A comparison of modelling approaches for the evaluation of the electrical performance of secondary batteries in battery management systems (BMS)

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Abstract

In hybrid electric vehicle battery packs, battery management systems (BMS) must approximate values that describe the pack's current operating state. Battery state of charge(SOC) and instantaneous usable power are examples of these. The estimation process must respond to changing cell characteristics as cells age in order to produce reliable predictions over the pack's lifespan. To suggest a system based on extended Kalman filtering(EKF) that can achieve these objectives on a lithium-ion battery pack with NMC/graphite chemistry. This report discusses several mathematical cell models that can be used in connection with this approach. The HEV implementation is a harsh environment, with rate specifications up to and above 20 degrees Celsius and very complex rate profiles. In comparison, portable-electronic devices with steady power output and fractional C rates are relatively benign. Methods for calculating SOC that work well in portable electronics can not work well in HEVs. If the HEV requires precise SOC estimation, then highly accurate cell model is needed. When the cell model input is equal to the cell current, the target is to make the cell model output resemble the cell terminal voltage under load as near as possible at all times. In this research report, three different models for cell to estimate terminal voltage have been implemented in MATLAB/Simulink environment. The three mathematical models are further implemented in a fourth electrical model called Thevenin Model. Results are presented to demonstrate the terminal estimation voltage as close to actual voltage and SOC estimation for all the proposed cell models.

Keywords: Battery management system (BMS), State of charge (SOC), The combined model, simple model, The zero-state hysteresis model, The thevenin model

1. Introduction

Advanced algorithms for a BMS for hybrid electric vehicle (HEV) applications are defined in this report. This BMS calculate SOC and instantaneous power available power to the battery. It also adjust to changing cell characteristics as the battery pack ages. The algorithms were tested on a lithium-ion with nickel-manganese-cobalt (NMC) cathode and graphite anode battery pack previously tested at Center for Advanced Life Cycle Engineering (CALCE), University of Maryland [14], but they should work for other battery chemistries as well.The three mathematical models used in this project are further implemented in a Fourth electrical model called Thevenin Model.

The HEV implementation is a harsh environment. Methods for calculating SOC that work well in portable electronics can not work well in HEVs. If the HEV requires precise SOC estimation, then highly accurate cell model is needed. A laboratory approach for measuring SOC is to discharge a cell entirely and record the discharged ampere-hours to calculate the cell's current remaining energy. This is the most precise SOC estimation technique, but it is inefficient in HEVs since the test wastes battery resources and can't dynamically estimate SOC.

The outcomes of laboratory experiments on physical cells are interpreted and compared to model predictions.More specifically, the model provides for extremely accurate SOC prediction, enabling the vehicle controller to safely use the battery pack's maximum operating range without fear of over- or under-charging batteries.

2. literature Review

Our application is to simulate cell dynamics in order to estimate SOC in a HEV battery pack. Several cell models have been proposed for SOC estimation. [8] presented many cell modelling methods in greater details for SOC estimation. The molecular level to design cell electrical dynamic model approach has been adopted in [4]. By using these models, accurate terminal voltage prediction achieved. However, measuring the many necessary physical parameters on a cell-by-cell basis in a high-volume consumer product couldn't considered. Other techniques such as cell modelling based on cell impedance over a wide range of ac frequencies at different states of charge have been involved in [1, 11]. Least-squares fitted to measure impedance values yield model parameter values. SOC may be derived indirectly by calculating current cell impedance and comparing it to known impedance's at different SOC stages. No direct method was used for measuring impedance by injecting signals into cells.

