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ACCURATE MEASUREMENT OF RESISTANCE AND INDUCTANCE OF TRANSFORMER WINDINGS

V. Didenko, D. Sirotin

Department of Information-Measurement Technologies – Institute of Automatics and Computer Engineering (IACE) – National Research University "Moscow Power Engineering Institute"

Phone: +7 495 3627368 Fax: +7 495 3627468 E-mail: didenkovi@mail.ru

Abstract: The leakage inductance and direct current (DC) resistance of windings are the most information-bearing parameters for diagnosis of voltage transformers. Measurement of these parameters with improved speed and accuracy by step function is suggested.

Keywords: Transformer, Inductance and Resistance of Transformer Windings, Step Response, Measurement error.

1. INTRODUCTION

Equivalent circuit of a voltage transformer (VT) is well known (Fig. 1) [1].

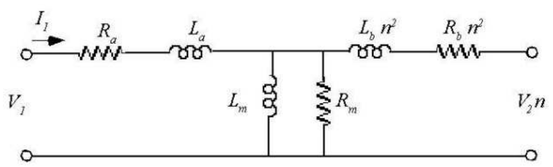

Fig.1. Equivalent circuit of the VT

Here: R_a – primary resistance, L_a – primary leakage inductance, R_m – excitation impedance, L_m – magnetizing inductance, R_b – secondary resistance, L_b – secondary leakage inductance, $N1$ – number of primary turns, $N2$ – number of secondary turns, $n = N1/_{N2}$ – turns ratio, $R_b n^2$ - secondary resistance referred to primary winding, $L_b n^2$ – secondary inductance referred to primary winding, $R_W = R_a + R_b n^2$ - resistance of windings, $L_W = L_a + R_b n^2$ - leakage inductance of windings. At the first approximation, used typically in literature as well as in this paper, $R_a = R_b n^2$ and $L_a = L_b n^2$. Therefore $R_W = 2 R_a$ and $L_W = 2L_a$. The number of serial RL-chains for three-phase transformer is in-and-out tripling. Resistance R_W and inductance L_W theoretically don't depend on magnetic features of a transformer and the value of input current. Inductance L_m and resistance R_m depend on magnetic features of the transformer. They can change their value as much as 2-3 times with change of input current from zero to the nominal value. The changes of resistance and leakage inductance of windings (R_W and L_W) vs. time are used for diagnosis of power transformers in the first turn and sometimes for low power transformers (in the transport, for example). The term "voltage transformer" is used in this paper both for power transformers and low power transformers which must be checked for the change of parameter values.

Measurement of all parameters on alternating current (AC) is analyzed deeply [1]. Measurement of short circuit resistance $R_{SC} \approx R_W = R_a + R_b n^2$ and inductance $L_{SC} \approx L_W = L_a + L_b n^2$ are used for diagnosis in practice [2]. It is difficult to find accurate values of R_a and R_b using AC. Therefore these resistances are practically measured using DC method with open circuit at secondary winding. Measurement time for this method equals to 7 time constants if settling error of 0.1 % is chosen. It is often more than 30 sec but such measuring time is not available for industry [3]. Therefore the quick measuring method of DC resistance of transformer's windings was developed [4]. Input current vs. time is measured after input voltage step with open secondary windings. DC resistance is found by extrapolation. The method is correct if L_m does not depend on current. In practice it can change by 2-3 times depending on current value. To decrease influence of this factor as well as influence of instrument error, measurement time must be chosen not less than about two constants of time. Then decrease of measurement time will be only about 3.5 times in comparison with the ordinary method and "30 sec" requirement can't be satisfied. Input voltage step for one phase was also proposed for inductance L_a measurement with open secondary windings and two short circuit primary windings [5]. This method is available only for three-phase transformers and is not accurate enough. The pulse input method is used and standardized for the purpose of diagnosis [6]. It is difficult to get high accuracy in pulse regime. In this paper the new method of resistance and inductance measurement is suggested. The method allows finding both short circuit resistance and inductance from one test with improved accuracy and speed. It can be used both for single- and three-phase transformers.

