(19) LE GOUVERNEMENT DU GRAND-DUCHÉ DE LUXEMBOURG
Ministère de l'Économie

(11) N° de publication : **LU503873**

(12) BREVET D'INVENTION B1

(21) N° de dépôt: LU503873

(51) Int. Cl.:
G01R 31/367, G01K 7/42, H01M 10/48

(22) Date de dépôt: 07/04/2023

(30) Priorité:

(43) Date de mise à disposition du public: 09/10/2023

(47) Date de délivrance: 09/10/2023

(73) Titulaire(s):
SOUTHWEST UNIVERSITY OF SCIENCE AND TECHNOLOGY – 621010 Mianyang City, Sichuan (Chine), SICHUAN XINZHI LVNENG MEASUREMENT AND CONTROL TECHNOLOGY CO., LTD. – 621010 Mianyang, Sichuan (Chine), CHENGDU UNIVERSITY OF INFORMATION TECHNOLOGY – 610225 Chengdu, Sichuan (Chine)

(72) Inventeur(s):
SHI Haotian – Chine, ZHU Yongjie – Chine, YU Chunmei – Chine, JIN Yuhong – Chine, WANG Shunli – Chine, JIN Siyu – Chine, HOU Yan – Chine, HUANG Qi – Chine, ZHANG Gexiang – Chine, CHEN Lei – Chine

(74) Mandataire(s):
Patent42 SA – 4081 Esch-sur-Alzette (Luxembourg)

(54) ONLINE SELF-ADAPTIVE METHOD FOR ESTIMATING BATTERY INTERNAL TEMPERATURE.

(57) The invention discloses an online self-adaptive method for estimating the battery internal temperature, which comprises the following steps: establishing a lumped thermal characteristic equivalent circuit model of the battery based on the modeling similarity between physical systems of the same order; establishing a state space model of the lumped thermal characteristic equivalent circuit model in a time domain state based on Kirchhoff's circuit laws; acquiring a battery internal temperature state model based on the state space model in the time domain state; obtaining thermal characteristic model parameters to be identified in the battery internal temperature state model based on the battery internal temperature state model by adopting the forgetting factor least square method; jointly estimating the parameters of the thermal characteristic model and the battery internal temperature by using a joint Kalman filter method.

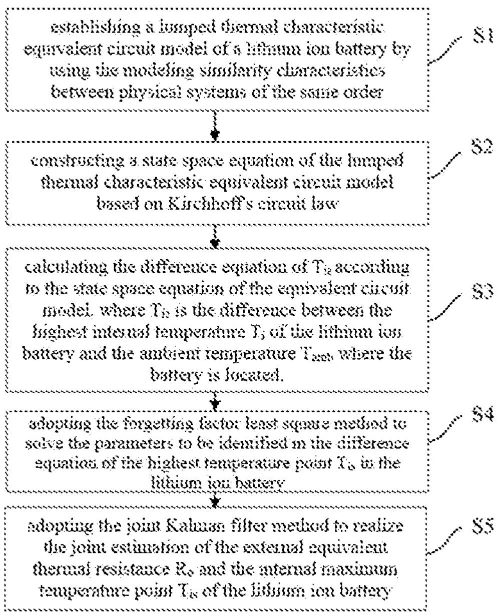

FIG. 1

DESCRIPTION

ONLINE SELF-ADAPTIVE METHOD FOR ESTIMATING BATTERY INTERNAL TEMPERATURE

TECHNICAL FIELD

The invention belongs to the technical field of power batteries, and in particular relates to an online self-adaptive method for estimating the battery internal temperature.

BACKGROUND

In recent years, benefiting from the explosive development of global new energy automobile industry, lithium-ion batteries have quickly become the mainstream power source due to their high energy density and long cycle life. Compared with its own defects such as aging, self-discharge and capacity decline, the safety problems caused by the difficulty in real-time prediction of battery temperature seriously restrict the large-scale development of new energy vehicles. Therefore, the thermal characteristics modeling and high-precision prediction of internal temperature of power battery are very important to prevent thermal runaway of battery and ensure safe and long-life operation. In addition, for the thermal management system of battery, different thermal management systems may have different temperature control modes, which makes different thermal management systems of battery have different external heat transfer coefficients. Using the same external heat transfer coefficient in different working conditions will increase the error of battery internal temperature estimation. Therefore, the adaptive working condition prediction method of battery external heat transfer coefficients is very important for high-accuracy thermal characteristic modeling and efficient thermal management system construction.

The complex internal structure and changeable application environment of power battery make it easy to produce uneven internal temperature distribution and high internal temperature during its use, which increases the difficulty of estimating the battery internal temperature. At present, the commonly used methods for measuring the battery internal temperature includes the internal temperature measurement method based on experiment, the internal temperature prediction method based on off-line and the internal temperature estimation method based on online estimation. The internal temperature measurement method based on experiment is usually to embed thermocouple in the battery, which is only suitable for testing the relevant thermal characteristics of the battery under experimental environmental conditions. In the practical application of the battery, the feasibility of this method is low and there are huge hidden dangers in the long-term use of the battery, which cannot guarantee the safety of the battery in use. The internal temperature prediction method based on off-line is based on the finite element numerical calculation method, and the internal temperature estimation of the battery is obtained by establishing the thermal model of the battery and carrying out off-line simulation. This method is usually used in the packaging design and module design of battery cells, and the finite element numerical calculation method has high computational complexity, which is not suitable for the practical application and thermal management of batteries.

The above-mentioned researches on the battery internal temperature are based on the laboratory or off-line, and the development of an application-grade vehicle-mounted battery thermal management system needs to meet the online estimation of the battery internal temperature. The internal temperature prediction method based on online estimation often takes practical application as the starting point to realize the thermal management of batteries. The prediction methods based on online estimation of battery internal temperature can be roughly divided into DC internal resistance method, electrochemical impedance spectroscopy (EIS) measurement analysis method and temperature difference transfer function method. Some researchers have studied the DC internal resistance method, using the functional relationship between DC internal resistance and the internal and external temperature of the battery to estimate the battery internal temperature by looking up the table or functional calculation. However, different types of batteries, even different batteries of the same type, have different functional relationships between DC internal resistance and internal and external temperatures of batteries, which makes the DC internal resistance method not universal.

In addition, the research on EIS measurement analysis method by scholars in the field is not rare, and the principle of this method is similar to that of DC internal resistance method. The battery internal temperature is estimated by looking up the table or calculating the function according to the corresponding functional relationship between the average amplitude and phase angle of the AC impedance of the battery and the battery internal temperature. However, EIS measuring instrument is not suitable for the practical application of automobiles because of its demanding working environment and extremely high price.

In view of the obvious disadvantages of the above methods, in order to improve the reliability of battery thermal modeling, the temperature difference transfer function method based on thermal network film modeling is applied. This method uses the transfer function between the battery internal temperature and the heating power of the system to calculate the battery internal temperature through the input current of the system. This kind of method is commonly used in the current battery internal temperature estimation, but this method belongs to open-loop estimation, and it cannot update the parameters of the transfer function adaptively according to the changes of the external environment, so the accuracy is low. From the above discussion, it can be found that the existing research on battery thermal characteristics modeling is often accompanied by high computational complexity. At the same time, the harsh environmental conditions also make most of the research stay in the laboratory stage, which cannot realize the actual vehicle application of the system. In addition, the uncertainty of external thermal resistance and the inability to estimate the internal text adaptively and accurately in changeable environment have not been paid enough attention.

SUMMARY

In order to solve the above technical problems, the invention provides an online self-adaptive method for estimating the battery internal temperature, which realizes the self-adaptive collaborative estimation of the parameters of a thermal characteristic model and the battery internal temperature, and solves the problem that the battery internal temperature is difficult to adaptively and accurately estimate online in the prior art.

In order to achieve the above purpose, the present invention provides an online self-adaptive method for estimating the battery internal temperature, which comprises the following steps:

establishing a lumped thermal characteristic equivalent circuit model of the battery based on the modeling similarity between physical systems of the same order;

establishing a state space model of the lumped thermal characteristic equivalent circuit model in a time domain state based on Kirchhoff's circuit laws;

acquiring a battery internal temperature state model based on the state space model in the time domain state;

obtaining thermal characteristic model parameters to be identified in the battery internal temperature state model based on the battery internal temperature state model by adopting the forgetting factor least square method;

jointly estimating the parameters of the thermal characteristic model and the battery internal temperature by using a joint Kalman filter method.

