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Determination of Magnetic Characteristics of Alternative Current Electrotechnical Devices Using the Method of Full-Scale-Model Tests

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Abstract: The study describes a method for obtaining weber-ampere characteristics of the electromagnetic AC devices using the method of natural-model tests. For natural-model tests of electrical devices a mathematical model implemented in the software package Labview has been proposed. During the research of the method, measuring of weber-ampere characteristics of the electrical device a toroidal output transformer was carried out. A comparison with the exemplary weber-ampere characteristic was carried out, the characteristics received using the method based on natural-model experiment. It is proposed to assess the degree of difference between these characteristics to use the distance between the two compared characteristics normally to a tangent point created in the analyzed point taken on the exemplary characteristics. The effect of current harmonics measurement error on the metrological performance of the proposed method has been studied.

Key words: Weber-ampere characteristic, electrical devices, natural-model tests, tangent, point, harmonics

INTRODUCTION

An integral part of the manufacturing process of electrical devices are automatic control systems that allow to increase efficiency of use of materials and performance parameters of products (Lankin, 2000; Lankin *et al*., 2003; Shaikhutdinov *et al*., 2015). No system of process control is relevant without effective diagnostic methods. Currently, diagnosis of electrical devices is carried out by analysis of their mechanical, electrical and magnetic characteristics. For receipt of each of these characteristics one needs to apply own test means.

Investigations of integral characteristic that contains information about the mechanical, electrical and magnetic parameters of electrical devices have been carried out (Gadyuchko, 2010; Lankin and Lankin, 2015). They showed that weber-ampere characteristic of operating cycle is such an integral characteristic of electrical devices and allows you to determine not only their technical condition but also to determine the type of fault.

For non-linear characteristics of complicated objects receipt it was suggested to use the harmonic balance inverted task solution (Lankin *et al*., 2014, 2015; Gorbatenko *et al*., 2015). Conducted mathematical analysis of the harmonic balance inverted task solution, computing and field experiments using a mathematical model and a number of electrical devices (moving coil relay, motor and toroidal transformer). The results of which suggest that the proposed method of determining the weber-ampere characteristics based on solving the inverse problem of harmonic balance, provides a description of the electrical device where error does not exceed 3%. This method can be used for testing electrical devices such as during their production and during their operation.

As another method for determining the magnetic properties of electrical devices we can propose a method of natural-model tests (Gorbatenko, 2011, Shaykhutdinov *et al*., 2013).

MATERIALS AND METHODS

Definitions of magnetic characteristics of alternative current electrical products by method of natural model tests: Algorithm of natural-model tests in relation to the problem of determining the weber-ampere characteristics of the electrical device of alternating current is that the external power supply terminals working coil unit is supplied with sinusoidal voltage and dependence of the current i(t) flowing in the coil from time t is measured. The level of difference in dependencies of the measured current i(t) and current $i^{(z)}(t)$ obtained as a result of

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mathematical modeling of the device operation is determined, z; number of iteration of optimization. For this purpose, value of the functional J that shows the difference between the currents i(t) and $i^{(z)}(t)$ is calculated and the condition execution is verified:

$$J \leq \varepsilon \tag{1}$$

where, ε current measurement error i(t). If condition (Eq. 1) is not satisfied, then parameters of the mathematical model that define the shape of the weber-ampere characteristic change, again dependence of $i^{(z)}(t)$ is determined and we calculate the functional J. If the condition (Eq. 1) is satisfied, the weber-ampere characteristic of the magnetic core of electrical device is found.

To calculate the dependence of $I^{(z)}(t)$, we use the method of harmonic balance (Xing *et al*., 2013), according to which the mathematical model of the electrical device is represented in the form of an equation of circuit for the working coil of electrical device:

$$u(t) = Ri(t) + \frac{d\Phi(i)}{dt} \tag{2}$$

Where:

u(t) = The voltage applied to the coil
R = The active component of the resistance of the coil
i(t) = The current flowing in the coil
Φ = The dependence of the magnetic flux in the magnetic circuit of the coil current

Dependencies u(t), i(t), Φ(t) are determined by the formulas:

$$u(t) = U_a \sin(\omega t) \tag{3}$$

$$i(t) = \sum_{m=1}^{n} I_{(2m-1)} \sin((2m-1)\omega t) \tag{4}$$

$$\Phi(i) = \sum_{m=1}^{n} k_{(2m-1)}\, i^{2m-1} \tag{5}$$

Where:

U_a = Voltage amplitude
ω = Angular frequency
$I_{(2m-1)}$ = (2m-1) current harmonic
n = The number of accounted for current harmonics
$k_{(2m-1)}$ = Weber-ampere characteristic approximation factor
i = The instantaneous value of current

Equation 2-5 form a mathematical model of the electrical device. The functional J, reflecting the difference between the currents i(t) and $i^{(z)}(t)$ is as follows:

$$J = \frac{\int_0^{T/2} \left(i(t) - i^{(z)}(t)\right) dt}{\int_0^{T/2} i(t)\, dt}$$

Given the current presentation form adopted in method of harmonic balance (Eq. 4), we proceed to discrete form of functional representation J:

$$J = \frac{\sum_1^n \left(I_{(2m-1)} - I_{(2m-1)}^{(z)}\right)}{\sum_1^n I_{(2m-1)}} \tag{6}$$

where, $I_{(2m-1)}$ and $I_{(2m-1)}^{(z)}$ (2m-1) harmonic of the measured and calculated at zth iteration on the models of currents in coil of electrical device.

RESULTS AND DISCUSSION

Results obtained by natural model tests: For natural model tests of electrical devices mathematical model represented by Eq. (2-5) was realized in software package Labview (Fig. 1). Functional diagram consists of blocks of data input, computational units, results display units and blocks of graphical display of processes in models of AC electrical product.

The model is introduced with measured: amplitude U_a and frequency ω of the input voltage, current harmonics $I_{(2m-1)}$ as well as the initial values of coefficients approximation weber-ampere characteristics $k_{(2m-1)}$. In the output of the program emulator values of current harmonics $I_{(2m-1)}^{(z)}$ are being formed, pictures of graphs of voltage "u (t)", current "I (t)", stream "psi (t)" change, weber-ampere characteristic "XY Graph" and current spectrogram "Waveform Graph".

According to the (Eq. 6) the functional J is evaluated and condition (Eq. 1) execution is checked. If the condition (Eq. 1) is not fulfilled then to minimize the functional (Eq. 6) procedure of simplex optimization is used (Glenn, 2009). The approximation coefficients of weber-ampere characteristics $k_{(2m-1)}$ are influencing factors in the simplex optimization.

To study the proposed method measurement of weber-ampere characteristics of electrical device, toroidal output transformer generator G3-33-STT-12A was carried out. Its magnetic circuit is made of transformer steel 3412 (E320), the tape thickness is 0.35 mm, width 40 mm, outer diameter 76 mm, internal diameter 40 mm. The working coil comprises 750 turns of wire SEW-2 with 0.2 mm in diameter.

