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State of Charge (SOC) Estimation of Li-Ion Battery

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***Abstract*— To carry out batteries optimum usage and preservation, battery management system (BMS) is employed. This BMS saves batteries from over-discharge, over-charge and maintain balance in cell. SOC estimation is of good sense for the secured operation of the battery. A correct SOC estimation is an important task. Increasing certainty of estimating SOC and reducing the complexness of model is very important for the state estimation. According to the most popular evaluation methods, Proportional-Integral (PI) Observer, Kalman Filter (KF) methods are projected for battery SOC estimation in EV. It is implemented in Simulink, and Python software. The performance comparison is done on the basis of graphs. It was aimed to catch the battery characterization and provide parameters to the system so as to estimate SOC precisely.**

Keywords*— State of Charge, PI Observer, Kalman Filter, Li-ion Battery, Electric Vehicle

I. INTRODUCTION

Electric vehicles (EVs) have a crucial role worldwide now. Being one of the foremost fundamental components in EVs, the battery has a great impact on the act of an EV. Considered as the only feasible solution for EVs in the current phase, li-ion battery has dragged complete attention. For estimating the drive distance of an EV, it is an important state. If we get a precise value for SOC estimation, the range that could be used to calculate drive distance can be protracted. The li-ion battery belongs to the type of rechargeable battery. These are electro-chemical systems with sturdy non-linearity, they shouldn't be over-charged or over-discharged to prevent damage to the battery, resulting in shortening of the battery life, or perhaps causing blast or catching fire [1].

The most important challenge for battery is estimating SOC. SOC of a battery is a vital parameter for a control strategy and it is employed to define its remaining capacity [2]. As we know, the SOC is a crucial parameter, as it reflects into battery behavior, therefore the accurate SOC estimation can not only save battery, but also limit over-discharge, improves the span of battery, and allow to make rational control approach to avoid power dissipation. It is a source of chemical energy storage, and directly accessing this energy is not possible. This problem makes the SOC estimation of battery tough [1]. Precise estimation of SOC remains terribly advance and is tough to carry out as the battery models are not much and we have parametric uncertainties.

SOC being one among the foremost vital specifications for batteries. SOC is calculated by the formula which is the ratio of current capacity denoted by (Q(t)) to the nominal capacity denoted by (Qn) of the battery [9]. The producer gives nominal capacity and also shows the maximum charge amount that can be stored in the battery. This is given by:

$$SOC(t) = \frac{Q(t)}{Q_n} \qquad (1)$$

There are number of methods for SOC estimation of Li-ion battery. The advantages and drawbacks of some of the methods are listed below [3]. The PI observer method is accurate, easy to use, and has less errors however, its disadvantage is robustness and fault estimation accuracy [1]. In the Coulomb Counting (CC) method, for SOC estimation the discharging current is measured of battery, and discharging current is integrated over time. It is uncomplicated and smooth to implement but, it needs prior knowledge of initial SOC and suffers from collecting errors of disturbance and measurement error [5]. The Open Circuit Voltage (OCV) methodology is about a linear relationship of SOC of the battery and its OCV. It is pretty much accurate, yet, it needs a long rest time for SOC estimation and, hence not feasible to use in real-time applications. Using the real-time measurement data for SOC estimation of the battery is hard and costly to measure [5]. The application of the Kalman Filter methodology is shown to provide verifiable SOC estimations for the battery by the real-time state estimation. It is accurate, online, and dynamic however, its disadvantage is it requires very complicated set of equations to urge results [11],[12]. The Neural Networks (NN) method has been used in many applications. In a non-linear system, it will effectively fit than on a linear system by calculating the correct coefficients of the learning mechanism [7]. It shows good results due to the powerful ability to approximate nonlinear functions but, it has drawbacks as the process is highly computational and very complex. The Internal Resistance method is simple and smooth however, its disadvantage is poor accuracy and also difficult to observe SOC [9].

