TRANSIENT THERMAL CHARACTERISTIC ANALYSIS AND CHARGING STATE ESTIMATION OF LITHIUM BATTERIES FOR AUTOMATED GUIDED VEHICLE DURING DISCHARGE

by

Chunyuan PIAN [a], ***Junfeng LIU*** [b*], ***Hongzhi ZHAO*** [a], **and** ***Liwei ZHANG*** [a]

[a] College of Physics and Electronic Engineering, Xinxiang University, Henan, China
[b] Institute of New Energy Materials and Power System, Xinxiang University, Henan, China

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The lithium batteries and their health management for automated guided vehicle power supply system are studied in depth in this paper. First, the transient heat generation for the discharge process of a lithium battery will cause it to work in an unhealthy state and non-linear conditions, seriously affecting the life expectancy. The thermal behavior for lithium battery discharge is studied in depth, and a reliable thermal model is constructed to provide a theoretical basis for designing a lithium battery health management system. Secondly, the accurate and reliable residual state estimation of the lithium battery cannot only provide visualized battery residual capacity, but also reflect the aging status of the lithium battery and other related information, and is one of the important functions to ensure the healthy operation of the lithium battery pack. A new support vector machine is proposed on account of the analysis of the equivalent circuit model of lithium battery, which combines genetic algorithm with particle swarm optimization to enhance the parameters of hybrid kernel function, to analyze accurately the charging status. Finally, the state-of-charge simulation of lithium batteries with variable current discharge is conducted, which proves that the support vector machine algorithm proposed in this paper can accurately judge the charging state of lithium batteries.

Key words: *automatic guided transport vehicle, transient thermal characteristics, lithium ion battery, charging state, support vector machine*

Introduction

As a wheeled mobile robot with rapid development and technological progress in recent years, automated guided vehicle (AGV) has been used in traditional manufacturing industries more and more widely, such as mechanical processing, electrical production, product manufacturing, e-commerce warehouse and other industries. With the advancement and popularization of communication technology and internet of things technology, AGV has begun to jump out of the application scope of traditional industries, and also plays an increasingly important role in emerging industries and mobile internet industries [1-3]. The AGV operation cannot only improve the carrying capacity, but also reduce the transportation cost, but the work of AGV must depend on the power supply of energy storage devices such as batteries. Therefore, the performance and reliability of AGV power supply system is directly related to the safety, efficiency, environmental protection, intelligent level and operation cost of AGV system, and

[*] Corresponding author, e-mail: yuehan19@sina.com

it is the heart and important component of AGV system. This puts forward higher requirements for the design of power supply system for AGV.

At present, lead-acid batteries and nickel-cadmium batteries are the main energy storage devices of AGV power supply system. They have low power density, large volume, short life, potential pollution and safety hazards, high maintenance costs, and are no longer suitable for large-scale installation of AGV system. Lithium batteries have the advantages that these batteries do not have, and are gradually replacing the traditional inefficient lead-acid batteries and nickel-cadmium batteries [4-6]. Traditional AGV power supply device mainly consists of battery energy storage unit, state of charge estimation unit, battery management system, battery charger and its connection device. The battery health management unit of the AGV power system is especially important, which ensures that the AGV can continue to work and operate healthily.

In summary, the thermal effect and battery health management of lithium batteries used in AGV power supply system are deeply explored and studied in this paper. The full text is divided into six parts. The research status of transient thermal characteristics analysis and charge state estimation of lithium batteries for AGV during discharge process are described in the first part. The dynamic thermal model is introduced as second part. The temperature rise features at the moment of discharge are analyzed in the third part. The research scheme of lithium battery state-of-charge (SOC) based on quantum particle swarm optimization (QPSO) and support vector machine (SVM) is presented in the fourth part. The simulation application and verification of SVM in SOC estimation of lithium battery are designed in the fifth part. The last part is a summary.

