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Technical solutions to reduce losses in magnetic cores and material consumption of three-phase transformer and reactor equipment

Purpose. *The increase in energy costs and the need for further energy saving lead to an increase in requirements for reducing losses in the magnetic cores of transformers and reactors.* ***Problem.*** *The improvement of transformer and reactor equipment is traditionally carried out by applying the achievements of electrical materials science and new technologies to traditional designs and structures of electromagnetic systems. The basis of modern transformers is made up of laminated and twisted magnetic cores. The disadvantage of laminated magnetic cores is large additional losses in corner zones due to the texture of anisotropic steel. Disadvantage of twisted three-phase three-contour magnetic cores is large additional losses caused by the lack of magnetic coupling of three separate magnetic flux contours. The disadvantages of combined joint tape-plate magnetic cores are the unsatisfactory use of the active volume and increased losses, which are determined by the uneven distribution of the magnetic field and the negative impact of steel texture in the corner zones of the twisted parts.* ***Aim.*** *To determine the possibility of improving three-phase transformers and reactors.* ***Methodology****. The improvement is achieved by geometrical and structural transformations of the outer contours and elements of the varieties of magnetic cores.* ***Results****. The possibility of eliminating additional losses of a planar laminated magnetic core by a combination of anisotropic and isotropic steels at the appropriate location in the yoke-rod and corner sections is determined. With an octagonal outer contour of the combined magnetic core, a reduction in mass is achieved without an increase in losses. The mutually orthogonal position of the steel layers or the elements of the joint twisted and combined three-phase planar and spatial magnetic cores achieves magnetic coupling and elimination of additional losses of individual twisted contour sections. The hexagonal configurations of the inner contours of the twisted yoke-corner parts and the cross-sections of the laminated rods of the variants of the axial spatial joint magnetic core improve the magnetic flux density distribution and reduce the main losses of the yokes, as well as reduce the complexity of manufacturing rods from identical rectangular steel layers.* ***Originality.*** *The paper presents constructive and technological proposals and features of varieties of non-traditional planar and spatial, laminated, twisted and combined tape-plate joint magnetic cores, which differ in the combination of anisotropic, isotropic and amorphous steels, as well as the multifaceted geometric shape of contours and the spatial arrangement of elements. Based on the identity of the optimal geometric ratios of the variants of electromagnetic systems of transformers and reactors, with joint planar and spatial twisted and combined and tape-plate magnetic cores, the unification of the structure of transformer and reactor equipment with a capacity of I-III dimensions.* References 29, figures 8.

Key words: **three-phase transformer, reactor, laminated twisted magnet core, transformer construction.**

Розглянуто стан розвитку трансформаторобудування. Визначена недостатня ефективність застосування відомих способів зниження втрат у магнітопроводах для задоволення нових вимог енергоресурсозбереження. Показана можливість удосконалення і уніфікації трифазних трансформаторів та реакторів на основі комбінацій анізотропної, ізотропної і аморфної сталей, багатогранних геометричних конфігурацій контурів та зміни положень в просторі шарів сталі, а також елементів планарних і просторових шихтованих, витих та комбінованих навито-пластинчастих магнітопроводів. Бібл. 29, рис. 8.

Ключові слова: **трифазний трансформатор, реактор, шихтований витий магнітопровід, трансформаторобудування.**

Problem definition. The increase in the cost of energy and the need for further energy conservation lead to an increase in requirements and regulations for increasing the efficiency of transformers. In particular, the Standards ND 428 and ND 538 for oil and dry transformers have been replaced by the more demanding European Standard EN 50464-1 and the International Standard IEC 60034-30. It is necessary to significantly reduce idle losses, first of all, in the most mass production range of power distribution three-phase transformers (TTs) with power of 25-2500 kV·A and a voltage of 6-10 kV. In addition to the main contribution to the total losses of power systems by the specified TTs, the energy efficiency of the power supply is additionally affected by the losses in the magnetic cores of three-phase reactors (TRs) of a similar power range. In this regard, the reduction of losses in magnetic cores of TTs and TRs of sizes I-III is an important current task [1-4].

