Weight-to-price Indicators of Electromagnetic Systems Single-Phase Transformers and Reactors with Twisted Magnetic Circuits

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***Abstract*—New technical proposals for improvement by changing the configuration and position in the space of active elements in order to reduce the material capacity and increase the reliability of single-phase transformers and reactors are presented. Based on mathematical models with partial or integral optimization criteria and a set of independent and dependent control variables, the optimal mass and cost parameters of single-phase electromagnetic systems variants that differ in the structure and configuration of the active elements are determined.**

Keywords—single-phase transformer and reactor, twisted magnetic circuit, weight-to-cost indicators, optimization, controlled variables.

I. INTRODUCTION

Single-phase transformers and reactors (throttles) are widely applied in various systems of electrical, radio and electronic equipment [1, 2].

By now, the design and structural solutions of the above-mentioned manufactured induction static devices (ISD) with the magnetic circuit traditional “rectangular” configuration of cross-sections reached the practical limit of development [3, 4].

Moreover, the main planar constructions (table 1, variants 1 and 2) of single-phased static electromagnetic systems (EMS) are not so convenient for integration to the equipment units, enclosed to the cylindrical and spherical housings with limited diameter [5, 6].

Traditional configurations of EMS elements of said ISD’s reduce the labor for the electromagnetic circuits manufacture due to the identity factor of electric steel (ES) layer width value, but make up the rectangular form of the coil winding turns. However, this shape increases the average length of the turn and material consumption and reduces the reliability of the windings. Therefore, the task for further enhancement of the single-phased ISD’s, intended for various purposes, remains important and actual.

II. ANALYSIS OF MAIN ACHIEVMENTS

Traditional ways to enhance the technical level of an electromechanical device EMS are the application of advanced electrical materials and manufacturing techniques, as well as optimization design [7]. Based on mastering the production of roll anisotropic ES, the mass production of twisted magnetic cores with a minimum thickness of ES layers is performed and the single-phase ISD loss reduction is achieved. The winding technology also reduces the labor input of producing magnetic circuits by application of complex automation means. The amorphous ES twisted magnetic cores are applied in a larger scale [3,4]. Moreover, the transformation of generating contours and structures of active elements is the non-traditional (heuristic) method of EMS enhancement [7-10].

Examples of non-traditional single-phased EMS [8-10] are given in table 1 (variants 3-6).

Magnetic conductors with hexagonal sections (in EMS variants 3, 4, 6, table 1) are formed by combination of wound sections, made of ES “wedge-shaped" tapes. Tapes with varying width are made by the “slant" division of a rectangular strip on two symmetric parts. Hexagonal cross-sections of rods reduce the average length of the turn and increase the reliability of winding coils relatively to an analog with a rectangular section by increase in the bending angle of the turns from 90 ° to 120 °. Table 1 (variants 5, 6) presents the three-rod EMS, which differ from the circular analogs [1] by elimination of the toroidal winding known disadvantages [8-10].

Maximum efficiency of using the given structure and design of EMS is achieved by means of the optimization target function (TF) extrema determination. Herewith, the special ISD optimization [6] is performed by application of the mass or contour volume criteria, and the cost minimum of EMS is selected as one of the power ISD optimization criterion [2, 8-10].

III. OBJECTIVE OF THE STUDY

Optimization comparative analysis of single-phased static EMS with twisted magnetic conductors variants, which differ by the configuration of the rod cross-sections and winding windows.

IV. STADY METHOD AND RESULTS

ISD optimization is performed on the basis of mathematic models with separate or integral optimization criteria and the complex of independent and dependent controlled variables (CV). Optimization CV include the electromagnetic loads (EML) and geometry elements, which correspond to certain configurations of the coil windings and the magnetic conductors [2]. For example, one of the mutually unacceptable geometric CV of traditional EMS optimization [1, 2] are the ratio of the rectangular section sides and the diameter of the forming contour of the segmented "stepped" rod cross-section. Said discrepancy aggravates the objective comparative analysis of various EMS structural variants. Due to this, TF method of technical level indicators (TLI) with relative geometric and electromagnetic CV is applied to the analysis of the EMS structure and configuration transformation influence on the weight-to-cost indicators of the single-phased ISD active part.

$$F_{kii} = K_{pii}(\sqrt[4]{I_{EML}})^3 I^*_{kii,} \qquad (1)$$

where I_{EML} – indicator of the initial data and EML; K_{pii} – component of the applied material specific performance parameter K≥3 optimization TF; I^*_{kii} – dimensionless optimization component, characterizing TF, the main of which are the weight function F_{1ii}, cost function F_{2ii} and active power losses F_{3ii} of ii EMS variant.

