Research on Method of Measurement Condition Assessment for Electronic Transformers

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Abstract. A mathematical statistics based measurement condition assessment method for electronic transformers is proposed in this paper. The key to this method is to calculate the feature information which can reflect the measurement condition of electronic transformer by analyzing the sampling value. The feature information obeys specific statistical distributions in normal condition. First, the sampling values are truncated by equal time intervals, then the initial phases are calculated and then differentiated. Finally, an approximation method is used to eliminate the influence of frequency fluctuations and the feature information which obeys normal distribution can be obtained. When the condition of the electronic transformer deteriorates, the distribution parameters of the feature information change. Changes are identified by mathematical statistics method so as to evaluate the measurement condition of the electronic transformers. The verification experiment is designed. The results show that this method can effectively identify the measurement noise of the electronic transformer.

1. Introduction

The power equipment on-line condition monitoring system, which adopts key parameters of the measuring equipment to evaluate the operation status of the equipment, builds a defense line for the "Strong Smart Grid". The on-line condition monitoring of primary equipments such as main transformers and circuit breakers has been put into practical application\cite{1-4}. The electronic transformers are important primary equipments in smart substations for voltage and current measurement. They provide data sources for relay protection, measurement-control, and energy metering. Once the measurement condition of the electronic transformer deteriorates, and excessive error or failure occur, the relay protection device will malfunction or be blocked, which seriously influencing the operational reliability of the power network.

The most important thing about electronic transformers is the measurement condition, in other words, the error. Generally speaking, evaluating the measurement condition depends on the standard implement. In order to ensure that the electronic transformers in operation are in good measurement condition, regular outage verification method has been adopted for a long time, which means cutting off the power supply so as to calibrating the equipments out of service at regular intervals. This method can be only carried out according to the maintenance plan and thus is not flexible. In order to overcome this defect, some research institutes and universities study the live working detection technology, i.e., the standard implement is connected to live lines\cite{5}\cite{6}, which brings security risk.
however. In order to evaluate the measurement condition of electronic transformers without standard equipments, there are mainly two methods[7-10]. The first one is based on signal processing, that is, to classify, extract and identify the feature of abnormal output signals of the electronic transformers. The earliest research results see [7], and [8] has done similar work. The second one is a model-based method. First, model the power transmission and transformation components, including physical model and mathematic analytic model. Then solve the theoretical true value according to the model. Finally, compare the theoretical true value with the actual measured value to analyze measurement condition of electronic transformers. Both of these two methods have some limitations, however.

(i) The first method can only identify sudden change but can not detect gradual change of the measurement condition of the electronic transformers. However, gradual change of the measurement error is performance which should be paid more attention to. Moreover, the method based on signal processing should be carried out under the premise that the measured signals of the electronic transformers are steady enough. Unfortunately, the gradually-changing measurement error can’t be distinguished from the fluctuations of the primary side signal under the requirements of 0.2 class accuracy with simple signal analysis method because the primary voltage and current signals of the power network are random and non-steady, which easily causes problems such as misjudgments.

(ii) The second method requires accurate model of the transmission lines and transformers. It’s difficult to satisfy the requirements of 0.2 class accuracy of the electronic transformers under engineering conditions by this method.

In a word, any promising method that could evaluate the measurement condition of electronic transformers has not been found yet.

2. Principle
The electronic transformers digitize the measured signal by time sequence, and the digitizing process is usually called sampling. The sampling rate of the electronic transformers is usually 4 kHz and the synchronous sampling interval 1s in engineering application.

The key of the measurement condition assessment method proposed in this paper is to calculate the feature information that can reflect the measurement condition of the electronic transformers by analyzing the sampling value. Normally the feature information obeys specific statistical distributions. When the measurement condition deteriorates, the quality of the sampling value becomes worse, causing changes of the statistical distribution of the feature information, which could be identified by mathematical statistics. Above is the basic principle of this method.

