Nonlinearity correction of the thermocouple based on neural network

Jianwen Tang, Yong Zhang, Xiaojun Tang, Junhua Liu
State Key Laboratory of Electrical Insulation and Power Equipment,
Xi'an Jiaotong University, P.R.China, 710049
tangjianwen@gmail.com

Abstract—**Thermocouples are widely used in the industrial measurement. However they have serious nonlinear problems in the larger range of measuring temperature, and result in the big error in the measuring results. Taking nickel chromium-Silicon nickel thermocouple (Type K) as an example, BP（Back Propagation）neural network technology was used to conduct corrections on the nonlinear input and output characteristics of the thermocouple. The C program on the nonlinearity correction model of the thermocouple was given and could be used in MCU（Micro Controller Unit）.**

Key words: BP neural network；thermocouple; nonlinear correction

I. INTRODUCTION

The structure of thermocouple is simple, easily made and has a wide temperature range. Because of the advantages of thermocouples, they are widely used in the field of temperature measurement. But thermocouple nonlinear correction (also known as linear processing), which has seriously affected the temperature measurement accuracy. International and domestic standards give thermoelectric potential-temperature tables, we can get results by looking up the tables, but this approach in the application process is very inconvenient, and a better way is to use neural network technology to establish the corresponding mathematical model to improve the linearity of the thermocouple. The neural network has a great of memory capacity; high-speed parallel computing capacity and transformation of non-linear, at any time to conduct further study, and can be used to effectively correct the non-linear system.

II. The nonlinearity of thermocouple

The types, specifications, and structures of thermocouple variety, almost all have the serious problem of non-linear, and there is a non-linear relationship between its output and the measured temperature. The measurement error is coming. This paper uses neural network technology to make a non-linear correction of nickel chromium-nickel silicon thermocouple (K). As for the K-type thermocouple when the temperature ranges between 0 and 200°C, basing on the table of thermoelectric potential and temperature, we can fit the following E~t relationship by the least squares principle:

$$E = c_0 + c_1 t + c_2 t^2 + \cdots \qquad (1)$$

E is potential thermoelectric when the $c_0 = -0.0311mv$, $c_1 = 0.0415mv/{}^\circ\mathrm{C}$, $c_2 = -3.5\times10^{-6} mv/{}^\circ\mathrm{C}^2$. The equation (1) tells us that the E-t relationship is nonlinear. The temperature at the cold point of the thermocouple is 0.

III. The nonlinear correction based on BP network

Make the thermoelectric potential E of-type

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from the thermocouple table as the neural network inputs and make the sub-degree temperatures in the table as the target value t, then begin then BP neural network training. When the deviation between the results of the training or the temperature integration values and the target values meets measurement requirements to reduce nonlinear end the training. Now as to the BP network output temperatures we can get $t' = t + \varepsilon$, and ε is the allowing measurement error, very small. Therefore, by BP neural network training, we can get a linear relationship between t and t', and the thermocouple nonlinear correction is finished.

A. The structure of BP neural network

BP neural networks generally use the three-tier (input layer, hidden layer and output layer) network structure, as shown in Figure 1. The input of Hidden nodes and output nodes in the network (neurons) is the weighted output of the former.

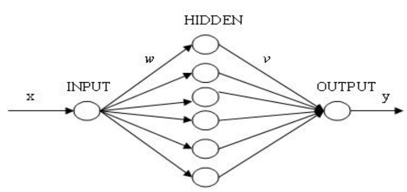

Figure 1 BP network structure

- The output of the entering layer neurons and its function is selected as the linear-type role, the node i for the output:

$$O_i = x_i \qquad (2)$$

While x_i is the importation of the i-node, i=1, 2,…n.

- The output of the hidden layer neurons and its function is the number of optional S-type, the node j for the output:

$$O_j = f(I_j) = \frac{1}{1+e^{-I_j}} \qquad (3)$$

The total import of j-node:

$$I_j = \sum_{i=1}^{n} O_i \cdot w_{ji} + b_j \qquad (4)$$

b_j is a hidden layer threshold of the j-node, and w_{ji} is a connecting weighted value between the hidden layer j-node and the entering layer i-node. For example, the hidden layer of the first node to enter:

$$I_1=w_{11}x_1+w_{12}x_2++w_{1n}x_n+b_1 \qquad (5)$$

- The output of the output layer neurons and its function often used role-linear function of the output nodes:

$$y_k=I_k \qquad (6)$$

The total input of k-node:

$$I_k = \sum_{j=1}^{l} O_j \cdot v_{kj} + b_k \qquad (7)$$

b_k is the threshold of the k-node of the output layer. v_{kj} is a connecting weighted value between the hidden layer j-node and the output layer i-node. For example, the output of the first node for the importation:

$$I_1=v_{11}O_1+v_{12}O_2+\ldots+v_{1l}O_n+b_1 \qquad (8)$$

The output of the output node is of its input:

$$y_1=I_1. \qquad (9)$$

B. Preparation of the training and testing samples

1) Thermocouple calibration. We use the given data from the international standard for temperature ITS-90 and GB/T 2614-1990 TC -Table and select the temperatures ranging from 0-200°C and their corresponding thermoelectric potential values as the calibration data.

