^ *Submitted: 3rd July 2022 to Autonomous Ground Vehicle Research Group, IIT Kharagpur.*

Battery Management System

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Abstract: We in here review the methods used in accomplishing the task no. one for Autonomous Research Group selections. The SoC curve is obtained for a AAA Zinc Carbon battery in this paper which is used to calibrate the BMS SoC estimator. Extended Kalman Filter which is a local linearizer is used to determine the curve. Reverse voltage protection, overcurrent and overcharge protection setups have been outlined as been built experimentally.

1. Introduction

Batteries are one of the components that has powered the exponential human developmental surge in this modern era. From our daily use appliances to niche applications of space exploration batteries have power system and management has been the core Demand for Lithium-ion batteries is projected grow to about 2 TWh by 2030.

Battery Management Systems are used to monitor battery pack parameters and control then as desired. They employ control as well as safety features to drive the power system. We hereby demonstrate a BMS who functions as the State of Charge estimator derived from voltage readings. The System further comprises of safety features, overcurrent, overcharge and reverse polarity protection. Arduino NANO is used as the processing unit for the BMS. Data visualization is carried out using Python 3.10.2 through Jupyter notebooks. The SoC estimator is derived from Extended Kalman Filter which uses Local Linearization for non-linear models. The V_{OC} vs SoC curve has a non-linear profile making the extended version of the estimator a suitable fit.

We thereby outline the methodology to obtain open circuit Voltage (V_{OC}) vs State of Charge (SoC) followed by a BMS functionality setup.

2. Task Outline

The pre-implementation experimentation consisted of obtaining the V_{OC} vs SoC plot which would be used to determine the SoC of the battery pack used during BMS functioning.

The experimental setup was partitioned into functional blocks as follows

- SoC Estimator
- Reverse Voltage Protection
- Overcurrent Protection
- Overcharge Protection
- Regulated Output Voltage Levels (5V & 3.3V)

3. Battery Modelling

The following sections brief on the mathematical and physical setup of the battery pack considered in the paper.

3.1 Battery Topology

The battery pack created was using R03USDG/1B (Panasonic) 1.5V AAA Zinc Carbon non-chargeable batteries. Four such batteries were put in series to create a net V_{OC} of 6V when fully charged. Cell holders were employed whose connectors were soldered to adjacent ones to make a series configuration.

Assuming the rated capacity of the AAA cell to be 600 mAh, employing a net of Q_{nom} (false value) = 2400 mAh for the pack[1].

3.2 Mathematical Modelling

The Dual Polarization model has been adopted in this paper, which is second order equivalent setup

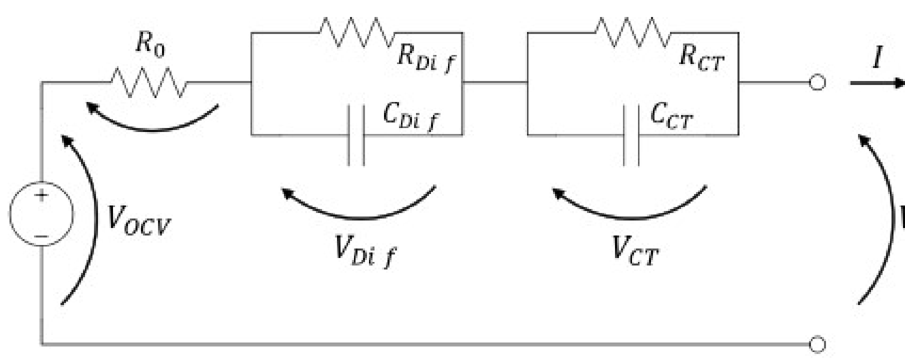

Figure 1: Dual Polarization battery model employed in the paper. Source: [1]

