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Estimation of State-of-Charge and State-of-Health of Batteries by using Different Adaptive Techniques

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Abstract: ***To know the performance and life cycle of the battery State-of-Charge (SOC) has to be calculated. SOC cannot calculate directly. Many chemical factors are involved in batteries, which causes non-linear elements in the battery. Therefore, the prediction of SOC is difficult.in this paper different adaptive techniques are used to find the SOC. Adaptive systems can automatically adjust the SOC for different type of batteries. 2Ah rating Lithium-ion battery is consider to estimate SOC and related parameters. Open circuit voltage method, current integral method and modified Kalman filter methods are discussed to obtain the internal parameters (*** U_{oc}, R_{int}, R, C ***) of the battery.***

Index Terms: ***Electrical Vehicle (EV), Battery Electrical Vehicle (BEV), State of Charge (SOC), Depth of Discharge (DOD), Open Circuit Voltage (OCV), Partial Differential Equation (PDF).***

I. INTRODUCTION

In recent years, Electric vehicles (EV) and Battery Electric vehicles (BEV) are more popular due to their high efficiency, low pollutant and low emission. Electric vehicles and battery electric vehicles are more dependently on battery. To know the performance of the battery State-of-Charge (SOC) can be calculated. SOC can be defined as it is the ratio of present charge available in the battery to the to the total charge of the battery. It can be measured in percentage form; the remaining discharged charge is called as Depth of Discharge (DOD). To avoid overcharge and discharge of battery, estimation of SOC is required. For a system the input is taken as battery terminal voltage or discharge current and the output is taken as available charge present in the battery.

SOC indicators are displayed in the vehicle like a fuel indicator. The fuel level can be easily measured but the SOC directly cannot measured. To estimate SOC different methods are involved those are direct methods, indirect methods, adaptive methods and hybrid methods.

In this paper we are discuss about adaptive methods. Coulomb-counting method and OCV (open circuit voltage) methods are very popular to estimate SOC, But the above methods are not accurate to estimate SOC. In this paper adaptive methods are used, the SOC can be calculated directly according to the discharge appear in the battery.

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The methods will give more accurate and more reliable results. The basic difference of internal combustion engine (ICE) vehicle and Hybrid Electric vehicle (HEV) are discussed in the following comparison table (1).

Due to their self-designing nature the adaptive systems are automatically varies accordance to the changes occur in a system.

$$SOC = \frac{\text{Present charge available in the battery}}{\text{Total charge of the battery}} \%$$

From the figure (1), It is clear that Present charge available in the battery is 75% it is called as State-of-Charge (SOC) for the battery and remaining discharge 25% is called as Depth-of-Discharge.

$$SOH = \frac{\text{Current performance at variuos temperatures}}{\text{Total Capacity}}$$

Battery performance can be understood by calculating the SOH (State-of-Health). Based on charging and discharging at a particular temperature battery SOH is obtained. Once, Battery performance can understand the life cycle of battery can also predicted. Li-ion (Lithium-Ion) batteries are used to calculate the State-of-Charge, Li-ion batteries has many advantages, those are Li-ion batteries has low self-discharge rate, low coast, high reliable, high energy to weight ratio and high power to weight ratio.

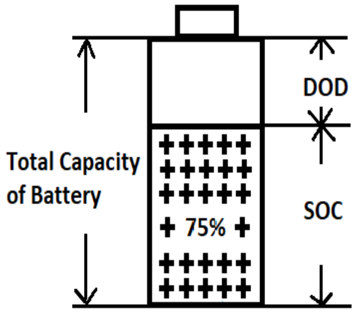

Fig. 1. Understanding diagram of SOC.

$$x(t) = x_0(t) - \frac{1}{Q}\int_0^t n\, i(t) \quad \ldots \quad (1)$$

Where x(t) is called as State-of-Charge (SOC), $x_0(t)$ is called as initial SOC, Q is called as rated capacity of the battery, $i(t)$ is called as instantaneous current.

