Analysis and Parameter Estimation of Li-ion Batteries, Simulations for Electric Vehicles

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Analysis and Parameter Estimation of Li-ion Batteries Simulations for Electric Vehicles

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Abstract— Electric vehicles are receiving considerable attention because they offer a more efficient and sustainable transportation alternative compared to conventional gasoline powered vehicles. Since the battery pack represents the primary energy storage component in an electric vehicle powertrain, but it requires accurate monitoring and control. In order to effectively estimate the battery pack critical parameters such as the battery state of charge (SOC), state of health (SOH), and remaining capacity, a correct battery model is needed as part of a robust SOC estimation strategy. As the battery degrades due to improper operating condition throughout the battery's lifespan. For effective battery management system design, it is critical that the physical model adapts to the parameter changes due to aging.

There is an effective method for offline battery model parameter estimation at various battery states of health. An equivalent circuit with one voltage source, one resistance in series, and several RC pairs modeled the battery charging and discharging dynamics throughout the lifespan of the battery. The modeling is done by using MATLAB/Simulink. A constant current pulse test is used to extract the model's parameters. The process is useful for creating a high fidelity model capable of predicting electrical current/voltage performance and estimating real-time state of charge.

Keywords- high-power lithium cell; thermal model, electrical equivalent lithium cell model. state of charge, pulse discharge test, energy storage; electric vehicle, hybrid electric vehicle

I. NOMENCLATURE

BMS	battery management system
R_i	internal resistance
R_dC_d	charge transfer and double layer capacity
C_n	capacitor *n*, where *n* is a natural number
C_Q	cell capacity (Ah)
C_T	heat capacitance (J m^{-3} K^{-1})
E_m	electromotive force of main branch
E_p	electromotive force of parasitic branch
ECM	equivalent circuit model
I_m	current in main branch (A)
I_n	current in branch *n*, where *n* is a natural number (A)
I_p	current in parasitic branch (A)
NMC	nickel-manganese-cobalt
OCV	open circuit voltage (V)
ECM	Equivalent circuit modeling
Ps	power dissipated inside the cell (W)
Qe	extracted charge from cell (Ah)
HEVs	hybrid electric vehicles
EVs	electric vehicles
Rn	resistor *n*, where *n* is a natural number (□)
RT	convection resistance (W1 m-2 K-1))
SOC	state of charge
T	inner cell temperature (ºC)
Ta	ambient temperature (ºC)
V	voltage (V)

II. INTRODUCTION

During the last several years, hybrid electric vehicles (HEVs) and battery electric vehicles (EVs) have received considerable attention due to their efficiency and sustainability. Lithium-ion (Li-ion) battery is broadly used as the energy sources in the systems such as portable electronic devices, power systems of aircraft and space and electric vehicle. The widely usage of Li-ion battery is due to its high energy ratio as well as high power ratio compared to lead-acid battery. However, the behavior of Li-ion battery should be predicted in order to optimize the energy usage and extend the battery's life. For example take a systems which include electric vehicles (EVs) and hybrid electric vehicles (HEVs). In both of these applications, we desire estimates of battery state of charge (SOC). Therefore the model of battery is important to let the circuit designer a guide to forecast the behavior of the battery and thus increase the power efficiency of the dynamic characteristics of the cells.

State-of-charge (SOC) is the capacity that remaining in a battery. The state of charge (SOC) of a battery or pack of batteries is analogous to a fuel gauge of a conventional vehicle and it is considered as a key parameter of a battery. For example in electric vehicle, a battery managing system (BMS) with the function of SOC estimation is required in order to let the user to know how long the EV can be used before it stops working. Moreover, since the Li-ion battery can't be overcharged or over-discharged, an accurate SOC estimation is very important to avoid the system from inadvertent battery abuse and thus ensuring safety.

Therefore, the battery modeling is a crucial issue in order to carry out an accurate SOC estimation. Since electrical model or circuit based model is more suitable been applied in electrical system, therefore it is widely been used in battery modeling. A conventional equivalent electrical circuit model consists of a voltage source which represents open circuit voltage (OCV), a series resistor R_i which represents internal resistance, and a R_dC_d pairs which represent the charge transfer and double layer capacity as shown in Fig.1. The value of $OCV_{(SOC)}$ is dependent on SOC.

