Dynamic Modeling and Simulation Charging and Discharging of a Lithium-Ion Battery

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Abstract

In this paper, the current model allows to predict the battery runtime and I-V performance. Furthermore, the dynamic features of a battery, such as nonlinear Voc (open circuit voltage), charge and discharge current, and transient response time that they have considered in the proposed model. Moreover, this model neglects the effects of cycle number, temperature, and self-discharge. Depending on the experimental data which has acquired from the previous literatures this model has been verified and found that the model is adequate to reflect the real-time behaviors of the Li-ion battery. An accurate and comprehensive electrical battery model has been proposed and implemented in a MATLAB environment.

Index Terms — Battery-modeling, battery storage system, lithium ion battery, modeling and simulation.

I. INTRODUCTION

The basic working principle of a chemical battery [1] is to convert the chemical energy stored inside the battery into electrical energy. Rapid development of portable electronics and the desire to use renewable resources have pushed the battery technologies to a mature level for nickel-metal hydride (NiMH), nickel cadmium (NiCd), polymer Li-ion, and lithium-ion (Li-ion) [2]. However, a limitation arises for such batteries ranges from not to have an adequate energy to meet an accumulative energy demand, as well size and capacity limitations [3]. The lower power dispersion and expanded battery runtime are also major concerns in the design of chemical batteries [4]. The intricate physical and dynamic properties of batteries are difficult to obtain and prohibits an accurate and comprehensive electrical modeling of a battery [1]. Lithium ion batteries possess high energy intensity, long lifetime, low maintenance, and low self-discharge as compared to other batteries. Furthermore, lithium ion batteries highly suitable for applications that require less self-discharge time [5]. Based on the above literature, it can be asserted that further research on lithium-ion batteries is an essence and addressed in this paper. The paper has been presented as follows: the first section provides background information and presents the thevenen-based electrical model of the battery. The proposed model and significance of various model parameters is introduced and explained in the second section. The third section describes and discusses the results obtained from the mathematical equations model. The fourth section compares the results obtained from the modeling with experimental at various operating conditions. Finally, a conclusion is presented to summarize concisely the finding.

II. BACKGROUND

Several models at various levels of complexity have been developed by previous researchers [6] to predict the performance of batteries and identify parameters such as battery runtime, usable capacity, and battery

efficiency. Researchers have developed electromechanical models [7]- [9] to improve physical design parameters of chemical batteries that considers coupled time-variant and partial differential equations

The consequence is obvious as such electromechanical models will increase the simulation time due to the integration of complex numerical algorithms that could result in limited information on the battery. In contrast, a mathematical model can predict the behavior of batteries, such as capacity, efficiency, and runtime of the battery. Moreover, the parameters (voltage and current) contain significant information for system designers to optimize and improve the battery model. The researchers often neglect or assume values that would certainly prohibit proper battery representation as well as impact on performance. Such huge deviation could yield an error in the magnitude of 5–20% error [10], and the impact on the accuracy could be almost (1%–5%). Electrical equivalent models [11]- [13] include voltage source, resistors, and capacitors that are essential to simulate and design the electrical equivalent of battery models. There are several advantages of electrical models, such as easy to handle, less simulation time, performance and others that elevates the performance understanding during study. Thevenin [11]- [14] Based Electrical Model of battery system received most of the attention in previous studies.

III. THEVENIN BASED ELECTRICAL MODEL

The thevenin-based model (at its most basic form is shown in Fig. 1.). It is a combination of charging and discharging resistances, open circuit voltage, and a combination of RC parallel network that can represent and predict transient response of a load as a function of state of charge (SOC). However, the disadvantages are the integral over voltage has been used to obtain state of charge (SOC) to represent the nonlinear open circuit voltage and state of charge (SOC) by using a variable capacitor instead Voc(SOC) [11]. Furthermore, this model has estimated the almost 5% runtime error and around 0.4 volt of error by using current of charging and discharging. Other models describe the relation between Voc (open circuit voltage) and state of charge (SOC). However, they disregard the transient behavior of batteries and lead to failed simulate performance battery circuit simulators. To solve this issue, this considered an obvious disadvantage in these models, by occupying on two RC parallel networks. Nevertheless, a specific state of charge (SOC) and temperature are conditions which need to work. Therefore, the battery runtime predicted by using the Thevenin based model which represents the battery performance in circuit simulation as a clear and accurate description.