Table.1. Comparison of ICEV versus HEV

Accessory	ICEV	HEV
power steering	Fan belt drives power-steering hydraulic pump	Electric motor directly drives power steering
Power brakes	Engine provides vacuum for power assist	Electric motor operates a vacuum pump for power assist
Air heating of passenger compartment	Hot water from engine cooling system	Electric heater or heat pump
12-volt accessories	Belt drives generator to charge battery	DC/DC converter reduces high voltage

II. BATTERY MODELLING:

In order to get the battery internal parameters (voltage, discharge current and temperature) and to manage the Battery Management System (BMS) we should go for modelling of battery. The most commonly used methods are Electrochemical model and Electric circuit model or Equivalent circuit model. Many Partial Differential equations (PDE) and Non-linear equations are present in Electrochemical modelling. Due the Non-linear equations the complexity increase and large number of unknown equations are also present. Therefore, Electrochemical models are not suitable for Battery Management system. For easy modelling of batteries equivalent circuit models are used, it consists of electrical sources such as Open Circuit Voltage (OCV), Terminal voltage, resistor and capacitors. Depends on the models the electrical parameters are connected in series, parallel, series/parallel manner.

The most commonly used equivalent circuit model is Thevenin's model. It consists of ideal open circuit voltage U_{oc} and a shunt resistance R_{int} are connected in series to the circuit. Therefore, it is called as Thevenin's model. RC parallel combination is added in series to the Thevenin model to increase the accuracy of the system. Consider less RC combinations, if we adding more RC combinations to the Thevenin model accuracy increase but the same complexity is also increase for designing the battery model. Equivalent circuit of a Lithium-ion battery as shown in Fig.2.

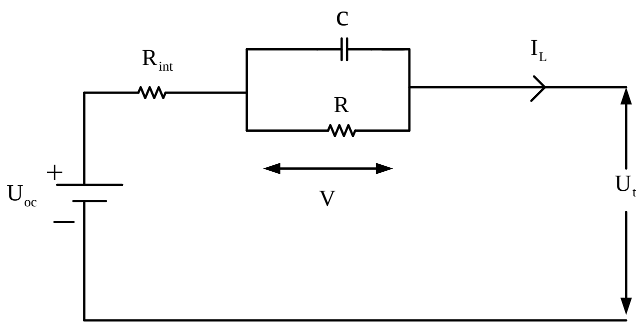

Fig.2. Equivalent circuit model of Lithium-ion model

From the Fig.2. U_{oc} is the Open Circuit Voltage (OCV) of a battery , R_{int} is internal resistance or shunt resistance U_t is the terminal voltage of a battery, Parallel RC combination is called as polarization resistance and capacitance of the battery and V is called as polarization voltage across the RC combination. Non-linear equations are present in the above battery model due to the Electrochemical operation. For modelling and to determine internal parameters the above equivalent circuit can be transferred into State Space Representation. The set of related equations are,

$$-U_{oc} + I_L R_{int} + V + U_t = 0 \quad \ldots \quad (2)$$

Assume Initial conditions are $u(t) = y(t)$, $x_1(t) = SOC$, $x_2(t) = V$.

$$V^{\bullet} = \frac{dv}{dt} = \frac{-V}{RC} + \frac{I_L}{C} \quad \ldots \quad (3)$$

From equation 2, U_{oc} is the function of SOC, therefore it can be written as

$$U_{oc} = U_t + V + I_L R_{int} \quad \ldots \quad (4)$$

$$SOC^{\bullet} = \frac{dU_{oc}}{dt} = 0 \quad \ldots \quad (5)$$

The State-Of-Charge (SOC) is mainly depends on rated capacity (Q) of the battery, therefore the state space representation as follows

$$\begin{pmatrix} SOC^{\bullet} \\ V^{\bullet} \end{pmatrix} = \begin{pmatrix} 0 & 0 \\ 0 & \frac{-1}{RC} \end{pmatrix} \begin{pmatrix} SOC \\ V \end{pmatrix} + \begin{pmatrix} \frac{1}{Q} \\ \frac{1}{C} \end{pmatrix} I_L \quad \ldots \quad (6)$$

Output equation $y(t) = U((t)$

$$U(t) = \begin{pmatrix} 0 & 1 \end{pmatrix} \begin{pmatrix} SOC \\ V \end{pmatrix} \quad \ldots (7)$$

From equations (6) & (7),

$$A = \begin{pmatrix} 0 & 0 \\ 0 & \frac{-1}{RC} \end{pmatrix}, B = \begin{pmatrix} \frac{1}{Q} \\ \frac{1}{C} \end{pmatrix}, C = \begin{pmatrix} 0 & 1 \end{pmatrix}, D=0;$$

To estimate the accurate SOC check whether the above state equations are controllable and observable, Therefore the observable and controllable representation is as follows.

$$Q_0 = \begin{pmatrix} C \\ CA \end{pmatrix}$$

$$Q_C = \begin{pmatrix} B & AB \end{pmatrix}$$

Where Q_0 & Q_C Are observability and controllability matrix representation

By applying row transformation method, the above matrix Q_0 is always full rank, therefore clearly it is observable and the battery states can easily estimate.