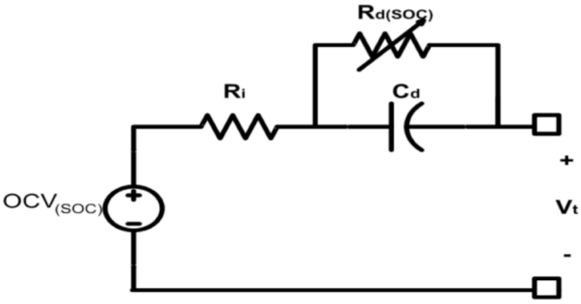


Fig.1. Mathematical model of a battery

Equivalent circuit modeling (ECM) is the most common approach for battery numerical analysis. For lithium cells, a one or two *RC* block model with no parasitic branch is a common choice. It has the advantage of being calculated simple and is easily combined with other methods such as coulomb counting with an OCV / SOC correlation for periodic recalibration during rest.

There are two type of Current tests have been used such as HPPC (Hybrid Pulse Power Characterization) test and pulse current discharge test in order to extract the parameters of the equivalent electrical circuit model. In HPPC test, battery is charged and discharged with a pulse current profile as shows in Fig.2a. On the other hand, pulse current discharge test or sometime called current pulse technique fig.2b. The battery is discharged by a current pulse (for example 1C, 3 minutes). For both current tests, the battery is required to rest for around one hour before the next cycle of current pulse so that to let the battery approaches equilibrium state. The parameters value and $OCV_{(SOC)}$-SOC relationship can be therefore easily obtained from voltage response of battery when the pulse current been applied.

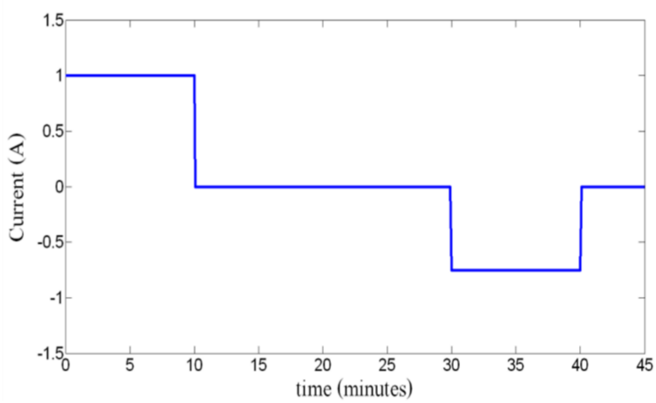


Fig.2a. Current Profile for HPPC Test

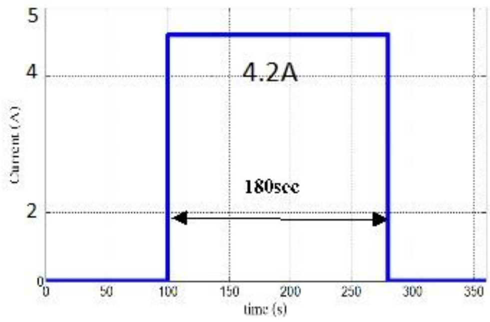


Fig.2b. Current pulse discharge Test

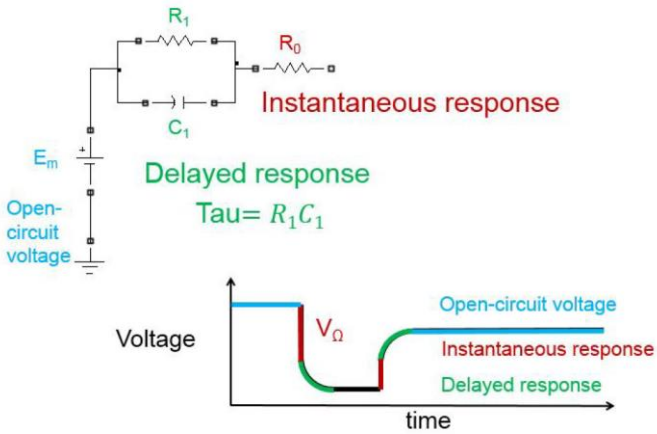


Fig.2c. Schematic illustration of the relationship between observed voltage dynamics and a model equivalent circuit to reproduce those dynamics.

This paper presents a method for developing lithium cell model. A numerical parameter estimation scheme using pulse current discharge tests on high power lithium nickel-manganese-cobalt oxide (NMC) cells under different operating conditions was implemented using MATLAB®, Simulink® and Simscape™.

