I J C T A, 9(16), 2016, pp. 8303-8312

Modified State Variable Approach using Kalman Filter for Battery Management of Electric Vehicle

Shruthi S.* and Supriya P.**

ABSTRACT

With a major global focus on sustainability and green environment, electric vehicles are likely to replace the conventional vehicles within two decades from now. Battery is a core component for electric vehicle. Suitable techniques for state of charge (SoC) estimation is significant in the battery of an electric vehicle. Various batteries could be employed for charge estimation. A single Lead acid battery is employed for the work. It is modeled with RC circuit model by using two state variables instead of the conventional three state variable. A discrete Kalman Filter is applied to the model and the SoC are compared for computation time and error. Graphs with SoC vs. time index using the two state variable and conventional method indicates that the two state variable approach converges in a shorter time. It is proposed to implement the Kalman based SoC estimation on an embedded platform.

Keywords: RC Circuit Model, Predict Equation, Update Equation, Terminal Voltage, State of Charge, Kalman Filter.

1. INTRODUCTION

Globally 15% of manmade carbon dioxide emission is from vehicles which causes pollution and global warming. In order to conserve energy and environment, development of electric vehicles are gaining more importance. In general battery forms the heart of electric vehicles, hence for effective battery management certain factors that affect the lifetime and performance of the battery has to be considered which can be regulated by estimating State of Charge (SoC) and State of Health (SoH) [6] of batteries. SoC of battery is an important parameter that has to be considered for intelligent battery management system [6][7], SoC is similar to fuel gauge in gasoline vehicles i.e. the SoC of the battery represents the amount of remaining power that is available in battery or it represents the amount of possible power that can be drawnfrom the battery. State of Health is another parameter that affects certain factors of battery like aging, lifetime, etc. In this paper the SoC of battery is estimated which helps tobalance the energyin battery without damaging it and also gives the distance until which the vehicle can travel with the amount of available power in the battery. SoC also indicates whether the driver has to recharge the battery or the remaining power available in the battery is sufficient to reach the appropriate destination. There are many algorithms proposed to estimate SoC of the battery, in this paper SoC of the battery is estimated using well known Kalman filter algorithm. Kalman filter is used as an estimator to find the SoC of battery. Section II gives the summary of related work done in SoC.

2. RELATED WORK

Traditionally there are various methods available to estimate the SoC of the battery [6][7][8], among them some of the methods used are Open Circuit Voltage method [6], the main disadvantage of this method is

---

* PG Research Scholar Department of Electrical and Electronics Engineering Amrita School of Engineering, Coimbatore Amrita Vishwa Vidyapeetham Amrita University, India, *Email: shruthisrikumaar@yahoo.com*

** Associate Professor Department of Electrical and Electronics Engineering Amrita School of Engineering, Coimbatore Amrita Vishwa Vidyapeetham Amrita University, India, *Email: psupriyamohan@gmail.com*

that it is efficient when the vehicle is at stop condition, the second method is Ah Counting method but its drawback is its high percentage of error, the other methods are Neural Networks [3][7][8], Direct measurement method [6], Kalman filter [1][6]. Neural networks is one of the efficient algorithm [3]to estimate SoC of the battery but the main drawback of Neural Network is its complex calculations and large reference data is required for calculations [8], whereas Kalman filter is a brilliant algorithm to estimate SoC of the battery using update and predict equations its famous for its less complexity and efficient estimation of the unknown parameter.

In this paper SoC of the battery is estimated using Kalman Filter algorithm. There are certain factors which has to be taken into account before estimating SoC of the battery [6][7] because SoC can be affected by factors like temperature, charging and discharging rates, self-discharge, aging etc. In this paper Lead Acid battery is chosen to estimate its SoC using Kalman filter. It is necessary to develop a battery model [1][2][3] to calculate certain parameter values of battery for estimating SoC.Plenty of battery models are available nowadays, among them the RC battery model [1-4] is used in this paper to design Lead acid battery, for further estimation of SoC using Kalman filter algorithm[1][2][3]. The problem formulation and methodology are described in section III. The results and comparison of existing and modified method are discussed in section IV. Conclusions and future work are given in section V.