Many papers represent equivalent circuit models for cells. To represent the open circuit voltage, [7, 2, 6] used voltage source or highly valued capacitor. The remaining circuit simulates the cell's intrinsic resistance as well as more dynamic effects such as terminal voltage relaxation. SOC can be calculated using a table lookup based on the OCV estimation. Here instead of SOC, OCV is fundamental state.
Coulomb counting is another method for SOC estimation. This is done by using open loop which is more sensitive to the measurement of current error. It is much accurate to the closed loop. [3]

3. Mathematical Modelling

3.1 Circuits Models

Open Circuit Voltage (OCV) is represented by a Controlled voltage source. The rest of the model include internal resistance of the cell and dynamic effects such as terminal voltage relaxation. The fundamental state used here is SOC instead of OCV and has similarities to circuit model.

For cell model, the only requirement is SOC to be constrain. SOC is denoted by "z_k" and is the member of the state vector x_k. To better understand of SOC, the following definitions are given as follows:

- When voltage v reaches v_h i.e $v = v_h$, cell is fully charged after being charged at infinitesimal current levels. The value of v_h at room temperature is 4.2 V.
- The cell is discharged, being drained at infinitesimal current levels. This occur at $v = v_1$ where $v_1 = 3.2$ V.
- A cell's capacity C is the highest amount of ampere-hours that can be taken from the cell until it is completely discharged at room temperature, beginning with the cell fully charged.
- At room temperature, number of ampere-hours that can be taken from the cell at the rate of C/30, beginning with fully cell charged is called Nominal capacitance C_n.
- Ratio of remaining capacity and nominal capacity is SOC of the cell. Remaining capacity is defined as: number of ampere-hours that can be taken from the cell before the cell fully charged at rate of C/30.

Based on the following definitions, SOC involving mathematical equations can be investigated.

$$z(t) = z(0) - \int_0^t \frac{\eta_i \, i \, \tau}{C_n} \tag{1}$$

where cell SOC is denoted by $z(t)$, instantaneous cell current is $i(t)$ and C_n is nominal cell capacity. η_i represents cell Coulombic efficiency. For charging it is equal is 1 and for discharging it is equal or less than 1. A discrete time approximate recurrence by using rectangular approximation for integration over time interval Δt ia written as:

$$z_{k+1} = z_k - \left(\frac{\eta_i \, \Delta t}{C_n} \right) i_k \tag{2}$$

Equation.(3) is basic equation for including SOC. It is in the form of cell model state vector. i_k is the input here. Additional model and output state equation can be added in cell model as desired. Firstly an output equation is added from the literature [9] to check its validity and how enhancement can be made. Next, cell hysteresis and dynamics to model cell terminal voltage relaxation state is added. At the last, incorporating temperature dependence to the model.
We are taking models where SOC is taken as state. Here the state vector is $x_k = z_k$. SOC is only state in equation.(3).

3.2 The combined Model

Terminal voltage can be predicted in different ways as SOC is now part of the model state. Other forms are adopted from [5] such as:
Shepherd model:

$$y_k = E_o - R\, i_k - \frac{K_i}{z_k}$$

Unnewehr universal model:

$$y_k = E_o - R\, i_k - K_i\, z_k$$

Nernst model:

$$y_k = E_o - R\, i_k - K_2\, ln(z_k) \, + K_3\, ln\,(1 - z_k)$$

where

- y_k = cell terminal voltage, R = internal resistance of cell. For different SOC levels, its different values can be used for charging and discharging.

- K_1, K_2, K_3 = constants for data fitting. K_i = polarization resistance.

All these terms collectively called ""the combined model". This combined model can perform better than the individual models. The combined model is presented as:

$$z_{(k+1)} = z_k - \left(\frac{\eta_i \, \Delta t}{C_n} \right) i_k \tag{3}$$

$$y_k = k_o - R\, i_k - \frac{K_1}{z_k} - K_2\, z_k + K_3\, ln(z_k) + K_4\, ln(1 - z_k) \tag{4}$$

By using system identification procedure, the combined model unknown parameters can be estimated. The advantage of this model is that its linearity in parameters and also that is, the unknowns occur linearly in the output equation.