III. Model Formulation

The parameters of the model can be extracted from the current pulse test. In the constant current pulse test, the battery is discharge with a constant current for a certain period so that the SOC of battery drops to the predicted level. For example, if the battery discharges with 1C for 180s, the SOC of the battery will drops 5%. After that, the battery will keep in rest for an hour to let the battery comes to equilibrium state. The equilibrium state is used to obtain the value of $OCV_{(SOC)}$.

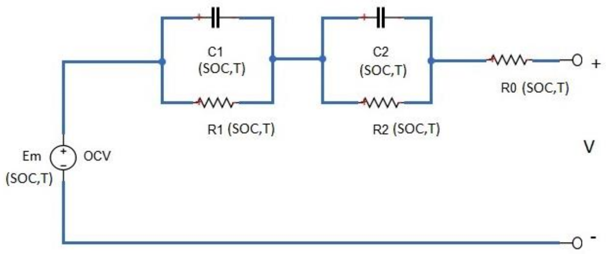


Fig.3. Mathematical model of a Lithium battery with 2RC

Depending on the characteristics of the problem to be analyzed, the number of *RC* blocks typically ranges from one to two, since larger numbers increase the effort and significantly improving model accuracy fig.3.

The estimation techniques can be applied to other equivalent circuit model topologies. The choice of the ECM of fig.3 implied that the fitting procedure involved the estimation of four independent parameters, namely *E*m (OCV), *R*0, *R*1,R2, *C*1 and C2 which vary with temperature and SOC of the cell.

A. Thermal Modeling

The value of the ECM components depends on SOC and inner cell temperature. The inner cell temperature is assumed to be uniform, and taken as the average temperature inside the cell. This cell temperature can be computed by solving the heat equation of a homogeneous body exchanging heat with the environment.

$$C_T \frac{dT}{dt} = -\frac{T - T_a}{R_T} + P_s$$

Applying a Laplace transformation:

$$T(s) = \frac{P_s R_T + T_a}{1 + R_T C_T s}$$

B. Cell capacity and state of charge

The cell capacity depends upon a number of factors, including:

- average cell discharge current and discharge time.
- inner cell temperature.
- value of the end-of-discharge voltage.
- storage time (self-discharge) number of charge-discharge cycles that the cell has undergone (aging)

For short periods of time the average cell discharge current, discharge time, and inner cell temperature.

Hence, cell capacity, $C_Q = C_Q(I,T)$

Assuming the cell to be fully charged at time t=0, the *extracted charge, Qe* is defined as:

$$Q_e(t) = \int_0^t I_m(\tau)d\tau$$

Then, the state of charge (SOC) is:

$$SOC = 1 - Q_e \,/\, C_Q$$

where C_Q is the capacity of the cell at the temperature and discharge current considered. For, any SOC it should consider the conditions under which a cell is discharged and refer to the particular discharge current and temperature under which the SOC has been evaluated.

C. Equivalent circuit model parameter

Each element of the equivalent circuit of fig.3 is a function of SOC and temperature (T).

*R0= R0(*SOC,*T)*
*R1=R1(*SOC,*T)*
*R2=R2(*SOC,*T)*
*C1=C1(*SOC,*T)*
*C2=C2(*SOC,*T)*
*Em= Em(*SOC,*T)*

IV. Modeling and Simulation

Before modeling of ECM I would like to discuss the chemistry of the cell which I choosed for my experiment. Panasonic lithium ion NMC cylindrical type cell of capacity 4.5Ah is used and were tested at ambient temperature 28*C.

The numerical analysis done here consisted of a simulation stage. The ECM was created using Simscape blocks and Simscape language. The drawing shown in fig.4 represented the circuit diagram with a double *RC* block. Each of the circuit elements was a subsystem consisting of custom electrical blocks, and blocks to calculate the properties of the circuit element.

