ТЕХНІЧНІ НАУКИ

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LOSSES OF ACTIVE POWER OF SINGLE PHASE TRANSFORMERS AND REACTORS AND TWISTED MAGNETIC CIRCUITS

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Features of active power losses calculation and optimization of transformers and reactors by the criterion of a minimum of losses on the basis of an objective functions with dimensionless indices of a technical level and invariant relative controlled variables method are shown. The effect on the loss of active power of the replacement of rectangular forming contours of rods and winding coils on hexahedral in variants of planar and radial three-rod static electromagnetic systems with twisted magnetic circuits at frequencies of 50 Hz and 400 Hz is determined.

Key words*: single-phased transformer, twisted magnetic core, mass-costing and energy indexes, controlled variables.*

Introduction. It is known [1] that over the past 30 ... 50 years spent 3 ... 4 times more fuel and energy resources relative to the total energy costs since the beginning of human existence until the 70's of the twentieth century. It is also defined in [2] that 40% of energy transmission losses from generating sources to consumers come from transformers. Due to the nonlinear dependence of mass and losses on power, the task of further improving transformers and reactors of low and average power of mass release, including single-phase, is important and relevant.

The growth of requirements for energy saving requires innovative means for further improvement of transformers and reactors. However, the main methods of modern improvement [2-7], which during the last century [8, 9], are the use of improved electromaterials, in particular, tape amorphous electrotechnical steel (ETSt) and twisted magnetic conductors, as well as optimization parametric synthesis within the framework of traditional structures of electromagnetic systems (EMS). In connection with the known technological advantages, the capacity limit for the application of tape (roll) magnetic circuits is expanded in the production of these induction static devices (ISD). In this case, the experience of the use of transformers with power (32 ... 1250) kVA with amorphous ETS shows that an increase of (30 ... 35)% of their cost will pay off in 3-5 years [7]. However, for a significant proportion of transformers and reactors in the first turn of a specialized purpose [10], the use of a significantly expensive amorphous ETSt with overhead losses (fragile "glass" metal) is unsuitable. In such ISD, wired textured magnetic fluxes are used, in which there are no "angular" losses of the technology of charging the ETSt plates, which is a significant advantage.

Analysis of main achievements. In particular, the tasks of traditional modernization in the conditions of practical limit of improvement of electric materials, hard competition and modern requirements of energy resources preservation, there is a need to solve problems of further development of ISD by non-traditional systematic and heuristic methods, in particular structural and geometric transformations of EMS elements [8-12].

The variant of such a transformation is the replacement of the rectangular forming contours (FC) of the rods and coils of the coils (the first two circuits, Table 1) on the hexagon. This replacement provides an opportunity to increase the reliability and electrodynamic stability of windings and improve other ISD quality indicators [8-12].

The hexagonal rods of the rods (circuits 3, 4 and 6, Table 1) are formed by the assembly of magnetic circuits from sections flowing from a variable width band. The required configuration of the tape is provided with a non-waste "squint" separating the rectangular scanning of the ETSt into two bundles of the same type. "Figure" cutting of roller ETS technological contaminants is not called and is used, for example, at the Minsk and Moscow transformer plants for the insertion of twisted sections in circular FC of three-phase EMS [8].

Replacement of a magnetic circuit formation of one or two sections (Schemes 1, 2, Table 1) for four, increases the labor-intensity of assembly several times. However, to approximate the magnetic properties of the magnetic circuit to the specific characteristics of the ETSt and minimize the coefficient of additional losses (K_n=1,1…1,3)), a small difference in the lengths of the magnetic lines (ETSt turns) on the external and internal contour [5] is required, which contradicts the rational geometric EMC ratio. Therefore, the sectioning of the magnetic circuit minimizes the magnitude of the Kd and is positive for reasons of energy conservation.

Another way of reducing the material intensity of single-phase EMS structural and geometric transformations is to increase the core of the magnetic flux to three and the location of their axes and winding coils at an angle of 60° (options 5, 6, Table 1) [8-12].

