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Battery State of Health Estimation Using Adaptive Kalman Filter Integrated with Advanced Charging Techniques

Abstract: - In order to replace internal combustion engine vehicles, EVs are used which have no carbon emissions. The EVs are driven using electrical power from a storage device which is preferable a high rating battery pack. The battery pack used in the EV technology is a Li-ion made which has high current discharge and fast charging capabilities. With the fast charging and high current discharge of the battery pack the health of the cells diminishes over a period of time. In this paper a battery SOH estimator is designed with Adaptive Kalman filter included. In order to improve the SOH of the battery, different charging techniques are adopted and imposed on the EV charger. The charging techniques are a) Continues charging b) Pulse charging and c) Burp charging. The SOH of the battery is determined by the Adaptive Kalman filter based estimator with these types of charging techniques. These charging techniques are applied to the same rating of the battery pack and also the charge/discharge current magnitude for the same time. The analysis is simulated in MATLAB Simulink software with block considered from 'Simelectronics' and 'Powersystems' subsets of the Simulink library browser. The graphs of the battery SOH are compared with different charging techniques for the same simulation time. The SOH of the battery estimation validates the optimal charging technique for the EV battery charging.

Keywords: EV (Electric Vehicle), Li-ion (Lithium-Ion), SOH (State of Health), Adaptive Kalman filter, MATLAB Simulink.

I. INTRODUCTION

In order to mitigate the global raising temperatures caused due to utilization of combustion engine vehicles for transportation need to be replaced with zero emission vehicles. These vehicles are categorized as 'hybrid electrical vehicles' and 'pure electrical vehicles'. The 'hybrid electrical vehicle' is a combination of combustion engine and electrical source which has carbon emissions. 'Pure electrical vehicles' are the only vehicles which have only electrical source for the vehicle's drive [1]. Due to complete electric source, there is zero carbon emission from the vehicle which is a great replacement to the present combustion engine vehicles. The electrical source used in the vehicle is a battery energy storage unit. There are different types of battery packs (Dry or wet) which are manufactured as per the requirement. The dry battery packs like Nickel-Cadmium or Nickel–metal hydride is used for lower discharge rate applications mostly in electronic devices. In the wet category the lead acid batteries are mostly used in vehicles which support medium power rating applications [2]. These battery pack in the vehicle are used for operating electronic devices in the vehicle. However, the lead-acid battery is not suitable for driving heavy rating equipment as the machine used for the drive needs high discharge current [3].

This can only be achieved by Li-ion battery which has the capability of high charge/discharge current. These battery packs have lesser volume and weight for the given storage capacity as

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compared to other types of batteries [4]. Therefore, as of the present available technology these Li-ion batteries are integrated into most of the electrical vehicles. These batteries need to be charged with electrical power for driving the machine of the vehicle. Each battery manufacturer has their own charging capacity and current magnitude restriction [5]. There are many types of charging circuits with reduced charge current ripple improving the health of the battery cells. With higher ripple DC voltage circuits, the battery cells may get damaged quickly reducing the reliability of the vehicle. Along with less current ripple circuit topologies, the health of the battery can also be improved with different charging techniques. The outline of the electric vehicle charging circuit can be observed in figure 1.

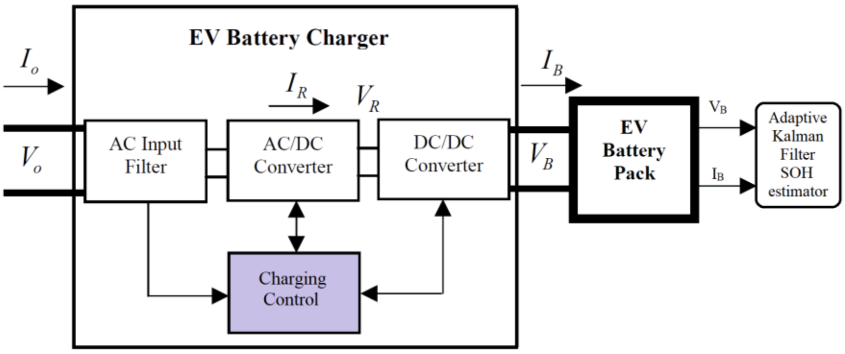

Figure 1: Electric vehicle battery charging structure

As presented in figure 1 the 'AC/DC converter' is a controlled rectifier which converters the AC grid voltage to controlled DC voltage. The 'DC/DC converter' controls the charge current to the EV battery pack which defines the health and reliability of the battery [6]. The 'AC/DC converter' and 'DC/DC' converter are controlled by a 'Charge Control' unit which operates as per the reference signals set by the manufacturer. The 'Charge Control' receives feedback signals from the battery voltage and current (V_B and I_B) which are needed for controlling the charge current. The 'Adaptive Kalam filter SOH estimator' is included at the EV battery side which needs V_B and I_B for the SOH estimation. The SOH of the battery is estimated as per the charge/discharge times and magnitude of charge/discharge current [7].

