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The electro-thermal equivalent circuit modeling and dynamic behaviour analysis of a Li-ion nickel manganese cobalt oxide cell.

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Abstract - This paper presents the modeling of a Li-ion NMC cell on MATLAB and analysis of the model for a particular drive cycle's load current profile. The Thevenin equivalent circuit with one RC branch has been modeled and simulated. The experiment results at three different temperatures were used as LUT(look up tables) to estimate the parameters R0,R1,C1,OCV(Open circuit voltage). The coulomb counting method is employed to estimate the SOC.

Keywords – Cell modeling, SOC(State of charge) , equivalent circuit , thermal model, terminal voltage.

I INTRODUCTION

The electrification of the vehicles and the new electric vehicles are very necessary for the sustainable transportation. The battery pack is the energy house of the EV and the motor draws current from it. Most of the E-vehicles uses Lithium chemistry based batteries/cells because of it's higher specific energy, higher power ratings and more cycle life and discharge rates. Before using the cells or a battery pack for an EV, it is necessary to test the battery pack or an individual cell under different conditions like at different temperatures and SOCs to understand the behaviour of the cell. An electrochemical cell is highly nonlinear system. Modeling the cell on MATLAB-simulink and simulations helps in saving time and carrying out lot more tests. It is possible to simulate the cell model for extreme conditions without any risk but if it was a physical test it would have ended up getting damaged. The main aim of the test is to measure OCV, SOC, Terminal voltage, cell temperature.

II. Equivalent circuit model

There are several ways to model a cell. The cell is highly nonlinear in nature. One of the best methods is the equivalent circuit model. This method has three more types. They are : 1. Internal resistance model. 2. One time constant method (One RC branch) 3. Two constant method (two RC branches).

Internal resistance model:

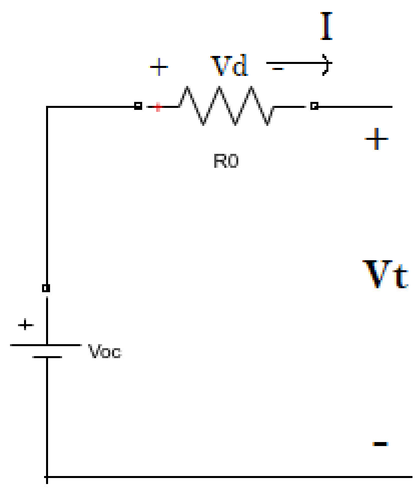

Figure 1 Internal resistance model

The internal resistance model consists of a voltage source and a resistor in series. It is not possible to get the transient behaviour of the cell with this model. This method is not suitable for the SOC estimation.

Discharging case, the current is positive.

Vt = Voc – Vd1. ------(1)

Vt = Voc – IxR0 ------(2)

Charging case, the current is negative.

Vt = Voc +Vd1. -------(3)

Vt = Voc + IxR0 ------(4)

The terminal voltage is equal to open circuit voltage when no load is connected and no current is drawn. When the load is connected across the terminal of the battery the voltage gets reduced due the voltage drop at R0.

One time constant model:

The one time constant model has a RC parallel branch in series with R0. This represents the transient behaviour of the cell.

Discharging case, the current is positive.

Vt = Voc – Vd1 –Vd2. ----- (5)

Vt = Voc – IxR0 – 1/c ∫ic dt ------(6)

Charging case, the current is negative.

Vt = Voc +Vd1 +Vd2. ----- (7)

Vt = Voc + IxR0 + 1/c ∫ic dt ------(8)

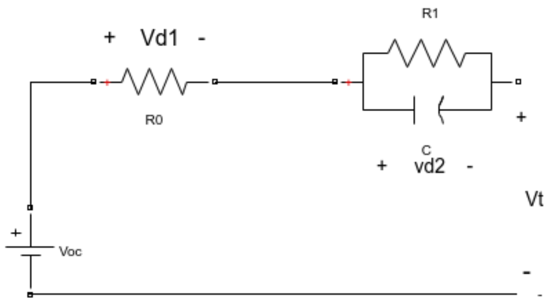

Figure 2 One time constant circuit.