With the structural stability of EMS variants with traditional (rectangular in ISD of small and medium power CV) and the influence of the factor of "technological conservatism", the feasibility of new developments and the practical use of non-traditional EMS proposals must be proved by objective analytical substantiation.

This justification is possible on the basis of target functions (TF) of the general structural synthesis of ISD [11].

The aim of the study The general optimization comparison, in addition to the analysis of mass indices [12], shows the loss of active power of single-phase EMS with twisted magnetic conductors, which differ in structural and geometric peculiarities.

Method and results of the study The main controlled changes (CV) of the optimization TF of the ISD with traditional FC are the geometric sizes and electromagnetic loading (EML) [4-6, 11]. Such CV (the diameter of the FC or the ratio of the sides of the rectangular intersection of the rod ...) do not satisfy the requirement of universality of application. Also, the optimization process with the variation of EML (the mean value of the induction amplitude of the rod B_c and windings current density j_n (n ≥ 1)) are tied to the specific execution, power range, type of cooling, which complicates the research structural synthesis of EMC.

The method of determining the general mathematical models of varieties of EMS must ensure their comparison, while observing the principle of electromagnetic equivalence of EMS variants of construction of ISD and the invariance of the form of the TF and CV. The versatile CV are accepted and identical for the variants of the structures and configurations of the EMS elements that are compared and by any other possible non-traditional EMS proposals. However, this principle is in contradiction with the process of parametric synthesis of EMS, which involves the change of EML, as well as control of design constraints, in particular checking the heating of windings. In turn, the variation of EML with parametric optimization contradicts the solving of the problem of generalized structural synthesis of EMS from the above-mentioned reasons for the presence of certain ranges of EML changes, which depends primarily on the power and method of heat removal from the EMS ISD [11, 12]. Therefore, in order to eliminate these contradictions, the main shortcomings and the individual optimization criteria must be presented in relatively large and non-dimensional forms.

The described conditions of the invariance of the comparative analysis of any ii – variants of EMS satisfy a universal TF with identical CV by separate criteria for the optimization of static and rotary converters and devices [11]

$$F_{\mathrm{k}ii} = \mathrm{K}_{\mathrm{п}ii}\left(\sqrt[4]{\Pi_{ii}}\right)^3 \Pi^*_{\mathrm{k}ii}, \qquad (1)$$

where Π_{ii} – indicator of output data and EMN (design specification) and EMN of ii – variants of EMS; K_{nii} – specific characteristic of the used material (ETSt), specific characteristics of other materials (copper, aluminum) are included in dimensionless wool, that is, with a ratio of K_{nii}, to an optimization dimensionless component Π^*_{kii}, which characterizes K≥3 TF of mass F_{1ii}, cost F_{2ii} and loss of active power F_{3ii}, as well as other possible special TF for example, contour volume, the minimum of which is the condition of installation in a cylindrical (spherical) shell of a limited diameter of equipment underwater (aerospace) apparatus [10].

Extreme Π^*_{kiie} of dimensionless component Π^*_{kii} CV (1) is an indicator of the technical level (ITL of an electromechanical device. In the case of transformers and reactors, geometric CV are used, when determining Π^*_{kiie} (K≥3), when determining Π^*_{kiie}, depending on the type, number and combination of winding materials (copper, aluminum), one or more relative electromagnetic CV are used. The main geometric CV are the ratio α_m and λ_0 accordingly to the diameters D_{1ii} and D_{2ii} of the calculation circles and height h_{0ii} and width b_{0ii} of the winding window of the magnetic circuit (diagrams of Table 1):

$$a_m = D_{1ii} / D_{2ii} ; \quad (2)$$

$$\lambda_0 = h_{0ii} / b_{0ii} . \quad (3)$$

In the CV of some EMS (Schemes 1-4, Tabl 1), an additional geometric CV is also used for the central angle of the rod α_c.