3. PROBLEM FORMULATION AND METHODOLOGY

The SoC of the battery is an important factor that has to be considered in electric vehicles because the precise estimation of SoC helps to prevent the battery from over discharging or charging which in turn helps to increase lifetime of the battery. By estimating SoC the driver can know whether the remaining amount of energy available in the battery is sufficient to travel further to reach the destination or it has to be recharged. The charge stored in the battery can be optimized by accurate SoC determination.

In this paper the parameters involved in estimating SoC [1][2] are taken into consideration and SoC of lead acid battery is calculated by using a well-known recursive algorithm known as Kalman Filter (KF) [1][2][3][4][8]. KF algorithm has many advantages over other traditional algorithms, KF predicts the next possible SoC value even though when the vehicle is in running condition.

Estimation of SoC using KF is an existing method but the state space modeling of the existing work [1][2] is different from the state space modeling done in this paper. The state variables considered for state space modeling are the two capacitor voltages which is shown in Fig. 1.

There are three steps to be followed to estimate the SoC using Kalman Filter the first step is modeling of battery, second step is state space modeling for the battery model and the third step is application of KF algorithm to estimate terminal voltage of the battery equivalent circuit model and further using the predicted terminal voltage using Kalman Filter the SoC can be estimated. The major focus of the work is applying a two state variable approach for the battery model. This reduces the computational burden of KF and also results in error reduction.

3.1. Lead Acid Battery Modelling

Several battery models are available in literature like RC battery model, Thevenin battery model, Rendell battery model etc. The proper choice of right battery model is essential for estimating SoC accurately. In view of its simplicity and dynamic characteristics RC circuit model is selected in this work.

The battery model comprises of two capacitors namely bulk capacitor and surface capacitor. In battery modeling the location of the capacitors has gained significant role in overall performance of the circuit. The bulk capacitor which is denoted as V_{blk} is used for charge storage (i.e., it acts as an energy storage element in the model). The surface capacitor is used to calculate the surface capacitance of the battery.

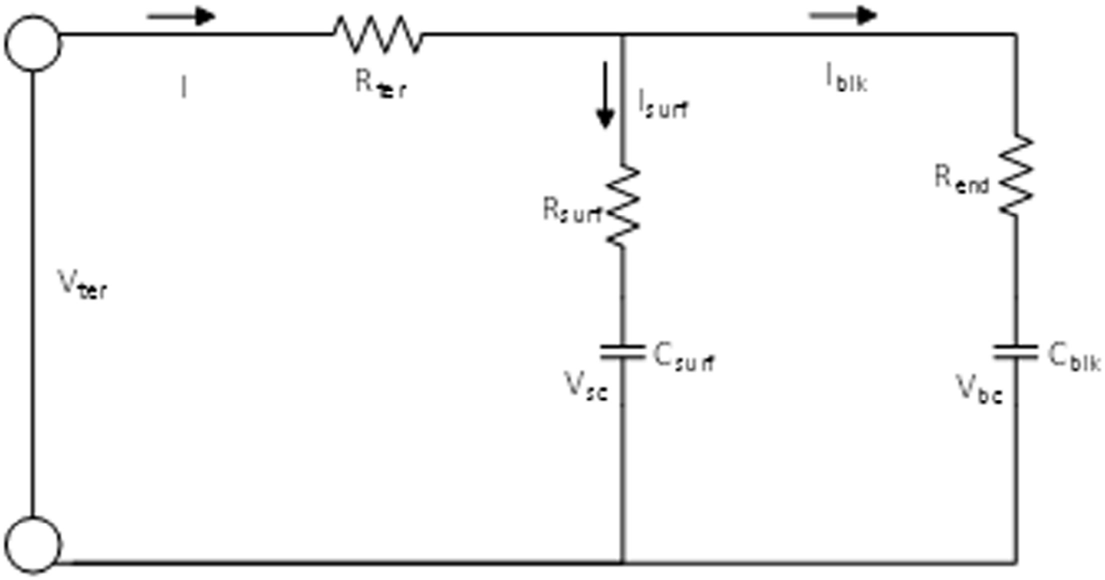

Figure 1: RC model of Lead Acid Battery

Voltage across the bulk capacitor is noted as V_{blk}, the voltage across the surface capacitor is denoted as the V_{surf} and the respective currents of RC battery model is denoted as I, I_{surf}, I_{blk}. The state space modeling of battery is done by considering the two state variables (voltage across bulk capacitor and voltage across surface capacitor) using state space equations which is explained in subsection B. Representation of RC battery model is shown in Fig. 1.

