Measurement 130 (2018) 1–7

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Evaluating the metering error of electronic transformers on-line based on VN-MWPCA

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ARTICLE INFO

Keywords:
Electronic transformers
Metering error
Evaluating
On-line
VN-MWPCA

ABSTRACT

Electronic transformers are used to measure the voltage and current signals, which are used to sense the state of the transmission networks. The deterioration of their metering error will affect the stable operation of the power system. The traditional method of evaluating the metering error of electronic transformers is to compare them with the standard transformer. There are outstanding problems such as over inspection and under inspection of the traditional method, which cannot be used for evaluating the metering error for a large number of electronic transformers on-line in a long-term. In this article, the correlation between primary transmission networks is analyzed to establish a new evaluation standard without a standard transformer. The standard can be calculated as a characteristic statistics, by using the measured data based on the VN-MWPCA proposed. Then the metering error of electronic transformers is evaluated by analyzing the abnormal change of the statistics. The field application analysis shows that the method proposed can be used to evaluate the metering abnormal of a Class 0.2 electronic transformer on-line accurately.

1. Introduction

As the ideal substitutes for traditional electromagnetic transformers, electronic transformers are widely used in smart substations to providing the accurate voltage and current measurement data for protection and power metering. However, their sensing units and digital processing units are susceptible to the operating environment, and their long-term stability need to be further improved. Yan Xu [1] fund out that the phase error of the electronic current transformer exceeds 20′ for load currents less than 0.2 In (where In represents the phase rated current), possibly leading to false conclusions. Influence of electric field may lead the electronic capacitive voltage transformers exceed the precision requirement of 0.2 class [2]. For the electronic current transformer based on Rogowski coil, Muhammad Shafiq [3] pointed out that the parameters such as core and coil diameter, diameter of the copper wire, significantly affect the measuring performance of the coil in terms of its sensitivity and bandwidth.

Due to technical limitations, the conventional method to evaluate the metering error of electronic transformers is to calibrate them with a standard voltage or current transformer off-line over a fixed period [4,5]. This method is disadvantageous as power cut is needed. For electronic transformers operating in high voltage environment, there are some difficulties in power cut. To solve this problem, Li [6] and Luo [7] et al. proposed a live calibration method to reduce the power cut time which is not caused by the fault. Live calibration is still in the process of development. And due to the impact of high voltage, it is not realistic to calibrate the electronic transformer with standard transformer in a long-term. That may cause the problems such as over inspection and under inspection. Therefore, it is need to study a new method to be studied to evaluate the metering error of electronic transformers on-line without the standard transformers.

There are two main trends about evaluating the electronic transformer without a standard transformer in current studies: signal processing and model analysis. Yang [8] proposed the sensor diagnosis based on morphology-wavelet, and Xiong [9] proposed the diagnosis of abrupt-changing of electronic transformer based on wavelet transform. Ting Lei [10] proposed an innovative condition monitoring technique of transformer based on a simplified Volterra model. These methods are realized based on the stability of the primary signal. However, the voltage and current signals of power system are dynamic and random variation in practice. Wang [11] proposed a method of gradual fault diagnosis for electronic current transformer based on current observer. Such method must rely on an accurate analytic model. As such model is not easily obtained for realistic components and operation environment, the accuracy of the model analysis cannot meet the metering error at 0.2 class [12,13]. Also due to limited validity of the model, it

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https://doi.org/10.1016/j.measurement.2018.07.083
Received 27 March 2018; Received in revised form 24 July 2018; Accepted 25 July 2018
Available online 31 July 2018
0263-2241/ © 2018 Published by Elsevier Ltd.

does not have universal applicability. In addition to the above methods, K. Lin [14] designed a hybrid fuzzy classifier system for power system sensor status evaluation. The sensor was rated according to four grades, the evaluation accuracy could not meet the metering error at 0.2 class too.

Electronic transformer is used to measure the voltage and current signals. And it means that the measurement data between the electronic transformers reflects the correlation between the primary physical signals of the transmission networks. For the above, a new method is proposed in this article to evaluate the metering error of electronic transformers on-line based on the moving window principal component analysis with variable N-Step-Ahead prediction. Firstly, the correlation between the primary transmission networks is analyzed to establish a new evaluation ‘standard’ in Section 2. And then the principal component analysis (PCA) is used to extract the characteristic statistic representing the evaluation ‘standard’ by the measured data in Section 3. The metering error of electronic transformers can be evaluated by analyzing the abnormal change of the statistics. According to the primary signals of transmission networks is time-varying, the moving window principal component analysis (MWPCA) is used to update the standard evaluation model. And then a variable N-Step-Ahead prediction evaluation method is proposed to evaluate the metering error of electronic transformers to adapt to gradual change of the metering error in Section 4. In Section 5, the field application analysis shows that the method accurately evaluates the metering deviation of the class 0.2 electronic transformers accurately without a standard transformer. Finally, the conclusion is drawn in Section 6.

