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4. POWER ENGINEERING AND ENERGY EFFICIENCY

DETERMINATION OF INDICATORS OF WEIGHT AND COST OF PLANARY SINGLE-PHASE ELECTROMAGNETIC SYSTEMS WITH RECTANGULAR CROSS-SECTIONS OF RODS

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In modern developments in the field of automation of technological processes, control systems for protection of electrical equipment, instrumentation, radio electronics, electrical systems and complexes, energy saving systems, as well as underwater (underground) -technological and aerospace purposes, one of the dimensional and material-intensive elements of modern electrical equipment is reactors. Most often, ESP uses traditional design solutions, such as planar (rod, armor) and spatial (toroidal) EMC with rectangular contours, which have a number of disadvantages. An alternative to this method of solving problems is a method of structural conversion of electromagnetic systems (EMC) of single-phase transformers. This method is to find new EMC structures that allow energy conservation, reducing the amount of useful space.

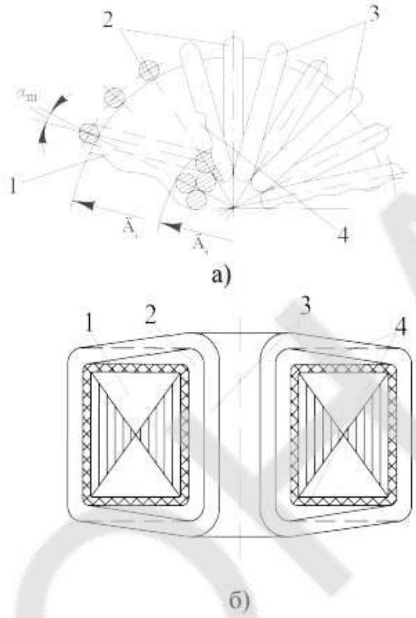
The aim of the work is a comparative analysis of mass and cost of single-phase planar rod and armor electromagnetic systems with rectangular sections of twisted magnetic conductors.

Keywords: single-phase transformer, magnetic circuit, optimization, comparative analysis.

1. ANALYSIS OF ADVANTAGES AND DISADVANTAGES OF SINGLE-PHASE TRANSFORMERS OF ROD CONSTRUCTION

1.1 The relevance of single-phase electromagnetic systems

The most popular in the "traditional" production of devices of planar EMF single-phase transformers do not meet the conditions of compact embedding in these shells and are characterized by mass dimensions that do not meet the requirements of special equipment. Symmetrical spatial EMCs are structurally adapted for placement in limited spherical and cylindrical volumes. Toroidal transformers have one of the single-phase versions of the spatial EMC with the configuration of the outer circuit, which corresponds to the circle. The presence of inclined media among the turns is due to the different values of the diameters Dn and Dv of the annular magnetic circuit on the calculations of transformers increased by 8-15% by the values of the winding stacking coefficient. This density, as well as the displacement at an angle α m of the opposite end sections of the coil, increase the average length of the coil, the loss and material consumption of the winding. The deterioration of heat dissipation caused by areas of hollow space, as well as the small bending radius of 900 angular zones of internal turns, reduce the reliability of toroidal transformers. In the "traditional" design and technical solutions of the active part of the transformers of small, medium and high power structures of planar and spatial EMC are formed by plane parallel andcylindrical surfaces forming rods and winding windows. The problem of creating systems of efficient electrical equipment for the conversion of electricity requires adequate calculations and comparative analysis of its elements. One of the material-intensive and dimensional elements in electrical installations up to 1000 kVA are single-phase transformers (OT) and reactors (OR) [1-5]. Such electromagnetic static devices (ESP) significantly affect the characteristics of electrical equipment in general: mass, dimensions, energy performance, as well as temperature and cost [1-3,6-10] and the task of improving them, in particular by optimizing the geometric ratios electromagnetic systems (EMC) are very relevant.



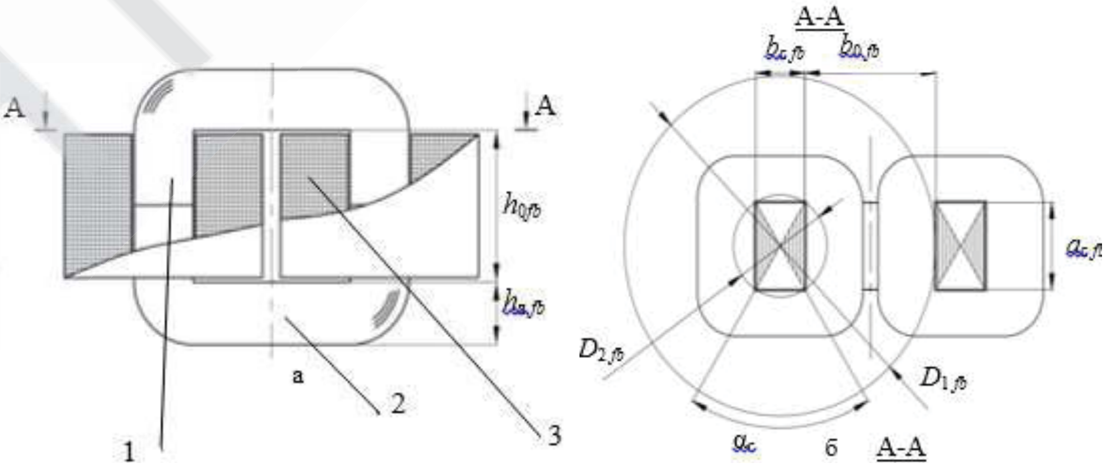
а)

б)