Dynamic thermal model study of lithium ion batteries

The performance and reliability of AGV power supply system are directly related to the safety, efficiency, environmental protection, intelligent level and operation cost of AGV operation. Therefore, lithium-ion batteries used in AGV power supply need to have high energy density, high power density and high reliability. Considering that the capacity of AGV batteries is generally 60-200 Ah, the discharge current heat generation of such large capacity lithium-ion batteries is the core of the AGV power supply health management and safety issues. The effect of lithium-ion battery discharge on its temperature rise and heating is a coupling process of multi-scale and multi-physical quantities. High temperature and low temperature will have irreversible effects on the battery's life. Therefore, it is necessary to establish an accurate thermal model of lithium-ion batteries and normalize the influencing factors before studying the thermal health management and control of lithium-ion batteries, so as to provide theoretical basis for the design of thermal health management unit.

The heating mechanism of lithium-ion batteries

Lithium battery's working principle is the result of complex physical displacement and chemical transformation of its internal lithium ions. In [7], on the basis of summarizing the existing research results, the thermal factors are creatively normalized to its internal impedance model, and then a more comprehensive and accurate heating equation for lithium ion batteries is obtained, which is approved by many scholars and verified by experiments:

$$q = \frac{I}{V_b}(V - U) + \frac{I}{V_b}\left(T\frac{\partial U}{\partial T}\right) \tag{1}$$

where Q is the heat production rate of lithium batteries, which is constant and can be obtained by looking up the battery specifications table, I – the discharge current of batteries, V_b – the volume of lithium batteries, U – the open circuit voltage of batteries, V – the rated voltage of batteries, and T – the ambient temperature.

Analysis of the influence of partial heat production on the structure of the battery

Figure 1 shows the effect of some parameters on the heat transfer of it [8]. Comparing with figs. 1(a) and 1(b), it can be found that the material and package of lithium battery shell have great influence on its heat production and heat transfer. Comparing with figs. 1(b) and 1(c), it can be found that the electrolyte of lithium battery has little influence on its heat distribution and can be neglected. Comparing with figs. 1(c) and 1(d), it is found that the heat transfer rate of lithium batteries is strongly correlated with their core ears and poles. Finally, comparing figs. 1(d) and 1(e), the external air-flow rate will affect and interfere with the heat generation and heat generation of the lithium battery. After the introduction of the electrode ear, the heat generation direction is consistent.

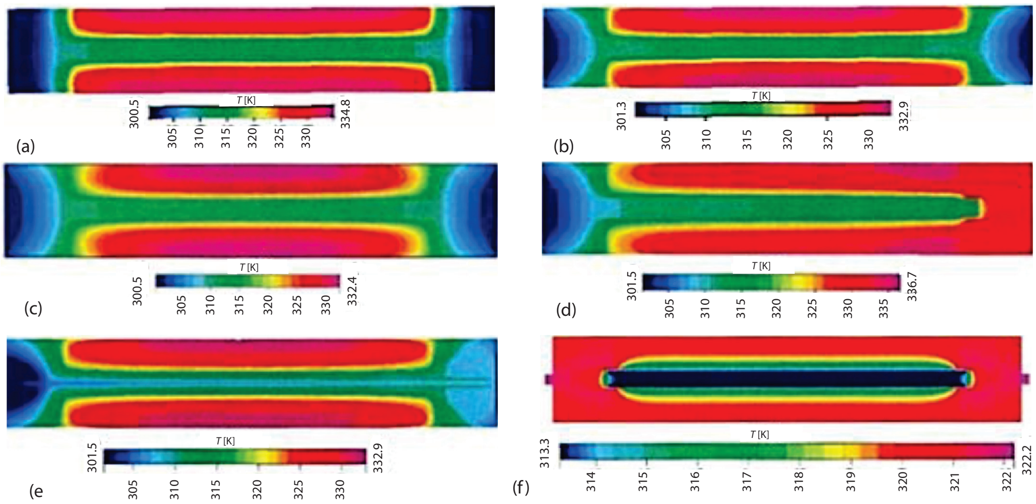

Figure 1. Effect of internal structure and parameters on heat transfer of lithium batteries; (a) only the core heat distribution (b) consider the shell heat transfer, (c) consider the shell and electrolyte, (d) consider the shell, electrolyte and tab, (e) Consider the outer casing, electrolyte and air-flow rate, and (f) consider the factors above and poles

Analysis of temperature rise characteristics of lithium ion battery during discharge

Lithium-ion battery in the adiabatic environment, the instantaneous heat generation reaction

According to the special requirements of AGV power supply system for lithium-ion batteries [9], three kinds of lithium-ion batteries with rated capacity of 100 Ah were compared and analyzed. Considering that AGV usually works indoors, constant current discharge analysis of lithium batteries is carried out under simulated indoor adiabatic environment. It can be concluded that the temperature/current-time curves measured by thermocouples are shown in figs. 2 and 3 when transient discharge test is carried out at room temperature and adiabatic environment.

