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State of Charge Estimation for Series-Connected Lithium Battery Pack Using Extended Kalman Filter

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ABSTRACT: The battery pack is one of the main components in electric vehicles which is usually composed of many cells connected in series. Battery state of charge estimation is one of the most important functions of the battery management system in electric vehicles. Due to the different manufacturing and operational conditions, all of the cells in a battery pack do not have the same states of charge and therefore, the cell and pack states of charge are not the same. This paper presents a method for battery pack state of charge estimation which benefits rather low computational cost as well as the high precision. First, the coulomb counting method and the open circuit voltage graph, which is obtained from the experimental results, are used simultaneously to estimate the pack average state of charge. Then, the extended Kalman filter method is used to estimate the difference between the pack average state of charge with those of the cells. The proposed method has been evaluated and verified using an experimental test bench for three series-connected lithium cells. Experimental test results indicate good performance of the proposed method in estimating the lithium battery pack state of charge.

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1- Introduction

The battery pack is one of the most important parts of Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) such that the vehicle performance during acceleration, regenerative braking, gradeability and all-electric range of these vehicles depends on the design of the battery system [1]. The Battery Management System (BMS) in EVs and HEVs is used for monitoring, management and protection of the batteries. One the key tasks of BMS is to estimate the battery pack State of Charge (SoC) which is an indicator of battery available energy [2-4]. This paper presents a method for estimation of a Lithium-ion battery pack SoC considering the differences between the cells. The proposed method has been evaluated and verified using an experimental setup containing three LiFePO4 cells which are connected in series and the results approves the efficacy of the proposed SoC estimation method.

2- Battery Pack Mean SoC Estimation

In order to estimate the SOC for the cells in a battery pack, a mean model and mean SoC estimation of the pack is required. The mean model consists of an Equivalent Circuit Model (ECM) which describes the relation between the current and mean cell voltage of the pack. The ECM in this research consists of the open circuit voltage and a series resistance. In order to extract the parameters of the ECM, discharge and charge pulses are applied to the cells.

The developed experimental test bench is shown in Fig. 1 which consists of three LiFePO4 cells connected in series, BMS, relay and fuse for protection, shunt resistor for current measurement, discharge elements, power supply and a laptop computer capable of Controller Area Network (CAN) signal read for monitoring and storage of the test results. The pack mean open circuit voltage and internal resistance obtained from the charge and discharge pulses are depicted in Figs. 2 and 3.

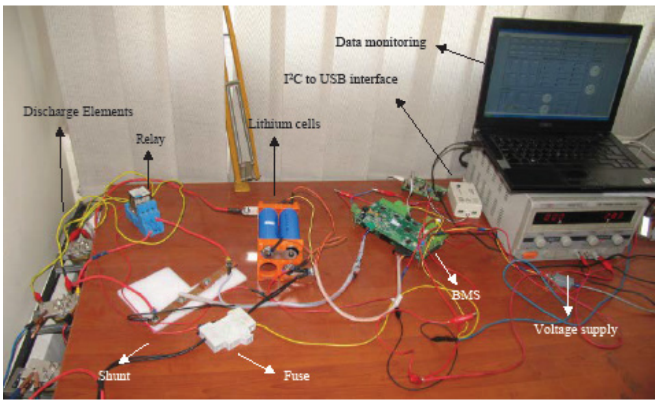

Fig. 1. Experimental test bench

To obtain the mean SoC for the pack, a combination of Coulomb counting method and the open circuit voltage is used. The estimated mean SoC during the discharge pulses is

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presented in Fig. 4 which shows maximum error of 2%.

