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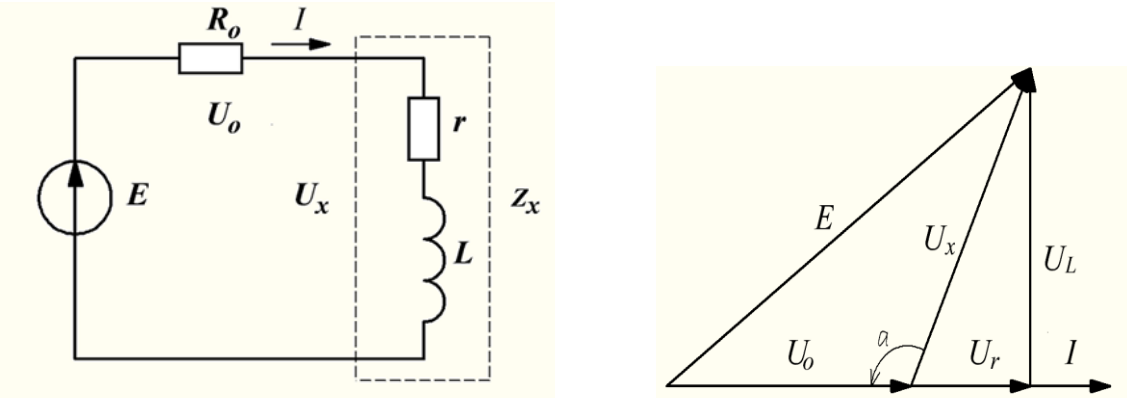
ON MEASURING THE COMPONENTS OF INDUCTIVE IMPEDANCE USING THE THREE VOLTMETER METHOD

The possibilities of the three voltmeter method for measuring inductance and its active resistance, as well as their frequency characteristics, are investigated. It is established that that in the frequency ange up to 100 kHz, the measurement error of inductance is no more than 0.3%, active resistance 8.7%, and quality factor 5%.
Keywords: inductance, resistance, impedance, three voltmeter method, measurement, frequency response, quality factor, approximate measure.

Introduction. Among the methods of measuring inductive impedance, the three voltmeter method [1, 2] is used at industrial frequencies (50, 400 Hz) to determine the power consumed by the receiver of electrical energy, its active resistance, reactance, and total resistance. Comparison of the *Q*-meter and bridge methods used to measure impedance components in a wide frequency range with the three voltmeter method shows that the latter has an undeniable advantage - operational simplicity and convenience, which means that to measure the receiver parameters, it is enough to determine the voltage in three sections of an electrical circuit consisting of an electrical energy receiver and a series-connected reference active resistance.

Objective. To evaluate the capabilities of the three voltmeter method for measuring the components of inductive impedance and determining their frequency characteristics in the range above industrial frequencies.

The main part. Fig. 1 shows the equivalent circuit of the measuring circuit (a) for determining the components of the inductive impedance by the three voltmeter method and its vector diagram (b), where E is the voltage is the harmonic oscillator, R_o is the reference resistance, L, r are the inductance and active resistance of the measured impedance z_x , U_o, U_x are the voltage drop across the reference resistance and the measured impedance, U_L, U_r are the reactive and active components of the voltage U_x , I is the current in the measuring circuit. The impedances of the inductance z_x and the measuring circuit z are as follows



a)b)

Figure 1 - Measuring circuit (a) and its vector diagram of voltages and current (b)

$$z_x = \sqrt{r^2 + \omega^2 L^2}, \tag{1}$$

$$z = \sqrt{(R_o + r)^2 + \omega^2 L^2}, \tag{2}$$

where ω is the oscillation frequency of the harmonic oscillator E. For a series circuit, the impedance values can be represented as

$$z_x = R_o U_x / U_o, \quad z = R_o E / U_o. \tag{3}$$

The following system of equations follows from (1) to (3)

$$\sqrt{r^2 + \omega^2 L^2} = R_o U_x / U_o, \tag{4}$$

$$\sqrt{(R_o + r)^2 + \omega^2 L^2} = R_o E / U_o, \tag{5}$$

whose solution allows us to obtain expressions for the active component of the inductive impedance

$$r = \frac{R_o}{2}\left(\frac{E^2 - U_x^2}{U_o^2} - 1\right) \tag{6}$$

and its inductance

$$L = \frac{R_o}{\omega}\sqrt{\frac{U_x^2}{U_o^2} - \frac{1}{4}\left(\frac{E^2 - U_x^2}{U_o^2} - 1\right)^2}\,. \tag{7}$$

From the last two expressions, it follows that the values of r and L can be found by measuring the voltages E, U_x and U_o, followed by calculation according to (6) and (7). It should be noted that the found components of the inductive impedance r and L will be real and positive if the following conditions are met

$$U_x^2 + U_o^2 \le E^2 \le (U_x + U_o)^2, \tag{8}$$

on the vector diagram (Fig. 1b), this means that the angle α can take on values in the limited range $\pi/2 \leqslant \alpha \leqslant \pi$.