2. REQUIREMENTS TO ACCURACY OF MEASUREMENT FOR DIAGNOSIS OF VOLTAGE TRANSFORMERS

According to the Standards of Russia, permissible changes of short circuit resistance and inductance are specified at the levels of 2 % and 3 % correspondingly. Investigations of Russian scientist A. Lurye showed that serious degradation of power transformers took place even at the change of L_{sc} about 0.1 %. Let us use metrology approach to find necessary level for accuracy of measurement. Here: δ_{Tr} -the relative permissible change of a transformer parameter (leakage inductance and resistance of windings), δ_{MAX} - the maximum relative error of measurement for the change of the corresponding transformer parameter, δ_C -the relative permissible change of the transformer parameter at control with given maximum error of measurement, *P* - probability to permit of application the transformer after control even for the relative permissible change of a transformer more than δ_{Tr}. Using analysis for certification of analog-to digital converters given in Russian standard MI 118-77, one can find relations between all parameters according to Table 1.

Table 1. Maximum error of measurement at control

$\delta_{MAX} / \delta_{Tr}$	*P*					
	0	0.1	0.15	0.2	0.25	0.3
	δ_C / δ_{Tr}					
1/10	0.90	0.94	0.95	0.95	0.96	0.97
1/5	0.80	0.88	0.89	0.91	0.93	0.94
¼	0.75	0.85	0.87	0,89	0.91	0.92
1/3	0.67	0.80	0.82	0.85	0.88	0.92
1/2,5	0.60	0.75	0.79	0.82	0.85	0.88
½	0.50	0.69	0.74	0.78	0.81	0.85

If, for example, one uses the worst case method (*P*=0), the level of control is equal to 0.90 of permissible change of a transformer parameter, then maximum error of measurement of the change for the corresponding parameter must be not more than 0.1 of permissible change of a transformer parameter. There are two measurements to find change of a parameter. Requirement to maximum error of each measurement depends on correlation between these measurements. If correlation is absent, then maximum error of each measurement must be $\sqrt{2}$ times less than maximum measurement error of the change for the corresponding parameter found from Table 1. Using this statement, relations from Table 1 and permissible change of leakage inductance in the range from 0.1 % to 3 %, one can find that maximum error of measurement must be chosen approximately in the range from 0.01% to 1 %. Maximum error of measurement for short circuit resistance (the same for resistance of windings) must be chosen approximately in the range from 0.14 % to 0.7 %. It is necessary to say that temperature coefficient of winding is usually about 0.4 %/°C. This error can be removed if temperature is defined. Measurement uncertainty of temperature must be in the range from 0.1°C to 0.6 °C in order to consider temperature effect as negligible one.

3. TRANSFORMER DATA SHEET RESEARCHES

To confirm importance of advanced method, investigation of Data Sheets for 20 Russian power transformers was carried out. Following parameters were reflected in the specifications: V_{OS} - open circuit primary voltage, P_{OS} - open circuit primary power, I_{OS} - open circuit current, V_{CS} -short circuit primary voltage, P_{CS} - short circuit primary power. One important parameter can be measured but was absent in investigated Data Sheet: φ_{SC} - phase angle for short circuit. If we suppose that $R_a \ll R_m$, $L_a \ll L_m$, then it is possible to find:

$$R_m = V_{OS}^2 / P_{OS} ,$$

$$L_m = 1/2\pi f \sqrt{(I_{OS}/V_{OS})^2 - (1/R_m)^2} .$$

Phase angle for open circuit can be found: $\varphi_{OS} = arctg R_m / 2\pi f L_m$. The parameters of the scheme shown in Fig. 1 were approximately found for the transformers under typical conditions: $R_a = R_b n^2$, $L_a = L_b n^2$, $\varphi_{OS} = \varphi_{SC}$. The results are shown in Table 2. Study of data given in Table 2 confirms conditions: $R_a \ll R_m$, $L_a \ll L_m$. Three time constants are shown in Table 1: τ_1, τ_2, and τ_3 in three last lines. Step response for open secondary winding is mainly defined by the value of τ_3 and forces to choose time measurement (see Introduction) up to $7L_m/R_a$=941 sec in ordinary regime and about 269 sec for measuring method [4]. Both results are not satisfactory from 30 sec requirement [3]. Accurate measurement at this interval is difficult due to influence of L_m stability (it depends on steel properties). Measurement during time interval, when τ_1 dominates, is not a good choice because high accuracy is not possible at high frequency [3]. Accurate measurement at this interval is also difficult due to influence of R_m stability (it depends on steel properties). Measurement during time interval, when τ_2 dominates, is an optimum choice. Especially important, that this time constant contains two of the most important parameters of transformers (L_{SC} and R_{SC}) used usually for diagnosis aims. Both L_{SC} and R_{SC} don't theoretically depend on steel properties. The method advanced in the paper is based on measurement in the time range where τ_2 time constant dominates.