This model is accurate to an extent and computationally lite.
Three time constant model:

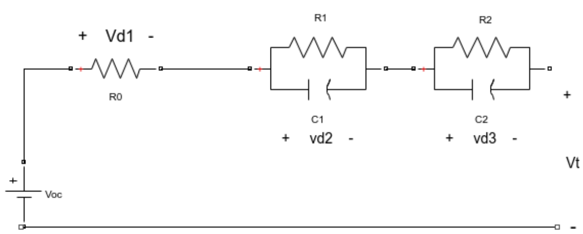

Figure 3 Three time constant cell model

The three time constant model is more accurate and best matches with the physical cell's dynamic behaviour. There are two RC parallel branch in series with the resistors. As the number of RC branches increases the accuracy increases but it will be computationally heavy so it takes more time for the simulation.

III. Experimental data

A cell SLPB120216216 by kokam battery manufacturing company's physical test data is used in the form of 1D and 2D LUTs(Look up table) for the parameter estimation using interpolation technique. The interpolation is a statistical method by which unknown values are estimated using know values. The table 1 contains the SLPB120216216 cell's specification. The cell test and parameter measurement were done at three different temperatures (278.15,293.15,313.15). The figure 4 depicts the cell discharge characteristic. Between t=0 to t=t0 , the Vt(terminal voltage) is constant and that is the no load condition where there is no current drawn from the cell, The Vt is equal to OCV.

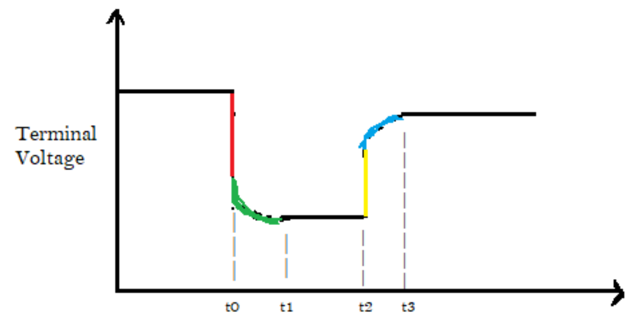

Figure 4 Cell discharge characteristic

At t0, the load is connected, so the load draws current from the cell, the terminal voltage suddenly drops (represented in red color). This is due to the fact that there is a voltage drop across the internal resistance (R0). The terminal voltage starts decreasing exponentially until t1. This transient behaviour can be well modeled using a RC branch in series with the internal resistance. Between t1 & t2 the capacitor c1 is fully charged and reached steady state. When the load is suddenly disconnected, there is sudden rise in terminal voltage that is because when the load is disconnected there is no current drawn from the cell so there is voltage drop across the R0. Since the capacitor takes time to discharge so we have exponential increase in terminal voltage and finally it settles at OCV. The final OCV after t3 is less than at t=0.
Measurement of cell parameters: The pulse discharge and charge techniques are used for the parameter estimation. There are two types of discharges one is short time discharge and the other is long term. The internal ohmic resistance R0 of the cell is calculated during short time discharge because only R0 responds quickly to the load current with sudden voltage drop. The R1 & C1 values are measured during long term discharge because of the capacitor, The voltage across the capacitor increases exponentially and reaches the steady state.

Table 1.Cell specifications

Capacity in mAh	31000
Cell length (m)	0.227
Cell width (m)	0.226
Cell thickness (m)	0.0078
Cell area(m^2)	0.0513
Cell volume (m^3)	4×10^{-3}
Cell mass (kg)	0.720
Cell heat capacity(Cp)- $J\ kg^{-1}\ K^{-1}$	810.5328
Cell volumetric heat capacity - $J\ m^{-3}\ K^{-1}$	2040000;
Convective heat exchange coefficient.- $W/(m^2K)$.	5

IV. Equivalent circuit parameter estimation.

The parameters to be estimated are SOC(State of charge), OCV(Open circuit voltage) , R0(Internal resistance), R1(Dynamic resistance) , C1(Dynamic capacitance), Vt(Terminal voltage), Cell temperature. The 20 degree Celsius ambient temperature is considered.

SOC estimation: There are several methods to estimate the SOC of a cell. The coulomb counting and kalman filter methods are most popular and gives very good estimation of SOC. The coulomb counting method has been used here.

$$\mathbf{SOC(t\text{-}1) = SOC(t) +/- \int \frac{I\,dt}{C \times 3600}} \text{ ------ } \mathbf{(9)}$$

The above formula is used for SOC calculation.

The SOC can also be estimated from the OCV but it is not possible for Li-ion chemistry based cells because of the linear region in the discharge curve. The OCV remains almost constant between 80% to 40% SOC.