$$Y = [y_1, y_2, ..., y_N]^T, \tag{5}$$

and the matrix

$$H = [h_1, h_2, ..., h_N]^T. \tag{6}$$

The rows of H are

$$h_j^T = [1, i_j^+, i_j^-, \frac{1}{z_j}, z_j, ln(z_j), ln(1 - z_j)], \tag{7}$$

where i_j^+ is equal to i_j if $i_j > 0, i_j^-$ is equal to i_j if $i_j < 0$ else i_j^+ and i_j^- are zero. Then $Y = H\theta$, where $\theta^T = [K_0, R^+, R^-, K_1, K_2, K_3, K_4]$ is the vector of unknown parameters. Using a result from least-squares estimation theory, we solve for the parameters θ using the known matrices Y and H as $\theta = (H^T H)^{-1} H^T Y$ [10].

3.3 The Simple model

The components of the combined model can be further evaluated for more investigation. The output equation of the model is divided into two parts. One part based on SOC and other depend upon i_k:

$$y_k = fn(z_k) - fn(i_k) \tag{8}$$

where

$$fn(z_k) = k_o - R\, i_k - \frac{K_1}{z_k} - K_2\, z_k + K_3\, ln(z_k) + K_4\, ln(1 - z_k)$$

and

$$fn(i_k) = R\, i_k$$

By Plotting the figure between $fn(z_k)$ and $fn(i_k)$ when the values are fit to parameters $K_o\ to\ K_4$ as shown in fig.1. The cell was completely charged first (constant current to 4.2 V). The cell was then discharged at a C/25 rate until it was fully discharged (3.0 V). After that, the cell was charged at a C/25 rate until the voltage reached 4.2 V. The low rates were used to keep the dynamics in the cells to a minimum. The OCV was calculated by averaging the cell voltage as a function of state of charge under discharge and under charge.

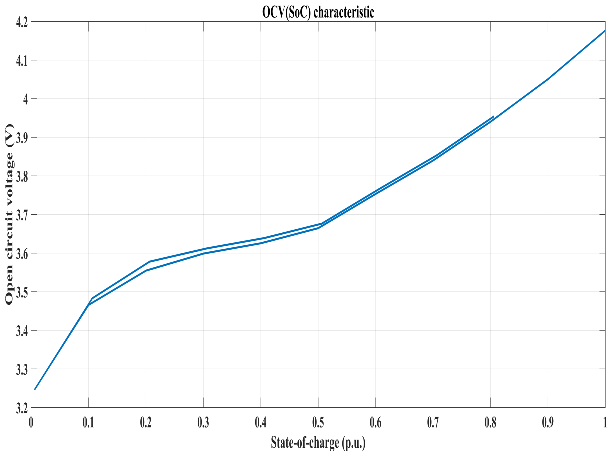

Figure 1: **OCV (SOC)**

The portion that is solely dependent on SOC deserves closer review. y_k, function of SOC, trying to attempting the OCV_{z_k} curve. More define form of the combined model can be implemented as:

$$z_{(k+1)} = z_k - \left(\frac{\eta_i\,\Delta t}{C_n}\right) i_k \tag{9}$$

$$y_k = OCV_{z_k} - R\, i_k \tag{10}$$

The output has been drawn from the equivalent model given by fig.2. Simple model composed of equations.(7), (8) and (3). Here the simple model is preferred because of it generalize form and less complex structure.This model type is also linear in the parameters. Off-line system identification is done as follows: We first form the vector

$$Y = [y_1 - OCV(z_1), y_2 - OCV(z_2, ..., y_n - OCV(z_N]^T, \tag{11}$$

and the matrix

$$H = [h_1, h_2, ..., h_N]^T. \tag{12}$$

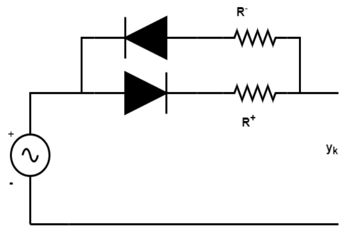

Figure 2: Equivalent circuit implemented by "simple" model, and approximated by "combined" model

The rows of H are

$$h_j^T = [i_j^+, i_j^-]. \tag{13}$$

Again, we see$Y = H\theta$, where $\theta^T = [R^+, R^-]$ is the vector of unknown parameters.We solve for the parameters θ using the known matrices Y and H as $\theta = (H^T H)^{-1} H^T Y$ [10].