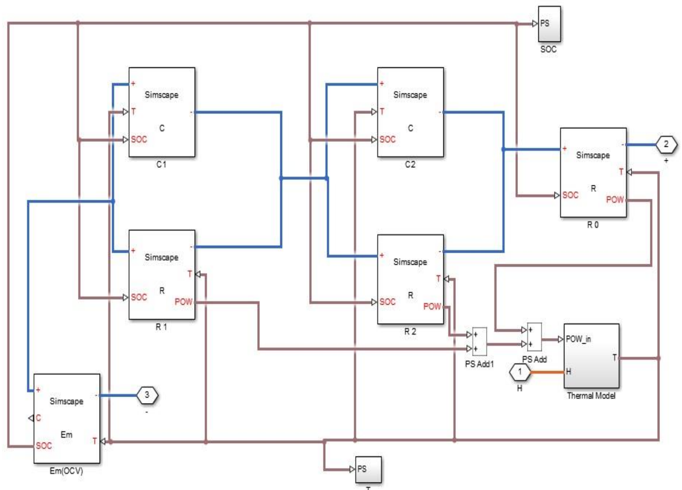


Fig. 3. Simscape Equivalent Circuit with Thermal Model

The resistive circuit elements were modeled as variable resistors, as shown in fig.4. These were modeled based on Ohm's Law, though a minimum resistance value was used to prevent the differential equation solver from entering a bad state during parameter estimation or simulation. The real power of the resistive elements was also calculated for later use in simulation of thermal dynamics. The value of the resistance was provided by a lookup table with one or two inputs of SOC and temperature.

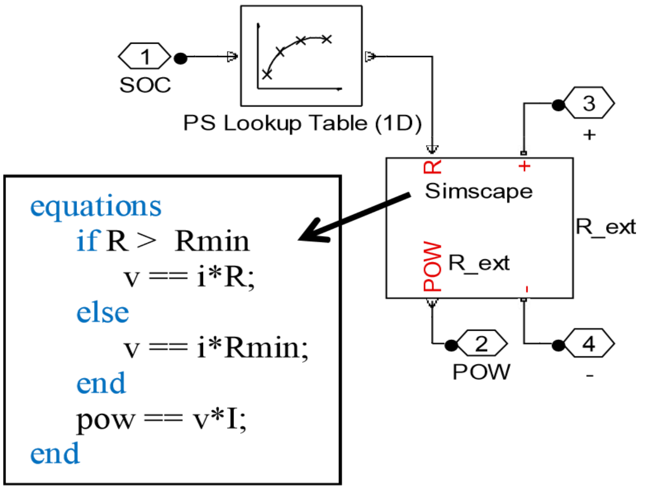


Fig. 4. Resistive Circuit Element and Simscape™ Language Code

The performance of lithium cells varies significantly from cell to cell. The empirical equation approach typically used for lead-acid batteries as in could not be used for lithium chemistry. Lookup tables were chosen for parameterization of the circuit elements for two reasons. One is that lookup tables are very flexible. Second, the pulse discharge technique provides sufficient cell performance information about the open-circuit voltage and *RC* network at each pulse for a numerical optimizer to isolate each parameter and each breakpoint within the lookup tables.

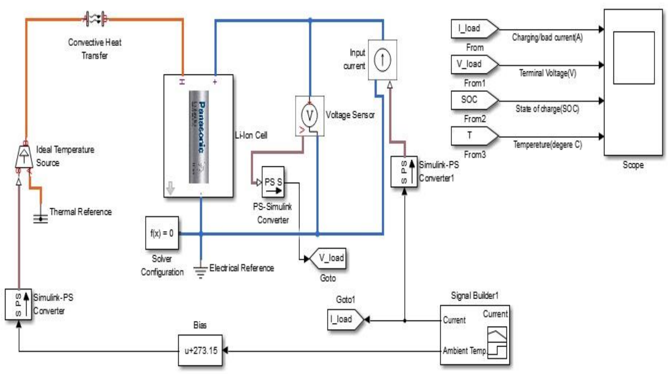


Fig.5. Simulink model of single lithium-ion cell

For parameter estimation, each temperature was considered independently. The lookup tables for each circuit element were chosen to be based on different points of SOC, with SOC breakpoints spaced with a bias slightly toward low and high SOC. More points could have been used, but more breakpoints would have provided a diminishing benefit for two reasons. One was that more parameter values would slow down the parameter estimation. The second was that the discharge pulses of 10% SOC would only provide the parameter estimator with good data near 10% SOC increments. Excessive breakpoints may have led to having too many parameters that were not well exercised in the data, which is a known problem when optimizing unconstrained lookup tables.

