

Study of the temperature processes at sensorless determination of electrical product magnetic characteristics

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Abstract. Actual is the use of senseless devices for determining the webere-ampere characteristics of electrical products. However, these devices are characterized by the error in determining the flux linkage, caused by inaccurate determination of the active component of the winding resistance during the test. In classical senseless devices, the active component of the winding resistance is determined immediately before measuring the webere-ampere characteristic and is then applied as a constant value. Thus, the error in determining the active component of the winding resistance is due to the error in determining its initial value and the temperature change in the active component of the winding resistance during the determination of the magnetic characteristic. The analysis of the temperature error of the sensorless devices is carried out. A functional relationship between the error in determining the flux linkage and the electrical parameters of the winding was revealed. This makes it possible to evaluate both the absolute and relative error in the determination of flux linkage and conclude that it is necessary to apply methods for compensating for the error in determining the active component of the winding resistance. The obtained analytical results are confirmed by modeling in the program of circuit analysis. The developed procedure for estimating the error of the flux-linkage determination is also verified on the experimental data.

1. Introduction

The complexity of the designs of electrical products, the trend of miniaturization and the reduction of material consumption make ever higher demands on the quality of the component parts. The quality of the parts is determined primarily by their mechanical, electrical and magnetic properties [1, 2]. And it is from the magnetic properties that the operational characteristics of electrical products depend, and the use of parts with high magnetic properties, for example as magnetic circuits, reduces the dimensions of electrical products. Information on the magnetic properties of parts allows you to detect defects at the assembly stages, and to identify shortcomings of other parts of the product by testing electrical assemblies. Using the results of tests of blanks and products in the process control subsystem for the production of electrical products, it is possible to increase the yield of suitable products and, thereby, significantly reduce economic costs [3,4].

Equally important is the diagnostics and monitoring of the technical condition of the machines in operation, as well as the forecasting of their technical condition, the sorting of the output, depending on the provision of the required electrical and mechanical parameters, as well as, for example, acoustic ones [5, 6], which are provided at a high level, in some cases very critical (the noise of submarine



engines).

The complexity of the task of monitoring magnetic properties is that the most informative characteristics of electrical products (EP) can not be accurately determined without the use of special measuring transducers, which greatly increases the test time and makes it difficult to conduct continuous monitoring [7, 8]. A promising direction in solving this problem is the use of sensorless control methods. In this case of magnetic monitoring as a source of magnetic field it is used the working winding of electrical products.

2. Materials and Methods

When developing elements of the theory of the magnetic field, methods of the theory of experimental design, measurement theory, mathematical modeling using licensed packages of GMSH, Octave application software were used [9].

During the test, heating occurs and, as a consequence, changes in the active component of the winding resistance, which causes an inadmissible error in determining the magnetic flux and, as a consequence, the webere-ampere characteristics of the EP (Fig. 1). In Fig. 1 we introduce next notation: ψ'_r , ψ''_r – flux linkages corresponding to the remanent magnetization of the sample; I'_c , I''_c – currents corresponding to the coercive force; ψ'_m , ψ''_m – saturation flux linkages; ψ_r , I_c , ψ_m – their actual values; $\Delta\psi_r$, ΔI_c , $\Delta\psi_m$ and $\delta\psi_r$, δI_c , $\delta\psi_m$ – their absolute and relative errors, respectively. In this cases, it is important to develop methods and devices for sensorless magnetic control with compensation for the temperature error [10].

Consider the magnetic system (Figure 1), the main elements of which are: the magnetizing winding of the product with the number of turns w connected to the current source $i(t)$, two ferromagnetic elements (for example, the core and the armature of the electromagnet) with an air gap between these elements [11].