In the paper, the non-PI Observer and PI observer method in Simulink, and Kalman Filter in Python is discussed. The paper is set in the following order. In Section II, we have discussed Battery Modelling. In Section III, we have discussed Software used for the estimation. In Section IV, we have listed and described the Methods of Estimation of SOC. In Section V, we have given the Results obtained from the methods used in detail which is followed by Conclusions in Section VI and References at the end.

II. BATTERY MODELLING

Battery Modelling is one of the vital steps. The Thevenin model is used for modeling the li-ion battery, however, it is not so accurate as all the parts can be amended, depending on the state of the battery and its conditions. It's difficult to get a simple battery model as the li-ion batteries are thought of to be advanced electro-chemical and robust nonlinear systems.

Many experiments are done for evaluation of the li-ion battery models, like the R-C first and second-order model, the impedance model, and many more [2],[12].

Research within the field of EV simulation, power circulation, and energy management strategy, and the SOC estimation of battery is experiencing a crucial increase. It has led the development in accuracy of battery models, particularly those regarding li-ion batteries has to turn into a vital objective. There are several parameters that have an effect on the battery model. It can be affected by surrounding noise, aging impact, the temperature in the surrounding, maintenance, application, and battery cycle [12].

A. Simple RC Model

Electrical equivalent circuit models have a combination of resistors, voltage sources, and capacitors. They work on modeling the behavior of battery. They are based on operating principles of the battery and reproduction of the dynamic attributes using circuit theory [1]. The R-C model of li-ion battery can be seen in fig 1. It has a voltage source ($E_0(z)$), a resistor (R_1), and a parallel capacitor (C_2) and resistor (R_2). R_1 is the battery resistance, polarization resistance denoted by R_2, transient voltage denoted by C_2 during discharging and charging. The voltage source (z) is the function of the SOC. The battery inner resistance is represented by the resistor. To model the chemical diffusion of electrolyte with the battery, capacitor C_2, and resistor R_2 are utilized [6].

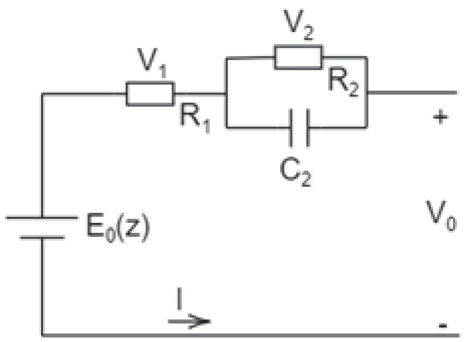

Fig. 1. Equivalent RC model circuit

The model is not precise, because of the model simplification, system non-linearity and unreliability of the real battery [10]. To satisfy the modelling errors, the nonlinear undefined noise is also given to the battery model.

$$\dot{V}_2 = -\left(\frac{1}{R_2C_2}\right)V_2 + \left(\frac{1}{C_2}\right)I + E_1v$$
$$\dot{z} = \left(\frac{n_i}{C_n}\right)I + E_2v \tag{2}$$
$$V_0 = E_0(z) + V_1 + V_2 + w$$

where v stands for disturbances, w stands for measurement errors, and coefficients of disturbances are denoted by E_1 and E_2.

B. Observer Model

Observability is the measure of how perfectly the internal states of a system can be implied by realization of its external outputs. For a system to be observable, it must be possible to resolve the states from the output observation over a defined time span. The observability is important to solve the issues of rebuilding immense state variables from significant variables. The observability of the model must be evaluated in order to satisfy that the states of battery can be estimated by the represented battery model. The observability matrix of the Battery Model can be given as:

$$O = \begin{bmatrix} C \\ CA \end{bmatrix} = \begin{bmatrix} 1 & a_i \\ \left(\frac{-1}{R_2C_2}\right) & 0 \end{bmatrix} \tag{3}$$

In practical situations, under no conditions, (-1/R2C2) or ai would be equal to nil or zero. Thus, the observability matrix would always be full rank. Under all operating condition, the battery model is observable. Hence, estimating internal states of the battery is feasible [1].

