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Torsion of Transformer Windings Under Short Circuit

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SUMMARY

The failure of helical and layer windings in torsion (spiralling) under short circuit can take on two forms: a) coiling of radially compressed internal windings; b) uncoiling of radially tensile external windings. The coiling spans only the extreme (top and bottom) turns and sometimes the entire winding. In contrast, the uncoiling always spans the entire winding height.
To investigate winding torsion, a system of electromagnetic (EM) forces acting upon a conductor element is considered. Winding torsion is mainly caused by uncompensated radial EM forces due to the helical effect, which is consistent with the IEC 60076-5:2006 publication. Although tangential EM forces may cause torsion, under the usual conductor helix angle value they are on the average one order of magnitude less than the static friction forces caused by the axial EM forces, and thus can be neglected. According to earlier research the tangential forces in the own EM field always act so as to cause winding coiling. This contradicts the pattern of uncoiling in the external windings. Thus, experimental observations and mathematical derivations allow ruling out the tangential forces as the cause of winding torsion. Besides the external EM short circuit forces, the conductors undergo the action of internal force factors in the form of initial bending moments occurring during winding fabrication. In the radially compressed windings, these moments prevent conductor curvature increase, and propagation of coiling deformations, localizing them at the top and bottom winding edges. In the radially tensile windings these moments facilitate conductor curvature decrease and propagation of uncoiling deformations throughout the entire winding height. Conductor hardening decreases coiling and increases uncoiling displacements under the same initial bending strains. Forces acting upon vertical and horizontal lead exits can facilitate as well as act against winding torsion. Thus, one must take them into account in the analysis of short circuit withstand capability of transformer windings.
In order to prevent torsion by means of axial compression, impractically high windings axial clamping forces may be required. Lead exits can be secured in place by some device, for which one must carry out strength analysis. A zero radial gap can be provided to prevent winding ends radial displacement and thus coiling. To prevent uncoiling, fibreglass bands can be applied. The formulae for determining the bands dimensions are given.
The paper demonstrates inconsistency of verification criteria that a) are based on limiting stress values, or b) do no take into account initial bending strains or, c) do not take into account static friction due to the action of axial EM forces.

KEYWORDS

Transformers, short circuit, forces, torsion, spiralling

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After short circuit withstand capability tests, in some windings there were detected coiling (Fig. 1) and uncoiling (Fig. 2) deformations. The former were observed only in radially compressed windings. In some cases coiling spanned only the outermost (top and bottom) turns of windings. Thus, during dismantling of a single phase 333 MVA 750 kV transformer, in the internal low voltage winding it was observed that the wires of the outer quarters of the first (top) and last (bottom) turn of the LV winding displaced in the circumferential and radial directions and rested upon the magnetic system leg. The winding ends displacements reached 30 – 40 mm. The uncoiling deformations spanned all the turns of radially tensile windings. During short circuit tests of a single phase autotransformer rated 130 MVA 500 kV took place uncoiling of all the HV tap winding turns (Fig. 2). It is perfectly obvious, that under uncoiling the winding diameter increases and conductor curvature decreases. The wires shift with regard to each other in the circumferential direction. Under winding coiling, the diameter of the wires spanned by deformations decreases, and the curvature increases, and their displacement in the circumferential direction takes place with regard to each other and with regard to the wires not spanned by the deformations. The presented damage kinds are usually called winding torsion (spiralling). Such damage can be caused by the forces acting on the windings and winding lead exits.

Fig. 1

Fig. 2

The electromagnetic (EM) forces acting upon the windings under short circuit are determined by the EM field; to calculate the latter, three models are used: plane-parallel, axisymmetric, and three-dimensional. For the field in the windings, these models produce sufficiently close results. So, in a first approximation it can be considered that the EM flux density virtually does not change around the winding circle, and its vector lies in the plane containing the winding axis – the axial plane. If the current direction is perpendicular to this plane, then the latter also contains the vector of the EM force applied to the conductor. In the helical winding case, the current $\mathbf{i}$ is directed at the angle θ with regard to the axial plane normal (Fig. 3, where θ is the helix angle of the average conductor in the winding radial direction; $\mathbf{t}$, $\mathbf{n}$, $\mathbf{b}$ are orts of the tangent, main normal and binormal to the conductor helix) [1]. The EM force vector $\mathbf{F}$ acting on the conductor unit length will be situated in the plane normal to the helix (the plane containing the main normal and the binormal). This plane is located at the angle θ to the axial plane. The force $\mathbf{F}$ can be decomposed into the radial component $\mathbf{F_r}$ and the component $\mathbf{F_{ac}}$ normal to it. The latter lies in the rectifying plane (the plane containing the tangent and the binormal) and can be represented as two mutually perpendicular axial $\mathbf{F_a}$ and circumferential $\mathbf{F_c}$ components. Thus, in the most general case, the EM force $\mathbf{F}$ decomposes into three mutually perpendicular components: radial $\mathbf{F_r}$, axial $\mathbf{F_a}$ and

