 0, 10 and 25 degrees Celsius. In the process, we could analyze the impact of temperature on equivalent circuit parameters for a given SOC level. It is observed from the estimated parameters that resistances of the equivalent circuit, R0, R1, and R2 decrease with increase in temperature and capacitances C1 and C2 increase with rise in the temperature. This information of equivalent circuit parameters is very crucial in SOC estimation of the battery. The outcome of the work will emphasis the need of equivalent circuit parameters for wide range of temperature. Since some of the parameters as mentioned in the discussion part, for example the values of capacitors do even change by the order of 50 times. Non availability of this information will make the SOC estimation poor and due to its nature battery becomes unsafe and non-reliable for use. On the other hand, complete battery parameter information will make the product globally acceptable, reliable and safe.

ACKNOWLEDGEMENTS

The authors would like to thank Dr. Suryanarayana K., Professor and Head Department of Electrical and Electronics Engineering, NMAMIT, Nitte and Ms. Spoorthy Shetty, Project Manager, L&T Technology Services, Bangaluru for providing the opportunity to carry out the work in Battery Management project and providing timely and valuable suggestions.

REFERENCES

[1] C. N. Van and T. N. Vinh, “State of charge estimation for lithium-ion batteries connected in series using two sigma point Kalman filters,” *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 12, no. 2, pp. 1334–1349, Apr. 2022, doi: 10.11591/ijece.v12i2.pp1334-1349.

[2] A. El Maliki, K. Anoune, A. Benlafkih, and A. Hadjoudja, “Estimating the state of charge of lithium-ion batteries using different noise inputs,” *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 15, no. 1, pp. 8–18, Mar. 2024, doi: 10.11591/ijpeds.v15.i1.pp8-18.

[3] N. K. Trung and N. Thi Diep, “Online parameter identification for equivalent circuit model of lithium-ion battery,” *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 31, no. 1, pp. 151–159, Jul. 2023, doi: 10.11591/ijeecs.v31.i1.pp151-159.

[4] M. Nizam and M. R. A. Putra, “Analysis of lithium-ion indirect liquid cooling battery thermal management system with high discharge rate,” *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 14, no. 3, pp. 1414–1420, Sep. 2023, doi: 10.11591/ijpeds.v14.i3.pp1414-1420.

[5] I. Chaoufi, O. Abdelkhalek, and B. Gasbaoui, “State of charge estimation of lithium-ion batteries using adaptive neuro fuzzy inference system,” *IAES International Journal of Artificial Intelligence (IJ-AI)*, vol. 11, no. 2, pp. 473–484, Jun. 2022, doi: 10.11591/ijai.v11.i2.pp473-484.

[6] J. Khalfi, N. Boumaaz, A. Soulmani, and E. M. Laadissi, “An electric circuit model for a lithium-ion battery cell based on automotive drive cycles measurements,” *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 11, no. 4, pp. 2798–2810, Aug. 2021, doi: 10.11591/ijece.v11i4.pp2798-2810.

[7] A. M. Alsabari, M. . Hassan, A. CS, and R. Zafira, “Modeling and validation of lithium-ion battery with initial state of charge estimation,” *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 21, no. 3, pp. 1317–1331, Mar. 2021, doi: 10.11591/ijeecs.v21.i3.pp1317-1331.

[8] A. Mondal, A. Routray, S. Puravankara, and D. Pahari, “On-line parameter identification and state of charge estimation of li-ion battery,” in *2020 IEEE 17th India Council International Conference (INDICON)*, IEEE, Dec. 2020, pp. 1–7. doi: 10.1109/INDICON49873.2020.9342215.

[9] Si Li and Ximing Cheng, “A comparative study on RC models of lithium-ion battery,” in *2014 IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia-Pacific)*, IEEE, Aug. 2014, pp. 1–4. doi: 10.1109/ITEC-AP.2014.6940818.

[10] Y. Zhao, W. Xie, Z. Fang, and S. Liu, “A parameters identification method of the equivalent circuit model of the supercapacitor cell module based on segmentation optimization,” *IEEE Access*, pp. 1–1, 2020, doi: 10.1109/ACCESS.2020.2993285.

[11] Y. Boujoudar, H. Elmoussaoui, and T. Lamhamdi, “Lithium-Ion batteries modeling and state of charge estimation using Artificial Neural Network,” *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 9, no. 5, pp. 3415–3422, Oct. 2019, doi: 10.11591/ijece.v9i5.pp3415-3422.

[12] L. Rimon, K. S. Muhammad, S. I. Sulaiman, and A. Omar, “System protection for lithium-ion batteries management system: a review,” *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 13, no. 3, pp. 1184–1190, Mar. 2019, doi: 10.11591/ijeecs.v13.i3.pp1184-1190.

[13] M. Ben Lazreg, S. Jemmali, B. Manai, and M. Hamouda, “Enhanced EKF and SVSF for state of charge estimation of Li-ion battery in electric vehicle using a fuzzy parameters model,” *IET Electrical Systems in Transportation*, vol. 12, no. 4, pp. 315–329, Dec. 2022, doi: 10.1049/els2.12056.

[14] Q.-Z. Zhang, X.-Y. Wang, and H.-M. Yuan, “Estimation for SOC of Li-ion battery based on two-order RC temperature model,” in *2018 13th IEEE Conference on Industrial Electronics and Applications (ICIEA)*, IEEE, May 2018, pp. 2601–2606. doi: 10.1109/ICIEA.2018.8398150.