The Adaptive Kalman Filter (AKF) is an extension of the Standard Kalman Filter (KF) that adjusts its parameters dynamically to accommodate time-varying, uncertain, or unknown system properties. The Kalman Filter is an optimal recursive algorithm for estimating the state of a linear dynamic system from noisy measurements. However, when the system's characteristics, such as process noise, measurement noise, or even the system model, are not constant or precisely known, the standard Kalman Filter may not perform well [8]. The Kalman Filter provides an optimal estimate of the system's state at each time step based on noisy measurements and the system's dynamic model.

The filter works recursively, updating estimates as new measurements are received without needing to store all previous data. It uses the innovation sequence (the difference between predicted and actual measurements) to adjust the noise covariance matrices. If the innovations deviate significantly from expectations, the filter assumes a mismatch in noise modelling and adjusts parameters accordingly [9]. The Adaptive Kalman Filter is an advanced version of the traditional Kalman Filter that dynamically adjusts its parameters to improve performance in systems with time-varying or uncertain characteristics. It is widely used in applications where robustness and flexibility in state estimation are crucial.

This paper is arranged with introduction to the proposed EV battery charge control structure and battery SOH estimation unit. The following section 2 includes the types of charging methods used for charging the Li-ion EV battery pack for improving the health and reliability of the system. The section 3 is the design of ‘Adaptive Kalam filter SOH estimator’ for defining the battery pack health with respect to the number of times of charge/discharge and magnitude ofcharge/discharge current. The simulation results for the same with different charging techniques imposed on the battery pack generating SOH graphs is presented in section 4. The section 5 has the conclusion to the paper validating the optimal charging method determined by better SOH value for the same conditions. The reference cited in the paper are included after section 5.

II. Charging Techniques

The EV charging is categorized majorly into two types, a) AC charging and b) DC charging which are named as per the input voltage of the charging circuit. However, in both the charging types the input to the EV battery is DC voltage [10]. Both the charging types have different power electronic circuits for maintaining the charging current to the EV battery pack. These charging types are also named as per the input voltage availability. The single-phase AC voltage source EV charging is called ‘Residential Charging’ and the three phase AC voltage source EV charging is called ‘Commercial Charging. The ‘commercial charging’ has higher charging current rating as compared to ‘residential charging’ as the current available is three times the single-phase source. The structures of the charging types are presented in figure 2.

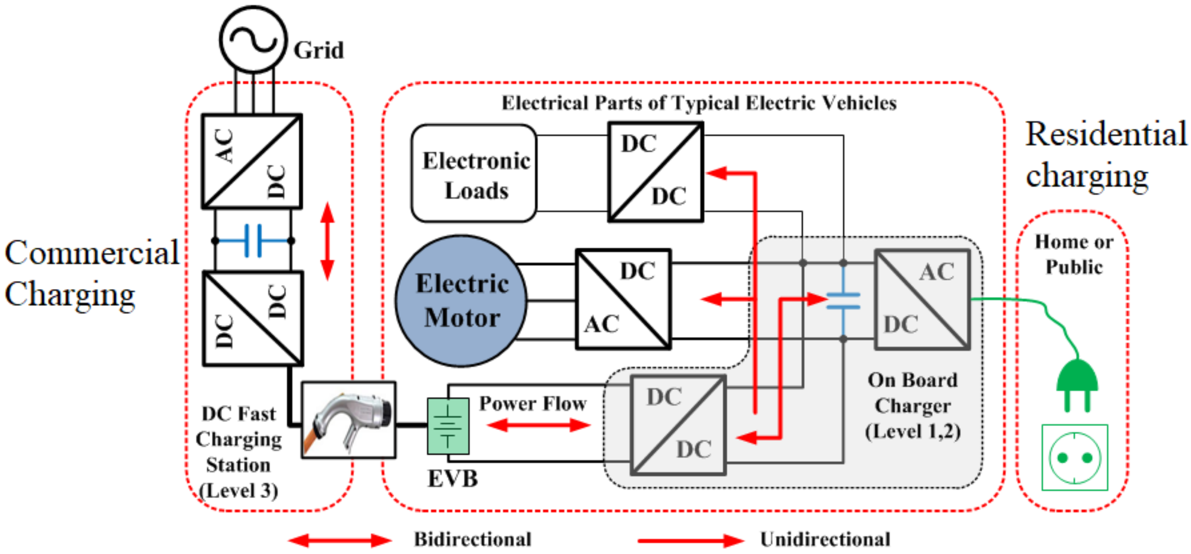

Figure 2: Structure of charging types include in EV

As observed in figure1 the ‘Residential Charging’ has an ‘On board charger’ which is a two-stage power circuit topology. In the first stage a ‘single phase uncontrolled AC/DC rectifier’ converts the single-phase AC to DC which is fed to DC/DC converter. The DC/DC converter stabilizes the voltage and regulates the charge current input to the EV battery. On the other side the ‘Commercial charging’ structure also has two-stage conversion system. However, in place of ‘single phase uncontrolled AC/DC rectifier’ a ‘three phase controlled rectifier’ is installed and the DC/DC converter has higher rating. These power circuits in the ‘Commercial charging’ are placed Off board which are place outside the vehicle providing DC voltage directly to the vehicle [11].