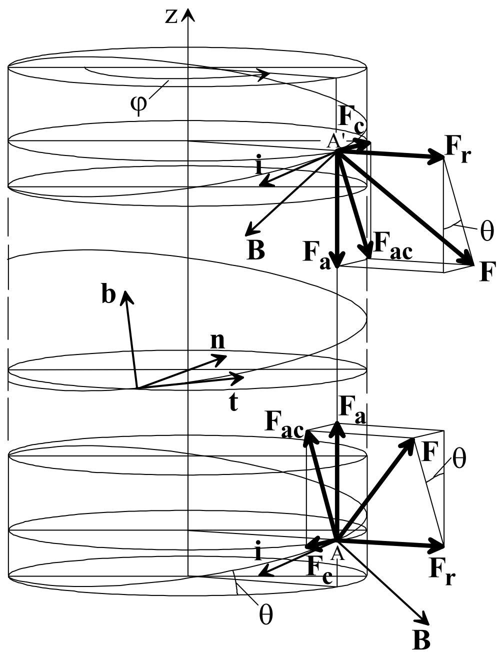

Fig. 3

circumferential $\mathbf{F_c}$. It is perfectly obvious, that $\mathbf{F_r}$ directed outward from the winding causes conductor tension, inward – compression, which may lead to buckling. The $\mathbf{F_a}$ in the top and bottom winding parts (points A and A' in Fig. 3) are usually directed oppositely and cause compression. The $\mathbf{F_c}$ in the top and bottom winding parts are also opposite, and upon first examination it is these that appear to cause winding torsion. Let us consider this question in greater detail.

As the flux density vector lies in the axial plane, there are only two of its components – the axial $\mathbf{B_a}$ and the radial $\mathbf{B_r}$ by which $\mathbf{F_r}$ and $\mathbf{F_{ac}}$ EM forces are determined:

$$\mathbf{F_r} = \mathbf{i} \times \mathbf{B_a}\,;\ \mathbf{F_{ac}} = \mathbf{i} \times \mathbf{B_r}\,. \tag{1}$$

The absolute values of the axial and circumferential forces can be determined by formulae

$$F_a = F_{ac}\cos\theta\,;\ F_c = F_a \mathrm{tg}\theta\,. \tag{2}$$

The average value of the conductor helix angle tangent is determined by expression

$$\mathrm{tg}\theta = \frac{(H + h_K)n_1}{\pi D}, \tag{3}$$

where D, H, h_K are the average diameter, wires (plexes) height, and radial ducts height; n_1 is the plexes quantity.

For windings with a small amount of plexes $(n_1 = 1 \div 4)$ $\mathrm{tg}\theta \le 0.02$. In the case of windings with multiple plexes $\mathrm{tg}\theta \le 0.1$.

As a rule, $\mathbf{F_a}$ has the maximum absolute values in the outermost (top and bottom) turns and is much smaller in the other winding parts. Therefore, when determining the moments causing winding torsion, in a first approximation, it is sufficient to take into account only the circumferential forces on the outermost turns. For calculation of the torsion moment absolute value about the winding axis z due to the circumferential EM forces (per one conductor) it holds true:

$$M_c = F_c \pi D \frac{D}{2}. \tag{4}$$

With regard to expressions (2) and (3) there follows

$$M_c = F_a \frac{D}{2}(H + h_K)n_1\,. \tag{5}$$

With $\mathbf{F_a}$ compressing the winding, the moments M_c will cause its coiling. With $\mathbf{F_a}$ directed outward from the winding, M_c will cause its uncoiling.

In the overwhelming majority of cases, $\mathbf{F_a}$ are compressive, therefore due to the action of $\mathbf{F_c}$, the windings must coil. Tests indicate that only the windings compressed by the **radial** forces coil, while those under tension by the **radial** forces uncoil (Fig. 2). This demonstrates that although $\mathbf{F_c}$ can influence windings torsion, the main role is played by the radial forces, and the mechanism of their action is as follows. Let us consider a ring that is under a load uniformly distributed around the circle with intensity F_r (Fig. 4). Under the action of such a load, the ring stays in equilibrium. If one mentally singles out a quarter of the ring, then the action of the remaining part upon it reduces to the internal forces $\mathbf{N}$ that counterbalance $\mathbf{F_r}$ applied to this quarter. From equilibrium conditions it follows that these internal forces in all the cross sections are equal by absolute value. They are aligned with the tangents to the ring axis and are equal by absolute value to