Analysis of the latest research. For more than 20 years, in works analyzing the development of transformer and reactor equipment, innovative structures have been classified based on the achievements of electrical materials science. The main innovations are reduced to the development of «dry» transformers with «encapsulated» and «cable» windings [5, 6]. Amorphous electrical steels (ESs), superconducting windings, and cryogenic technology are also used [7, 8]. Instead of toxic oil for cooling, the use of organosilicon liquid and elegas begins [9-11]. In addition, an important factor in increasing the technical level of TTs and TRs is the use of optimization methods in their design [12, 13].

About 50 % of the losses at the nominal load of the transformers are due to losses during idle operation. The costs of their compensation many times exceed the costs of short-circuit losses. Due to the real partial average load of transformers, reduction of idle losses is a priority.

In the past decades, losses in magnetic cores have been reduced due to the use of ESs with improved specific characteristics. The production of cold-rolled anisotropic and amorphous ESs has been mastered. In general, meeting the requirements of the new Standards is achieved by reducing electromagnetic loads or using a strip amorphous ES, which involves an increase in material capacity (in amorphous and anisotropic ES, the saturation magnetic flux density is 1.6 T and above 2 T, respectively). In addition, the filling factor of the amorphous ES cross-section of the rod is 0.8-0.85 in comparison with the similar coefficient of 0.96-0.97 when using a crystal ES. TTs with composite windings and «high-temperature» superconductivity are being created [8, 9, 14]. However, distribution TTs of the main power range with technologies of closed high-temperature cryogenic cooling systems have no advantages over conventional TTs, which is due to the complexity of the cryogenic structural part. There is a need for cooling during commissioning and return of superconductivity after protective switching off.

In general, «amorphous» and «superconducting» TTs differ in their increased cost. The fragility of amorphous ES and superconducting composite «high-temperature» windings precludes their use in transport and other special TTs.

There are methods of comprehensive assessment of the technical condition of functioning transformers and recommendations for their further use [15]. However, fines are provided for the operation of operational transformers that do not meet the above Standards.

The structural and constructive basis of TT and TR consists of charged and twisted magnetic cores. The texture of the anisotropic ES creates a multiple increase in losses in the zones of magnetic flux reversal relative to the rolling direction of the layers of the laminated magnetic core. The volumes of these zones are reduced by using oblique joints in the corners and in two-frame (divided by width into sections) magnetic cores [16, 17]. Complex equipment for the formation of oblique joints with a change in size and a small shift of the joints of adjacent layers during the assembly of magnetic cores (Step-lap, Malty step-lap technologies) was created [4]. The shift is achieved by applying the initial configuration of the smaller sides of the plates (Fig. 1,*a*) or by reducing the areas of oblique joints and forming the angular protrusions of «whiskers» (Fig. 1,*b*), which are actually hidden waste.

According to [18], oblique joints are not an effective solution for improving laminated magnetic cores of TTs of I-II dimensions. Also, the increase in the losses of ready-made planar laminated magnetic cores relative to the specific losses of anisotropic ES along the rolling stock reaches 37-58 %, regardless of the shape of the joints. This is a well-known problematic issue of modern TTs (TRs).

The production of magnetic cores with laminated stacking is complemented by ES tape (roll) winding technologies. Such technologies are used for the manufacture of sections (contours) of three-contour continuous and joint twisted and combined magnetic cores [9, 16, 19-21]. The production of twisted three-phase three-section planar and spatial magnetic cores is increasing in connection with the expansion of the use of amorphous ES [19, 20]. In recent times, twisted split contact magnetic cores have been replaced by analogs with the formation of covering layers by separation and bending of sections of the ES tape. Conditionally oblique connections of parts of magnetic corers are formed with a small shift of the joints of adjacent layers. A reduction in contact losses and magnetization current is achieved (Unicore – magnetic cores) [20]. However, the absence of a magnetic connection of the twisted sections determines the vector composition of the action in the core sections of the sectional magnetic fluxes. The consequence of the magnetic separation of the sections is the third harmonics of the indicated fluxes and additional 30-35 % losses, which do not depend on the texture and brand of ES. This is another well-known problematic issue of transformer and reactor equipment.

On the basis of the above, the task of reducing idle losses and losses in the magnetic cores of TTs and TRs without increasing their mass and cost indicators is difficult and has not yet been resolved.

The goal of the work is to reduce the losses of TTs' and TRs' magnetic cores while reducing their material consumption.