To determine F_{3ii} of ISD types, including single-phase transformers (SPT) and single-phase reactors (SPR) on the basis of specific components Π^*_{3ii} the correlation CV of $K_{\text{п}ii}$ coefficients of additional losses of specific characteristics of materials is also used,

$$K_{nii} = K_d \gamma_o \Pi_{\text{по}} / K_{nii} \gamma_s P_{pm} , \quad (4)$$

where K_d, K_{nii} – coefficients of additional short circuit losses (load losses of the winding) and loss of non-working motion (loss in the magnetic circuit) of the transformer (reactor) with the *ii* – variant of EMS; γo(s) – specific mass of the winding (magnetic core); $\Pi_{\text{по}}$– specific losses of the winding; P_{pm} – specific losses of the ETSt of the magnetic circuit [5, 6].

In addition to the indicated CV, the components Π^*_{kii} depend on the coefficient $K_{зо}$ of filling the winding with the active material (voltage class) of ISD:

$$\Pi^*_{1(2)i} = f_{1(2)}(K_{30}, \alpha_c, a_m, \lambda_0); \quad (5)$$

$$\Pi^*_{3ii} = f_3(K_{30}, \alpha_c, a_m, \lambda_0, K_{nii}). \quad (6)$$

When the dimensionless optimization components are defined, a collection is used Indicators Пii CV (1) SPT (SPR) accordingly Π_{ot} and Π_{or} are determined [11, 12]:

$$\Pi_{ot} = \frac{S_n}{4{,}44 B_c f_1}\left(\frac{K_{U1}\cos\varphi_2}{\eta\cos\varphi_1 J_1} + \frac{K_{U2}}{J_2}\right);$$

$$\Pi_{or} = \frac{Q_n}{4{,}44 B_c f_1 J_o},$$

where S_n i Q_n – nominal capacities of the transformer and reactor; f_1 – current frequency; KU1, KU2, η, $Jo_1(2)$, $\cos\varphi_2(1)$ i $J_1(2)$ – coefficients of nominal voltage change under load, energy load factor, previously taken at designing the value of the efficiency coefficient and energy coefficient and the current density of the primary (secondary) winding SPT; η – preliminary calculated transformer efficiency; J_0 – current density of MPR winding.

Components Π_{ii} CV (1) are not part of the optimization components (5), but the relative electromagnetic CV(4) are dependent only on the CF (2), (3) and α_c. Components П*ii* are also not part of the component (6), but their own electromagnetic CV (4) is a function of Bc and Jn. Therefore, the problem of comparative energy efficiency analysis of the investigated variants is solved by comparing the two values ITL (Π^*_{3iie})' and (Π^*_{3iie})" 'of each EMS. Extremes (Π^*_{3iie})' and (Π^*_{3iie})" 'are determined at the minimum (') and maximum (") fixed values of CV $K_{\text{п}ii}$'("). The boundary values '(") of electromagnetic CV correspond to known ranges of EML changes in constructive execution and within the boundaries of EML changes [5,6], which respectively exist and are used in the design of ISD.

It was shown in [11] that identical EMS structures of transformers and reactors with closed magnetic circuits, with identical individual optimization criteria and relative units, have relatively similar average warp lengths, mass and losses of rated windings and magnetic conductors, as well as the main ITL and optimal geometric ratios of EMS according to the criteria of mass, cost and loss of active power and contour volume. Therefore, the average length of the circle of the equivalent design voltage of the transformer (in relative units) can be determined on the basis of replacement of the winding system of different voltages by winding a structurally-equivalent reactor with current density J_o. This significantly simplifies the construction of the MM EMS with constructive uncertainty of the coordinates of the average turns (concentrators) of windings, for example, EMS (Schemes 5, 6, Table 1).

In accordance with the principle of EMN (identity $П_{ot(or)}$) in the analysis of the energy efficiency of the compared ISD, the one-wave classes of voltage (the value of K_{zo}) of windings, the magnitudes of the EML, the design performance, the cooling modes, the coefficients of filling the K_{zs} of the magnetic circuit, the coefficients of stacking and protrusion at impregnation of windings [5, 6]. With the identity of the production technology of twisted magnetic circuits, the magnitude of the coefficients of the additional losses of the non-operating motion of the EMS variants (Table 1) are taken equal K_{dii}=K_n.