[15] F. Khanum, E. Louback, F. Duperly, C. Jenkins, P. J. Kollmeyer, and A. Emadi, “A kalman filter based battery state of charge estimation MATLAB function,” in *2021 IEEE Transportation Electrification Conference & Expo (ITEC)*, IEEE, Jun. 2021, pp. 484–489. doi: 10.1109/ITEC51675.2021.9490163.

[16] S. Jung and A. Tullu, “Characteristics evaluation of 14 battery equivalent circuit models,” *IEEE Access*, vol. 11, pp. 117200–117209, 2023, doi: 10.1109/ACCESS.2023.3325395.

[17] P. Kollmeyer, “Panasonic 18650PF li-ion battery data,” *Mendeley Data*, vol. 1, 2018.

[18] G. L. Plett, *Battery management systems, Volume I: Battery modeling*. 2015.

[19] R. Ahmed *et al.*, “Model-based parameter identification of healthy and aged li-ion batteries for electric vehicle applications,” *SAE International Journal of Alternative Powertrains*, vol. 4, no. 2, pp. 233–247, 2015, doi: 10.4271/2015-01-0252.

[20] W. Zhang, L. Wang, L. Wang, C. Liao, and Y. Zhang, “Joint state-of-charge and state-of-available-power estimation based on the online parameter identification of lithium-ion battery model,” *IEEE Transactions on Industrial Electronics*, vol. 69, no. 4, pp. 3677–3688, 2021, doi: 10.1109/TIE.2021.3073359.

[21] S. Li and X. Cheng, “A comparative study on RC models of lithium-ion battery,” in *2014 IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia-Pacific)*, 2014, pp. 1–4, doi: 10.1109/ITEC-AP.2014.6940818.

[22] Y. Zhao, W. Xie, Z. Fang, and S. Liu, “A parameters identification method of the equivalent circuit model of the supercapacitor cell module based on segmentation optimization,” *IEEE Access*, vol. 8, pp. 92895–92906, 2020, 10.1109/ACCESS.2020.2993285.

[23] K. I. Alsharif *et al.*, “A novel modal representation of battery dynamics,” *IEEE Access*, vol. 10, pp. 16793–16806, 2022, doi: 10.1109/ACCESS.2022.3149617.

[24] H. Karlsen, T. Dong, Z. Yang, and R. Carvalho, “Temperature-dependence in battery management systems for electric vehicles: challenges, criteria, and solutions,” *IEEE Access*, vol. 7, pp. 142203–142213, 2019, doi: 10.1109/ACCESS.2019.2943558.

[25] V. Sangwan, R. Kumar, and A. K. Rathore, “Estimation of model parameters and state-of-charge for battery management system of Li-ion battery in EVs,” in *2017 IEEE Transportation Electrification Conference (ITEC-India)*, IEEE, Dec. 2017, pp. 1–6. doi: 10.1109/ITEC-India.2017.8333889.

[26] F. Rukavina, D. Leko, M. Matijašić, I. Bralić, J. M. Ugalde, and M. Vašak, “Identification of equivalent circuit model parameters for a li-ion battery cell,” in *2023 IEEE 11th International Conference on Systems and Control (ICSC)*, IEEE, Dec. 2023, pp. 671–676. doi: 10.1109/ICSC58660.2023.10449745.

[27] R. Cipin, M. Toman, P. Prochazka, and I. Pazdera, “Identification of li-ion battery model parameters,” in *2019 International Conference on Electrical Drives and Power Electronics (EDPE)*, IEEE, Sep. 2019, pp. 225–229. doi: 10.1109/EDPE.2019.8883926.

BIOGRAPHIES OF AUTHORS

Girisha Joshi a member, EEE working as an Associate Professor in the department of Electrical and Electronics Engineering, NMAMIT Nitte. His teaching and research focus is on power electronics, Motor control and battery management systems. He received his B.E. in Electrical Engineering (2007), M. Tech in Power Electronics (2012) and Ph.D. (2021) from Visvesvaraya Technological University Belagavi. The author has a teaching experience of 16 years and handled subjects like power electronics, analog electronic circuits, transformers and induction motors, DC and synchronous machines, soft computing, smart grid, field theory. He joined as a lecturer in the department of Electrical and Electronics Engineering of St Joseph Engineering College, Vamanjoor in 2007. Presently he is working on projects related to interior permanent magnet synchronous motor (IPMSM) control and battery management system (BMS). He can be contacted at email: girishjoshi85@nitte.edu.in.

Lakshmi Narayana Valluru a Battery Systems Engineer at L&T Technology Services, possesses 3+ years of hands-on experience in Batteries and Battery Management Systems (BMS). His background is master’s in technology (MTech) in power electronics and drives. His specialized skills include battery parameter estimation, encompassing SOC, SOH, and equivalent circuit model (ECM) parameter estimation. His expertise contributes significantly to the advancement of energy storage technologies. He can be contacted at email: valluriveera123@gmail.com.

Amol Prakash Khade a Senior Software Engineer at L&T Technology Services**.** His background in Bachelor of Engineering in Electronics and Telecom. He has 7+ years of experience in Embedded software and product development. He has a specialization in Electric vehicle architecture and different ECU components like BMS, VCU, and Inverter controller. Specialization in automotive battery management system software development and testing. His expertise in algorithm development for SOC, State of Health (SOH) and MATLAB modeling. He can be contacted at email: amolkhade909@gmail.com.