Research method and results. Presented in [1-11] as new developments, electromagnetic systems (EMSs) of TTs and TRs are made in the same technical solutions of magnetic cores for more than a century. These developments in the structural and constructive sense have reached a certain limit of development. The trends of structural and technological inertia of electromechanical engineering have also been preserved recently. Further improvement of TTs and TRs with stacked and twisted magnetic cores is possible by the methods of their structural and geometric transformations and the use of combinations of ES brands [18, 22, 23].

The outer «conventional» rectangular contour of a planar laminated magnetic core [24-26] forms a significant unevenness of the magnetic flux density distribution in the range of 0.01-2.1 T in the corners (Fig. 1,*c*). The outer sections of the corners with height h_c (Fig. 1,*a*,*b*) are underloaded and are practically a useless weight supplement of the magnetic core.

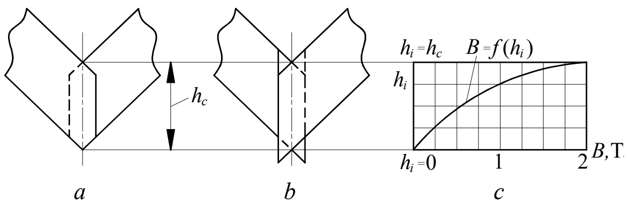

Fig. 1. Schemes of variants of the rod's and yoke's plate structures with two-plane (*a*) and oblique (*b*) separations of the steel strip and the dependence of the distribution of magnetic flux density (*c*) on the height of the corner zone of the laminated rectangular magnetic core

Unconventional proposals for reducing losses include magnetic cores with a combination of ES brands. To reduce losses by reducing the unevenness of the distribution of the magnetic field in the cross section and corners, the outer part of the two-frame laminated magnetic core is proposed to be made with improved magnetic properties relative to the inner part [27].

Other proposals for the improvement of the planar laminated magnetic core are options with a combination of isotropic and anisotropic ESs. In a magnetic core with direct junctions (Fig. 2,*a*,*b*), the combination of the specified ESs alternates in adjacent layers [28]. Corner zones contain only isotropic ES, which completely eliminates significant additional losses in corner zones. However, approximately half of each variant of the combined magnetic core [28] contains an isotropic ES with increased specific losses, which reduces the efficiency of this innovation.

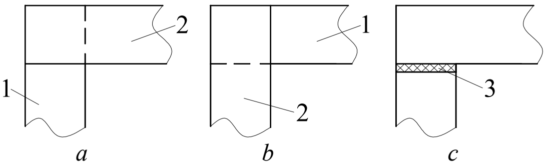

Fig. 2. Schemes of variants of corner zones of a planar laminated magnetic core with direct joints of adjacent layers of the transformer (*a*, *b*) and the reactor's magnetic core (*c*): 1 – anisotropic steel; 2 – isotropic steel; 3 – insulating gasket

A general drawback of traditional TTs' and TRs' structures is the disunification of internal structures, i.e., connections of rod's and yoke's sections of planar magnetic corers. With the general identity of the variants of the external configuration, the TTs' magnetic cores are stacked with shift of oblique (Fig. 1,*a*,*b*) or straight (Fig. 2,a,*b*) joints, and the TRs' magnetic cores contain structural gaps between the rods with insulating gaskets (Fig. 2,*c*).

The further development of the offer of non-conventional combinations of elements of the laminated magnetic core is the installation of plates of anisotropic ES in the zones of orthogonal change of the flux direction relative to the texture. Plates of chevron-shaped isotropic ETS with opposite sides of different widths are used. In the side corners of the planar magnetic core, these plates are installed in adjacent layers with the opposite direction. In the opposite middle corners (T-shaped sections), chevron plates are installed with the orthogonal position of the middle corners (Fig. 3,*a*). The chevron plates of the anisotropic ES of the side sections can be made with rounding of the axial corners to reduce the uneven distribution of the field. The rounding radius corresponds to the insulating gap h_i between the magnetic core and the winding (Fig. 3,*b*).