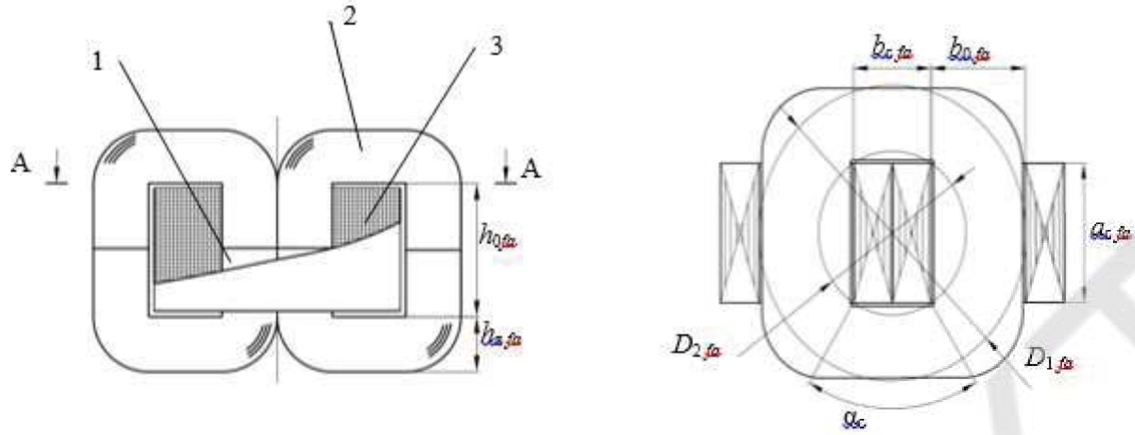
Fig. 1 Design and technical features on the fragment of the top view (a) and cross section (б) of the toroidal electromagnetic system: 1-magnetic circuit; 2-turns of the first (inner) layer; 3-turns of the second layer; 4-slope environment

1.2 Analysis of previous research

One of the most common are single-phase EMF ESP, which are given in [6-10]. The most used in various systems of electrical equipment are rod (Fig. 1, a) and armor (Fig. 1, б) EMC OT with twisted rectangular magnetic conductors of rectangular configurations.



a) b)



c) d)

Fig.2 - Structural diagrams and calculated geometrical parameters of the rod (a, b), armor (c, d) planar electromagnetic systems with rectangular winding windows and cross sections of the cores of the twisted magnetic circuit: 1 - rod; 2 - yoke; 3 - winding

In the works [11-17], devoted to the improvement and optimization of ESP, instead of geometric dimensions, relative geometric controlled variables were used, using which the limits of rational geometric ratios of winding window and rod cross section were met. In [15] on the basis of these variables [14] the criterion of minimum losses was determined. In [16] the optimization technique is made and the comparison of rod and armor variants of single-phase EMC with twisted and charged magnetic conductors with rectangular cross-sections of rods is made. This technique was based on the objective functions of individual criteria (minimums of mass, cost and volume) in determining the induction and average current density of windings based on temperature restrictions. Certain graphical dependences are obtained, however, the numerical results of comparing the characteristics of single-phase electromagnetic systems are uncertain. In general, the analysis of the work of domestic and foreign scientists raises the question of solving the problem of mass and cost minimization and optimal geometric ratios of these EMC variants of single-phase transformers and reactors, which has not been solved so far.According to the method of calculation of single-phase and three-phase transformers and reactors with rectangular sections of magnetic core rods contain inaccuracies and errors and no methods that allow to assess the technical level of ICP at the stage of choosing the basic structure, ie methods of structural synthesis of these devices. Also for the first time the problem is set and the generalized method of optimization of traditional EMC of single-phase and three-phase transformers and reactors with rectangular UK on separate criteria (weight, cost, losses) at definition of induction and average current density of windings at optimum geometrical ratios and set temperatures is developed. The possibility of optimization of transformers and reactors with the use of general CF and dimensionless (relative) controlled variables, which are offered in. It is determined that for all EMC structures with rectangular forming contours, the optimal ratio of the sides of the cross section of the rod is close to two, and the ratio of the sides of the window is more than two. As in the graphical dependences of the choice of optimal geometric ratios, including single-phase EMC, on the ratios of specific mass values.

1.3 Method of comparative analysis of electromagnetic systems

Numerical comparison of EMC variants is possible on the basis of development of design mathematical models (MM), which meet the requirements of invariance and electromagnetic equivalence of comparison and allow to determine generalized indicators of technical level of traditional and any other design of ESP.

The conditions of electromagnetic equivalence of comparison are met by the method of MM with objective functions (CF), which contain dimensionless optimization components with universal relative geometric and electromagnetically controlled variables (KZ) [18-20]. The extremes of these optimization components, ie indicators of the objective functions of individual optimization criteria, are indicators of the technical level (PTR) of EMC

$$F_{кii} = K_{цii}(\sqrt[4]{П_{вд}})^3 П^*_{кii}, \tag{1}$$

where$П_{вд}$- indicator of output data and electromagnetic loads; $К_{цii}$- component of specific characteristics of K≥3 CF materials of separate optimization criteria; $П^*_{кii}$-dimensionless optimization component, which characterizes each of the ii-CF, the main of which are the functions of mass F_1ii, cost F 2ii and active power losses F_3iiii-th variant of EMC.