The V_{ter} and I can be measured from the RC battery model and the SoC is represented in terms of parameters like V_{sc}, V_{bc} R_{ter}, R_{surf} and R_{end}.

Where,

V_{ter} – Terminal voltage,
V_{sc} – Surface voltage,
V_{bc} – Bulk capacitance voltage,
R_{ter} – Terminal resistance,
R_{surf} – Surface resistance,
R_{end} – End resistance.

The values of capacitors and resistors used in the lead acid RC battery model is given in Table I.[2]

By applying basic circuit network theories the following equations are derived from the above battery model.

Table 1
Values Of Resistors And Capacitors Of Rc Battery Model

Bulk Capacitor	8837.83 F
Surface Capacitor	82.11 F
Terminal Resistor	0.0002745 Ω
End Resistance	0.00375 Ω
Surface Resistance	0.375 Ω

The terminal voltage of the RC battery can be represented as,

$$V_{ter} = IR_{ter} + I_{blk}R_{end} + V_{bc} \tag{1}$$

Similarly, the terminal voltage of the RC model of lead acid battery can also be written as,

$$V_{ter} = IR_{ter} + I_{blk}R_{surf} + V_{sc} \tag{2}$$

From the above two equations,

$$I_{blk}R_{end} = I_{surf}R_{surf} + V_{sc} - V_{bc} \tag{3}$$

By applying Kirchhoff’s current law to Fig. 1, the following equations are obtained

$$I = I_{surf} + I_{blk} \tag{4}$$

Therefore,

$$I_{surf} = I - I_{blk} \tag{5}$$

By substituting equation (5) in equation (3) equation (6) is formed.

$$I_{blk}(R_{surf} + R_{end}) = IR_{surf} + V_{sc} - V_{bc} \tag{6}$$

Using the above voltage and current equations the State Space modeling of RC battery model is done in the next section.

3.2. State Space Modelling of RC circuit

The state space modeling of the battery is the second step that has to be followed to predict SoC, the state space modeling helps to compute what will be the future value of a particular state variable of the model. The state variable is not unique for any system. In this paper the state space modeling is done for the RC battery model which is represented above in Fig.1.Hence, the proposed work employs two state variables namely, bulk capacitor (V_{bc}) and the voltage across the surface capacitor (V_{sc}) and terminal voltage (V_{ter}). Considering V_{bc} and V_{sc} as state variables for the RC battery model explained in III.A; 7, 8 & 9 equations are obtained. It is know that, $i = C\frac{dv}{dt}$, assume that the bulk capacitance is varying with a low gradient then the voltage across the bulk capacitor can be given as,

$$I_{blk} = C_{blk}\dot{V}_{bc} \tag{7}$$

Substituting equation (7) in equation (6),

$$\dot{V}_{bc} = \frac{I_{surf}R_{surf}}{C_{blk}\left(R_{surf} + R_{end}\right)} + \frac{V_{sc}}{C_{blk}\left(R_{surf} + R_{end}\right)} - \frac{V_{bc}}{C_{blk}\left(R_{surf} + R_{end}\right)} \tag{8}$$

Similarly the voltage across the surface capacitor can be denotes as,

$$\dot{V}_{sc} = \frac{I_{surf}R_{surf}}{C_{blk}\left(R_{surf} + R_{end}\right)} - \frac{V_{sc}}{C_{blk}\left(R_{surf} + R_{end}\right)} + \frac{V_{bc}}{C_{blk}\left(R_{surf} + R_{end}\right)} \tag{9}$$

