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Estimation of SOC and SOH of Li-Ion Batteries

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ABSTRACT
Battery is the most widely used energy storage device. Since its invention, it has become a common power source for various household, commercial and industrial applications. Despite its ever increasing importance, many challenges remain unsolved to characterize and manage the battery. Among them, one fundamental issue is the estimation of state of charge (SoC), and Sate of health (SOH) of battery. SoC expressed in percentage, refers to the amount of capacity available in a battery. SoC is critical for modelling and managing batteries. If SoC is 100%, reflects a full battery and if SoC is 0%, reflects an empty battery. This project aims at developing an estimate the SoC and remaining runtime of a rechargeable battery. The combined estimation of SOC method is based on Coulomb Counting technique.

General Terms
Battery level Indicator, State of Charge (SOC), State of Health (SOH) Li-ion Battery.

Keywords
SOC of Li-Ion Battery, SOH of Li-ion Battery.

1. INTRODUCTION
State of Charge (SoC) of a battery indicates the capacity remaining inside the battery. SoC is usually expressed in percentage. If SOC is 100%, it indicates that the battery is fully charged. If SoC is 0%, it indicates that the battery is empty [1]-[12]. The SoC of a battery is simply calculated as,

$$SoC = SoC_i - \frac{\int I\,dt}{Q_{nom}}$$

SoC_i = Initial SoC

Q_{nom} = Nominal Capacity of Battery

I = Current flowing through the battery

The magnitude of current is taken as positive for discharging process and negative for charging process.

SoC determination is an increasingly important issue in battery technology. A precise knowledge of SoC provides additional control over charging and discharging process, which can be employed for better utilization of stored energy. Accurate SoC determination for battery powered applications is also important for user convenience. A good SoC estimation leads to longer battery life, better utilization of stored energy and increased reliability of the battery pack. SoC has strong dependency on temperature and age of the battery. The terminal voltages, operating currents and surface temperatures are the direct measurable parameters of a battery. But, the complex inter-relationship between these parameters makes SoC estimation an intricate task. Many attempts have been made in literature to estimate SoC accurately. Developing efficient yet accurate SoC estimation algorithms remains a challenging task.

1.1 SoC Estimation Methods
There are two methods existing in literature for SoC estimation of a battery [5].

- Direct Measurements
- Book-Keeping Systems

1.1.1 Direct Measurements
The direct measurement method is based on a reproducible and pronounced relation between a measured battery variable and the SoC [4]-[6]-[10]. This battery variable should be electrically measurable in the practical set-up. Examples of such battery variables are battery terminal voltage "V" and battery impedance "Z". Most relations between battery variables depend on the temperature "T". Therefore, besides the voltage (or) the impedance, the battery temperature should also be measured. The relation "f_T^d" is between the measured battery variable and the SoC, can be stored in the system. The basic principle for SoC estimation based on direct measurement is shown in figure 1.

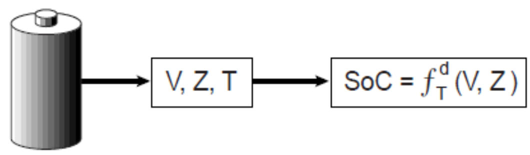


Fig 1: SoC estimation based on direct measurement.

1.1.2 Book-Keeping Systems
Book-Keeping systems are based on current measurement and integration [6]-[10]. This method is also known as "Coulomb Counting" method, which literally means "counting the charge flowing into (or) out of the battery. This yields an accurate SoC estimation when all the charge applied to the battery can be retrieved under any condition and at any time. The basic principle for SoC estimation based on book-keeping system is shown in the Figure 2.

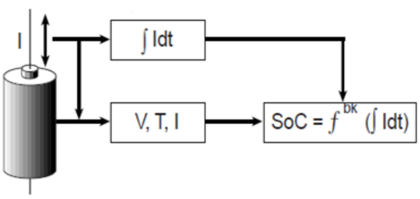


Fig 2: SoC estimation based on book-keeping system.

