Applied Energy Symposium 2020: Low carbon cities and urban energy systems
October 10-17, 2020
Paper ID: CUE2020-D-134

AN H-∞ AND ANN JOINT METHOD FOR ONLINE SUPERCAPACITOR TEMPERATURE ESTIMATION

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ABSTRACT

The supercapacitor thermal management system is of great significance to the safe operation and aging monitmoring of the supercapacitor. This paper provides a solution for estimating the internal temperature through the surface temperature, instead of directly measurement. By adopting a suitable electrothermal coupling model of supercapacitor, the internal temperature can be estimated online via an H-infinity filter. Besides, in order to reduce error caused by model inaccuracy and noise changing, this paper uses the neural network to correct the result of the H-infinity filter. To verify the effectiveness of method proposed in this paper, a series of experiments is designed and conducted. The results shows that the H-∞-ANN joint filter has less error than H- infinity filter alone.

Keywords: Temperature observation, Supercapacitor, Online implementation

1. INTRODUCTION

With advantages of high power density, long cycle life and wide operating temperature range, supercapacitor is a new type of energy storage device and widely used in large-scale energy storage fields such as UPS[1], renewable clean energy[2], voltage compensation[3] and electric vehicles[4]. Repetitive high current charge and discharge pulses, as are common in the automotive driving conditions, can lead to the formation of temperature gradients where the internal structure of the cell is hotter than the surface. However, it is usually impossible to directly measure the internal temperature of a supercapacitor in actual use. With the increasing application of supercapacitors, the requirements for thermal management of supercapacitors have also increased, and the monitoring of the maximum temperature of the cell has become necessary. According to the GD22-2019 standard issued by the China Classification Society, the thermal management system of the supercapacitor module must monitor the maximum temperature of each cell, because supercapacitors are often packaged and used in the form of series modules due to their low cell voltages, a large amount of heat will be generated inside the stacks during use, resulting in severe temperature rise. High temperature will aggravate the aging of supercapacitor, electrolyte evaporation and internal redox reaction[5], in severe cases, it can even cause thermal runaway. Therefore, how to estimate the internal temperature of the supercapacitor without directly inserting the temperature probe into the supercapacitor has become an important issue.

There are challenges in estimation of the internal temperature. Firstly, a suitable model must be selected to describe the electrical and thermal behavior of the supercapacitor. An overly complex model will lead to high resource consumption for calculations, while an oversimplified model will lead to large errors between actual data and model calculation results. Secondly, even if a suitable model is selected, due to the interference of noise and the imprecision of model parameters, the error of the result obtained by directly using the model to calculate the temperature is too large. Therefore, an appropriate filter network should be designed to assist temperature estimation.

Selection and peer-review under responsibility of the scientific committee of CUE2020

Many researchers have studied the thermal behavior of supercapacitors. Wasim Sarwar et al.[6] introduced pseudo-3-D thermal model through defining thermal parameters through x, y and z directions. Kai Wang et al.[7] established a three-dimensional thermal model of stacked supercapacitor, and studied the temperature field distribution of supercapacitor under small current charge and discharge by combining experiment and simulation. Dae Hun Lee et al. [8] measured the heating rate of stacked supercapacitors during charging and discharging, proposed a three-dimensional thermal model of symmetrical supercapacitors, and studied the influence of ambient temperature on the internal maximum temperature. Hamid Gualous et al. [9] proposed a thermal model of symmetrical supercapacitor by using the finite difference method, studied the thermal behavior of the supercapacitor under constant current charge and discharge of small and medium current, and measured the internal temperature rise of the supercapacitor through the experiment of built-in thermocouple. However, the models used in these studies are too complex to be used online; in addition, the influence of noise and error must be considered when the temperature is estimated online, and these studies mostly use the open-loop calculation method, which is lack of robustness.

This article is structured as follows: Firstly, for further research of the filter, section 2 briefly introduces the electro-thermal coupling model. Secondly, section 3 explains the design ideas and framework of H-∞-ANN joint filter. In order to verify the effectiveness of the adopted model and the improvement effect of the neural network, section 4 introduces the settings of experiments, and conducts analysis and discussion based on the experimental results. Finally, section 5 gives a conclusion of the paper.

2. MODELLING FOR SUPERCAPACITOR

Supercapacitor models include electrical model, thermal model and electro-thermal coupling model. The electric model and the thermal model without coupling have lower accuracy, so this article uses the electro-thermal coupling model to model the supercapacitor.

