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Estimation of Battery State of Charge Using the Kalman Filter – An Application Aspect

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ABSTRACT: **Batteries have become an integral part of electronic gadgets and, to some extent, human life. Battery modelling and estimating the state of charge are essential considerations for performance parameters. This paper explores battery modelling in the MATLAB Simulink® environment. A Kalman filter is employed to demonstrate its application in estimating the battery's state of charge. The actual value of the battery's state of charge and the calculated values are compared to verify the model's effectiveness and the Kalman filter.**

KEYWORDS: **Battery modelling, State of Charge, Kalman Filter, MATLAB Simulink®**

INTRODUCTION:

Batteries play a vital role in energy storage. They convert chemical energy into electrical energy, powering electronics and various systems. Modern smartphones, backup systems, electric vehicles, portable gadgets, laptops, and many other applications would not be possible without these storage devices. Batteries consist of cells connected in series. Each cell contains an anode and a cathode with an electrolyte that enables the free movement of ions [1-3].

Batteries are classified based on their usability as rechargeable or non-rechargeable. Rechargeable batteries are secondary, while non-rechargeable batteries are primary or single-use. Alkaline batteries are primary batteries. Lithium-ion, lithium iron phosphate, nickel-metal hydride, sodium-ion, and lead-acid batteries can be charged and discharged multiple times and are referred to as rechargeable or secondary batteries. Among these options, lithium-ion (Li-ion) batteries have gained immense popularity due to their long cycle life, lightweight, and high energy density. Large battery packs, on the order of kilowatt hours (kWh) or even megawatt hours (MWh), are currently used in various large-scale operations in energy storage. The shift from fossil fuels to renewable energy generation has also boosted the application of batteries in large-scale energy storage. Along with their advantages, batteries pose challenges such as performance degradation over time, environmental and hazardous concerns, toxicity issues, disposal problems, and a limited lifespan. Efforts are being made to develop sustainable and safer batteries, such as solid-state batteries, but it may take time to commercialise them [4-7].

Batteries must be studied mathematically to assess their performance parameters. One such parameter is the battery's charge state, or SoC. This paper proposes a method to estimate the battery's state of charge using a Kalman filter. A Kalman filter is a mathematical algorithm for calculating the system's state over time. With the Kalman filter, the system's future state can be predicted based on available measurements. It constantly refines estimations and makes them as accurate as possible. Thus, the measured and estimated variables will have a minimal error gap. The Kalman filter assumes that the system and measurement noise are normally distributed and random [8-11].

MODELLING OF BATTERIES AND METHODOLOGY:

Based on the charge dynamics, batteries are modelled as single-time or two-time dynamics, as illustrated in Figures 1(a) and 1(b). They combine resistor and capacitor elements, which can accurately predict the battery's internal and external behaviour under load. Resistance signifies the internal resistance of a battery, while capacitance reflects the electrochemical reactions and polarisation that occur during charging and discharging. These models enable engineers to anticipate the behaviour under various loading conditions. Moreover, they can also forecast the impact of temperature on batteries, including internal voltage drops and charge/discharge rates.

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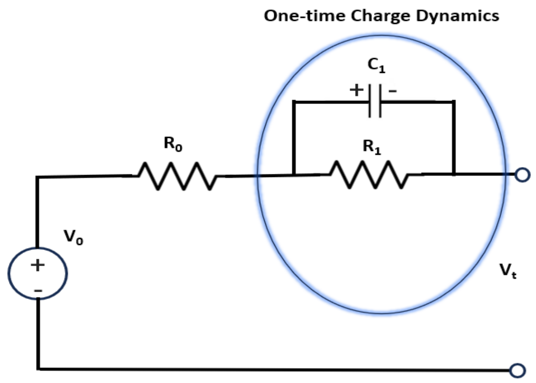