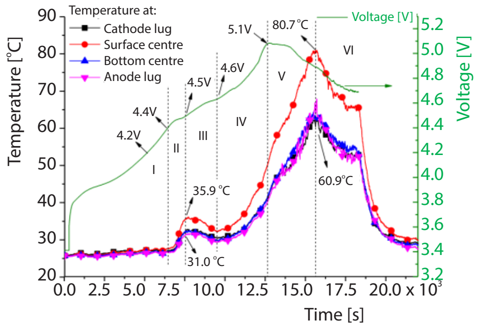

Figure 2. Discharge process, temperature, and time curves of lithium batteries

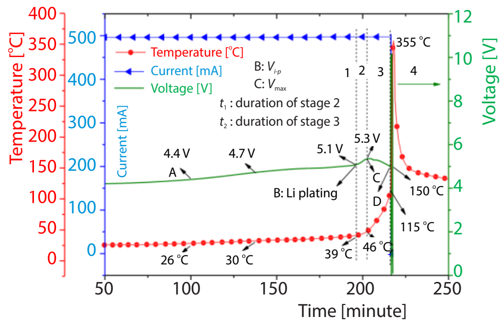

Figure 3. Discharge process, temperature, and time curves of lithium batteries in adiabatic temperature

The results show that the discharge current and voltage are both related to the instantaneous heat generation on the surface of the discharge.

Lithium battery discharge instant test

For exploring the transient thermal features of lithium-ion batteries used in AGV power supply system during discharge and to construct an accurate battery health management system, it is necessary to obtain the internal resistance at different temperatures and the temperature rise curves at different discharge rates through experiments, and then calculate the current heat yield at the moment of discharge [10]. According to the capacity allocation requirements of common AGV power supply system, the single lithium battery provided by Xinxiang Taihang Jiaxin Electrical Technology Co., Ltd. is used as the experimental object. The model is JX22A353010 [11]. The experimental platform is shown in fig. 4. The parameters of the experimental object are shown in tab. 1. The *P* in the figure is the positive pole, *N* – the negative pole, and 1-6 – the hot spot test point.

Figure 4. Lithium-ion batteries for laboratory use and their hot spot test lines

Firstly, the discharge temperature is measured. According to the electrochemical-thermophysical decoupling dynamic heat generation model of lithium battery, the radiation heat transfer coefficient is simplified and the heat transfer:

$$-k_{\xi}\frac{\partial T}{\partial \xi} = Q_c + Q_r = (h_c + h_r)(T - T_a) = h_{\text{comb}}(T - T_a) \tag{2}$$

Table 1. Individual lithium-ion battery parameter table

Lithium battery parameters	Numerical value
Cathode material	Li-ion
Anode material	Graphite
Battery plate size [cm]	20 × 17.3 × 6.3
Positive size [mm]	45 × 17 × 0.45
Negative size [mm]	47 × 19 × 0.45
Single cell quality [g]	15000
Rated voltage [V]	28
Voltage range [V]	24-32
Rated capacity [Ah]	200

where Q_r is the energy loss during heat transfer, Q_c – the heat exchange, h_{comb} denotes coefficient of thermocouple, x-, y-, z- are the co-ordinate system, T – the surface temperature of lithium battery, and T_a – experimental temperature.

On account of the battery's constant specific heat capacity, the reduced heat transfer coefficients of temperature changes during the static process can be measured [12]:

$$C_p M \frac{\mathrm{d}T}{\mathrm{d}t} + h_{\text{comb}} A(T - T_a) = 0 \tag{3}$$

where C_p is the battery's heat capacity coefficient in detail, M – the battery's mass, and A – the stands for its effective cross-section area.