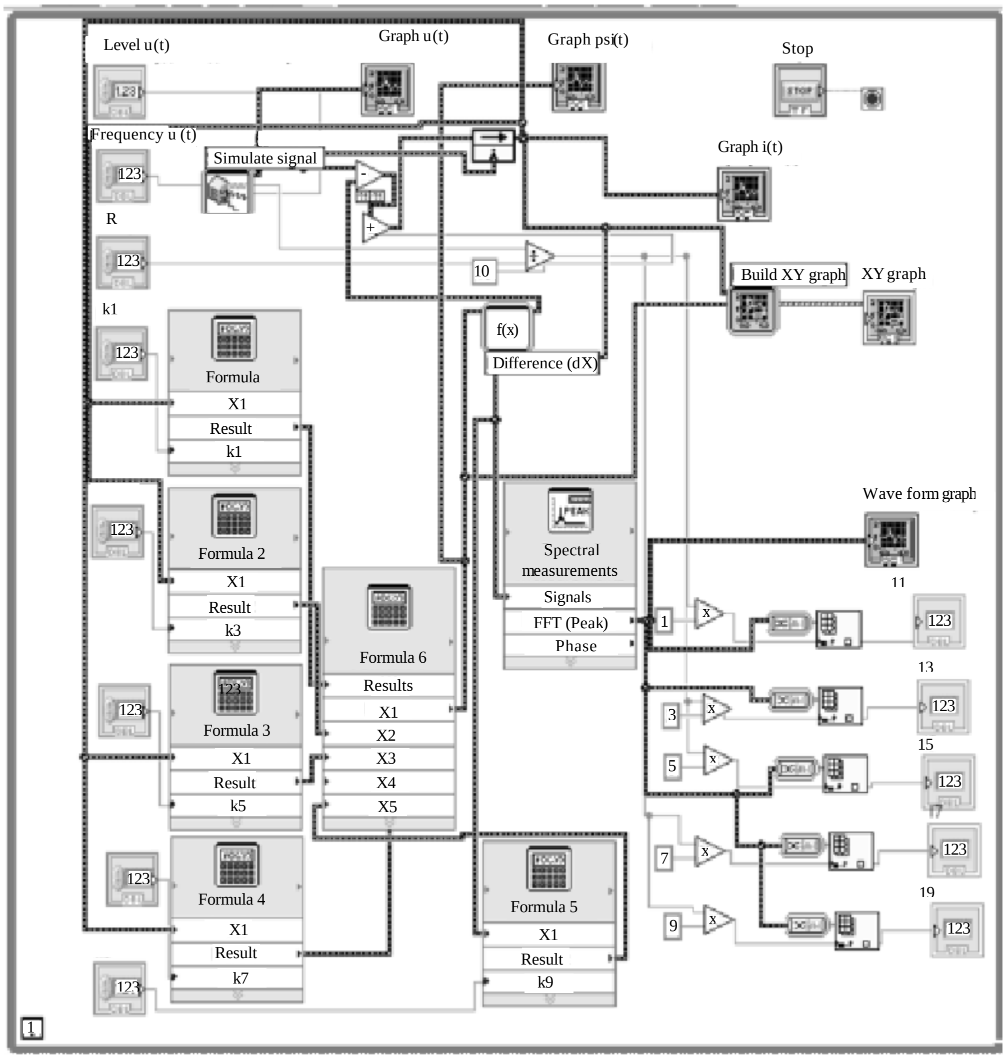

Fig. 1: Functional diagram of the emulation program in package Labview

The following equipment was used: a laboratory autotransformer Wusley tdgc 8A, RMS Multimeter Fluke 289 (AC voltage measurement error of 0.4%, AC measurement error 0.7%), a digital oscilloscope Tektronix 2024b (measurement error 3%).

Measurement of the examplary weber-ampere characteristics of the magnetic transformer was performed at a frequency of 50 Hz with a specially applied measuring coil having 37 turns of wire SEW-2 with a diameter of 0.8 mm. The measurements were performed using a known circuit with inverters of medium straightened and amplitude values (Antonov *et al*., 1986). With exemplary weber-ampere characteristic the characteristic obtained by the proposed method based on the natural-model experiment was compared. To assess the degree of difference of these characteristics, we used methodology that finds the maximum distance between the two compared characteristics along the normal to a tangent made in the analyzed point, taken on the examplary characteristics (Antonov *et al*., 1986; Lankin and Lankin 2014) (Fig. 2):

$$\delta = \max_{j=1,m}\left[\sqrt{(\Delta\Phi_j/\Phi_j)^2 + (\Delta I_j/I_j)^2}\right] \quad (7)$$

Where:

m = The number of analysis points (m = 7)

$\Delta\phi_j$, Φ_j, ΔI_j, I_j = Its found from the graph whereas the dependence Φ(i) measured and $\Phi^{(z)}$(i) received on model

Figure 3 shows an exemplary Φ(i) and obtained by means of a mathematical model $\Phi^{(1)}$(i) weber-ampere characteristics on the first iteration of the simplex

