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MINIMIZATION OF ACTIVE POWER LOSSES IN ALTERNATING CURRENT MAGNETIC SYSTEMS

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Abstract

In magnetic systems of electromagnetic alternating current devices, active power losses occur in steel and copper, reducing which is an urgent task. In order to minimize the loss of active power, a method based on the geometric optimization of the magnetic system has been developed. The optimization criteria are the coefficients of the proportionality principle. The last requirement is necessary for the proper coordination of the designed device with other mechanisms and for improving the technical and economic performance of the devices. One of the proportionality principles for electromagnetic devices is the construction of designs with a given coefficient $n_0 = h_0/c_0$*, where* h_0/c_0*, and are the height and thickness of the winding, respectively, as the overall dimensions of the device are mainly determined by these parameters. As a rule, the value of the coefficient* n_0 *can be ensured after the preliminary calculation of the magnetic circuit. On the other hand, there are complex interrelations between the coefficient* n_0 *ampere-turns, and the temperature rise of the winding. Excessive increase or decrease of the coefficient* n_0 *disrupts this principle, reduces the current density in the winding, increases the cross-section of the material and the winding capacity, and fails to achieve the specified temperature rise of the winding, etc. In this case, the main task of optimizing the winding dimensions is to ensure the maximum current density in the winding while maintaining the given coefficient* n_0*, temperature rise, and the ampere-turn values obtained from the preliminary calculation. In this study, for the most common electromagnetic design, considering the given ratios of winding height to its thickness, temperature rise, and ampere-turns, the optimal parameters and dimensions of the magnetic system have been determined. Loss minimization has been carried out for electromagnetic devices with voltage winding and current winding.*

Key words: electromechanical device, control system, frequency converter, control device, power part, modulation method, output voltage, three-phase autonomous voltage inverter, semiconductor device, analog-to-digital converter, controller, comporator.

I. Introduction

It is well-known that reducing losses of active power in electromagnetic devices operating with alternating current of various purposes (chokes, measurement transformers, relays, displacement and force transducers, etc.) is absolutely necessary, as it enhances the technical and economic performance of these devices. The research conducted in this direction has led to the development of electrical steels and conductive materials with improved characteristics. However, reducing losses of active power in alternating current magnetic systems (ACMS) is possible through the proper selection of the geometry of the magnetic system (MS) design.

In this study, the active resistances of the excitation winding (EW) r, the losses of active power in the EW windings P_{10}, the short-circuited turn (SCT) P_s, and the steel sections of the magnetic circuit P_m of alternating current magnetic systems (ACMS) are minimized using geometric optimization methods.

The optimization criteria are dimensionless coefficients of the proportionality principle: n_a=b/a, n_c=b/c , $n_0=h_0/c_0$ [3]. In this case, the core area of the magnetic circuit S_c=ab and the area of the EW $S_c=c_0h_0$ are considered as constant parameters, as they are respectively defined by the known values of magnetic induction in the core B_{max} and the ampere-turns of the EW F=IW [1,5].

In electromagnetic devices with current windings, the current value I in the winding remains constant when the air gap of the armature changes (I=const). However, in electromagnetic devices with voltage windings (U=const), increasing the armature air gap leads to an increase in the coil current because the coil inductance L decreases [1,2]. Due to this, the method of determining active power losses differs between I=const and U=const cases. In the former case $P_{10} \sim I^2$, while in the latter case, $P_{10} \sim U^2$.

The same applies to the losses of active power P_m caused by losses in the steel sections of the magnetic circuit. Additionally, some ACMS contain short-circuited turns (SCT), which also contribute to losses P_s. As a result, the total losses P are determined as the sum of P_{10}, P_s and P_m. This further complicates the determination of active power losses in ACMS [5-9].

The diagrams of the most common alternating current magnetic systems are shown in Fig. 1-3, where the main dimensions of the structures are indicated.

Taking into account the above, solutions to the following tasks are considered here:

1. Determination of the main dimensions and parameters of the MS using dimensionless coefficients of the proportionality principle $n_0=h_0/c_0$, n_a=b/a, n_c=b/c.
2. Selection of methods for determining active power losses for various alternating current magnetic systems [3].
3. Minimization of active power losses in the current winding (I=const), voltage winding (U=const) and closed loop.
4. Determination of the optimal values of the geometric dimensions of the magnetic circuit and EW.
5. Minimization of active power losses in the steel of the split pole of a single-phase electromagnet [8].