The ‘Commercial Charging’ also known as ‘DC fast charging’ provides higher charge currents as compared to ‘Residential charging’ as the power source is a three phase AC supply. The current rating provided by the three-phase supply is three times more than the single-phase supply as in ‘Residential charging’. The ‘DC fast charging’ makes the EV battery charge faster which may deteriorate the battery pack’s health affecting the reliability of the vehicle. In order to avoid these circumstances and effects on the EV battery pack different ‘DC fast charging’ methods need to be adopted. The charging methods are a) Continues charging b) Pulse charging and c) Burp charging. The DC/DC converter of the ‘Commercial charging’ module need to be controlled by these charging methods for improving the performance [12]. In the mentioned methods the ‘Continuous charging’ is the conventional method of charging with fixed current/voltage reference. The ‘Constant Current’ or ‘Constant Voltage’ modes are switched as per the SOC (State of Charge) of the battery. The battery health drops badly with the ‘Continuous charging’ method which need to be replaced by the other two charging methods.

2.1Pulse Charging

The pulse charging method uses the same charging circuit as the fast-charging module, and the current magnitude is also maintained the same. However, the input current to the EV battery is fed in pulse format by creating a 'zero current conduction' for small instants of time. The 'zero current conduction' time is called the rest period, which stops the EV battery from charging for a small instant of time. This allows ions within the battery (typically lithium ions in Li-ion batteries) to stabilize and redistribute, preventing excess heat buildup and internal damage [13]. The time and amplitude can be varied according to the EV battery pack condition and charging stage, optimizing the charging process. The pulse charging current with rest periods is presented in figure 3.

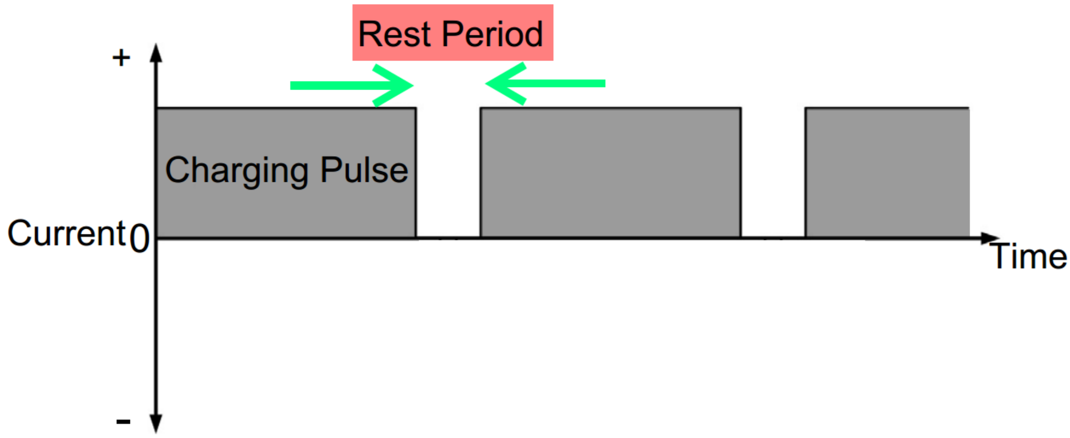

Figure 3: Pulse charging current conduction

High charging currents in traditional charging methods produce heat, which can deteriorate battery components over time. Pulse charging addresses this issue by allowing the battery to cool during rest periods. This technique can shorten overall charging time by delivering more current during pulses while managing heat. By preventing excessive heat buildup and ensuring even distribution of ions, pulse charging can prolong the battery's lifespan and reduce wear and tear. The rest periods also enable voltage measurement and prevent overcharging, which is beneficial for battery longevity and safety. Additionally, during pulses, the battery can accept more current in specific situations, enhancing overall charging efficiency [14].

Pulse charging requires advanced control electronics to effectively manage pulse timing, frequency, and amplitude. Different battery chemistries, such as lithium-ion and nickel-metal hydride, require customized pulse charging protocols, emphasizing the need for optimization to maximize benefits. With the growing need for faster charging and longer battery life in electric vehicles, pulse charging holds promise as a technique. It can be particularly valuable in public fast-charging stations where minimizing charge time and preserving battery health is crucial.