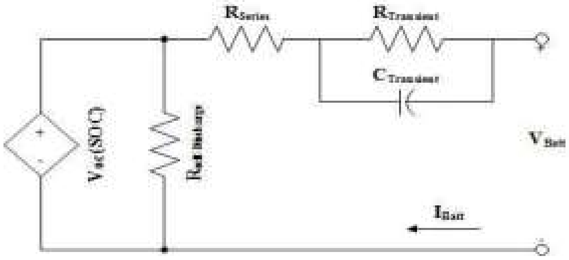

Fig. 1. Thevenin Based Electric Model.

IV. BATTERY SYSTEM MODELING

A. LITHIUM ION BATTERY

Fig. 2 explains the proposed electrical battery model which is more accurate and comprehensive to simulate battery performance. This proposed model, which is like the thevenin based on model [15], integrates two RC networks to simulate transient response, voltage controlled source to simulate the open voltage source related to (SOC) state of charge, and charging resistor and discharging resistor to study the effects of charging and discharging currents on the model the proposed battery model parameters are as follows:

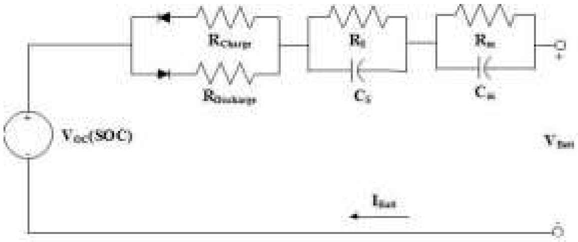

Fig. 2. Proposed electrical battery model

V **battery**	Output voltage [V].
Voc	Battery opens circuit voltage [V].
SOC	State of charge.
SOC**init**	Initial state of charge
C**usable**	Usable capacity that can be diverse with the amount of current
I**battery**	Charging and discharging currents
Rc	Charging resistance battery
Rd	Discharging resistance battery
Rs	Transient resistance on short time
Rm	Transient resistance on Long time
Cs	Transient capacitor on short time
Cm	Transient on capacitor Long time

These components make this model can estimate and accurately predict the steady state and transient response in short and large real time and holding the whole dynamic electrical characteristics of a battery such as:

1- Battery Capacity.
2- Open circuit voltage (VOC).
3- Transient Response of Battery at real time (RC network).

B. BATTERY CAPACITY

Usable battery capacity is the energy which is extracted from the chemical reactions that occur inside a battery. An equivalent series resistor (parallel R charging and R discharging, R transient short time, and R Transient Long time) modeled the usable capacity. The main assumption of the proposal battery model is the equally actual time for charging and discharging of battery and the proposal model ignored (number of cycles, self-discharge, and temperature).

C. OPEN CIRCUIT VOLTAGE (VOC)

The open circuit voltage of a battery is the value of electrical voltage of a battery when the battery does not connect with an external load [16]. The value of change of the open circuit voltage (Voc) is dependent on the state of charge of the battery (SOC). The equation below shows the relationship between Voc and SOC [17].

$$V_{oc}(SOC) = -1.031\times \exp^{-35\times SOC} + 3.685 + 0.2156\times SOC - 0.1178\times SOC^{2} + 0.321\times SOC^{3} \quad (1)$$

Likewise, the state of charge (SOC) to a battery is expressed as,

$$SOC = SOC_{inital} - \int (I_{bat} \div C_{usable})dt \quad (2)$$

Where,

Ibat is charging and discharging currents Cusable is usable capacity that vary with the amount of current. SOC (state of charge) initial value is specified by setting the value of SOC as 100% at fully charged and 0% at fully discharged.

D. INTERNAL IMPEDANCE

The equivalent impedance of a battery consists of battery internal resistance charging, which is used when a battery is charging, battery internal resistance discharging, which is used when a battery is discharging, and two RC networks formed from R transient short time, R transient Long time, C transient short time, and C Transient Long time. As shown in Fig. 3.