Optionally, the step of establishing a state space model of the lumped thermal characteristic equivalent circuit model in a time domain state based on Kirchhoff's circuit laws includes:

Processing a heating power model based on the lumped thermal characteristic equivalent circuit model to obtain a new heating power model of the lumped thermal characteristic equivalent circuit model;

obtaining the state models of the highest temperature node in the center of the battery and the temperature node in the surface area of the battery, based on the new heating power model and the Kirchhoff circuit law;

obtaining an observation model of T_{ss} based on the difference between the highest temperature node in the inner center of the battery and the ambient temperature where the battery is located;

acquiring a state space model of the lumped thermal characteristic equivalent circuit model based on the state model and the observation model.

Optionally, the new heating power model is:

$$Q \approx I^2 R_s + IT\,(dE)/dT \Leftarrow E - U_L = IR_s$$

Where Q is the heating power, R_s is the DC internal resistance of the battery, I is the charging and discharging current of the battery, T is the battery temperature, E is the balanced electromotive force inside the battery, and U_L is the terminal voltage of the battery;

the state model is:

$$\begin{cases} \dfrac{dT_{is}}{dt} = -\dfrac{1}{R_i C_i} T_{is} + \dfrac{1}{R_i C_i} T_{ss} + \dfrac{Q}{C_i} \\ \dfrac{dT_{ss}}{dt} = \dfrac{1}{R_i C_s} T_{is} + \left(\dfrac{1}{R_i C_s} + \dfrac{1}{R_o C_s}\right) T_{ss} \end{cases} \Leftarrow \begin{cases} T_{is} = T_i - T_{amb} \\ T_{ss} = T_s - T_{amb} \end{cases};$$

wherein, Q is the heating power, T_i is the highest temperature in the center of the battery, T_s is the surface temperature of the battery, T_{amb} is the ambient temperature of the battery, R_i is the internal thermal resistance of the battery, R_o is the external thermal resistance of the battery, C_i is the equivalent thermal capacity of the battery, C_s is the equivalent hot melting of the battery shell, T_{is} is the difference between the highest temperature T_i of the internal central temperature of the battery and the ambient temperature T_{amb} of the battery, and T_{ss} is the difference between the surface temperature T_s of the battery and the ambient temperature T_{amb} of the battery;

The observation model is:

$$\underbrace{T_{ss}}_{y_t} = \underbrace{[0 \quad 1]}_{C_t} \underbrace{\begin{bmatrix} T_{is} \\ T_{ss} \end{bmatrix}}_{x_t} + \underbrace{[0]}_{D_t} \underbrace{[Q]}_{u_t}$$

where, y_t is the system output in time domain, C_t is the output matrix in time domain, x_t is the system state variable in continuous state, D_t is the branch transfer matrix in time domain, and u_t is the system input in continuous state.

Optionally, the step of acquiring a battery internal temperature state model based on the state space model in the time domain state includes:

Acquiring a transfer function of the state space model based on the new heating power model and the internal temperature state of the battery, wherein the internal temperature state of the battery is the difference between the highest point of the internal central temperature of the battery and the ambient temperature where the battery is located;

carrying out integrated deformation on the transfer function by using Z transform to obtain the internal temperature state model of the battery.

Optionally, the battery internal temperature state model is:

$$T_{is,k+2} = \alpha_1 T_{is,k+1} + \alpha_2 T_{is,k} + \beta_1 Q_{k+1} + \beta_2 Q_k$$

where $T_{is,k}$ is the temperature value of the highest temperature point in the battery at time k, $T_{is,k+1}$ is the temperature value of the highest temperature point in the battery at time k+1, $T_{is,k+2}$ is the temperature value of the highest temperature point in the battery at time k+2, Q_k is the heating power of the battery at time k, Q_{k+1} is the heating power of the battery at time k+1, α_1, α_2, β_1 and β_2 are the parameters to be identified of the difference equation of the internal temperature state model.

Optionally, the step of obtaining thermal characteristic model parameters to be identified in the battery internal temperature state model based on the battery internal temperature state model by adopting the forgetting factor least square method comprises:

acquiring an exogenous autoregressive model based on the battery internal temperature state model;

solving the thermal characteristic model parameters that need to be identified in the battery internal temperature state model by the least method based on the exogenous autoregressive model.

Optionally, the exogenous autoregressive model is as follows:

$$\boldsymbol{Y} = \boldsymbol{\varphi}^T \boldsymbol{\theta} \Leftarrow \begin{cases} \boldsymbol{\theta} = [\alpha_1, \alpha_2, \beta_1, \beta_2]^T \\ \boldsymbol{\varphi} = \{\boldsymbol{\varphi}_0, \boldsymbol{\varphi}_1, \boldsymbol{\varphi}_2, \cdots, \boldsymbol{\varphi}_k, \cdots, \boldsymbol{\varphi}_{n-2}\} \\ \boldsymbol{Y} = [T_{is,2}, T_{is,3}, T_{is,4}, \cdots, T_{is,k+2}, \cdots, T_{is,n}]^T \\ \boldsymbol{\varphi}_k = [T_{is,k+1}, T_{is,k}, Q_{k+1}, Q_k]^T \end{cases}$$

Where $\boldsymbol{Y}$ is the output matrix of the exogenous autoregressive model, $\boldsymbol{\varphi}$ is the data matrix, $\boldsymbol{\theta}$ is the coefficient matrix, and $\boldsymbol{\varphi}_k$ is the system data matrix at time **k**;

the parameters of the thermal characteristic model parameters are C_i, R_i and C_s; the thermal characteristic model parameter equation is:

$$\begin{cases} C_i = \Delta t/\beta_1, R_i = (\beta_1\beta_2)/(\beta_2 - \alpha_2\beta_1) \\ C_s = (\Delta t\beta_1)/R_o + \Delta t(\alpha_1 - 2) - \Delta t/\beta_1 \end{cases},$$

Where C_i is the equivalent heat capacity inside the battery, R_i is the internal thermal resistance of the battery, C_s is the equivalent hot melt of the battery shell, andΔt is the system sampling time.

Optionally, the step of jointly estimating the parameters of the thermal characteristic model and the battery internal temperature by using a joint Kalman filter method comprises:

acquiring the state space model in the discrete state of the lumped thermal characteristic equivalent circuit model based on the state space model in the time domain state;

constructing the JKF model of self-adaptive cooperative estimation of the external equivalent thermal resistance and the internal temperature state of the battery by using the joint Kalman filtering method and based on the state space equation in the discrete state;

realizing the joint estimation of the parameters of the thermal characteristic model and the internal temperature based on the JKF model.

Optionally, the state space model in the discrete state is:

$$\begin{cases} \underbrace{\begin{bmatrix} T_{is,k+1} \\ T_{ss,k+1} \end{bmatrix}}_{x_{d,k+1}} = \underbrace{\begin{bmatrix} 1 - \frac{\Delta t}{R_iC_i} & \frac{\Delta t}{R_iC_i} \\ \frac{\Delta t}{R_iC_s} & 1 - \left(\frac{\Delta t}{R_iC_s} + \frac{\Delta t}{R_oC_s}\right) \end{bmatrix}}_{A_d} \underbrace{\begin{bmatrix} T_{is,k} \\ T_{ss,k} \end{bmatrix}}_{x_{d,k}} + \underbrace{\begin{bmatrix} \frac{\Delta t}{C_i} \\ 0 \end{bmatrix}}_{B_d} \underbrace{\begin{bmatrix} Q_k \end{bmatrix}}_{u_k} + \underbrace{\begin{bmatrix} w_k^1 \\ w_k^2 \end{bmatrix}}_{w_k} \\ \underbrace{T_{ss,k+1}}_{y_k} = \underbrace{\begin{bmatrix} 0 & 1 \end{bmatrix}}_{C_d} \underbrace{\begin{bmatrix} T_{is,k} \\ T_{ss,k} \end{bmatrix}}_{x_{d,k}} + \underbrace{\begin{bmatrix} 0 \end{bmatrix}}_{D_d} \underbrace{\begin{bmatrix} Q_k \end{bmatrix}}_{u_k} \end{cases}$$

Where $x_{d,\ k+1}$ are the state variables of the system at time k+1 in discrete state, $x_{d,\ k}$ are the state variables of the system at time k in discrete state, u_k is the input variable of the system at time **k**, w_k is system noise, y_k is the output variable of the system at time **k** in discrete state, A_d is the system matrix in discrete state, B_d is the control matrix in discrete state, C_d is the observation matrix in discrete state and D_d is the direct transfer matrix in discrete state.