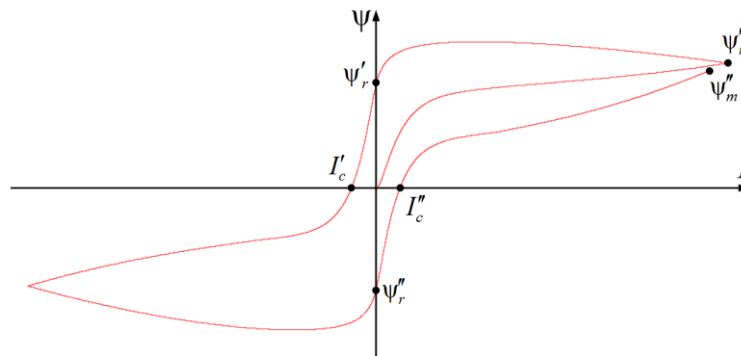


Figure 1. Magnetic characteristic with characteristic points

In classical senseless devices, the active resistance component of the working winding EP is preliminarily determined and then used in calculating the magnetic flux as a constant value [12]. Therefore, classical sensorless devices determine the flux linkage by expression:

$$\psi = \int_0^t (u - iR_l) dt + C,$$

where u - winding voltage, i - current flowing through the winding, R_l - the active component of the winding resistance, determined immediately before measuring the magnetic characteristic; C - integration constant.

The actual value of flux linkage is determined by the formula:

$$\psi_d = \int_0^t (u - i \cdot (R_1 + \Delta R^\Sigma)) dt + C,$$

where ΔR^Σ – total accumulated absolute error in determining the current value of the active component of the winding resistance.

Due to this, the absolute error in the determination of the flux linkage is determined by the expression:

$$\Delta\psi = \psi - \psi_d = \int_0^t (i \Delta R^\Sigma) dt. \quad (1)$$

In case of accurate initial determination of the value of the active component of the winding resistance – $\Delta R^\Sigma \approx 0$. Then, during the test, a current change occurs (increase, decrease, change of direction), leading to heating of the EP and, as a consequence, to a change ΔR^Σ . After integrating the sign of $\Delta\psi$ corresponds to the sign of the expression $i \Delta R^\Sigma$. And when expression $i \Delta R^\Sigma$ changes its sign, the direction of $\Delta\psi$ change is changes too. Thus, the change in the error in determining the flux linkage is nonmonotonic in nature.

Let's analyze the thermal processes of the EP winding. Two thermal processes lead to a change in the temperature of the winding: an increase in temperature due to heat generation during the flow of electric current along it and a change in the temperature of the winding, due to heat exchange with the environment (air, other EP-details). The resulting change in winding temperature is determined by the amount of heat received or given, in accordance with expression:

$$dQ_1 = cm\Delta T,$$

where dQ_1 – amount of heat received or returned; c – specific heat of winding; m – winding mass; ΔT – temperature variation. According to the Joule-Lenz law, the amount of heat received by the winding when an electric current flows through it is given by

$$dQ_2 = i^2 R(t^\circ C) dt.$$

Let us consider a special case in which the subject EP has a steady room temperature and the process of measuring the magnetic characteristic is fast enough, so that the heat exchange between the winding EP and the surrounding medium can be neglected. In this case, all the amount of heat released in the winding, due to the flow of electric current through it, will go to increase its temperature – $dQ_1 = dQ_2$ and consequently:

$$cm\Delta T = i^2 R(t^\circ C) dt.$$

We express from this relation the change in temperature:

$$\Delta T = \frac{i^2 R(t^\circ C) dt}{cm}.$$

The current value of the active component of the winding resistance from temperature is given by:

$$R(t^\circ C) = R_1 \cdot (1 + \alpha \Delta T),$$

where α – copper temperature coefficient.

Substitute the value of ΔT in this expression:

$$R(t^\circ C) = R_1 \cdot \left(1 + \alpha \cdot \frac{i^2 R(t^\circ C) dt}{cm} \right).$$

Expressing the current value of the active component of the winding resistance from this expression, we get:

$$R(t^\circ C) = \frac{cmR_1}{cm - \alpha R_1 i^2 dt}. \quad (2)$$

Using the expression (2), it is possible to calculate the value of the active component of the winding resistance at any time during the determination of the EP magnetic characteristic, using i as the value

of the effective current, while not taking into account the heat transfer between the winding and the environment, the change in specific heat due to temperature change, and The change in the active component of the winding resistance between its initial change and the current calculated value. Iterative calculation avoids the last drawback and uses instantaneous current values in the calculation:

$$R(t^{\circ}\text{C})_k = \frac{cmR(t^{\circ}\text{C})_{k-1}}{cm - \alpha R(t^{\circ}\text{C})_{k-1} i_k^2 \cdot \Delta t}, \quad (3)$$

where i_k - the current value for each k measurement (for $k = 1..N$, where N is a the number of measured points, when determining the magnetic characteristic); Δt - step of digitization; wherein $R(t^{\circ}\text{C})_0 = R_l$.