Then, according to the change characteristics of the internal resistance of lithium batteries, the relationship between the average internal resistance and the heat production of bateries is fitted [13]:

$$R_{ava,a} = 1082 \cdot \mathrm{e}^{-3390\left(\frac{1}{T_a + 273} - \frac{1}{263}\right)} \tag{4}$$

Analysis of thermal characteristics of lithium battery discharge

Figure 5 is a graph showing the temperature change of the battery under high and low temperature adiabatic conditions at 0.5 °C, 1.5 °C, and 3 °C discharge rates. The results show that the rising temperature of lithium batteries increases linearly with the discharge time during the transient discharge of lithium batteries. The heating rate of lithium batteries at different discharge rates and the ratio between them can be further obtained by eq. (4) to support the healthy management of lithium batteries for AGV power supply system.

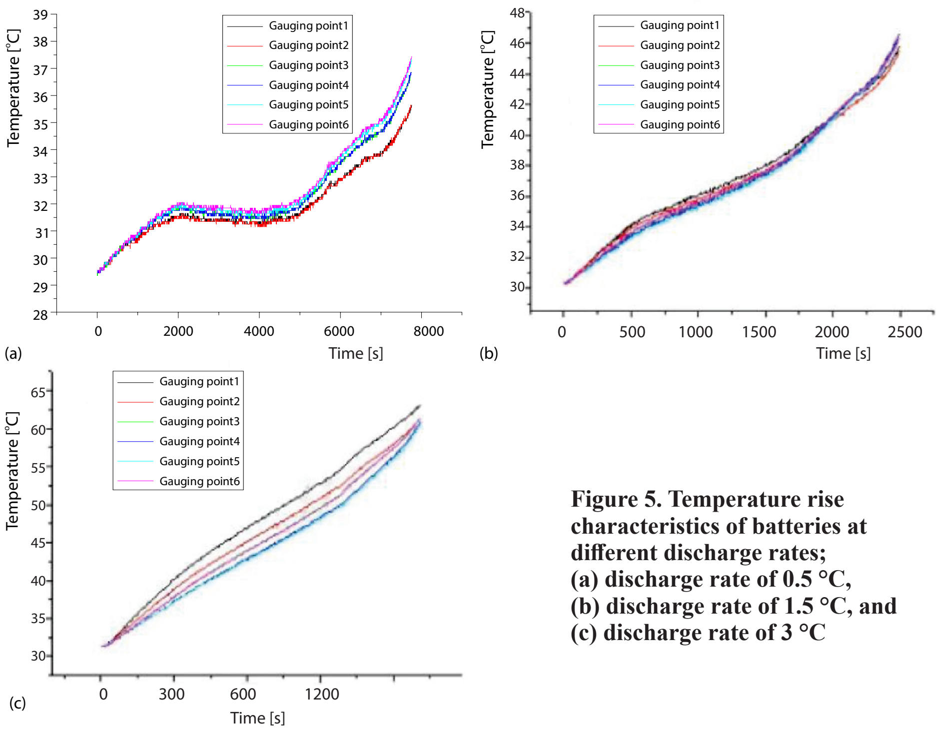

Figure 5. Temperature rise characteristics of batteries at different discharge rates; (a) discharge rate of 0.5 °C, (b) discharge rate of 1.5 °C, and (c) discharge rate of 3 °C

Research on lithium battery SOC based on QPSO SVM

As the core component of the AGV power system, the lithium battery directly reflects the healthy operation status of the AGV. Therefore, proper estimation of the battery SOC is essential for safe operation of the AGV [14]. In order to overcome the shortcomings of SOC estimation strategy commonly used at home and abroad, a new hybrid kernel function SVM is proposed to realize accurate estimation of SOC in current-varying discharge state.

Establishment of equivalent circuit model for lithium battery

The internal structure is shown in fig. 6 below, and the equivalent circuit model is explained in fig. 7 [15].

