METHODS OF SELECTION OF FREQUENCY FOR ELECTROMAGNETIC FIELD OF EDDY-CURRENT TRANSFORMER WITH U-TYPE CORE BY ITS INTERACTION WITH A TESTED FERROMAGNETIC SPECIMEN

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Frequency of electromagnetic field is one of essential parameters determining technical realization for eddy-current transformer (ECT). Such factors as engineering specification for testing, terms of application and possibilities for realization influence on frequency selection. For selecting working frequency of ECT it is important to have frequency dependencies for its parameters, for example, frequency dependencies of its active resistance and reactance. In the quite a number of works [1, 2, 3] there have been received such dependencies but they are quite cumbersome and require a lot of calculation. In the given work, when studying interaction of ECT with ferromagnetic conducting medium, we propose to view it as nonlinear inductance coil.

U-type ECT over the tested medium is presented in fig.1. As shown in fig.1 l - distance between core centres of ECT; h - thickness of the tested specimen; b - width of the tested area; d - diameter of ECT core (b=d).

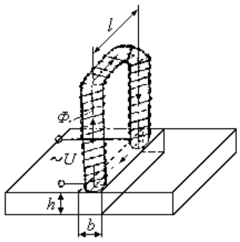


Fig.1. U-type ECT over the tested ferromagnetic plate.

The analysis of interaction is created under the following assumptions: magnetic fluxes in the core and the tested area are equal and evenly distributed.

The equivalent circuit of ECT is given in fig.2, vector diagram in fig 3. In equivalent circuit R – resistance of coil winding (ECT), L_σ - leakage inductance, g_0, b_0 – active and reactive electric conduction of ECT, U_0 - voltage applied to outlets of ECT. Parameters g_0, b_0 are determined by the following way [4, 5]:

$$g_0 = \frac{I_a}{U_0} = \frac{I_a U_0}{U_0^2} = \frac{P_{fer}}{U_0^2}, \tag{1}$$

where P_{fer} – losses in core material ECT;

w – number of turns in coil ECT;

ω – circular (cyclic) frequency;

δ – magnetic loss angle;

Φ – magnetic flux in ECT core;

U_0 – voltage on ECT outlets (see fig.1, 2):

$$U_0 = U_{cb} = \omega w \Phi \tag{2}$$

If we replace hysteresis loop by ellipse, then the losses in volume unit of core ferromagnetic material [6]:

$$P_{fer1} = \mu_{r1} \mu_0 \omega H^2 \sin\delta_1, \tag{3}$$

where H – magnetic field intensity in the core;

μ_{r1} – relative magnetic permeability of ECT core material;

μ_0=4π·10^{-7} – constant

δ_1 – magnetic loss angle for ECT core material.

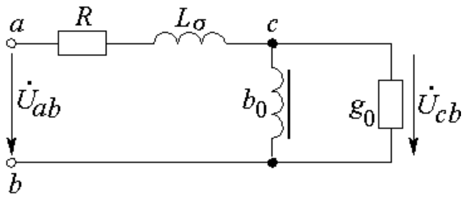


Fig.2. Equivalent circuit of ECT.

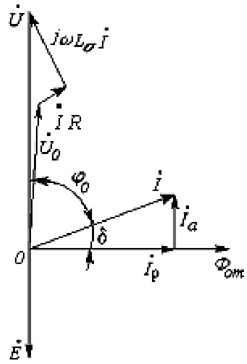


Fig.3. Vector diagram.

As is known, magnetic field strength [4, 5]:

$$H = \frac{B}{\mu_{r1}\mu_0} = \frac{\Phi}{\mu_{r1}\mu_0 S_1}, \tag{4}$$

where B – magnetic inductance in ECT core;

S_1 – core cross-section area.

By substituting expression (4) into expression (3), we receive:

$$P_{fer1} = \frac{\omega \Phi^2 \sin\delta_1}{\mu_{r1}\mu_0 S_1^2} \tag{5}$$

Losses in the core material:

$$P_{fer} = P_{fer1} V_1 = \frac{\omega \Phi^2 V_1 \sin\delta_1}{\mu_{r1}\mu_0 S_1^2} \tag{6}$$

where V_1 – core size.