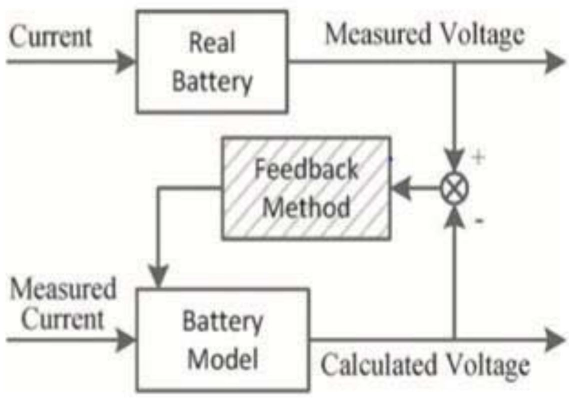

Fig. 2. Block diagram of Simple Feedback Model

Observer model as shown in fig 2, it has a Real Battery and Battery Model. The current is input to Real Battery and Measured Voltage is output. The input to battery model is Measured Current with feedback and output is Calculated Voltage. Feedback is the difference between Measured Voltage and Calculated Voltage. It is given to the Battery Model [13].

III. Software Design

A. Simulation Software

Simulation operating system or software is based on the operation of modeling actual circumstances with a collection of numerical equations. They are widely used to design equipment so that with less process modifications the end product is near to required specifications. When the fine for false operation is highly expensive, such as chemical factory operators, nuclear energy power plant operators, a clone of the original control panel is attached to a real-time simulation of the physical response, giving us the valuable coaching expertise without fear of a fatal result.

1) Advantages of Simulation

- It helps to study the performance of a system without building it.
- The results are correct in general, as compared to the scientific model.
- The unexpected behavior of the system can be determined.

- It helps to determine the correctness and efficiency of the system.

2) Disadvantages of Simulation

- It is expensive to develop a simulation model.
- It is costly to conduct a simulation.
- Sometimes it is tough for interpreting results of the simulation.
- In normal conditions effect on the system cannot be predicted in results.

B. *Software Required*

There is various software used by the users in order to get results for their problem statements according to the feasibility of the system. All software helps the user to achieve their target as per the built-in features and support the software can provide.

For estimating the SOC of the battery in the project we have used Simulink, and Python. In this section, we will describe the MATLAB Simulink, and Python software.

1) MATLAB Simulink: MATLAB is a multi-parameter numerical computing environment and proprietary coding language build by MathWorks. It is a superior language for technical computing. It allows users to do matrix manipulations, plotting of functions and knowledge, implementing algorithms, building up user interfaces, and connecting with codes written in various languages. Its typical uses include math and computation.

Simulink is a MATLAB based graphical programming environment for modeling, simulation, and to analyze multi-domain dynamic models. Its basic interface is a graphical block depiction tool and a custom pack of block libraries. It is widely used in automatic controlling and digital signal processor for multiple domain simulation and model-based design. A set of blocks is found in the block library which can be used by users in Simulink.

2) Python: Python is a high level, interpreted language. Python's style philosophy emphasizes code readability with its evident use of great white space. A number of essential libraries used for calculations and plotting results are matplotlib, math, and NumPy. It is a multi-parameter coding language. Several different paradigms are supported via extensions, including design by logic and contract programming. It also features dynamic name resolution, that binds techniques and variable names throughout program execution.

IV. Methods For Estimation

Battery being a strong nonlinear electro-chemical system, we cannot know about all the properties easily. There are various ways for SOC estimation of battery. From all the way to estimate, we have worked on a few methods and the results are shown in the next section.

A. *Simple Feedback Model*

The Simple Feedback Model is shown in fig 2. In this method, we don't have any block to update the results of the battery voltage. The change between the voltages is directly given to the battery model as one of the inputs with measured current [8].

For Simple Feedback, we have done a simulation of the model design as per the Simple feedback model circuit in MATLAB Simulink. The battery block named Equivalent Circuit Battery is available in the Simulink Library which requires parameters like Open circuit voltage E_m, Resistance R_1, Series resistance R_0, Capacitance C_1, Temperature. These parameters are already given in the required array form.