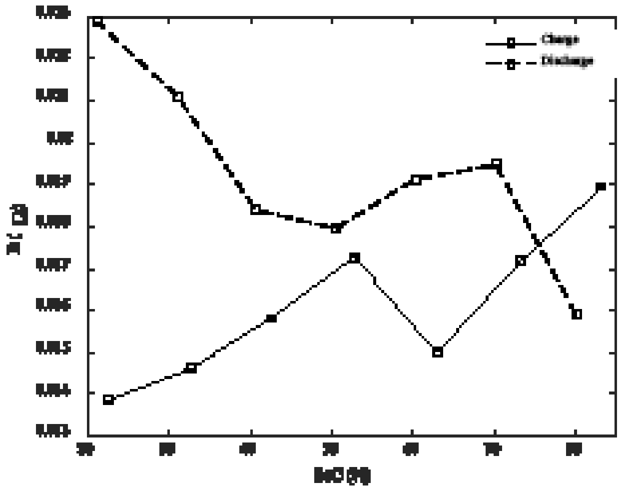

Fig. 2. Mean internal resistance vs. SoC

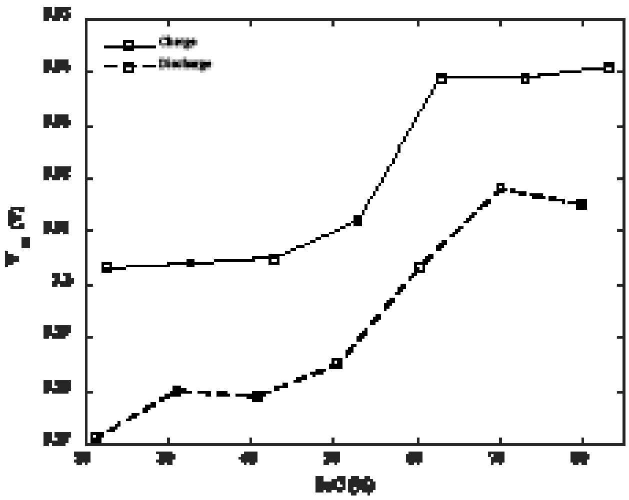

Fig. 3. Mean open circuit voltage vs. SoC

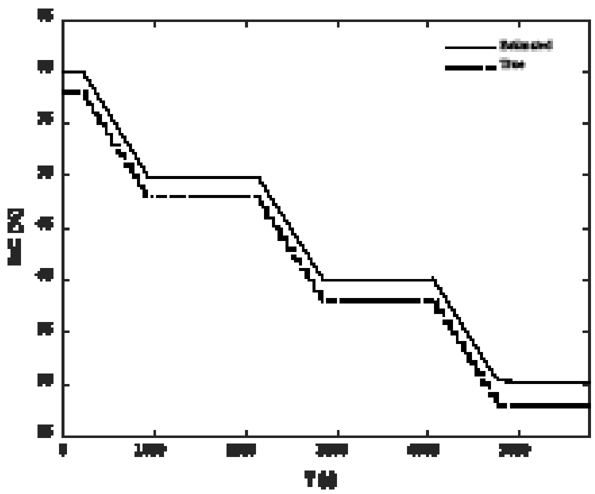

Fig. 4. Mean SOC during discharge pulses

3- Cell SoC Estimation Using Extended Kalman Filter

The Extended Kalman Filter (EKF) is a kind of Kalman filter which is used for estimation of the states or parameters in nonlinear systems. The EKF is applied for estimation of the SoC difference between the individual cells and the mean SoC of the pack. The formulation of EKF for state estimation is given in Table 1.

Table 1. EKF formulation

*Model	$x_{k+1} = f\left(x_k, u_k\right) + w_k$ $y_k = g\left(x_k, u_k\right) + e_k$
Definitions	$A_{k-1} = \left.\dfrac{\partial f\left(x_{k-1}, u_{k-1}\right)}{\partial x_{k-1}}\right\|_{x_{k-1}=\hat{x}_{k-1}^{+}}$ $C_k = \left.\dfrac{\partial g\left(x_k, u_k\right)}{\partial x_k}\right\|_{x_k=\hat{x}_k^{-}}$
Initial values	$\hat{x}_0^{+} = E\left[x_0\right]$ $P_0 = E[(x_0 - x_0^{+})(x_0 - x_0^{+})^T]$
Calculations	1. $\hat{x}_k^{-} = f\left(\hat{x}_{k-1}^{+}, u_{k-1}\right)$ 2. $S_k^{-} = A_{k-1} P_{k-1} A_{k-1}^T + \Sigma_w$ 3. $L_k = S_k^{-} C_k^T \left[C_k S_k^{-} C_k^T + \Sigma_v\right]^{-1}$ 4. $\hat{x}_k^{+} = \hat{x}_k^{-} + L_k\left(y_k - g\left(\hat{x}_k^{-}, u_k\right)\right)$ 5. $P_k = \left(I - L_k C_k\right) S_k^{-}$

*Parameters w_k and e_k are independent zero-mean Gaussian noises with variances Σ_w and Σ_e .

