Error analysis method of intelligent electricity meter based on improved BP neural network

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Abstract: Many smart electricity meters work in different nonideal environments. The complexity of the working environment often leads to the difference between the measurement error of electricity meters and the ideal conditions. In this paper, BP neural network is improved to make it suitable for error analysis of intelligent electricity meter. By identifying, processing, analyzing and integrating a large number of experimental data, the error model of smart electricity meter is established. Then the internal relationship between various stress factors and the error of electricity meter is revealed from the data level. This method can accurately predict the error of electricity meters under certain conditions and lay a foundation for error correction of smart electricity meters in the future. In this paper, the realization process of the method is briefly described through simulation experiments, and the feasibility, rationality and reliability of the method are verified.

1. Introduction
In smart power grid, smart electricity meters undertake the tasks of power data collection, measurement and transmission, and greatly promote information analysis, integration and optimization and information presentation [1]. Except the traditional electricity consumption metering function, smart electricity meters also develop intelligent functions such as two-way multi-rate metering function, client-end control function, two-way data communication function of various data transmission modes, anti-power theft function and so on. The improvement of the functions of smart electricity meters is in line with the development trend of smart grid and new energy, and its development also promotes the integration of the physical layer and the information layer of modern power system [2].

The powerful function of smart electricity meters also means that the structure of smart electricity meters is more complex and precise than that of traditional power metering equipment. Therefore, the error of smart electricity meter is more complicated [3]. Many scholars and technicians have explored the error of smart electricity meters and made some progress. Literature [4] used pseudo-random test signals to simulate complex load environment and predicted dynamic errors of electricity meters. Literature [5-6] analyzed the influence of various environmental factors based on the error model of internal components of electricity meters. Literature [7] measured the parameter drift of electricity meter components at different temperatures, and combined with the simulation results of the temperature field of the electricity meter as a whole, estimated the environmental error of the electricity meter. In
engineering, some methods are also adopted to measure the error of electricity meters. Generally, they are inspected and collected completely before use, and a part of them is extracted to carry out performance test [8].

In the error analysis method described in this paper, the diversity and difference of the working environment are fully considered, and the influence of various working environment factors on the smart electricity meter is attributed to various stresses, and the correlation between various stresses and errors is analyzed by using the improved BP neural network algorithm. This method uses machine learning method to construct the stress error model of smart electricity meters, which can make the error prediction value of smart electricity meters have a higher confidence interval under certain conditions, and lay a foundation for the error correction of smart electricity meters in the future.

2. Typical stress selection of intelligent electricity meter

The stresses of smart electricity meters usually include electrical stress and environmental stress [9]. Electrical stress refers to the voltage stress and current stress that components in a circuit bear. In the internal circuit of an electricity meter, the input bias, the change of load and the fluctuation of component parameters and other factors will change the electrical stress. The environmental stress refers to the effect of the environment in which the smart electricity meter is located on it. These environmental stresses are externally manifested as temperature, humidity, air pressure, wind speed, illumination, salt spray, rainfall, ultraviolet ray, etc. The electric stress and the environmental stress act on the electricity meter simultaneously and affect the measurement error of the electricity meter together [10].

To find and watt-hour meter error associated with the closest several stress, with the improved principal component analysis (PCA), a set of orthogonal vectors, by looking for the sample space with this set of orthogonal to scale out of the overall situation, so as to realize a few principal components is used to describe the original high-dimensional data, and to maximize the retention of original data information [11].

Among the 60725 effective data samples obtained by the experiment, each sample has 8 sample data. The sample data matrix $X_{60725 \times 8}$ can be obtained as follows: each row vector is 1 observation data sample $x_i$, where $0 < i \leq 60725$; Each column vector is the characteristic quantity $x_j$ of the corresponding observation sample, where $0 < j \leq 8$. In order to eliminate data differences caused by dimensional differences, the original feature vector needs to be standardized, and its calculation formula is as follows:

$$
\tilde{x}_j = \left( x_j - \bar{x}_j \right) / s(x_j)
$$

(1)

Where, $\tilde{x}_j$ is the normalized characteristic quantity, $\bar{x}_j$ is the mean value of the characteristic quantity, and $s(x_j)$ is the standard deviation of the characteristic quantity.

Assume that the matrix after normalization is $\tilde{X}$, and the covariance matrix is $P$, that is:

$$
P = \text{cov} \left( \tilde{X} \right) = \frac{1}{n-1} \tilde{X} \cdot \tilde{X}^T
$$

(2)

The eigenvalue $\lambda_i$ and eigenvector $e_i$ of the covariance matrix $P$ were calculated, $P=\text{EDE}^T$, $D$ was a diagonal matrix arranged in descending order of eigenvalue, $D=\text{diag}(\lambda_1, \lambda_2, \cdots, \lambda_{60725})$, $E$ was the set of eigenvector $e_i$ corresponding to eigenvalue $\lambda_i$, and $E$ was an orthonormal matrix. $E=\text{diag}(e_1, e_2, \cdots, e_{60725})$, and the principal component vectors $y_1, y_2, \cdots, y_{60725}$ are obtained by linear variation of Equation (3).
The contribution rate corresponding to the $k$th principal component is:

$$\alpha = \frac{\lambda_k}{\sum_{i=1}^{n} \lambda_i}$$  \hspace{1cm} (4)

The experimental results show that the cumulative contribution rate of the first four principal components reaches $95\%$, and the four principal components are temperature, humidity, air pressure and electrical stress. Therefore, the above stress is selected as the typical stress and used as the input variables of the following model.