B. *PI Observer Model*

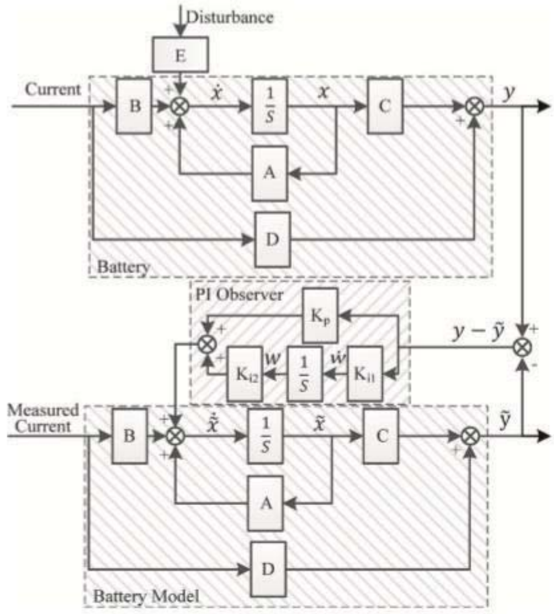

Fig. 3. Diagram of PI Observer Model

Proportional-Integral (PI) Observer model is shown in fig 3. In this method, we have a PID block. The difference between the Voltages is given to the Battery Model as one of the inputs with Measured Current. The PI observer SOC estimation methodology is based on the Luenberger observer method, and feedback signals has an integral part in addition to it.

The block is used in the PI mode. This block implements continuous-time and discrete-time PI control algorithms, also includes advanced features like anti-windup, external reset, and signal tracking. Considering the error present, we have a disturbance block added to the battery to get accurate results in Simulink.

PI tuning is the process of determining the values of proportional-integral gains of a PI controller in order to achieve desired performance and design requirements. The tuning appears easy, but is a complex work to determine the gain of your control system for best performance. They can be tuned manually or by rule-based methods.

C. *Kalman Filter based Estimation*

Kalman filter has a sequence of measurements decisive over time, having different turbulence and various defects. It produces estimates of undetermined variables that are more accurate rather than which are based on individual measurement, by estimating a probability distribution over the variables for every time frame.

It is an estimator that assumes required parameters from indirect, imprecise, and unsure measurements. The estimated state of the system is recorded and hence the variance of the estimate. It reduces the Mean-Square-Error (MSE) of predicted variables. It is based on linear dynamic systems discretized within the time domain within which estimated state from the previous time step and present measurement is required to estimate for the present state [11].

The sequence of the KF technique for estimating SOC is expressed as follows:

Prediction update:

$$\tilde{x}_r^- = A_d \tilde{x}_{r-1}^+ + B_d u_r$$
$$P_r^- = A_d P_{r-1}^+ A_d^T + Q$$

Kalman Gain matrix update:

$$K_r = P_r^- C_d^T (C_d P_r^- C_d^T + S)^- \quad (4)$$

State estimation update:

$$\tilde{x}_r^+ = \tilde{x}_r^- + K_r(y_r - C_d \tilde{x}_r^- - D_d u_r)$$

Error covariance update:

$$P_r^+ = (I - K_r C_d) P_r^-$$

where $\tilde{x}_r^-$ denotes prior state estimation at r step, $\tilde{x}_r^+$ denotes posterior state estimation at r step, P_r denotes error covariance at r step of state estimation, S denotes covariance of measurement error w, Q denotes covariance of disturbance v.

V. Results

It is clear that the error for these estimation strategies are not same. There are various types of errors that are present in the system. In the simulation, we get ideal solutions if we don't add noise or disturbance in the system or plant but in hardware, there is noise already present which causes errors in measurement and fluctuations in the path. Minimizing the errors helps us to get a more accurate estimation and desired measurement free from errors.

A. Simple Feedback Model

As seen from the block diagram in fig 2, there is no correcting block in the system which would minimize the error to get an accurate result. From the plot in fig 4, we can say that the Real Battery does not follow the same path of the Battery Model as there is no correcting element in the system.