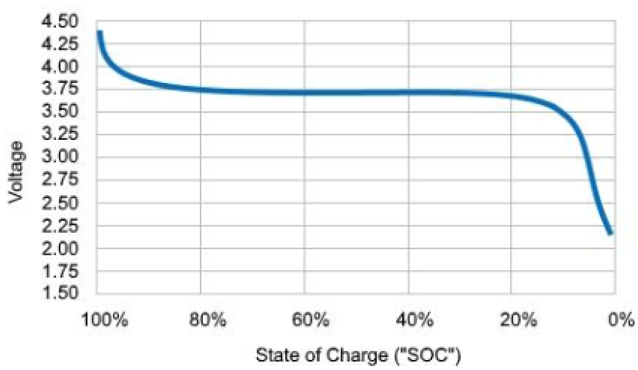

Figure 5 Typical Li-ion discharge curve

The capacity of the cell varies with temperature; the 1D LUT is used to get capacity at different temperatures.

Table 2. 1D LUT Temperature & Capacity

Temperature(K)	**Capacity(C) in Ah**
278.15	28.01
293.15	27.63
313.15	27.64

OCV estimation: The OCV is a function of SOC & Temperature, so the 2D LUT is used. The figure 5 shows the SOC & OCV Simulink model.

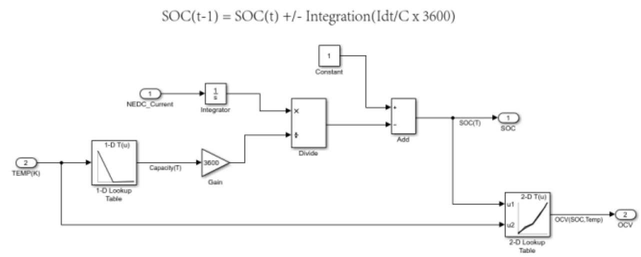

Figure 6 OCV & SOC Model

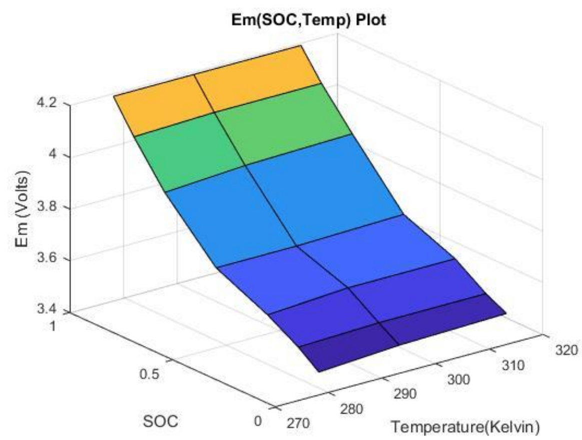

Figure 7 ocv(soc , temp) 2D LUT plot

R0 and P0 estimation: The internal resistance is a function of SOC and temperature. So the R0 values were measured during the physical test for different SOCs & temperatures and used in model as 2D LUT.

P0 = power loss across R0 = I^2 x R0 ---- (10).