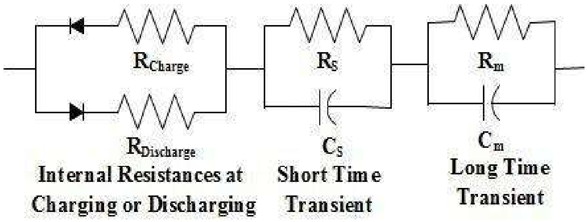

Fig. 3. The internal impedance of proposed battery model

The instantaneous drop of voltage in the terminal voltage of a battery is caused by R charging resistance battery or R discharging resistance battery. This study assumes that this immediate voltage drops can be related to the internal Ohmic resistance of the battery and values of charging and discharging resistors are not constant with a variety of charging and discharging currents. The values of charging and discharging resistors are estimated by using the curve below, as Fig.

4. This curve describes the battery charging voltage, open circuit voltage (Voc), and battery discharging voltage for battery cell at I=33A [18]. On this curve, figure 4 the charging and discharging current is the same at about 33A. These resistances (for charging and discharging) can be calculated at several of (SOC), based on the following equations,

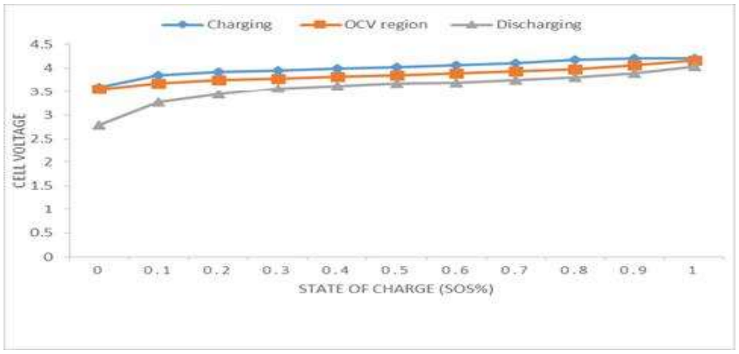

Fig. 4. Cell voltage as a function of (SOC)

1. Internal Charging Resistance

$$\boldsymbol{Rc(SOC) = (V(t)_{Charging} - V_{oc}) / I} \qquad \textbf{(3)}$$

as shown in figure 5

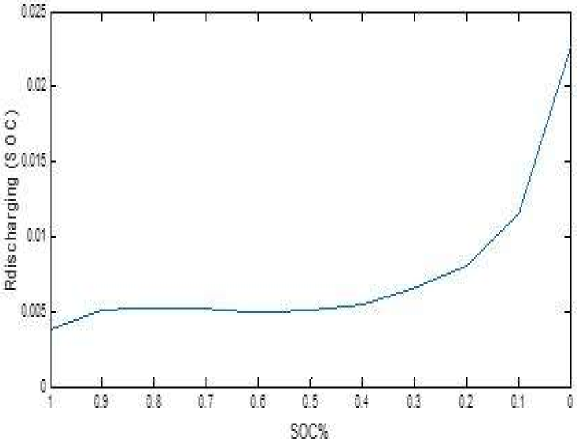

Fig.5.Charging resistance as a function of (SOC)

2. Internal Discharging Resistance

$$Rd(SOC) = (V_{oc} - V(t)_{Discharging}) / I \qquad (4)$$

As shown in Fig. 6.

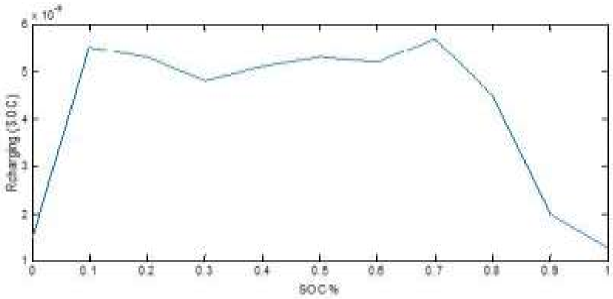

Fig. 6. Discharging resistance as a function of (SOC)

3. RC Transient Response

Fig. 7 illustrates the battery voltage response, which is shown on the short and long term. The transient response curve generally includes immediate drops of voltage. Also, its curve is dependent on voltage drops [15], which occur at a step load current.

