Research on estimating method for the smart electric energy meter's error based on parameter degradation model

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Abstract. The performance of the smart electric energy meter deteriorates during the operation, which will affect the accuracy of energy metering. In order to estimate the smart meter's error during the operation, a method based on parameter degradation model is proposed. The meter's degradation parameters and degradation acting parameters are determined, aiming at building parameter degradation model and putting forward error estimation constraint. Big data analysis methods are adopted in the process of solving degradation network. As the data are of multiple categories and data changing rates are variable, pre-processing method of differential normalized data is employed. Additionally, feed-forward neural network is adopted to approximate degradation characteristics, because elementary function is incapable of describing degradation network. Therefore, the smart meter's error can be estimated according to the error estimation constraint, assuming degradation acting parameters pre-determined. Case analysis results show that estimation results using the proposed method is in accordance with operating state in short time, and absolute error is less than 0.1\%, demonstrating that the error of smart meters can be estimated with this method effectively and dynamically.

1. Introduction
The smart meter is the key equipment for electricity measurement in the power system and the basis for settlement of electricity trade. The accuracy of smart meter directly relates to the economic benefits of the power grid and the trade fairness of the users. While, regular tests are still taken on most of the meters or off-line maintenance only when the measurement error exceeds the error limit, which affects the reliability of power supply and increases the cost of operation and maintenance\cite{1-4}.

In this paper, an estimating model for the smart meter's error is proposed according to the metrological characteristics, basing on temperature, humidity, load and historical data. The neural network algorithm is adopted to estimate the error, then the historical calibration data is applied to modifying the estimating results, and the validity has been verified in the end.

2. Parameter degradation model
2.1. The principle of the model

The parameter degradation of a system or equipment generally means that the performance deteriorates. At present, the state estimating models and methods for most power equipments already have a complete system[5]. For complex equipments or systems, there are usually several parameters describing the state. For example, the state parameters of a transformer include dissolved gas in the oil, insulation resistance, dielectric loss, moisture content in oil, etc[6-8]. While for a circuit breaker, the state parameters usually include contact abrasion, opening/closing coil current, breaking stroke and so on[9]. Each parameter needs to be considered when a state estimating model is established.

Suppose the set of a certain device’s state parameters is defined as \( \{P_1, P_2, \ldots, P_n\} \), then a simple and effective estimating model can be described as: if \( \max|P_i| (i=1, 2, \ldots, n) \) exceeds the threshold, some performance of the device will deteriorate and the normal operation of the device will be influenced. The above estimating model is not suitable for the smart meter's error, mainly for three reasons.

1) Generally, the smart meter's parameters degradation under the influence of some degradation acting parameter, will not lead to malfunction of the meter;

2) The degradation of smart meter's parameters has directionality. That is, the effect of each parameter degradation on the meter's measurement error isn’t the same, which may be complementary thus not affect the overall accuracy;

3) Under the above premise, the performance parameters can't be used as the basis for estimation.

The theoretical research suggests that many aspects affect the performance of the smart meter, including the temperature and humidity of environment; electrical parameters such as load, frequencies and harmonics; electromagnetic fields, vibration and communication anomalies; power grid events such as pressure loss and interruption[10-13]. According to whether or not the smart meter's normal work is affected, they can divide into reliability and stability factors; according to the influence time, they divides into the persistent and the occasional influencing factors.

Among them, three factors which influence the smart meter's error largely are selected as the degradation acting parameters to build the model, which are the temperature, humidity of the environment and the load, respectively. The three factors influence the smart meter at the same time, which affect the measurement error.

To simplify the model, only single-phase energy metering is considered. Single-phase energy metering can be equivalent to a multi-input single-output system, of which the inputs are actual energy \( W_0 \), temperature, humidity and load, and the output is the energy shown in the smart meter. Its equivalent diagram is shown in figure 1.

![Equivalent schematic for input and output of single-phase energy metering system.](image)

**Figure 1.** Equivalent schematic for input and output of single-phase energy metering system.

The degradation acting parameters including temperature, humidity and load will lead to the smart meter's error. Therefore, the degradation parameters of the smart meter include the following three parts: the smart meter's ratio error under the influence of temperature, the meter's ratio error under the influence of humidity and the ratio error under the influence of load. For the system shown in figure 1, the measurement error of the energy ratio error depends on the three parts, which is shown in figure 2.
Figure 2(a). Ratio error of energy under the temperature's influence.

Figure 2(b). Ratio error of energy under the humidity's influence.

Figure 2(c). Ratio error of energy under the load's influence.