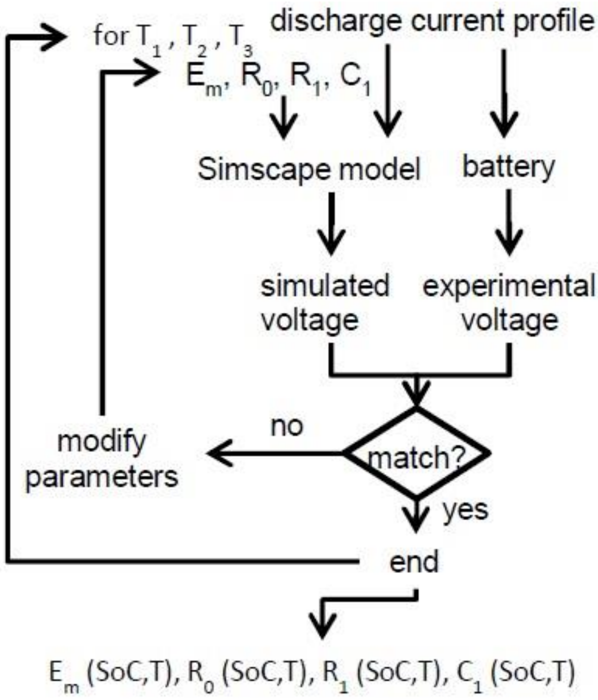


Fig.6. Flow diagram of the parameter estimation procedure

The pulse discharge curve for each temperature was run individually through an estimation task. This produced a set of one-dimensional lookup tables versus SOC for the parameters at different temperature.

V. Simulation Results

After the modeling of equivalent circuit of lithium-ion cell for a single cell, it is simulated for 40000 seconds. The experimental data is imported and applied to the ECM. In Simulink model there is two pack of 10 lithium ion cells connected in series. The Simulink and Simulation results are mentioned and illustrated below in the paper.