II. Statement and solution of the problem.

In this context, we utilize expressions for the electrical resistances of the excitation winding and the short-circuited turn.

$$Z = \frac{U}{I} = r_{10} + r_{\sim} + j(x_{1s} + x_m); \tag{1}$$

$$r_{10} = \rho_1 \frac{l_1 w_1^2}{k_{з1} S_{01}}; \quad r_k = \rho_k \frac{l_k w_k^2}{k_k S_k} \tag{2}$$

$$x = x_s + x_m = \sigma x_m \tag{3}$$

for the ampere-turns of the excitation winding (EW) and the short-circuited turn (SCT).

$$F_1 = j_1 k_{31} S_{01}; \quad F_2 = j_k k_k S_{02}; \quad F_2 = b_2 F_1, \tag{4}$$

for magnetic resistances of steel and air sections:

$$\dot{Z}_m = \frac{\dot{F}_1}{\dot{\Phi}_0} = R_m + jX_m \tag{5}$$

$$R_m = \rho_R \frac{l_m}{S_c}; \quad X_m = \rho_x \frac{l_m}{S_c}; \quad R_\delta = \frac{\delta}{\mu_0 S_c}, \tag{6}$$

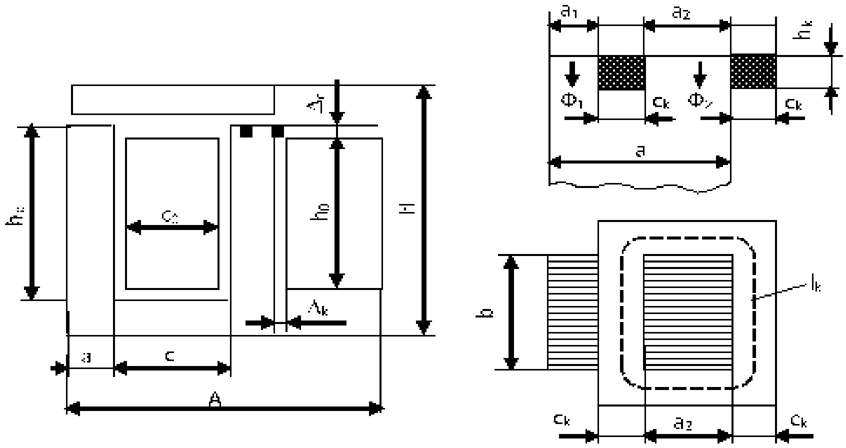
for losses of active capacities in the excitation winding P_{10}, the short-circuited coil P_k and the steel sections P_c:

$$P_{10} = I^2 r_{10}; \quad P_k = I_k^2 r_k; \quad P_c = I^2 r_\sim, \tag{7}$$

for the temperature rise of the excitation winding (EW) and the short-circuited turn (SCT).:

$$\tau_1 = \frac{P_{10} + P_k + P_c}{k_T S_{ox}}; \quad \tau_k = \frac{P_k}{k_T S_{ox}} \quad , \tag{8}$$

where r_{10} and r_k are the active resistances of the excitation winding (EW) and the short-circuited turn (SCT); $r_{\sim}$ is the equivalent active resistance, attributed to losses in the steel and SCT; x_{1s} and x_m are the leakage inductive resistance and the main inductive resistance of the EW, corresponding to leakage fluxes and the working magnetic flux Φ_0 ; ρ_1 and ρ_κ are the specific electrical resistances of the EW and SCT conductors; ρ_R and ρ_x are the specific active and reactive magnetic resistances of the steel; κ_{31} and κ_K are the fill factors of copper in the EW and SCT; σ is the coefficient of magnetic flux dispersion; j_1 and j_2 are the current densities in the EW and SCT; l_{cp1} and l_k are the average lengths of the winding turns in the EW and SCT; l_m is the average length of the path of the working magnetic flux Φ_0 ; R_m and x_m are the active and reactive magnetic resistances of the steel sections; R_δ is the magnetic resistance of the air gap δ through which the magnetic flux Φ_0 passes; τ_1 and τ_κ are the temperatures of overheating of the EW and SCT.



a) b)