The following describes the calculation process of the feature information in detail. Assuming the expression of the measured analog signal is given by

\[ u_i(t) = U_i \cos(\omega_0 t + \phi_0) \]  

where \( \omega_0 \) is the angular frequency and \( \phi_0 \) is the initial phase of the measured signal. Take the measured values at equal time intervals to calculate the phase \( \phi_i \) and the difference between adjacent phases according to equation (2), which yields a constant \( \Delta \phi \).

\[ \Delta \phi = \phi_{i+1} - \phi_i \]  

The phase difference will be a constant \( \Delta \phi \) if the time interval is \( \Delta t \).

\[ \Delta \phi = \omega_0 \Delta t \]  

Equation (3) actually shows the relationship between the phase and instantaneous frequency, as shown in figure 1.
Figure 1. Diagram of constant phase difference.

Assuming that the error of the measuring system obeys random distribution, thus when \( \omega_b \) is constant, \( \Delta \phi \) should also obey random distribution. Particularly, when \( \Delta t \) equals integral multiple of the period, the measured value of \( \Delta \phi \) obeys random distribution of zero mean. The following further explains how the distribution of \( \Delta \phi \) is affected by the deterioration of the measurement condition of the electronic transformer. Making Fourier expansion of equation (1) yields

\[
f(t) = a_0 + \sum_{k=1}^{\infty} (a_k \cos(k\omega_0 t) + b_k \sin(k\omega_0 t))
\]

where \( a_0 \) is the DC component, \( \omega_0 \) is the angular frequency of the fundamental wave, \( a_k \) and \( b_k \) are coefficients of the harmonics. If \( \omega_b \) is constant and there is no DC component in the wave, then truncate the sampling value of \( nT \) length, and the initial phase of the fundamental wave is given by

\[
\phi_0 = \arctan(b_b / a_b)
\]

where

\[
a_b = \frac{2}{nT} \int_0^{nT} f(t) \cdot \cos(\omega_0 t) dt
\]

\[
b_b = -\frac{2}{nT} \int_0^{nT} f(t) \cdot \sin(\omega_0 t) dt
\]

If the measurement condition of the electronic transformer changes, the measured value will be a superposition of the measured signal and the error. Let the error be \( g(t) \). Thus the initial phase \( \phi'_0 \) can be obtained by truncating the sampling value of \( nT \) length from the initial time, given by

\[
\phi'_0 = \arctan(b'_b / a'_b)
\]

where

\[
a'_b = \frac{2}{nT} \int_0^{nT} [f(t) + g(t)] \cdot \cos(\omega_0 t) dt
\]

\[
b'_b = -\frac{2}{nT} \int_0^{nT} [f(t) + g(t)] \cdot \sin(\omega_0 t) dt
\]

\( \phi_0 \) will equal \( \phi'_0 \) if and only if

\[
\frac{b'_b}{a'_b} = \frac{b_b}{a_b} = \frac{b'_b}{a'_b}
\]
\[
\begin{align*}
\alpha^n &= \frac{2}{nT} \int_0^{nT} g(t) \cdot \cos(\omega t) dt \\
\beta^n &= -\frac{2}{nT} \int_0^{nT} g(t) \cdot \sin(\omega t) dt
\end{align*}
\]

where \(\phi\) is the initial phase of the consecutive intervals. The condition is extremely strict and harsh for the establishment of equation (7) for the same electronic transformer. Therefore, as long as the measurement condition deteriorates and the error is superimposed on the measured signal, \(\Delta \phi \neq 0\). Since \(\Delta \phi\) is the difference between two initial phases of consecutive intervals, the distribution of \(\Delta \phi\) will be affected inevitably. Therefore, the statistical distribution of \(\Delta \phi\) can reflect the measurement condition of electronic transformers, which is called feature information in this paper.

3. Simulation verification

Assuming that the amplitude of the measured signal is 1, and the sampling error of the electronic transformers obeys the \(N(0,0.001)\) normal distribution, which simulates the measurement noise in fact. The measured signal is a standard 50Hz sine wave. Take the interval as 1s, truncate the first 5 cycles to calculate the initial phases and the feature information is obtained after differential process. The time domain distribution and statistical distribution are shown in figure 2 and figure 3, respectively.

Assuming that the measurement condition deteriorates and the measuring noise increases, and the quality of the sampling data declines. The sampling error increases to obey the \(N(0,0.01)\) normal distribution. Then the time-domain distribution and the statistical distribution of the feature information obtained are shown in figure 4 and figure 5, respectively.
Comparing figure 3 with figure 5, we can see that under the simulation condition described in this paper, the feature information of the electronic transformer obeys the standard normal distribution approximately. It also indicates that when the measurement condition of the electronic transformer deteriorates, the amplitude of the feature information increases, and the corresponding statistical distribution parameters change significantly.