3.4 The zero state hysteresis model

There are some flaws exposes in the combined and simple model such as subtle effect. In predicting SOC, it has serious consequences as shown in [9]. The cell voltage still relaxes to a value less than the true OCV for that SOC after a discharge. The cell voltage relaxes to a value greater than the true OCV for that SOC after a charge. This is not explained in previous models. Hysteresis model presented this effect which occurs in cell.

In certain ways, the cell voltage lags behind the predicted voltage. It may also be described as a system property in which a change in the direction of the independent variable causes the dependent variable to fail to retrace the path it took in the forward direction. (For better understanding hysteresis phenomena, check [12]). The hysteresis model basic equations are:

$$z_{(k+1)} = z_k - \left(\frac{\eta_i\,\Delta t}{C_n}\right) i_k \tag{14}$$

$$y_k = OCV_{z_k} - s_k M(z_k) - R\, i_k \tag{15}$$

Sign of current is represented by s_k.

$$s_k = 1,\ for\ i_k > \epsilon,$$

$$s_k = -1,\ for\ i_k < -\epsilon$$

$$s_k = s_k - 1, \ for \ |i_k| \leq \epsilon$$

$M(z_k)$ is half the distance between the charge/discharge curve's two legs.This model type is also linear in the parameters. Off-line system identification is done as follows: We first form the vector

$$Y = [y_1 - OCV(z_1), y_2 - OCV(z_2, ..., y_n - OCV(z_N]^T, \tag{16}$$

and the matrix

$$H = [h_1, h_2, ..., h_N]^T. \tag{17}$$

The rows of H are

$$h_j^T = [i_j^+, i_j^-, s_j]. \tag{18}$$

Again, we see$Y = H\theta$, where $\theta^T = [R^+, R^-, M]$ is the vector of unknown parameters.We solve for the parameters θ using the known matrices Y and H as $\theta = (H^T H)^{-1} H^T Y$ [10].

3.5 The Thevenin Model

Fig.(3) shows the representation of the Thevenin model. It consists of certain electrical components such as R_o is internal resistance, R_p, C_p and V_p are the polarization resistance, capacitance and voltage respectively. y_k is the estimated terminal voltage of the battery. The mathematical representation of the thevenin model is given as:

$$y_k = OCV_{z_k} + V_p + IR_o \tag{19}$$

Where I is the current and its value is positive upon charging and negative when there is discharging mode. The equation for polarization voltage is determined by apply Kirchhoff's current at the node of parallel combination of polarization resistor and capacitor and is defined as:

$$\dot{V_p} = \frac{-V_p}{R_p C_p} + \frac{1}{C_p} I \tag{20}$$

Applying transfer function to convert equation 20 into s-domain form:

$$y_k s = OCV(s) + \left(\frac{R_p}{R_p C_p s + 1} + R_o \right) I(s) \tag{21}$$

One way to calculate the Thevenin parameters values is by using Recursive Least Square (RLS) [13].In this project the author did not calculate them but took as references [14].