Figure 1(a) One-time charge dynamics of a battery

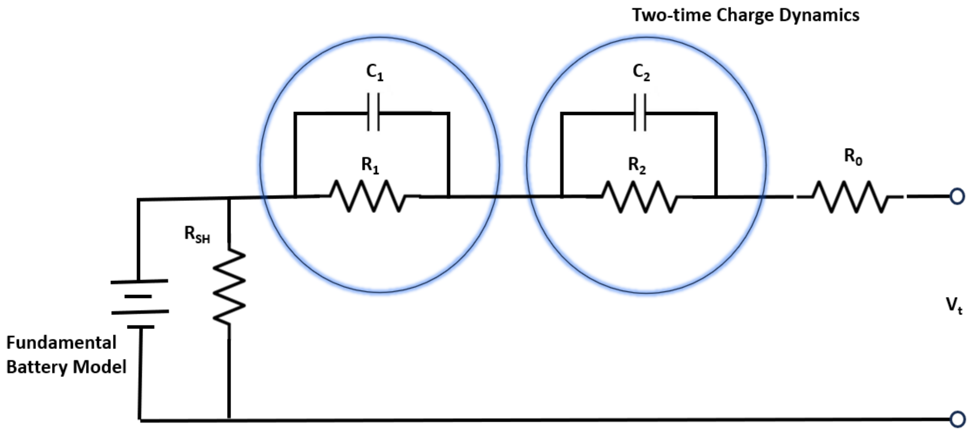

Figure 1(b) Two-time charge dynamics of a battery

In these figures,
V_0 = Open circuit voltage
V_t = Terminal voltage
R_1 & R_2 = First and second polarisation resistors
C_1 & C_2 = First and second polarisation capacitors
R_{SH} = Shunt resistance
R_0 = Open circuit resistance or no-load resistance

Considering these models, mathematical equations for two-time dynamics can be written as

$$\frac{dSOC}{dt} = -\frac{i}{3600\ AH} \quad (1)$$

$$\frac{dV1}{dt} = \frac{i}{C1\ (SoC,T)} - \frac{V1}{R1\ (SoC,T)C1\ (Soc,T)} \quad (2)$$

$$\frac{dV2}{dt} = \frac{i}{C2\ (SoC,T)} - \frac{V1}{R2\ (SoC,T)C2\ (Soc,T)} \quad (3)$$

$$V_t = V_0\ (SoC,\ T) - iR_0 - V_1 - V_2 \quad (4)$$

Apart from the conventions discussed before, there are other conventions.

AH = Battery capacity in Ampere Hours
T = Temperature in degrees centigrade
V_1 = Voltage across the first RC network
V_2 = Voltage across the second RC network

RESULTS AND DISCUSSION:

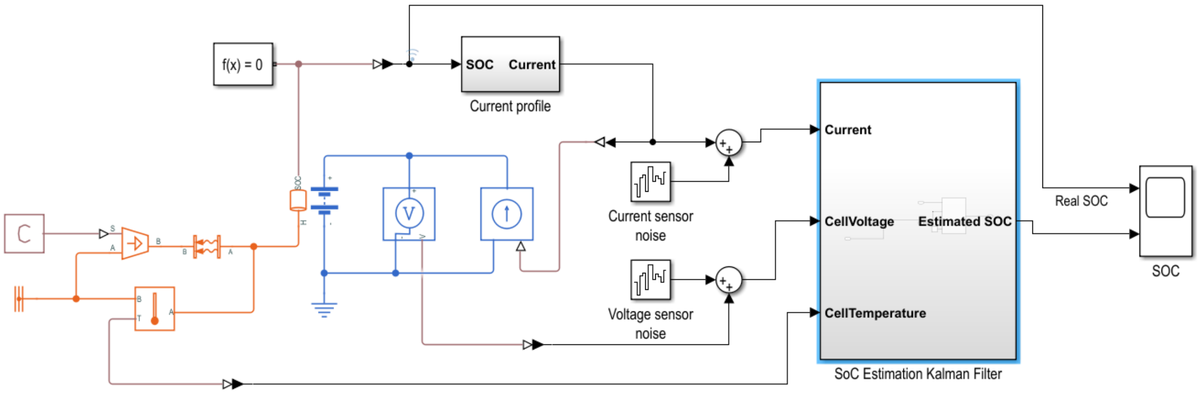

Figure 2. Estimation of Battery SoC Using Kalman Filter – A Model in MATLAB Simulink®