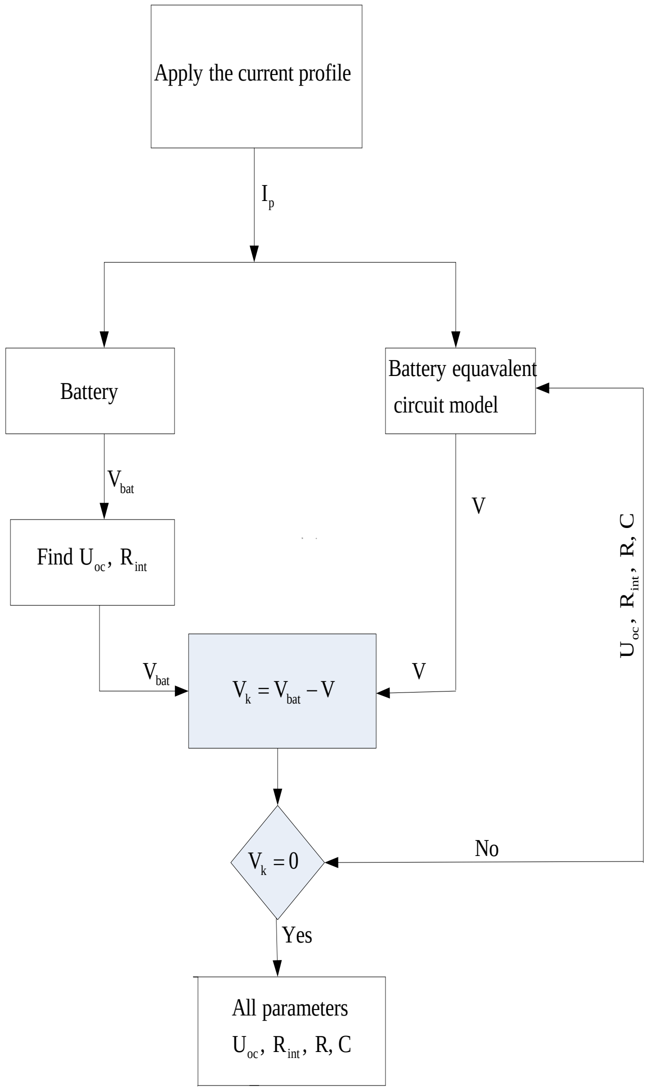

Fig.3. Diagram for steps to identify All parameters.

However, SOC is not a directly measurable Quantity for that so many estimation methods are involved to find accurate SOC. Although some estimation methods are proposed to get accurate SOC, the following methods are used to find the accurate SOC.

III. RESULT AND DISCUSSION:

Apply the current profile to the Li-ion battery under No-load condition, by using open circuit voltage method we should find the open circuit voltage. Once find the open circuit voltage calculation of internal resistance is very easy. Now we are already know the values of U_{oc}, R_{int} After that the battery is converted into the electrical circuit model i.e. Thevenin's model circuit as shown in the figure (2), from that electrical circuit model the polarization capacitance and resistance has to be evaluated by using different techniques. In this paper modified Kalman filter method is used to determine the above parameters (U_{oc} , R_{int} ,R and C) and compare with the basic current integral method . Therefore, from result and discussion point of view the basic current integral method and modified Kalman filter methods are discussed.

3.1. Open Circuit Voltage (OCV) Method:

Open Circuit Voltage (OCV) method is a direct method to determine the SOC, OCV is the difference between two terminals (positive, negative) or two ends of the battery without apply any load. the typical waveform of open circuit voltage versus SOC as shown in figure (4).