4. Experiment verification
A verification experiment is designed to verify whether the proposed method can identify the deterioration of the measurement condition of the electronic transformer in practical application. It is necessary to eliminate the accumulative phase change caused by frequency fluctuations since $\omega_0$ is not constant in actual systems. Taking the time interval of 1s as an example, assuming that the frequency deviation measured at time $kT_0$ is $\Delta f(kT_0)$, the cumulative effect of frequency fluctuations on the phase in 1s is approximately given by

$$\Delta \phi(kT_0) = \Delta f(kT_0) \cdot 2\pi$$

The unit of $\Delta \phi(kT_0)$ will be radian if the unit of $\Delta f(kT_0)$ is Hz.

4.1. Scheme of the experiment
One of the key points of the electronic transformer used in the experiment is that the error should be adjustable during the experiment. LPCT+data collector structure is applied to realizing system functions of the electronic current transformers (ECTs) in this paper. The measurement error is
changed with the sampling data bits from the data collector. Key parameters of the transformer and the data collector are shown in table 1, and figure 6 shows the schematic diagram of the experiment.

**Table 1.** Key parameters of the transformer and data collector.

| Parameter name                  | Parameter                              |
|---------------------------------|----------------------------------------|
| Rated current                   | 300A                                   |
| Accuracy class                   | 0.2S                                   |
| Size of the core                 | L=130.37cm  S= 2.5cm²                  |
| Material and model of the core   | Nanocrystalline alloy 1K107            |

![Figure 6. Schematic diagram of the experiment.](image)

4.2. Results of the experiment

Carry out the experiment according to the schematic diagram shown in figure 6, and change the measurement error of the electronic transformer with data truncation method. In order to increase the quantization error, we can truncate several higher bits of the 24-bit sampling data of the A/D converter to reduce the effective bit number. The variance of the measurement error of the electronic transformer increases remarkably with this method. Let the sampling data of the 24-bit A/D converter be $D_{24}$

$$D_{24} = b_{24}b_{23} \cdots b_0$$

Truncating higher $k$ bits of $D_{24}$ with the rounding method yields

$$D_k = \left[ b_{\frac{24}{k}}b_{\frac{23}{k}} \cdots b_{\frac{24-k}{k}} + \text{sgn}(b_{\frac{24-k-1}{k}}) \right] \times 2^{24-k} \quad (8 \leq k \leq 20)$$

First we test the system for 10 minutes under normal condition, then truncate the A/D sampling data, and test for another 10 minutes. The above experiment process is repeated three times, with $k$ taking 18, 14 and 10 respectively. One error data is tested per second and a total of 3 groups of data are obtained, with 1200 calculated phases in each group. Test data of 18-bit, 14-bit, and 10-bit truncation are shown in figure 7-(a), (b) and (c), respectively.

![Figure 7. Test data of 18-bit, 14-bit, and 10-bit truncation.](image)
Calculate the distribution parameters of phase difference before and after the truncation, as shown in table 2.

**Table 2. Distribution parameters of phase difference before and after the truncation.**

| Truncation bits | Before  |  | After  |  |
|-----------------|---------|-----------------|--------|-----------------|
|                 | Mean value | Variance | Mean value | Variance |
| 18              | 0.173    | 23.269 | 0.253   | 25.681 |
| 14              | 0.267    | 21.584 | 0.305   | 29.187 |
| 10              | -0.096   | 21.689 | 0.139   | 41.562 |

It can be seen from figure 7 that abnormal change in the condition of measurement error can be simulated by gradually decreasing sampling bits of the A/D converter. With the increasing of measurement error, the variance of the phase difference of the measuring points tends to increase. Thus the measurement error of electronic transformers can be determined by the variation of the variance.

5. Conclusions
A novel evaluation method without standard implement is proposed in this paper, which evaluates the error condition of electronic transformers in operation. The key to this method is to find out the feature information of the measurement condition of the standard electronic transformer, and to determine whether there exists abnormal change in the measurement error according to the feature information, so as to evaluate the error condition of the evaluated electronic transformer. This method is fundamentally different from the existing research findings, and is much more practical since the standard is not indispensable any more.

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