According to [5, 6], in modern SPT and SPT anisotropic ETS grades 3406 - 3409 at frequencies of 50 Hz and 400 Hz, accordingly J_0=1,4– 2,5 A/mm^2 [5, 6] with K_{zs} = 0,96 – 0,97 at the thickness of tape δc = 0,27 – 0,35 mm, K_{zs} = 0,9 at the thickness of the tape (roll) δ_c = 0,15 mm. For calculations at a frequency of 50 Hz K_{nii} and the values B_c = 1,45 – 1,7 T i K_{zs}=0,97 (δc = 0,35 mm) and mark of anisotropic roll ETSt 3407 are taken, in which at f_1 = 50 Hz specific losses at B_c = 1,45 T and B_c = 1,7 T are ETSt 3407 P1.45/50 = 0,988 W / kg, P1.7/50 = 1,36 W / kg. ETSt density γ_c=7650 kg/m^3. For calculations at a frequency of 400 Hz, K_{nii} and the values B_c = 1 – 1,4 T, K_{zs}=0,9 (δc = 0,15 mm) and mark of anisotropic roll ETSt 3407 are taken, in wich specific losses at B_c = 1 T and B_c = 1,4 T are ETS 3407 P1/400 = 10,63 W / kg, P1.5/400 = 23,924 W / kg. ETSt densit γ_c=7750 kg/m3.

In calculations of single-phase ISD "dry" and "oil" performance with a power of 10 ... 160 kVA, as well as 160 ... 630 кV·A, the values K_d < 1,04 і K_d < 1,075 [26] are used. Accepted K_d = 1,04. For copper AMO with γo = 8900 kg/m^3, $K_{по}$ = 2,4·10^{12} W m^4 /(A^2·kg) і при f_1= 50 Hz, in the ranges S_n = 0,3-1 кV·A and S_n = 1 – 2,5 кV·A accordingly J_0 = 2,4 – 1,7 A/mm and J_0 = 1,7 – 2,4mm^2 [20 - 23]. Also, for f_1= 50 Hz for copper AMO in oil SPT at S_n =2,5 – 63 kV·A, J_0 = 1,8 – 2,2 A/mm^2 and at S_n = 63 – 630 kV·A, J_0 = 2,2 – 3,5 A/mm^2, and in the "dry" SPT with S_n = 10 – 1600 кV·A half-volume of the current density of the primary and secondary concentric windings is J_0 = 1,4–2,5 A/mm^2 [5, 6].

In connection with the dependence of additional losses of the magnetic core on geometric and technological factors [5, 6], the determination of EMS variants (Table 1) is performed on the basis of the above values of EMN, specific characteristics and K_d with the minimum and maximum values of Kd [5].

At K_d=1,1 the value of the CV (4) at a frequency of 50 Hz is in the ranges:

$$K_{n1} \geq \frac{1{,}04 \cdot 8900 \cdot 2{,}4 \cdot 10^{-12}\left(1{,}4 \cdot 10^6\right)^2}{1{,}1 \cdot 7650 \cdot 1{,}36} = 3{,}805;$$

$$K'_{n1} \geq \frac{1{,}04 \cdot 8900 \cdot 2{,}4 \cdot 10^{-12}\left(2{,}4 \cdot 10^6\right)^2}{1{,}1 \cdot 7650 \cdot 1{,}36} = 11{,}181;$$

$$K''_{n1} \geq \frac{1{,}04 \cdot 8900 \cdot 2{,}4 \cdot 10^{-12}\left(3{,}5 \cdot 10^6\right)^2}{1{,}1 \cdot 7650 \cdot 0{,}988} = 32{,}731 \cdot$$

Accepted as boundary K_{n1min} and K_{n1max} ratio (4) for K_d =1,1 and frequency f_1=50 Hz

