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The determination of measuring transformer windings impedance by using an three stage measuring method

Abstract

A developed three stage method for determination the windings impedance of measuring transformer are shown in this paper. During the measurement process, there is no need to use the standard voltage divider instead, a voltage divider having the constant, unknown error is used. This ratio error is eliminated during measuring procedure. In this paper, the obtained measurement results of the winding impedance and uncertainty budged are presented..

Keywords: windings impedance, measuring transformer, transformer ratio error.

1. Introduction

Transformers are generally represented by their equivalent circuits for the purpose of analysis. The equivalent circuit configuration depends on desired accuracy of calculations and is changed from a very accurate representation to a simplified approximation. Determining of the transformer equivalent circuit parameters is a difficult task because these parameters are associated with many factors, among others, such as electromagnetic induction, the effect of frequency, hysteresis losses whether the magnetic flux leakage. Transverse equivalent circuit parameters have relatively large values of impedance, therefore they can be accurately determined, even for low-power transformers. Unfortunately, longitudinal parameters associated with low-power transformer windings have small quantities of impedance values and, therefore, their reliable measurement isn't a simple issue. Especially difficult is determination of the leakage reactance of windings, which are wound on the core and form a closed magnetic circuit. The leakage flux in the transformer has been studied and it is constant and linear over the normal operating range. The components of leakage flux are nearly directly proportional to the currents producing them, because the paths of leakage flux are in the air for a considerable portion of their lengths. To create the transformer equivalent circuit, it is necessary to separate the reactance of the magnetic core and the small leakage reactance.

In the measurements of small impedances, the differential methods are often used because of a high degree of accuracy. Such methods may include the procedure described in [1]. This method is based on an accurate measurement of the two orthogonal components of differential voltage appearing on the measuring diagonal of transformer bridge.

2. Measurement of windings impedance

The impedance measurement procedure is based on simultaneous comparison of the ratio voltage of the reference divider A_s and the tested divider A_x with the same nominal ratio, in three stages. Both dividers are parallel supplied from a common source of sinusoidal AC voltage of stable amplitude, frequency and low coefficient of THD. In the first measurement procedure stage the differential voltage $\Delta\underline{U}$ occurring between the taps of both dividers is measured by a lock-in amplifier (Fig. 1).

The difference voltage is determined by the formula

$$\Delta\underline{U}_1 = \underline{I}_{\mathrm{lo}} \frac{\underline{Z}_{x1}\underline{Z}_{x2}}{\underline{Z}_{x1}+\underline{Z}_{x2}}. \tag{1}$$

In the second stage a low value impedance, e.g. a resistor of low resistance R, is connected in series to the one of winding of tested transformer. Then again both components of the differential voltage denoted by $\Delta\underline{U}_2$ are measured. The differential voltage of this circuit can be expressed by the equation

$$\Delta\underline{U}_2 = \underline{I}_{\mathrm{lo}} \frac{(\underline{Z}_{x1}+R)\underline{Z}_{x2}}{\underline{Z}_{x1}+R+\underline{Z}_{x2}}. \tag{2}$$

In the third stage the resistor R is transferred to the second winding and the differential voltage is measured again. This voltage is denoted by $\Delta\underline{U}_3$

$$\Delta\underline{U}_3 = \underline{I}_{\mathrm{lo}} \frac{\underline{Z}_{x1}(\underline{Z}_{x2}+R)}{\underline{Z}_{x1}+\underline{Z}_{x2}+R}. \tag{3}$$

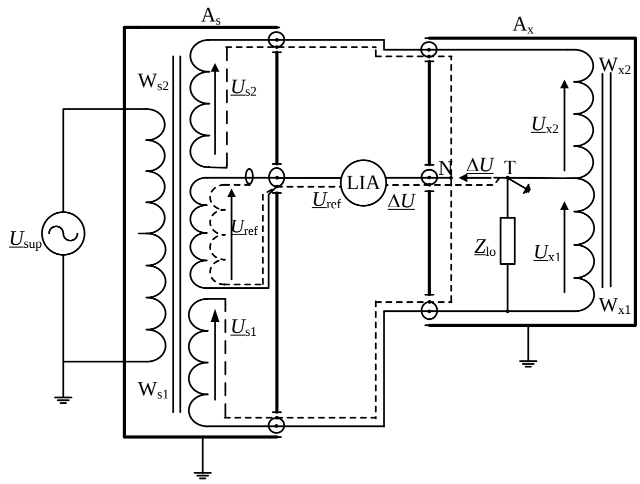


Fig. 1. Constructional diagram of the measuring circuit

Subtracting Eq. (1) from Eqs. (2) and (3) and dividing the resulting equations by one another, it is obtained