Extrema I^*_{kii} of TF dimensionless components (1) are ISD TLI. Each I^*_{kii} depends on coefficient of filling the winding window with the winding coil conducting material (voltage class) K_{fw} and two universal identical and acceptable for all existing or possible EMS variants geometric CV – ratio a_m of external diameter D_{1ii} and internal diameter D_{2ii} pitch circles of magnetic conductor of each EMS ii variant (table 1), ratio λ_0 of height h_{0ii} and width b_{0ii} of winding window and the rod central angle α_c [9, 10]:

$$I_{1(2)ii} = f(K_{30}, a_m, \lambda_0, \alpha_c); \qquad (2)$$

$$a_m = D_{1ii}/D_{2ii}; \qquad (3)$$

$$\lambda_0 = h_{0ii}/b_{0ii}; \qquad (4)$$

Component K_{pii} of target function (1) includes, depending on the optimization criterion, the ratio of the material relative density indicators (ES and winding copper) (kg/m³) $\gamma_o/\gamma_c = 8{,}9/7{,}6$ and their value C_o/C_c=3.5…5.5, laying ratio K_l=1.13 and bulging ratio K_b =1.15 of coil turns if impregnation is applied [1], as well as ES magnetic conductor filling ratio, K_{fs}=0.91. Calculations are made at various K_{fw}= 0.3…0.2 and ratios of the specific cost values of active materials in the range of C_o/C_c= 3.5…5.5.

TABLE I COST INDICATORS OF THE TWISTED MAGNETIC CONDUCTOR SINGLE-PHASED ELECTROMAGNETIC SYSTEM VARIANTS

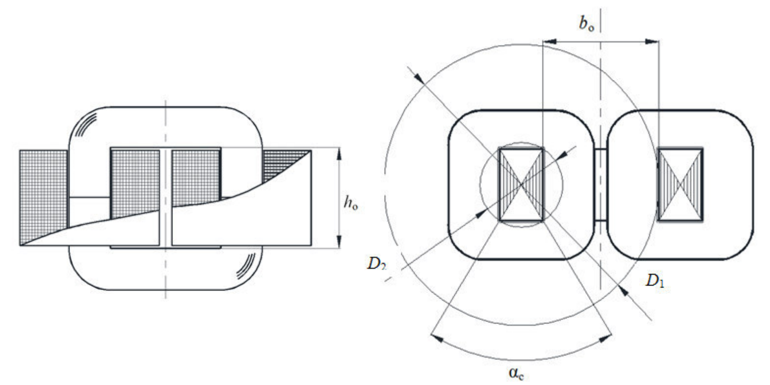
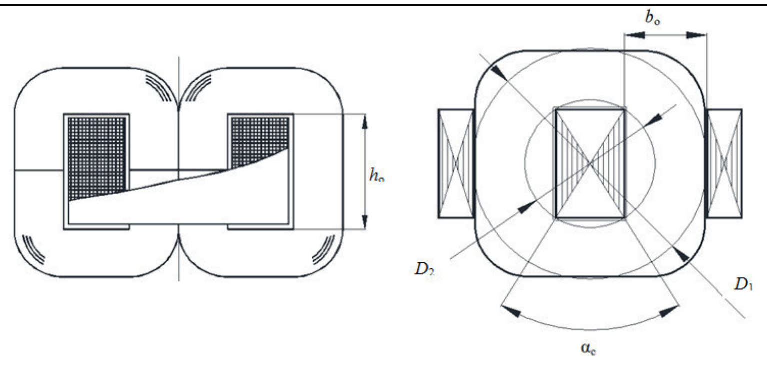
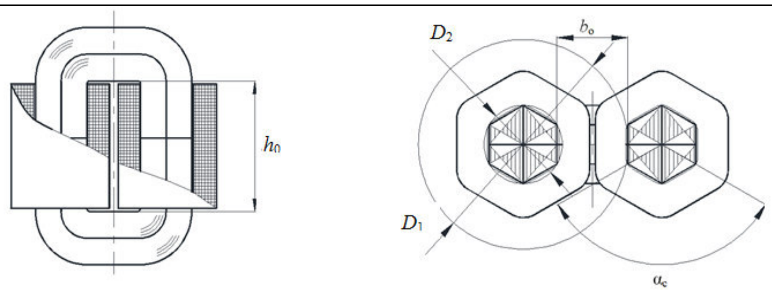
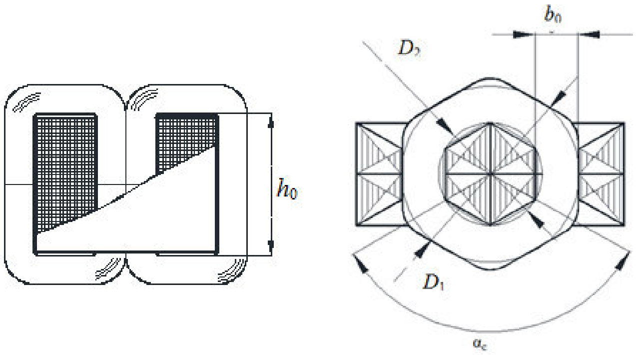
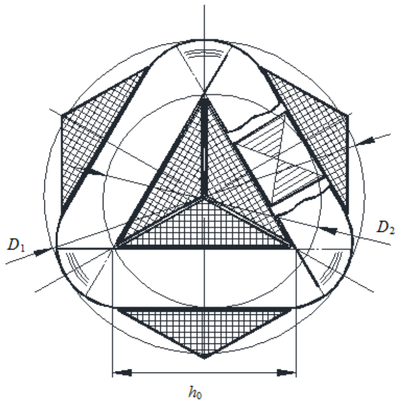
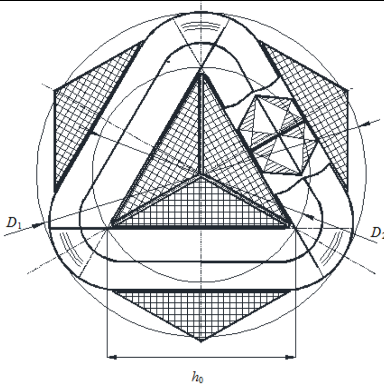
Variant No.	Structural design	Indicator designation	
		Weight	Cost
1	2	3	4
1		I^*_{1tre}	C^*_{2tre}
2		I^*_{1tae}	C^*_{2tae}