2. Physical signals of transmission networks analysis

As shown in Fig. 1, the transmission and transformation systems run in three-phase structure. The voltage or current signal of the primary power system is as follows:

$$\dot{X}_A + \dot{X}_B + \dot{X}_C = V\dot{U}F \tag{1}$$

where $\dot{X}_A$, $\dot{X}_B$, $\dot{X}_C$ are the three-phase primary physical voltage or current signals. $V\dot{U}F$ represents the primary three-phase unbalance. The resistive component of $\dot{X}_A$, $\dot{X}_B$, $\dot{X}_C$ then should be as follows:

$$X_A cos\theta_A + X_B cos\theta_B + X_C cos\theta_C = Re(V\dot{U}F) \tag{2}$$

where X_A, X_B, X_C are the amplitude of the primary three-phase physical t signals, and $cos\theta_A$, $cos\theta_B$, $cos\theta_C$ are their initial phase. When three-phase electronic transformers run normally, the metering error can be negligible. (2) is available as follows:

$$X_a cos\theta_a + X_b cos\theta_b + X_c cos\theta_c = Re(VU\dot{F})/k \tag{3}$$

where X_a, X_b, X_c are the amplitude of the primary three-phase secondary signals, and $cos\theta_a$, $cos\theta_b$, $cos\theta_c$ are their initial phase, k is the sensing coefficient of the electronic transformer.Then (3) is written in matrix:

$$Xl = vuf \tag{4}$$

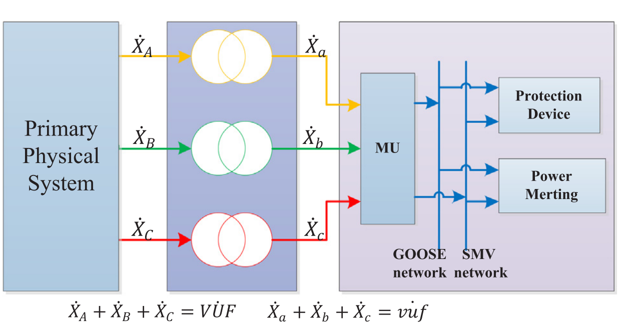

Fig. 1. The block diagram of electronic physical correlation.

where $X = (X_a, X_b, X_c)$, $l = (cos\theta_a, cos\theta_b, cos\theta_c)^T$, $vuf = Re(VU\dot{F})/k$. For arbitrary sampling times, vectors l and vuf are constants. That is, there is a linearly correlation between the sampled values of three-phase electronic transformers at any sampling time, which can be regarded as an evaluation standard. Through the correlation analysis of three-phase measurement data, the accurate evaluation of the metering error can be realized for electronic transformer.

3. Method

In order to separating association data from measured data, this article uses principal component analysis (PCA) [15–17] to analysis the data correlation. PCA is a ‘model-free’ method suitable for feature extraction and dimension reduction of mass data. It is used for converting several correlated variables into a few values of linearly uncorrelated variables. When something wrong occurs in the three-phase electronic transformers, there is a certain degree of metering error from the measured data of the linearly uncorrelated variables, and anomaly can be calculated by detecting the degree of error.

3.1. Principal component analysis

For the measured data of three-phase electronic transformers, the PCA is calculated as follows: assume that the sample data is $X^0 \in \Phi^{n\times m}$, where m is the number of variables (for three-phase electronic transformers, $m = 3$), n is the number of samples. Firstly, the data should be standardized, and the standardized data matrix is given as follows:

$$X = (X^0 - 1_n b^T)\Sigma^{-1} \tag{5}$$

where $1_n = [1, 1, ..., 1]^T \in \Phi^{n\times 1}$, $b = (X^0)^T 1_n/n$ is the mean vector of the data. $\Sigma = diag\ \sigma_1^2, ..., \sigma_m^2$ is the variance matrix of the data.

Mathematically, the standardized matrix data can decomposed as follows:

$$X = \hat{X} + E = TP^T + T_e P_e^T \tag{6}$$

where $\hat{X} = TP^T$ is the principal component space of data matrix X, $E = T_e P_e^T$ is the residual space of data matrix X. In normal operation, the principal component space is considered as the real value, and the residual space is the error noise. P is the principal component load matrix and the P_e is the residual load matrix.

The load matrix P and P_e can be calculated as follows:

$$R = X^T X/(n-1) = [P\ P_e]\Lambda[P\ P_e]^T \tag{7}$$

where matrix R is the covariance matrix of data matrix X. P and P_e are the eigenvectors of matrix R.

3.2. Metering error anomaly detection

When PCA is used to evaluate a statistical process, the squared prediction error SPE is usually used. The SPE statistic is given as follows:

$$SPE = (XP_eP_e^T)(XP_eP_e^T)^T = XP_eP_e^TX^T \leqslant SPE_\alpha^2 \tag{8}$$

where SPE_α^2 is the control limit of SPE statistic at significance level α, which can be calculated as follows:

$$SPE_\alpha^2 = \theta_1\left[\frac{C_\alpha\sqrt{2\theta_2 h_0^2}}{\theta_1} + 1 + \frac{\theta_2 h_0(h_0-1)}{\theta_1^2}\right]^{\frac{1}{h_0}} \tag{9}$$

where $\theta_i = \sum_{j=\alpha+1}^{3}\lambda_j^i (i = 1, 2, 3)$, $h_0 = 1 - 2\theta_1\theta_3/3\theta_2^2$, and C_α is the critical value of normal distribution at significance level α.

When the measured data of electronic transformer is free of faults, the measured data is as follows:

$$x(t) = I_i(kA_{ti} + s_{xi} + v_{ti}) \tag{10}$$

where I_i is the basis of a unit orthonormal vector I. According to the

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