They do not intersect each other's paths. Hence, non-PI observer block in the system does not give accurate results as it does not follow the path to the required one. Hence, it is not feasible to use a simple feedback model system to estimate SOC.

Error plot for non-PI observer is shown in fig 5 From the plot, the value of Error is high and increases with time. The error values are linearly increasing with time. Such error values are not suitable for the estimation of SOC. Hence, this method should not be used for the estimation of SOC.

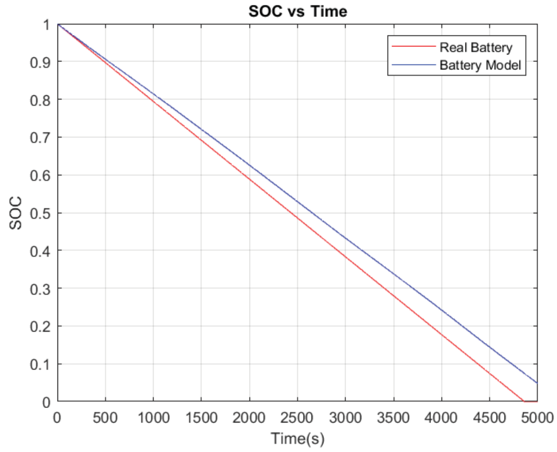

Fig. 4. SOC Vs Time for Simple Feedback Model

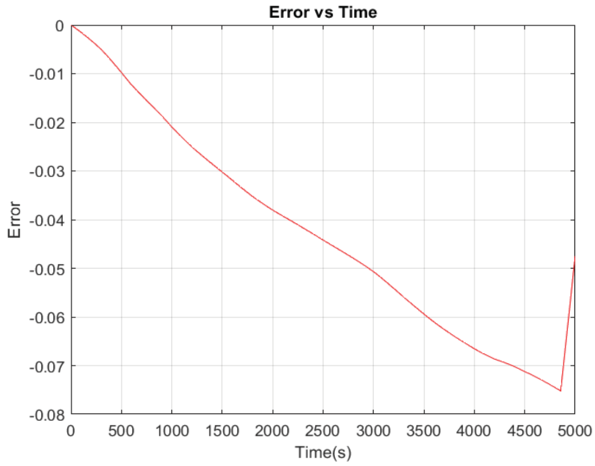

Fig. 5. Error Vs Time for Simple Feedback Model

The Battery Voltage vs Time plot for the Simple Feedback Model is displayed in fig 6. As it can be observed the graph, the Battery Model and Real Battery curve do not follow the same path. There is a sudden drop in the plot of real battery whereas the battery model curve increases in the beginning and drops linearly after a time span. Both curves have different endpoints. There are continuous changes in the plot. It doesn't follow a particular path.

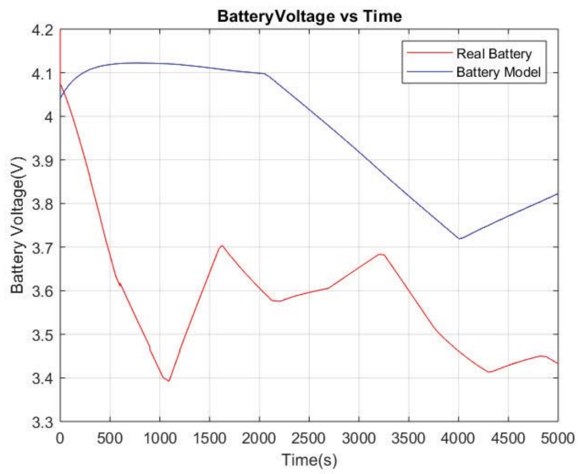

Fig. 6. Battery Voltage Vs Time for Simple Feedback Model

B. *PI Observer Model*

There is a block present in the system for correcting system errors and minimizing them continuously. It helps the system to get more accurate results and the error percentage is also reduced in a small percentage of the band. As can be seen from the plot fig 7 that the Real Battery follows the same path of Battery Model with some displacement due to disturbance in the surrounding which is added with the help of a white noise source block in Simulink. Adding disturbance helps to predict the surrounding conditions in which the system is placed. Hence, PI observer block in the system gives accurate results and is easy to use with fewer errors as compared to simple feedback method or non-PI observer block method. These errors can be minimized to a much smaller percentage we can get the actual conditions for the battery and the system.