By substituting expressions (6) and (2) into expression (1), we receive:

$$g_0 = \frac{V_1 \sin\delta_1}{\mu_{r1}\mu_0 \omega w^2 S_1^2} \tag{7}$$

It follows from the vector diagram (fig.3) that tangent of magnetic loss angle:

$$tg\delta_1 = \frac{I_a}{I_p} = \frac{g_0 U_0}{b_0 U_0} = \frac{g_0}{b_0} \tag{8}$$

The latter expression allows to determine reactive conductivity of ECT:

$$b_0 = \frac{g_0}{tg\delta_1} = \frac{V_1 \cos\delta_1}{\mu_{r1}\mu_0 \omega w^2 S_1^2} \tag{9}$$

Let us express parameters of sequential equivalent circuit for ECT coil through parameters of parallel circuit (fig.2) [5]:

$$R_0 = \frac{g_0}{y_0^2} = \frac{g_0}{g_0^2 + b_0^2} = \frac{g_0}{g_0^2\left(1 + \frac{1}{tg^2\delta_1}\right)} = \frac{tg^2\delta_1}{g_0\left(1 + tg^2\delta_1\right)}, \tag{10}$$

$$X_0 = \frac{b_0}{y_0^2} = \frac{\frac{g_0}{tg\delta_1}}{g_0^2 + b_0^2} = \frac{\frac{g_0}{tg\delta_1}}{g_0^2\left(1 + \frac{1}{tg^2\delta_1}\right)} = \frac{tg\delta_1}{g_0\left(1 + tg^2\delta_1\right)} \tag{11}$$

Substituting g_0 in expressions (10), (11) by expression (7), we receive:

$$R_0 = \frac{\mu_{r1}\mu_0 \omega w^2 S_1^2 tg^2\delta_1}{V_1 (1 + tg^2\delta_1)\sin\delta_1}, \tag{12}$$

$$X_0 = \frac{\mu_{r1}\mu_0 \omega w^2 S_1^2 tg\delta_1}{V_1(1+tg^2\delta_1)\cos\delta_1} \tag{13}$$

Expressions (12), (13) can be rewritten in other way, taking into account that $\frac{tg^2\delta_1}{\left(1+tg^2\delta_1\right)} = \sin^2\delta_1$, then:

$$R_0 = \frac{\mu_{r1}\mu_0 \omega w^2 S_1^2 \sin\delta_1}{V_1}, \tag{14}$$

$$X_0 = \frac{\mu_{r1}\mu_0 \omega w^2 S_1^2 \cos\delta_1}{V_1} \tag{15}$$

Sequential equivalent circuit for section *cb* is presented in fig.4.

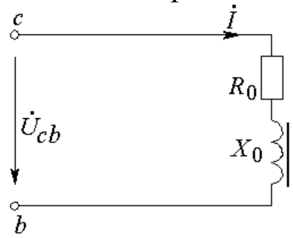


Рис.4. Sequential equivalent circuit for section *cb.*

In the presence of ferromagnetic tested medium, ECT magnetic flux is locked though this medium, therefore the value of losses P_{fer} changes owing to the losses in the tested area:

$$P_{fer}^{/} = \frac{\omega \Phi^2 V_1 \sin\delta_1}{\mu_{r1}\mu_0 S_1^2} + \frac{\omega \Phi^2 V_2 \sin\delta_2}{\mu_{r2}\mu_0 S_2^2}, \tag{16}$$

where μ_{r2} – relative magnetic permeability of the tested material;

δ_2 – magnetic loss angle for tested medium material;

S_2, V_2 – cross-section area and the volume of the tested area under ECT.