The two standard equations for state space modeling are,

State Equation:

$$\dot{x} = Ax(t) + Bu(t) \tag{10}$$

Output Equation:

$$Y(t) = C\dot{x} + Du(t) \tag{11}$$

In this research the state variable and is given as,

$$\dot{x} = \begin{bmatrix} \dot{V}_{bc} \\ \dot{V}_{sc} \end{bmatrix} \tag{12}$$

and

$$x = \begin{bmatrix} V_{bc} \\ V_{sc} \end{bmatrix} \tag{13}$$

The input variable of the RC circuit model is current which is denoted as *u(t)* in equation (10). The A, B, C and matrix are obtained by state space modeling. The equations (8 and 9) can be further modified into equation (14 and 15) by substituting equation 16 and 17 in 8 and 9 which is represented below,

$$\dot{V}_{bc} = E.IR_{surf} + E.V_{sc} - EV_{bc} \tag{14}$$

$$\dot{V}_{sc} = F.IR_{surf} - F.V_{sc} + FV_{bc} \tag{15}$$

Where,

$$E = \frac{1}{C_{blk}(R_{surf} + R_{end})} \tag{16}$$

$$F = \frac{1}{C_{surf}(R_{surf} + R_{end})} \tag{17}$$

The current input to the RC battery model is represented as I, therefore, $u(t) = I$. Matrices A, B, C, D are calculated using state space modeling. The values of A, B, C, D are expressed in equations (18-21),

$$A = \begin{bmatrix} -E & E \\ F & -F \end{bmatrix} \tag{18}$$

$$B = \begin{bmatrix} R_{surf}E \\ R_{end}F \end{bmatrix} \tag{19}$$

$$C = \begin{bmatrix} \frac{R_{surf}}{(R_{surf} + R_{end})} & \frac{R_{end}}{(R_{surf} + R_{end})} \end{bmatrix} \tag{20}$$

$$D = \begin{bmatrix} R_{ter} + \frac{R_{surf}R_{end}}{R_{surf} + R_{end}} \end{bmatrix} \tag{21}$$

The derived values of A, B, C, D from equations 18-21 are substituted in equation 10 and 11 to obtain the exact state and output equations of the RC battery model which is given below, State Equation:

$$\begin{bmatrix} \dot{V}_{bc} \\ \dot{V}_{sc} \end{bmatrix} = \begin{bmatrix} -E & E \\ F & -F \end{bmatrix} \begin{bmatrix} V_{bc} \\ V_{sc} \end{bmatrix} + \begin{bmatrix} -R_{surf}E \\ -\dfrac{1}{C_{surf}} + F \end{bmatrix} I \tag{22}$$

Output Equation:

$$[V_{ter}] = \begin{bmatrix} \dfrac{R_{surf}}{(R_{surf}+R_{end})} & \dfrac{R_{end}}{(R_{surf}+R_{end})} \end{bmatrix} \begin{bmatrix} V_{bc} \\ V_{sc} \end{bmatrix} + \begin{bmatrix} R_{ter} + \dfrac{R_{surf}R_{end}}{R_{surf}+R_{end}} \end{bmatrix} I \tag{23}$$

The calculated two state space equations are used in Kalman filter for recursive estimation of terminal voltage. The next section of this paper deals with the state of charge estimation of the lead acid battery using KF algorithm.

3.3. Kalman Filter algorithm used to estimate terminal voltage

When an electric vehicle is considered to find out the State of Charge of the battery, it is compulsory to measure the terminal voltage of the battery at every instances but that is not possible by using old traditional methods, so Kalman Filter which is famous for its recursive algorithm is used to estimate to predict the terminal voltage of the battery at every instances. In this paper the Kalman Filter is used as an estimator to estimate V_{ter}. KF has standard five equations which is known as Predict and Update equations, those equations are used to find the value to be estimated. Update and predict equations are given below,

PREDICT:

1. $\hat{x}_n = A_n x_{n-1} + B_n u_n$
2. $P_n = A_n P_{n-1} A_n^T + Q_n$

UPDATE:

3. $\hat{x}_{n|n} = \hat{x}_{n|n-1} + K_n \left(y_n - \hat{x}_{n|n-1} \right)$
4. $K_n = P_{n|n-1} H_n^T (H_n P_{n|n-1} H_n^T + R_n)$
5. $P_{n|n} = (I - K_n H_n) P_{n|n-1}$