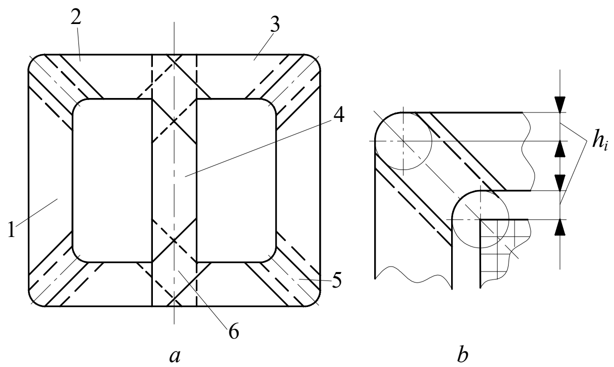

Fig. 3. Scheme of (a) three-phase with rounded corners (*b*) magnetic core with plates 1-4 of anisotropic and plates 5, 6 of isotropic electrical steels

Inseparable connection of anisotropic and isotropic sections of chevron plates in the joints by welding reduces the current and losses of idle. Eliminating the significant complication of the production of magnetic cores with the connection of the joints of isotropic and anisotropic ESs is possible by integral welding and transverse separation of strip blanks.

ES tandem blanks for cross-sectioning into combined plates (Fig. 4) are formed by combining and connecting along the lines of joints of anisotropic (Fig. 4,*a*) and isotropic (Fig. 4,*b*) ES strips. One, two or more fragments of isotropic ETC strips can be welded to the fragment(s) of the anisotropic ETC strip. Before connecting the fragments, the anisotropic components are located with the direction of the texture, which is parallel to the lines of separation (Fig. 4,*c*). Separated sections of fragments with two or several seams are cut at given angles into plates (Fig. 4,*d*,*e*) with a combination of ESs [29]. Fragments can be connected by one of the methods of welding (laser, electron beam, diffusion, etc.). Determining the method and process of such welding is a separate research task.

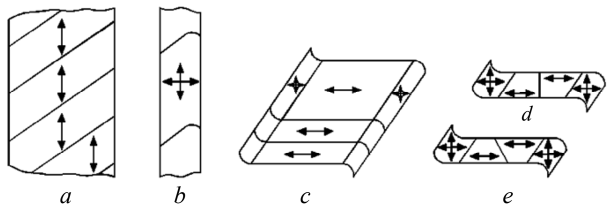

Fig. 4. Schematic diagrams of cutting and connecting components of the combined magnetic core: transverse divisions of the package of anisotropic (↔) (*a*) and isotropic (✥) (*b*) ESs into fragments; welding fragments along the lines of joints to the blank and its division into sections (*c*); separation of fragments into combined plates (*d*, *e*)

One of the directions of structural and geometric transformations of static EMSs is the replacement of conventional rectangular and circular forming contours of active elements with non-conventional ones, in particular octagonal and hexagonal contours [22, 23, 29]. In addition to the proposals for designs and methods (Fig. 3, 4), reducing the mass of isotropic components relative to analogs [27, 28] while reducing the total mass and losses is possible by replacing the rectangular outer contour of the planar magnetic core with an octagonal one. Rod and yoke areas (Fig. 5,*a*) are formed by plates of trapezoidal anisotropic ES.

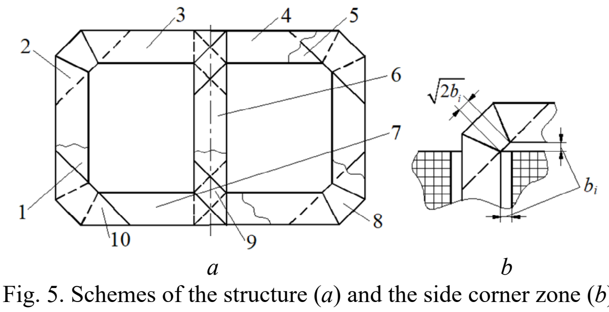

Fig. 5. Schemes of the structure (*a*) and the side corner zone (*b*) of a planar rod magnetic core of reduced mass with plates 1-7 of anisotropic and plates 8-10 of isotropic steels

Trapezoidal plates of adjacent layers differ in length and angles. The short bases of the long plates are equal to the long bases of the short plates and these bases are opposite. The sides of the anisotropic plates connect to the plates of the isotropic ES located in the side corners (Fig. 5,*a*). In this way, an octagonal external contour of the magnetic core is formed. At the same time, the uniformity of the field distribution increases and the unused mass of the corner zones is removed (Fig. 5,*b*). The middle angular (T-shaped) sections are divided by smaller and larger sides of the parallelogram plates of the isotropic ES, which are oppositely located in the middle layers. Trapezoidal or parallelogram plates of the anisotropic ES are installed on the axis of the central rod part of the magnetic corer (Fig. 5,*a*). In the corners, in the absence of an insulating gap b_i (Fig. 5,*b*), triangular plates can also be installed between trapezoidal plates.