In this case one can represent active resistance and reactance of sequential equivalent circuit in the form of two components (fig.5):

$$R_0^{/} = R_1 + R_2 = \frac{\mu_{r1}\mu_0 \omega w^2 S_1^2 \sin\delta_1}{V_1} + \frac{\mu_{r2}\mu_0 \omega w^2 S_2^2 \sin\delta_2}{V_2} \tag{17}$$

$$X_0^{/} = X_1 + X_2 = \frac{\mu_{r1}\mu_0 \omega w^2 S_1^2 \cos\delta_1}{V_1} + \frac{\mu_{r2}\mu_0 \omega w^2 S_2^2 \cos\delta_2}{V_2}, \tag{18}$$

where R_1, X_1 – resistances corresponding to the processes in ECT core;

R_2, X_2 – resistances corresponding to the processes in the tested area.

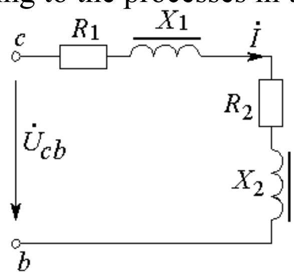


Fig.5. Sequential equivalent circuit of ECT in the presence of the tested medium.

Active resistance and reactance of ECT were measured by device E7-20 in the frequency range from 100 to 200000 Hz. This device is able to measure active resistance *R* and full resistance *Z* and also phase shift angle between voltage and current. Measurements were done on frequencies 100,200,500,1000,2000,5000,10000,20000, 50000, 100000, 200000 Hz at different thicknesses of the tested medium.

For calculating active resistance and reactance of ECT it is necessary to have values of relative magnetic permeabilities core material and the tested medium. Relative magnetic permeability core material was determined by measured active resistance and reactance of ECT in the absence of the tested medium from expressions (14), (15) or by known active resistances and reactance of ECT in the presence of the tested medium from expressions (17), (18):

$$\mu_{r1} = \frac{R_0 V_1}{\mu_0 \omega w^2 S_1^2 \sin\delta_1} \tag{19}$$

$$\mu_{r1} = \frac{X_0 V_1}{\mu_0 \omega w^2 S_1^2 \cos\delta_1}, \tag{20}$$

where R_0, X_0 – active resistance and reactance of ECT received in the result of measurements;

$\delta_1 = \frac{\pi}{2} - \varphi$ – magnetic loss angle in the core;

φ – phase shift angle between voltage and current measured by device E7-20;

$$\mu_{r1} = \frac{R_0^{/}}{\mu_0 \omega w^2 \sin\delta_1 \left(\frac{S_1^2}{V_1} + \frac{S_2^2}{V_2} \right)}, \tag{21}$$

$$\mu_{r1} = \frac{X_0^{/}}{\mu_0 \omega w^2 \cos\delta_1 \left(\frac{S_1^2}{V_1} + \frac{S_2^2}{V_2} \right)}. \tag{22}$$

Relative magnetic permeabilities received from expressions (19) and (20) are given in table1.

Table 1. Dependency of relative magnetic permeability on frequency.

f	100	200	500	10^3	$2\cdot10^3$	$5\cdot10^3$	10^4	$2\cdot10^4$	$5\cdot10^4$	10^5	$2\cdot10^5$
μ_1	167	96.3	62.97	56.66	54.98	54.47	54.41	54.45	54.92	56.6	63.9

With assistance of expressions (21), (22) we determined value of magnetic permeability at different values of tested area thickness and then we determined their average value. Average values for relative magnetic permeability are given in table 2.

Table 2. Dependency of average magnetic permeability on frequency.

f	100	200	500	10^3	$2\cdot10^3$	$5\cdot10^3$	10^4	$2\cdot10^4$	$5\cdot10^4$	10^5	$2\cdot10^5$
μ_1	665.4	621	621	451	331	220	158	114	76.9	59.1	51.2

Relative magnetic permeability of the tested medium was taken same as the one for core material.

In fig. 6 you can see a graph of experimental dependencies of ECT reactance on frequency and thickness of the tested medium (X_{d1}, X_{d2},…, X_{d7} - ECT reactance on different frequencies and thicknesses of the tested area, thickness in the latter case being seven times as big as in the former one).

