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Introducing a novel strategy to manage lithium-ion cells in fast-charge discharge operations with Model predictive controller

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ABSTRACT: To prevent safety issues such as thermal runaway, lithium-ion batteries must be constantly monitored via an appropriate battery management system. Most thermal management methods are based on designing suitable cooling systems. In addition, since the surface temperature is measurable through a sensor, it is considered the main criterion of thermal management. However, in extremely fast charge-discharge operations, the core temperature can be significantly higher than the surface temperature. Thus, the cooling system may not be able to solely maintain the core temperature in the safe range. The objective of this paper is to combine electrical and thermal management and set the core temperature as the main criterion. To achieve that, model predictive control is implemented to control the supplied or drawn current of the battery cell, and the Sigma point Kalman filter is used to estimate the states of the experimentally derived electrothermal model. The simulation and experimental results indicate that incorporating model predictive controller and Kalman filter Estimators can be a novel strategy to simultaneously manage electrical and thermal states in both charge and discharge operations. It is also expected that controlling the electrical and thermal states of battery cells in fast charge-discharge operations may increase the safety and lifetime of the cell.

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1- Introduction

Today lithium-ion battery cells have become an indispensable part of hybrid and electric vehicles due to having higher capacity and power than their counterparts. Despite their notable features, Lithium-ion cells are susceptible to high and low temperatures. For instance, in high temperatures (Typically above 110 $^{\circ}C$) the risk of thermal runaway, which may lead to fire and explosion, is high[1]. Apart from safety issues, temperature has a significant impact on battery degradation in the long term. Thus, to reduce the capacity and power fading of cells, it is suggested that the temperature of the battery cell is kept below 50 $^{\circ}C$ [2]. Most of the thermal management methods are based on designing cooling systems. However, in practice, these methods may consider the surface temperature as the main criterion whereas, the internal temperature can be drastically higher. Some studies report that under fast charge-discharge operations, the temperature difference between the surface and core temperature of cylindrical cells can be more than 10 $^{\circ}C$ [3]. To this end, it is reasonable to monitor the core temperature in high-power applications as well as the electrical states of the battery cell. Similar to the core temperature, the state of charge cannot be measured directly. Therefore, most advanced battery management systems are designed based on a model. One of the successful model-based management strategies is the model predictive controller (MPC), which can handle physical hard constraints in multivariable processes. De Souza[4] utilized MPC with an enhanced electrothermal model to manage a lithium-ion cell in a fast charge problem. The experimental results indicate that MPC and extended Kalman filter can constrain the internal states of a battery cell. However, electrical and thermal management was only considered for the problem of fast charging. Thus, its crucial to extend this management to a discharge problem as well.

Based on the above explanation, the contribution of this work can be summarized as follows: designing a low-cost, accurate electrothermal model of a 38120 Lithium-ion cell, designing and tuning a nonlinear estimator for estimating the internal states of the battery cell, designing an optimal controller for a cylindrical lithium-ion cell that can simultaneously manage electrical and thermal states in fast charge operations and extending the model-based management to charge-discharge operations.

2- Design

In this paper, the equivalent circuit model is coupled to two state thermal model to represent the electrical and thermal behavior of a battery cell. To identify electrical parameters, dynamic current profiles are applied to the cell

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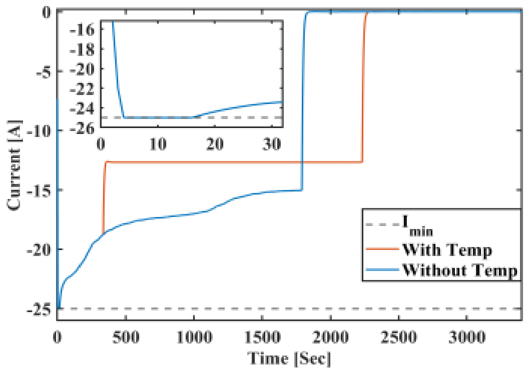

Fig. 1. The applied current with and without temperature constraint

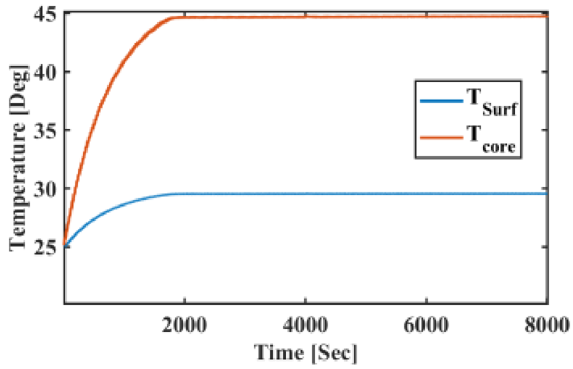

Fig. 3. The temperature management of the cell under square wave current profile

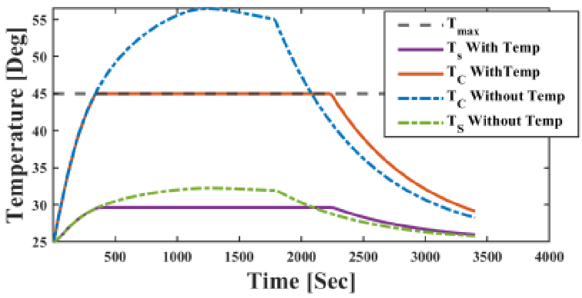

Fig. 2. The Temperature evolution during fast charge with and without temperature constraint