TABLE I - CONTINUATION

1	2	3	4
3		I^*_{1hre}	C^*_{2hre}
4		I^*_{1hae}	C^*_{2hae}
5		I^*_{1rte}	C^*_{2rte}
6		I^*_{1rhe}	C^*_{2rhe}

For comparison of the considered variants in accordance with the electromagnetic equivalence principle [8], the applied materials, the winding current density values, mean values of the magnetic field induction amplitudes in rods and yokes, as well as ISD design versions and cooling techniques are respectively taken as equal.

In calculation, the transformer winding system is replaced with the design winding of the reactor, which is structurally and electromagnetically equal to said transformer [10].

The results of TLI optimization calculation for the single-phased EMS variants (table 1) are given in tables 2 and 3.

TABLE II WEIGHT INDICATORS OF THE TWISTED MAGNETIC CONDUCTOR SINGLE-PHASED ELECTROMAGNETIC SYSTEM VARIANTS

Coefficient of filling the winding window, p.u.	Γ^*_{1tre}	Γ^*_{1tae}	Γ^*_{1hre}	Γ^*_{1hae}	Γ^*_{1rte}	Γ^*_{1rhe}
0.3	19.75	20.36	18.08	18.96	17.27	16.43
0.25	20.78	21.59	19.11	20.18	18.22	17.38
0.2	22.17	23.25	20.50	21.84	19.50	18.66

TABLE III Cost indicators of the twisted magnetic conductor single-phased electromagnetic system variants

Ratio of armature copper and electrical steel	**Coefficient of filling the winding window, p.u.**	Γ^*_{2tre}	Γ^*_{2tae}	Γ^*_{2hre}	Γ^*_{2hae}	Γ^*_{2rte}	Γ^*_{2rhe}
1	2	3	4	5	6	7	8
	0.3	41.96	42.51	33.79	38.46	36.83	30.82
3.5	0.25	42.59	42.83	35.76	38.88	37.11	32.32
	0.2	43.81	43.61	38.75	39.79	37.83	34.64
	0.3	46.09	46.94	36.02	42.36	40.65	33,08
4.0	0.25	46.53	47.05	37.89	42.60	40.76	34.48
	0.2	47.55	47.61	40.77	43.32	41.28	36.68
	0.3	50.22	51,37	38.25	46.26	44.47	35.34
4.5	0.25	50.48	51.28	40.02	46.33	44.42	36.64
	0.2	51.28	51.62	42.78	46.84	44.31	38.72
	0.3	54.35	55.8	40.48	50.16	48.3	37.60
5.0	0.25	54.42	55.51	42.15	50.05	48.07	38.79
	0.2	55.01	55.62	44.79	50.36	48.19	40.76
	0.3	58.48	60.23	42.71	54.06	52.12	39.86
5.5	0.25	58.37	59.74	44.28	53.78	51.72	40.95
	0.2	58.74	59.62	46.81	53.89	51.64	42.8

V. CONCLUSION

Optimization calculations show, that by the replacement of the rod rectangular contours and the application of the magnetic conductor tree-dimensional three-rod configuration, achieved by placing two symmetric sections at angle of 60°, the respective reduction by 8% and 20% of weight and cost of the single-phased copper-winding twisted magnetic conductor ISD EMS can be obtained.

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