2.1 Thermal Model

According to the internal heating mechanism of supercapacitors, heat generation includes reversible heat and irreversible heat[10], which can be expressed as[11]:

$$Q_h = \begin{cases} ESR(T,I)I(t)^2 + \alpha I(t), \text{charge} \\ ESR(T,I)I(t)^2 - \alpha I(t), \text{discharge} \end{cases} \quad (2.1)$$

α is an empirical parameter, and its value can be identified by repeatedly charging and discharging the supercapacitor under constant current to a thermal steady state as shown in Fig.1. According to [12], its expression can be written as:

$$\alpha = \frac{C_{Heat}\Delta T}{I\Delta t} \quad (2.2)$$

Where C_{Heat} is the equivalent heat capacity of the supercapacitor, ΔT is the difference between the maximum and minimum temperature fluctuations of the supercapacitor, Δt is the time difference between the peak and the valley, and I is the current.

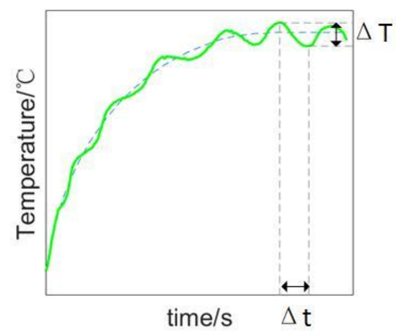

Fig.1:Temperature of supercapacitor charging and discharging by a constant current

The inner and surface materials of the supercapacitor are different, so their thermal parameters are also different[12]. Considering this situation, a second-order thermal model is used for supercapacitor modeling, as shown in Fig.2.

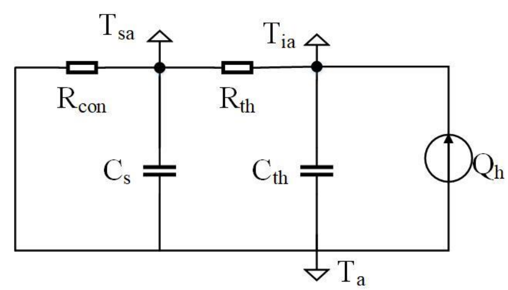

Fig.2 Thermal Model of Supercapacitor

Q_h represents the heat generation rate of the supercapacitor which can be calculated by (2.1), T_a is the ambient temperature, T_{sa} and T_{ia} respectively represent the temperature difference between the shell and the ambience and the temperature difference between the inside and the ambience. C_{th} represents the total heat capacity of the electrolyte of the supercapacitor, R_{th} represents the total series thermal resistance between the electrolyte and the shell, C_S is the heat capacity of the supercapacitor shell, R_{con} is the thermal resistance of air convection. The discrete equation of the model can be derived as:

$$T_{ia}(k+2)=aT_{ia}(k+1)+bT_{ia}(k)+cQ(k+1)+dQ(k) \quad (2.3)$$

Where

$$\begin{cases} a=2-\dfrac{t}{R_{th}C_{th}}-\dfrac{t}{R_{con}C_s}-\dfrac{t}{R_{th}C_s} \\ b=(1-\dfrac{t}{R_{th}C_{th}})(\dfrac{t}{R_{con}C_s}+\dfrac{t}{R_{th}C_s}-1) \\ c=\dfrac{t}{C_{th}} \\ d=\dfrac{t}{C_{th}}(\dfrac{t}{R_{con}C_s}+\dfrac{t}{R_{th}C_s}-1) \end{cases} \quad (2.4)$$

Thus the parameters can be identified by least square method.

2.2 *Electro-Thermal Coupling Model*

As Fig.3 shows, The electro-thermal coupling model uses a first-order nonlinear model which includes two components, ESR and C. For hybrid supercapacitors, Laurent Pilonden et al. explained the relationship between ESR and temperature and current through electrochemical method [13]. It can be concluded that ESR is related to temperature and current.

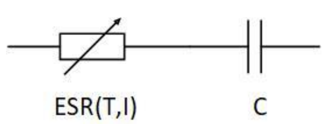

Fig.3 First-order electrical model of supercapacitor

Through the polynomial empirical model, the supercapacitor ESR under different temperature and current is expressed as:

$$ESR(T,I)=aT+bI+cT^2+dI^2+eTI+f \quad (2.5)$$

3. H-∞&ANN JOINT FILTER FOR TEMPERATURE ESTIMATION

Although the temperature inside the supercapacitor can be directly predicted according to the parameters of the supercapacitor electrothermal coupling model and the measurement of the input, there are errors in the model and the measured value, and the direct prediction accuracy is low and is affected by the cumulative error.