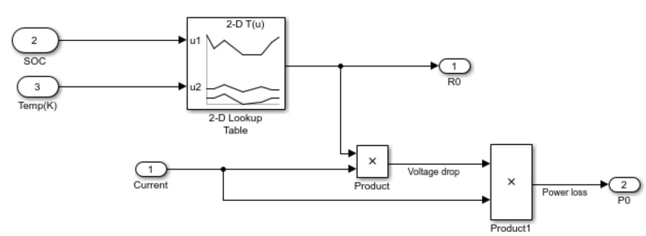

Figure 8 R0 & P0 estimation model

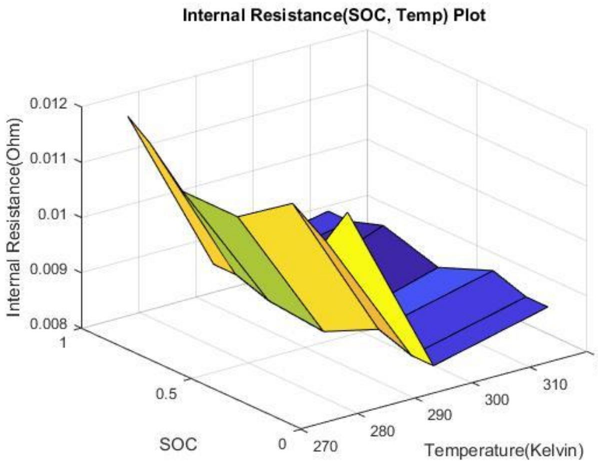

Figure 9 R0 (SOC , Temp) 2D LUT plot

R1 & P1 estimation: The dynamic resistance R1 is estimated using 2D LUT. R1 is a function SOC and temperature. P1 is the power loss across R1. Lets consider I_1 is the current flowing through the resistor R1. It varies with time as the capacitor charges up and at steady state it will be equal to the load current.

$P1 = I_1 \times (I_1 \times R1)$ ---- (11)

$Vd2 = I_1 \times R1$ ---- (12)

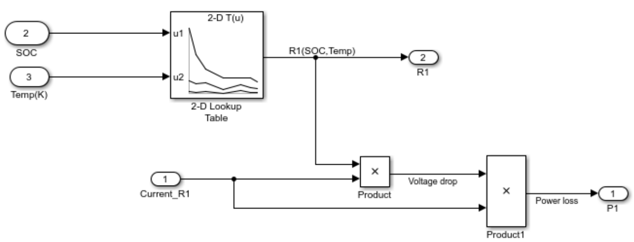

Figure 10 R1 & P1 estimation model

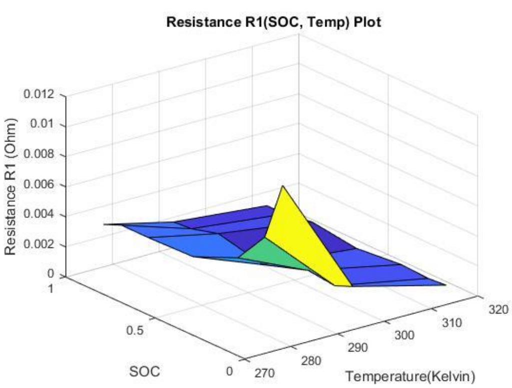

Figure 11 R1(SOC, Temp) plot

Capacitor C1: The cell doesn't have constant capacitance, the capacitor's capacitance varies with Soc and temperature.

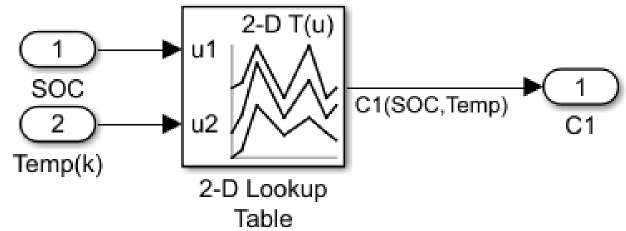

Figure 12 C1 estimation model

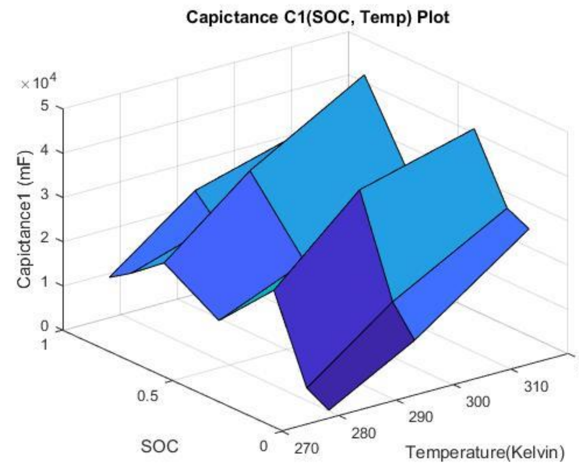

Figure 13 C1 (SOC , Temp) 2D LUT plot

Thermal model of the cell: The cell temperature rises as the load is connected to the cell. The power loss across the internal resistance R0 & R1 is one of the reason for temperature rise. The cell temperature also depends on the surrounding environment temperature. For the simulation purpose 20 degree Celsius constant external temperature is considered and this is also the initial temperature.
The below equations are used to estimate the cell temperature.

C_T x dT/dt = (Tamb - T) x R_t + P_Loss --- (13)

P_Loss = P1 + P2 ---- (14)

R_t = h_conv(w/m^2-k) x Cell area ---(14)

C_T = 1/(cell_Cp_heat x cell_mass)

Units for C_T - J/kg-k.