4. STEP RESPONSE OF VOLTAGE TRANSFORMER FOR SHORT CIRCUIT OF SECONDARY WINDING

Step response of the circuit shown in fig.1 is

Table 2. Results of the Data Sheet research

Parameter	Max	Min
L_m, H	$1.52 \cdot 10^3$	6.42
R_m, Ω	$266 \cdot 10^4$	$111 \cdot 10^2$
L_a, H	0.728	0.00254
R_a, Ω	41.1	0.145
L_a / L_m	$0.697 \cdot 10^{-3}$	$0.181 \cdot 10^{-3}$
R_a / R_m	$0.242 \cdot 10^{-4}$	$0.355 \cdot 10^{-5}$
$\tau_1 = L_a / 2R_m$, sec	$2.07 \cdot 10^{-7}$	$0.404 \cdot 10^{-7}$
$\tau_2 = L_a / R_a$, sec	0.0329	0.0151
$\tau_3 = 2L_m / R_a$, sec	251	49.0

approximately

$$I_1(t) = V_1\left[\frac{1}{2R_m}\left(1 - e^{\frac{-t}{\tau_2}}\right) + \left(\frac{1}{2R_a} - \frac{1}{R_m}\right)\left(1 - e^{\frac{-t}{\tau_2}}\right) + \left(\frac{1}{2R_a} + \frac{1}{2R_m}\right)\left(1 - e^{\frac{-t}{\tau_3}}\right)\right] . \quad (1)$$

Current I_1 vs. time using (1) is shown in fig. 2 by MATHCAD 14 for the following parameters: $L_a = 0.47$ H, $R_a = 0.12$ kΩ, $R_m = 72$ kΩ, $L_m = 1.1$ kH, $V_1 = 10$ V. The result of step function for fig.1, found by Microcap, showed difference from fig. 2 not more than 0.2% for time interval from 10^{-5} to 10 seconds.

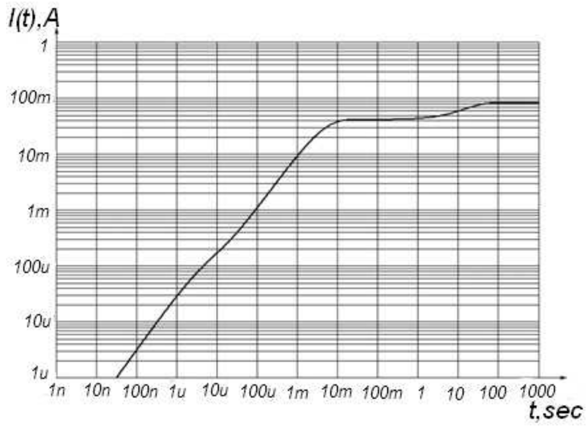

Fig. 2. Step response with input voltage step 10 V.

One can see three exponents in fig. 2 in accordance with (1) and equations from table 1: $\tau_1 = 3.26 \times 10^{-6}$ sec, $\tau_2 = 3.92 \times 10^{-3}$ sec, $\tau_3 = 18.3$ sec. The second exponent is principally interested for us, time constant of which is defined by required parameters. At the first approximation, the influence of the first and the third exponents can be neglected if we take into account the relevant time period. It is possible to find parameters L_{sc} and R_{sc} at the interval from $10\tau_1$ to $10\tau_2$ approximately ignoring the first and the third exponents. However measurement error in this case is not less than 1%. Authors offered improved method taking into account the first exponent (as a constant in time interval from $10\tau_1$) and the third exponent (as a linear function for time interval less than $0.1\tau_3$). Then measurement error about 0.2% is available. The measurement time is less than 330 ms for the simplified method and is less than 25 s for the improved method. The fact that we can get full windings resistance instead of each winding resistance separately is mostly the advantage of this method. This result is better meets the test's procedure at AC for short circuit secondary winding. The suggested method can be used for three-phase transformers if step response is found for each phase separately.

5. EXPERIMENTAL INVESTIGATION OF A TRANSFORMER AND IMPROVEMENT OF THE EQUIVALENT CIRCUIT

Resistance and leakage inductance of windings for a low power transformer were measured by digital RLC-meter E7-22 at two frequencies: 120 Hz and 1000 Hz. Resistance of windings was measured also at DC. The results are shown in Table 3.