Optionally, the JKF model is:

$$\begin{cases} x_{J,k+1} = f(x_{J,k}, u_k) + w_k \approx \boldsymbol{A}_J x_{J,k} + \boldsymbol{B}_J u_k + w_k \\ y_k = h(x_{J,k}, u_k) + v_k \approx \boldsymbol{C}_J x_{J,k} + \boldsymbol{D}_J u_k + v_k \end{cases}$$

where $x_{J,k}$ is the 3-dimensional system state matrix at time k, $x_{J,k+1}$ is the system state matrix engraved at time k+1, u_k is the input variable of the system at time k, y_k is the output variable of the system at time k in discrete state, $\boldsymbol{A}_J$ is the 3×3 -dimensional system matrix, $\boldsymbol{B}_J$ is the 3×1 -dimensional control matrix, $\boldsymbol{C}_J$ is the 1×3 -dimensional output matrix, $\boldsymbol{D}_J$ is the direct matrix, w_k is the system noise and v_k is the observation noise.

Compared with the prior art, the invention has the following advantages and technical effects:

According to the invention, a battery lumped thermal characteristic model is established, and the discrete state space equation expression of the thermal characteristic model is realized by combining a control theory. Considering the uncertainty of external thermal resistance, the error can be controlled within 0.5℃ by combining the forgetting factor least square algorithm with the joint Kalman filter algorithm, and the initial values of different external equivalent thermal resistances will converge to the same value with the iteration, thus realizing the adaptive collaborative estimation of the parameters of thermal characteristic model and the battery internal temperature, and solving the problem that it is difficult to estimate the battery internal temperature adaptively and accurately in the prior art.

BRIEF DESCRIPTION OF THE FIGURES

The accompanying drawings, which constitute a part of this application, are used to provide a further understanding of this application. The illustrative embodiments of this application and their descriptions are used to explain this application, and do not constitute an improper limitation of this application. In the attached drawings:

FIG. 1 is a flowchart of an embodiment of the present invention;

FIG. 2 is a schematic diagram of a lumped thermal characteristic model according to an embodiment of the present invention.

DESCRIPTION OF THE INVENTION

It should be noted that the embodiments in this application and the features in the embodiments can be combined with each other without conflict. The present application will be described in detail with reference to the attached drawings and examples.

It should be noted that the steps shown in the flowchart of the accompanying drawings may be executed in a computer system such as a set of computer-executable instructions, and although the logical order is shown in the flowchart, in some cases, the steps shown or described may be executed in a different order from here.

The invention provides an online self-adaptive method for estimating the battery internal temperature, and the specific process is shown in FIG. 1, which comprises the following steps:

establishing the lumped thermal characteristic equivalent circuit model of the battery based on the modeling similarity between physical systems of the same order;

establishing a state space model of the lumped thermal characteristic equivalent circuit model in a time domain state based on Kirchhoff's circuit laws;

acquiring a battery internal temperature state model based on the state space model in the time domain state;

obtaining thermal characteristic model parameters to be identified in the battery internal temperature state model based on the battery internal temperature state model by adopting the forgetting factor least square method;

jointly estimating the parameters of the thermal characteristic model and the battery internal temperature by using a joint Kalman filter method.

Further, the step of establishing a state space model of the lumped thermal characteristic equivalent circuit model in a time domain state based on Kirchhoff's circuit laws includes:

Processing a heating power model based on the lumped thermal characteristic equivalent circuit model to obtain a new heating power model of the lumped thermal characteristic equivalent circuit model;

obtaining the state models of the highest temperature node in the center of the battery and the temperature node in the surface area of the battery, based on the new heating power model and the Kirchhoff circuit law;

obtaining an observation model of T_{ss} based on the difference between the highest temperature node in the inner center of the battery and the ambient temperature where the battery is located;

acquiring a state space model of the lumped thermal characteristic equivalent circuit model based on the state model and the observation model.

Further, the step of acquiring a battery internal temperature state model based on the state space model in the time domain state includes:

Acquiring a transfer function of the state space model based on the new heating power model and the internal temperature state of the battery, wherein the internal temperature state of the battery is the difference between the highest point of the internal central temperature of the battery and the ambient temperature where the battery is located;

carrying out integrated deformation on the transfer function by using Z transform to obtain the internal temperature state model of the battery.

Further, the step of obtaining thermal characteristic model parameters to be identified in the battery internal temperature state model based on the battery internal temperature state model by adopting the forgetting factor least square method comprises:

acquiring an exogenous autoregressive model based on the battery internal temperature state model;

solving the thermal characteristic model parameters that need to be identified in the battery internal temperature state model by the least method based on the exogenous autoregressive model.

Further, the step of jointly estimating the parameters of the thermal characteristic model and the battery internal temperature by using a joint Kalman filter method comprises:

acquiring the state space model in the discrete state of the lumped thermal characteristic equivalent circuit model based on the state space model in the time domain state;

constructing the JKF model of self-adaptive cooperative estimation of the external equivalent thermal resistance and the internal temperature state of the battery by using the joint Kalman filtering method and based on the state space equation in the discrete state;

realizing the joint estimation of the parameters of the thermal characteristic model and the internal temperature based on the JKF model.

The specific flow of this embodiment is shown in FIG. 1, and the implementation steps are as follows:

S1, establishing a lumped thermal characteristic equivalent circuit model of a lithium ion battery by using the modeling similarity characteristics between physical systems of the same order. As shown in FIG. 2, the composition of the model is based on the similarity between lumped electrical characteristic modeling and thermal characteristic modeling of the battery, and the thermal characteristic network of the battery is described by an equivalent electrical characteristic network. Among them, the current source, capacitance and resistance of the electrical characteristic network are equivalent to the heating power, heat capacity and thermal resistance of the thermal characteristic network respectively. Q is the total heating power of the battery, and there are two ways to conduct it: one is to heat the battery, and the other is to conduct it through thermal resistance. T_i is the highest temperature in the center of the battery, T_s is the surface temperature of the battery. T_{amb} is the ambient temperature of the battery. T_0 is the model reference temperature point, and in general, T_{amb} is set as the external reference temperature point, that is, $T_{amb} = T_0$. R_i is the internal thermal resistance of the battery, which is related to the introduction coefficient of the battery. R_o is the external thermal resistance of the battery, which is related to the heat transfer coefficient outside the battery. C_i is the equivalent thermal capacity of the battery. C_s is the equivalent hot melting of the battery shell. It is worth noting that the cylindrical battery sample used in the embodiment of the invention is an aluminum shell with excellent thermal conductivity, and the heat capacity of the shell is extremely small. The invention realizes the modeling and solving of the thermal characteristics of the battery based on FIG. 2.

S2, constructing a state space equation of the lumped thermal characteristic equivalent circuit model based on Kirchhoff's circuit law.

S21, in order to reduce the computational complexity of the battery heat source, further simplifying the Bernardi's heating power equation according to Kirchhoff's law, LU503873 and obtaining a simplified expression for calculating the heating power of the battery lumped parameter thermal model:

$$Q \approx I^2 R_s + IT(dE)/dT \Leftarrow E - U_L = IR_s$$

Where Q is the heating power, R_s is the DC internal resistance of the battery, I is the charging and discharging current of the battery, T is the battery temperature, E is the balanced electromotive force inside the battery, and U_L is the terminal voltage of the battery;

S22, using the similarity of system modeling to express the thermal characteristic model in time domain state space equation. Obtaining the differential equations of T_i node and T_s node based on Bernardi's simplified equation and Kirchhoff's circuit law in circuit science:

$$\begin{cases} \dfrac{dT_{is}}{dt} = -\dfrac{1}{R_i C_i} T_{is} + \dfrac{1}{R_i C_i} T_{ss} + \dfrac{Q}{C_i} \\ \dfrac{dT_{ss}}{dt} = \dfrac{1}{R_i C_s} T_{is} + \left(\dfrac{1}{R_i C_s} + \dfrac{1}{R_o C_s}\right) T_{ss} \end{cases} \Leftarrow \begin{cases} T_{is} = T_i - T_{amb} \\ T_{ss} = T_s - T_{amb} \end{cases}$$

In the formula, Q is the heating power, T_i is the highest temperature in the center of the battery, T_s is the surface temperature of the battery, T_{amb} is the ambient temperature of the battery, R_i is the internal thermal resistance of the battery, R_o is the external thermal resistance of the battery, C_i is the equivalent thermal capacity of the battery, C_s is the equivalent hot melting of the battery shell, T_{is} is the difference between the highest temperature T_i of the internal central temperature of the battery and the ambient temperature T_{amb} of the battery, and T_{ss} is the difference between the surface temperature T_s of the battery and the ambient temperature T_{amb} of the battery.