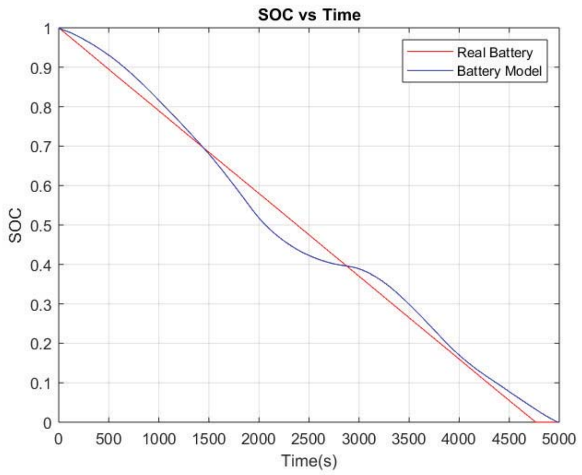

Fig. 7. SOC Vs Time for PI Observer Model

Error plot for PI observer is shown in fig 8. As can be seen from the plot the value of Error is very less. The values of the error curve lie between 0.07 units in positive y-axis to 0.04 units in the negative y-axis. Such results are suitable for estimation of SOC. Hence, this method can be considered for estimation of SOC of li-ion battery.

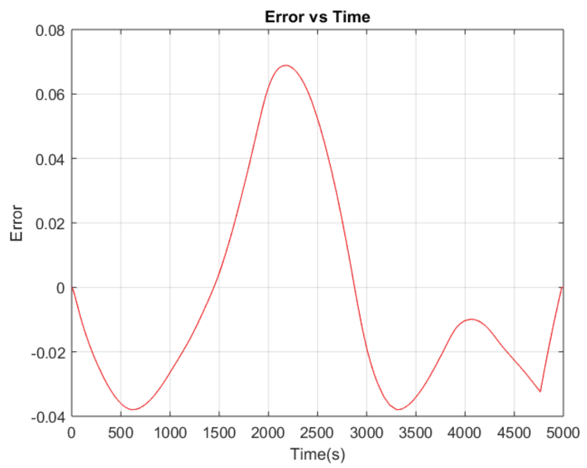

Fig. 8. Error Vs Time for PI Observer Model

The Battery Voltage Vs Time plot for the PI Observer Model is presented in fig 9. As it can be observed that the Battery Model curve and real Battery curve do follows the same path. There is a sudden drop in the plot of real Battery as well as the Battery Model curve. Both curves have the same path with a small error. There are continuous changes in the plot.

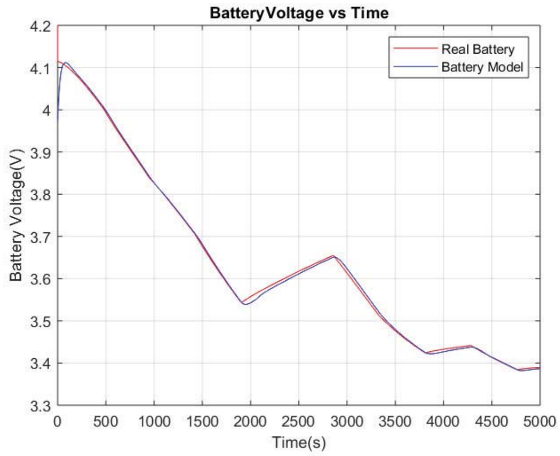

Fig. 9. Battery Voltage Vs Time for PI Observer Model

C. *Kalman Filter based Estimation*

KF is one of the most accurate methods. It has been used in various experiments to get the results. As it can be observed from the graph in fig 10 that the True SOC path is similar to the Estimated SOC path with some continuous displacement due to disturbance in the surrounding. This disturbance helps to get results in the surrounding conditions. This disturbance can be reduced if the noise is reduced which would bring us the ideal conditions. The plotted result is a simulation result in the python language. Hence, the KF method is accurate, online, and dynamic however, its drawback is it requires a highly complex set of equations to get results. It is the most accurate method from the methods listed in this work.