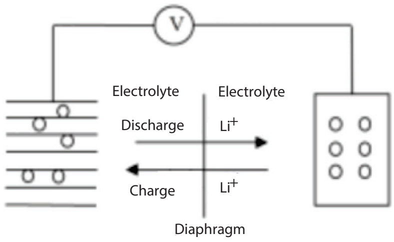

Figure 6. Basic structure of lithium battery

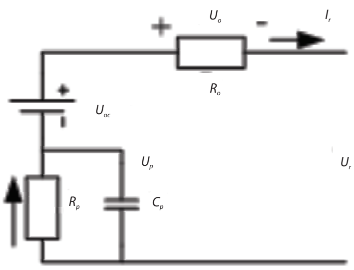

Figure 7. Equivalent circuit model of lithium battery

Lithium battery status of charge estimation strategy

Considering the equivalent circuit model of the lithium battery, the SOC can be expressed:

$$z(t) = z(0) - \int_0^t \frac{\eta_i i(\tau)}{C_n} \mathrm{d}\tau \tag{5}$$

where η_i represents the Coulomb constant, and for equivalent circuit of the model of fig. 7, the space equation of the lithium battery can be obtained:

$$\begin{cases} z_{k+1} = z_k - \left(\dfrac{\eta_i \Delta t}{C_n}\right) i_k \\ y_k = OCV(z_k) - Ri_k \end{cases} \tag{6}$$

Therefore, it is only needed to obtain an accurate estimation value of the identified equation y_k by the system parameter algorithm, and the status of charge can be evaluated.

Lithium battery state of charge analysis based on hybrid kernel function SVM

The SVM algorithm

First, the optimal linear function of the classification decision of the support vector constructed in high-dimensional space:

$$f(x) = \mathrm{sign}[\omega^T \varphi(x) + b] \tag{7}$$

Parameter *ω, b* can be simplified by eq. (8):

$$\begin{aligned}&\min_{\omega,b\xi_i} \quad \frac{1}{2}\omega^T\omega + C\sum_{I=1}^{n}\xi_i\\&s.t. \quad y_i[\omega\varphi(x_i)+b]\geq 1-\xi_i, \forall i=1,2...n\\&\qquad\qquad \xi_i\geq 0, \quad i=1,2,...,n\end{aligned} \tag{8}$$

The Lagrangian equation is transformed into the eq. (8) to obtain the eq. (9):

$$\begin{aligned}&\min\left\{\frac{1}{2}\sum_{i-1}^{n}\sum_{j=1}^{n}a_i a_j y_i y_j \varphi(x_i)^T\varphi(x_j)-\sum_{i=1}^{n}a_i\right\}\\&s.t. \quad 0\leq a_i\leq c, \sum_{i=1}^{n}a_i y_i=0\end{aligned} \tag{9}$$

Further, defining a non-linear transformation function is called a kernel function, *K*:

$$K(x,x_k)=\varphi(x_i)^T\varphi(x_i) \tag{10}$$

By selecting the appropriate kernel function, simultaneous (9) and (10), the dual problem is turned into:

$$\begin{aligned}&\min\left\{\frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n}a_i a_j y_i y_j K(x_i,x_j)-\sum_{i=1}^{n}a_i\right\}\\&s.t. \quad 0\leq a_i\leq c, \quad \sum_{i=1}^{n}a_i y_i=0\end{aligned} \tag{11}$$

By solving the dual problem (9), the result can be obtained:

$$\omega=\sum_{i=1}^{n}a_i y_i\varphi(x_i) \tag{12}$$

Thus, the optimal linear decision function is obtained:

$$f(x)=\text{sign}\left[\sum_{i=1}^{n}y_i a_i K(x_i,x)+b\right] \tag{13}$$

The mapping relationship from input space to high-dimensional feature space is shown in fig. 8.