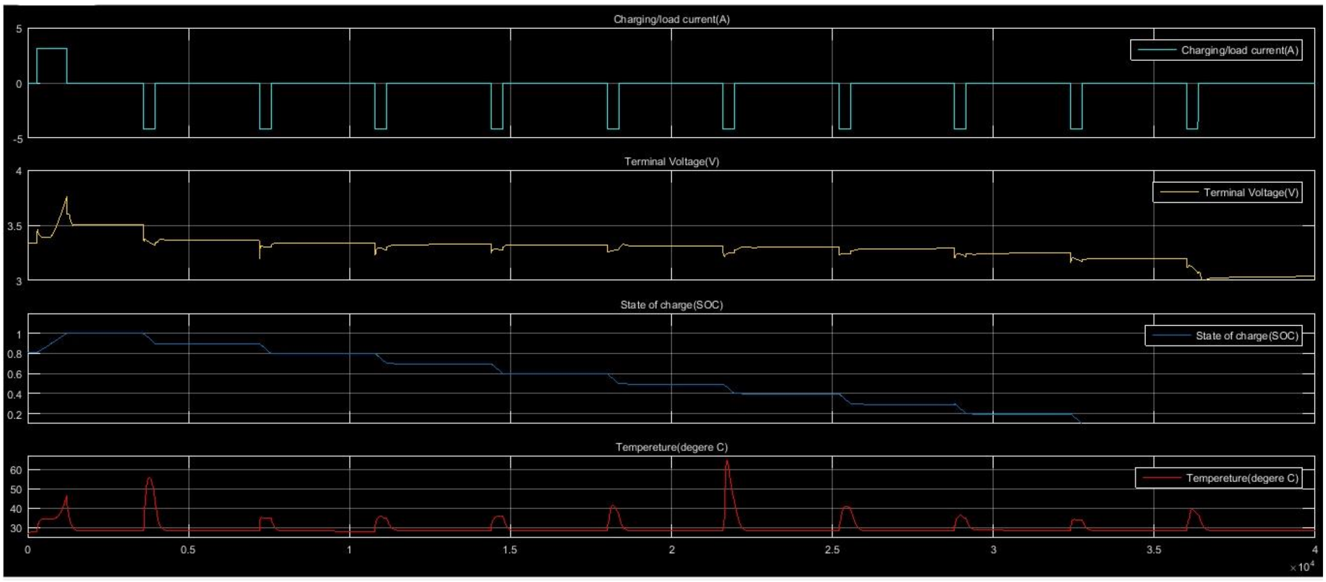


Fig.7. Simulation result for single lithium-ion cell

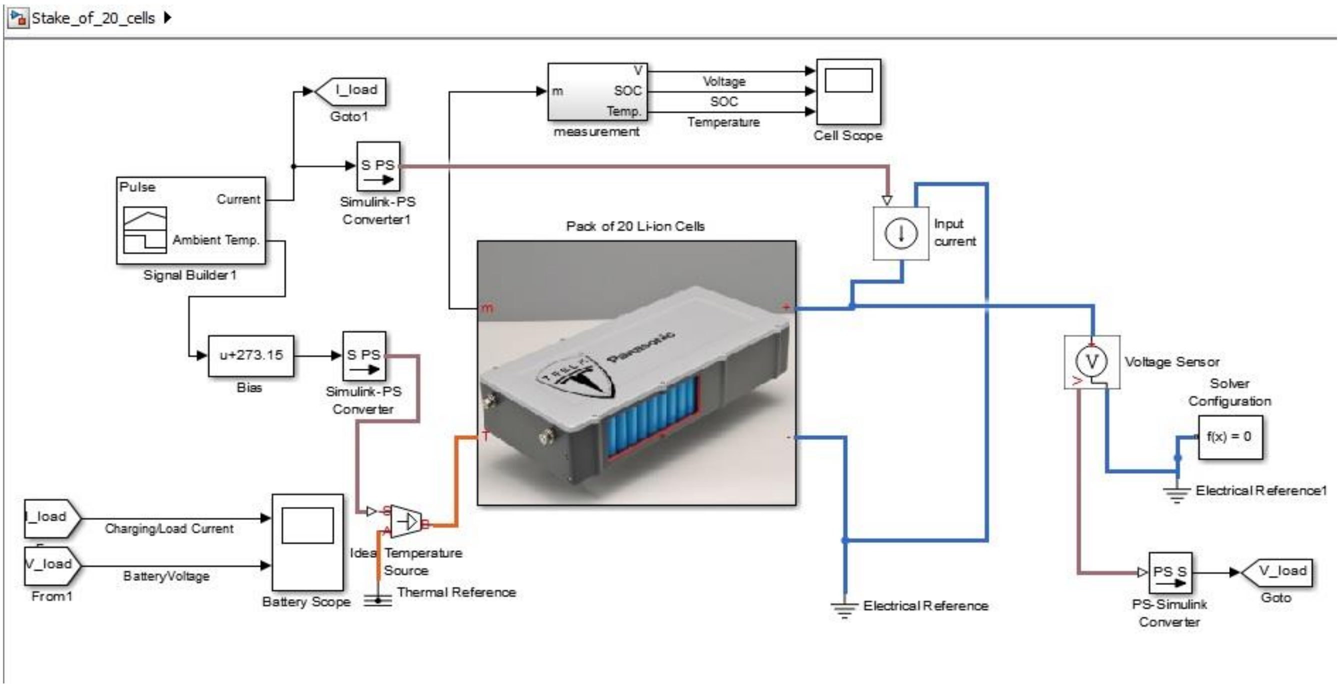