Table 3. Experimental tests of a transformer

Frequency, Hz	0	120	1200
Short circuit resistance, R_{SC}, Ω	7.10	9.25	41.53
Short circuit inductance, L_{SC}, H	-	48.18	40.55

The data from Table 3 show that the model of a transformer given in Fig. 1 is available only for narrow frequency range. It is not very important if modeling takes place for 50 Hz only. When voltage step is used then response can be change in comparison with picture given in fig 2, for example. To model the increase of equivalent resistance and the decrease of equivalent inductance vs. frequency (these changes are clear from Table 3) a new model of a voltage transformer was proposed (Fig. 3). Typical values of parameters found for the low power transformer are shown in fig. 3.

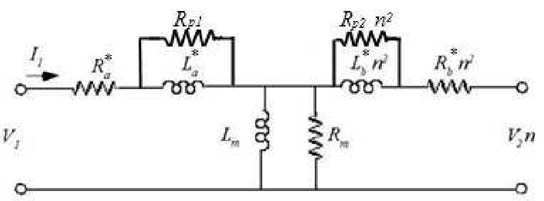

Fig. 3. A new equivalent circuit of the VT.

Application of two additional resistors in parallel with leakage inductances allows us to model the increase of equivalent resistance and the decrease of equivalent inductance vs. frequency. The result of step function for fig.3, found by Microcap, is shown in fig. 4. Very close result was found by physical test. The main difference between figures shown in fig. 2 and fig. 4 is a current step in the beginning. This step must be considered for accurate measurement of transformer parameters.

6. ELECTRONIC CIRCUIT FOR TESTING

To form a step function of input voltage with very low output resistor, a special electronic circuit was designed (see fig. 5).

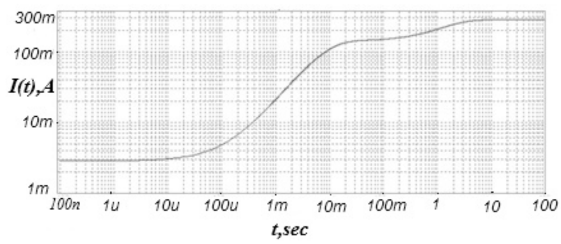

Fig. 4 Step response with input voltage step 1 V.

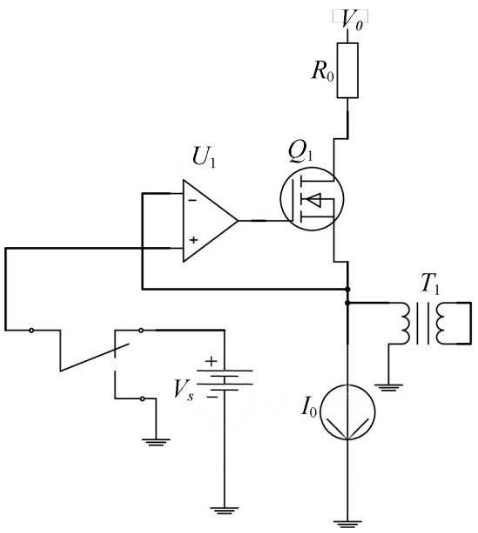

Fig. 5 Simplified circuit for voltage transformer investigation.

Step function is organized by switch of DC voltage source V_S. Due to negative feedback, practically the same voltage feeds the primary winding of the investigated voltage transformer. The slew rate of operational amplifier is not less than 10 V/μs and does not practically influence on measurement accuracy of resistance and inductance.

Input current of the transformer is practically the same as drain current of MOSFET. This current is measured by analog-to-digital converter (ADC) connected to accurate resistor R_0. Standard voltage generator and ADC were used from PXI-6259 module by National Instruments Company. The nominal range of PXI-6259 for this study is 1 V. Absolute error is less than 220 μV at this range and is practically negligible. The initial current I_0 is connected to the source of transistor Q_1. Current level I_0 is sufficient to maintain the transistor Q_1 in the open state at the initial time. Initial current is simply substituted from ADC result.

7. CONCLUSIONS

Step response of voltage transformer gives better results at short circuit of the secondary windings in comparison with open circuit of the secondary windings. Three exponents take place at this case. The most important exponent is the second one (τ_2). The parameters of this exponent are the most important transformer parameters (L_{sc} and R_{sc}). The simple method of their measurement gives accuracy about 1% with time measurement less than 330 ms while the improved method gives accuracy about 0.2% with time measurement about 25 s. The previous method required about 300 s for measurement of winding resistance only with less accuracy.

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