Figure 1. *Magnetic system of a single-phase electromagnet with a split pole.*

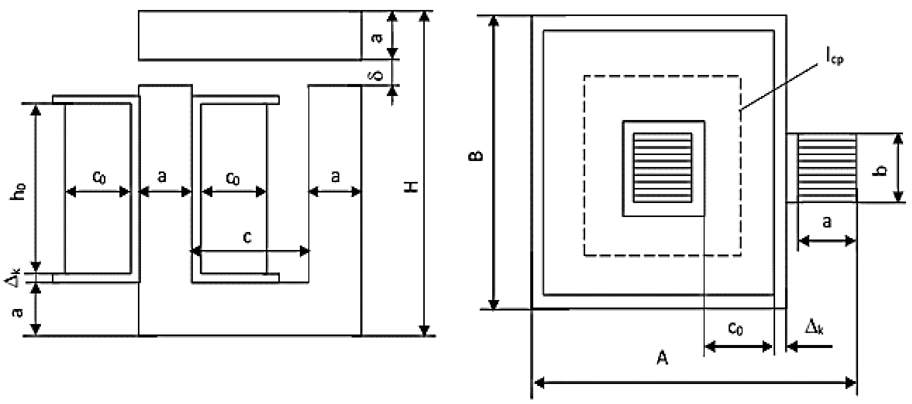


Figure 2. *Magnetic system of an inductive displacement transducer.*

The subscripts "1" and "k" in the formulas correspond respectively to the EW (excitation winding) and SCT (short-circuited turn). Formulas with the subscript "k" relate to Figures 1 and 2b.

The notations in the provided expressions are well-known [1-5] and do not require explanations. Equations (2) and (7) take into accou nt the overheating temperatures τ_1 and τ_k of the windings [3,5].

III. Definition of linear dimensions and key parameters in terms of dimensionless quantities.

To simplify optimization problem solutions, we will express linear dimensions and fundamental parameters in terms of dimensionless quantities.
Using the notations provided in Figures 1-2, we determine the overall dimensions of the magnetic system for a single-phase electromagnet and an inductive displacement transducer.

$$A = 2a + 2c_0 + 4\Delta_k \approx 2a + 2c = 2c\left(1 + \frac{n_c}{n_a}\right), \quad (9)$$

$$B = b + 2c_0 + 4\Delta_k \approx b + 2c = c(2 + n_c) \quad (9,a)$$

$$H = \delta_{mak} + 2a + h_0 + 2\Delta_k \approx \delta_{mak} + c\left(n_0 + 2\frac{n_c}{n_a}\right) \quad (9, b)$$

where

$$n_a = \frac{b}{a}; \;\; n_c = \frac{b}{c}; \;\; n_0 = \frac{h_0}{c_0}; \;\; b = cn_c; \;\; \frac{a}{c} = \frac{n_c}{n_a}. \quad (10)$$

$4\Delta_к \ll (2a + 2c_0)$; $4\Delta_к \leq (b + 2c_0)$; $2\Delta_к \ll (2a + h_0)$; $c = c_0$

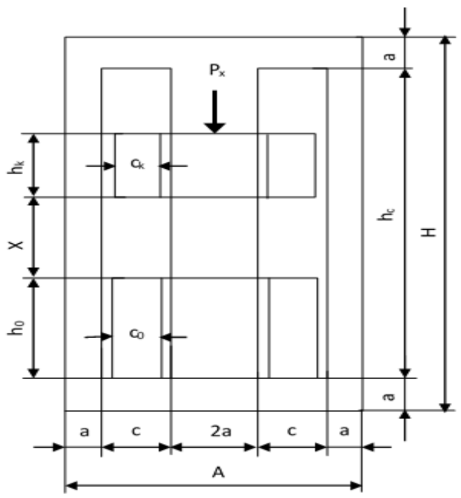


Figure 3. *Magnetic system of a force transducer.*

For the force transducer magnetic system (see Figure 3), we obtain:

$$A = 4a + 2c = 2c\left(1 + \frac{n_c}{n_a}\right) \quad (10, a)$$

$$B = b + 2c_0 + 4\Delta_k \approx b + 2c = c(2 + n_c) \quad (10, b)$$

$$H = x_{мак} + h_0 + h_k + 2a = x_{mak} + n_0 c_0 + n_{e2} c_k + 2a = x_{mak} + c\left(n_0 + n_{e2}\frac{c_k}{c} + 2\frac{n_c}{n_a}\right) \quad (10, c)$$

where

$x = x_{mak}$; $h_c = x_{mak} + h_0 + h_k$; $c_0 \approx c$;
$n_{e2} = h_k / c_k$; $4\Delta_k \ll (b + 2c_0)$.