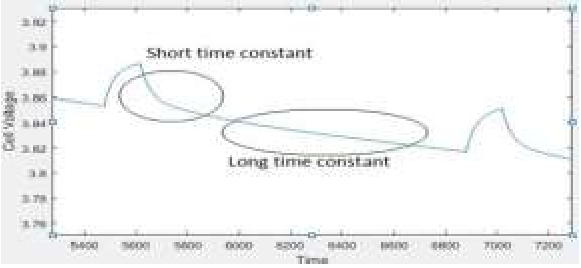

Fig. 7 Transient Response to a step load current event

Thus, as shown in Fig. 8. the RC network, which includes Rs is transient resistance on a short time, Rm is transient resistance on a Long time, Cs is transient on capacitor at a short time, and Cm is transient on capacitor at a Long time, characterize the transient response. Recent research on batteries have applied the two RC networks instead the one or three RC network because the RC network keeps errors to a rate of about 1mV for all battery curves. The following equations describe behaviors of transients on short and long time. Fig. 8. describes the characteristic parameters of transients on short time.

$$I_{battery} = I_R + I_C \qquad (5)$$

$$V_{Rs} = V_{Cs} = V_s \qquad (6)$$

$$I_{battery} = \underline{V_s} + C_s\,\underline{dV_s} \qquad (7)$$

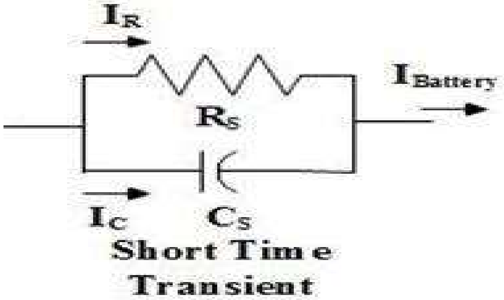

Fig. 8. Characteristic parameters of transient on short time

So, the behaviors of short and long time respectively as shown in Fig. 9.

$$V_s = \frac{dV}{dt} = \frac{I_{battery}}{C_s} - \frac{V}{C_s R_s} \qquad (8)$$

$$V_m = \frac{dV}{dt} = \frac{I_{battery}}{C_m} - \frac{V}{C_m R_m} \qquad (9)$$

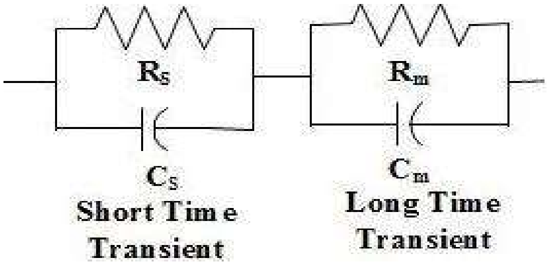

Fig. 9. RC network

The equations below help to calculate the values of transient response components Rs, Cs, Rm, Cm, which are as functions of state of charge SOC [15].

$$R_s(SOC) = 0.3208\times \exp^{-29.14\times SOC} + 0.04669 \quad (10)$$

$$C_s(SOC) = -752.9 \times \exp^{-13.51\times SOC} + 703.6 \quad (11)$$

$$R_m(SOC) = 6.603\times \exp^{-155.2\times SOC} + 0.04984 \quad (12)$$

$$C_m(SOC) = -6056\times \exp^{-27.12\times SOC} + 4475 \quad (13)$$

For example, Fig. 10. shows the calculated nonlinear battery parameter Voc (open circuit voltage) as a function of the state of charge (SOC) for one cell.

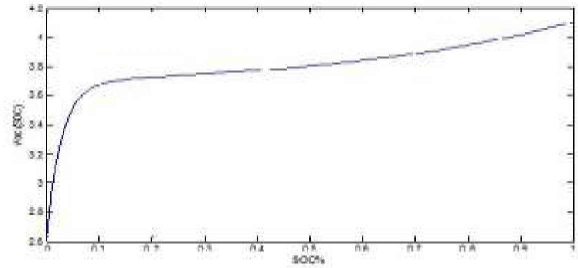

Fig. 10. Voc (open circuit voltage) as a function of SOC

From this curve, the changes on the nonlinear open circuit voltage (Voc) are divided into two parts that are related to SOC. The first section within 0 to 20% shows the change is sharp, which electrochemical reactions are responsible for this clear change. On the other hand, the second section within 20 to 100% shows the change is regularly rising.