Where,

$\hat{x}_n$: Estimated state

A : Transition matrix of states

u : Control variables

Q : Process variance matrix (error due to process)

y : Measurement variables

H : Measurement matrix

K : Kalman gain

R : Measurement variance matrix

B : Control matrix

P : State variance matrix

The $\hat{x}_n$ is the value that has to be predicted using Kalman Filter in this work it is the terminal voltage that has to be estimated at every instances. The sampling time period is assumed to be -1 for discrete system here Ts = -1 is considered to be the sample time. Further the noise *W* and *V* are added for accurate results. *W* is a representation of presence of disturbance in system and some inaccuracies. *V* is due to the measurement noise effect. Once the both noises are taken into consideration the overall KF equation changes to as follows,

$$\dot{X} = AX(t) + Bu(t) + w \tag{24}$$

$$Y(t) = C\dot{X} + Du(t) + v \tag{25}$$

The process and measurement variance i.e. Q and R were assigned values as 1 and 10. Further the KF standard equations are executed simultaneously by substituting all values calculated and the terminal voltage is determined. Measurement error and estimated error is also calculated using the covariance which is shown in Table II. The ultimate advantage of Kalman Filter is that it minimizes the sum of mean square error.

4. RESULTS AND DISCUSSION

Simulation of KF algorithm to estimate SoC is done using MathWorks Inc. –MATLABR2015a software in Microsoft Windows 7. The terminal voltage estimated of lead acid battery model using KF and RC battery model by considering two state variables (V_{bc} and V_{sc}) is shown in Fig. 2. The Fig. 3. Shows the SoC calculated using terminal voltage estimated using KF by considering two state variables (V_{bc} and V_{sc}).

The calculation of SoC using V_{ter} is done by using equation 26. The terminal voltage and the SoC is estimated for 60, 000 time instants.

$$SoC = \frac{(V_{ter} - MinV)}{(OCV - MinV)} \times 100 \tag{26}$$

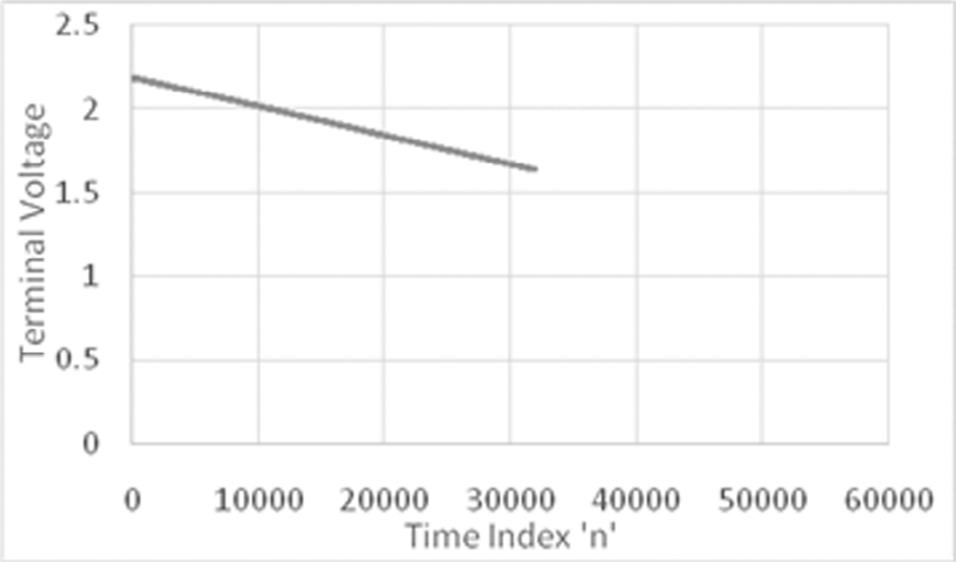

Figure 2: Estimated Terminal Voltage using KF by considering V_{bc} and V_{sc}

The results of three state variable conventional model [1][2][3] is discussed for completion the V_{ter} for such state space model for 60,000 seconds is portrayed in Fig. 4. The SoC of the same is plotted in Fig. 5.