2. BATTERY PARAMETER ESTIMATION

2.1. Equivalent Circuit Model

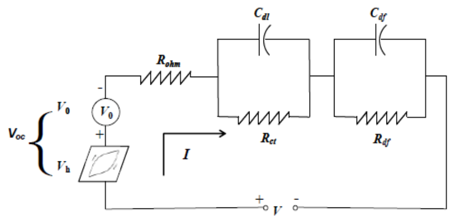


Fig. 3 A Two-RC-Pair Equivalent Circuit Model of a Battery.

Various equivalent circuit models have been combined estimation of SOC to evaluate the state of charge of Lithium-Ion batteries [8]-[9]. The RC model was designed by the famous SAFT Battery Company, and has achieved good application via the Advisor software [12]. As shown in Figure 1, it consists of two capacitors (*C*dl, *C*df) and three resistors (*R*ohm, *R*ct, *R*df). Resistors *R*ohm, *R*df, *R*ct are named ohmic resistance, charge transfer resistor and diffusion resistance, respectively. The capacitor *C*dl, is named double layer capacitor and capacitor *C*df is named diffusion capacitance. SOC can be determined by the voltage across the two RC pairs each of which accounts for the dynamic of double layer and diffusion respectively. *V*oc, *V*o and *V*h are open circuit voltage, thermodynamic voltage and hysteresis voltage, respectively. Voltage equation of two-RC-pair equivalent circuit model is described by

$$V(k) = Voc + I(k)Rohm + Vdl\,(k) + Vdf\,(k) \quad (1)$$

Thus the dynamic behaviour of a Li-ion battery can be characterized as a second-order system approximately and to characterize a second-order system, a two-RC-pair equivalent circuit shown in Fig. 1 is widely used.

For some batteries, the relationship between OCV and SOC is history and path dependent. This phenomenon is known as battery hysteresis, resulting in a nonlinear many-to-many mapping between OCV and SOC. It should be noted that battery hysteresis is a static phenomenon which distorts the one-to-one OCV-to-SOC static mapping. To compensate for the battery hysteresis, the OCV is further divided into two parts: Vo and *V*h, where Vo is the thermodynamic voltage which has a one-to-one relationship to SOC, and *V*h represents the battery hysteresis voltage. The sum of Vo and *V*h gives Voc [10].

3. COMBINED ESTIMATION OF STATE OF CHARGE (SOC)

SoC estimation is an increasingly important issue in battery technology [7]-[11]. This paper presents a new algorithm for SoC estimation of a rechargeable battery. The combined estimation of SOC method estimates the SoC of a battery based on book-keeping, direct measurement and model-based approaches.

The SoC estimated from Coulomb counting can include a large error due to flaws in terminal current measurement and/or initial SoC estimation. To recalibrate the SoC estimated by Coulomb counting method, a method combining Coulomb counting, direct measurement and model-based approach is combined estimation of SOC. The block diagram of the combined estimation of SOC is shown in figure 4.

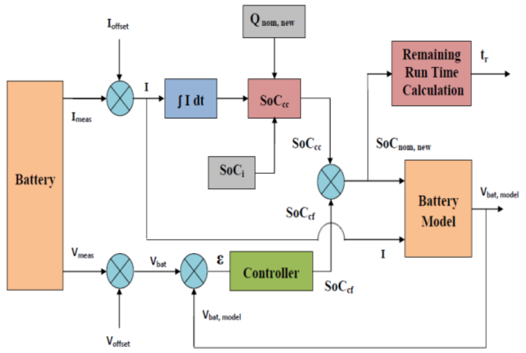


Fig 4: Combined estimation of SOC.