The state space equation used for estimation of the cells' SoC is given by Eqs. (1) and (2).

$$\begin{cases} \Delta R_k^i = \Delta R_{k-1}^i + w_k^R \\ v_k^i = V_{oc}\left(\bar{z}_k + \Delta z_k^i\right) - \left(\bar{R}_k + \Delta R_k^i\right) i_k + e_k \end{cases} \tag{1}$$

$$\begin{cases} \Delta z_k^i = \Delta z_{k-1}^i + w_k^z \\ v_k^i = V_{oc}\left(\bar{z}_k + \Delta z_k^i\right) - \left(\bar{R}_k + \Delta R_k^i\right) i_k + e_k \end{cases} \tag{2}$$

where Δz_k^i and ΔR_k^i are the difference between the SoC and internal resistance of the ith cell with the mean SOC and internal resistance of the pack, respectively, and and w_k^z are e_k zero-mean Gaussian noises. Since the differences between the mean and actual values of the SoC are low, it is possible to increase the time step of the estimation process to reduce the computational cost. Using the estimated states of the above system, the SoC and internal resistance of the cells can be calculated using the following equations:

$$\begin{cases} z^i = \bar{z} + \Delta z^i \\ R^i = \bar{R} + \Delta R^i \end{cases} \tag{3}$$

4- Results

In this section, the mean SoC and internal resistance are calculated using the approach explained in section 2 and the estimation is combined with the estimation based on the EKF to obtain the SoC for the pack. The relevant parameters for simulation are given in Table 2.

Table 2. Relevant parameters used in the simulation

Variable	Parameter	Value
Capacity	Q	10Ah
Initial SoC difference	Δz_0^i	0
Initial resistance difference	ΔR_0^i	0.02Ω
System noise variance	w_k^z	1×10^{-10}
Measurement noise variance	e_k	1×10^{-10}
System noise variance	w_k^R	1×10^{-10}
Initial value of the covariance matrix	P_0	10^5

The actual cell voltages and the estimation results are shown in Figs. 5 and 6. The maximum error of 3% is achieved is SoC estimation of the cells.

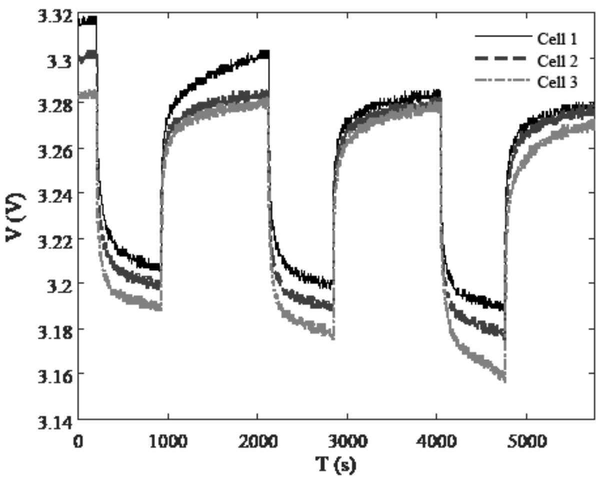

Fig. 5. Actual cell voltages

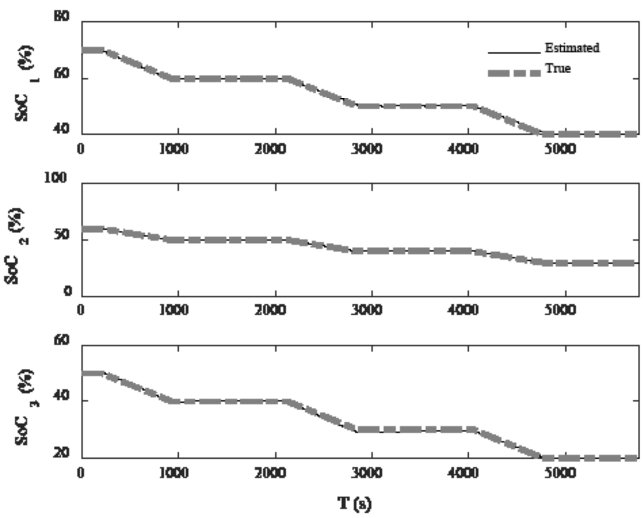

Fig. 6. SoC estimation results

5- Conclusion

In this paper, a SoC estimation method is presented for a battery pack containing series-connected cells. Using a combination of Coulomb counting method and the open circuit voltage the pack mean SoC is estimated. In addition, an EKF-based method is developed for estimation of the SoC deviations from the mean values. Experimental and simulation results approve the efficacy of the poposed estimation method.

6- References

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