Each of $П^*_{kiie}$depends on the coefficient of filling the winding window with the conductive material of the winding coils (voltage class) $К_{зо}$ and two identical and acceptable for any of the existing and possible variants of EMC short circuit - the ratio $a_м$ outer diameter D_{1ii} andinner diameter D_{2ii} calculation circuits of each magnetic circuit *ii-th* EMC variant (Table 1), the ratio λ_0 altitude h_{0ii} to width b_{0ii} winding window. The third relative geometric short circuit used in EMC optimization is the trigonometric function of the Central angle of the rod $t(\alpha_c)$ [18-20]:

$$П_{1(2)ii} = f(К_{30}, a_м, \lambda_0, t(\alpha_c)); \tag{2}$$

$$a_м = D_{1ii}/D_{2ii}; \tag{3}$$

$$\lambda_0 = h_{0ii}/b_{0ii}; \tag{4}$$

Component $К_{щii}$the objective function (1) includes, depending on the optimization criterion, the ratio of specific densities of materials (winding copper and ETS) (kg/m^3) $\gamma_o/\gamma_c = 8{,}9/7{,}65$and their values C_o/C_c=3,0…5,5, as well as stacking coefficients $K_у$=1,13 and bulging $K_в$ =1,15 turns of coils during impregnation [7-10] and the filling factor of the magnetic circuit ETS, $K_{зс}$=0,91. The calculations are performed at different voltage classes ($K_{зо}$ = 0,3 ... 0,2) and the actual ratios of the unit values of active materials in the range$C_c/C_o = 3{,}0...5{,}5$. A comparative analysis of these options according to the principle of electromagnetic equivalence [18-20] adopted in accordance with the same materials used, current density windings, the average values of the amplitudes of the magnetic field in the core and yoke and performance and cooling ESP ways, that is the same figures $П_{вд}$. In the calculations, the system of transformer windings is replaced by the design winding of a structurally and electromagnetically equivalent reactor [20]. EMC analysis is performed taking into account expressions (1) - (4), as well as the basic equations of communication of the parameters of the magnetic circuit and winding [18-20]. Such equations relate the cross-sectional area of the rod of the magnetic circuit S_{ci}, and the area of the winding window S_{oi}, as well as the mass of the winding system $m_{oi}$and the average length of the turn l_{wi}:

$$S_{ci} = \Pi_{вд} / \left(S_{oi}\text{К}_{зо}\right); \tag{5}$$

$$m_{oi} = S_{oi}\gamma_0 \text{К}_{зо} l_{wi}\,. \tag{6}$$

2. DEVELOPMENT OF MATHEMATICAL MODELS OF SINGLE-PHASE TRANSFORMERS

2.1. Development of mathematical models of mass and cost of a rod electromagnetic system with a charged magnetic wire

Development of MM variants of single-phase EMC with rectangular sections of rods of twisted magnetic conductors is performed using the notation of the dimensions of the elements (Fig. 1, b, d). The size of the sides $a_{cfb(fa)}$ and $b_{cfb(fa)}$ the cross section of the rod is determined by $D_{2fb(fa)}$ and $t(\alpha_c)$ equation:

$$a_{cfb(fa)} = D_{2\,fb(fa)} \sin\left(\alpha_c/2\right) \tag{7}$$

$$b_{cfb(fa)} = D_{2\,fb(fa)} \cos\left(\alpha_c/2\right) \tag{8}$$

The ETS cross-sectional area of the rod of each of the EMC magnetic circuits (Fig. 1, b, d) is determined taking into account (7) and (8)

$$S_{cfb(fa)} = D_{2\,fb(fa)}{}^2 \sin\left(\alpha_c\right)/2 \tag{9}$$

Widths of winding windows b_{0fb}(Fig. 1, b) and b_{0fa}(Fig. 1, d)depend on $D_{2fb(fa)}$, (3)and (8)

$$b_{0\,fb(fa)} = \left(D_{2\,fb(fa)}/2\right) - \left(b_{c\,fb(fa)}/2\right) = D_{2\,fb(fa)}/2\left(a_m - \sin\left(\alpha_c/2\right)\right); \tag{10}$$

The mass of the ETS of the EMC magnetic circuit (Fig. 1, b) is determined using (4), (9) and (10)

$$\begin{aligned} m_{mfb} &= \text{К}_{зс}\gamma_c\left(2h_{0\,fb}S_{c\,fb} + 2b_{0\,fb}S_{c\,fb} + \pi S_{c\,fb}b_{c\,fb}\right) = \\ &= 0{,}5\text{К}_{зс}\gamma_c D_{2\,fb}^3 \sin\alpha_c\left(\left(a_m - \sin\left(\alpha_c/2\right)\right)\times\left(\lambda_0 + 1\right) + \pi\sin\left(\alpha_c/2\right)\right) \end{aligned} \tag{11}$$

The mass of the ETS of the EMC magnetic circuit (Fig. 1, d) is determined using (4), (9) and (10)

$$\begin{aligned} m_{mfa} &= \text{К}_{зс}\gamma_c\left(4h_{0\,fa}S_{c\,fa} + 4b_{0\,fa}S_{c\,fa} + 2\pi\left(b_{cfa}/2\right)^2 a_{cfa}\right) = \\ &= 0{,}5\text{К}_{зс}\gamma_c D_{2\,fa}^3 \sin\alpha_c\left(\left(a_m - \sin\left(\alpha_c/2\right)\right)\times\left(\lambda_0 + 1\right) + 0{,}5\pi\sin\left(\alpha_c/2\right)\right) \end{aligned} \tag{12}$$