In the optimal control of engineering practice, state variables are often required as feedback quantities. In the embedded system application of lithium-ion battery, the value of T_{ss} is easier to be measured safely than that of T_{is}, therefore, the embodiment of the invention selects the output vector of the thermal characteristic model as T_{ss}, and the observation equation in the continuous time state is obtained:

$$\underbrace{T_{ss}}_{y_t} = \underbrace{\begin{bmatrix} 0 & 1 \end{bmatrix}}_{C_t} \underbrace{\begin{bmatrix} T_{is} \\ T_{ss} \end{bmatrix}}_{x_t} + \underbrace{[0]}_{D_t} \underbrace{[Q]}_{u_t}$$

Where y_t is the system output in time domain, C_t is the output matrix in time domain, x_t is the system state variable in continuous state, D_t is the branch transfer matrix in time domain, and u_t is the system input in continuous state.

S3, calculating the difference equation of T_{is} according to the state space equation of the equivalent circuit model, where T_{is} is the difference between the highest internal temperature T_i of the lithium-ion battery and the ambient temperature T_{amb} where the battery is located.

S31, taking the heating power Q as the system input and the highest internal temperature T_{is} as the system output, obtaining the system transfer function based on LTCM:

$$G(s) = \frac{1+R_i/R_o+C_sR_is}{C_sC_is^2+(C_s+C_i+R_iC_i/R_o)s+1/R_o} \Leftarrow G(s) = \frac{T_{is}(s)}{Q(s)}$$

S32, integrating and deforming the transfer function of the lumped thermal characteristic model by Z transform to obtain the difference equation of the thermal characteristic model, that is, the difference equation of T_{is}:

$$T_{is,k+2} = \alpha_1 T_{is,k+1} + \alpha_2 T_{is,k} + \beta_1 Q_{k+1} + \beta_2 Q_k$$

where $T_{is,k}$ is the temperature value of the highest temperature point in the battery at time k, $T_{is,k+1}$ is the temperature value of the highest temperature point in the battery at time k+1, $T_{is,k+2}$ is the temperature value of the highest temperature point in the battery at time k+2, Q_k is the heating power of the battery at time k, Q_{k+1} is the heating power of the battery at time k+1, α_1, α_2, β_1 and β_2 are the parameters to be identified of the difference equation of the internal temperature state model.

In the formula, α_1, α_2, β_1 and β_2 are the parameters to be identified, and their specific expansion forms are as follows:

$$\begin{cases} \alpha_1 = -\Delta t/R_iC_i - \Delta t/R_oC_s - \Delta t/R_iC_s + 2 \\ \alpha_2 = (1-\Delta t/R_iC_i)(\Delta t/R_oC_s + \Delta t/R_iC_s - 1) \\ \beta_1 = \Delta t/C_i, \beta_2 = (\Delta t/C_i)(\Delta t/R_oC_s + \Delta t/R_iC_s - 1) \end{cases}$$

Considering the uncertainty characteristics of the external equivalent thermal resistance R_o value of the battery, when identifying the parameters in LTCM, the invention couples R_o with the state variables of the thermal characteristic model, so as to realize the independent identification of R_o and the collaborative estimation of the internal temperature, and further, the calculation equations of the thermal parameters C_i,

R_i and C_s of the battery can be obtained:

$$\begin{cases} C_i = \Delta t/\beta_1, R_i = (\beta_1\beta_2)/(\beta_2 - \alpha_2\beta_1) \\ C_s = (\Delta t\beta_1)/R_o + \Delta t(\alpha_1 - 2) - \Delta t/\beta_1 \end{cases}$$

Where C_i is the equivalent heat capacity inside the battery, R_i is the internal thermal resistance of the battery, C_s is the equivalent hot melt of the battery shell, andΔt is the system sampling time.

S4, adopting the forgetting factor least square method to solve the parameters to be identified in the difference equation of the highest temperature point T_{is} in the lithium-ion battery.

S41, further deforming the obtained difference equation form to obtain an exogenous autoregressive model suitable for online iteration form:

$$Y = \varphi^T \theta \Leftarrow \begin{cases} \theta = [\alpha_1, \alpha_2, \beta_1, \beta_2]^T \\ \varphi = \{\varphi_0, \varphi_1, \varphi_2, \cdots, \varphi_k, \cdots, \varphi_{n-2}\} \\ Y = [T_{is,2}, T_{is,3}, T_{is,4}, \cdots, T_{is,k+2}, \cdots, T_{is,n}]^T \\ \varphi_k = [T_{is,k+1}, T_{is,k}, Q_{k+1}, Q_k]^T \end{cases}$$

Where $\boldsymbol{Y}$ is the output matrix of the exogenous autoregressive model, $\boldsymbol{\varphi}$ is the data matrix, $\boldsymbol{\theta}$ is the coefficient matrix, and $\boldsymbol{\varphi_k}$ is the system data matrix at time **k**;

S42. Based on the exogenous autoregressive model, the parameters of LTCM (Lumped Thermal Characteristic Model) are solved, where the parameters of the thermal characteristic model are C_i, R_i and C_s. The main steps of identifying LTCM parameters by FFRLS algorithm are as follows:

1): Assigning an initial value to k and initializing a coefficient matrix and an error covariance matrix $\boldsymbol{P}_0$:

$$\begin{cases} k = 0, \hat{\boldsymbol{\theta}}_0 = E[\theta_0] \\ P_0 = E[(\theta_0 - \hat{\boldsymbol{\theta}}_0)(\theta_0 - \hat{\boldsymbol{\theta}}_0)^T] \end{cases}$$

2) reading the data matrix $\boldsymbol{\varphi}_{k+1}$ at the time k+1 and calculating the gain matrix $\boldsymbol{G}_{k+1}$;

$$\boldsymbol{G}_{k+1} = \boldsymbol{P}_k\phi_{k+1}/(\lambda + \phi_{k+1}{}^T\boldsymbol{P}_k\phi_{k+1})$$

3) updating the error covariance matrix $\boldsymbol{P}_{k+1}$ at time k+1;

$$\boldsymbol{P}_{k+1} = (\boldsymbol{E} - \boldsymbol{G}_{k+1}\phi_{k+1}{}^T)\boldsymbol{P}_k/\lambda$$

4): calculating the coefficient matrix at time k+1:

$$\begin{cases}\hat{\theta}_{k+1}=\hat{\theta}_k+G_{k+1}\varepsilon_{k+1}\\ \varepsilon_{k+1}=Y_{k+1}-\phi_{k+1}{}^T\hat{\theta}_k\end{cases}$$

5): using the calculation equations of C_i, R_i and C_s to realize the identification of LTCM parameters in a cyclic iteration until the end of the complete time series.

In the formula of the above steps, $\boldsymbol{P}_{k+1}$ is the error covariance matrix of the coefficient matrix at time k+1, $\boldsymbol{G}_{k+1}$ is the gain matrix of FFRLS algorithm at time k+1, and ε_{k+1} is the innovation value at time k+1, which indicates the error value between the measured value and the estimated value of the highest temperature inside the battery. λ is the forgetting factor of the algorithm. In this embodiment, the value of the forgetting factor λ is 0.98. Using the system input data matrix ,

the values of the coefficient matrix are obtained under the iterative computation of FFRLS. Further, the parameter values of LTCM are obtained through the calculation equations of C_i, R_i, and C_s.

S5, adopting the joint Kalman filter method to realize the joint estimation of the external equivalent thermal resistance R_o and the internal maximum temperature point T_{is} of the lithium ion battery.

S51, from the point of view of engineering practice, the state equation description of the thermal circuit model in time domain is not suitable for online temperature estimation. Therefore, the state space equation in the time domain is discretized to obtain the state space equation in the discrete state of the system based on LTCM:

$$\begin{cases}\underbrace{\begin{bmatrix}T_{is,k+1}\\T_{ss,k+1}\end{bmatrix}}_{x_{d,k+1}}=\underbrace{\begin{bmatrix}1-\frac{\Delta t}{R_iC_i} & \frac{\Delta t}{R_iC_i}\\ \frac{\Delta t}{R_iC_s} & 1-\left(\frac{\Delta t}{R_iC_s}+\frac{\Delta t}{R_oC_s}\right)\end{bmatrix}}_{A_d}\underbrace{\begin{bmatrix}T_{is,k}\\T_{ss,k}\end{bmatrix}}_{x_{d,k}}+\underbrace{\begin{bmatrix}\frac{\Delta t}{C_i}\\0\end{bmatrix}}_{B_d}\underbrace{[Q_k]}_{u_k}+\underbrace{\begin{bmatrix}w_k^1\\w_k^2\end{bmatrix}}_{w_k}\\ \underbrace{T_{ss,k+1}}_{y_k}=\underbrace{[0\quad 1]}_{C_d}\underbrace{\begin{bmatrix}T_{is,k}\\T_{ss,k}\end{bmatrix}}_{x_{d,k}}+\underbrace{[0]}_{D_d}\underbrace{[Q_k]}_{u_k}\end{cases}$$

In the formula, $x_{d,k}$ and $x_{d,k+1}$ are the state variables of the system at time k and k+1 in discrete state, y_d is the system output vector in discrete state, u_k is the system input variable at time k, $\boldsymbol{A}_d$ is the system matrix in discrete state, $\boldsymbol{B}_d$ is the control matrix in discrete state, $\boldsymbol{C}_d$ is the observation matrix in discrete state and $\boldsymbol{D}_d$ is the direct transfer matrix in discrete state, since the direct transfer of the input vector is not considered in

the discrete state space equation of the thermal characteristic model, that is, $\boldsymbol{D}_d$=0, w_k LU503873
and v_k are respectively the system noise and the observation noise.