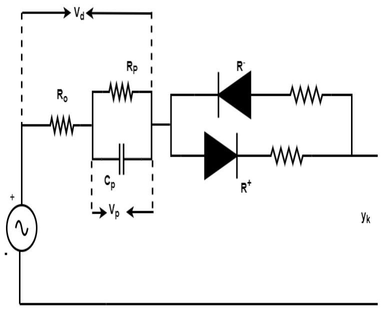

Figure 3: Equivalent circuit implemented by "Thevenin" model [13]

4. Simulations and Results

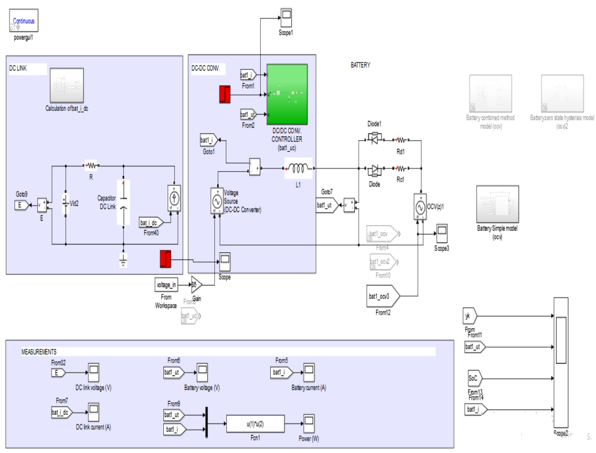

Figure 4: Simulink block for BMS

The MATLAB/Simulink-based environment has been used for showing performance of the circuit models: The simple model, The combined model and The zero-state hysteresis model given by equations 3, 10 and 14 for the simple model, equations 3 and 4 for the combined model and equations 14 and 15 for the zero state hysteresis model and equation 21 for thevenin model. The goal is to have the cell model output resemble the cell terminal voltage under load as closely as possible, at all times, when the cell model input is equal to the cell current. The simulink block for BMS along with circuit models has been presented in 4. R_{d1} and R_{c1} are the discharging and charging resistance of the battery. Battery model used here is Lithium-ion

and its single cell parameters are given in table 1. For every SOC lookup vaues, values of OCV will be calculated in table 2.
The Cell Thevenin Resistance and Capacitance were extrapolated from the previous tests and model at [14] The pack parameters for lithium-

Parameter	Value
R_{d1}	0.125
R_{c1}	0.115
Coulomb efficiency	1
Time step	0.01(s)
Cell capacity	7200(As)
Cell Thevenin capacitance	1127.6(F)
Cell Thevenin resistance	0.00345(Ohm)

Table 1: Lithium ion single cell parameters

SOC	OCV
0.0066	3.2472
0.1004	3.4658
0.2004	3.5546
0.3003	3.5987
0.4002	3.6254
0.5002	3.6645
0.6001	3.7531
0.7000	3.8397
0.8000	3.9400
0.8999	4.0502
0.9998	4.1763

Table 2: SOC and OCV lookup table

ion battery are given in table 3 The discharging resistance of the pack battery is the combination of single cell resistance and ratio of series and parallel cells of the battery. The number of series and parallel combination of cells are 86 and 44 respectively. Similarly other parameters details such as pack charging resistance ($R_{c_{pack}}$), cell capacity pack ($Bat1\ C_{n_{pack}}$), SOC lookup table in case of pack ($bat1\ OCV\ lookup - table_{pack}$), ($bat1\ Unom_{pack}$), ($bat1\ Uexp_{pack}$), ($bat1\ Umin_{pack}$) are given below:

$$R_{d_{pack}} = R_{d1} * \frac{Bat1.Nseries}{Bat1.Nparallel}$$

$$R_{c_{pack}} = R_{c1} * \frac{Bat1.Nseries}{Bat1.Nparallel}$$

$$Bat1\ C_{n_{pack}} = bat1.C_{n_{cell}} * Bat1.Nparallel$$

$$Bat1\ OCV\ lookup - table_{pack} = Bat1.Nseries* [OCV\ values\ from\ table.2]$$

$$Bat1\,Unom_{pack} = mean*(Bat1\ OCV\ lookup{-}table_{pack})$$

$$Bat1\,Uexp_{pack} = max*(Bat1\ OCV\ lookup{-}table_{pack})$$

$$Bat1\,Umin_{pack} = min*(Bat1\ OCV\ lookup{-}table_{pack})$$

The set points and initial conditions for running simulation to estimate the terminal voltage (y_k) are given as:

$$Bat1.initial_z = 0.7$$

$$Bat1.initial_{OCV} = interpl(bat1\ OCV\ lookup - table_{pack}, bat1\ OCV\ lookup - table, Bat1.initial_z)$$