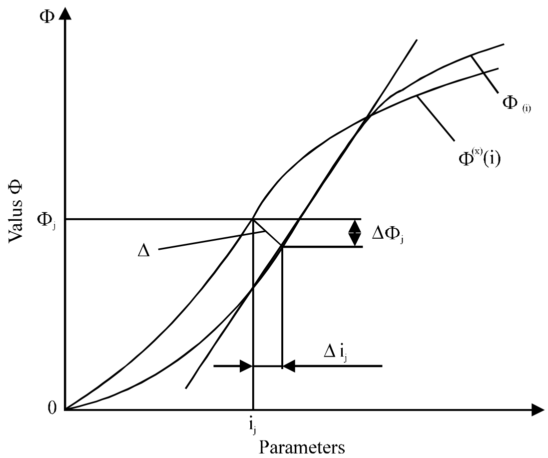

Fig. 2: The calculation of the degree of characteristics difference

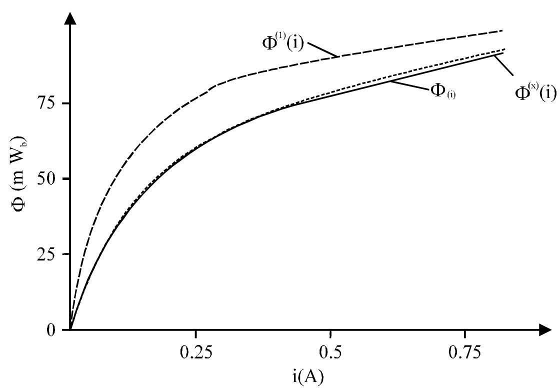

Fig. 3: Measured and received on model weber-ampere characteristics

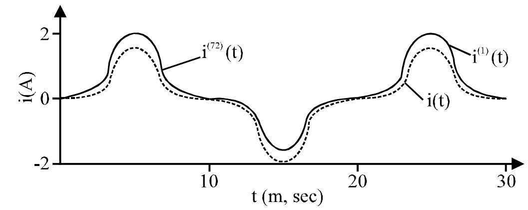

Fig. 4: Measured and received currents on model

optimization and Fig. 4 dependence from time t of the measured current i(t) and the current $\Phi^{(1)}(i)$ received from the mathematical modeling of the device operation. One can see that the currents are significantly different. Measurement of $I_{(2m-1)}$ current harmonics was made by a digital oscilloscope Tektronix 2024b.

To satisfy condition Eq. 1, it required to carry out seventy-two iterations, in the result of convergence of dependencies of currents i(t) and $i^{(72)}(t)$ (Fig. 4), the difference δ exemplary Φ (t) weber-ampere characteristics and obtained using the proposed method $\Phi^{(72)}(i)$ (Fig. 3) do not exceed 1.5%.

To determine the effect of current harmonics measurement error on the metrological performance of the proposed method a computational experiment was performed. The measured values of the current harmonics were artificially "noised" using the signal with amplitude ±4.4% of their absolute values. These studies were conducted with the assistance of the theory of planning of multifactor experiment.

As the zero values of the factors the measurement results of the first five odd current harmonics I_1-I_9 were taken. Upper and lower values of each factor is obtained by adding or subtracting a predetermined value of the absolute measurement error (±4.4%).

The response in the experiment is the degree of difference of characteristics δ between the two compared characteristics calculated by (Eq. 7).

As an exemplary characteristics weber-ampere characteristic obtained in the center of the plan was taken, i.e., according to the measured values of the current harmonics.

Orthogonal central composite plan of experiment is built (Table 1). Its core is a fractional factorial experiment 2^{5-2}. The interval of variation for each factor was set so that their values corresponded to the absolute error of measurement of current harmonics -3%. Given the size of the star shoulder the maximum change in current harmonics was ±4.4%.

The dependencies of the degree of characteristics difference δ were received from the values of the first five odd current harmonics. In physical values of factors:

$$\delta = 281.52 - 44.37I_1 + 5.16I_1^2 + 52.92I_3^2 + 429.52I_5^2 - 8.90I_7 - 351.59I_9 + 1247.54I_9^2$$

in the coded values of factors:

$$Y = 0.148 + 0.038X_1 + 0.087X_1^2 + 0.044X_3^2 + 0.1X_5^2 + 0.029X_7 + 0.033X_9 + 0.023X_9^2$$

Processing of the results of the experiment was carried out using the software statistica 10 (Table 2 and 3)

Summary: We proposed and investigated an effective method for determining the weber-ampere characteristics of electrical devices based on experimental studies and mathematical modeling. Mathematical model of the tested electrical device was constructed using the method of harmonic balance. The advantage of this method is the possibility of applying for the non-destructive testing of electrical devices during the manufacturing process.

Table 1: Matrix of experiment planning

I_1		I_3		I_5		I_7		I_9		
a	b	a	b	a	b	a	b	a	b	δ
-1	4.199	-1	0.928	-1		1	0.264	1	0.148	0.26
1	4.459	-1	0.928	-1	0.496	-1	0.248	1	0.148	0.44
-1	4.199	1	0.986	-1	0.496	-1	0.248	-1	0.140	0.33
1	4.459	1	0.986	-1	0.496	1	0.264	-1	0.134	0.41
-1	4.199	-1	0.928	1	0.526	1	0.264	-1	0.134	0.31
1	4.459	-1	0.928	1	0.526	-1	0.248	-1	0.140	0.41
-1	4.199	1	0.986	1	0.526	-1	0.248	1	0.148	0.33
1	4.459	1	0.986	1	0.526	1	0.264	1	0.148	0.58
1.471	4.520	0	0.957	0	0.511	0	0.256	0	0.144	0.31
-1.471	4.138	0	0.957	0	0.511	0	0.256	0	0.144	0.41
0	4.329	1.471	0.999	0	0.511	0	0.256	0	0.144	0.18
0	4.329	-1.471	0.915	0	0.511	0	0.256	0	0.144	0.35
0	4.329	0	0.957	1.471	0.534	0	0.256	0	0.144	0.33
0	4.329	0	0.957	-1.471	0.488	0	0.256	0	0.144	0.44
0	4.329	0	0.957	0	0.511	1.471	0.267	0	0.144	0.28
0	4.329	0	0.957	0	0.511	-1.471	0.245	0	0.144	0.07
0	4.329	0	0.957	0	0.511	0	0.256	1.471	0.150	0.31
0	4.329	0	0.957	0	0.511	0	0.256	-1.471	0.138	0.14
0	4.329	0	0.957	0	0.511	0	0.256	0	0.144	0