The state space formulation in discrete time domain is

$$\begin{cases} SoC(k+1) = SoC(k) - \dfrac{\Delta t}{Q_{nom}} I(k) \\ V_{CT}(k+1) = e^{-\frac{\Delta t}{\tau_{CT}}} V_{CT} + R_{CT}\left(1 - e^{-\frac{\Delta t}{\tau_{CT}}}\right) I(k) \\ V_{Dif}(k+1) = e^{-\frac{\Delta t}{\tau_{Dif}}} V_{Dif} + R_{Dif}\left(1 - e^{-\frac{\Delta t}{\tau_{Dif}}}\right) I(k) \end{cases}$$

Using Kirchoff's Voltage Law on the model, we get

$$V(k) = V_{OCV} - V_{CT}(k) - V_{Dif}(k) - R_0 I(k)$$

As V_{OC} is a function of SoC, we use the model outlined in [6]. Hence the relation governing the fit is

$$V_{OC} = K_0 - \frac{K_1}{SoC} - K_2 SoC + K_3 \ln(SoC) + K_4 \ln(1 - SoC)$$

[1] The capacity was assumed due to the unavailability of datasheet even after contacting manufacturers. The value taken (600 mAh) is considered taking into account batteries of similar chemical and physical designs (general ranges 450 – 650 mAh).

Redesigning,

$$V_{OC} = \begin{bmatrix} 1 & -\frac{1}{SoC} & -SoC & \ln(SoC) & \ln(1-SoC) \end{bmatrix} \begin{bmatrix} K_0 \\ K_1 \\ K_2 \\ K_3 \\ K_4 \end{bmatrix}$$

Putting it into operator form

$$\begin{bmatrix} SoC \\ V_{CT} \\ V_{Dif} \end{bmatrix}_{k+1} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{-\frac{\Delta t}{\tau_{CT}}} & 0 \\ 0 & 0 & e^{-\frac{\Delta t}{\tau_{Dif}}} \end{bmatrix} \begin{bmatrix} SoC \\ V_{CT} \\ V_{Dif} \end{bmatrix}_k + \begin{bmatrix} \frac{\Delta t}{Q_{nom}} \\ R_{CT}\left(1 - e^{-\frac{\Delta t}{\tau_{CT}}}\right) \\ R_{Dif}\left(1 - e^{-\frac{\Delta t}{\tau_{Dif}}}\right) \end{bmatrix} I(k)$$

Equivalently

$x(k+1) \;=\; Ax(k) \;+\; BI(k)$

The value during discharge was assumed as 600mAh which is inaccurate. After discharging we took the battery to about 1V. and the SoC reached: -0.804127088

3.3 Renormalizing Method

Let x = 0.804127088 be the offshoot in the negative x-axis for the SoC

Q_{nom} is the assumed capacity, while Q'_{nom} is the true capacity

$$SoC(k+1) = 1 - \frac{1}{Q_{nom}} \sum_{n=1}^{k} I(n)\Delta t$$

$$SoC'(k+1) = 1 - \frac{1}{Q'_{nom}} \sum_{n=1}^{k} I(n)\Delta t$$

These equations give

$$Q_{nom}(SoC(k) - 1) = Q'_{nom}(SoC'(k) - 1)$$

Boundary value condition: SoC = -x → SoC' = 0; SoC = 1 → SoC' = 1

Renormalization:

$$1 + \frac{Q_{nom}}{Q'_{nom}}(SoC(k) - 1) = SoC'(k)$$

Applying boundary condition

$$1 + \frac{Q_{nom}}{Q'_{nom}}(-x - 1) = 0$$

$$\frac{Q_{nom}}{Q'_{nom}} = \frac{1}{1+x}$$

Therefore, the true capacity is

$$Q'_{nom} = Q_{nom}(1 + x)$$

$$\Rightarrow True\ Capacity = Q'_{nom} = 1{,}082.4762528\ mAh$$

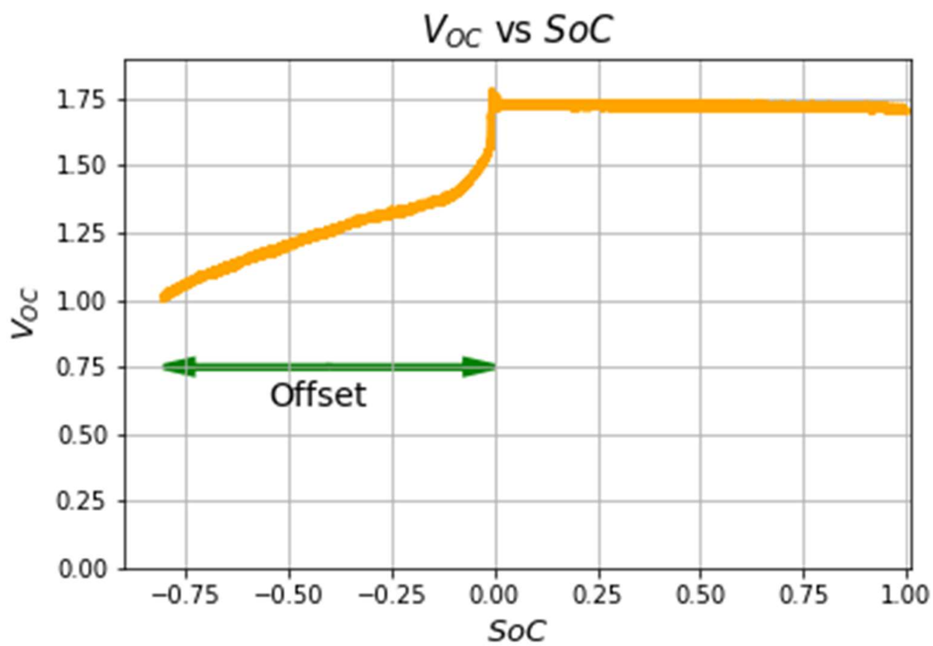

Figure 2

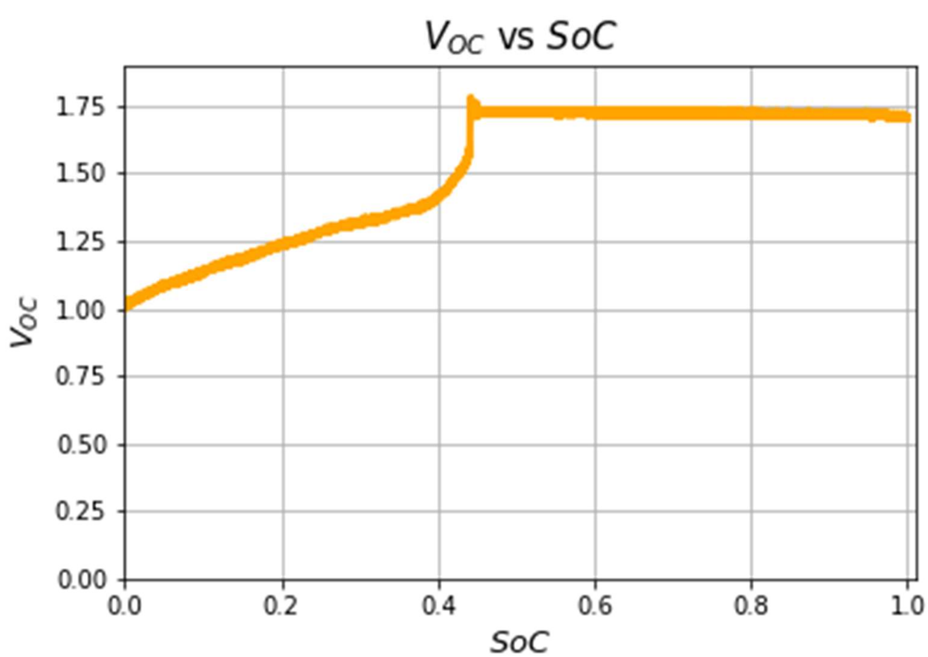

Figure 3

4. V_{OC} versus SoC Determination

When no load is connected (i.e. current is 0A), the voltage across the battery pack is V_{OC} . If the load is connected, the voltage measured is *V(k)*. Therefore, we measure, The V_{OC} when the coupling transistor is not active. While we make the circuit complete (transistor active) we can measure the *V(k)* using Arduino across the resistor.