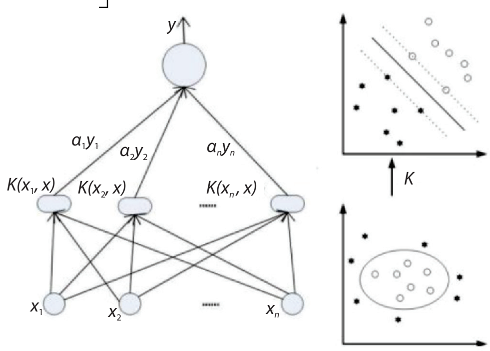

Figure 8. Mapping relation of input space to high dimensional feature space

Application and simulation of SVM in SOC estimation of lithium battery

The constant current discharge experiment, pulse discharge experiment and DST condition experiment were designed for verifying the estimation of battery SOC based on the SVM based algorithm proposed in this paper.

Constant current pulse experiment

The experiment selects the constant current discharge of 1.5 °C discharge rate at 25 °C ambient temperature, and performs multiple cycles. The comparison between the SOC curve and the real SOC curve is explained in fig. 9.

The DST working condition experiment

The DST experiment can simulate the actual work and operation of the AGV more accurately. The simulation results are shown in fig. 10.

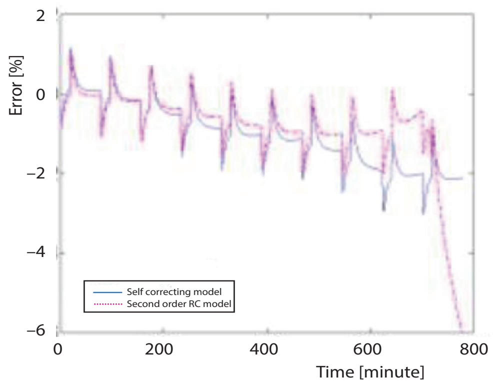

Figure 9. The SOC estimation error curve of pulse discharge test

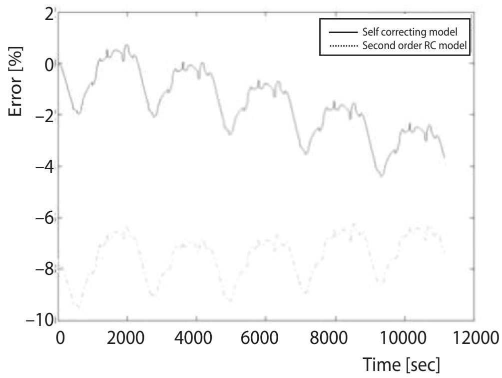

Figure 10. The SOC estimation error comparative curves in DST condition

The simulation results of battery SOC estimation based on SVM show that the strategy can correct the SOC curve of battery, thus improving the accuracy and reliability of SOC estimation, and has strong engineering value.

Conclusions

The lithium batteries used in AGV power supply system are taken as the research object. The thermal characteristics and lithium battery's health management are deeply studied, especially the state of charge estimation technology. The following conclusions are obtained:

- An accurate and reliable dynamic thermal model was established. The model and heat production characteristics of lithium-ion batteries are quite different from those of traditional lead-acid batteries and nickel-chromium batteries. The traditional thermal model can lead to low simulation accuracy of lithium batteries under high-rate discharge conditions and high temperature conditions since the actual electrode characteristic parameters of lithium electrons are dynamic. In this paper, the correlation model of heat production process and temperature is constructed, and the function parameters of the traditional thermal model are optimized, which can accurately predict the thermal characteristics of lithium batteries.
- An accurate model of the temperature rise characteristics at the moment of discharge was established. The transient heating of lithium batteries during discharge can make them work in unhealthy and non-linear conditions, which seriously affects the life estimation of lithium batteries. A reliable thermal model is constructed by analyzing the thermal behavior of lithium batteries at the moment of discharge, which provides a theoretical basis for the depict of thermal health management unit.
- A support vector machine parameter optimization theory based on the combination of quantum algorithm and particle swarm optimization is presented. The recent algorithm can be

implemented at different times and under different conditions. The SOC of lithium battery can be estimated accurately. A novel support vector machine was constructed to optimize the parameters of hybrid kernels. The simulation experiment of lithium battery charging state estimation was carried out. The results prove that the support vector machine algorithm accurately estimates the charging status of lithium batteries, and then realize the personalized monitoring and management of lithium batteries in AGV power supply system. It provides a basis for timely improvement of the health management of lithium batteries, effectively improves the service life of lithium batteries, and increases the safety of AGV power supply system.

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