Curve 1 shows an actual input signal, and curve 2 shows the signal with ratio error. Assuming that the degradation parameter of the smart meter is zero at the initial time. During the operation, they are degrading in their respective dimensions and the direction is uncertain. When three parameters are degraded to \( f_{WT}, f_{WH}, \) and \( f_{WL} \) at some point, the discrete electric energy is:

\[
W = \sum_{i=0}^{N} \left( \alpha_i + \beta_i + \gamma_i \right) W_0
\]  

In the equation (1), \( \alpha_i \) is the energy measurement error coefficient caused by \( f_{WT} \), \( \beta_i \) is the measurement error coefficient caused by \( f_{WH} \), and \( \gamma_i \) caused by \( f_{WL} \). The range of \( \alpha_i \)'s, \( \beta_i \)'s and \( \gamma_i \)'s value are: \(-1 \leq \alpha_i \leq 1, -1 \leq \beta_i \leq 1, -1 \leq \gamma_i \leq 1 \). When \( \alpha_i + \beta_i + \gamma_i = 1 \), the measurement accuracy of the smart meter is unchanged, indicating that the influence of each degradation acting parameter on the smart meter's error is complementary. Based on the above analysis, the following conclusion can be obtained: compared with the existing state estimating model for the equipments or systems, the parameter degradation of the smart meter has directivity.

2.2. Model establishment

In order to simplify the model, the three degradation parameters \( f_{WT}, f_{WH}, \) and \( f_{WL} \) are merged into one degradation parameter, namely the energy's measurement ratio error \( f_w \). The three factors influence the smart meter at the same time, which affect the degradation parameter \( f_w \). The degradation process can
be described as follows:

\[
f_w(t) = g(Temp(t), Hum(t), Load(t)) \quad (2)
\]

In the upper equation, \(Temp(t)\) is a function of temperature over time, \(Hum(t)\) is a function of humidity and \(Load(t)\) of load. Let:

\[
\varepsilon = f_w(t) \quad (3)
\]

\[
a = (Temp(t), Hum(t), Load(t)) \quad (4)
\]

The solution of the equation (2) is \(A\), and then equation (2) can be written as:

\[
\varepsilon = A\alpha \quad (5)
\]

Equation (5) is defined as the parameter degradation equation of the smart meter, where \(\varepsilon\) is the degradation parameter, \(\alpha\) is the degradation acting parameter, and the solution matrix \(A\) is the degradation network under the degradation acting parameters. The meter's measurement ratio error is used as the estimated constraint:

\[
\eta_w = \frac{W - W_0}{W_0} \quad (6)
\]

In the upper equation, \(\eta_w\) is the average energy's measurement error. Equation (5) and (6) constitute a model for smart meter's error estimating.

3. The solution method of the parameter degradation network
Using reasonable data processing method to obtain the parameter degradation network is the key to estimating the smart meter's error according to the historical operation data.

3.1. Data pre-processing
The degradation acting parameters of the degradation model include temperature, humidity and load. When the data being obtained, data volume varies according to different sampling frequencies. For example, the temperature and the humidity are sampled every three minutes, while the ratio error of the measured energy is sampled every minute. The cardinality and dimensions of all kinds of data are not consistent. For example, the base of temperature is 25, and the base of load is 0.5. In order to synchronize the data, the sampling rate of them should be unified. In order to unify the weights and dimensions of variables, all kinds of data should be dealt with normalization processing. Because the temperature and humidity will not mutate, a first-order linear interpolation method can be used to expand the data of temperature and humidity. Taking the temperature data processing as an example, assuming that the sampling temperature of \(i\) and \(j\) is \(T(i)\) and \(T(j)\), the amount of data is increased to \(N\) times. When the data is expanded, the interpolation sequence between the two temperature sampling values is:

\[
T(i+k) = \begin{cases} T(i) + \frac{T(j) - T(i)}{N} \cdot k & k = 1, 2, \ldots, N - 1 \\ T(j) & k = N \end{cases} \quad (7)
\]

Humidity data is also dealt in the same way, and the sampling rate of temperature and humidity after treatment is as same as that of load.

Suppose that the variables sequence is \{\(W_1, W_2, \ldots, W_n, W_{n+1}\)\}, then its maximum change gradient with the method of differential normalization is defined as:

\[
\Delta W = \max(\Delta W_i)(i = 2, 3, \ldots, n, n+1) \quad (8)
\]

The variable sequence is dealt with differential normalized as follows:
\[ W_i = \frac{W_{i+1} - W_i}{\Delta W} \] (9)

The equation (5) can be rewritten as the normalized form:

\[ \Delta \varepsilon = B \cdot \Delta \alpha \] (10)

In the above equation, \( \Delta \varepsilon \) is the differential normalized degradation parameter, \( \Delta \alpha \) is the differential normalized degradation acting parameter, and \( B \) is the corresponding differential normalized degradation network.

3.2 The solution method of degradation network

The essence of solving the parameter degradation network is to solve the coefficient matrix \( B \) of equation (10) based on the known degradation acting parameters and the degradation parameter. The elements of matrix \( B \) are not analytical, and cannot be described by constants or elementary functions. An artificial intelligence learning method is adopted to approximate the input and output characteristics of the actual coefficient matrix \( B \). This paper uses BP neural network to complete, as shown in figure 3 [14].