R_0	0.2Ω
R_{CT}	1mΩ
R_{Dif}	10mΩ
τ_{CT}	4s
τ_{Dif}	100s
Q_{nom}	1.082Ah

Table 1: Battery model parameters.

The pin A0 measures the V_{OC}, while A1 measures V(k). Current through resistor (value = R_0) is calculated as $I=V(k)/R_0$. The Dual Polarization parameters used for the Extended Kalman Filter as given in the adjacent table no. 1.

The Kalman Estimator equations used won't be highlighted in this paper. The references [1], [2]be used to review the algorithmic steps. The values K_i (as described in [2]) are set as below

$$\theta = \begin{bmatrix} K_0 \\ K_1 \\ K_2 \\ K_3 \\ K_4 \end{bmatrix} = \begin{bmatrix} 2.22221763 \\ -0.0119085674 \\ 0.492858021 \\ 13186.4572 \\ -13185.9561 \end{bmatrix}$$

Detailed procedure and code given in form of a Jupyter Notebook:
https://github.com/PrasannaPaithankar/AGV-Embedded-Task/blob/main/V_oc-vs-SoC-Determination/EKF_plotting.ipynb

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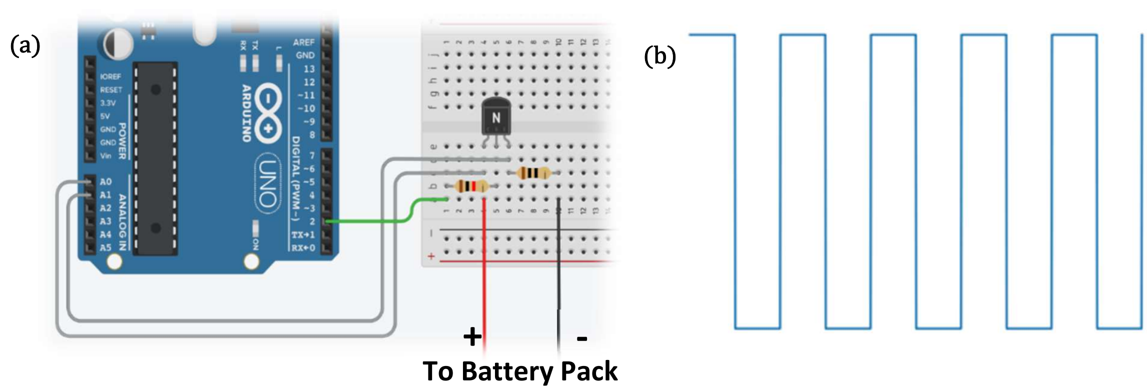

Figure 4: (a)The battery discharge measurement setup. (b)The Voltage at base of the BJT. During the High region V(k) is measured and during Low time V_{OC} is. The cycle time period in the setup is 0.1s