S52, realizing the adaptive common estimation strategy of external equivalent thermal resistance R_o and internal temperature state T_{is} based on JKF (Joint Kalman filter) and Kalman filtering algorithm. JKF algorithm takes R_o as one of the position state variables of the system, and realizes the adaptive identification of R_o through online state estimation algorithm. Constructing a JKF algorithm for adaptive collaborative estimation of external equivalent thermal resistance and internal temperature of battery. The state space equation of JKF algorithm is as follows:

$$\begin{cases} x_{J,k+1} = f(x_{J,k}, u_k) + w_k \approx \boldsymbol{A}_J x_{J,k} + \boldsymbol{B}_J u_k + w_k \\ y_k = h(x_{J,k}, u_k) + v_k \approx \boldsymbol{C}_J x_{J,k} + \boldsymbol{D}_J u_k + v_k \end{cases}$$

Where $x_{J,k}$ is the 3-dimensional system state matrix, and the matrix is expressed as $x_{J,k} = [T_{is,k} \quad T_{ss,k} \quad R_{o,k}]^T$. u_k is the input variable of the system at time k, the matrix is expressed as $u_k = Q_k$. y_k is the output variable of the system at time k in discrete state, the matrix is expressed as $y_k = T_{ss,k}$. $\boldsymbol{A}_J$ is the 3×3 -dimensional system matrix, $\boldsymbol{B}_J$ is the 3×1 -dimensional control matrix, $\boldsymbol{C}_J$ is the 1×3 -dimensional output matrix, $\boldsymbol{D}_J$ is the direct matrix, the specific expansion form of the matrix of $\boldsymbol{A}_J$, $\boldsymbol{B}_J$, $\boldsymbol{C}_J$ and $\boldsymbol{D}_J$ is as follows:

$$\begin{cases} A_J = \begin{bmatrix} A_d & 0 \\ 0 & 1 \end{bmatrix} & B_J = [\Delta t / C_i \quad 0 \quad 0]^T \\ C_J = [0 \quad 1 \quad C_3] & D_J = [0] \end{cases}$$

Where C3 is calculated as follows:

$$\boldsymbol{C}_3 = \frac{\partial h(x_{J,k}, u_k)}{\partial R_o} = \frac{\partial h(x_{J,k}, u_k)}{\partial x_{J,k}} \cdot \frac{dx_{J,k}}{\partial R_o} = \frac{dT_{ss,k}}{dR_o} = \frac{\Delta t}{{R_o}^2 C_s}$$

Finally, based on the state space equation of LTCM system in discrete state, the recursive iterative process of JKF algorithm suitable for online embedded application is obtained. The main steps are as follows:

1): assigning an initial value to k, and initializing a coefficient matrix and an error covariance matrix;

$$\begin{cases} k = 0, \hat{x}_0^+ = E[x_0] \\ \Sigma_{\hat{x},0}^+ = E[(x_0 - \hat{x}_0^+)(x_0 - \hat{x}_0^+)^T] \end{cases}$$

2): updating the state variables in time:

$\hat{x}_{l,k+1}^{-} = A_l \hat{x}_{l,k}^{-} + B_l u_k$

3): updating error covariance matrix in time:

$\Sigma_{\hat{x},k+1}^{-} = A_l \Sigma_{\hat{x},k}^{+} A_l^{T} + \Sigma_{w,k}$

4): calculating the Kalman gain:

$K_{k+1} = \Sigma_{\hat{x},k+1}^{-} C_l^{T} / (C_l \Sigma_{\hat{x},k+1}^{-} C_l^{T} + \Sigma_{v,k})$

5): updating the state variable measurement:

$\hat{x}_{l,k+1}^{+} = \hat{x}_{l,k+1}^{-} + K_{k+1}[y_{k+1} - (C_l \hat{x}_{l,k+1}^{-} + D_l u_{k+1})]$

6): updating the error covariance matrix measurement:

$\Sigma_{\hat{x},k+1}^{+} = (E - K_{k+1} C_l) \Sigma_{\hat{x},k+1}^{-}$

7): Iterating the equivalent thermal resistance R_o of the calculation part and the internal temperature state T_{is} circularly until the end of the complete time series.

The above implementation of the present invention only takes the commercial 18650 battery as an example to realize the modeling of the lumped thermal characteristics of the battery and the adaptive collaborative estimation of the model parameters and the battery internal temperature, but it can be understood that those skilled in the art can make any changes and changes without departing from the spirit and scope of the present invention.

The above is only the preferred embodiment of this application, but the protection scope of this application is not limited to this. Any change or replacement that can be easily thought of by a person familiar with this technical field within the technical scope disclosed in this application should be included in the protection scope of this application. Therefore, the protection scope of this application should be based on the protection scope of the claims.

CLAIMS

1. An online self-adaptive method for estimating the battery internal temperature, characterized by comprising the following steps:

establishing a lumped thermal characteristic equivalent circuit model of the battery based on the modeling similarity between physical systems of the same order;

establishing a state space model of the lumped thermal characteristic equivalent circuit model in a time domain state based on Kirchhoff's circuit laws;

acquiring a battery internal temperature state model based on the state space model in the time domain state;

obtaining thermal characteristic model parameters to be identified in the battery internal temperature state model based on the battery internal temperature state model by adopting the forgetting factor least square method;

jointly estimating the parameters of the thermal characteristic model and the battery internal temperature by using a joint Kalman filter method.

2. The online self-adaptive method for estimating the battery internal temperature according to claim 1, characterized in that the step of establishing a state space model of the lumped thermal characteristic equivalent circuit model in a time domain state based on Kirchhoff's circuit laws comprises:

processing a heating power model based on the lumped thermal characteristic equivalent circuit model to obtain a new heating power model of the lumped thermal characteristic equivalent circuit model;

obtaining the state models of the highest temperature node in the center of the battery and the temperature node in the surface area of the battery, based on the new heating power model and the Kirchhoff circuit law;

obtaining an observation model of T_{ss} based on the difference between the highest temperature node in the inner center of the battery and the ambient temperature where the battery is located;

acquiring a state space model of the lumped thermal characteristic equivalent circuit model based on the state model and the observation model.

3. The online self-adaptive method for estimating the battery internal temperature LU503873
according to claim 2, characterized in that the new heating power model is:

$$Q \approx I^2 R_s + IT\,(dE)/dT \Leftarrow E - U_L = IR_s$$

where Q is the heating power, R_s is the DC internal resistance of the battery, I is the charging and discharging current of the battery, T is the battery temperature, E is the balanced electromotive force inside the battery, and U_L is the terminal voltage of the battery;

the state model is as follows:

$$\begin{cases} \dfrac{dT_{is}}{dt} = -\dfrac{1}{R_i C_i} T_{is} + \dfrac{1}{R_i C_i} T_{ss} + \dfrac{Q}{C_i} \\ \dfrac{dT_{ss}}{dt} = \dfrac{1}{R_i C_s} T_{is} + \left(\dfrac{1}{R_i C_s} + \dfrac{1}{R_o C_s}\right) T_{ss} \end{cases} \Leftarrow \begin{cases} T_{is} = T_i - T_{amb} \\ T_{ss} = T_s - T_{amb} \end{cases}$$

where, Q is the heating power, T_i is the highest temperature in the center of the battery, T_s is the surface temperature of the battery, T_{amb} is the ambient temperature of the battery, R_i is the internal thermal resistance of the battery, R_o is the external thermal resistance of the battery, C_i is the equivalent thermal capacity of the battery, C_s is the equivalent hot melting of the battery shell, T_{is} is the difference between the highest temperature T_i of the internal central temperature of the battery and the ambient temperature T_{amb} of the battery, and T_{ss} is the difference between the surface temperature T_s of the battery and the ambient temperature T_{amb} of the battery;

the observation model is:

$$\underbrace{T_{ss}}_{y_t} = \underbrace{\begin{bmatrix} 0 & 1 \end{bmatrix}}_{C_t} \underbrace{\begin{bmatrix} T_{is} \\ T_{ss} \end{bmatrix}}_{x_t} + \underbrace{\begin{bmatrix} 0 \end{bmatrix}}_{D_t} \underbrace{\begin{bmatrix} Q \end{bmatrix}}_{u_t}$$

where, y_t is the system output in time domain, C_t is the output matrix in time domain, x_t is the system state variable in continuous state, D_t is the branch transfer matrix in time domain, and u_t is the system input in continuous state.