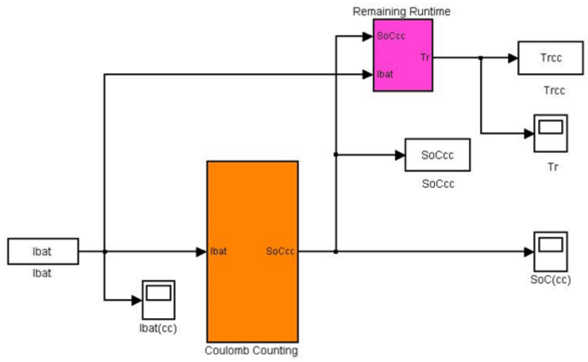
The measured current and voltage at the battery terminals are summed with an offset to obtain accurate measurement values. The measured current "I" is integrated with time. The procedure for obtaining "SoC_i" is explained in the next section. Then the SoC is estimated using Coulomb Counting method as explained by equation 2.1. The corresponding Open-Circuit Voltage (OCV) for the SoC estimated by Coulomb counting method is obtained from an OCV-SoC relationship. The procedure for obtaining OCV-SoC relationship is explained in the next section.

The voltage "OCV (SoC)" and battery current "I" are applied to the battery model and terminal voltage "$V_{bat,\ model}$" is obtained. The combined estimation battery model is explained in the next section. The parameters of the battery model such resistances and capacitances change with age and temperature. The procedure for capturing parameters of the battery model is also explained in the next section.

The terminal voltage obtained from the battery model (i.e.) "$V_{bat,\ model}$" is compared with the measured terminal voltage "V_{bat}". The error "ε" in the terminal voltage is processed by a controller producing a correction factor "SoC_{cf}". This correction factor is summed with the SoC determined from Coulomb counting method to estimate the accurate state-of-charge "SoC_e". The method for designing and tuning a controller is presented in the next section.

3.2 MATLAB/SIMULINK Modelling

The MATLAB/Simulink model of the \coulomb Counting technique is shown in Figure. The capacity of the battery is considered to 1000mAh. The initial SOC is assumed to be 100%. The model is simulated for 20000 seconds and the SOC is shown in figure 5.



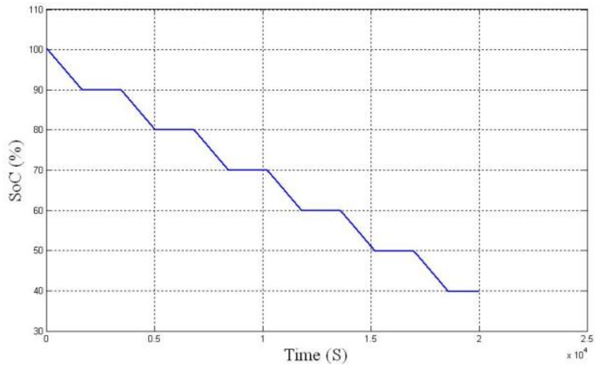


Fig 5: MATLAB/Simulink Model of Coulomb Counting Method& Simulation Result for SoC Estimation by Coulomb Counting Method.

3.3 MATLAB/Simulink Model of the combined estimation of SOC Method

The MATLAB/SIMULINK model of Coulomb Counting technique is shown in Bellow. The controller employed is a PI controller. The correction factor obtained from the controller is summed up with the SoC obtained from Coulomb Counting technique.

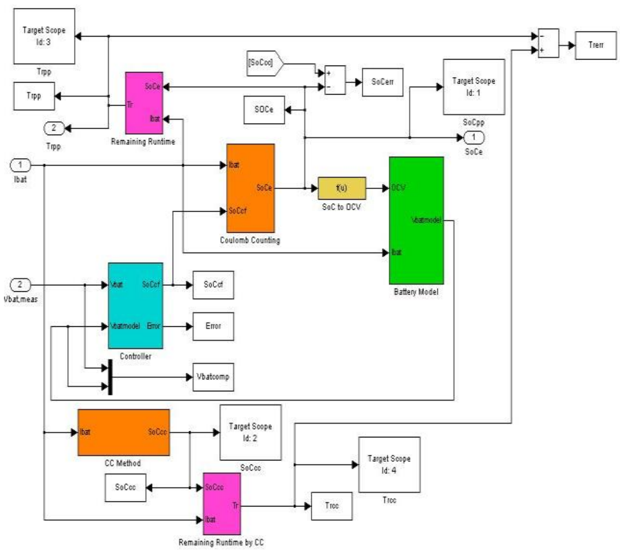


Fig 6: MATLAB/Simulink Model of the combined estimation of SOC Method.