The plot obtained through the measurement with the fitting curve as a subplot

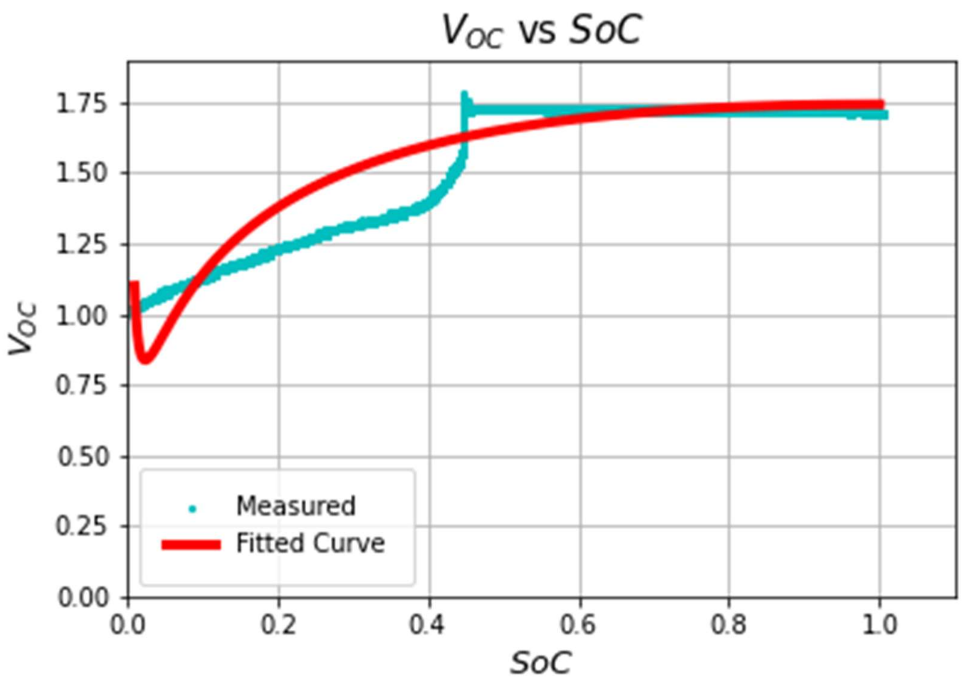

Figure 5

The covariance plot of the fitting parameters (θ)

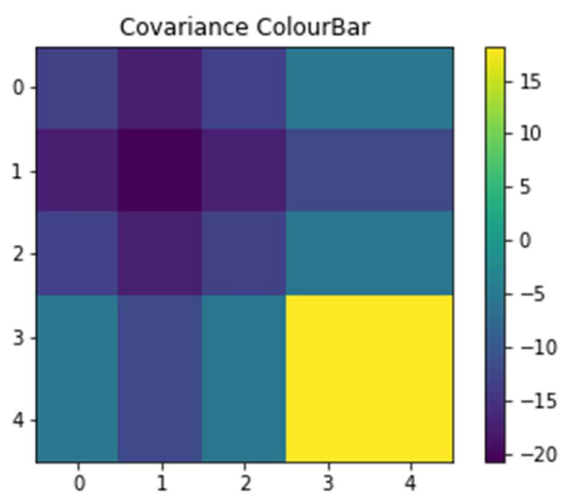

Figure 6

Generated by Prasanna Paithankar
Python: 3.10.2
Matplotlib: 3.5.1
Numpy: 1.21.4
Scipy: 1.7.2
Pandas: 1.3.4

5. Protection Features

The following battery management safety controls have been implemented

5.1 Reverse Polarity Protection

A Power N-channel Power mosfet is to be used to protect the load from reverse voltage hazards. These faults occur due to reversing terminal plug-in of the battery into the BMS.

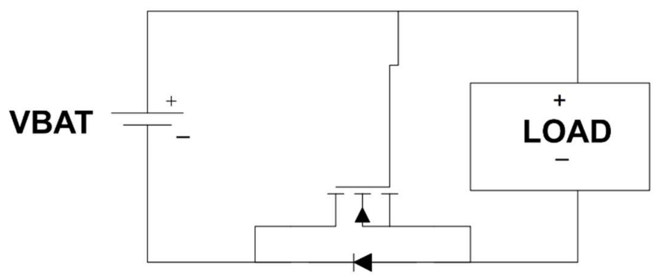

Figure 7: NMOS FET employed for reverse voltage protection in the BMS circuit. Source: [3]

The ideal mosfet will only offer no resistance path if the positive terminal of the battery pack is connected to the positive terminal of the load (the load positive and mosfet gate is shorted) forming a conductive trace. Reversing the connections switches off the mosfet creating a high impedance path.

Normally a mosfet will provide a path resistance in order of 0.1Ω. For the experimental setup we have employed a NPN Bipolar Junction Transistor (BJT), 2N3904 which is suitable for less dauting experiments.