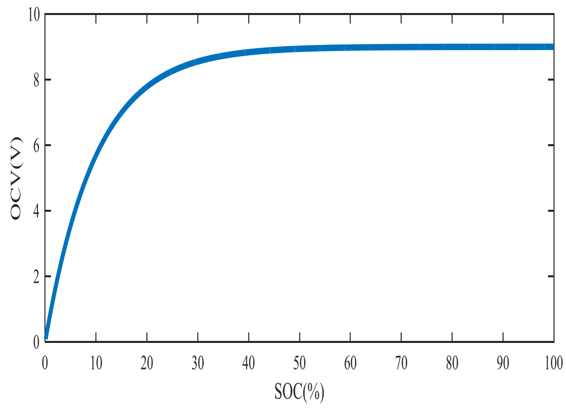

Fig.4. Typical Waveform of Open Circuit Voltage with respect to SOC

While testing of battery the Multimeter or voltmeter is used to determine the OCV, That OCV is directly proportional to the SOC or linear relation with SOC. For Lead-Acid battery the OCV is Linear relationship with SOC but for Li-Ion battery so many nonlinear parameters are involved therefore it is variable with temperature as shown in figure 4. For all batteries the relationship between OCV and SOC are vary with respect to the temperature and many chemistry related non-linear parameters

$$OCV(t) = a_1 x(t) + a_0 \qquad \dots (8)$$

Where $ocv(t)$ is the open circuit voltage of the battery $x(t)$ is the SOC of the battery at ' t 'and a_0 is the battery terminal voltage at SOC=0%. After obtaining a_0 , a_1 has to be find. the estimation of OCV is almost equivalent to the estimation of SOC.

3.2. Current Integral Method:

Current Integral Method is also known as coulomb-counting method or Ampere Hour method it was the simplest method to estimate the SOC. In order to get the SOC integrate the battery current (discharge/charge) with respect to time and it was depending on the previous value of SOC(t-1). The SOC can be determine by using following equation.

$$x(t) = (x_0(t-1) - \frac{1}{Q}\int_0^t ni(t)) * 100\% \qquad \dots (9)$$

Where x(t) is called as State-of-Charge (SOC) and $x_0(t-1)$ is called as Previous value of SOC at initial charge.

The initial charge can be obtained from above open circuit voltage method. Equation 9 can be written in the form of discrete recursive form as

$$x(k) = (x_0(k-1) - \frac{1}{Q}\int_0^t n(k)i(k)T_S) * 100\% \quad \ldots(10)$$

Where , T_S is the Sampling period in seconds.in a current integral method so many factors are affected the accuracy of SOC those are temperature, Discharge current and cycle life of a battery.it has a following difficulties to estimate the accurate SOC.

a) Current integral method integrates the charge/discharge current signal with respect to time, but it was avoiding Noise signal therefore the estimation of result becomes very poor.

b) n (Charge/Discharge Coefficient) is a time-variable one, it was depending on battery parameters especially more effect on temperature. when temperature is varies with respect to time then n cannot measure accurately.

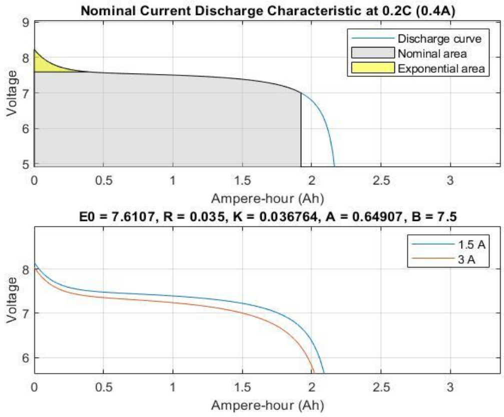

Fig.5. Nominal Current Discharge characteristics of 2Ah Battery at 0.4A rating using current integral method.

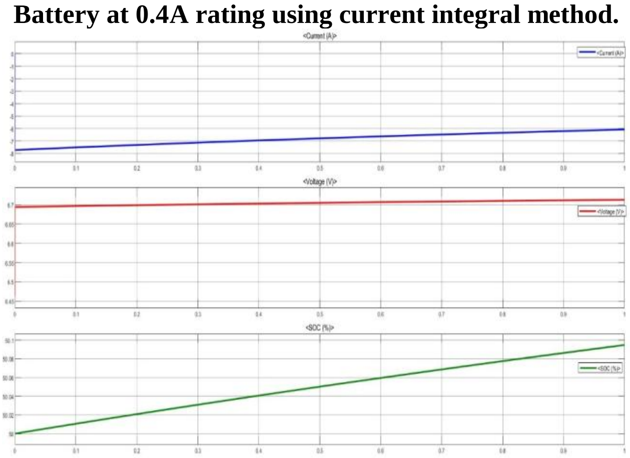

Fig.6. Current, Voltage and SOC Waveforms for the Current integral method.