An improved method is, to establish a closed-loop observer, and feedback the difference between the measured value and estimated value of the supercapacitor surface to the observer for real-time correction.

3.1 *H-∞-ANN Joint Filter*

The heat transfer model of the supercapacitor can be regarded as a linear system, so an H-infinity filter can be designed for it. The design concept of the H-infinity filter is to estimate the state of the system in the worst case (considering the uncertainty of the model and the unknown of the noise parameters). Therefore, the method has stronger robustness and is used in this paper.

However, as stated in the design concept of the H-infinity filter, it always considers the worst case, so the prediction is so ;conservative that it is not always fit the actual situation. Therefore, the result of the H-infinity filter sometimes has large errors.

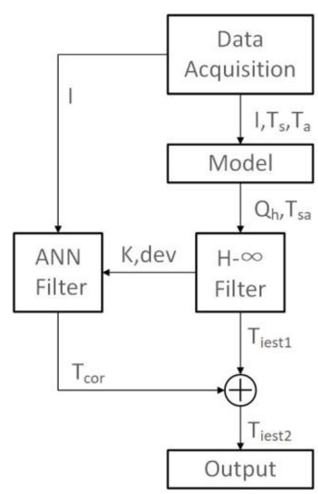

Fig.4 System flow chart of H-∞-ANN joint filter

In order to make the result closer to the true value, a neural network model can be established to correct the result obtained by the H-infinity filter. The system flowchart of the entire H-∞-ANN filter is in Fig.4. The input is the state variables in the iterative process of the H-infinity filter, and the output is the correction of the estimated value for the H-infinity filter.

3.2 H-∞ Filter

For a linear discrete system, it can be described by the following equation:

$$X(k+1) = A\ X(k) + B_k U_k + w_k \qquad (3.1)$$

$$Y(k) = C_k X(k) + v_k \qquad (3.2)$$

And for supercapacitor cell, (3,1) and (3.2) can be more specific as:

$$\begin{cases} \begin{bmatrix} T_{ia}(k) \\ T_{sa}(k) \end{bmatrix} = \begin{bmatrix} 1-\frac{t}{C_{th}R_{th}} & \frac{t}{C_{th}R_{th}} \\ \frac{t}{C_s R_{th}} & 1-\frac{t}{C_s R_{th}}-\frac{t}{C_s R_{con}} \end{bmatrix} \begin{bmatrix} T_{ia}(k) \\ T_{sa}(k) \end{bmatrix} + \begin{bmatrix} \frac{t}{C_{th}} \\ 0 \end{bmatrix} \left[\dot{Q}(k)\right] + w_k \\ T_{sa}(k) = [0 \quad 1] \begin{bmatrix} T_{ia}(k) \\ T_{sa}(k) \end{bmatrix} + v_k \end{cases} \qquad (3.3)$$

The H-infinity filter can be continuously updated with the following equation:

$$\begin{cases} \overline{x}_{k+1} = A_k \hat{x}_k + B_k U_k + w_k \\ P^-_{k+1} = A_k P^+_k A^T_k + Q \\ K_{k+1} = P^-_{k+1}[I - \frac{1}{\gamma} S P^-_{k+1} + C^T_{k+1} R^{-1}_{k+1} C_{k+1} P^-_{k+1}]^{-1} C^T_{k+1} R^{-1} \\ dev_{k+1} = y_{k+1} - C_{k+1}\overline{x}_{k+1} \\ \hat{x}_{k+1} = \overline{x}_{k+1} + K_{k+1} dev_{k+1} \\ P^+_{k+1} = P^-_k (I - \frac{1}{\gamma} S P^-_k + C^T_k R^{-1} C_k P^-_k)^{-1} \end{cases} \qquad (3.4)$$

3.3 ANN Correction

By reasonably designing the neural network, the error value of the temperature estimation can be further reduced. The input of the neural network is the gain K of H-infinity filter, the measurement deviation dev and the measurement current I, and the output is the temperature correction value T_{cor}. After testing, the hidden layer of neural network is designed as two layers, with 6 and 2 neurons respectively. Fig.5 indicates the structure of ANN used in this paper.

4. EXPERIMENT

The structure of the supercapacitor experiment platform includes DC-DC, supercapacitor and the host computer with data acquisition system. The host computer sets the current and voltage values and transmits them to the DC-DC converter. The voltage, current and temperature data are collected and sent to the host computer. The real object of the supercapacitor is shown in Fig. 6, and the parameters are shown in Table 1.