2.2 Burp Charging

Similar to the pulse charging technique, the burp charging also has rest periods for small instants of time. However, in the burp charging during the rest period the battery pack is discharged with current magnitude three times the charging current. This method of charging is also called as 'Reflex charging' as the battery reflexes are improved [15]. The burp charging current conduction of the EV battery pack is presented in figure 4.

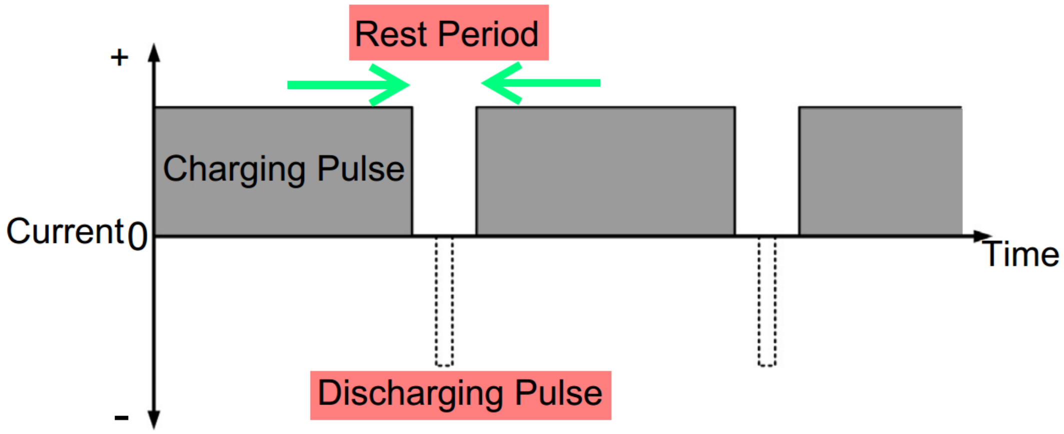

Figure 4: Burp charging current conduction

During the charging of the battery oxygen gas is accumulated at the electrodes which forms bubbles in the cell effecting the surface area leading the increase in internal impedance. This reduces the efficiency of the battery charging and heat builds up in the body of the battery pack. The oxidation caused due to continuous or pulse charging at the reacting plate of electrodes placed in the battery cell will be removed during the discharge pulse. Due to sudden discharge of the battery the chemical process is reversed relaxing the battery by burping the bubbles caused by the oxidation [16]. This improves the charge efficiency and reduction of heating in the battery pack. The burp charging method increases the life of the battery cell and the reliability of the complete battery pack.

III. Adaptive Kalman Filter SOC and SOH Estimator

The Adaptive Kalman Filter (AKF) extends the traditional Kalman filter. It is used in systems where the noise characteristics, such as process noise and measurement noise, change over time. In a standard Kalman filter, the noise covariance matrices Q (process noise) and R (measurement noise) are assumed to be constant and known [17]. However, in many real-world applications, these noise parameters are not static and may change over time due to environmental conditions, system degradation, or sensor characteristics. The AKF dynamically adjusts the 'covariance matrices' to track and estimate the true state of the system, even when the noise statistics change over time.

The AKF adjusts the system and measurement noise by varying the state estimation weight of the filter as per the requirement [18]. This improves the SOC estimation convergence and preciseness. The expressions for the state relationship equation of the battery pack are given as:

$$\dot{x} = Ax + BI \quad (1)$$

$$y = Cx + DI \quad (2)$$

From the given equations (1) and (2) the A, B, C and D parameters are given as:

$$A = \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{-\alpha} & 0 \\ 0 & 0 & e^{-\alpha} \end{bmatrix} \quad (3)$$

$$B = \begin{bmatrix} -\frac{\int_{t0}^{t} \eta dt}{Q_N} \\ R_{p1} - R_{p1} e^{-\alpha_1} \\ R_{p2} - R_{p2} e^{-\alpha_2} \end{bmatrix} \quad (4)$$

$$C = \begin{bmatrix} \frac{d_{ocv}}{d_{soc}} & -1 & -1 \end{bmatrix} \quad (5)$$

$$D = -R_0 \quad (6)$$

Here, R_0 is the internal resistance of the battery cell, R_{p1} and R_{p2} are the polarization resistors, α is the innovation length, ηdt is the change in efficiency of the cell as per charge and discharge, Q_N is the sensitivity factor. d_{ocv} and d_{soc} are the change in open circuit voltage and state of charge of the battery cell [19].