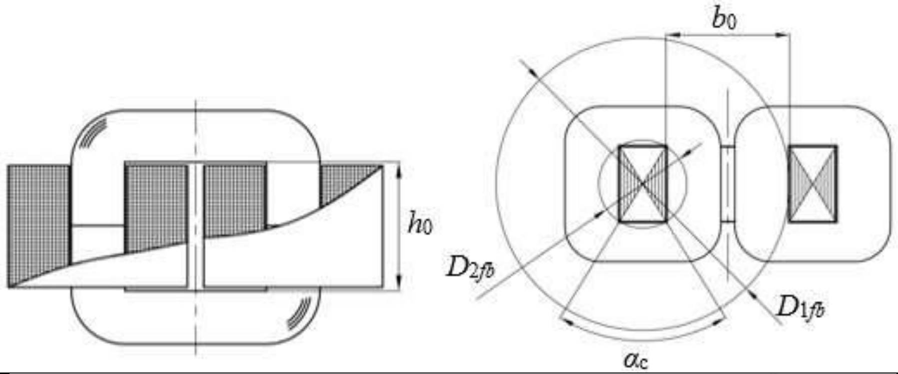
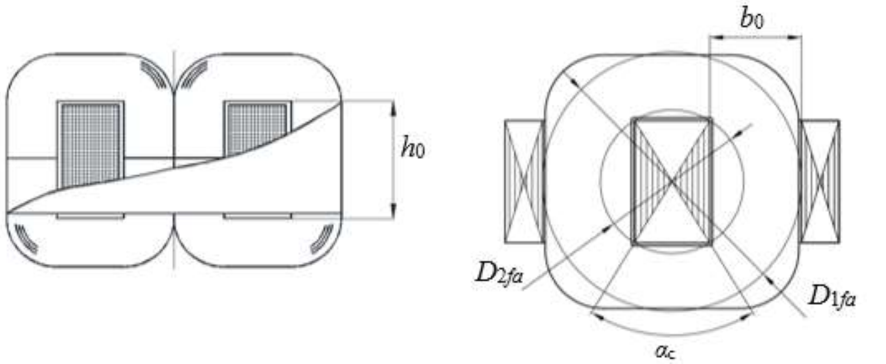
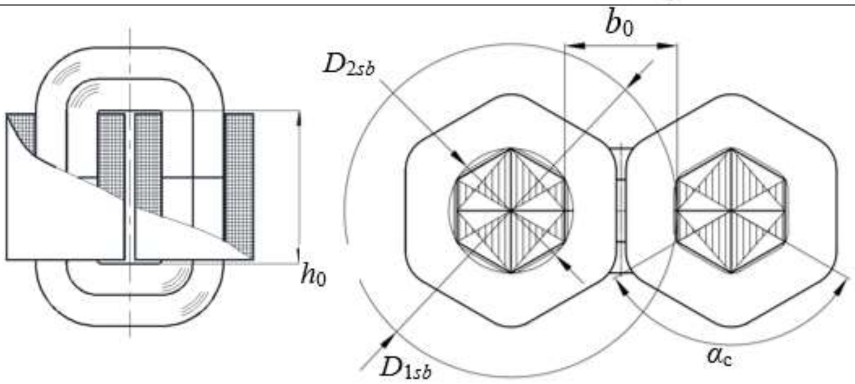
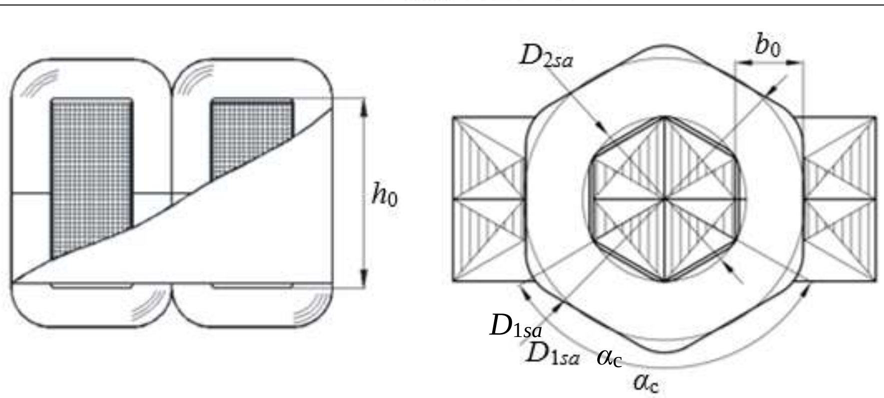
$$3{,}8 \leq K_{n1} \leq 11{,}1(32{,}7) \qquad (7)$$