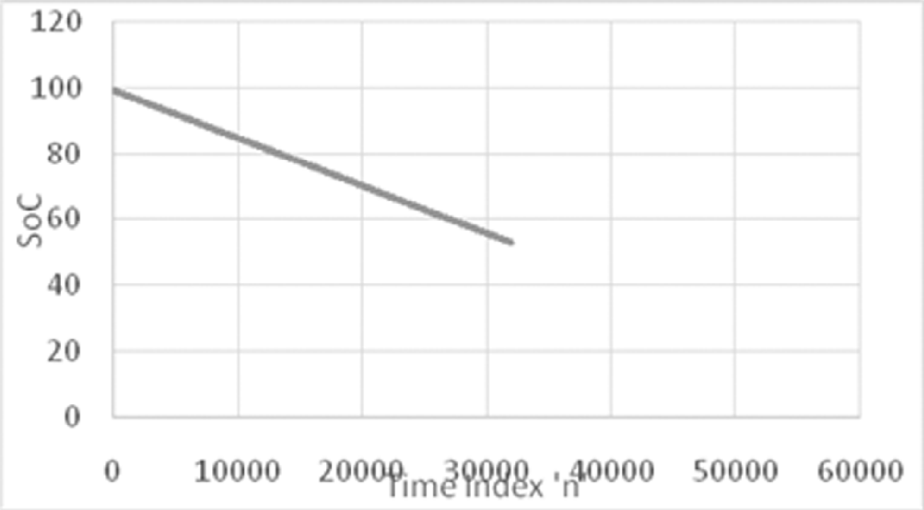

Figure 3: SoC of RC battery model using V_{bc} and V_{sc} as State Variables.