4. The online self-adaptive method for estimating the battery internal temperature according to claim 2, characterized in that the step of acquiring a battery internal temperature state model based on the state space model in the time domain state comprises:

acquiring a transfer function of the state space model based on the new heating power model and the internal temperature state of the battery, wherein the internal temperature state of the battery is the difference between the highest point of the internal central temperature of the battery and the ambient temperature where the battery is located;

carrying out integrated deformation on the transfer function by using Z transform to obtain the internal temperature state model of the battery.

5. The online self-adaptive method for estimating the battery internal temperature according to claim 4, characterized in that the difference equation of the battery internal temperature state model is as follows:

$$T_{is,k+2} = \alpha_1 T_{is,k+1} + \alpha_2 T_{is,k} + \beta_1 Q_{k+1} + \beta_2 Q_k$$

where $T_{is,k}$ is the temperature value of the highest temperature point in the battery at time k, $T_{is,k+1}$ is the temperature value of the highest temperature point in the battery at time k+1, $T_{is,k+2}$ is the temperature value of the highest temperature point in the battery at time k+2, Q_k is the heating power of the battery at time k, Q_{k+1} is the heating power of the battery at time k+1, α_1, α_2, β_1 and β_2 are the parameters to be identified of the difference equation of the internal temperature state model.

6. The online self-adaptive method for estimating the battery internal temperature according to claim 1, characterized in that, the step of obtaining thermal characteristic model parameters to be identified in the battery internal temperature state model based on the battery internal temperature state model by adopting the forgetting factor least square method comprises:

acquiring an exogenous autoregressive model based on the battery internal temperature state model;

solving the thermal characteristic model parameters that need to be identified in the battery internal temperature state model by the least method based on the exogenous autoregressive model.

7. The online self-adaptive method for estimating the battery internal temperature according to claim 6, characterized in that the exogenous autoregressive model is as follows:

$$\boldsymbol{Y} = \boldsymbol{\varphi}^T \boldsymbol{\theta} \Leftarrow \begin{cases} \boldsymbol{\theta} = [\alpha_1, \alpha_2, \beta_1, \beta_2]^T \\ \boldsymbol{\varphi} = \{\boldsymbol{\varphi}_0, \boldsymbol{\varphi}_1, \boldsymbol{\varphi}_2, \cdots, \boldsymbol{\varphi}_k, \cdots, \boldsymbol{\varphi}_{n-2}\} \\ \boldsymbol{Y} = [T_{is,2}, T_{is,3}, T_{is,4}, \cdots, T_{is,k+2}, \cdots, T_{is,n}]^T \\ \boldsymbol{\varphi}_k = [T_{is,k+1}, T_{is,k}, Q_{k+1}, Q_k]^T \end{cases}$$

where $\boldsymbol{Y}$ is the output matrix of the exogenous autoregressive model, $\boldsymbol{\varphi}$ is the data matrix, $\boldsymbol{\theta}$ is the coefficient matrix, and $\boldsymbol{\varphi_k}$ is the system data matrix at time **k**;

the parameters of the thermal characteristic model parameters are C_i, R_i and C_s;

the thermal characteristic model parameter equation is as follows:

$$\begin{cases} C_i = \Delta t/\beta_2, R_i = (\beta_1\beta_2)/(\beta_2 - \alpha_2\beta_1) \\ C_s = (\Delta t\beta_1)/R_o + \Delta t(\alpha_1 - 2) - \Delta t/\beta_2 \end{cases},$$

where C_i is the equivalent heat capacity inside the battery, R_i is the internal thermal resistance of the battery, C_s is the equivalent hot melt of the battery shell, andΔt is the system sampling time.

8. The online self-adaptive method for estimating the battery internal temperature according to claim 1, characterized in that the step of jointly estimating the parameters of the thermal characteristic model and the battery internal temperature by using a joint Kalman filter method comprises:

acquiring the state space model in the discrete state of the lumped thermal characteristic equivalent circuit model based on the state space model in the time domain state;

constructing the JKF model of self-adaptive cooperative estimation of the external equivalent thermal resistance and the internal temperature state of the battery by using the joint Kalman filtering method and based on the state space equation in the discrete state;

realizing the joint estimation of the parameters of the thermal characteristic model and the internal temperature based on the JKF model.

9. The online self-adaptive method for estimating the battery internal temperature according to claim 8, characterized in that the state space model in the discrete state is:

$$\begin{cases} \underbrace{\begin{bmatrix} T_{is,k+1} \\ T_{ss,k+1} \end{bmatrix}}_{x_{d,k+1}} = \underbrace{\begin{bmatrix} 1-\frac{\Delta t}{R_i C_i} & \frac{\Delta t}{R_i C_i} \\ \frac{\Delta t}{R_i C_s} & 1-\left(\frac{\Delta t}{R_i C_s}+\frac{\Delta t}{R_o C_s}\right) \end{bmatrix}}_{A_d} \underbrace{\begin{bmatrix} T_{is,k} \\ T_{ss,k} \end{bmatrix}}_{x_{d,k}} + \underbrace{\begin{bmatrix} \frac{\Delta t}{C_i} \\ 0 \end{bmatrix}}_{B_d} \underbrace{[Q_k]}_{u_k} + \underbrace{\begin{bmatrix} w_k^1 \\ w_k^2 \end{bmatrix}}_{w_k} \\ \underbrace{T_{ss,k+1}}_{y_k} = \underbrace{[0 \quad 1]}_{C_d} \underbrace{\begin{bmatrix} T_{is,k} \\ T_{ss,k} \end{bmatrix}}_{x_{d,k}} + \underbrace{[0]}_{D_d} \underbrace{[Q_k]}_{u_k} \end{cases}$$

where $x_{d,\ k+1}$ are the state variables of the system at time k+1 in discrete state, $x_{d,\ k}$ are the state variables of the system at time k in discrete state, u_k is the input variable of the system at time **k**, w_k is system noise, y_k is the output variable of the system at time **k** in discrete state, A_d is the system matrix in discrete state, B_d is the control matrix in discrete state, C_d is the observation matrix in discrete state and D_d is the direct transfer matrix in discrete state.

10. The online self-adaptive method for estimating the battery internal temperature according to claim 8, characterized in that the JKF model is as follows:

$$\begin{cases} x_{J,k+1} = f(x_{J,k}, u_k) + w_k \approx \boldsymbol{A}_J x_{J,k} + \boldsymbol{B}_J u_k + w_k \\ y_k = h(x_{J,k}, u_k) + v_k \approx \boldsymbol{C}_J x_{J,k} + \boldsymbol{D}_J u_k + v_k \end{cases}$$

where $x_{J,k}$ is the 3-dimensional system state matrix at time k, $x_{J,k+1}$ is the system state matrix engraved at time k+1, u_k is the input variable of the system at time k, y_k is the output variable of the system at time k in discrete state, $\boldsymbol{A}_J$ is the 3×3 -dimensional system matrix, $\boldsymbol{B}_J$ is the 3×1 -dimensional control matrix, $\boldsymbol{C}_J$ is the 1×3 -dimensional output matrix, $\boldsymbol{D}_J$ is the direct matrix, w_k is the system noise and v_k is the observation noise.

REVENDICATIONS

1. Un procédé auto-adaptatif en ligne pour estimer la température interne de la batterie, caractérisé en ce qu'il comprend les étapes suivantes :

établir un modèle de circuit équivalent de caractéristique thermique groupée de la batterie sur la base de la similarité de modélisation entre des systèmes physiques du même ordre;

établir un modèle d'espace d'état du modèle de circuit équivalent de caractéristique thermique groupée dans un état de domaine temporel basé sur les lois de circuit de Kirchhoff;

acquérir un modèle d'état de température interne de batterie basé sur le modèle d'espace d'état dans l'état du domaine temporel;

obtenir des paramètres de modèle de caractéristique thermique à identifier dans le modèle d'état de température interne de la batterie à partir du modèle d'état de température interne de la batterie en adoptant la méthode du facteur d'oubli des moindres carrés;

estimer conjointement les paramètres du modèle de caractéristique thermique et la température interne de la batterie à l'aide d'une méthode de filtre de Kalman conjointe.