At K_d =1,3 the value of the CV (4) at a frequency of 50 Hz is in the ranges:

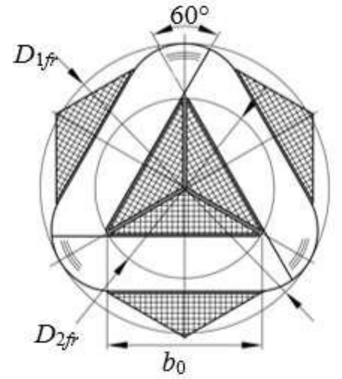
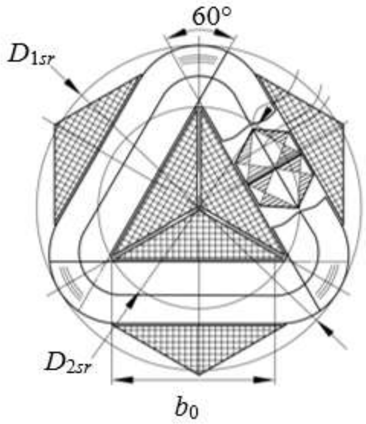
$$K_{n2} \geq \frac{1{,}04 \cdot 8900 \cdot 2{,}4 \cdot 10^{-12}\left(1{,}4 \cdot 10^6\right)^2}{1{,}3 \cdot 7650 \cdot 1{,}36} = 3{,}219;$$

Table 1

Variants of constructive schemes and designation of indicators of the technical level of single-phase static electromagnetic systems

№ Figure	Constructive scheme	Designation of the indicator
1	2	3
1		Π^*_{3fb}
2		Π^*_{3fa}
3		Π^*_{3sb}
4		Π^*_{3sa}

Continue table 1

5		Π^*_{3fr}
6		Π^*_{3sr}

$$K'_{n2} \geq \frac{1{,}04 \cdot 8900 \cdot 2{,}4 \cdot 10^{-12}\left(2{,}4 \cdot 10^{6}\right)^{2}}{1{,}3 \cdot 7650 \cdot 1{,}36} = 9{,}46;$$

$$K''_{n2} \geq \frac{1{,}04 \cdot 8900 \cdot 2{,}4 \cdot 10^{-12}\left(3{,}5 \cdot 10^{6}\right)^{2}}{1{,}3 \cdot 7650 \cdot 0{,}988} = 27{,}695.$$

Accepted as boundary K_{n2min} and K_{n2max} ratio (4) for K_d=1,3 and frequency f_1=50 Hz

$$3{,}219 \leq K_{n1} \leq 9{,}46(27{,}695) \tag{8}$$

According to [5], in modern SPT and SPR at the frequency f_1=400 Hz anisotropic ETSt of grades 3406-3409 with K_{zs}= 0,9 is used at tape thickness δ=0,15 mm. For the calculations of K_{nii} the following is taken:

At K_d=1,4 the value of the CV (4) at a frequency of 50 Hz is in the ranges:

$$K_{n1} \geq \frac{1{,}04 \cdot 8900 \cdot 2{,}4 \cdot 10^{-12}\left(1{,}4 \cdot 10^{6}\right)^{2}}{1{,}4 \cdot 7750 \cdot 23{,}924} = 0{,}377;$$

$$K'_{n1} \leq \frac{1{,}04 \cdot 8900 \cdot 2{,}4 \cdot 10^{-12}\left(2{,}4 \cdot 10^{6}\right)^{2}}{1{,}4 \cdot 7750 \cdot 10{,}633} = 0{,}493;$$

$$K''_{n1} \leq \frac{1{,}04 \cdot 8900 \cdot 2{,}4 \cdot 10^{-12}\left(3{,}5 \cdot 10^{6}\right)^{2}}{1{,}4 \cdot 7750 \cdot 10{,}633} = 2{,}36.$$