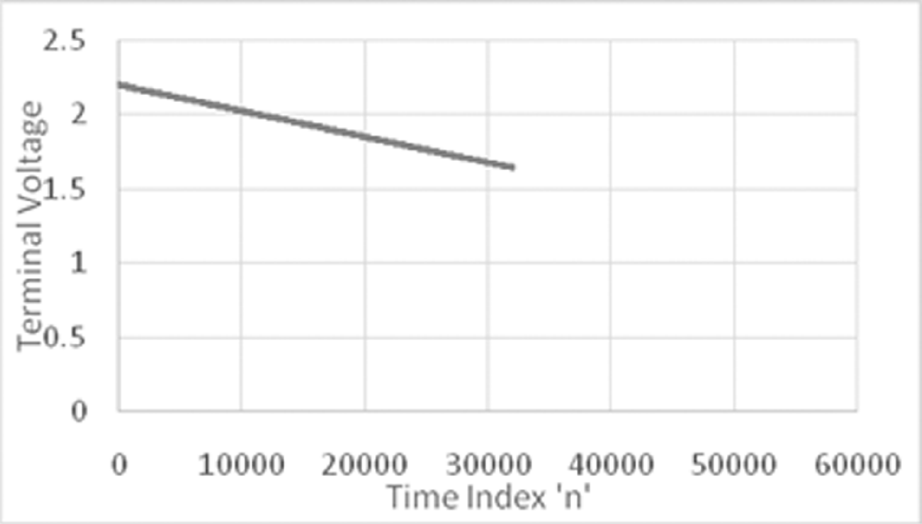

Figure 4: V_{ter} Estimated using KF for three variable State Space modeling

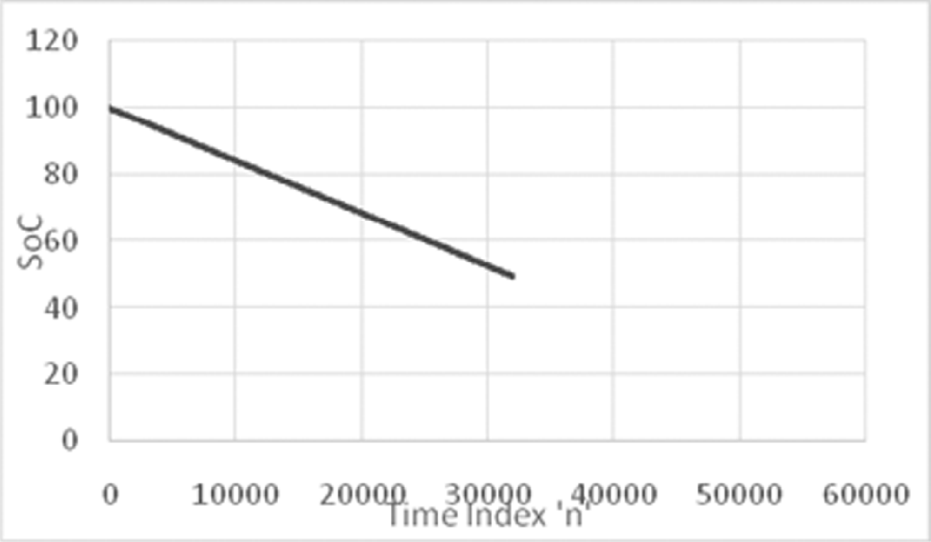

Figure 5: SoC calculated for three variable State Space model

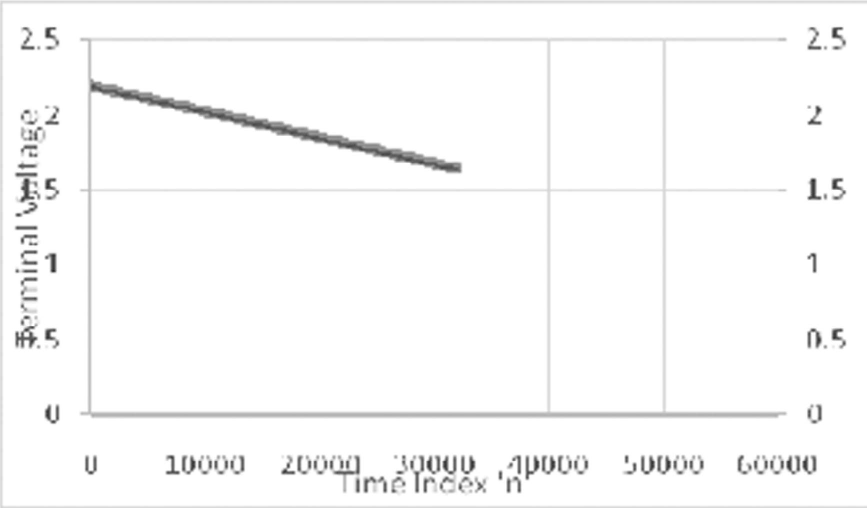

Figure 6: Comparison of estimated V_{ter} using two methods.

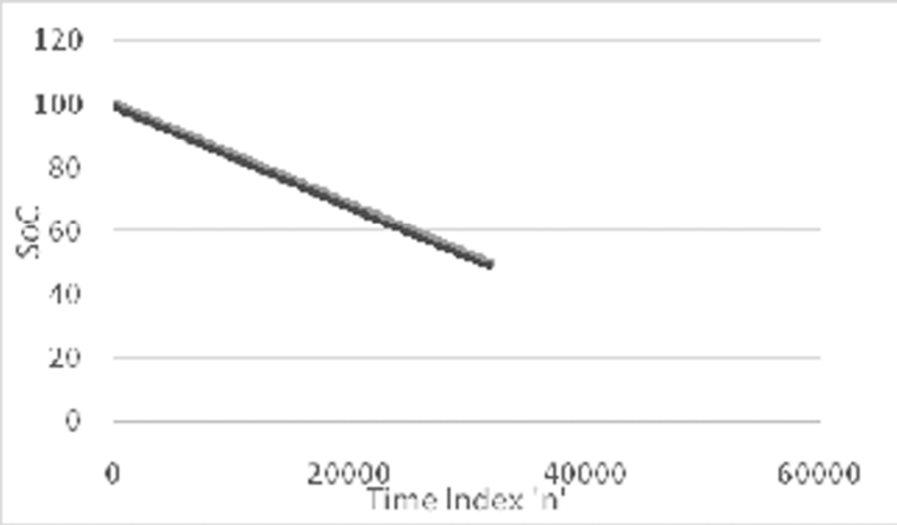

Figure 7: Comparison of SoC estimated using two methods

The comparison of terminal voltage estimated using KF from two different state space modeling is plotted in Fig. 6.

The comparison of SoC estimated using both the methods is shown in Fig. 7.

The comparison of the estimated error, the measured error and the time taken for execution of both the existing method and modified method is shown in Table. II.