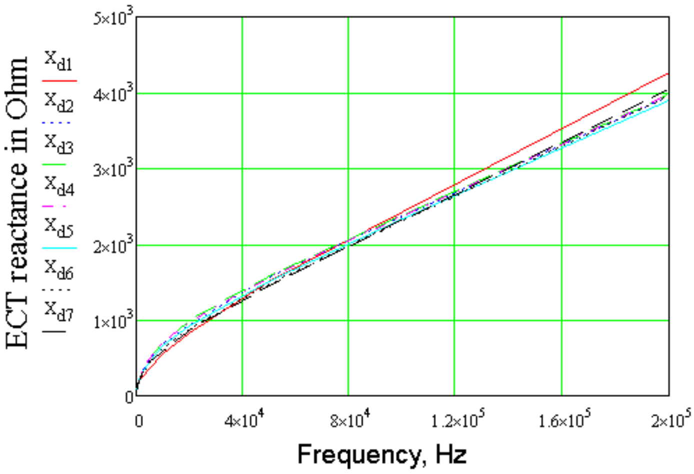


Fig.6. Experimentally received graphs of dependencies ECT reactance.

Graphs of dependencies reactance on frequency calculated through expression (18) are shown in fig.7 *a*, *b* (X_1, X_2,…, X_7 - ECT reactance on different frequencies and thicknesses of the tested area, thickness in the latter case being seven times as big as in the former one).

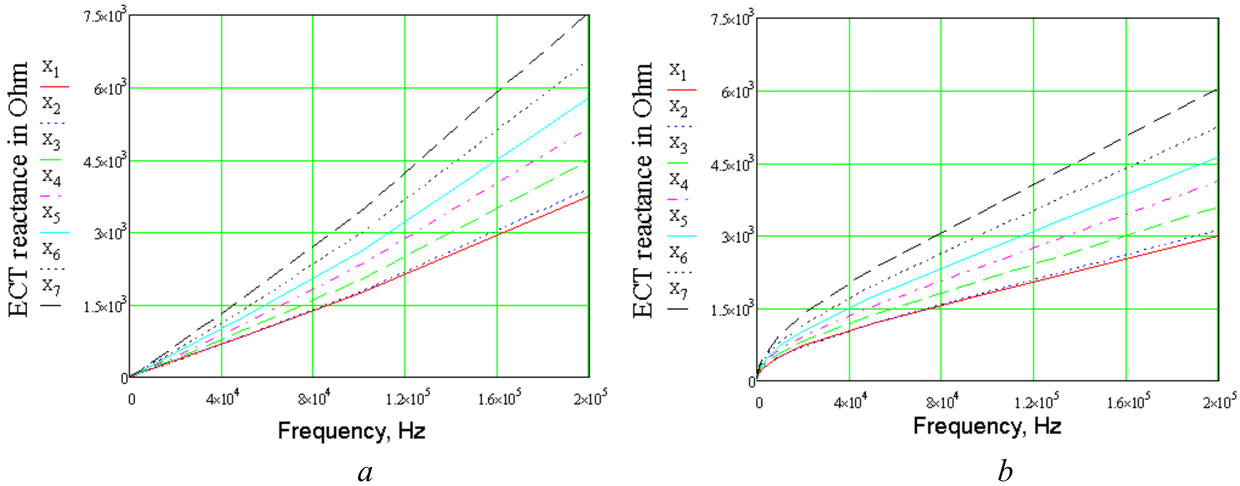


Fig.7. Graphs of dependencies ECT reactance received through eexpression (18) and:
a) relative magnetic permeability values from table 1;
b) relative magnetic permeability values from table 2.

In fig.8 and fig.9 are presented graphs of dependencies active ECT resistance received experimentally (R_{d1}, R_{d2},…, R_{d7}) and calculated through expression (17).