This section consists of further three subsection. Subsection 4.1 shows the simulation performance of the simple model in term of estimated terminal voltage, actual voltage, charging/discharging current and SOC. Similarly subsection 4.2 shows behavior of the combined cell for said properties discussed earlier. Simulation discussion for the zero state hysteresis model and Thevenin model is done in subsection 4.3 and 4.4 respectively.

4.1 The simple model

Here, the performance of the the simple model has been done. The simulink model for equations 9 and 5 are shown in fig. 6. The model parameters used for the implementation of the Simple model is given in tab. 3. In fig. 2, y_k is the terminal

Parameter	Value
R	0.253091021257146

Table 3: Circuit Model parameters

estimation voltage which is the required goal of the model to achieve it as same as the actual voltage.

$bat1 - OCV$ is the open circuit voltage signal of the simple model which is fed into the battery model shown in fig. 2. The behavior of the terminal estimation voltage y_k and actual voltage is shown in fig. 6. It is clearly shown that terminal voltage almost achieve the same level as actual voltage. The first phase of both voltages is due to discharges spike by SOC, and second phase is due

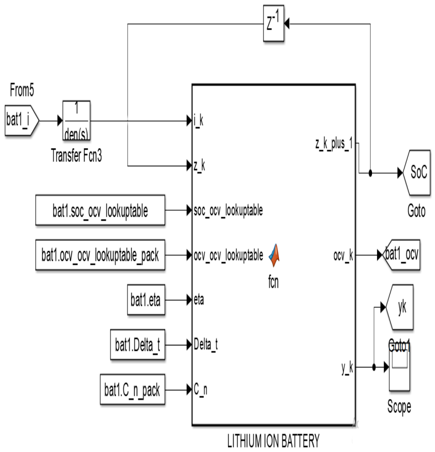

Figure 5: The simple model simulink block

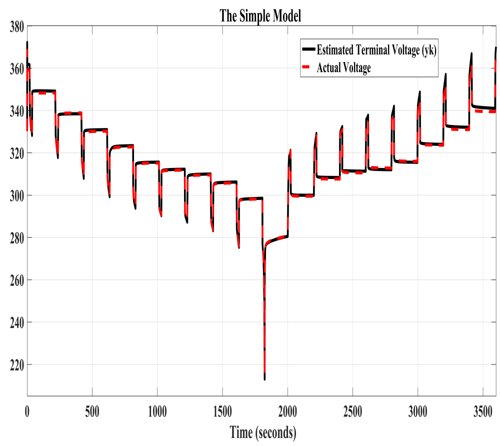

Figure 6: Terminal estimated Vs actual voltage

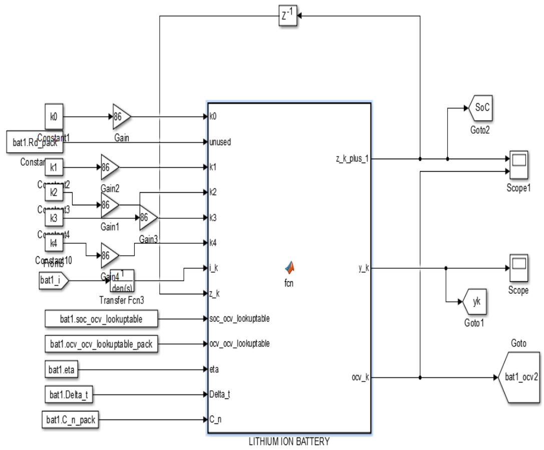

Figure 7: The combined model simulink block

to the charges spike. The simple model perform well.