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To determine the possibility of measuring the components of inductive impedance, the measuring circuit was assembled according to Fig. 1a. Coils from a set of exemplary inductance measures of type L - 0170 of class 0.2, category III, were used as the measured impedance. The measurements were performed at a frequency of 1 kHz with a B7-27A/1 voltmeter using a Г3-118 harmonic oscillator. An exemplary resistor of the МЛТ-2 type with an active resistance of 1475 Ω (at a frequency of 1 kHz) was chosen as an exemplary resistance R_o.

Table 1 shows the measurement results, where L_o is the nominal value of the inductance reference measures; L_∂, r_∂ are the actual values of the inductances and active resistance of the measures obtained by the bridge meter E7-8; L, r are the inductance and active resistance of the reference measures determined by the method of three voltmeters.

Table 1

Measurement results of exemplary inductance measures

L_o, mH	0,2	0,5	1	2	5	10	20	50	100	200
L_∂, mH	0,201	0,501	1	1,999	4,997	10	20,01	49,99	100	199,9
r_∂, Ω	1,612	1,944	2,97	4,73	9,98	20,6	75,2	125,5	294	241
L, mH	0,225	0,518	0,997	1,984	4,907	9,99	19,9	49,98	99,97	200,5
r, Ω	1,499	1,999	2,987	4,948	11,67	20,7	76,92	125,6	292,7	217,6

Using the least squares method, linear regression equations for inductance were obtained $L = f(L_\partial)$

$$L = -0{,}0641 + 1{,}0026L_\partial \qquad (9)$$

and active resistance $r = \varphi(r_\partial)$

$$r = 1{,}0182 + 0{,}9601r_\partial; \qquad (10)$$

at a significance level of 0.001, the correlation coefficients were for inductance $r_L \approx 1$, for active resistance $r_r \approx 0{,}9983$; standard deviation of a single measurement of inductance $\sigma_L = 0{,}1168$ mH, active resistance

σ_r = 6,5419 Ω, the average relative error of inductance measurement was 0.3%, and of active resistance - 8.7%.

The results of the frequency response study are shown in Fig. 2.

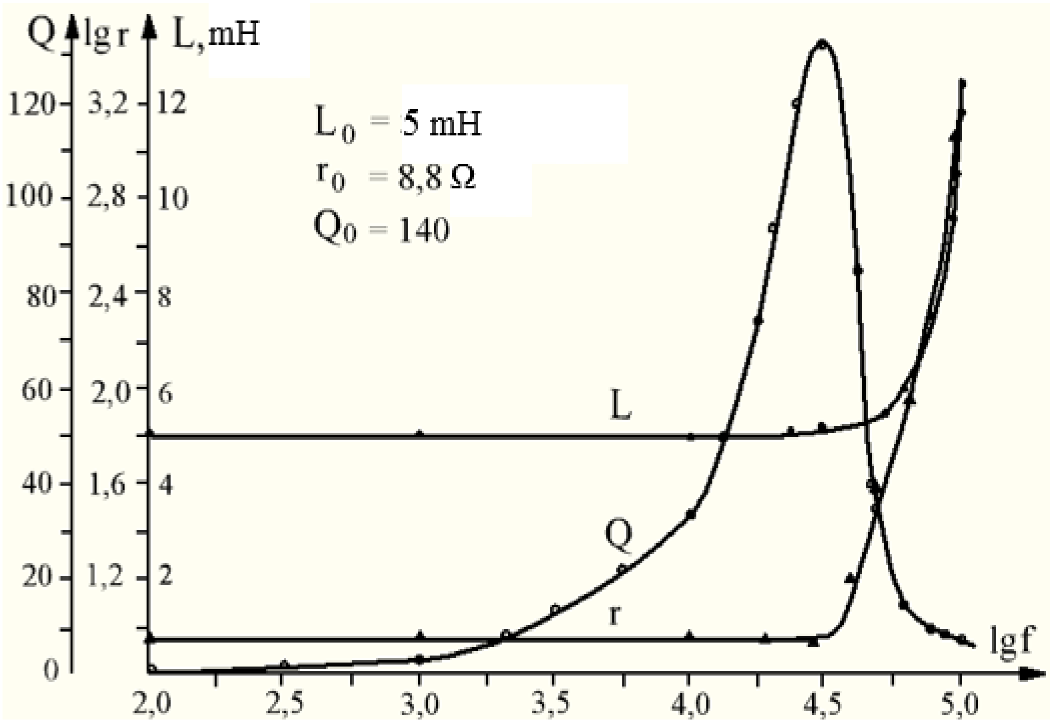

Figure 2 - Frequency characteristics of the inductance *L*, active resistance *r* and quality factor *Q* of the reference inductance measure L_o