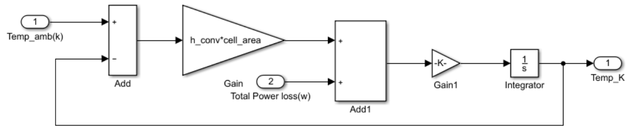

Figure 14 Thermal model of the cell

Terminal voltage estimation: The terminal voltage will be less than the OCV of the cell in case of discharging due the voltage drop across R0 , R1 & C1.

From figure 2

Vt = Voc – Vd1 –Vd2 ---(15)

Voltage across capacitor = $\frac{1}{C}\int I_2\,dt$

I_2 = Current in capacitor branch. It will become zero at steady state

Load current (I)= $I_1 + I_2$ --- (16)

Vd2 = I_1 x R1 --- (17)

Vd2 = I x R0 --- (18)

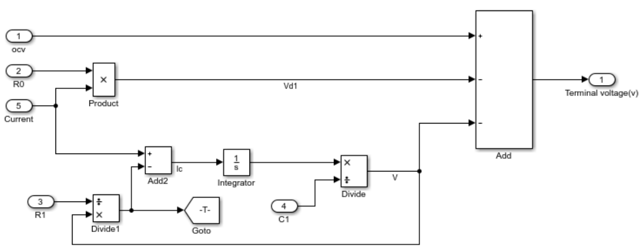

Figure 15 Terminal voltage estimation model

V. Simulation results & analysis

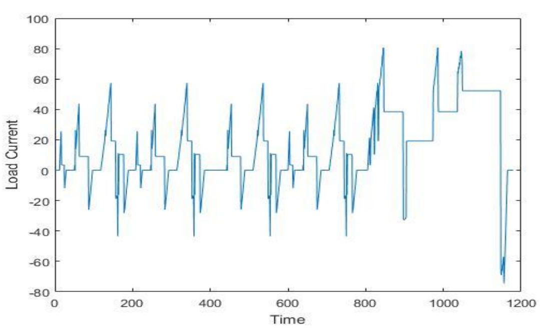

Figure 16 NEDC load current

The NEDC(New European drive cycle) load current profile is the input for the proposed model. Negative current is due to regenerative braking(Second quadrant operation). The current flows from the motor(load) to the source(Cell/battery).

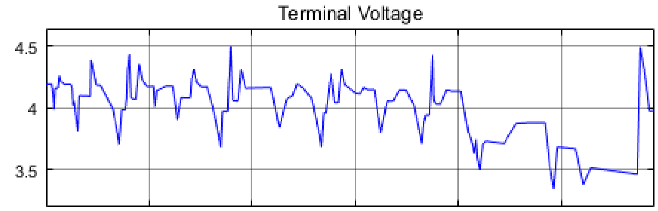

Figure 17 Terminal voltage

The terminal voltage is not going below 2.8v cut off voltage, Over discharging damages & reduces the cells life cycle.

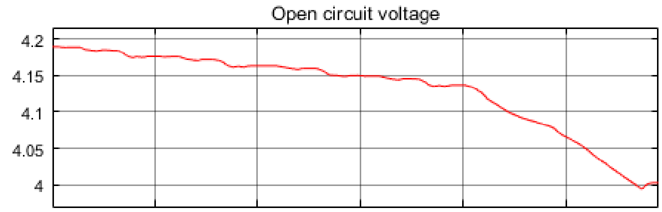

Figure 18 OCV

The decrease in OCV is due to the discharge current and the increase is due to the regenerative energy where the current flows into the cell.

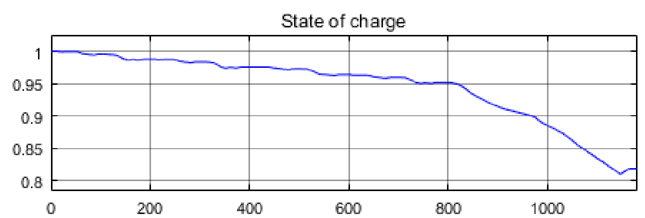

Figure 19 SOC

The SOC decreases from 100% to 80% for 1180 seconds , 11.023 km NEDC drive cycle.