2) Training samples. Selected the temperatures ranging from 0 to 200°C, according to the table of NiCr-nickelsilicon thermocouple (K), the temperatures selected are 1, 3, 5, 7……197, 199, 200°C and the corresponding potential for the importation of samples thermoelectric, The temperatures corresponding to the output samples, are the training samples, a total of 101. Then select the thermoelectric potential as the corresponding to the temperatures of 0, 5, 10, 15……195, 200°C as input samples, and the temperature corresponding is the output samples, these samples are the testing samples, a total of 41 groups.

C. BP-Training flow chart

BP network of learning processes is shown in Figure 2.

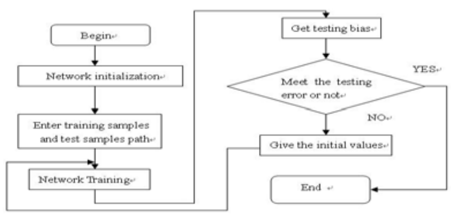

Figure 2 BP network training process and algorithm

D. Neural network on training

1) The function of BP Design instrument. In this paper, the Electrical Technology Laboratory of Xi'an Jiaotong University provides an innovative training of the neural network for the thermocouple nonlinear correction. The Figure 3 is BP neural network training panel.

The instrument panel of the BP network training has the following modules:

Module 1-Training sample file path:

(1).Entering sample file path. In the text box, enter the training samples for the importation of paper path.

(2).The file path of output sample. In the text box, enter the expectations of training samples sample output of the path to the file.

Module 2-testing samples of the file path:

(3).Entering sample file path. In the text box to enter the test samples of imported samples of the path to the file

(4).Outputting sample file path. in the text box to enter the test samples in the hope that the output of samples documentation path.

Module 3-the network structure:

(5).Hidden nodes. Set BP network number of hidden layer neurons.

(6).Hidden response function. Select BP network hidden layer neurons in response to function.

(7).Output of the response function. Select BP network output layer neurons responding to function.

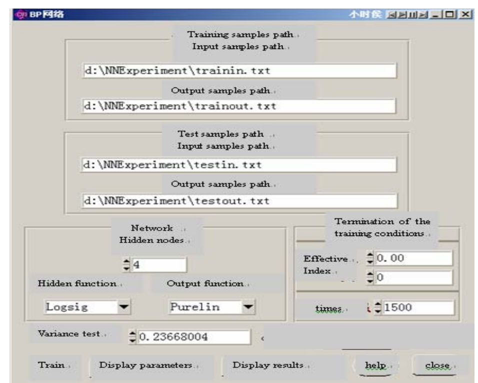

Figure 3 Panel of BP neural network design instrument

Module 4-training conditions:

(8).Effective number. Training conditions for the termination of the standard deviation expressed as $a*10^{-b}$, while the number refers to the effective is a.

(9). Index: b.

(10).Training in algebra. In the BP network training process, when the training algebra reaches to the number which is sat in the box, stop the training. When the training sample files' paths are sat, and the BP neural network structure is designed, click "Training" button, begin neural network training. When the training is finished, the BP Design instrument will give testing results and the network parameters.

2) BP network training and testing. The number of hidden nodes is 6, hidden response function is the number of sig function, logsig, and the output of the response function is pure linear function, purelin. The termination of the training conditions is training for the 1000 algebra. Click on the button training network "training", at last the smallest result is 0.03963582. Get the weighted values and the threshold values as the result of BP network training.

E. The results and analysis of nonlinear correction

1) Thermocouple nonlinear correction model. The non-linear correction model structure established by BP neural network can be described by the weighted values and the threshold values, the threshold values and the weighted values are shown as follows:

The weighted values between the entering layer and the hidden layer:

w_1=[-30.473488 -38.820904 -1.644704 -2.235481 0.099258 95.799098]

The weighted values between the outputting layer and the hidden layer:

w_2=[-20.979834 31.472969 -6.901741 1.78862 1014.294648 -254.668243]

Hidden threshold values:

b_1=[-47.329741 -25.972066 12.099975 4.515939 -0.050021 86.879988]

The threshold of the outputting layer:

b_2=-234.662545.

We can easily get a equality of t'-E:

The output of the entering layer: $O_i=E(t,0)$.