Based on (3), (5) and (10) we obtain the relationship between $S_{cfb(fa)}$ and $b_{0fb(fa)}$

$$\begin{aligned} S_{c\,fb(fa)} &= \Pi_{вд}\Big/\left(S_{0\,fb(fa)}\text{К}_{зо}\right) = \\ &= 4\Pi_{вд}\Big/\left(D_{2\,fb(fa)}^2\lambda_{0\,fb(fa)}\left(\sin\left(\alpha_c/2\right)\right)^2\text{К}_{зо}\right); \end{aligned} \tag{13}$$

$$S_{0\,fb(fa)} = h_{0\,fb(fa)}b_{0\,fb(fa)}\text{К}_{зо} = b_{0\,fb(fa)}^2\lambda_{0\,fb(fa)}\text{К}_{зо} \tag{14}$$

where$S_{0fb(fa)}$ – the area of the EMC winding window (Fig. 1b, d), From the equality of equations (2.21) and (2.24) it follows:

$$\text{К}_{\text{зс}} D_{2\,fb(fa)}^{2} \sin(\alpha_{\text{с}})/2 == 4\Pi_{\text{вд}} \Big/ D_{2\,fb(fa)}^{2} \lambda_{0\,fb(fa)} \left(a_m - \sin(\alpha_{\text{с}}/2)\right)^2 \text{К}_{\text{зо}}$$

$$D_{2\,fb(fa)} = \sqrt[4]{8\Pi_{\text{вд}} \Big/ \left(\text{К}_{\text{зо}} \text{К}_{\text{зс}} \lambda_{0\,fb(fa)} \sin(\alpha_{\text{с}})\left(a_m - \sin(\alpha_{\text{с}}/2)\right)^2\right)} \tag{15}$$

After substituting equations (15) in (11), the equation of the ETS mass of the EMC magnetic circuit (Fig. 1, b) will look like

$$m_{\text{м}fb} = \gamma_{\text{с}} \left(\sqrt[4]{\Pi_{\text{вд}}}\right)^3 \Pi_{m(fb)}^{*} \tag{16}$$

where $\Pi_{m(fb)}^{*}$ – dimensionless indicator of the mass of the magnetic circuit (Fig. 1, b),

$$\Pi_{mfb}^{*} = \left(\sqrt[4]{8 \Big/ \left(\text{К}_{\text{зо}} \text{К}_{\text{зс}} \lambda_0 \sin(\alpha_{\text{с}})\left(a_m - \sin(\alpha_{\text{с}}/2)\right)^2\right)}\right)^3 \times$$
$$\times 0{,}5\text{К}_{\text{зс}} \sin\alpha_{\text{с}} \left(\left(a_m - \sin(\alpha_{\text{с}}/2)\right)\left(\lambda_0 + 1\right) + \pi \sin(\alpha_{\text{с}}/2)\right) \tag{17}$$

After substituting equations (15) in (12), the equation of mass ETS of the EMC magnetic circuit (Fig. 1, d) will be transformed into

$$m_{\text{м}fa} = \gamma_{\text{с}} \left(\sqrt[4]{\Pi_{\text{вд}}}\right)^3 \Pi_{m(fa)}^{*} \tag{18}$$

where $\Pi_{m(fa)}^{*}$ – dimensionless indicator of the mass of the magnetic circuit (Fig. 1, d),

$$\Pi_{mfa}^{*} = \left(\sqrt[4]{8 \Big/ \left(\text{К}_{\text{зо}} \text{К}_{\text{зс}} \lambda_0 \sin(\alpha_{\text{с}})\left(a_m - \sin(\alpha_{\text{с}}/2)\right)^2\right)}\right)^3 \times 0{,}5\text{К}_{\text{зс}} \gamma_{\text{с}} \sin\alpha_{\text{с}} \times$$
$$\times \left(\left(a_m - \sin(\alpha_{\text{с}}/2)\right)\left(\lambda_0 + 1\right) + 0{,}5\pi \sin(\alpha_{\text{с}}/2)\right) \tag{19}$$

The average coil length of the EMC coil (Fig. 1.b) is determined on the basis of (7), (8) and (10)

$$l_{wfb} = 2\left(a_{cfb} + b_{cfb}\right) + \pi b_{0\,fb}/2 = D_{2\,fb} \times \left(\sin(\alpha_{\text{c}}/2) + \cos(\alpha_{\text{c}}/2) + \frac{\pi}{8}\left(a_m - \sin(\alpha_{\text{c}}/2)\right)\right) \tag{20}$$

The average coil length of the armor EMC (Fig. 1.d), is determined on the basis of (7), (8) and (10)

$$l_{wfa} = 2\left(a_{cfa} + b_{cfa}\right) + \pi b_{0\,fa} = D_{2\,fb} \times \left(\sin(\alpha_{\text{c}}/2) + \cos(\alpha_{\text{c}}/2) + \pi\left(a_m - \sin(\alpha_{\text{c}}/2)\right)/4\right) \times$$
$$\times \left(\sin(\alpha_{\text{c}}/2) + \cos(\alpha_{\text{c}}/2) + \pi\left(a_m - \sin(\alpha_{\text{c}}/2)\right)/4\right) \tag{21}$$

Substituting (14) and (10), (15) in (20) we obtain the equation of the mass of the copper winding for EMC (Fig. 1, b)

$$m_{ofb} = \left(\sqrt[4]{8\Pi_{\text{ид}} \Big/ \left(\text{К}_{\text{зо}} \text{К}_{\text{зс}} \lambda_0 \sin(\alpha_{\text{с}})\left(a_m - \sin(\alpha_{\text{с}}/2)\right)^2\right)}\right)^3$$
$$\times \gamma_{\text{о}} \text{К}_{\text{в}} \text{К}_{\text{у}} \text{К}_{\text{зо}} 0{,}5\lambda_0 \left(a_m - \sin(\alpha_{\text{с}}/2)\right)^2 \times \left(\left(\sin(\alpha_{\text{с}}/2) + \cos(\alpha_{\text{с}}/2)\right)\right) \tag{22}$$
$$+ \pi\left(a_m - \sin(\alpha_{\text{с}}/2)\right)\Big)/8 = \gamma_{\text{о}} \left(\sqrt[4]{\Pi_{\text{ид}}}\right)^3 \Pi_{ofb}^{*}$$

where Π_{ofb}^{*}–the relative mass of the active materials of the EMC winding (Fig. 1, b).