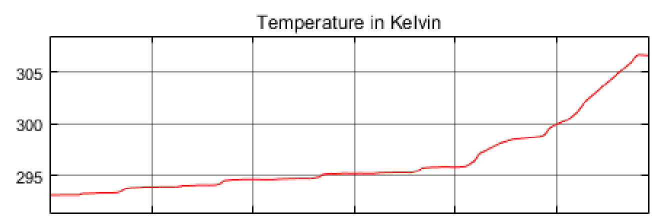

Figure 20 Cell Temperature

The cell temperature increases due to the heat dissipation(power loss) at R0 and R1.

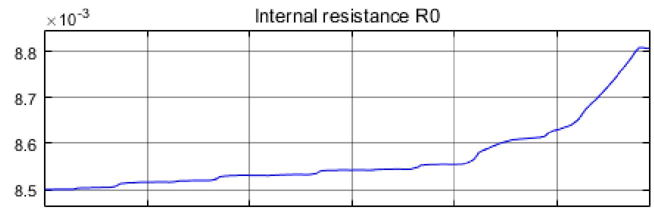

Figure 21 Internal resistance R0

Over the time the internal resistance of the cell increases it opposes the flow of current and there will be more voltage drop across it, more heat dissipation and decrease in terminal voltage.

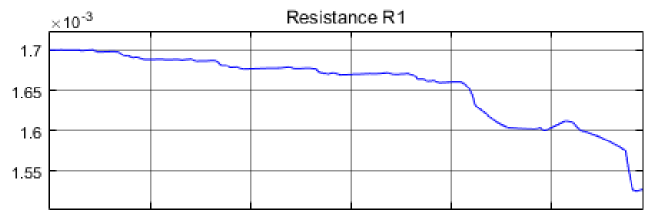

Figure 22 Resistance R1

The resistance R1 decreases over the time and so it accounts for less power loss across it over the time. The time constant of the RC branch is given by Tc = R1 x C1 So the time constant decreases and helps the cell in reaching the steady state quickly.

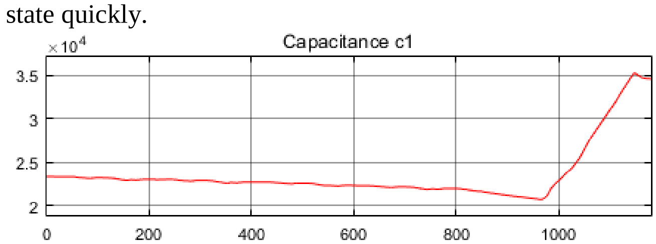

Figure 23 Capacitance C1

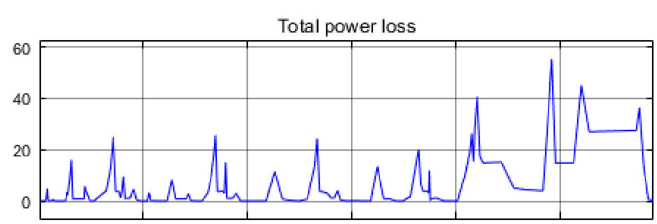

Figure 24 Total power loss

The total power loss is the sum of power loss across internal resistance R0 and R1.

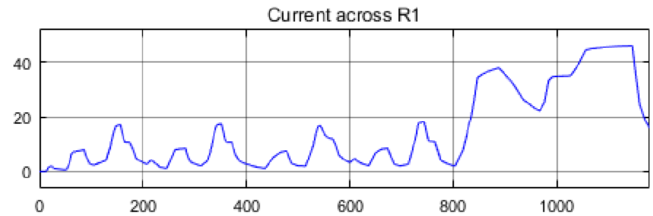

Figure 25 Current through R1

The load current gets divided into I_1 and I_2 in two branches. resistor and capacitor branch. At time t=0 when load is connected more current flows through the capacitor branch and the capacitor gets charged. As the capacitor gets charged the current in the capacitor branch decreases exponentially.

V. Conclusion

The presented equivalent circuit method of cell modeling on Matlab-Simulink is very helpful in testing the cells under extreme conditions in less time without any risk. The physical tests are carried out with the risk of damaging the battery/cell. But physical laboratory tests are necessary to develop the look up tables of parameters. The one RC time constant method gives a really good estimation of parameters and it is computationally inexpensive. More the data points in the LUT the better is the model based parameter estimation. A neural networks can also be used for the parameter prediction with very less errors by training the neural net using experiment data.

VI. REFERENCES

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