2. Le procédé auto-adaptatif en ligne pour estimer la température interne de la batterie selon la revendication 1, caractérisé en ce que l'étape d'établissement d'un modèle d'espace d'état du modèle de circuit équivalent de caractéristique thermique groupée dans un état de domaine temporel basé sur les lois de circuit de Kirchhoff comprend :

traiter un modèle de puissance de chauffage basé sur le modèle de circuit équivalent de caractéristique thermique groupée pour obtenir un nouveau modèle de puissance de chauffage du modèle de circuit équivalent de caractéristique thermique groupée;

obtenir les modèles d'état du nœud de température le plus élevé au centre de la batterie et du nœud de température dans la surface de la batterie, à partir du nouveau modèle de puissance de chauffage et de la loi du circuit de Kirchhoff;

obtenir un modèle d'observation de T_{ss} basé sur la différence entre le nœud de température le plus élevé au centre intérieur de la batterie et la température ambiante où se trouve la batterie;

acquérir un modèle d'espace d'état du modèle de circuit équivalent de caractéristique thermique groupée basé sur le modèle d'état et le modèle d'observation.

3. Le procédé auto-adaptatif en ligne pour estimer la température interne de la batterie selon la revendication 2, caractérisé en ce que le nouveau modèle de puissance de chauffage est :

$$Q \approx I^2 R_s + IT\,(dE)/dT \Leftarrow E - U_L = IR_s$$

parmi eux, Q est la puissance de chauffage, R_s est la résistance interne continue de la batterie, I est le courant de charge et de décharge de la batterie, T est la température de la batterie, E est la force électromotrice équilibrée à l'intérieur de la batterie et U_L est la tension aux bornes de la batterie;

le modèle étatique est le suivant:

$$\begin{cases} \dfrac{dT_{is}}{dt} = -\dfrac{1}{R_i C_i} T_{is} + \dfrac{1}{R_i C_i} T_{ss} + \dfrac{Q}{C_i} \\ \dfrac{dT_{ss}}{dt} = \dfrac{1}{R_i C_s} T_{is} + \left(\dfrac{1}{R_i C_s} + \dfrac{1}{R_o C_s}\right) T_{ss} \end{cases} \Leftarrow \begin{cases} T_{is} = T_i - T_{amb} \\ T_{ss} = T_s - T_{amb} \end{cases}$$

parmi eux, Q est la puissance de chauffage, T_i est la température la plus élevée au centre de la batterie, T_s est la température de surface de la batterie, T_{amb} est la température ambiante de la batterie, R_i est la résistance thermique interne de la batterie, R_o est la résistance thermique externe de la batterie, C_i est la capacité thermique équivalente de la batterie, C_s est la fusion à chaud équivalente de l'enveloppe de la batterie, T_{is} est la différence entre la température la plus élevée T_i de la température centrale interne de la batterie et la température ambiante T_{amb} de la batterie, et T_{ss} est la différence entre la température de surface T_s de la batterie et la température ambiante T_{amb} de la batterie;

le modèle d'observation est le suivant:

$$\underbrace{T_{ss}}_{y_t} = \underbrace{\begin{bmatrix} 0 & 1 \end{bmatrix}}_{C_t} \underbrace{\begin{bmatrix} T_{is} \\ T_{ss} \end{bmatrix}}_{x_t} + \underbrace{\begin{bmatrix} 0 \end{bmatrix}}_{D_t} \underbrace{\begin{bmatrix} Q \end{bmatrix}}_{u_t}$$

parmi eux, y_t est la sortie du système dans le domaine temporel, C_t est la matrice de sortie dans le domaine temporel, x_t est la variable d'état du système dans l'état continu, D_t est la matrice de transfert de branche dans le domaine temporel et u_t est l'entrée du système dans l'état continu.

4. Le procédé auto-adaptatif en ligne pour estimer la température interne de la batterie selon la revendication 2, caractérisé en ce que l'étape d'acquisition d'un modèle d'état de température interne de batterie basé sur le modèle d'espace d'état dans l'état temporel comprend :

acquérir une fonction de transfert du modèle d'espace d'état à partir du nouveau modèle de puissance de chauffage et de l'état de température interne de la batterie, parmi eux, l'état de température interne de la batterie est la différence entre le point le plus haut de la température centrale interne de la batterie et la température ambiante où se trouve la batterie;

effectuer une déformation intégrée sur la fonction de transfert en utilisant une transformée en Z pour obtenir le modèle d'état de température interne de la batterie.

5. Le procédé auto-adaptatif en ligne pour estimer la température interne de la batterie selon la revendication 4, caractérisé en ce que l'équation de différence du modèle d'état de température interne de la batterie est la suivante :

$$T_{is,k+2} = \alpha_1 T_{is,k+1} + \alpha_2 T_{is,k} + \beta_1 Q_{k+1} + \beta_2 Q_k$$

parmi eux, $T_{is,\,k}$ est la valeur de température du point de température le plus élevé dans la batterie à l'instant k, $T_{is,\,k+1}$ est la valeur de température du point de température le plus élevé dans la batterie à l'instant k+1, $T_{is,\,k+2}$ est la valeur de température du point de température le plus élevé de la batterie à l'instant k+2, Q_k est la puissance de chauffage de la batterie à l'instant k, Q_{k+1} est la puissance de chauffage de la batterie à l'instant k+1, α_1, α_2, β_1 et β_2 sont les paramètres à identifier de l'équation de différence du modèle d'état de température interne.

6. Le procédé auto-adaptatif en ligne pour estimer la température interne de la batterie selon la revendication 1, caractérisé en ce que, l'étape d'obtention de paramètres de modèle de caractéristiques thermiques à identifier dans le modèle d'état de température interne de la batterie à partir du modèle d'état de température interne de la batterie en adoptant la méthode du facteur d'oubli des moindres carrés comprend :

acquérir un modèle autorégressif exogène basé sur le modèle d'état de température interne de la batterie;

résoudre les paramètres du modèle de caractéristique thermique qui doivent être identifiés dans le modèle d'état de température interne de la batterie par la méthode des moindres basée sur le modèle autorégressif exogène.

7. Le procédé auto-adaptatif en ligne pour estimer la température interne de la batterie selon la revendication 6, caractérisé en ce que le modèle autorégressif exogène est le suivant :

$$\boldsymbol{Y} = \boldsymbol{\varphi}^T \boldsymbol{\theta} \Leftarrow \begin{cases} \boldsymbol{\theta} = [\alpha_1, \alpha_2, \beta_1, \beta_2]^T \\ \boldsymbol{\varphi} = \{\varphi_0, \boldsymbol{\varphi}_1, \varphi_2, \cdots, \boldsymbol{\varphi}_k, \cdots, \boldsymbol{\varphi}_{n-2}\} \\ \boldsymbol{Y} = [T_{is,2}, T_{is,3}, T_{is,4}, \cdots, T_{is,k+2}, \cdots, T_{is,n}]^T \\ \varphi_k = [T_{is,k+1}, T_{is,k}, Q_{k+1}, Q_k]^T \end{cases}$$

parmi eux, $\boldsymbol{Y}$ est la matrice de sortie du modèle autorégressif exogène, $\boldsymbol{\varphi}$ est la matrice de données, $\boldsymbol{\theta}$ est la matrice de coefficients, et $\boldsymbol{\varphi_k}$ est la matrice de données système à l'instant **k**;

les paramètres des paramètres caractéristiques thermiques du modèle sont C_i, R_i et C_s;

l'équation du paramètre du modèle de caractéristique thermique est la suivante:

$$\begin{cases} C_i = \Delta t/\beta_1, R_i = (\beta_1\beta_2)/(\beta_2 - \alpha_2\beta_1) \\ C_s = (\Delta t\beta_1)/R_o + \Delta t(\alpha_1 - 2) - \Delta t/\beta_1 \end{cases},$$

parmi eux, C_i est la capacité calorifique équivalente à l'intérieur de la batterie, R_i est la résistance thermique interne de la batterie, C_s est la fonte à chaud équivalente de l'enveloppe de la batterie et Δt est le temps d'échantillonnage du système.

8. Le procédé auto-adaptatif en ligne pour estimer la température interne de la batterie selon la revendication 1, caractérisé en ce que l'étape d'estimation conjointe des paramètres du modèle de caractéristique thermique et de la température interne de la batterie en utilisant un procédé de filtre de Kalman conjoint comprend :

acquérir le modèle d'espace d'état dans l'état discret du modèle de circuit équivalent de caractéristique thermique groupée à partir du modèle d'espace d'état dans l'état du domaine temporel;

construire le modèle JKF d'estimation coopérative auto-adaptative de la résistance thermique équivalente externe et de l'état de température interne de la batterie en utilisant la méthode de filtrage de Kalman conjointe et basée sur l'équation d'espace d'état à l'état discret;

réaliser l'estimation conjointe des paramètres du modèle de caractéristique thermique et de la température interne à partir du modèle JKF.