Hidden output: $o_j = f(I_j) = \frac{1}{1+e^{-I_j}}$

The total input of the hidden layer j-node:

$I_j=O_i \times w_{1j}+ b_j$

The output of the outputting layer:

$t' = I$,

While $I = \sum_{j=1}^{6} o_j \cdot w_{2j} + b_2$

$$t' = \frac{w_2}{1 + e^{-(w_1 E(t,0)+b1)}} + b2$$

So any thermoelectric potential E can be passed on a t' corresponding temperature, which is the temperature after non-linear correction.

2) Nonlinear correction analysis. The testing samples with data on BP to build the network model were tested, and the testing results were shown in table 1.

TABLE 1.THEORY TEMPERATURE AND THE TEMPERATURE OF THE TEST RESULTS

The theoretical values/℃	0.0	5.0	....	200.0
The test results/℃	0.002668	4.973522	...	199.967966

The actual temperature curve and calculated curve based on BP networks are provided by figure 4. The largest fitting deviation is 0.8347°C.

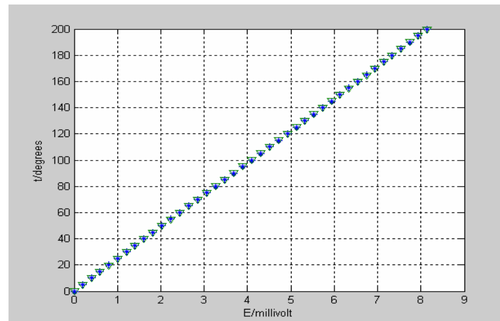

Figure 4 the comparisons between the actual temperature curve and calculated curve based on BP networks

The theoretical values in the table are the temperatures in the table. Before the neural network training, according to test sample data (E, t) can be obtained a equation by the linear least-squares fitting:

$$t = 24.4412 \times E + 0.2628$$

The largest fitting deviation can be obtained $\Delta L_m = 0.8347$ °C, then, the linearity of K-type thermocouple:

$$\delta_L = \frac{\Delta L_m}{Y_{FS}} \times 100\% = 0.41\%$$

After the neural network training, according to test sample data (E, t) can be obtained a equation by the linear least-squares fitting:

$$t' = 1.0001 \times t + 0.0037$$

The largest fitting deviation can be obtained $\Delta L_m = 0.0842$ °C, then, the linearity of K-type thermocouple:

$$\delta_L = \frac{|\Delta L_m|}{Y_{FS}} \times 100\% = 0.0421\%$$

Comparing specific linearity is shown in table 2.

TABLE 2. THE PERFORMANCE COMPARISON BEFORE AND AFTER NEURAL NETWORK TRAINING

	The largest fitting deviation/℃	The linearity
Before training	0.8347	0.41 %
After training	0.0842	0.0421 %

The results can be seen from Table 2. After the neural network training, the nonlinear of thermocouple has been significantly improved between temperatures of 0 and 200.

IV. TRANSPLANTING THE PROGRAM FORMULA TO MCU

In this paper, the C language based on the AT89C52 which is 8-bit makes a description about the thermocouple nonlinear correction procedures. Because the largest input voltage of the 8-bit A / D converter of MCU is 5V, the resolution is $5/2^8 = 0.02\text{V}$, and the output voltage of thermocouple is about millivolt level. When the temperature reaches 200°C, the thermoelectric power is 8.138mV; the maximum voltage corresponding to MCU is 5V, so the largest gain is 614. When the temperature is 1°C, the thermoelectric power is 0.0397mV, and the minimum gain is 504. In this paper, the gain is choosed to be 600. As to the experiment, the paper uses an analog voltage source of 0-5V insteading of the output voltage of thermocouple which is amplified by 600 times.

This paper has hade a test for 7 voltages, after the voltage of the thermocouple is amplified by 600 times, we can get the input voltages shown in table 3. These data are different from the training samples and test samples. The results are shown in table 3.

TABLE 3.THE TESTING RESULTS

Input voltage/V	1.242	0.63	0.222	1.476	1.758	2.298	2.904
BP output temperature/℃	51.10	26.26	9.26	60.48	71.89	93.93	118.51
MCU output temperature/℃	51	26	9	60	72	94	119
Absolute deviation	0.1	0.26	0..26	0.48	0.11	0.07	0.49

As shown in table 3, the output values of MCU are different from the values of the BP network, but the largest absolute deviation is not beyond 0.5°C.

V. CONCLUSION

In this paper, we make a correction of non-linear on K-type nickel chromium-nickel silicon thermocouple based on BP neural network, and get the correction model. The linearity lowers an order of magnitude than the original linearity. The model can be transplanted into MCU, and the thermocouple nonlinear correction is realized.

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