The experimental frequency dependences of the inductance *L*, active resistance *r*, and *Q* factor were determined in the range of 0.1-100 kHz. A reference measure with an inductance of L_o = 5 mH, an ohmic resistance of 8.8 Ω and a *Q* factor of 140. The obtained dependences show that in the frequency range from 0.1 to 30 kHz, the active resistance *r* and inductance *L* remain practically unchanged with deviations within the experimental error. After 30 kHz, the active resistance *r* begins to increase its value, which can be explained by the growing influence of the proximity effect and the skin effect. An increase in inductance *L* is also observed due to the shunting effect of the distributed capacitance of the coil and the measuring circuit as a whole, which form a parallel circuit with the inductance with a certain natural resonance frequency f_o. As the frequency f increases at $f < f_o$, the impedance of the parallel circuit increases, which causes an apparent increase in the inductance *L*. This phenomenon introduces an error in the determination of inductance at frequencies close to the coil's natural resonance frequency. The error can be reduced by taking into account the value of the distributed capacitance, which requires consid-

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eration of a slightly different equivalent circuit diagram of the measuring circuit, which takes into account the interturn capacitance of the measured coil, input capacitances of measuring devices and connecting conductors. Frequency dependence of quality factor $Q = 2\pi fL/r$ of the tested reference inductance measure has a maximum of Q = 133 at a frequency of f = 30 kHz, the value of which differs by 5% from the Q-factor specified in the reference measure passport.

Conclusions. The results of the study allow us to draw the following conclusions:

- the method of three voltmeters is sufficiently simple to measure the components of inductive impedance at fixed frequencies above industrial ones; in the range up to 100 kHz, the relative error in determining inductance is no more than 0.3%, active resistance - 8.7%, and quality factor - 5%, which corresponds to the accuracy class of the used measuring devices;

- the method allows obtaining an informative characteristic in the form of frequency dependencies of the active resistance and inductance; this makes it possible to select a frequency range in which the interfering effect of the distributed capacitance is insignificant, as well as to find the optimal frequency at which the inductance quality factor is maximum;

- further improvement of the accuracy of determining the actual values of the inductive impedance components is possible by taking into account the shunting effect of the distributed capacitance.

ЛІТЕРАТУРА

1. Ознакомление с методом трех вольтметров: веб-сайт.
URL: http//www.vunivere.ru/work 36704 (дата звернення: 29.08.2023).

2. Твердоступ Н.И. Особенности измерения индуктивного импеданса на низких частотах. *Системні технології*. Дніпропетровськ, 2016. Вип. 1(102). С. 87 - 92.

REFERENCES

1. Oznakomlenie s metodom threh voltmetrov: web-sait.
ULR http//www.vunivere.ru/work 36704 (data zvernennja: 23.08.2023).

2. Tverdostup N.I. Osobennosti izmereniya induktivnogo impedansa na nizkih tchastotah. *Systemni technologii*. Dnipropetrovsk, 2016. Vyp. 1(102). S. 87 - 93.

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Про вимірювання складових індуктивного імпедансу методом трьох вольтметрів

Метод трьох вольтметрів дозволяє визначати складові індуктивного імпедансу вимірюванням напруг на досліджуваному імпедансі, на еталонному активному опорі і на виході джерела гармонійної напруги, яке живить вимірювальне коло. Проведено аналіз вимірювального кола до методу трьох вольтметрів, знайдені математичні вирази для розрахунку активного опору і індуктивності як складових досліджуваного імпедансу за результатами виміру трьох напруг. Щодо величин напруг на досліджуваному імпедансі, на еталонному активному опорі і на виході джерела гармонійної напруги обґрунтована умова, при виконанні якої отримані результати будуть дійсними. Методом трьох вольтметрів експериментально в діапазоні до 100 кГц визначені частотні характеристики активного опору, індуктивності і добротності еталонної котушки із набору зразкових мір індуктивності із заздалегідь відомими параметрами. Експериментальні частотні залежності вказують на наявність ділянки постійного значення складових імпедансу на низьких частотах. На частотах більше 30 кГц наявні ділянка зростання активної складової із за впливу ефекту близькості і скін ефекту та ділянка уявного збільшення індуктивності із за впливу розподіленої ємності котушки. Отримані характеристики дозволяють вибрати діапазон частот, в якому заважаючий вплив розподіленої ємності мінімальний а також визначити оптимальну частоту, при якій добротність індуктивності максимальна. Відносна похибка визначення індуктивності склала 0,3%, активного опору – 8,7%, добротності – 5%.

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