Accepted as boundary K_{n1min} and K_{n1max} ratio (4) for K_d=1,4 and frequency f_1=400 Hz

$$0{,}38 \leq K_{n1} \leq 0{,}49(2{,}36) \tag{9}$$

At Kd =1,7 the value of the CV (4) at a frequency of 400 Hz is in the ranges:

$$K_{n2} \geq \frac{1{,}04 \cdot 8900 \cdot 2{,}4 \cdot 10^{-12}\left(1{,}4 \cdot 10^{6}\right)^{2}}{1{,}7 \cdot 7750 \cdot 23{,}924} = 0{,}14;$$

$$K'_{n2} \leq \frac{1{,}04 \cdot 8900 \cdot 2{,}4 \cdot 10^{-12}\left(2{,}4 \cdot 10^{6}\right)^{2}}{1{,}7 \cdot 7750 \cdot 23{,}92} = 0{,}41;$$

$$K''_{n2} \leq \frac{1{,}04 \cdot 8900 \cdot 2{,}4 \cdot 10^{-12}\left(3{,}5 \cdot 10^{6}\right)^{2}}{1{,}7 \cdot 7750 \cdot 0{,}988} = 1{,}05.$$

Accepted as boundary $K_{n2\min}$ and $K_{n2\max}$ ratio (4) for K_d =1,7 and frequency f_1=400 Hz

$$0{,}14 \leq K_{n1} \leq 0{,}41(1{,}05) \qquad (10)$$

When constructing MM with the components (5), (6), of determining losses of single-phase static EMS variants (Table 1) using the mass equation [12] of the elements of the EMS.

The optimization calculations results of EMS variants parameters (Table 1) for values (f1=50 Hz) and (f1=400 Hz) are shown in Table. 2 and Table 3. The basic version of the comparative analysis adopted a traditional rod EMS with rectangular FK (Scheme 1, Table 1).

The performed optimization calculations show that structural-geometric transformations of traditional EMS (variants 1, 2, Table 1) to the species (options 3-6, Table 1) in addition to improving the mass performance reduces the loss of active power of ISD.

Table 2

Extreme values of active power losses of wired electromagnetic system at frequency f1 = 50 Hz

Indicator	Coefficient of winding windows filling, r.u.	Indicator of active power loss, r.u. at the ratio of additional losses coefficients, specific characteristics of materials and electromagnetic loads.					
		3,805	11,181	32,737	3,2	9,46	27,7
1	2	3	4	5	6	7	8
1	0,3	39,476	74,5	148,386	35,865	67,241	132,895
	0,25	40,914	76,385	150,851	37,243	69,048	135,267
	0,2	42,863	78,937	154,191	39,109	71,496	138,464
2	0,3	38,444	69,523	133,781	35,185	63,137	120,385
	0,25	40,155	71,763	136,706	36,823	65,285	123,192
	0,2	42,472	74,798	140,678	39,042	68,196	127,001
3	0,3	38,662	72,708	144,164	35,151	65,604	129,178
	0,25	40,102	74,582	146,66	36,531	67,414	131,611
	0,2	42,053	77,087	150,026	38,4	69,877	134,766
4	0,3	37,767	67,974	130,277	34,593	61,774	117,281
	0,25	39,48	70,219	133,194	36,232	63,927	120,1
	0,2	41,799	73,264	137,176	38,455	66,843	123,92
5	0,3	36,916	70,196	140,497	33,49	63,294	125,754
	0,25	38,202	71,894	142,736	34,72	64,92	127,899
	0,2	39,942	74,191	145,765	36,384	67,12	130,8
6	0,3	35,126	67,725	136,985	31,787	60,947	122,437
	0,25	36,254	69,216	138,953	32,865	62,375	124,321
	0,2	37,78	71,233	141,614	34,324	64,307	126,871

Table 3

Extreme values of active power losses of wired electromagnetic system at frequency f1 = 400 Hz

Indicator	Coefficient of winding windows filling, r.u.	Indicator of active power loss, r.u. at the ratio of additional losses coefficients, specific characteristics of materials and electromagnetic loads					
		0,311	1,109	2,36	0,14	0,406	1,048
1	2	3	4	5	6	7	8
1	0,3	13,329	20,935	32,859	11,68	14,235	20,354
	0,25	14,182	21,993	34,236	12,289	15,112	21,396
	0,2	15,337	23,425	36,106	13,583	16,3	22,807
2	0,3	14,317	21,464	32,668	12,767	15,168	20,917