$$\underline{Z}_{x1} = \underline{Z}_{x1}\sqrt{\frac{\Delta\underline{U}_3-\Delta\underline{U}_1}{\Delta\underline{U}_2-\Delta\underline{U}_1}}. \tag{4}$$

Solving the system of equations (1) and (4) one obtains

$$\underline{Z}_{x1} = \frac{\Delta\underline{U}_1}{\underline{I}_{\mathrm{lo}}}\left(1+\sqrt{\frac{\Delta\underline{U}_3-\Delta\underline{U}_1}{\Delta\underline{U}_2-\Delta\underline{U}_1}}\right), \tag{5}$$

$$\underline{Z}_{x2} = \frac{\Delta\underline{U}_1}{\underline{I}_{\mathrm{lo}}}\left(1+\sqrt{\frac{\Delta\underline{U}_2-\Delta\underline{U}_1}{\Delta\underline{U}_3-\Delta\underline{U}_1}}\right). \tag{6}$$

The all parameters of Eqs. (5) and (6) can be measured in the circuit, so it is possible to calculate the leakage impedance of the windings of transformer divider.

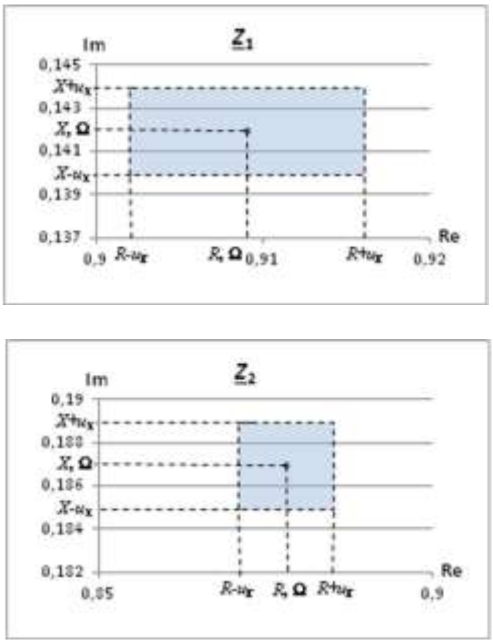
3. Research results

There are presented exemplary measurement results of components of the windings impedance. The measurements were made for the measuring transformer made on a toroidal core of Finemet tape, with dimensions 10/60/40 mm, placed in the case made of teflon. The measuring transformer consisted of two 192-turn windings of 0.5 mm diameter copper wire, wound evenly in two layers. The winding layers were isolated one of the other with a layer of insulation of thickness equal to about 0.3 mm. The supply voltage of both transformer dividers was U_{sup} = 20 V, f = 1 kHz. Tested divider was loaded by the impedance of the value R_{lo} = (500±0,02) Ω.

Measured values of windings impedance:

- primary winding resistance: R_1=(0.909±0.007) Ω
- primary winding reactance X_1=(0.142±0.002) Ω
- secondary winding resistance R_2=(0.878±0.007) Ω
- secondary winding reactance X_2=(0.187±0.002) Ω

a)



b)

Fig. 2. Graphical representation of the uncertainty interval on complex plane a) for the primary winding impedance, b) for the secondary winding impedance

Tab. 1. Measurement result uncertainty assessment for the primary winding resistance of the measuring transformer under test