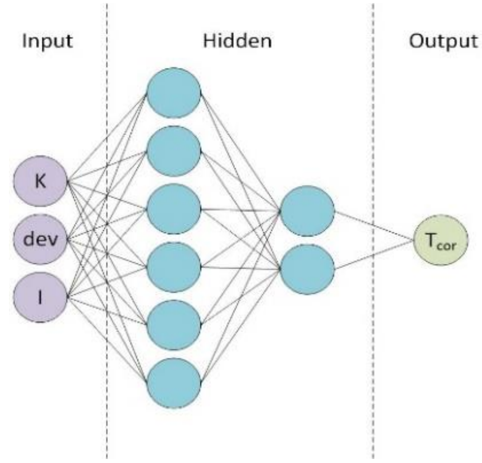

Fig.5 Structure of ANN

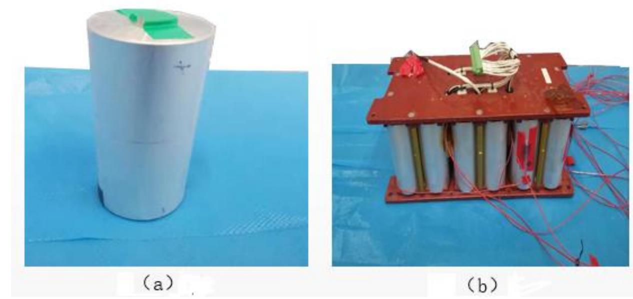

Fig.6 Supercapacitor used in the experiment
(a) Cell (b) Stack

Table 1. Parameters of Supercapacitor

Voltage Range	Temperature Range	Capacitance	ESR
2.5-4.0 V	20-60 ℃	28000 F	0.35 m Ω

4.1 Experiments for accuracy of model

In order to verify the accuracy of the model used in section 2, a random current is applied to charge the supercapacitor and observe the temperature rise. Since the highest temperature is the internal temperature of the supercapacitor and cannot be measured, the positive electrode temperature is generally used to replace the highest temperature. Hamid Gualous et al. verified the feasibility of the above scheme through experiments [10].

Results of experiment and simulation temperature are shown in Fig.7, and error analysis are shown in Table 2. The model has certain errors, due to the approximation and simplification. However, the RMSE and MAE shown in table 2 is less than 0.5℃, so the accuracy of the model is guaranteed within a certain range and can be used for subsequent research.

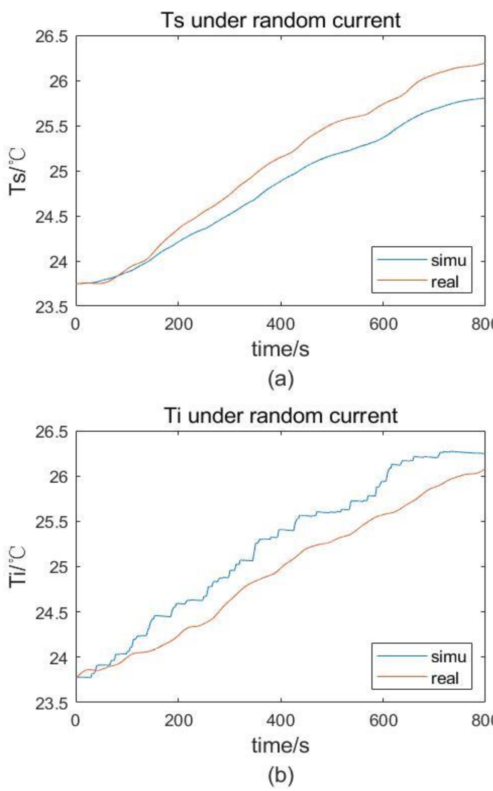

Fig.7:Experiments and Simulation Results under different currents. (a) Shell Temperature. (b) Internal Temperature

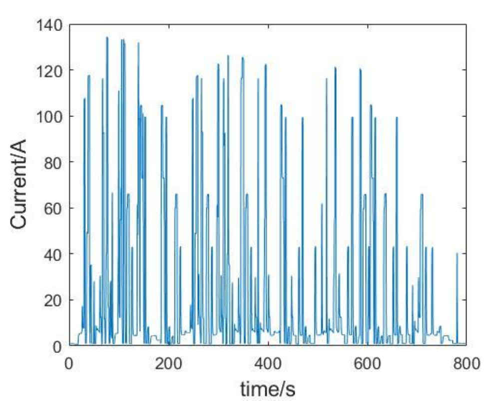

Fig.8:The random currents waveform

Table 2. Error Analyses for Fig.7

	T_{ia}	T_{sa}
RMSE	0.3175	0.2725
MAE	0.4614	0.4517

4.2 Validation of H-∞-ANN joint filter

The temperature estimation method is validated by experiments carried out by applying different currents (30A, 50A, 70A, 90A) to the supercapacitor to charge and discharge periodically. H-∞ filter and H-∞-ANN joint filter are used to estimate the internal temperature of supercapacitor. Fig.9 shows the waveform of the current, Fig.10 shows the result with ANN and without ANN, and Fig. 11 shows the difference in absolute error between the temperature estimation with and without ANN ($\left|T_{iest2}-T_i\right|-\left|T_{iest1}-T_i\right|$).