It is possible to eliminate losses from the third contour harmonics of the magnetic field of a three-phase planar three-section magnetic core with twisted components in a structure with an orthogonal position of the layers of the middle and side elements (Fig. 6,*a*). Lateral C-shaped elements are made by cutting a twisted blank or of curved strips of anisotropic ES. The middle element for extracting additional losses of orthogonal rotation of the flux and reducing additional losses of phase asymmetry can be made of the best brands of isotropic ES. The transverse section of the strip (Fig. 6,*b*) makes it possible to form oblique joints of the middle and side elements.

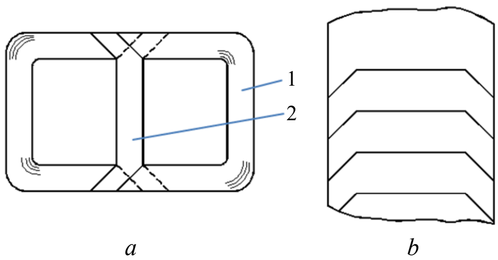

Fig. 6. Structural scheme (*a*) of a planar joint magnetic corer with twisted side 1 and laminated 2 middle elements and separation of the strip (*b*) of steel on the plates of the middle element

Sectioning of the magnetic core by width (Fig. 6,*a*) in addition to oblique connections, reduces the magnetic resistance of the joints by reversing the sections in each pair of adjacent middle and side elements.

In addition to the combined strip-plate one, it is possible to manufacture a twisted variant of the scheme of the magnetic core (Fig. 6,*a*). It is possible to make two identical twisted magnetic cores from sections of two twisted cut blanks. The blanks with the same heights h_m and identical cross-sections differ in the lengths l_1 and l_2 of the internal rectangular contours:

$$l_1 = h_m + 2b_v + 2b_t; \quad l_2 = 2b_v + b_t,$$

where b_v and b_t are the width of the winding window and the thickness of the technological waste layer of the ES (cutting disc).

The winding coils are wound on insulating frames covering the side and middle elements of the magnetic core (Fig. 6,*a*). Such frames make up the supporting base of EMS with fragile amorphous ES. Mutually orthogonal layers of ES of butt joints of the middle and side sections of the magnetic core of TTs' schemes (Fig. 6,*a*) should be insulated by applying a thin, durable heat-resistant coating.

Another variant of the technical solution containing C-shaped parts of twisted blanks is a T-shaped EMS spatial design (Fig. 7,*a*). For the coincidence of the directions of the ES layers, under the condition that the joints are coplanar, one of the C-shaped sections of the magnetic core is connected to the other two with the arrangement of the side surfaces in orthogonal planes (Fig. 7,*b*).

Losses from the third harmonics of the contour fluxes are also absent in the variants of the spatial EMS mentioned above with a common magnetic connection of the rods and yoke parts of the contact magnetic core when the primary winding is connected by a triangle. However, such EMSs are made in traditional circular forming contours of winding coils and rods. The circular contours of the rods of the specified options are filled, if there are central technological holes, with concentric turns of isotropic or involutely curved sheets of anisotropic ES. Rods made of ES packages of different widths are also used (Fig. 8,*a*). The indicated types of sections and structures of the rods fill the contour circles by 80-90 % and are installed between twisted jugular-angled end parts with triangular internal contours.

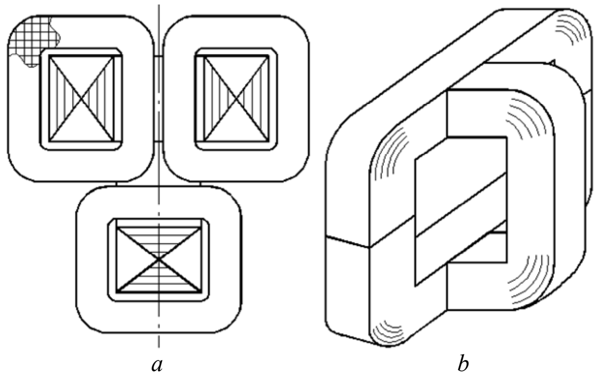

Fig. 7. Design scheme (*a*) and magnet core (*b*) of spatial EMS with T-shaped orthogonal location of twisted areas