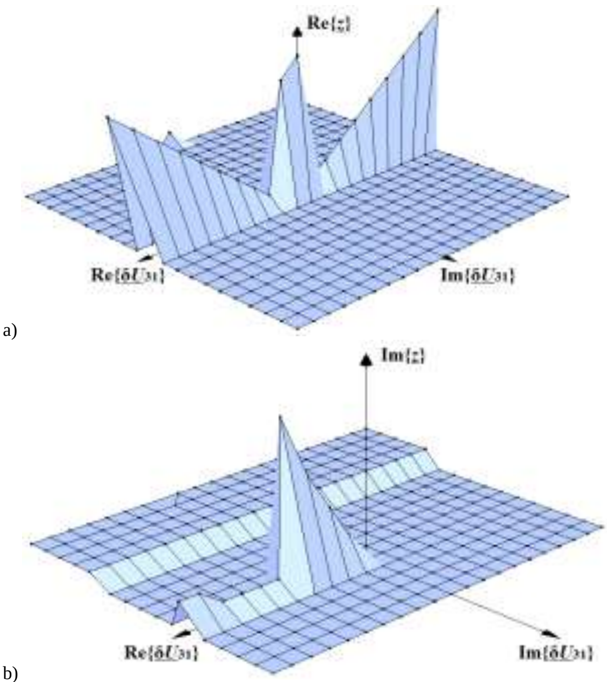
Symbol	Est. value	Uncertainty values		Sensitiv. coeff.	Part in the standard uncertainty	Covariance
X_i	x_i, mV	$u_A(x_i)$, mV	$u_B(x_i)$, mV	c_i (mA)$^{-1}$	$u_i(y)$ mV	cov (Re{$\underline{\Delta U}_x$}, Im{$\underline{\Delta U}_x$}), mV
Re{$\underline{\Delta U}_1$}	4.4654	0.0033	0.0258	–0.0110	–0.0003	0.00004
Im{$\underline{\Delta U}_1$}	0.8257	0.0007	0.0048	0.2060	0.0010	
Re{$\underline{\Delta U}_2$}	8.9931	0.0104	0.0520	–0.0040	–0.0002	0.00020
Im{$\underline{\Delta U}_2$}	1.0199	0.0008	0.0059	–0.0510	–0.0003	
Re{$\underline{\Delta U}_3$}	9.2095	0.0126	0.0532	0.0095	0.0005	0.00003
Im{$\underline{\Delta U}_3$}	0.5064	0.0006	0.0030	0.0480	0.0001	

Type A uncertainty takes into account a series of 38 measurements of the two orthogonal components of differential voltage vectors $\underline{\Delta U}_3$ – $\underline{\Delta U}_1$, $\underline{\Delta U}_2$ – $\underline{\Delta U}_1$. Standard uncertainty is obtained by assuming a uniform distribution. The uncertainty assessment does not take into account the uncertainty of load current, because it was treated as a constant, which was determined as a ratio of supply voltage of very high stability to the transformer output load. The part of the uncertainty of load current in the standard uncertainty is negligibly small.

Tab. 2. Measurement result uncertainty assessment for the primary winding reactance of the measuring transformer under test

Symbol	Est. value	Uncertainty values		Sensitiv. coeff.	Part in the standard uncertainty	Covariance
X_i	x_i, mV	$u_A(x_i)$, mV	$u_B(x_i)$, mV	c_i (mA)$^{-1}$	$u_i(y)$ mV	cov (Re{$\underline{\Delta U}_x$}, Im{$\underline{\Delta U}_x$}), mV
Re{$\underline{\Delta U}_1$}	4.4654	0.0033	0.0258	0.1940	0.0050	0.00004
Im{$\underline{\Delta U}_1$}	0.8257	0.0007	0.0048	–0.0100	0.0000	
Re{$\underline{\Delta U}_2$}	8.9931	0.0104	0.0520	0.0480	0.0025	0.00020
Im{$\underline{\Delta U}_2$}	1.0199	0.0008	0.0059	–0.0095	–0.0001	
Re{$\underline{\Delta U}_3$}	9.2095	0.0126	0.0532	–0.0440	–0.0024	0.00003
Im{$\underline{\Delta U}_3$}	0.5064	0.0006	0.0030	0.0140	0.0000	

The charts calculated for complex root appearing in equations 5 and 6 are shown in Fig.3.



a)

b)