V. SIMULATION AND RSULTS

A. at charging case.

The equation below shows the charging state,

$$V_{battery}(t) = V_{oc}(SOC) + V_{ch}(SOC) + V_s(t, SOC) + V_m(t, SOC) \quad (14)$$

Where,

$$V_{ch}(SOC) = I_{charging} \times R_c(SOC) \quad (15)$$

$I_{charging} = 1.25A$

$$V_s(SOC) = I_{charging} \times R_s(SOC) \times \exp^{-t/\tau s} \quad (16)$$

$$\tau s = R_s(SOC) \times C_s(SOC) \quad (17)$$

$$V_m(SOC) = I_{charging} \times R_m(SOC) \times \exp^{-t/\tau m} \quad .(18)$$

$$\tau m = R_m(SOC) \times C_m(SOC) \quad (19)$$

Fig.11 illustrates direction of current in charge situation.

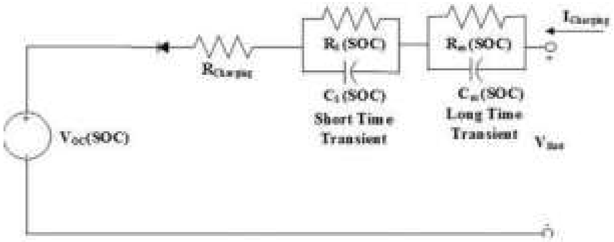

Fig. 11 State of Charging

Fig. 12 clarifies the curve of voltage charging battery as a function of SOC, which begins from 0 to 100 % SOC. Observe that the range between 0 - 10 % SOC rises steeply, regularly increases between 10 - 80 % SOC, and it raises gradually between 80 - 100 %.

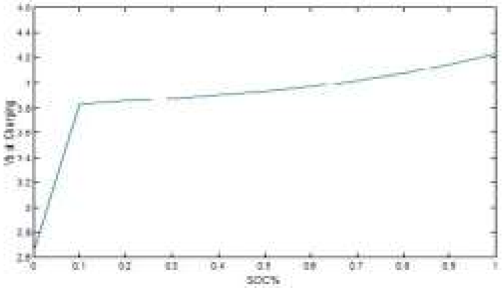

Fig. 12 Charging voltage curve of Lithium ion battery at 1.25A

Figures 13, 14, and 15 show the dynamic model of Lithium ion battery at charging and voltage curves which described the change voltage of lithium ion battery with continuous and pulse current as a function of SOC and time, respectively.

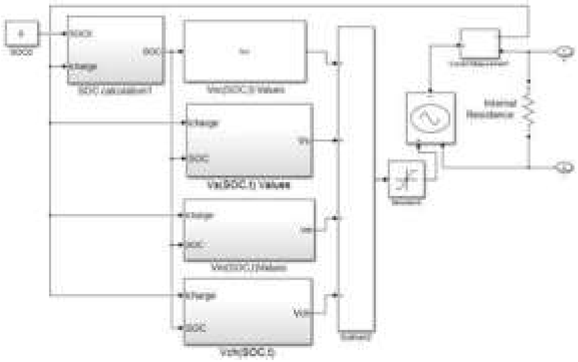

Fig. 13. A dynamic model at charging case

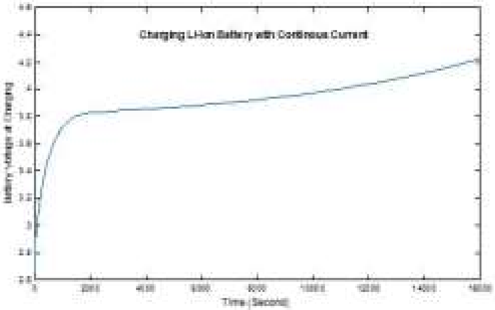

Fig. 14 voltage curve at charging case as a function of (SOC,t)

B. At Discharging Case

The equation below shows the discharging state.

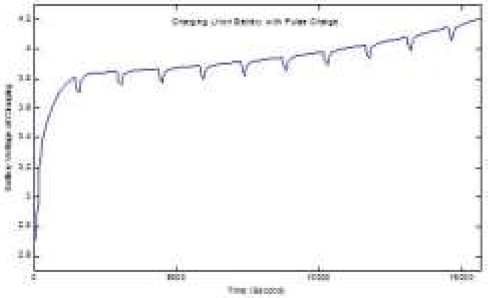

Fig. 15 1.25A pulse charging curve of Li-Ion battery as a function of (SOC,t)

$$V_{battery}(t) = V_{oc}(SOC) - Vd(SOC) - V_s(t, SOC) - V_m(t, SOC) \qquad (20)$$

Where,

$$V_{ch}(SOC) = I_{discharging} \times R_d(SOC) \qquad (21)$$

Fig. 16 illustrates the direction of the current in a discharge situation.