The proportional and integral constants of the PI controller are obtained by tuning. The tuning of these parameters is done using the Simulink Response Optimization toolbox. The above model is run in real-time where the battery current and voltage are acquired from the hardware test bench.

4. HARDWARE TEST SETUP

The combined estimation of SOC algorithm is validated on a sophisticated hardware test bench. This part of the paper will explain the hardware test set up used for validating the combined estimation of SOC algorithm.

Block Diagram

The block diagram of the hardware test set up is shown in figure 7.

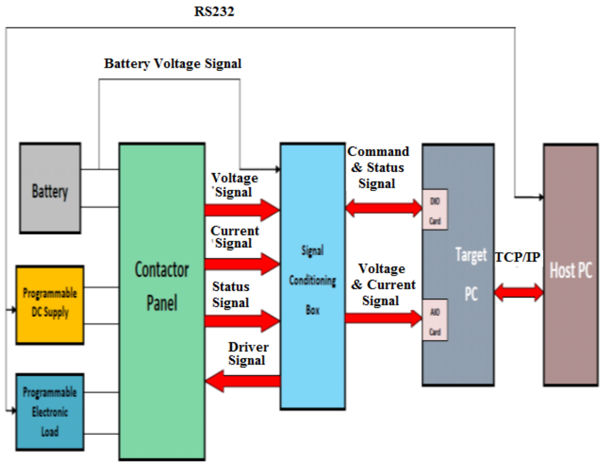


Fig 7: Hardware test set up.

4.1 Battery

The battery used for validating the combined estimation of SOC algorithm is a Lithium-Ion battery. Li-Ion battery chemistry has many advantages. The major advantage of Li-Ion battery is its negligible self-discharge. Since, the combined estimation of SOC algorithm doesn't account for self-discharge; it would be advantageous for estimating the SoC accurately [2]-[3]. The battery is enclosed in a separate chamber which is provided with cooling facilities. This is to ensure that the operating temperature of the battery remains almost constant.

4.2 Programmable DC Supply

The test setup shown in figure 5.1 can be used to estimate SoC for any battery chemistry. Since, different battery chemistry demands for a different charging regime, a programmable DC supply is used. For instance, Li-Ion battery should be charged using Constant Current Constant Voltage (CCCV) principle. So, this DC supply can be programmed for different voltages and currents as required for battery charging.

The programmable DC supply can be programmed using SCPI commands. This DC supply is controlled from the hyper terminal of the host PC. Using SCPI commands it is possible to set the output voltage and currents of the DC supply. This DC supply can be operated in Constant Current (CC) mode and Constant Voltage (CV) mode as required. The DC supply employed in this test bench is a 60V, 250A load.

4.3 Programmable Electronic Load

The battery has to be tested with various discharge current profiles. So, a programmable load is used for this purpose. This load can be controlled from the hyper terminal of the host PC. Using SCPI commands it is possible to configure the load for sinking required currents with required voltage.

4.4 Contactor Panel

The contactor panel consists of three contactors K_1, K_2 and K_3 used to connect the battery, DC supply and load to a common bus bar. These contactors can be driven from the host PC using Opto 22 modules and relays. The drive signals for these contactors are obtained from signal conditioning box which in turn receives the command signals from the target PC. The contactor panel also consists of current transducers for sensing various currents flowing in the circuit. The currents flowing in the circuit are sensed by using current transducer. The current transducer gives a voltage output proportional to current flowing. This voltage is routed to target PC by using Signal Conditioning Box (SCB) and DAQ devices. The voltages at various points in the circuit are routed directly to the SCB and are acquired by target PC using DAQ device.