$$\begin{aligned}\Pi^*_{ofb} &= \left(\sqrt[4]{8/\left(\text{К}_{\text{зо}}\text{К}_{\text{зс}}\lambda_0\sin(\alpha_{\text{с}})(a_m-\sin(\alpha_{\text{с}}/2))^2\right)}\right)^3\\ &\times\gamma_{\text{о}}\text{К}_{\text{в}}\text{К}_{\text{у}}\text{К}_{\text{зо}}0{,}5\lambda_0(a_m-\sin(\alpha_{\text{с}}/2))^2 \qquad (23)\\ &\times((\sin(\alpha_{\text{с}}/2)+\cos(\alpha_{\text{с}}/2)))+\frac{\pi}{8}(a_m-\sin(\alpha_{\text{с}}/2))\end{aligned}$$

Substituting (14) and (10), (15) in (21) we obtain the equation of the mass of the copper winding for EMC (Fig. 1, d)

$$\begin{aligned}m_{ofa} &= \left(\sqrt[4]{8\Pi_{\text{вд}}/\text{К}_{\text{зо}}\text{К}_{\text{зс}}\lambda_0\sin(\alpha_{\text{с}})(a_m-\sin(\alpha_{\text{с}}/2))^2}\right)^3\\ &\times\gamma_{\text{о}}\text{К}_{\text{в}}\text{К}_{\text{у}}\text{К}_{\text{зо}}0{,}5\lambda_0(a_m-\sin(\alpha_{\text{с}}/2))^2 \qquad (24)\\ &\times(\sin(\alpha_{\text{с}}/2)+\cos(\alpha_{\text{с}}/2)+\pi(a_m-\sin(\alpha_{\text{с}}/2))/4)=\gamma_{\text{о}}\left(\sqrt[4]{\Pi_{\text{ид}}}\right)^3\Pi^*_{ofa}\end{aligned}$$

where Π^*_{ofa} - optimization component of CF mass of active materials of each of EMC windings (Fig. 1, d)

$$\begin{aligned}\Pi^*_{ofa} &= \left(\sqrt[4]{8/\left(\text{К}_{\text{зо}}\text{К}_{\text{зс}}\lambda_0\sin(\alpha_{\text{с}})(a_m-\sin(\alpha_{\text{с}}/2))^2\right)}\right)^3\times\gamma_{\text{о}}\text{К}_{\text{в}}\text{К}_{\text{у}}\text{К}_{\text{зо}}0{,}5\lambda_0(a_m-\sin(\alpha_{\text{с}}/2))^2\\ &\times(\sin(\alpha_{\text{с}}/2)+\cos(\alpha_{\text{с}}/2)+0{,}25\pi(a_m-\sin(\alpha_{\text{с}}/2))) \qquad (25)\end{aligned}$$

Mass$m_{afb}$and cost C_{afb}active materials EMC (Fig. 1, b), are determined on the basis of (16) and (22) equations:

$$m_{afb}=m_{mfb}+m_{ofb}=\gamma_{\text{с}}\left(\sqrt[4]{\Pi_{\text{ид}}}\right)^3\Pi^*_{mfb}+\gamma_{\text{о}}\left(\sqrt[4]{\Pi_{\text{ид}}}\right)^3\Pi^*_{ofb}=\gamma_{\text{с}}\left(\sqrt[4]{\Pi_{\text{ид}}}\right)^3\Pi^*_{1fb} \qquad (24)$$

$$\text{C}_{afb}=\text{C}_{mfb}+\text{C}_{ofb}=\gamma_{\text{с}}\text{C}_{\text{с}}\left(\sqrt[4]{\Pi_{\text{ид}}}\right)^3\Pi^*_{mfb}+\gamma_{\text{о}}C_{\text{о}}\left(\sqrt[4]{\Pi_{\text{ид}}}\right)^3\Pi^*_{ofb}=\gamma_{\text{с}}\left(\sqrt[4]{\Pi_{\text{ид}}}\right)^3\Pi^*_{2fb} \qquad (25)$$

where Π^*_{1fb} та Π^*_{2fb} – optimization components of CF mass and cost of planar EMC (Fig. 1, b) with rectangular sections of twisted rod magnetic circuit:

$$\begin{aligned}\Pi^*_{1fb} &= \left(\sqrt[4]{8/(\text{К}_{\text{зо}}\text{К}_{\text{зс}}\lambda_0\sin(\alpha_{\text{с}})((a_m-\sin(\alpha_{\text{с}}/2)))^2)}\right)^3\\ &\times\text{К}_{\text{зс}}0{,}5\sin\alpha(a_m-\sin(\alpha_{\text{с}}/2))(\lambda_0+1)+\pi\sin(\alpha_{\text{с}}/2)+\frac{\gamma_{\text{о}}}{\gamma_{\text{с}}}\text{К}_{\text{в}}\text{К}_{\text{у}}\text{К}_{\text{зо}} \qquad (26)\\ &\times0{,}5\lambda_0(a_m-\sin(\alpha_{\text{с}}/2))^2(\sin(\alpha_{\text{с}}/2)+\cos(\alpha_{\text{с}}/2))+\pi(a_m-\sin(\alpha_{\text{с}}/2))/8)\end{aligned}$$

$$\begin{aligned}\Pi^*_{2fb} &= \left(\sqrt[4]{8/(\text{К}_{\text{зо}}\text{К}_{\text{зс}}\lambda_0\sin(\alpha_{\text{с}})((a_m-\sin(\alpha_{\text{с}}/2)))^2)}\right)^3\\ &\times\text{К}_{\text{зс}}0{,}5\sin\alpha_{\text{с}}(a_m-\sin(\alpha_{\text{с}}/2))(\lambda_0+1)+\pi\sin(\alpha_{\text{с}}/2)+\frac{\text{C}_{\text{о}}\gamma_{\text{о}}}{\text{C}_{\text{с}}\gamma_{\text{с}}}\text{К}_{\text{в}}\text{К}_{\text{у}}\text{К}_{\text{зо}} \qquad (27)\\ &\times0{,}5(a_m-\sin(\alpha_{\text{с}}/2))^2(\sin(\alpha_{\text{с}}/2)+\cos(\alpha_{\text{с}}/2))+\pi(a_m-\sin(\alpha_{\text{с}}/2))/8\end{aligned}$$