Let's analyze the expressions (2), (3) taking into account the world tendency to reduce the weight and size parameters, when $m \rightarrow 0$:

$$R(t^{\circ}\text{C}) = \lim_{m \rightarrow 0} \frac{cmR_l}{cm - \alpha R_l i^2 dt} = \lim_{m \rightarrow 0} \frac{\frac{cmR_l}{cm}}{\frac{cm - \alpha R_l i^2 dt}{cm}} = \lim_{m \rightarrow 0} \frac{R_l}{1 - \frac{\alpha R_l i^2 dt}{c} \cdot \frac{1}{m}} = \lim_{m \rightarrow 0} \frac{R_l}{1 - \frac{k}{m}},$$

coefficient $k = \frac{\alpha R_l i^2 dt}{c} > 0$ is a positive constant, because tabular coefficients of copper α , c and

the active component of the winding resistance is always positive; the square of the current value of the current is positive $i^2 > 0$; when the instantaneous current value assumes a zero value, the active component of the winding resistance does not change; $dt > 0$ - positive period of time. In this way

$\lim_{m \rightarrow 0} \frac{k}{m} \rightarrow +\infty$. In case $R(t^{\circ}\text{C}) > 0$ it is true that $R(t^{\circ}\text{C}) = \lim_{m \rightarrow 0} \frac{R_l}{1 - \frac{k}{m}} > 0$; and in case of $R_l > 0$ it is true

that $1 - \frac{k}{m} \geq 0$, or $\frac{k}{m} \leq 1$. Thus we obtain a system under which the expressions (2) and (3) have meaning:

$$\begin{cases} \lim_{m \rightarrow 0} \frac{k}{m} \rightarrow +\infty; \\ \frac{k}{m} \leq 1. \end{cases}$$

So $\frac{k}{m} = 1$ - is the maximum value for which the expressions (2) and (3) have a physical meaning. So we have:

$$R(t^{\circ}\text{C}) = \lim_{m \rightarrow 0} \frac{R_l}{1 - \frac{k}{m}} = \lim_{m \rightarrow 0} \frac{R_l}{1 - 1} = +\infty.$$

The analysis of expressions (2) and (3) shows that the trends of miniaturization lead both to a greater absolute value of the active component of the winding resistance, and to its greater increment in the process of sensorless determination of the magnetic characteristic of EP.

3. Results and Discussion

By using of KEK-03-MMM-150 a proportional electromagnet was tested with a sinusoidal current and the necessary electrical parameters for $R(t^{\circ}\text{C})$ calculation corresponding the equation (3). When the expression (3) was realized, it was also taken into account that the winding had a mass $m = 0,027 \text{ kg}$ and it is made of copper, the specific heat of which at room temperature is

$c = 385 \text{ J/(kg} \cdot \text{K}^{-1})$. Fig. 2 shows the calculated active component of the winding resistance, the relative change in the active component of the winding resistance was $\delta R = 0,2 \%$.

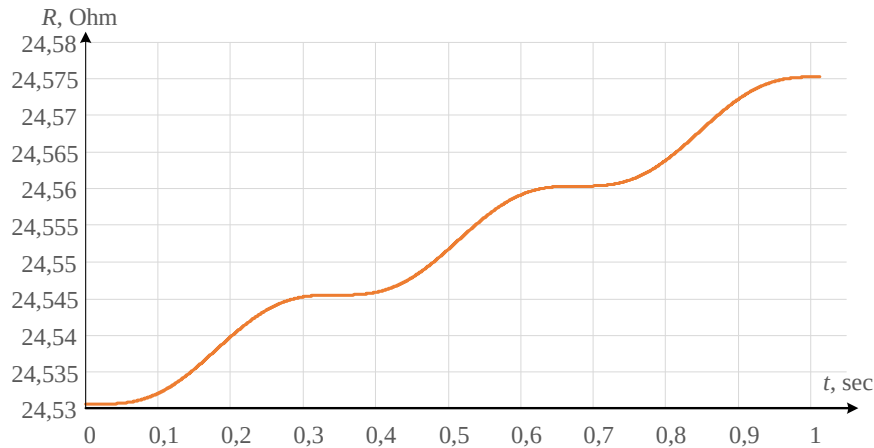


Figure 2. Time diagram of the calculated active component of the EP-winding resistance

Modeling of the sensorless device in the Micro-Cap circuit analysis program was carried out. The results of simulation of a sensorless device are given in Table 1.

