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ON-SITE CALIBRATION OF CURRENT TRANSFORMERS

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Abstract: Periodic calibration of current and voltage transformers, used with electricity meters, is required by electrical regulation bodies. However, this task is difficult to do because of the large time-consuming. The high voltage network must be disconnected for many hours, which means high cost and service problems. This paper discusses an alternative calibration procedure for current transformers that uses a minimum intervention on the high voltage side.

Keywords: ratio error, compensation, high voltage, measuring transformer.

1. INTRODUCTION

Energy measurement is an important element because of the large amount of money related to it. A medium hydroelectric plant can deliver USD 100 million per year. A measuring error of 1% means USD 1 million each year. This high value justifies the effort that people related to this topic do, in order to reduce the measuring uncertainty. Modern electronic meters, used in the field, have increased their accuracy up to 0.2%, and some of them reach errors lower than 0.1%. But, measuring nodes have more components than energy meters. Current and voltage transformers are necessary for reducing high voltage variables to the lower levels needed by the meters (usually 100 V and 5 A). These components must also be periodically calibrated, and their uncertainties must be similar to the meters.

On-field calibration of energy meters is a relative easy task. There is no need to interrupt the electricity service, and portable equipment can be used. This is not the same case for measuring transformers. Conventional calibration requires using heavy and large calibration equipment, and it is necessary to disconnect the transformer under test from the high voltage network. This means that some parts of the high voltage system must be grounded for many hours. It represents high costs, and in some places it is not possible to disconnect the service for a long time.

Indirect methods for current transformer calibration have been proposed, but they require measuring the turn ratio, and this leads to complex and time-consuming operations [1], equivalent to direct measurements. As an alternative, a different calibration method, for current transformers, is described. It uses only information from the low voltage side (output winding) and it does not require disconnecting the high voltage winding. Although the current through the primary circuit must be null, the total time required for the calibration is very short. This proposal is also useful for transformers used in power generators, where it is very difficult to access to the primary circuit.

2. TRANSFORMER MODEL

In current transformers, the main error source at power frequencies is the influence of the magnetizing current. Fig. 1 shows a schematic transformer circuit, being R_m and L_m non-linear components (magnetizing branch). The errors (difference between output and input currents) are due to the magnetizing current I_m. This current depends on the magnetizing voltage V_m, which depends on the output voltage V_L. In this way, the actual load Z_L (modulus and phase) has a large influence on the transformer error. From a theoretical point of view, low values of the load intrinsically reduce the errors. However, manufacturers use some compensating methods that increase errors at low loads. Generally, the magnetizing current reduces the output current and leads to negative ratio errors. To compensate that, manufacturers reduce the secondary turn number, from its nominal value. In this way, the ratio errors are centered, being positive at low loads. This modification of the turn number must be taken into account in the proposed method, and an estimation of the actual turn number is necessary.

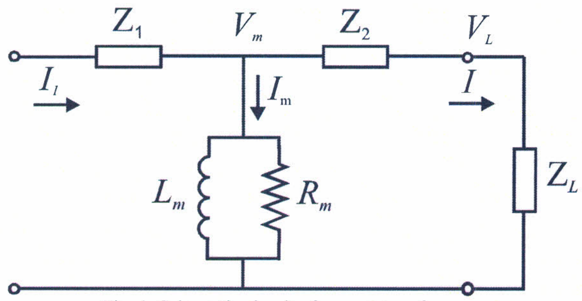
Fig. 1. Schematic circuit of current transformers.

To fulfill the standards [2], the transformer errors must be into the accuracy class for currents between 1% and 120% of the nominal one, and burdens between 25% and 100% of its nominal value. Many points must be tested to corroborate that the transformer maintain its accuracy class.