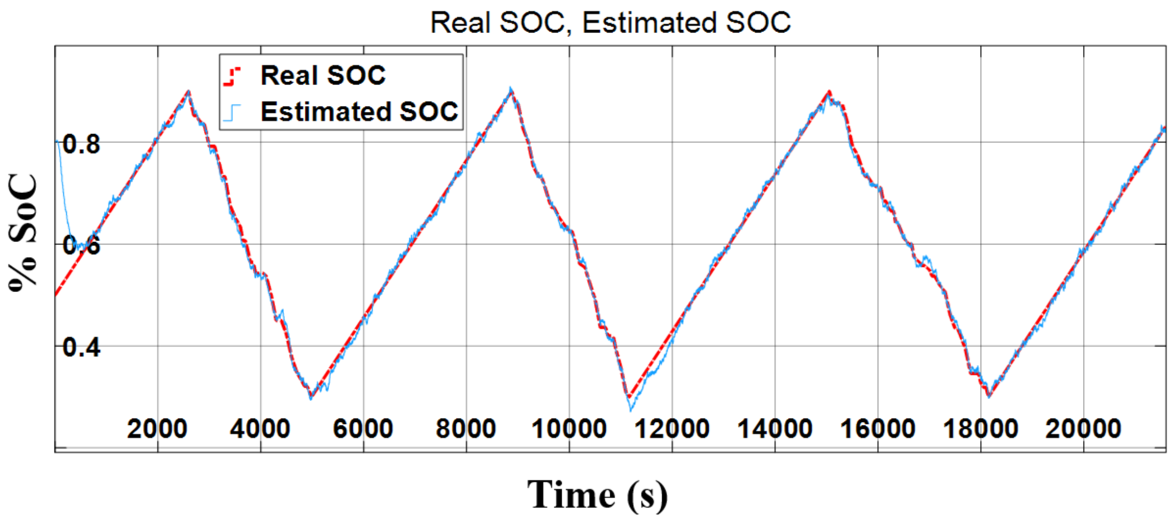

Figure 3. Real SoC and Estimated SoC of a Battery with the MATLAB Simulink® Model

As demonstrated in Figure 2, a MATLAB Simulink® model [12-14] was developed with these considerations in mind. As discussed, a Kalman filter was employed to estimate the battery's initial state of charge, which was 0.5. The estimator was set at 0.8 initially. The battery charging and discharging were observed for 6 hours (21600 seconds). The Kalman filter took 10 minutes (600 seconds) to converge to the estimated values nearly equal to a battery's real value of the SoC.
Based on the MATLAB Simulink®, results for the genuine battery state of charge (SoC) and the estimated SoC were obtained and plotted, as presented in Figure 3. These results show that the Kalman Filter estimation approximates the battery's actual SoC. Initially, it took approximately 600 seconds (10 minutes) to converge; however, after this initial period, the model predicts the battery's Soc with minimal error. Thus, real and estimated values after 10 minutes of simulation show effective implementation of the battery model in the MATLAB Simulink® environment.

CONCLUSION:

The battery's state of charge is estimated using a Kalman Filter, and the battery is modelled in the MATLAB Simulink® environment. The total simulation time for comparing the real and estimated SoC was six hours (21600 seconds). A Kalman Filter converges to an estimated value of battery SoC with the real value within a minimum error in 600 seconds (10 minutes). Thus, the battery state of charge can be accurately estimated using a Kalman Filter, and matching the real and estimated SoC for a battery demonstrates the effective implementation of the MATLAB Simulink® battery model.

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AUTHOR CONTRIBUTION STATEMENT:

Both authors have contributed equally to the preparation of the manuscript.

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