Table 1. Results of a sensorless device simulation

Parameters	Experiments No.							
	1	2	3	4	5	6	7	8
R_l , Ohm	12.25	24.5	24.5	49	98	12.25	49	98
R_{ll} , Ohm	12.2745	24.5	24.549	49.098	98.196	12.2745	49.098	98.196
δR , %	0.2	0	0.2	0.2	0.2	0.05	0.8	3.2
cm	14.6	-	29	58.5	117	58	14.5	7.25
I_c , A	-0.055398							
ψ_r , Wb	0.034006							
ψ_m , Wb	0.164811							
I'_c , A	-0.056444	-0.055479	-0.057262	-0.058124	-0.063877	-0.055398	-0.06898	-0.187729
$\Delta I'_c$, A	-0.001046	-8.1E-05	-0.001864	-0.002726	-0.008479	0.034006	-0.013582	-0.132331
$\delta I'_c$, %	1.9	0.15	3.4	4.9	15.3	0.16	24.5	239
I''_c , A	0.057167	0.055394	0.058968	0.0625	0.069669	-0.055782	0.084681	0.350093
$\Delta I''_c$, A	0.001769	4E-06	0.00357	0.007102	0.014271	-0.000384	0.029283	0.294695
$\delta I''_c$, %	-3.2	-0.01	-6.4	-12.8	-25.8	0.7	-53	-532
ψ'_r , Wb	0.03462	0.034026	0.037321	0.035653	0.039203	0.05584	0.042263	0.105603
$\Delta \psi'_r$, Wb	0.000614	2E-05	0.003315	0.001647	0.005197	0.000442	0.008257	0.071597
$\delta \psi'_r$, %	1.8	0.06	9.7	4.8	15.3	-0.8	24.3	210.6
ψ''_r , Wb	-0.035064	-0.033974	-0.036169	-0.038327	-0.042721	0.034486	-0.051608	-0.17753
$\Delta \psi''_r$, Wb	0.001058	3.2E-05	0.002163	0.004321	0.008715	0.00048	0.017602	0.143524
$\delta \psi''_r$, %	3.1	0.1	6.4	12.7	25.6	1.4	51.8	422
ψ'_m , Wb	0.164817	0.164681	0.16487	0.164868	0.16615	-0.034248	0.166256	0.180226
$\Delta \psi'_m$, Wb	6E-06	-0.00013	5.9E-05	5.7E-05	0.001339	0.000242	0.001445	0.015415
$\delta \psi'_m$, %	0.01	-0.08	0.04	0.04	0.8	0.7	0.9	9.4
ψ''_m , Wb	-0.164706	-0.164628	-0.164554	-0.165327	-0.16529	0.164629	-0.16675	-0.179639
$\Delta \psi''_m$, Wb	0.000105	0.000183	0.000257	0.000516	0.000479	-0.000182	0.001939	0.014828

Parameters	Experiments No.							
	1	2	3	4	5	6	7	8
$\delta\psi''_m, \%$	0.06	0.1	0.16	0.3	0.3	-0,11	1.2	9.0

In Table 1 the following notation is used: R_{II} - the final value of the active component of the winding resistance; experiments No. 1, 3-5 were carried out at $\delta R = 0,2\%$, to ensure that the coefficient cm in manual mode was selected; experiments No. 2 $\delta R = 0\%$ demonstrates a high accuracy of the determination of the characteristic points in the absence of an error in determining the active component of the winding resistance; experiments No. 6-8 take into account that the decrease in the mass-dimension parameters of the EP-winding leads to both an increase in the active component of the winding resistance and a decrease in the cm coefficient, so increases the rate of change in the active component of the winding resistance during the determination of the magnetic characteristic.

4. Conclusion

The obtained results confirm the theoretical conclusions made and prove the high increasing relevance of the development of sensorless methods and devices for determining the electrical products magnetic characteristics.

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