Table 2: Listening from programm statistica 10

Factors	Effect	SE Pure error	t (38)	p	-95% Cnf. limit	+95% Cnf. limit	Coefficient	SE coeff.	-95% conf. limit	+95%conf. limit
Mean/Interc.	0.147799	0.005273	28.03106	0.000000	0.137125	0.158473	0.147799	0.005273	0.137125	0.158473
Var1 (L)	0.075308	0.005704	13.20188	0.000000	0.063760	0.086856	0.037654	0.002852	0.031880	0.043428
Var1 (Q)	0.173994	0.006544	26.58657	0.000000	0.160745	0.187242	0.086997	0.003272	0.080373	0.093621
Var2 (L)	-0.004873	0.005704	-0.85424	0.398327	-0.016421	0.006675	-0.002436	0.002852	-0.008210	0.003337
Var2 (Q)	0.087233	0.006544	13.32944	0.000000	0.073985	0.100482	0.043617	0.003272	0.036992	0.050241
Var3 (L)	0.002774	0.005704	0.48633	0.629523	-0.008774	0.014322	0.001387	0.002852	-0.004387	0.007161
Var3 (Q)	0.201884	0.006544	30.84328	0.000000	0.188636	0.215132	0.100942	0.003272	0.094318	0.107566
Var4 (L)	0.058757	0.005704	10.30036	0.000000	0.047209	0.070305	0.029378	0.002852	0.023604	0.035152
Var4 (Q)	0.002745	0.006544	0.41945	0.677253	-0.010503	0.015994	0.001373	0.003272	-0.005252	0.007997
Var5 (L)	0.066552	0.005704	11.66685	0.000000	0.055004	0.078099	0.033276	0.002852	0.027502	0.039050
Var5 (Q)	0.046564	0.006544	7.11509	0.000000	0.033316	0.059813	0.023282	0.003272	0.016658	0.029906

Effect estimates Var: Var6; R^2 = 64383 Adj: 5664, 5 factors, 1 blocks, 57 runs; MS Pure error = 0003009

Table 3: The result of the experiment of ANOVA and factors

Factors	SS	df	MS	F	p
Var1 (L)	0.052435	1	0.052435	174.2897	0.000000
Var1 (Q)	0.212656	1	0.212656	706.8455	0.000000
Var2 (L)	0.000220	1	0.000220	0.7297	0.398327
Var2 (Q)	0.053454	1	0.053454	177.6740	0.000000
Var3 (L)	0.000071	1	0.000071	0.2365	0.629523
Var3 (Q)	0.286296	1	0.286296	951.6164	0.000000
Var4 (L)	0.031920	1	0.031920	106.0974	0.000000
Var4 (Q)	0.000053	1	0.000053	0.1759	0.677253
Var5 (L)	0.040951	1	0.040951	136.1154	0.000000
Var5 (Q)	0.015230	1	0.015230	50.6246	0.000000
Lack of fit	0.372211	8	0.046526	154.6489	0.000000
Pure error	0.011432	38	0.030085		
Total SS	1.077131	56			

ANOVA Var: Var6; R^2 = 64383 Adj: 5664, 5 factors, 1 blocks, 57 runs; MS Pure Error = 0003009 DV: Var6

CONCLUSION

Analysis of regression equations shows that the relationship between the variations of the current harmonics and the degree of difference in the characteristics **δ** is mainly quadratic and none of the harmonics has any dominant influence on **δ**. Table 1 shows that by varying the values of the current harmonics in the range of ±4.4%, the characteristics difference degree **δ** does not exceed 0.6%.

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