9. Le procédé auto-adaptatif en ligne pour estimer la température interne de la batterie selon la revendication 8, caractérisé en ce que le modèle d'espace d'état à l'état discret est:

$$\begin{cases} \underbrace{\begin{bmatrix} T_{is,k+1} \\ T_{ss,k+1} \end{bmatrix}}_{x_{d,k+1}} = \underbrace{\begin{bmatrix} 1-\frac{\Delta t}{R_i C_i} & \frac{\Delta t}{R_i C_i} \\ \frac{\Delta t}{R_i C_s} & 1-\left(\frac{\Delta t}{R_i C_s}+\frac{\Delta t}{R_o C_s}\right) \end{bmatrix}}_{A_d} \underbrace{\begin{bmatrix} T_{is,k} \\ T_{ss,k} \end{bmatrix}}_{x_{d,k}} + \underbrace{\begin{bmatrix} \frac{\Delta t}{C_i} \\ 0 \end{bmatrix}}_{B_d} \underbrace{[Q_k]}_{u_k} + \underbrace{\begin{bmatrix} w_k^1 \\ w_k^2 \end{bmatrix}}_{w_k} \\ \underbrace{T_{ss,k+1}}_{y_k} = \underbrace{\begin{bmatrix} 0 & 1 \end{bmatrix}}_{C_d} \underbrace{\begin{bmatrix} T_{is,k} \\ T_{ss,k} \end{bmatrix}}_{x_{d,k}} + \underbrace{[0]}_{D_d} \underbrace{[Q_k]}_{u_k} \end{cases}$$

parmi eux, $x_{d,\,k+1}$ sont les variables d'état du système à l'instant k+1 en état discret, $x_{d,\,k}$ sont les variables d'état du système à l'instant k en état discret, u_k est la variable d'entrée du système à l'instant **k**, w_k est le bruit du système, y_k est la variable de sortie du système à l'instant **k** à l'état discret, A_d est la matrice du système à l'état discret, B_d est la matrice de commande à l'état discret, C_d est la matrice d'observation à l'état discret et D_d est la matrice de transfert direct à l'état discret.

10. Le procédé auto-adaptatif en ligne pour estimer la température interne de la batterie selon la revendication 8, caractérisé en ce que le modèle JKF est le suivant : LU503873

$$\begin{cases} x_{J,k+1} = f(x_{J,k}, u_k) + w_k \approx \boldsymbol{A}_J x_{J,k} + \boldsymbol{B}_J u_k + w_k \\ y_k = h(x_{J,k}, u_k) + v_k \approx \boldsymbol{C}_J x_{J,k} + \boldsymbol{D}_J u_k + v_k \end{cases}$$

parmi eux, $x_{J,k}$ est la matrice d'état système à 3 dimensions à l'instant k, $x_{J,k+1}$ est la matrice d'état système gravée à l'instant k+1, u_k est la variable d'entrée du système à l'instant k, y_k est la variable de sortie du système à l'instant k à l'état discret, $\boldsymbol{A}_J$ est la matrice système 3×3-dimensionnelle, $\boldsymbol{B}_J$ est la matrice de commande 3×1-dimensionnelle, $\boldsymbol{C}_J$ est la matrice de sortie 1×3-dimensionnelle, $\boldsymbol{D}_J$ est la matrice directe, w_k est le bruit du système et v_k est le bruit d'observation.

FIGURES

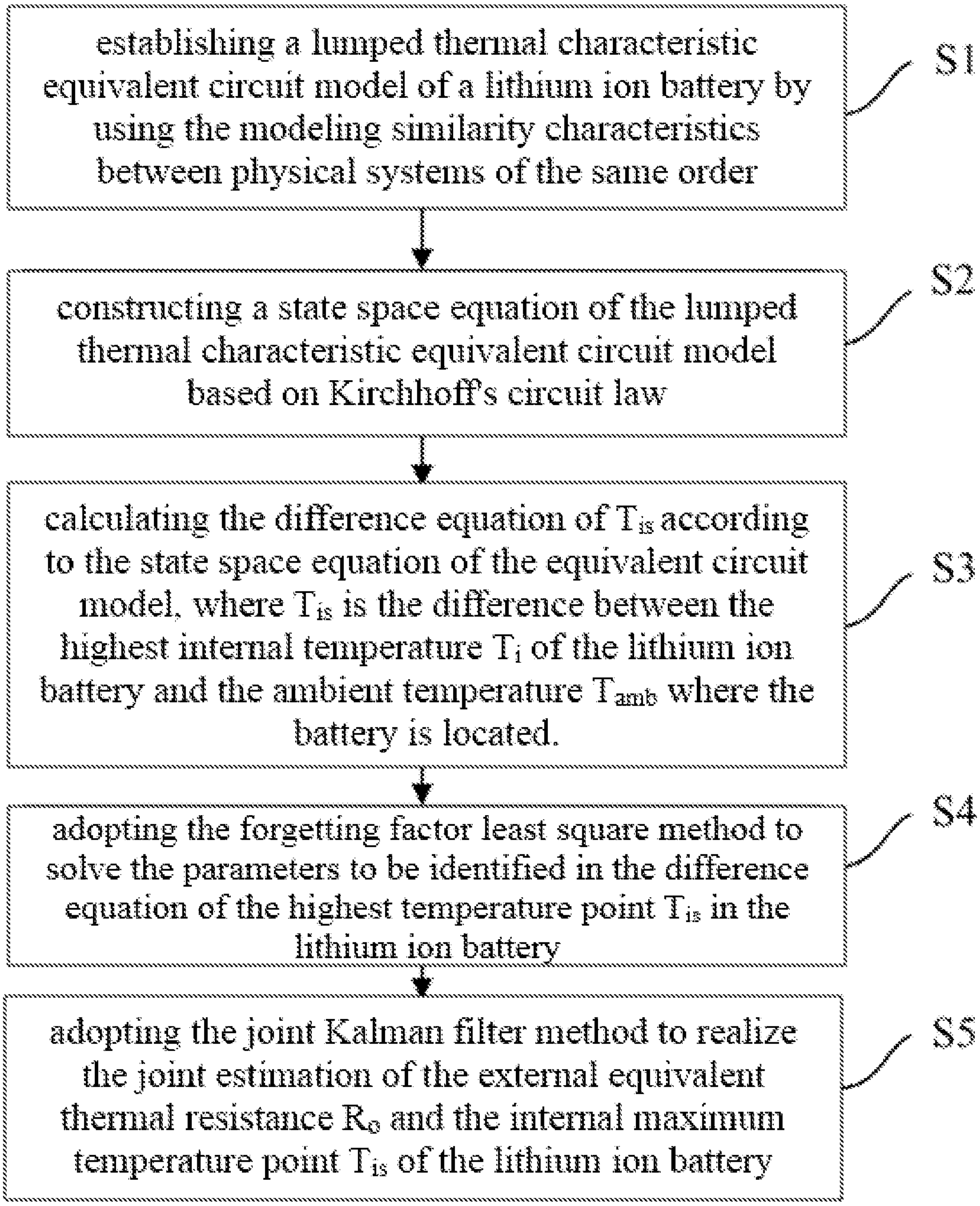

FIG. 1

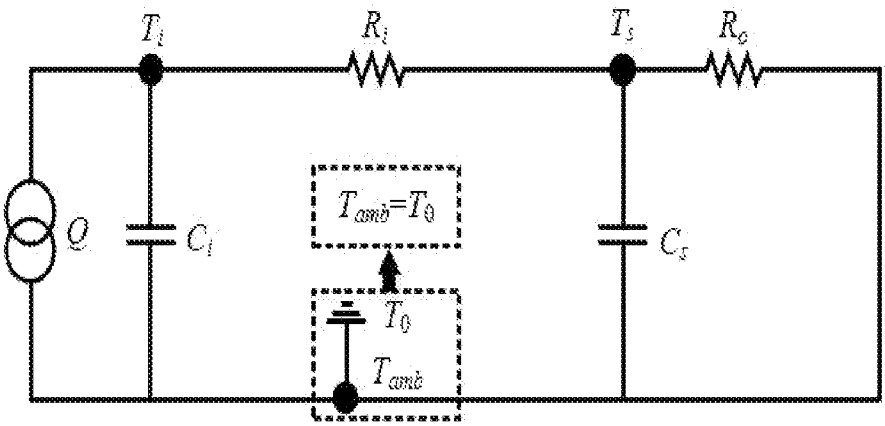

FIG. 2