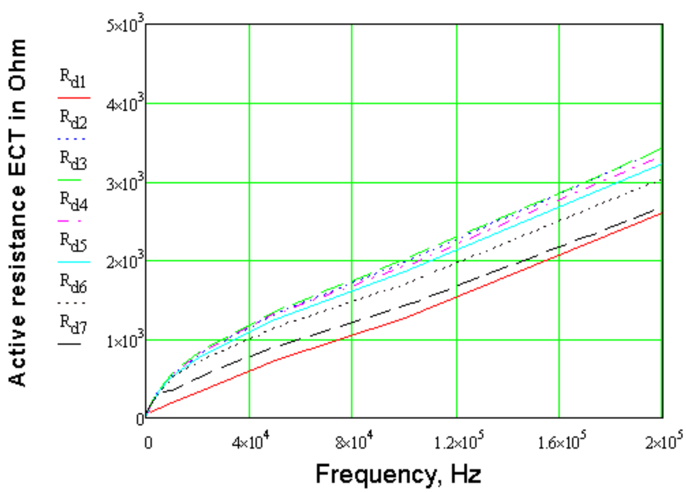
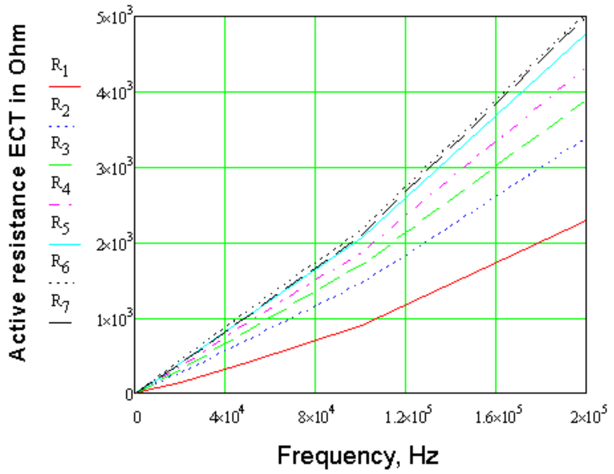
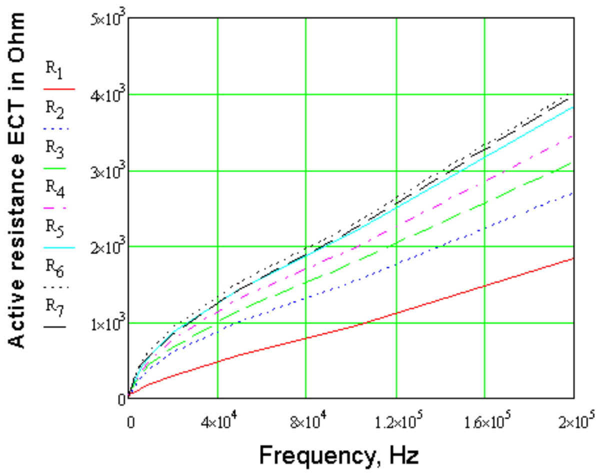


Fig. 8. Graphs of dependencies active ECT resistance received experimentally.



a



b

Fig.9. Graphs of dependencies active ECT resistance received through eexpression (17) and:
a) relative magnetic permeability values from table 1;
b) relative magnetic permeability values from table 1.

Comparison of results received experimentally and calculated through expressions (17) and (18) shows that these results are most similar on frequencies from 100 Hz to 17 kHz. From 17 kHz to 200 kHz the tendency persists of changing values.

Analyzing dependence of ECT resistance increment $\frac{\Delta R}{\Delta \omega}$, $\frac{\Delta X}{\Delta \omega}$ on frequency we come to the conclusion that these increments little depend on thickness of the tested area on frequencies more than 20 kHz. Therefore the working frequency should be taken in the range from 20 kHz to 200 kHz.

Thus, for selection of working frequency it is necessary to calculate resistance increments $\frac{\Delta R}{\Delta \omega}$, $\frac{\Delta X}{\Delta \omega}$ through expressions (17), (18) and select the frequency on which these increments depend little from frequency.

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