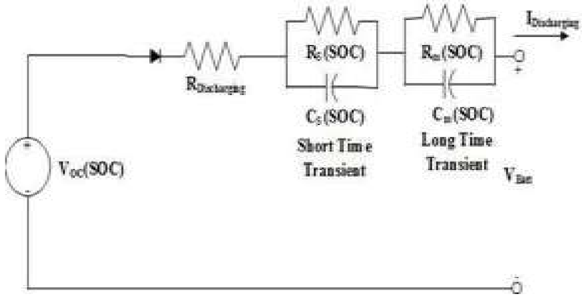

Fig. 16. State of Discharging

Fig. 17 explains the voltage discharging battery as a function of SOC, which starting drop from 100% SOC. Note that the range between 100 - 80 % is changing gradually and regularly decreases between 80 - 10 % SOC. Otherwise, the range between 10 - 0 % SOC steeply discharging.

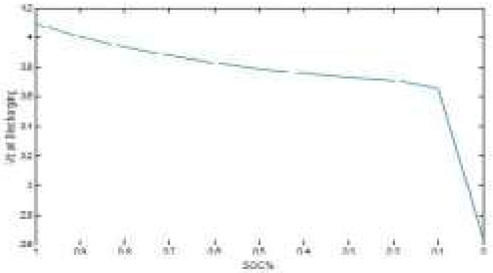

Fig. 17 discharging curve of Lithium ion battery at 0.5A

The dynamic model discharging as shown in figure 18, which illustrates the discharging voltage of battery was beginning from 100% SOC and finished at 0%. Fig 19 and Fig 20 are the curves, which illustrate discharging voltage of battery with continuous and pulse current as a function of SOC, and time, respectively.

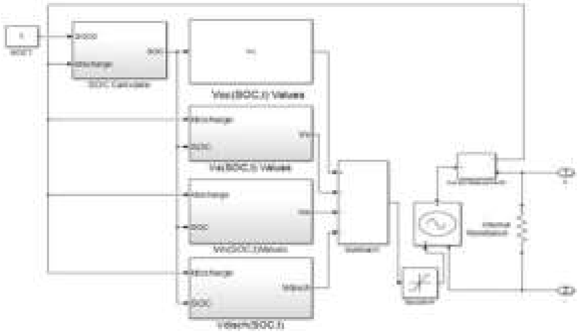

Fig. 18 dynamic model at discharging case

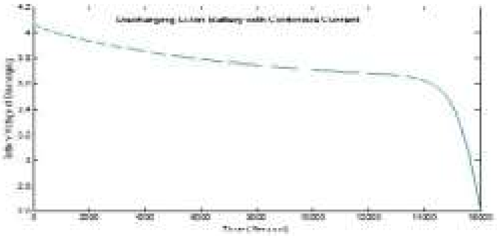

Fig. 19 A voltage curve at discharging case as a function (SOC,t)

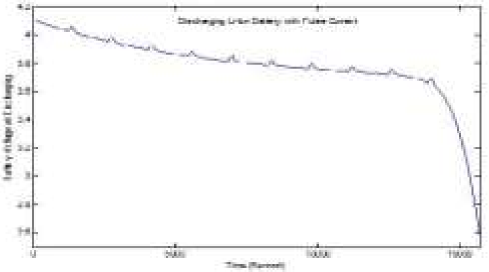

Fig. 20. A 0.5A pulse discharging curve of Li-Ion battery as a function of (SOC, t)

VI. CONCLUSION

This study sheds light on the impacts of charging and discharging resistance as a function of SOC on whole dynamic modeling battery. This work assumed that there is a difference between the charging and discharging resistances. Furthermore, the dynamic model of Lithium ion battery considers the behavior of transients on short and long time. The charging and discharging results display that the developed battery model can describe and identify all dynamic parameters of Lithium ion battery. This model neglected the cycle number, self-discharge, and working on almost constant temperature the rate of voltage error at 10 to 100% SOC was 30mv. In general, this model can offer a great opportunity to designers and researchers who are working in renewable energy, to predict I-V characteristics and add improvements on system efficiency and extend battery runtime.

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