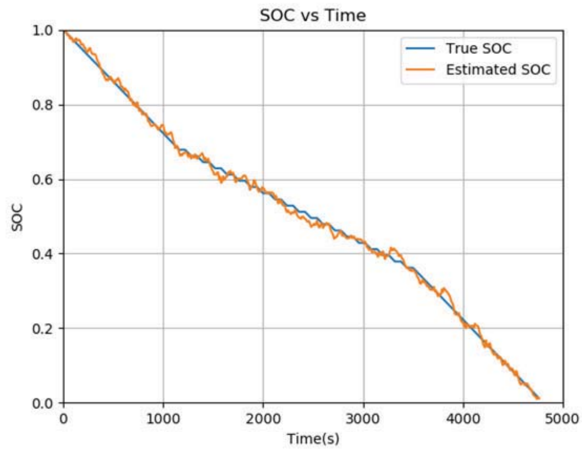

Fig. 10. SOC Vs Time for Kalman Filter Model

Error plot for KF Model is shown in fig 11. As you can see in the plot the value of Error is very less. The values of the error curve lie between 0.032 units in positive y-axis to 0.022 units in negative y-axis nearly. This is the most accurate result we were able to get from the methods used. Such results are perfectly suitable for estimating SOC. Hence, KF method should be used for estimating the SOC of li-ion battery.

The Battery Voltage Vs Time plot is given by fig 12 for the KF Model. It can be observed that the Battery Model curve (True Voltage) and (Measured Voltage) Real Battery curve follow the same path. There are many variations in the curves. Both the curves have the same path with small error. There are continuous changes in the plot.

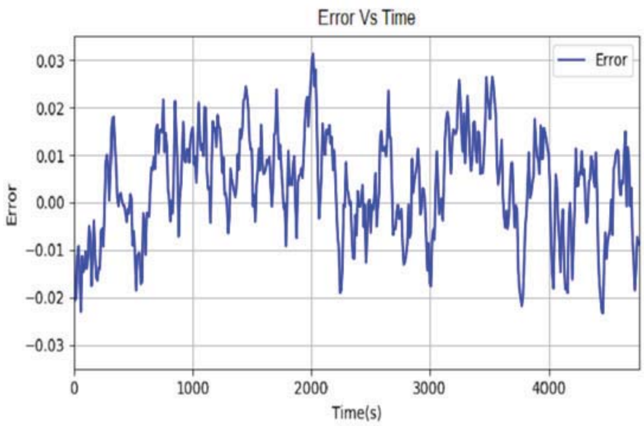

Fig. 11. Error Vs Time for Kalman Filter Model

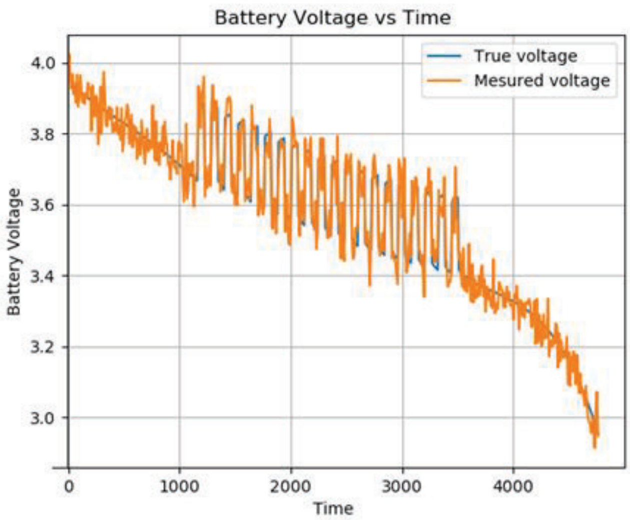

Fig. 12. Battery Voltage Vs Time for Kalman Filter Model

VI. CONCLUSION

From all the methods, we have used Simple Feedback Method, PI Observer Method, and Kalman Filter method for estimating SOC. From all the simulations, we can say that the best method to estimate SOC is Kalman Filter based method.