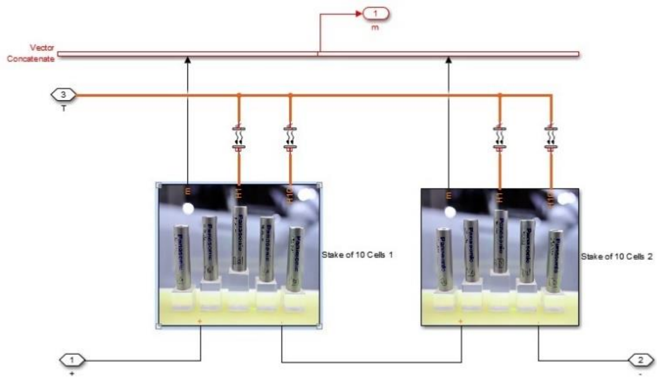
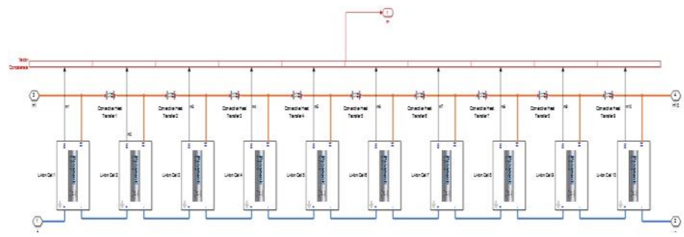
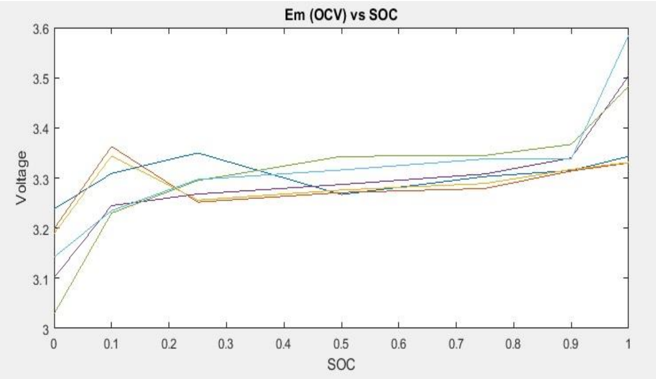
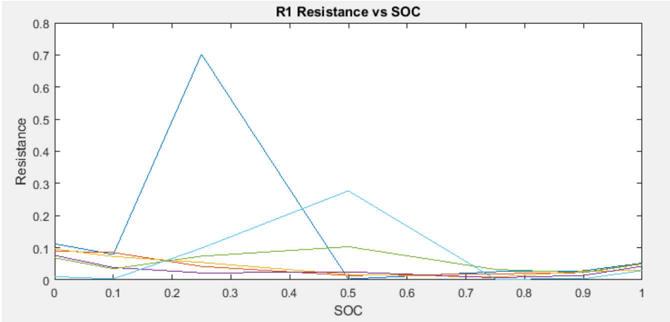