![Figure 3. Structure diagram of network.](image)

![Figure 4. Estimation procedure based on parameter degradation model.](image)

In this paper, the input is the differential normalized degradation acting parameter \( \Delta \alpha \), and the output is the differential normalized degradation parameter \( \Delta \varepsilon \). The transformation function of the degradation network to the input approximates the coefficient matrix \( B \) in equation (10).

4. Estimation steps based on a parameter degradation model

In this paper, the steps of smart meter's error estimation based on the parameter degradation model is shown in figure 4.

1) Data pre-processing. Data samples are treated with sampling rate unification and differential normalization, getting \( \{ \Delta \text{Temp}(1), \Delta \text{Temp}(2), ..., \Delta \text{Temp}(n) \} \), \( \{ \Delta \text{Hum}(1), \Delta \text{Hum}(2), ..., \Delta \text{Hum}(n) \} \), \( \{ \Delta \text{Load}(1), \Delta \text{Load}(2), ..., \Delta \text{Load}(n) \} \) and \( \{ \Delta \varepsilon_{\text{w1}}, \Delta \varepsilon_{\text{w2}}, ..., \Delta \varepsilon_{\text{wn}} \} \) respectively.

\( \{ \Delta \text{Temp}(i), \Delta \text{Hum}(i), \Delta \text{Load}(i) \} \) is the input of figure 3, and \( \{ \Delta \varepsilon_{\text{wi}} \} \) is the output of figure 3.

2) Solve the degradation network. According to the input and output sample obtained by (1), the BP neural network is adopted to iteratively approximate the coefficient matrix \( B \) and verify the mean square error until it is less than the set value.

3) Estimate the meter's error. The degradation acting parameters \( \{ \Delta \text{Temp}, \Delta \text{Hum}, \Delta \text{Load} \} \) of the real
time measurement is the input to the degradation network, and the change of the degraded parameter is obtained. Combined with the initial value of the degraded parameter, the state parameters of the smart meter are obtained, and the smart meter's error is estimated according to equation (7).

5. Case analysis

In order to verify the effectiveness of the estimating model and method, an on-line monitoring system of smart meter's measurement error is established, the structure diagram of which is shown in figure 5. The monitoring method can be described as follows.

The signal passes through two channels to calculate the smart meter's error. One of the channels is a standard channel, which uses the standard voltage transformer and the standard current transformer to measure the voltage and current signals respectively. The sampling unit collects the signal and calculates the standard electrical energy. The other one is a testing channel. In this channel, the tested smart meter measures the voltage and current signals and outputs the pulses proportional to the electrical energy. The PPS (Pulse per second) acquisition unit combines the pulse number with the pulse constant of the smart meter to calculate the measured electrical energy. The standard electric energy and the measured electric energy are input to the error calculation unit for calculation, and finally the measurement electric energy's ratio error is obtained.

![Figure 5. Online monitoring system structure diagram.](image)

(1) Intercept the temperature, humidity, load and smart meter's ratio error data from 10 a.m. to 5 p.m. on April 7, 2015, as samples. The temperature and humidity data were collected every 3 minutes using the Rotronic Instruments HP22 temperature and humidity meter, and the load was recorded every minute by the electrical energy shown in the smart meter.

The data is shown in figure 6.

![Figure 6(a). The temperature data.](image)  ![Figure 6(b). The original humidity data.](image)
As shown in figure 6(a)-(c), the original temperature, humidity and load change in the day smoothly. Figure 6(d) shows the original data of smart meter's error fluctuating in a day.

(2) Use data samples to solve the degradation network, and set the approximation error to 0.01%.

The result of iterative solution is shown in figure 7.

It can be seen from figure 7 that the mean square error is less than 0.01% after 85 iterations.

(3) The real-time measurement of the degradation acting parameter is adopted to estimate the short-time error of the smart meter after 5:00 pm on April 7, the result is shown in figure 8.

In figure 8, the blue line is the estimation error, and the red line is the error actually obtained. It can be seen that the estimating results based on the parameter degradation model are basically in line with the trend of actual results, and the absolute error of the short-term estimating error is no more than 0.1%.
compared with the actual error.

6. Conclusion
In this paper, we propose a smart meter's error estimating method based on parameter degradation model to estimate the smart meter's error during the operation, considering the combined effect of various error factors such as temperature, humidity and load under the actual operating conditions, and an on-line monitoring system for smart meter's error was established. Through the case analysis, it is found that the estimating error is basically the same as the actual error, the absolute error is less than 0.1%, which shows that this error estimation method based on parameter degradation model for the smart meter can effectively estimate the smart meter's error during the operation.

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