Mass$m_{afa}$and cost C_{afa}active materials EMC (Fig. 1, d) are determined on the basis of (17) and (24) equations:

$$m_{afa}=m_{mfa}+m_{ofa}=\gamma_{\text{с}}\left(\sqrt[4]{\Pi_{\text{вд}}}\right)^3\Pi^*_{mfa}\gamma_{\text{о}}\left(\sqrt[4]{\Pi_{\text{вд}}}\right)^3\Pi^*_{ofa}=\gamma_{\text{с}}\left(\sqrt[4]{\Pi_{\text{вд}}}\right)^3\Pi^*_{1fa} \qquad (28)$$

$$\text{C}_{afa}=\text{C}_{mfa}+\text{C}_{ofa}=\gamma_{\text{с}}\text{C}_{\text{с}}\left(\sqrt[4]{\Pi_{\text{вд}}}\right)^3\Pi^*_{mfa}+\gamma_{\text{о}}C_{\text{о}}\left(\sqrt[4]{\Pi_{\text{вд}}}\right)^3\Pi^*_{ofa}=\gamma_{\text{с}}\left(\sqrt[4]{\Pi_{\text{вд}}}\right)^3\Pi^*_{2fa} \qquad (29)$$

where Π^*_{1fa} та Π^*_{2fa} – dimensionless indicators of mass and cost of planar armor EMC (Fig. 1, d) with a rectangular cross section of the rod of the twisted magnetic circuit:

$$\begin{aligned}\Pi^*_{1fa} &= \left(\sqrt[4]{8/\left(\text{K}_{\text{зо}}\text{K}_{\text{зс}}\lambda_0\sin(\alpha_{\text{c}})\left((a_m-\sin(\alpha_{\text{c}}/2))\right)^2\right)}\right)^3\\ &\times\text{K}_{\text{зс}}0{,}5\sin\alpha_{\text{c}}(a_m-\sin(\alpha_{\text{c}}/2))(\lambda_0+1)+\\ &+0{,}5\pi\sin(\alpha_{\text{c}}/2)+\frac{\gamma_{\text{o}}}{\gamma_{\text{c}}}\gamma_{\text{o}}\text{K}_{\text{в}}\text{K}_{\text{у}}\text{K}_{\text{зо}}\times0{,}5\pi\sin(\alpha_{\text{c}}/2)+\frac{\gamma_{\text{o}}}{\gamma_{\text{c}}}\gamma_{\text{o}}\text{K}_{\text{в}}\text{K}_{\text{у}}\text{K}_{\text{зо}}\times\\ &\times(\sin(\alpha_{\text{c}}/2)+\cos(\alpha_{\text{c}}/2)+\pi(a_m-\sin(\alpha_{\text{c}}/2))/4)\end{aligned}\qquad(30)$$

$$\begin{aligned}\Pi^*_{2fa} &= \left(\sqrt[4]{8/\left(\text{K}_{\text{зо}}\text{K}_{\text{зс}}\lambda_0\sin(\alpha_{\text{c}})(a_m-\sin(\alpha_{\text{c}}/2))^2\right)}\right)^3\times\text{K}_{\text{зс}}0{,}5\sin\alpha_{\text{c}}(a_m-\sin(\alpha_{\text{c}}/2))(\lambda_0+1)+\\ &+0{,}5\pi\sin(\alpha_{\text{c}}/2)+\frac{\text{C}_{\text{o}}\gamma_{\text{o}}}{\text{C}_{\text{c}}\gamma_{\text{c}}}\gamma_{\text{o}}\text{K}_{\text{в}}\text{K}_{\text{у}}\text{K}_{\text{зо}}\times\lambda_0 0{,}5(a_m-\sin(\alpha_{\text{c}}/2))^2(\sin(\alpha_{\text{c}}/2)+\cos(\alpha_{\text{c}}/2)+\\ &+\pi(a_m-\sin(\alpha_{\text{c}}/2))/4)\end{aligned}\qquad(31)$$

Table 1 - Extreme values of controlled variables and mass indices of single-phase rod and armor electromagnetic systems with rectangular cross-sections of rods of twisted magnetic conductors

Minimum mass index	The filling factor of the winding window, acting	Extreme values of controlled variables			The value of the minimum mass of the EMC, Acting
		a_{m}, acting.	λ_{0}, acting.	α_{c},	
1	2	3	4	5	6
Π^*_{1fbe} (fig. 1, b)	0,3	1,879	2,1	50,474	19,748
	0,25	2,013	2,095	50,362	20,778
	0,2	2,196	2,089	50,229	22,172
Π^*_{1fae} (fig. 1, e)	0,3	1,443	2,081	50,062	20,363
	0,25	1,537	2,076	49,957	21,587
	0,2	1,665	2,07	49,836	23,245

Extremes (minimums) $\Pi^*_{2fb(fa)\text{e}}$ optimization components of CF (27) and (31), obtained for three values $\text{K}_{\text{зо}}$, are shown in table 2.