Table 2
Comparison of Results Obtained Using Existing and Modified Method

Conventional Method (V_{bc}, V_{sc} & V_{ter})	*Proposed method* (V_{bc} & V_{sc})
MeasErrCov = 1.001360	MeasErrCov = 1.001360
EstErrCov = 1.918588e-04	EstErrCov = 1.579692e-05
Elapsed time = 0.263020 s	Elapsed time = 0.226151 s

From the above table, the estimated error covariance calculated using modified state variables is less compared to the estimated error covariance calculated using existing approach.

5. CONCLUSION

A two state variable approach for the RC circuit model of a Lead acid battery is proposed. The distinct advantage of this method over the conventional three state variable method with discrete Kalman Filter as an estimator is evident from Table II and from the graphs shown in Fig. 7. The error covariance calculated using the proposed method is less compared to that of the existing method. Since only two state variable is considered the computation complexity and time taken for execution of Kalman Filter algorithm is reduced when compared to conventional three state variable method. As part of the implementation it is intended to do a hardware justification for the SoC estimation using discrete Kalman Filter. Also other factors like temperature and age of the battery are likely to influence the SoC estimation.

REFERENCES

[1] Ting, T. O., KaLok Man, Chi-Un Lei, and Chao Lu. "State-of-charge for battery management system via kalmanfilter." IAENG Engineering Letters, vol. 22, pp. 75-82, 2014.

[2] Bhangu, Bikramjit S., Paul Bentley, David A. Stone, and Christopher M. Bingham. "Nonlinear observers for predicting state-of-charge and state-of-health of lead-acid batteries for hybrid-electric vehicles." Vehicular Technology, IEEE Transactions,vol. 3,pp. 783-794, 2005.

[3] T. O. Ting, KaLok Man, Eng Gee Lim, and Mark Leach,"Tuning of Kalman Filter Parameters via Genetic Algorithm for State-of-Charge Estimation in Battery Management System," The Scientific World Journal, 2014.

[4] Benila.B, S.Vasantharathna, S.Geetha, "Estimation of State Of Charge in Lead Acid Batteries Using Extended Kalman Filter," International Journal of Industrial Electronics and Electrical Engineering, Vol. 2, Issue-6, June 2014.

[5] A. Vasebi, S.M.T. Bathaee, M. Partovibakhsh, "Predicting state of charge of lead-acid batteries for hybrid electric vehicles by extended Kalman filter," Energy Conversion and Management, vol. 49, Issue 1, pp. 75-82, January 2008.

[6] Huihui, Wang, and Zhang Hongpeng. "SOC estimation and simulation of electric vehicle lead-acid storage battery with Kalman filtering method." In Electronic Measurement & Instruments (ICEMI), 2013 IEEE 11th International Conference on, vol. 2, pp. 599-603. IEEE, 2013.

[7] Wang, Haiying, Shuangquan Liu, Shiwei Li, and Gechen Li. "Study on State of Charge Estimation of Batteries for Electric Vehicle." In The 2nd International Conference on Advanced Signal Processing, ASP, vol. 3, pp. 10-14. 2013.

[8] Rahimi-Eichi, H. Mo-Yuen Chow, "Adaptive parameter identification and State-of-Charge estimation of lithiumion batteries," In IECON 2012-38th Annual Conference on IEEE Industrial Electronics Society, pp. 4012-4017, 2012.

[9] Rahimi-Eichi, H. Ojha, U. Baronti, F. Chow,"Battery Management System: An Overview of Its Application in the Smart Grid and Electric Vehicles," in Industrial Electronics Magazine, IEEE, vol. 7 no. 2, pp. 4-16, June 2013.

[10] Puranik, Shreya V., and Sadashiva Chakrasali. "Comparative Study on SOC Estimation Techniques for Optimal Battery Sizing for Hybrid Vehicles," International Journal on Recent and Innovation Trends in Computing and Communication, vol. 3, no. 4, pp. 2321-8169, April 2015.

[11] Amir Vasebi, Maral Partovibakhsh, S. Mohammad Taghi Bathaee, "A novel combined battery model for state-of-charge estimation in lead-acid batteries based on extended Kalman filter for hybrid electric vehicle applications," Journal of Power Sources, vol. 174, Issue 1, pp. 30-40, November 2007.