3.3. Modified Kalman Filter:

The block diagram of modified Kalman filter as shown in the Figure (5). the state space representation of the battery is obtained from Figure (2), equations (3) and (5) represents the state space representation by including the estimated parameter SOC. Initialize or apply the current profile to the battery model and get the sigma points for the battery. For calculation of Kalman gain (K) compare the practical open circuit voltage to the evaluated voltage if the applied current has large initiative then modify the evaluated points accordingly Kalman's gain (K) Then only accurate SOC can be obtained.

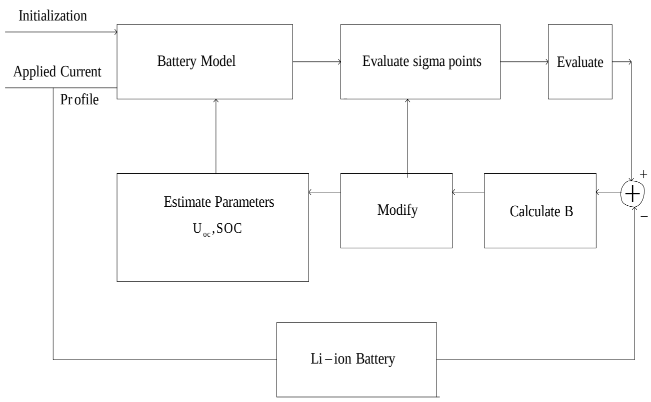

Fig.7.Block Diagram of Modified Kalman Filter.

Finally based on the voltage-current estimation Kalman gain, SOC and state matrix are in equation (6) and (7). The following difficulties are solved by using Modified Kalman filter method.

1) By using this method, we should not avoid the Noise signal therefore the estimated results are accurate compared to current integral method.
2) Charge/Discharge coefficient was mostly depending on temperature, while obtained this coefficient accurately without any effect.

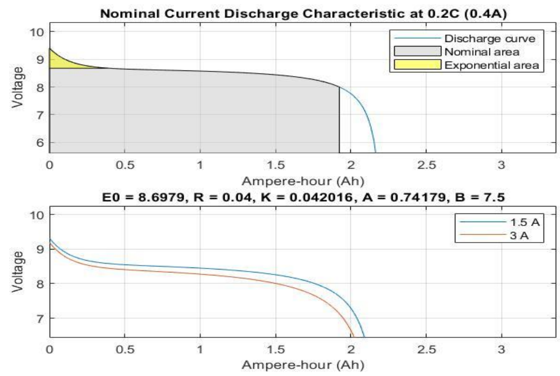

Fig.8. Nominal Current Discharge Characteristics of 2Ah Battery at 0.4A rating using modified Kalman filter.

Table.2. Specifications 2Ah Li-ion Battery 50% SOC

S. No	Parameter	Value	Units
1	Nominal Voltage	9	Volts
2	Rated Capacity	2	Ah
3	Initial SOC	50	%
4	Battery response time	10	Sec
5	Internal resistance	0.04	Ohm
6	Nominal Discharge current	0.86957	Amperes

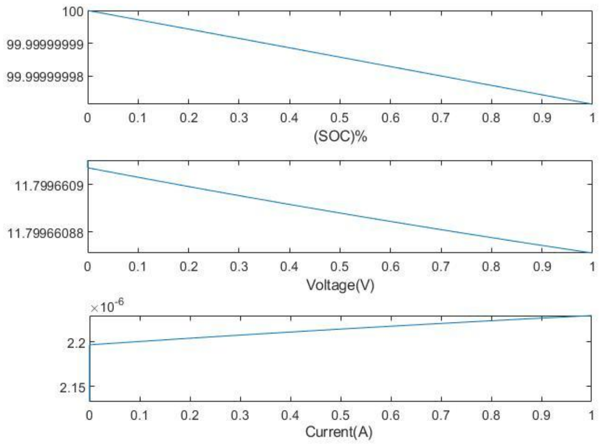

Fig.9. SOC, voltage and current waveforms of Modified Kalman filter.

IV. CONCLUSION AND FUTURE SCOPE:

This paper represents an alternate approach to estimate Accurate SOC. SOC estimation of Batteries in Electrical Vehicles (EV) are suffers from the noise and also temperature variation with respect to time. In this paper Open circuit voltage method, Current integral method and Modified Kalman filter methods are discussed. Among all above methods the Modified Kalman filter approach has given accurate results and also the battery internal parameters are calculated successfully without any effect. The future scope of this paper was online methods has to introduce to estimate accuracy SOC, those are Hybrid methods like Combined of ampere-hour method and Kalman filter method and also artificial neural network and Support vector-based methods are used.

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