Table 2 - Extreme values of the cost of single-phase rod and armor electromagnetic systems with rectangular sections of the rods of twisted magnetic conductors

Minimum value indicator, acting	The filling factor of the winding window, acting	The ratio of the costs of winding copper and electrical steel, acting				
		3,5	4	4,5	5	5,5
Π^*_{2fbe} (fig. 1,b)	0,3	37,682	40,597	43,393	46,088	48,696
	0,25	39,091	42,054	44,893	47,629	50,274
	0,2	40,999	44,027	46,926	49,715	52,411
Π^*_{2fae} (fig. 1, d)	0,3	36,827	39,454	41,964	44,376	46,706
	0,25	38,502	41,186	43,748	46,208	48,581
	0,2	40,771	43,532	46,164	48,689	51,122

3.DESCRIPTION AND COMPARISON OF INDICATORS OF ELECTROMAGNETIC SYSTEMS OF SINGLE-PHASE TRANSFORMERS WITH TWISTED AND SHIFTED MAGNETIC WIRES

Losses in the magnetic circuit of the distribution transformer can be reduced in two ways: by improving the quality of the material, by changing the design. In most modern distribution transformers, the magnetic circuit is made of cold-rolled anisotropic electrical steel. There are modern developments using amorphous steel, but due to the high cost of its economic efficiency has not been proven. The design of the magnetic circuit is not so simple. According to the method of connecting the rods with the yokes, the magnetic conductors are divided into butt, stacked, wound.

In the charged magnetic conductors, the plates of the rods and yokes are collected in the loop - the charge, so they do not have a continuous joint in the plane of the cross section, which leads to a significant reduction in nonmagnetic gaps and no-load current in comparison with buttoral magnetic conductors. According to the shape of the joint of the plates of the rods and the yoke of the loaded magnetic circuit are made with straight, oblique joints.

Magnetic conductors, the individual parts of which are made by winding from strips of electrical steel, and then fastened into a single system, are called coiled. The coiled magnetic circuit shown in Figure 4 has a low no-load current, which is due only to the loss of electrical steel, because there are no air gaps and areas in which the direction of magnetic flux does not coincide with the direction of rolled steel, but because it can not be disconnected, windings can not be worn. It is necessary to wind windings directly on a magnetic conductor is not technological and expensive.

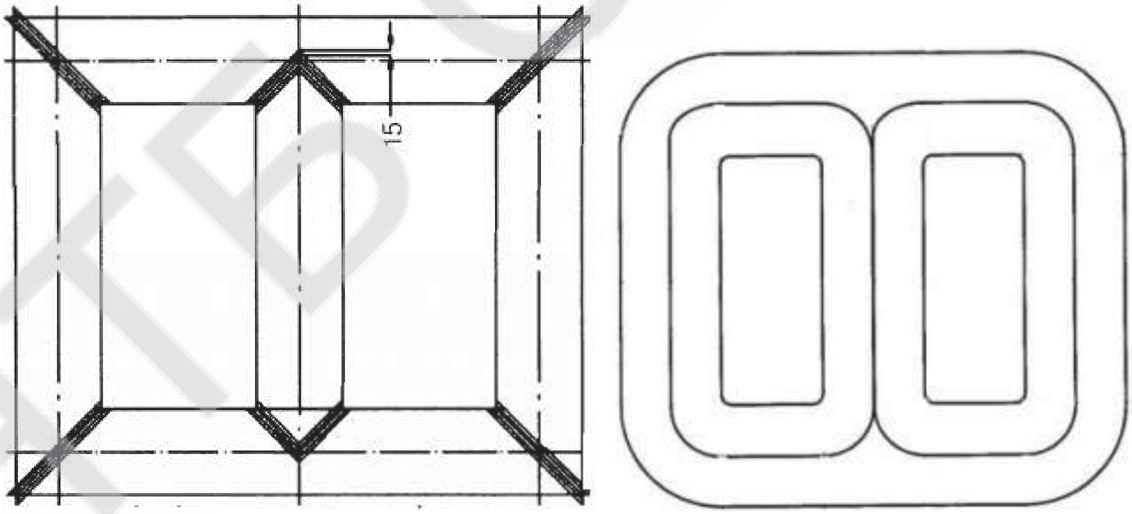


Fig. 3 - charged magnetic circuit; twisted magnetic circuit.

Table 3. shows the results of comparison of the calculated values of the technical level of variants of electromagnetic systems and the results of tests of samples of single-phase transformers with twisted magnetic circuits. Structural transformations of the active part are characterized by changes in indicators.

Table 3 - Extreme values of the controlled variables and indicators of the massiplanar rod electromagnetic system with a rectangular cross section of the rods of the charge

Mass index	The filling factor of the winding window, acting	Extreme values of controlled variables			The value of the mass of the EMC, Acting
		$a_{m,}$ Acting.	λ_0Acting.	α_c,	
Π^*_{1sf}	0,2	2,204	2,205	0,819	22,586
	0,25	2,024	2,220	0,824	21,189
	0,3	1,891	2,233	0,829	20,157

Table 4 - Extreme values of controlled variables and cost indicators of a planar rod electromagnetic system with a rectangular cross section of the rods of the shunt magnetic circuit

Cost indicator, acting	The filling factor of the winding window, acting	The ratio of the costs of winding copper and electrical steel, acting				
		3,5	4	4,5	5	5,5
Π^*_{2sf}	0,2	42,021	45,153	48,151	51,038	53,828
	0,25	40,106	43,172	46,111	48,943	51,682
	0,3	38,692	41,710	44,605	47,396	50,097

The results of calculations (Table 3,4) are graphically explained (Fig. 4–5), and show a numerical comparison of mass values in EMC with twisted and charged magnetic circuits.