From Fig.10-12 it can be seen that the accuracy of temperature estimation using joint filter is higher than that using H - infinity filter only. Thus the ANN network effectively compensates the error of H-infinity filter.

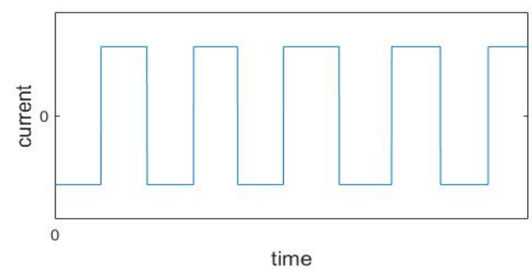

Fig.9 Waveform of current

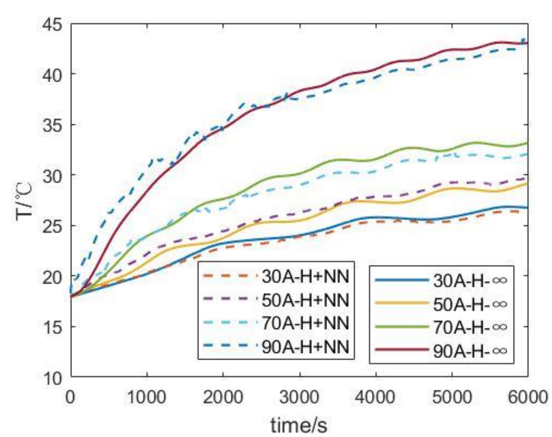

Fig.10 Estimation of internal temperature

5. CONCLUSION

In this paper, an H-∞-ANN joint observer is established to predict the internal temperature of supercapacitor based on an electro-thermal coupling model. The structure of the model is simple, but it can meet the accuracy requirements. Through the comparison between experiment and simulation, the RMSE of this estimation method is less than 0.5℃, and the MAE is less than 1℃, which is smaller than that of the original filter and accurate enough for practical applications. In the follow-up works, we will continue to do further research on the specific use of this method.

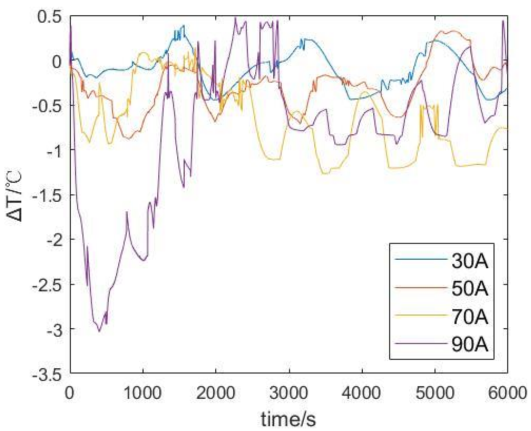

Fig.11 Difference in absolute error

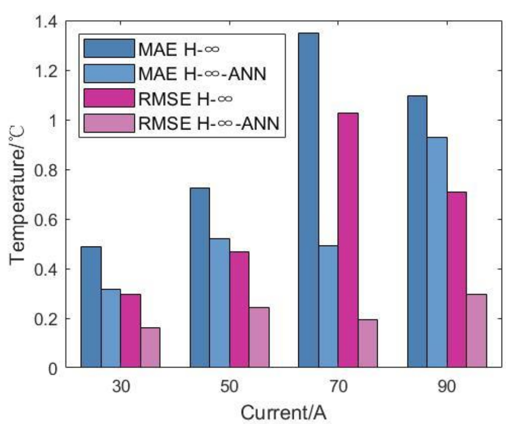

Fig.12 Error bar of Fig.10

ACKNOWLEDGEMENT
The work is supported by the National Natural Science Foundation of China (No.51777141), the Fundamental Research Funds for the Central Universities (inter-disciplinary program) under contract No. kx080020173427, and the China Scholarship Council (The International Clean Energy Talent Programme, 2017).

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