5.2 Overcurrent Protection

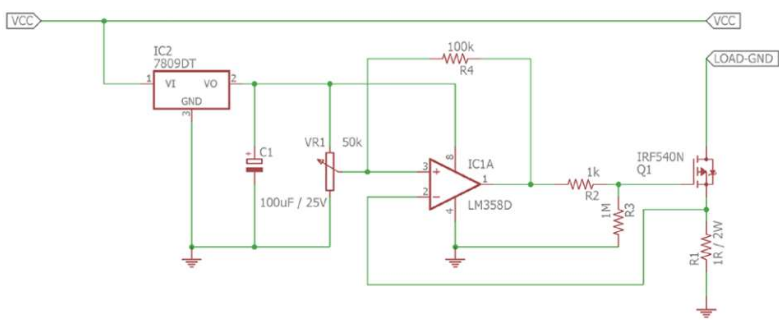

Figure 8: Overcurrent Protection Circuit based on Op-amp. Source: Circuit Digest

The adjacent circuit has been coupled with a 7805 linear voltage regulator, therefore incorporating both overcurrent protection and regulated voltage supply.

The potentiometer is used to set safe current limits.

5.3 Overcharge Protection

The overcharge protection circuitry is thoughtfully designed using op-amp.

Let the battery pack voltage be V. When the voltage goes above a certain threshold the op-amp switched off the transistor and the charger is cut-off from the battery pack

Figure 9 showing the Overcharge Protection Circuit based on Op-amp.

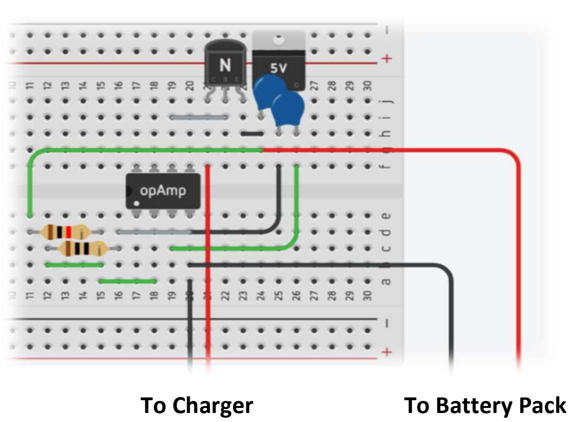

Figure 9

6. Conclusion

A BMS was tested to estimate SoC of a given battery pack incorporating standard safety thresholds. The initial battery pack assumed was rectified after data processing to get a scaled plot. Setup was successfully built and demonstrated using the workhorse NANO.

References

[1] C. Taborelli and S. Onori, "State of charge estimation using extended Kalman filters for battery management system," 2014 IEEE International Electric Vehicle Conference (IEVC), 2014, pp. 1-8, doi: 10.1109/IEVC.2014.7056126.

[2] yu, Zhihao & Huai, Ruituo & Xiao, Linjing. (2015). State-of-Charge Estimation for Lithium-Ion Batteries Using a Kalman Filter Based on Local Linearization. Energies. 8. 7854-7873. 10.3390/en8087854.

[3] Texas Instruments. "Reverse Current/Battery Protection Circuits". 2003.

[4] Zhang, Ruifeng & Xia, Bizhong & Li, Baohua & Cao, Libo & Lai, Yongzhi & Zheng, Weiwei & Wang, Huawen & Wang, Wei & Wang, Mingwang. (2018). A Study on the Open Circuit Voltage and State of Charge Characterization of High Capacity Lithium-Ion Battery Under Different Temperature. Energies. 11. 2408. 10.3390/en11092408.

[5] Rzepka, Benedikt & Bischof, Simon & Blank, Thomas. (2021). Implementing an Extended Kalman Filter for SoC Estimation of a Li-Ion Battery with Hysteresis: A Step-by-Step Guide. Energies. 14. 3733. 10.3390/en14133733.

[6] Plett, G.L. Extended Kalman filtering for battery management systems of Lipb-based HEV battery packs—Part 2. Modeling and identification. *J. Power Sources* 2004, *134*, 262–276.

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