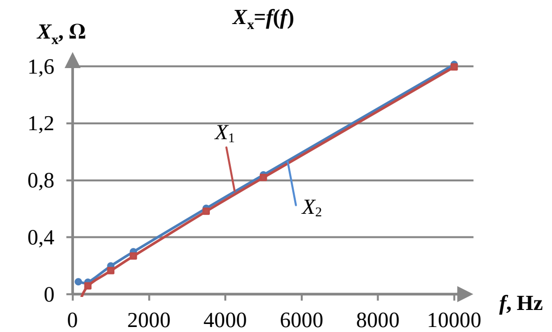
Fig. 3. The exemplary z-plane of complex root occurring in primary winding impedance (1) as function of differential voltages a) Re{z} = f (Re{$\underline{\delta U}_{31}$}, Im{$\underline{\delta U}_{31}$}) for Re{$\underline{\delta U}_{21}$}=0 and Im{$\underline{\delta U}_{21}$}=−100, b) Im{$z$} = f (Re{$\underline{\delta U}_{31}$}, Im{$\underline{\delta U}_{31}$}) for Re{$\underline{\delta U}_{21}$}=−50 and Im{$\underline{\delta U}_{21}$}=0

The charts illustrate any exemplary dependencies of particular winding impedance components on the values of difference voltages. Such graphical representation (5-dimensional) both of the components (Re{z} and Im{z} = f(Re{$\underline{\delta U}_{31}$}, Im{$\underline{\delta U}_{31}$}, Re{$\underline{\delta U}_{21}$}, Im{$\underline{\delta U}_{21}$}), will let us to draw conclusions concerning the developed method of measurement.

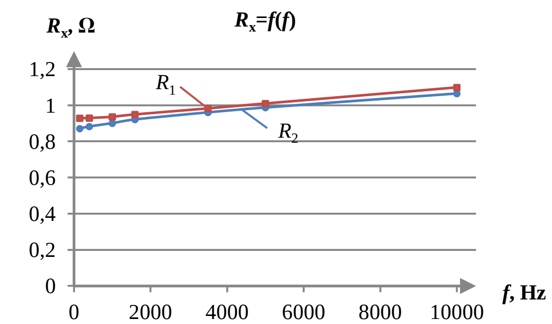
4. Impedance components

Each of transformer winding impedance has two components, resistance and reactance. The resistive component is associated with the active power losses in the windings conducting current. While the reactive component is associated with the reactive power losses, because not all primary flux is intercepted by the secondary coil. Some flux part leaks into the surroundings, some is consumed by core losses caused by eddy currents or hysteresis. These two causes can be summed and represented by the series inductance of the primary and secondary transformer winding. Such a winding impedance model applied for transformers working at low and medium frequencies.

Using the described method there also were measured the components of the winding impedance as a function of the frequency of the transformer loaded by resistance R_{lo}. Obtained values of impedance components are differ by different frequencies of the supply voltage. As can be seen in the charts (Fig. 4), the measured parameters monotonically increase with increase in the frequency.



a)



b)

Fig. 4. The winding impedance of the divider loaded by resistance R_{lo} = 500 Ω vs. the frequency, a) leakage reactance, b) windings resistance

In order to minimize power losses related to the leakage flux in the core a high resistivity material which reduces eddy currents and flux leakage can be used. New generation of materials used for the accurate transformer cores have thin laminations, or are made of the grain oriented silicon steel, so the flux is oriented along the grain, this minimizes required core mass and losses.

5. Conclusions

There have been presented the circuit and formulas for calculating the windings impedance of a measuring transformers with 1:1 nominal ratio.

Measurement procedure consists of three stages. Each stage differ by windings resistance of tested transformer, which are changed by connection in series an external resistor to relevant transformer windings. The procedure was carried out in the way to eliminate the impact of electromagnetic disturbances and minimize significant sources of systematic measurement errors. None unexpected significant systematic errors have been detected in the measuring circuit.

Fig. 4 shows the monotonic character of leakage reactance which increase with the increase of frequency. Winding resistance increase is probably due to the skin effect and the leakage reactance increase results from the proportional dependency on the frequency.

6. References

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