The factors $\alpha_1$and α_2 are updated as per the polarization resistors and capacitors (Cp1 and Cp2) of the battery.

$$\alpha_1 = \frac{\Delta t}{R_{p1} C_{p1}} ; \alpha_2 = \frac{\Delta t}{R_{p2} C_{p2}} \quad (7)$$

The estimated parameters form the above expression are expressed as:

$$\dot{x} = \begin{bmatrix} SOC \\ V_{p1} \\ V_{p2} \end{bmatrix}, y = V_0 , \ x \epsilon R^3 \quad (8)$$

From the given expression the SOC and voltages of polarization elements are estimated. Along with the SOC the SOH of the battery cell can be also estimated as per the given weighted expressions of the ‘Kalman Filter [20]. The SOH of the battery degrades as per the charging current magnitude and number of charge cycles. When the SOH of the battery completely deteriorates, the cells of the battery stop holding the charge. It is very vital to estimate the SOH of the Li-ion battery ensuring reliability and safety issues. The SOH if the battery cell can be estimated with respect to the maximum capacity available and the internal ohmic resistance of the cell [21]. The estimated internal ohmic resistance is expressed as:

$$R_0(k+1) = R_0(k) + r(k); k = 1,2,3, \dots \dots \dots 2N \quad (9)$$

Here, $r(k)$ is the noise in the system for which the mean value is always ‘0’. This noise signal is added to the internal ohmic resistance to ensure real time value generation. The observed voltage of the cell is given as:

$$V_0(k) = V_{ocv}(k) - I(k)R_0(k) - V_{p1} - V_{p2} + \gamma(k) \quad (10)$$

Here, $\gamma(k)$ is the noise of the system observed which is also having a mean value ‘0’. The final state relationship with the given equations in the system are:

$$x_1(k+1) = x_1(k) + r(k)$$

$$y_1(k) = Ex_1(k) + F + \gamma(k) \quad (11)$$

Here, $E = -I(k)$ and $F = V_{ocv}(k) - V_{p1} - V_{p2}$. With this state space equation of the ‘Adaptive Kalman Filter’ and ‘Kalman filter’ the SOH if the Li-ion battery cell us estimated with different charging methods [22]. The final SOH comparisons in graphical representation are presented in the following section.

IV. Result Analysis

A simulation design in modeled with a single battery cell imposed with different charging methods by varying the charge current input to the cell. However, the charge cycles for all the techniques are maintained same with time variation. The simulation time is also set same for all the charging methods for the comparative analysis. The below parameters are updated to the simulation models for generating the comparative graphs.

Table 1: Simulation parameters

Name of the module	Parameters
Li-ion battery cell	V_{min} = 3.49V, V_{max} = 4.19V, R_{0min} = 0.0089, R_{0max} = 0.0117, T_{min} = 278K, T_{max} = 313K Capacity = 27Ah
Common simulation time	36000sec
Current sensor noise	Noise power = 0.001 Sample time = 1 Seed = 1
Voltage sensor noise	Noise power = 0.001 Sample time = 1 Seed = 23341
Continuous charging method	Charge current = 10A Discharge current = -30A One cycle Charge or discharge time = 2500sec
Pulse charging	Charge current = 10A Discharge current = -30A One cycle Charge or discharge time = 2500sec Rest period time = 1sec Rest period discharge current = -10A
Burp charging	Charge current = 10A Discharge current = -30A One cycle Charge or discharge time = 2500sec Burping time (small charge time) = 1sec

As per the given parameters the simulation models are run with the same simulation time, charge or discharge cycles and rest periods. The graphs of different parameters of the battery and SOH are plotted below with time as reference.