Continue table 2

	0,25	15,33	22,721	34,309	13,727	16,21	22,156
	0,2	16,702	24,425	36,532	15,077	17,621	23,835
3	0,3	13,194	20,612	32,242	11,585	14,077	20,045
	0,25	14,044	21,671	33,629	12,39	14,952	21,088
	0,2	15,201	23,105	35,495	13,488	16,142	22,501
4	0,3	14,208	21,195	32,149	12,693	15,04	20,661
	0,25	15,224	22,453	33,785	13,657	16,085	21,9
	0,2	16,588	24,159	36,028	14,946	17,498	23,58
5	0,3	12,175	19,335	30,611	10,618	13,029	18,806
	0,25	12,925	20,294	31,846	11,327	13,802	19,73
	0,2	13,946	21,563	33,504	12,295	14,852	20,981
6	0,3	11,17	18,082	28,919	9,671	11,993	17,554
	0,25	11,825	18,905	30,004	10,29	12,667	18,363
	0,2	12,721	20,016	31,451	11,14	13,589	19,458

Conclusions. 1. Active power losses indicators of transformer EMS variant 1, deteriorate relative to option 2, (Table 1), depending on the values K_{zo} =0,2…0,3 and K_n by 0,17(1,9)% … 8,8(9,8) % at f_1=50 Hz and by 1,17(0,58) … 9,9(8,5) % at f_1=400 Hz accordingly. 2. Active power losses indicators of EMS depending on the values K_{zo} and K_n (variant 3, table 1) are improved by 2,7(2,85)…1,81(1,9)% and variant 4 by 11,03(12,2)…1,67(3,5) % at f_1= 50 Hz and by 1,7 (1,9)…0,7 (0,81) % and 0,22(2,2)…-9,1 (-8)%, at f_1= 400 Hz relative to the base rod EMS (variant 1). 3. Indicators of the active power consumption of the radial three-sectional EMS (variant 5, table 1), depending on the values K_{zo} and K_n are improved by 5,5 (5,3)…7,0 (6,6)% and variant 6 by 8,2 (7,7)…12,2 (14,4) % at f_1 = 50 Hz and by 7,2 (6,8)%...9,5(9,1)%, 12,9 (12)…18 (17,2)% at f_1= 400 Hz relative to the base rod EMS.

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А. А. Ставинський, О. С. Садовий, О. М. Циганов. **Втрати активної потужності в електромагнітних системах однофазних трансформаторів і реакторів з витими магнітопроводами.**

Показано особливості розрахунку втрат активної потужності і оптимізації трансформаторів і реакторів за критерієм мінімуму втрат на основі об'єктивних функцій з безрозмірними індексами технічного рівня і методу інваріантних відносних керованих змінних. Визначено вплив на втрати активної потужності заміни прямокутних утворювальних контурів стрижнів і обмотувальних котушок на шестигранні у варіантах плоских і радіальних тристержневих статичних електромагнітних систем з витими магнітопроводами при частотах 50 Гц і 400 Гц.

***Ключові слова**: однофазний трансформатор, витий магнітопровід, масово-вартісні і енергетичні індекси, керовані змінні.*

А. А. Ставинский, А. С. Садовой, А. Н. Цыганов. **Потери активной мощности в электромагнитных системах однофазных трансформаторов и реакторов с витыми магнитопроводами.**

Показаны особенности расчета потерь активной мощности и оптимизации трансформаторов и реакторов по критерию минимума потерь на основе объективных функций с безразмерными индексами технического уровня и метода инвариантных относительных управляемых переменных. Определено влияние на потерю активной мощности замены прямоугольных образующих контуров стержней и обмоточных катушек на шестигранниках в вариантах плоских и радиальных трехстержневых статических электромагнитных систем с витыми магнитопроводами при частотах 50 Гц и 400 Гц.

***Ключевые слова**: однофазный трансформатор, витой магнитопровод, массо-стоимостные и энергетические индексы, управляемые переменные.*