The PI Observer-based battery SOC estimation algorithm has been suggested for li-ion battery as it includes easy modeling also the properties indicate that a non-complex R-C model may be appropriate for modeling of the li-ion battery. The curves of Estimated SOC and the Reference SOC coincides with each other very fast, and the error values are seen in a short band.

From the above methods used for estimating the SOC of the li-ion battery, we are able to say that the Kalman filter methodology is incredibly correct than the rest methodologies. It shows results with minimum error within the prediction when compared to PI observer and Non-PI observer method.

REFERENCES

[1] Jun Xu, Chunting Chris Mi, Binggang Cao, Junjun Deng, Zheng Chen, Siqi Li, "The State of Charge Estimation of Lithium-Ion Batteries Based on a Proportional-Integral Observer," IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, VOL. 63, NO. 4, MAY2014.

[2] J. Xu, C. Mi, B. Cao, and J. Cao, "A new method to estimate state of charge of Li-ion batteries based on the battery impedance model," J. Power Sources, vol. 233, pp. 277–284, Jul. 2013.

[3] Zhongyue Zou, Jun Xu, Chris Mi, Binggang Cao and Zheng Che, "Evaluation of Model Based State of Charge Estimation Methods for Lithium-Ion Batteries, "Energies 2014, 7, 5065-5082; doi:10.3390/en7085065

[4] X.Hu, F.Sun, and Y.Zou, "Estimation of state of charge of a Lithium-ion battery pack for electric vehicles using an adaptive Luenberger observer," Energies, vol. 3, no. 9, pp. 1586–1603, 2010.

[5] Matúš Danko, Juraj Adamec, Michal Taraba, Peter Drgona. "Overview of batteries State of Charge estimation methods" , Transportation Research Procedia, 2019

[6] Wang, Yujie, Duo Yang, Xu Zhang, and Zonghai Chen. "Probability based remaining capacity estimation using data-driven and neural network model", Journal of Power Sources, 2016.

[7] Jozsef Menyhart, Robert Szabolcsi. "Artificial Intelligence Applied for Technical Status Diagnostics of the Batteries of Automated Guided Vehicles" , 2019 International Conference on Military Technologies (ICMT), 2019

[8] Bai, Guangxing, Pingfeng Wang, Chao Hu, and Michael Pecht. "A generic model-free approach for lithium-ion battery health management" , Applied Energy, 2014.

[9] Wen-Yeau Chang, "The State of Charge Estimating Methods for Battery: A Review, " Volume 2013 |Article ID 953792

[10] Jun Xu, Binggang Cao, Junyi Cao, Zhongyue Zou, Chunting Chris Mi, Zheng Chen. "A Comparison Study of the Model Based SOC Estimation Methods for Lithium-Ion Batteries" , 2013 IEEE Vehicle Power and Propulsion Conference (VPPC), 2013

[11] Furqan Asghar, Muhammad Talha, Sung Ho Kim, In-Ho Ra. "Simulation Study on Battery State of Charge Estimation Using Kalman Filter" , Journal of Advanced Computational Intelligence and Intelligent Informatics, Vol.20No.6,2016

[12] H.He, R.Xiong, X.Zhang, F.Sun, and J.Fan, "State-of-charge estimation of the Lithium-ion battery using an adaptive extended Kalman filter based on an improved Thevenin model," IEEE Trans. Veh. Technol., vol. 60, no. 4, pp. 1461–1469, May 2011.

[13] Z. Yang, D. Patil, B. Fahimi. "Online Estimation of Capacity Fade and Power Fade of Lithium-Ion Batteries Based on Input–Output Response Technique" , IEEE Transactions on Transportation Electrification, 2018