3. ON-FIELD MEASUREMENTS

As was previously discussed, conventional tests for error measurements require to interrupt the electricity service for many hour. As an alternative, errors can be estimated from special tests performed from the secondary. This method [3] requires knowing the values of the series impedances Z_1, Z_2, as well as magnetizing impedances, as a function of the magnetizing voltage. To get these values, the primary current is opened and a low voltage, low power source is applied directly to the secondary. The curve $V_L(I)$ is measured (amplitude and phase), and from it, the magnetizing impedances are calculated. The series impedance Z_2 can be estimated from the secondary resistance (information of the transformer manufacturer or direct measurement), because generally the secondary series inductance can be neglected. Then, the voltage V_m can be computed, adding the voltage drop on Z_2 to V_L.

$$\boldsymbol{Z}_1 = R_1 + jX_1, \quad Z_2 = R_2 \tag{1}$$

$$\frac{1}{\boldsymbol{Z}_m} = \frac{1}{R_m} - \boldsymbol{j}\frac{1}{X_m} \tag{2}$$

R_i are the resistances, X_i the inductive reactances, and $\boldsymbol{Z}_m$ is the magnetizing impedance. Their non-linear behaviors are taken into account varying their values according to the voltage. Although non-linear behavior is considered, sinusoidal analysis can be used because current transformers are designed far from saturation, so that the waveform distortions are low. Additionally, the standards require to measure ratio errors only at the fundamental frequency. Complex variables (phasors) are represented by bold symbols, otherwise they represent rms values.

In this way, the magnetizing current $\boldsymbol{I}_m$ (real and quadrature components, I_R and I_{XL}) is measured versus the applied voltage; and conductance $1/R_m$ and susceptance $1/X_m$ of the magnetizing branch are calculated. As an example, Fig. 2 and 3 show the behavior of both parameters in a real transformer.

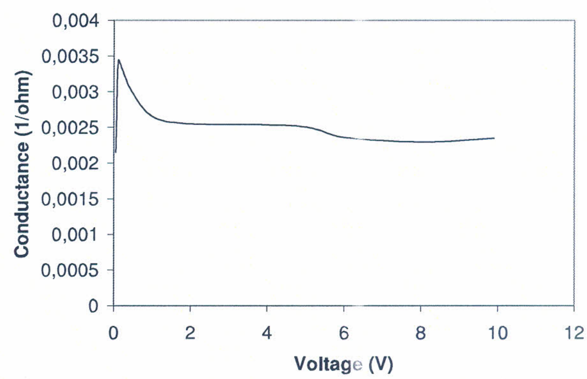

Fig.2. Variation of the conductance $1/R_m$ versus the magnetizing voltage.

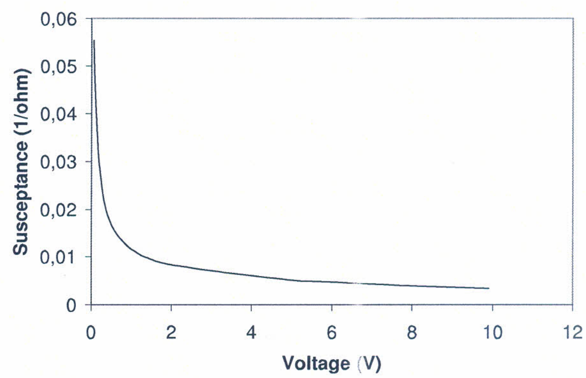

Fig.3. Variation of the susceptance $1/X_m$ versus the magnetizing voltage.

In this case, while the real part remains practically constant over the full voltage range, the inductive component varies between 0.005 Ω^{-1} and 0.06 Ω^{-1}, depending on the voltage.

In addition to these parameters, the actual turn ratio must be also known. If a conventional bridge were used for this measurement, it would be necessary to disconnect the primary winding from other parts of the high-voltage network. This work will take excessive time and the usefulness of this alternative calibration method would be doubtful. A new method for estimating the actual turn ratio of the transformer is proposed, using only manufacturer information (manufacturer test certificate). From errors declared in that certificate, the turn ratio can be computed, as follows.

The actual ratio error of the transformer, defined from the secondary, is

$$\boldsymbol{e} = \frac{\boldsymbol{I}}{\boldsymbol{I}_1} - 1 + \eta \qquad (3)$$

where $\boldsymbol{I}_1$ is the input current, $\boldsymbol{I}$ is the output current and η is the relative difference between the actual turn ratio and the nominal one. Using the proposed model, this leads to

$$\eta = \boldsymbol{e} + \frac{I_m}{I_1} \qquad (4)$$

As $\boldsymbol{e}$ is a complex variable ($e=\varepsilon+j\delta$), and η is real, it follows that

$$\eta = \varepsilon + \mathrm{Re}\left(\frac{I_m}{I_1}\right) \approx \varepsilon + \mathrm{Re}\left(\frac{I_m}{I}\right) \qquad (5)$$

$$0 = \delta + \mathrm{Im}\left(\frac{I_m}{I_1}\right) \approx \delta + \mathrm{Im}\left(\frac{I_m}{I}\right) \qquad (6)$$