3. Stress error model of intelligent electricity meter

The stress error model of intelligent electricity meter is the correlation degree model between the error data of intelligent electricity meter and the stress factor, which reflects the internal relationship between the stress factor and the error from the data level and reveals the cause of the stress error. In view of the problem that the offset generated by stress error $\Delta p$ is difficult to be modeled and estimated by traditional methods, this paper proposes a stress error model for intelligent electricity meters based on the improved BP neural network. Its establishment and analysis process is shown in Figure 1 below:

![Fig. 1 Flow chart of stress error model establishment for intelligent electricity meter](image)

The original historical data of the typical stress mentioned above, namely temperature, humidity, air pressure and electrical stress, often have various defects, which are manifested as frequent missing data and abnormal data. Therefore, pre-processing work should be carried out, which is mainly divided into data cleaning, data transformation and data protocol.

For the BP neural network, as long as the number of neurons in the hidden layer is appropriate, the nonlinear function between error and stress can be approximated under any accuracy requirements. In the three-layer neural network structure, the preprocessed typical stress parameters $x = [x_1, x_2, \cdots, x_n]$ are set as the input vector, $y = [y_1, y_2, \cdots, y_n]$ the output vector of the hidden layer, the error of the smart electricity meter $z = [z_1, z_2, \cdots, z_m]$ as the output vector, the actual error $t$ as the expected output vector, and $w$ as the connection weight of the neural network. First, the typical stress data is linearly processed and then transmitted to the input layer. Then, Sigmoid function is used as the activation function in the middle layer and the output layer. In the forward propagation process, n-dimensional samples, i.e., typical stress parameter $x$, are received by the input layer, and the processed results of each unit are transmitted to the middle hidden layer. The processed number $net_i$ is received by the middle hidden layer, and the output $y=f(net_i)$ is the activation function. The principle of the output layer is similar to that of the intermediate hidden layer. After the intermediate layer is transferred to the output layer, the final output layer outputs the m-dimensional vector $z$.

In the network output error $z$ did not meet the requirements of setting up the intelligent watt-hour meter, into the back propagation network to process the data link, the error signal from the back forward
weight value and threshold value of each unit changes, including the modified weight using the algorithm, this paper, based on the principle of gradient descent method to complete the process of back propagation. The error function of the output layer is set as $E$, and its expression is:

$$E(w) = \frac{1}{2} \sum_{k=1}^{m} (t_k - z_k)^2 = \frac{1}{2} \| y - z \|^2$$  \hspace{1cm} (5)$$

Where, $w$ is all the weights. In the initial stage of the model, the initial weight is set to a random value within a certain range, and then the weight is updated according to the direction in which the normal error of gradient descent decreases. The adjustment quantity is:

$$\Delta w = -\eta \frac{\partial E}{\partial w}$$  \hspace{1cm} (6)$$

Where, $\eta$ is the learning rate. The weight updating method from the middle hidden layer to the output layer is as follows:

$$\Delta w_{kj} = -\eta \frac{\partial E}{\partial w_{kj}} = -\eta \frac{\partial E}{\partial z_k} \frac{\partial z_k}{\partial \text{net}_k} \frac{\partial \text{net}_k}{\partial w_{kj}} = \eta (t_k - z_k) f'(\text{net}_k) y_j$$  \hspace{1cm} (7)$$

The process of model training is to reduce the error value through multiple iterations. The weight vector is updated as follows in the ith iteration:

$$w_{(i+1)} = w_{(i)} + \Delta w_{(i)}$$  \hspace{1cm} (8)$$

Finally, when the value of the output error function reaches the end condition, the iterative calculation stops and the training of the neural network model is completed. The trained model can excavate the nonlinear relationship between the stress characteristic value and the error value of the electric energy meter and predict the error more accurately under certain conditions.

4. Case study

According to the error situation and original data of smart electricity meters in typical provinces such as Xinjiang, Heilongjiang, Fujian and Xizang, and based on the algorithm of improved BP neural network, the error model of smart electricity meters under typical stress conditions is established. The error analysis is divided into two processes: experimental test and model building. Based on the experimental test of electrical stress, the influence model of electrical stress error is established.

According to the above scheme, it is found that the influence curves of temperature stress, humidity stress and air pressure stress on the error of the electricity meter are shown in Figure 2, Figure 3 and Figure 4 below:

![Fig. 2 The effect of temperature on the meter](image2)

![Fig. 3 The effect of humidity on the error of the meter](image3)
Although there are great regional differences and environmental conditions, the connection between stress and error in smart meters applies to all selected regions. The analysis shows that for the environmental stress, when the other stress variables are fixed, the error is the minimum at about 25 degrees Celsius. Below this inflection point, the lower the temperature, the greater the error of the electricity meter, which basically presents a linear negative correlation. Above this inflection point, the higher the temperature, the greater the error, showing a positive linear correlation. When other stress variable is fixed, the higher the humidity, the bigger the error, in the case of humidity is not high, the error and the humidity is about the relationship between the natural logarithm, when humidity is bigger, continue to increase the humidity, the error still increase, but growth slowed markedly when other stress variables fixed, air pressure around 101 kpa, minimum error, below the inflection point, the lower the air pressure. The larger the error of the electricity meter is, the linear negative correlation is basically presented. Above this inflection point, the higher the air pressure, the greater the error, showing a positive linear correlation.

5. Conclusion
In this paper, a stress error analysis method for smart electricity meters is proposed and applied to typical areas, and the following conclusions are drawn:

1) In this paper, the influence of various stresses on the error of smart electricity meters in actual use is fully considered, and an additional error is introduced in the error modeling to realize the error model correction of smart electricity meters;

2) In this paper, BP neural network is improved to make it suitable for the stress error analysis of intelligent electricity meters, so that the error prediction will be more accurate and reliable;

3) This method can accurately predict the error of electricity meters under certain conditions, and lay a foundation for error correction of smart electricity meters in the future.

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