The indicated circular and triangular contours of parts of the magnetic core have a negative effect on the use of the active volume of the EMS and increase losses in ES of TTs (TRs) with a magnetic core (Fig. 8,*a*). There is a significant uneven distribution of the magnetic field along the radial length l_a of a rectangular cross-sectional yokes with zero values of magnetic flux density on the inner and outer winding layers of the ES. This increases the magnetic flux density in the middle parts of the yokes and corners and causes an increase in losses, which is taken into account depending on the magnetic flux density by the corresponding coefficients. At the same time, the increase in losses when using anisotropic ES is also caused by the mismatch of the directions of the field lines in the corners with the direction of the texture of the twisted parts. Therefore, it is advisable to make the yoke-corner and rod parts of the combined butt-wound-plate magnetic core of isotropic or amorphous and anisotropic ES.

Improvement of the EMS with a tape/roll-plate magnetic core is possible by replacing the circular and triangular contours of parts of the magnetic core with hexagonal ones (Fig. 8,*b*,*c*). The mentioned transformations lead to a decrease in the unevenness of the field in the radial direction of the yoke, that is, along the length l_a (Fig. 8,*a*,*b*). At the given average value of the amplitude of the magnetic flux density of the yoke B_{am}, distribution 1 changes to distribution 2 (Fig. 8,*d*). In this way, the magnetic flux densities in the main average volumes of the ES of the yokes and corners are reduced and the losses are reduced.

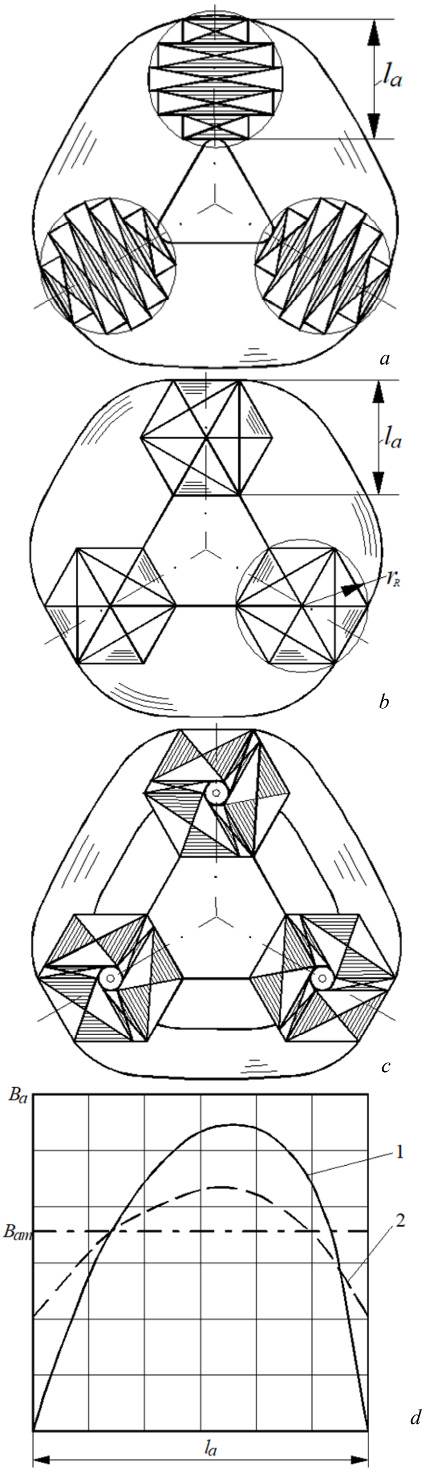

Fig. 8. Structural and geometrical features of three-phase tape-plate magnetic core variants with circular and triangular (*a*) and hexagonal (*b*, *c*) contours of rods and yoke-cirner parts and options for distribution of the magnetic flux density in yokes (*d*) with triangular (1) and hexagonal (2) internal contours

Identical rectangular plates of ES of rods (Fig. 8,*b*) almost completely fill ES hexagonal contours and fill the circumscribed circle with a coefficient of 0.826. In connection with the ratio of the lengths of the circle of the radius r_R (Fig. 8,*b*) and the inscribed hexagon 1.047, by replacing the circular configurations of the turns with the hexagonal ones, some reduction in the mass and losses of the winding is achieved for a given cross-sectional area of the rod. The presence of the central holes of the hexagonal rods reduces the mass and losses of the magnetic core using double-contour joint-corner parts and the structure of the rods from identical ES plates (Fig. 8,*c*).