4.2 The Combined Model

Here, the performance of the Combined model has been done. The simulink model for equations.3 and 4 are shown in fig. 7. The model parameters used for the implementation of the Combined model is given in tab. 4. In fig. 8, behavior of "yk" terminal estimation voltage which is the required goal of the model to achieve it as same as the actual voltage. The combined model slightly under perform as there are some steady state errors showing in the fig. 8. By comparing fig. 6 of the simple model and fig. 8 of the combined model for the terminal estimation voltage and actual voltage, the simple model perform better in estimating the exact the terminal voltage as value of the actual voltage.

Parameter	Value
k0	3.22901051353494
R	0.253091021257146
k1	0.00301866406686573
k2	-0.803016645948219
k3	-0.0907895654362170
k4	-0.0248733178576978

Table 4: Circuit Model parameters for The Combined Model

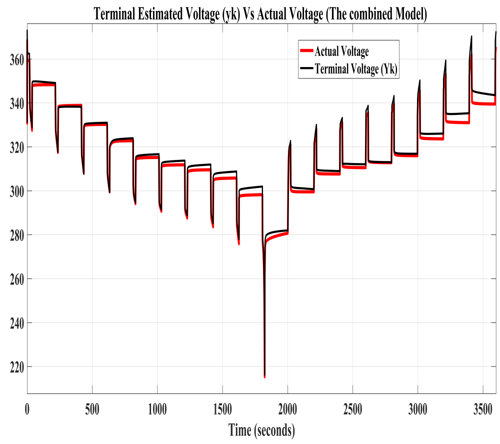

Figure 8: Terminal Voltage (yk) vs actual voltage of the Combined Model

4.3 The zero state Hysteresis Model

The implementation of the zero state hysteresis model has been done in this section.The model parameters used for the implementation of The zero-state Hysteresis model is given in tab. 5. The

Parameter	Value
R	0.253091021257146
M	-0.00188930759029581

Table 5: Circuit Model parameters for The zero-state Hysteresis Model

simulink model for equations. 14 and 15 are shown in fig. 9. Fig. 10 shows the comparison of actual voltage and estimated terminal voltage. It is cleared that zero state hysteresis achieved remarkably this level. It is noted that value of actual voltage and terminal estimated voltage is 4.2. In graph, analysis for pack battery cells i.e 86.

By closely monitoring the behaviour of all proposed cell models for terminal estimated voltage of the battery; figs. 6, 8 and 10. The results are more effective with the zero state hysteresis model as compared to the other proposed cell models having no disturbance or steady state error in achieving the same level with actual voltage. Other cells model such as the combined model, does show some steady state error, disturbance and spike of terminal estimation voltage over actual voltage. The

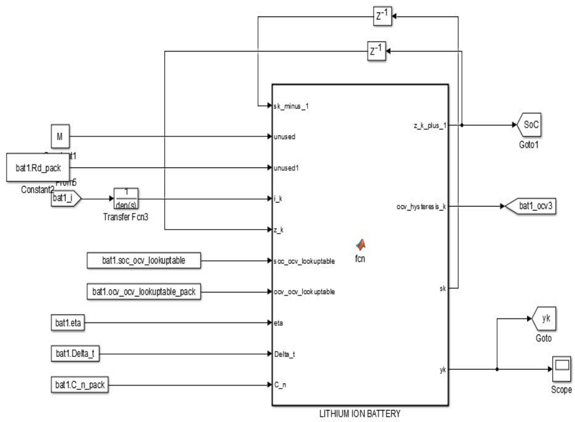

Figure 9: Simulink model zero hysteresis model

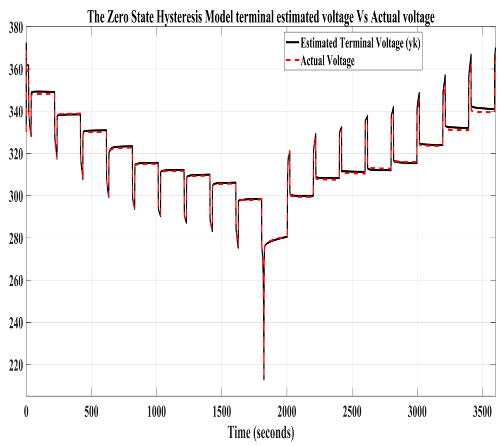

Figure 10: Terminal voltage Vs Actual Voltage of the zero state Hysteresis Model

simple model does good job in maintaining the level of the both voltages at almost at the same level.