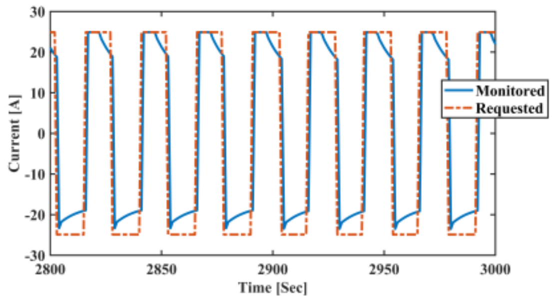

Fig. 4. Restricting the applied current to manage the core temperature

via a battery tester. subsequently, from the measured voltage and identification toolbox in [5], the electrical parameters are identified. For the identification of thermal parameters, the battery cell is placed inside a chamber with a 12V fan. To raise the surface and core temperature the battery cell is cycled under square wave current with the amplitude of 25 amperes. The measured surface temperature, air temperature, and voltage are then used to identify thermal parameters by the least square method. In practice, the voltage, current, and surface temperature of a battery cell are measured. Therefore, the value of the state of charge and core temperature which cannot be measured directly. To overcome this issue, a closed-loop estimator must be designed. In this work, the Sigma-point Kalman filter is utilized to estimate states [6]. As stated, MPC is an optimal control strategy that can handle hard constraints on inputs and states. Thus, MPC can be an effective approach to controlling the applied current to the battery cell. The optimal increment of the current subject to voltage, current, state of charge, and core temperature can be obtained by minimizing the following cost function:

$$J = (R_{ref} - Y_{z,k+1})^T Q (R_{ref} - Y_{z,k+1}) + \Delta I^T{}_{k+1} R \, \Delta I_{k+1} \quad (1)$$

The objective of equation (1) is to track the reference state of charge by penalizing the increment of applied current. Apart from charging, the MPC must control the internal states of a battery cell in discharge operations. In general, the reference state of charge is not defined in charge-discharge operations. Thus, the following cost function is defined

$$J = \left(I_{ref} - I_k\right)^T \left(I_{ref} - I_k\right) \quad (2)$$

In contrast to equation (1), the cost function in equation (2) is based on tracking the reference current. Hence, the objective of the controller is to minimize the deviation between the optimized current and the reference current.

3- Results and Discussion

In this section, a summary of MPC simulation performance in fast charge and fast charge-discharge is discussed. The constraints of the battery cell in both simulations are as follows

$$-25 \le i_k \le 25 \quad (3)$$

$$2.2 \le V_k \le 3.6 \quad (4)$$

$$-25 \le i_k \le 25 \quad (5)$$

$$2.2 \le V_k \le 3.6 \quad (6)$$

To assess the MPC performance in the fast charge problem the reference state of charge is set to %90. As inferred from Figure 1. and Figure 2. The charging process begins with the maximum current magnitude for a short period. Once the voltage reaches its maximum, the current is adjusted to keep the voltage in the safe region. Up to this point, the current profile is similar to the constant-current constant-voltage protocol. However, as the process of charging continues, the limit of core temperature is reached. Thus, the magnitude of current experiences a sudden drop. Hereafter, the battery cell is charged with constant current until the state of charge reaches the defined reference. One may note that adding the core temperature to MPC constraints has negatively impacted the charge time. Nevertheless, when thermal restrictions are neglected, the core temperature significantly exceeds the thermal limits for a large portion of the charging process.

Similar to the charging problem, the internal states of the cell must be managed during discharge operations. To evaluate the performance of MPC in charge-discharge problem a square wave current is chosen as a reference. From Figure 3. It is evident that under square wave current with high amplitude, the temperature of the core and surface of the cell is increasing in 0-1950 timespan. In this stage, the objective of MPC is tracking the reference current. However, when the limit of core temperature is reached, the controller must deviate from the reference current as minimum as possible. The deviation from the reference current can be seen in Figure 4.

4- Conclusions

In this paper, a model-based management of a lithium-ion cell based on MPC and sigma-point Kalman filter is designed. The results indicate that MPC can keep electrical and thermal states in fast charge operations. Furthermore, by modifying the cost function, the application of MPC is extended to fast charge-discharge operations.

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