Reasoned selection of a certain technical solution from the available options for new design or proof of the advantages of newly created innovations requires solving the problem of structural or structural-parametric optimization. Mathematical models of the specified problems must satisfy the conditions of invariance. The first is the availability of mathematical models with objective functions of a universal type and assembly order with the same set of controlled variables for any known and new proposals of a technical object. The second is the compliance of mathematical models with the requirements of comparison of measurement units, that is, the results of calculations of optimization criteria must be determined in dimensionless or specific (relative) units.

Such conditions are met by the method of universal target functions of dimensionless indicators of the technical level and relative geometric and electromagnetic controlled variables [22-24]. When applying the specified method, the identity of the general type of target functions of transformers, reactors and induction machines [22, 23] was revealed which corresponds to the general electromagnetic principle of their action. Objective functions *k* – the individual optimization criteria (masses *k* = 1, costs *k* = 2, losses *k* = 3), *ij* – the EMS option of TTs and TRs are determined by the equations:

$$F_{KTTij} = K_{MK}\left(\Pi_{TT}\right)^{3/4}\Pi^{*}_{KTTij}\,;$$

$$F_{KTRij} = K_{MK}\left(\Pi_{TR}\right)^{3/4}\Pi^{*}_{TRij}\,,$$

where K_{MK} is the component of the specific characteristics of one of the EMS active materials; $\Pi_{TT(TR)}$ and $\Pi^{*}_{KTT(TR)ij}$ is the indicator of output data and electromagnetic loads and dimensionless optimization component *ij* – variant of the EMS of the TTs (TRs), which corresponds to *k* – the optimization criterion.

The components $\Pi^{*}_{KTT(TR)ij}$ are nonlinear equations with relative controlled variables. Their extrema $\Pi^{*}_{TT(TR)e}$ represent indicators of technical level of *ij* – EMS variants [22-24].

When applying the mentioned method, the identity of the indicators of the technical level and, accordingly, the optimal geometric ratios of the same constructions and structures of TTs and TRs were revealed [22]. This makes it possible to manufacture on the basis of the same twisted or combined butt magnetic cores schemes (Fig. 6,*a*; Fig. 8,*b*,*c*) of unified optimized EMS of TTs and TRs, which differ in the number of winding coils in the winding window. Such unification will lead to a significant effect in the production of TTs and TRs of I-III dimensions.

Conclusions.

1. Oblique and double-contour (frame) connections of corner, rod and yoke sections, respectively, used in

laminated textured magnetic cores do not provide a significant reduction in additional losses during idle operation of conventional variants of three-phase transformers (TTs) and reactors (TRs).

2. Utilization instead of anisotropic one of strip amorphous electrical steel (ES) is limited by the technological limit of the power of TTs (TRs) with twisted magnetic cores and significantly worsens their mass and cost performance. At the same time, the issue of reducing significant additional losses of twisted three-phase three-contour magnetic cores remains problematic.

3. The improvement of TTs (TRs) with laminated textured planar magnetic cores is ensured by the location in the zones of change in the flow direction of the fragments of the isotropic ES with the rounding of right angles or the octagonal configuration of the external contours.

4. Elimination of losses from the third harmonics of contour currents is achieved by replacing twisted three-phase magnetic cores with separate cores with planar and spatial butt-joint magnetic cores with magnetic connection of rod and yoke-corner parts.

5. On the basis of the identity of the optimal geometric ratios of the same general structures of TTs and TRs, it seems appropriate to develop their unified electromagnetic systems with variants of joint planar and spatial twisted and strip-plate magnetic cores, which differ, respectively, in the orthogonal arrangement of the ES layers or the position in space of the middle and side sections and hexagonal configurations of rod contours and internal yoke contours.

6. The construction of spatial strip-plate contact magnetic cores should be based on a combination of brands of isotropic and anisotropic ESs in yoke-corner parts and rods.

Conflict of interest. The authors declare no conflict of interest.

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