The perimeters of the cross-sectional areas of the magnetic circuit rods M_c and the excitation winding M_0:

$$M_c = 2(a + b) = 2a(1 + n_a) = 2N_c\sqrt{S_c}; \quad (11)$$

$$M_0 = 2(c_0 + h_0) = 2c_0(1 + n_0) = 2N_0\sqrt{S_0}, \quad (12)$$

where

$$N_c = \frac{1+n_a}{\sqrt{n_a}}; \quad N_0 = \frac{1+n_0}{\sqrt{n_0}} \ . \tag{13}$$

The cross-sectional areas of the excitation winding S_0 and the magnetic circuit rod S_s

$$S_0 = c_0 h_0 = n_0 c_0^2 \ ; \quad S_s = a \cdot b = n_a a^2 = c_0^2 \frac{n_c^2}{n_a} \ . \tag{14}$$

According to equation (6), the active and reactive magnetic resistances of the steel sections through M_0 can be determined as:

$$R_m = \frac{\rho_R}{S_c}(M_0 + a'); \quad X_m = \frac{\rho_x}{S_c}(M_0 + a') \ , \tag{15}$$

where

$$l_m = 2(2a + h_c + c) = M_0 + a'; \tag{15,a}$$

$$a' = 4a + 10\Delta_k + 2\Delta_c = \Delta + 4\sqrt{\frac{S_c}{n_a}}; \quad \Delta = 10\Delta_k + 2\Delta_c; \quad \mathrm{c} = \mathrm{c}_0 + 3\Delta_k; \quad \mathrm{h_c} = h_0 + \Delta_c + 2\Delta_k;$$

$$a = \sqrt{\frac{S_c}{n_a}}; \quad \mathrm{c}_0 = \sqrt{\frac{S_0}{n_0}} \ .$$

The thickness of the excitation winding frame wall is approximately $\Delta_\kappa \approx (0.5 \div 1.0)10^{-3}$ m. The active resistances of the excitation winding and the short-circuited turn are determined by:

$$r_{10} = m_0' \left(M_c + 8\Delta_k + 4\sqrt{\frac{S_0}{n_0}} \right); \tag{16}$$

$$r_k = m_k' \left(2a_2 + 4c_k + 2\sqrt{n_a S_c} \right), \tag{17}$$

where

$$m_0' = \frac{\rho_1 w_1^2}{k_{30} S_0}; \quad m_k' = \frac{b_k^2 w_k^2 \rho_k}{k_k S_k}; \quad \mathrm{l_{cp}} = l_a + 4c_0; \quad l_a = 2(a + b + 4\Delta_k) = M_c + 8\Delta_k; \tag{18}$$

$$l_k = 2(a_2 + b + 2c_k) = 2a_2 + 4c_k + 2\sqrt{n_a S_c}; \tag{19}$$

The cooling area of the excitation winding, determined by the coefficient n_0 and the perimeter M_c, is calculated as:

$$S_{ox} = n_0 c_0 (l_a + 8c_0) = n_0 c_0 (M_c + 8\Delta_k + 8c_0) \tag{20}$$

In reference [3], the main linear dimensions and parameters of the direct current magnetic system are expressed in terms of dimensionless quantities in order to determine the dimensions of the magnetic system while considering the principle of proportionality. Explanations for the symbols provided above are also given.

From equations (11)–(16), it is easy to conclude that the magnetic resistances (R_m and X_m) and the electrical resistance (r_{10}) of the magnetic system are directly proportional to the perimeters M_c and M_0. Since these dimensions depend respectively on the dimensionless coefficients N_c and N_0, or on the optimization criteria n_a and n_0, the minimization of active power losses P_{10} should be carried out based on expressions (7) and (11)–(16). These expressions take into account the temperatures of overheating τ_1 and τ_k (or the dependence of specific electrical resistances ρ_1 and ρ_2 respectively on τ_1 and τ_k) and the influences of the coefficients n_a, n_c, and n_0 on the fundamental parameters and dimensions of the magnetic system [10-18].

IV. Conclusions

Active power losses in the steel sections of the magnetic circuit, the excitation winding conductors, and the short-circuited turn depend on the parameters of the electrical, magnetic, and thermal circuits of alternating current electromagnetic devices. Initial analytical expressions based on the equations of these circuits were derived, allowing linear dimensions and key parameters of ACMS to be expressed in terms of dimensionless quantities. The minimum values of the active electrical resistances of the excitation winding and the short-circuited turn, as well as active power losses, depend on the dimensional sizes of the cross-sectional areas of the excitation winding M_0 and the core.

In AC electromagnetic devices, the values of active power losses in the excitation winding conductors and the steel sections of the magnetic circuit vary significantly depending on the design of the ACMS. Through a comparative analysis of methods for determining active power losses, it was established that the method of equivalent electrical resistance allows for simultaneous consideration of all types of active power losses. However, in this case, the analytical expressions of parameters are quite cumbersome and do not allow for separate determination and comparison of all types of active power losses.

This drawback does not apply to the energy method and geometric optimization of the dimensions of the excitation winding and magnetic circuit. Optimization is carried out for electromagnetic devices with voltage and current windings, where the optimization criteria are the coefficients of proportionality principle n_a, n_c and n_0.

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