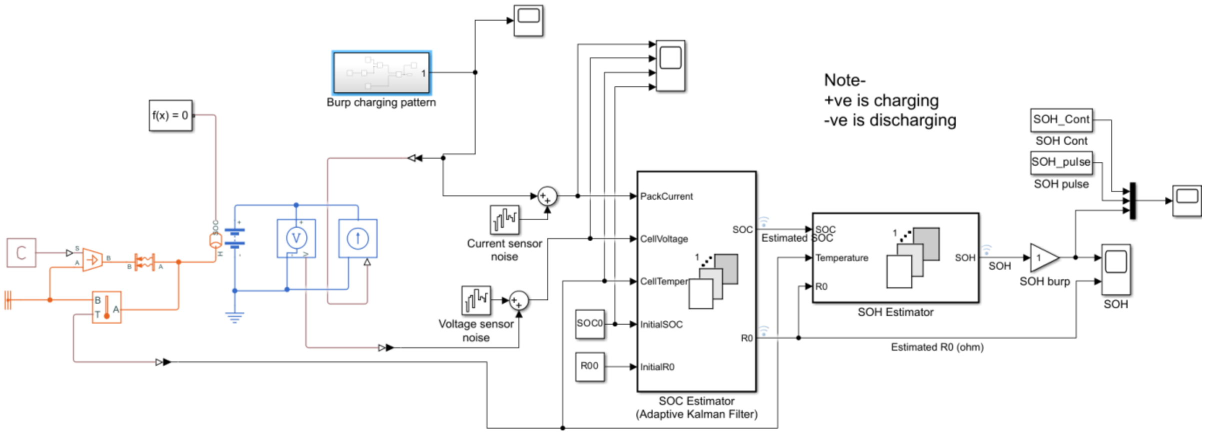

Figure 5: Simulation modeling of the Li-ion battery SOH estimator

The simulation model diagram of a Li-ion battery cell charging with different methods with SOH estimation using 'Adaptive Kalman Filter' can be observed in figure 5. The battery used here is imported from 'Electrical sources' of the Simulink library. The voltage and current measurement of the battery are fed to 'SOC Estimator (Adaptive Kalman Filter)' block. Along with the cell voltage and current, cell temperature, Initial SOC and Initial R0 are also defined. As per different input charge currents to the cell, the characteristics of the cell for each charging method are presented in figures 6 to 8.

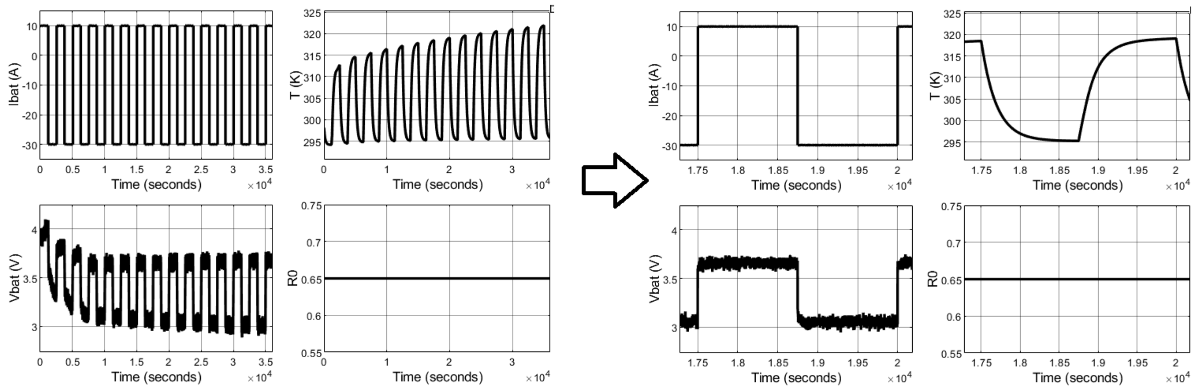

Figure 6: Li-ion Battery cell characteristics for continuous charging

The figure 6 has the graphs of the battery current (Ibat), battery voltage (Vbat), Cell temperature (T) and initial internal resistance (R0) when charged with continuous current method. The same values with one cycle of charge and discharge can be observed in the adjacent zoomed figure.

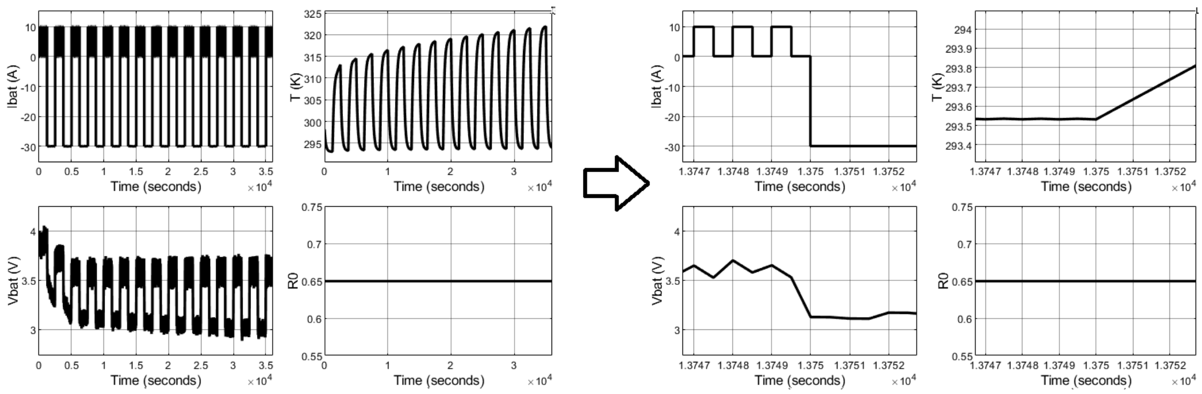

Figure 7: Li-ion Battery cell characteristics for Pulse charging

The same battery characteristics with different charging methods Pulse and Burp can be observed in figures 7 and 8. It is observed that the charging current to the cell is changing as per the signal set at the input with respect to which the characteristics of the battery cell are varying.