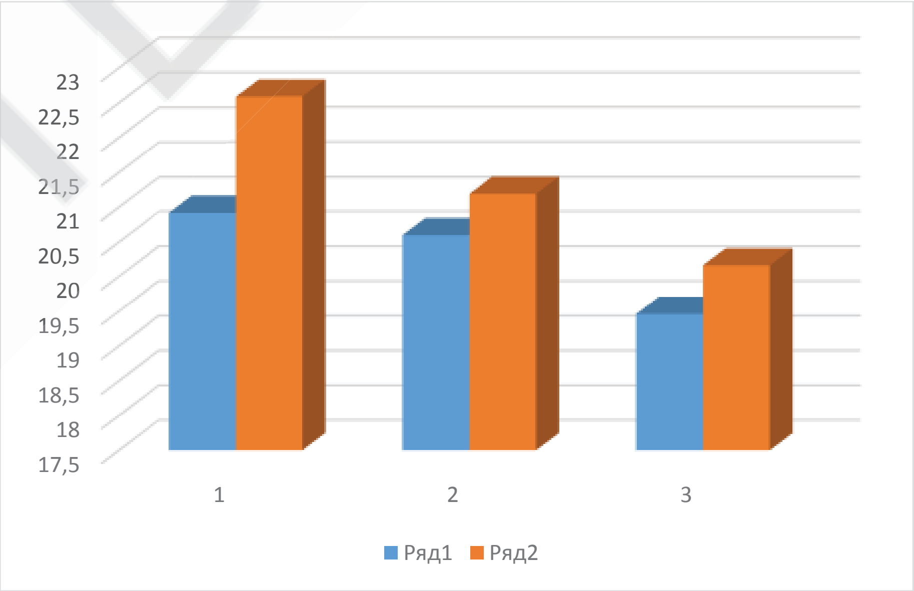


Fig. 4 Diagrams of comparison of indicators of technical level (mass) of single-phase electromagnetic systems with twisted and shifted magnetic conductors

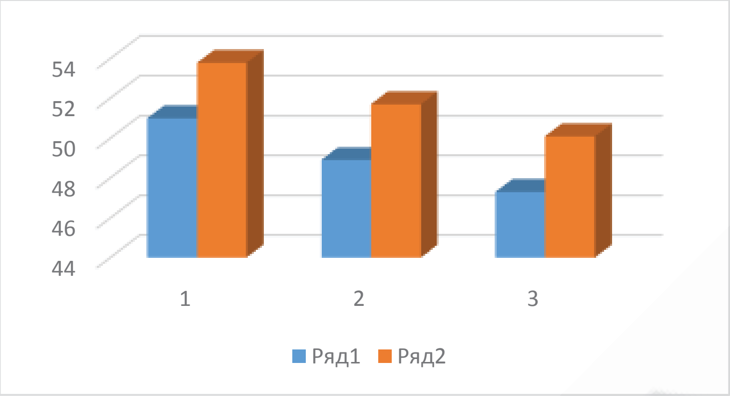


Fig. 5 Diagrams of comparison of indicators of technical level (cost 5; 5,5) of single-phase electromagnetic systems with twisted and charged magnetic conductors

Modern requirements to reduce material consumption, losses and increase the reliability of electrical equipment, as well as known structural and structural features and shortcomings of electromagnetic systems with traditional (rectangular) contours indicate the need to improve distribution and special induction static devices of different power, including single-phase transformers and single-phase reactors with twisted magnetic conductors.

Comparison of characteristics of industrial and experimental single-phase transformers with rectangular cross-sections of twisted magnetic conductors. An industrial sample of a single-phase transformer with a traditional magnetic core and an experimental sample of a single-phase transformer with a radial electromagnetic system, which is an analogue, were used.

Fig. 6 - Elements of the active part of the transformer: a - magnetic circuit; b - winding system

Both samples are designed for electrical and electronic equipment, power supply converters and other electrical equipment. By design, single-phase transformer versions are dry and have rated capacities $S_{н} = 0{,}9\ \text{кВ} \cdot \text{А}$and a voltage of 220/22 V. In comparison, control measurements of the mass of the elements of the active part were performed. The total mass of the transformer was $m_{afb} = \ 1{,}9\ \text{кг}$, of which 1.3 kg belongs to the magnetic circuit, and the mass of the winding copper, taking into account the terminals and sleeves is 0.61 kg.Calculation of the objective mass function m_{afb} and active power losses based on measured data and equations of mathematical models of the electromagnetic system showed that the efficiency value is 89%, which corresponds to the value of the efficiency of single-phase transformer rod design in the power range 60 ... 120 W and "passport" data. The calculated and real values of the mass of the electromagnetic system also almost coincide. Thus, the adequacy of mathematical models developed on the basis of the basic method is confirmed.The question of choosing a certain variant of the structure and forming circuits of rods and winding coils in the design can be solved on the basis of values of technical level indicators that meet certain optimization criteria for special transformers and reactors, or on the basis of structural-parametric synthesis of power induction static devices. criterion with the components of the objective function, namely F_{2ij} and F_{3ij}, as well as taking into account the technology and equipment used in the manufacture of magnetic conductors.

CONCLUSION

1. Indicators of technical level are determined by the criteria of minimums of mass and cost of rod and armor EMC, which made it possible to perform a numerical comparison of optimized mass values at different fill factors of the winding window.

2. The indicators of the mass of the planar rod EMC improve relative to the armor EMC by (4.6… 3)%, and the cost deteriorates by (0.6… 4)%.

3. The question of application of the EMC variant is determined by the conditions of a specific technical task for design and the requirements of design constraints of parametric synthesis.

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