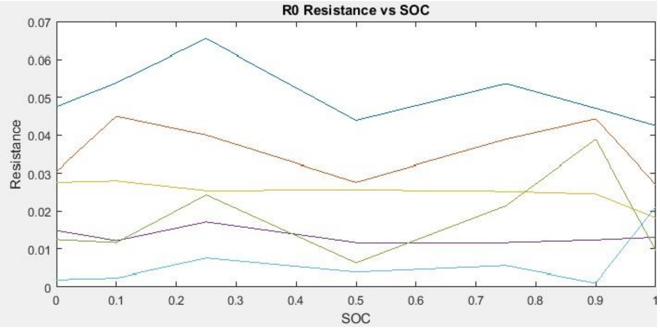
Fig.8. Simulink model of a pack of Lithium-ion cells (20)

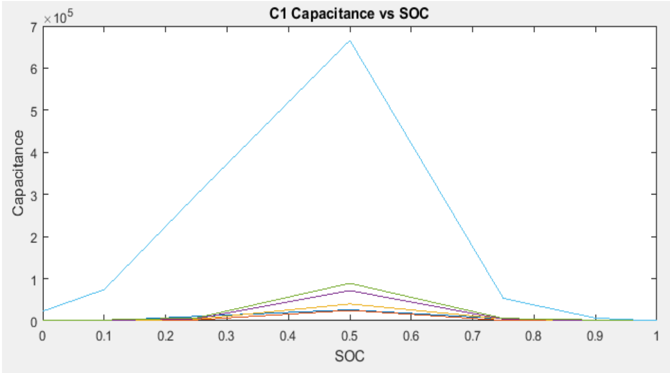


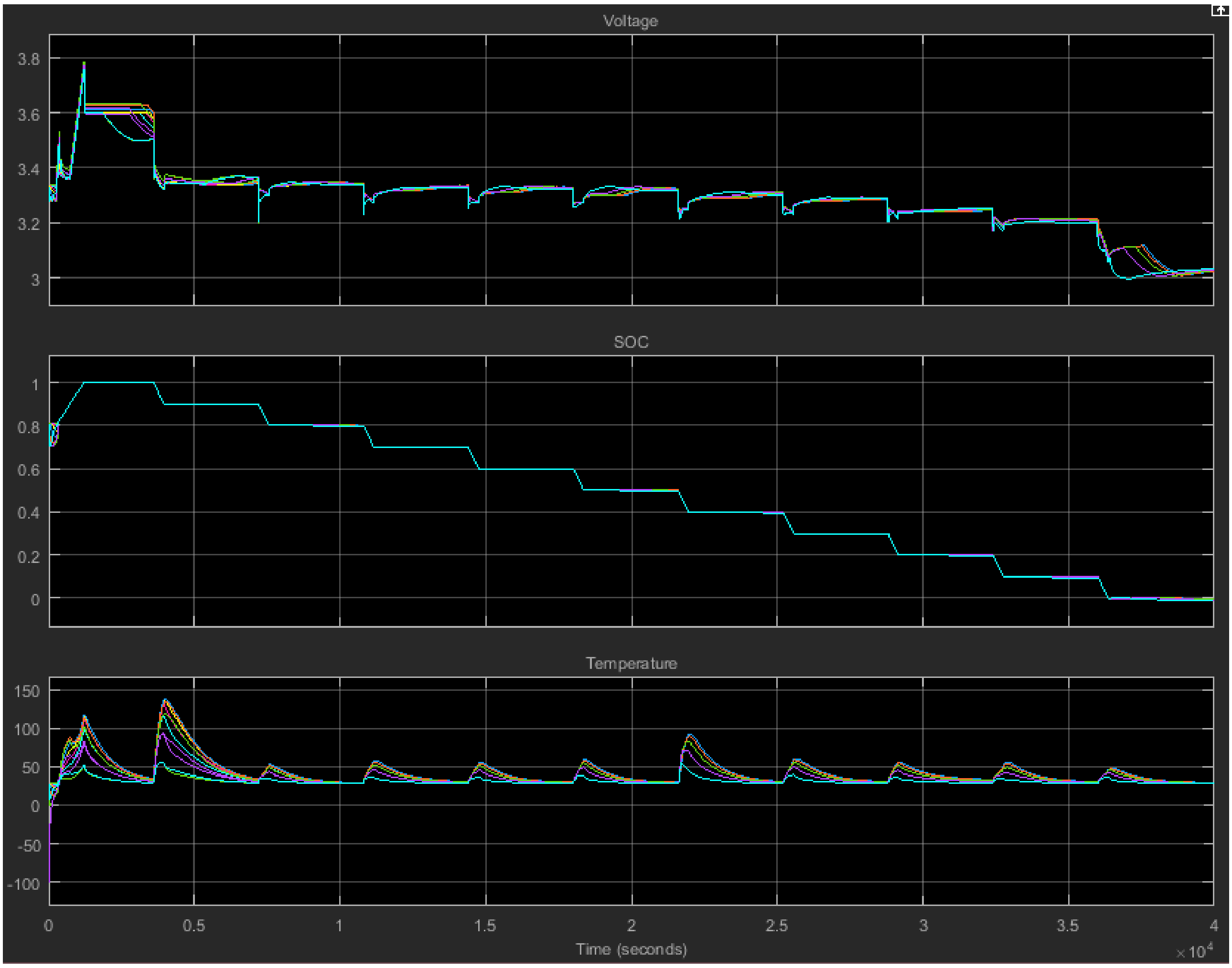



Em (OCV) vs SOC
Voltage
SOC


R1 Resistance vs SOC
Resistance
SOC


R0 Resistance vs SOC
Resistance
SOC


C1 Capacitance vs SOC
Capacitance
SOC


Voltage
SOC
Temperature
Time (seconds)

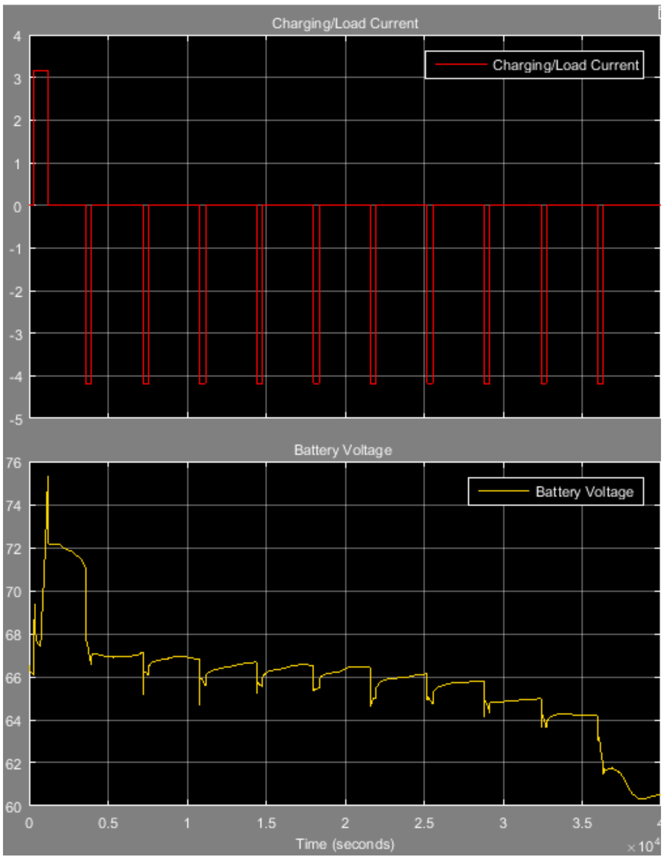


Fig.9. Simulation results for the pack of lithium-ion cells

VI. Conclusion

This paper illustrates a practical method for evaluating the equivalent circuit parameters using pulse discharge experimental data to create lookup tables with cell temperature and SOC as independent variables. A simple single-cell thermal model was also developed in this paper. However, cells are generally combined into cell packs, whose thermal parameters are different from those of single isolated cells.

VII. References

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