4.5 Signal Conditioning

The currents flowing through various components are sensed by using current transducer and the voltages across various components are measured. Many sensors and transducers require signal conditioning before a computer-based measurement system can effectively and accurately acquire the signal. The sensed current signals and the measured voltage signals are conditioned by using SCB. Then, these signals are acknowledged by data acquisition (DAQ) devices. The voltages measured at various points are sensed using a voltage divider networks consisting of resistors in series. The SCB acquires digital signals from target PC through DAQ devices and provides drive signals for the contactors. The analog and digital signal conditioning are shown in the figure 7 and 8.

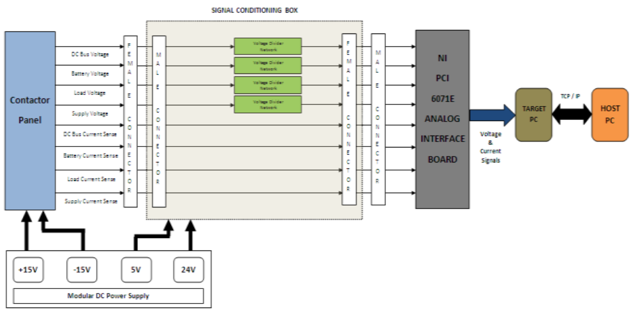


Fig 8: Analog Signal Conditioning

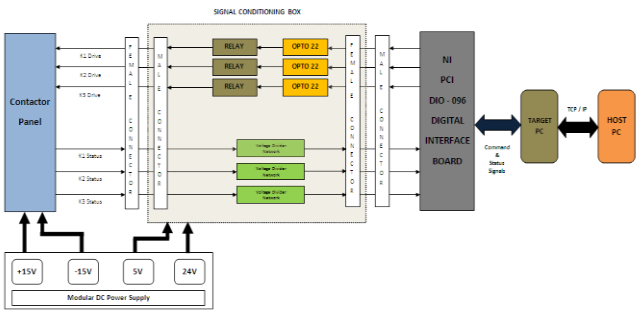


Fig 9: Digital Signal Conditioning

4.6 Target PC

A target PC may be a general-purpose computer, a special-purpose device employing a single-board computer or any other intelligent device. Usually the target machine is not able to host all the development tools. The target PC acquires required voltage and current signals for SoC estimation. The target PC can be one of the following:

- **Desktop PC** - This computer is booted from a special target boot disk created by xPC Target. When you boot the target PC from the target boot disk, xPC Target uses the resources on the target PC (CPU, RAM, and serial port or network adapter) without changing the files already stored on the hard drive. After you are done using your desktop computer as a target PC, you can easily reboot your computer without the target boot disk. You can then resume normal use of your desktop computer using the pre-existing operating system and applications.
- **Industrial PC** - This computer is booted from a special target boot disk, or with the xPC Target Embedded Option, booted from a hard disk or a flash memory.

4.7 Host PC

The host PC is the machine on which programs are written compiled. The host PC can be a desktop PC (or) notebook PC. All of the development tools are installed on this machine. The compiler is built to run on this machine. The executables are built on host PC and are transferred to target PC. The debugger, which is running on the host machine, has to talk to the program running on the target machine.

5. TEST RESULTS AND COMPARISON

The battery is tested with a discharge current of pulse profile as shown in figure 10. The amplitude of pulse current is chosen to be 10A. Various voltages and currents acquired by target PC are displayed in the target PC and also in the GUI of host PC developed for the hardware test bench. When SoC button is enabled, the estimated SoC is displayed in the target PC as well as the GUI of host PC. The SoC estimated by Coulomb counting method and proposed method are shown in figure 11.