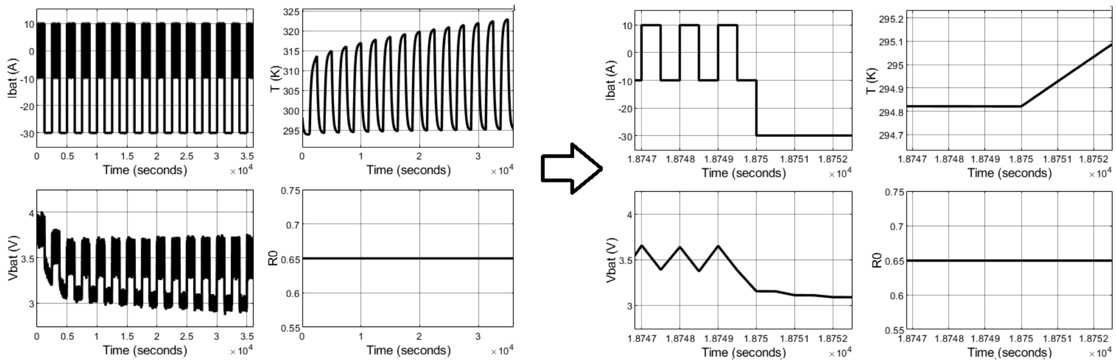

Figure 8: Li-ion Battery cell characteristics for Burp charging

During pulse charging the current does not have negative side current during the rest period. Whereas, in burp charging during the rest period there is a negative current during the rest period. The figures 9, 10 and 11 are the estimated SOH and R0 of the battery cell with continuous, pulse and burp charging methods respectively.