From these equations, it is easy to see that

$$(\eta - \varepsilon_k)^2 + \delta_k^{\ 2} = \left(\frac{Z_{Lk}}{Z_m}\right)^2 \qquad (7)$$

where the sub-index k indicates different conditions of load and current of the transformer under tests (i.e. k=1: around 25% of load and 100% of In, k=2: around 100% of load and 20% of In). Z_{Lk} includes R_2. These conditions are selected in such a way that the voltage V_m were the same for both. Then, Z_m has the same value in both cases, so that it does not depend on k. Resolving (7) we obtain

$$\eta = \frac{\varepsilon_2 Z_{L1}^{\ 2} - \varepsilon_1 Z_{L2}^{\ 2} \pm \sqrt{\Delta}}{Z_{L1}^{\ 2} - Z_{L2}^{\ 2}} \qquad (8)$$

being

$$\Delta = \left(\varepsilon_1 Z_{L2}^{\ 2} - \varepsilon_2 Z_{L1}^{\ 2}\right)^2 - \left(Z_{L1}^{\ 2} - Z_{L2}^{\ 2}\right)\times \left(Z_{L1}^{\ 2}\left(\varepsilon_2^{\ 2} + \delta_2^{\ 2}\right) - Z_{L2}^{\ 2}\left(\varepsilon_1^{\ 2} + \delta_1^{\ 2}\right)\right) \qquad (9)$$

The values of all variables included in (8) and (9) can be got from the manufacturer calibration certificate. Note that this certificate is used only to calculate the actual turn number ratio. Other model parameters are estimated from tests.

With the values of all parameters, it is possible to compute the errors of the transformer under different loads and output currents, as many authors have proposed [3]. It is possible to show that the estimated errors (real and imaginary parts) are

$$\varepsilon_e = \frac{V_m}{\sqrt{(V_m + AI_R + BI_{XL})^2 + (BI_R - AI_{XL})^2}} - 1 \qquad (10)$$

$$\delta_e = -Artg \frac{BI_R - AI_{XL}}{V_m + AI_R + BI_{XL}} \qquad (11)$$

where

$$A = \mathrm{Re}(\boldsymbol{Z}_2 + \boldsymbol{Z}_L), \ B = \mathrm{Im}(\boldsymbol{Z}_2 + \boldsymbol{Z}_L) \qquad (12)$$

The magnetizing voltage can be calculated as

$$V_m = I\sqrt{A^2 + B^2}\ , \qquad (13)$$

and from it, the currents through the resistive and inductive branches of the magnetizing impedance, I_R and I_{XL}. For this last estimation, curves like shown in Fig. 2 and 3 are used.

4. EXAMPLES

Many transformers were tested using this method. As an example, results of a 1500 A/5 A, 30 VA, class 0.5 are shown in Table 1.

Table 1. Calculated and measured errors of a 1500 A/5 A current transformer.

TESTED POINT		CALCULATED ERROR		MEASURED ERROR	
Current (% of In)	Load (% of ZLn)	Ratio (%)	Phase (min)	Ratio (%)	Phase (min)
5	25	-0,20	6	-0,17	6
20	25	-0,16	4	-0,14	4
100	25	-0,13	2	-0,14	3
120	25	-0,13	2	-0,16	3
5	100	-0,50	9	-0,46	9
20	100	-0,40	5	-0,38	6
100	100	-0,28	0	-0,34	3
120	100	-0,27	0	-0,35	4

The differences between calculated and measured errors are lower than 0.08% for ratio, and lower than 4 minutes for phase displacement. These differences are around 10 times lower than the limits stated by the standard (between 0.5% and 1.5% for ratio errors, and 30 min to 90 min for phase displacement), which are covered by the uncertainty of the measurements. The proposed calibration method gets equivalent results than conventional methods, without the need of disconnecting the primary winding from the high voltage network.

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