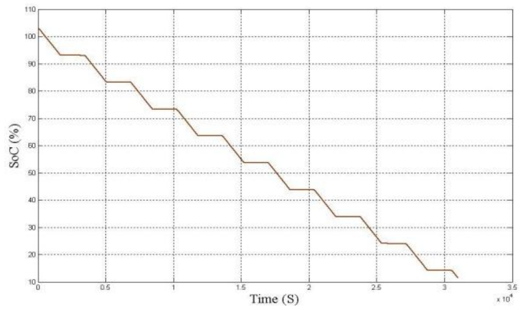


Fig 10: SoC Estimated by Coulomb Counting Technique

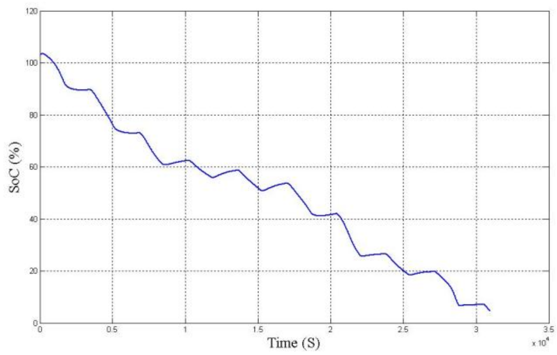


Fig 11: SoC Estimated by Combined estimation of SOC Technique

Comparison of Test Results

The figure 12 shows comparison between measured and estimated battery terminal voltage wave form. Here voltage discharge with respect to time is shown. The battery last up to 20000 sec.

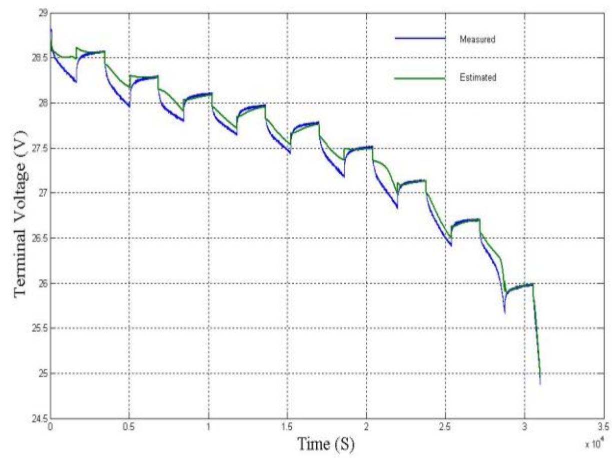


Fig 12: Comparison of Measured and Estimated Battery Terminal Voltages.

Figure 13 shows the comparison of estimated SOC which is shown in percentage. Here coulomb counting method and combined estimation of SOC is shown. The combined estimation of SOC gives the accurate output.

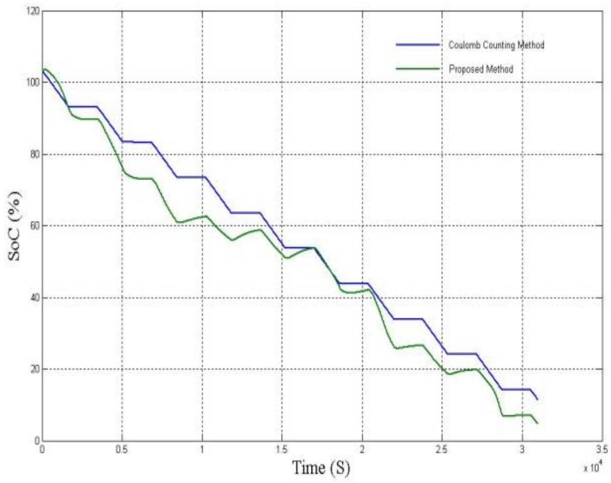


Fig 13: Comparison of Estimated SoC

6. CONCLUSION

With the rising importance for battery, both in the automotive industry and the energy sector, it is of critical importance to develop more accurate algorithms for SOC estimation of the battery. This paper presents a novel technique for SoC estimation of the battery where the SoC estimated by Coulomb Counting method is corrected using the battery model and a PI controller. The combined estimation of SOC method has an advantage of estimating SoC accurately even if there is an error in determining initial SoC and flaws in current measurement. Based on experimental results obtained from battery testing, the battery equivalent model parameters are estimated. Then the combined estimation of SOC estimation technique is employed for the estimation of SoC which is further used in order to compute the remaining runtime of the battery.

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