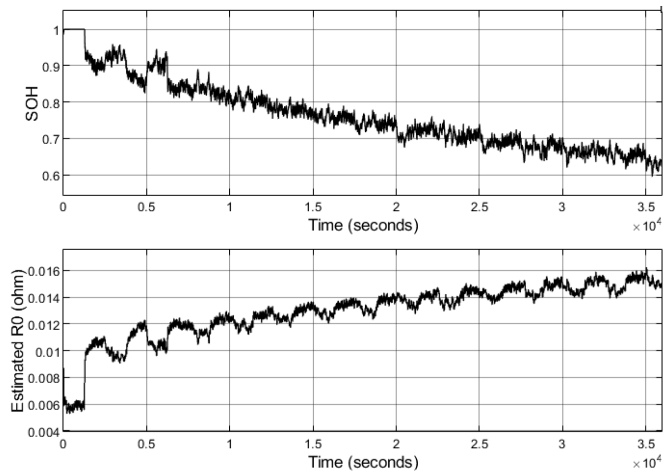

Figure 9: SOH and R0 estimated for continuous charging

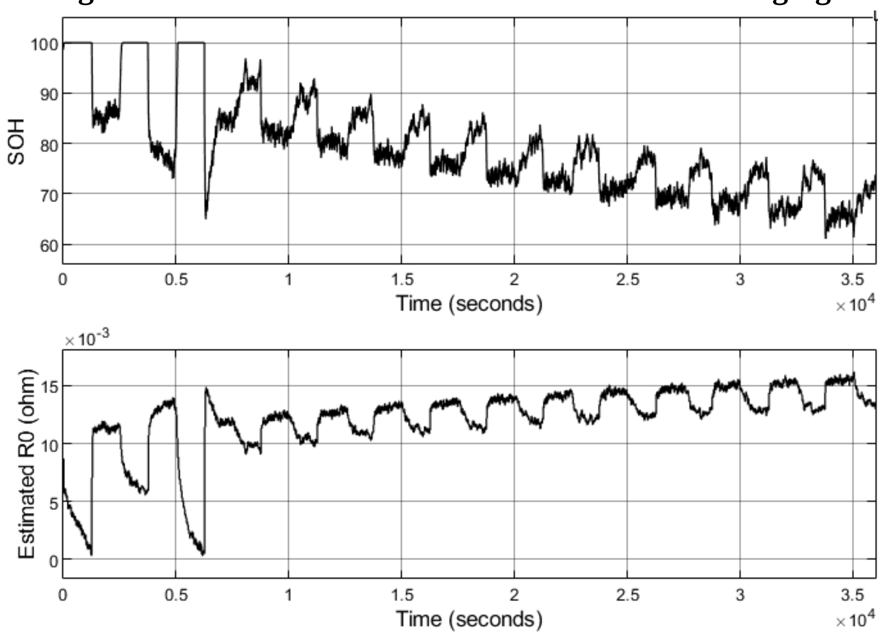

Figure 10: SOH and R0 estimated for pulse charging

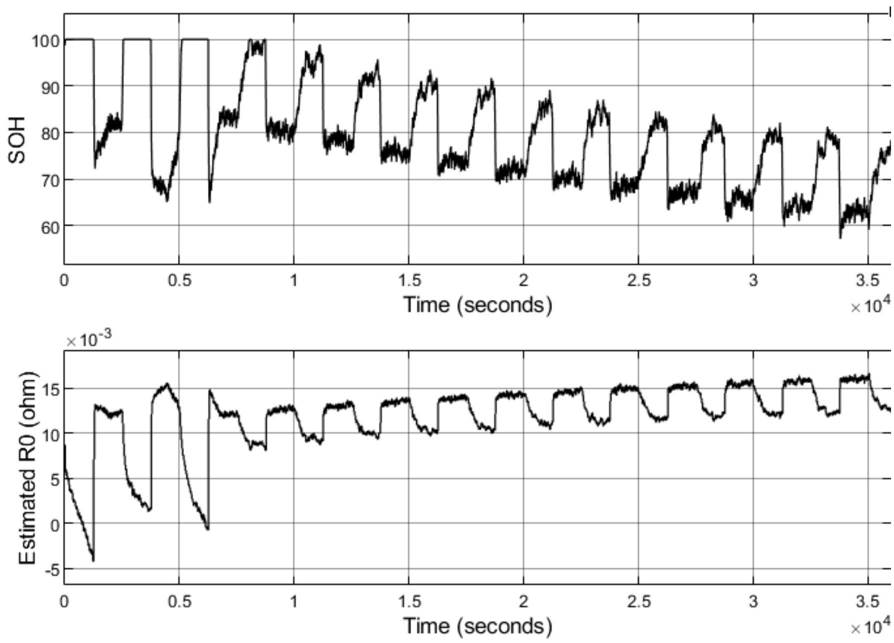

Figure 11: SOH and R0 estimated for burp charging

A SOH comparison graph with all the three charging methods is presented in figure 12 marked with different colors. ‘Black’ represents continuous charging, ‘Red’ represents pulse charging and ‘Blue’ represents burp charging.

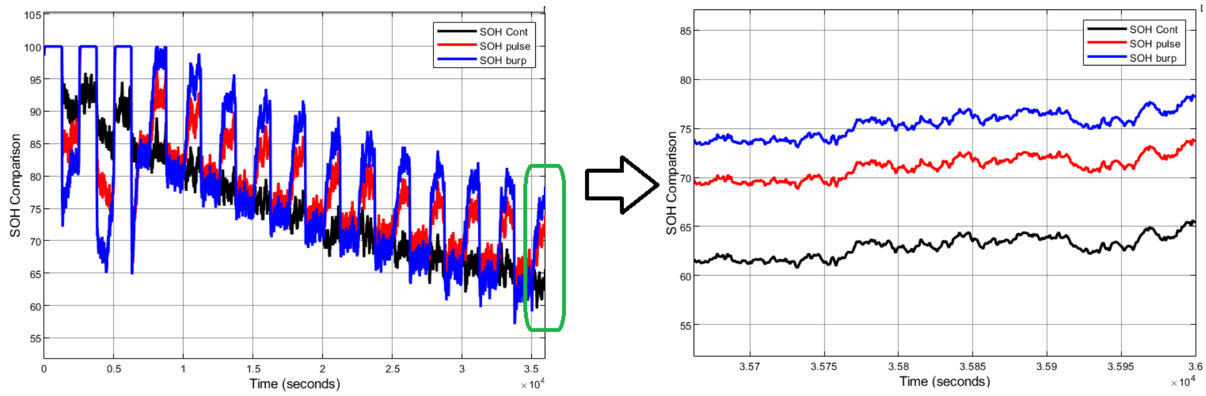

Figure 12: SOH comparison graph

As per the given comparison graph (figure 12), the SOH estimation of the battery cell has better value for burp charging method compared to other two methods for the same number of charging cycles and charge current magnitude. This validates that the ‘Burp charging’ method increases the health and reliability of the battery cell and overall EV battery pack compared to any other charging methods.

V. CONCLUSION

Modeling of different charging methods with Li-ion battery cell performance analysis using ‘Adaptive Kalman Filter’ SOC is achieved using blocks from MATLAB Simulink software. The estimated SOC and the internal resistance of the battery cell defines the health of the battery. Both the values from the ‘Adaptive Kalman Filter’ along with temperature of the cell are used to estimate the SOH of the battery cell. The charge current pattern input to the battery cell is changed with different charging methods, however the current magnitudes in charge and discharge modes are maintained same. To estimate the health of the battery cell the number of charge and discharge cycles are maintained same in every charging method. The SOH comparison graph of ‘Continuous’ ‘Pulse’ and ‘Burp’ charging methods shows better health quality of the battery cell for Burp charging method. This is achieved due to the burping of the cell oxidation with small discharge current during the rest period of the charging. As the health of the cell improves the reliability of the complete EV battery pack improves increasing the battery pack life.

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