4.4 The Thevenin model

Here introducing thevenin model consisting of thevenin resistance and capacitance in battery which are not been calculated from the author. The model parameters have been extracted by the following paper which worked on the same battery pack [14].In this section the author used the thevenin circuit model, which is made by adding a RC block to the equivalent model, implementing it for each model previous tested. New simulation has been done for this case by considering all the proposed mathematical cell models for observing the terminal voltage estimation with actual voltage: The simple model, The combined model and the zero state hysteresis model. The new simulink block for the thevenin circuit BMS is shown in fig. 11 where the actual voltage has been compared with the voltage of the three models. Fig. 12

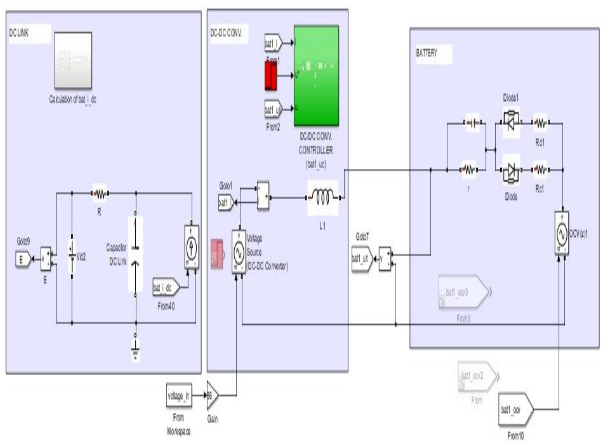

Figure 11: BMS Simulink block with thevenin circuit

shows the comparison of terminal estimation voltage with actual voltage for all the proposed models. It is clearly shown the performance of the zero state hysteresis model outclass the other models in term of thevenin circuit battery too.

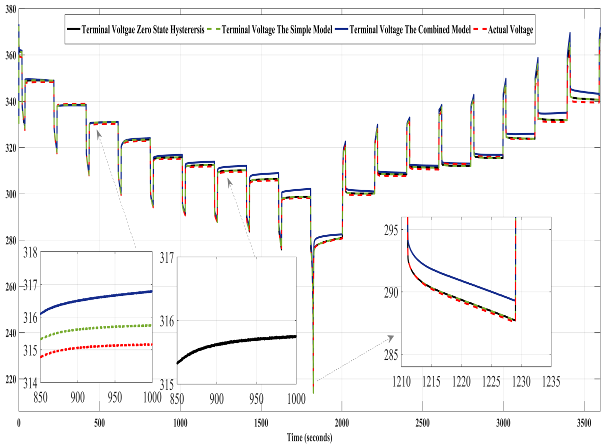

Figure 12: Terminal estimated Voltage Vs Actual Voltage: Thevenin Model implenting and comparing all the other three models

5. Conclusions

This report has proposed three mathematical cells structure for the purpose of modeling Lithium-ion NMC/graphite cell dynamics for their eventual role in HEV BMS algorithms. Three different models for cell to estimate terminal voltage have been implemented in MATLAB/Simulink environment. Results are presented to demonstrate the terminal estimation voltage as close to actual voltage and SOC estimation for all the proposed cell models. Single-state model are very simple, perform up to expectation level. Adding hysteresis and filter states to the model aids performance, at some cost in complexity. The combined cell model perform slightly below than simple model.

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