$$N = F_r \frac{D}{2}. \tag{6}$$

The internal forces $\mathbf{N}$ (Fig. 4) counterbalance the load applied to the ring quarter. Therefore, the action of $\mathbf{F_r}$ applied to the ring quarter reduces to two forces $\mathbf{P}$ that are equal by absolute value to $\mathbf{N}$ $(P = N)$ and oppositely directed along the lines of their action. The internal forces $\mathbf{N}$ counterbalance $\mathbf{P}$ (Fig. 4). If one now considers a helical winding under similar conditions, then the load applied to the outer quarters of the first and last turns will reduce to forces P, acting upon the winding ends (Fig. 5, where s is winding pitch). And these are not counterbalanced on the winding ends (unlike in the complete ring). The forces $\mathbf{P}$ on the helical winding ends that are called uncompensated and produce torsion moments with regard to the winding axis z, the absolute values of which in a first approximation are determined by expression

$$M_r = P\frac{D}{2}. \quad (7)$$

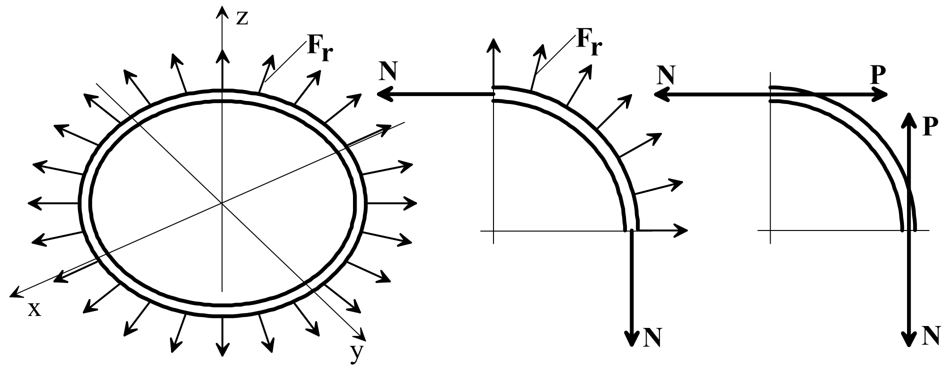

Fig. 4

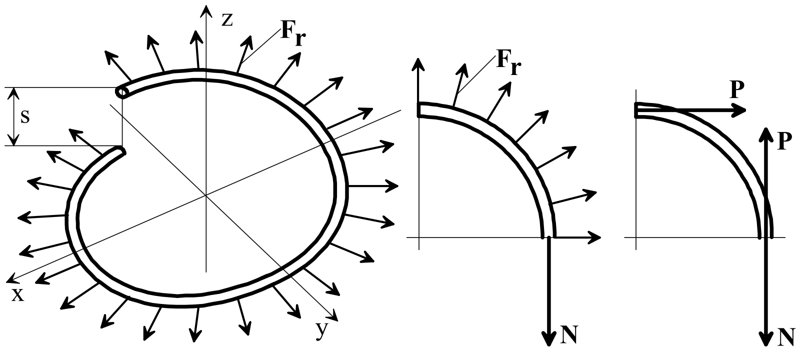

Fig. 5

With regard to formula (6) one finally obtains

$$M_r = F_r\frac{D^2}{4}. \quad (8)$$

Using expressions (5) and (8), it follows

$$\frac{M_r}{M_c} = \frac{F_r}{F_a}\cdot\frac{D}{2(H+h_K)n_1}. \quad (9)$$

The analysis of (9) demonstrates that M_r (8), on average is approximately by an order of magnitude greater than M_c (5). At that, the tensile radial forces produce uncoiling moments, and the compressive ones – coiling moments. Thus, winding torsion must be caused by $\mathbf{F_r}$, while $\mathbf{F_c}$ can be ignored in a first approximation in the study of this phenomenon. However, in order to verify validity of this statement, one must also consider the action of $\mathbf{F_a}$.

The components $\mathbf{F_a}$ press the extreme winding turns to the other elements with the total forces equal by absolute value (per one conductor) to

$$F = F_a\pi D. \quad (10)$$

This force causes occurrence of friction forces F_{fr} that prevent winding torsion. The maximum total static friction force in the considered case by absolute value equals to

$$F_{fr} = fr\cdot F, \quad (11)$$

where fr is the coefficient of static friction between winding elements.

The maximum friction moment preventing winding torsion is determined by expression

$$M_{fr} = F_{fr}\frac{D}{2}. \quad (12)$$

With regard to formulae (10), (11), one obtains

$$M_{fr} = F_a \pi D \cdot fr \frac{D}{2}. \quad (13)$$

Using expressions (5), (8) and (13), it follows

$$\frac{M_r}{M_{fr}} = \frac{1}{2\pi fr}\frac{F_r}{F_a}; \quad (14)$$

$$\frac{M_c}{M_{fr}} = \frac{tg\theta}{fr}. \quad (15)$$

For friction pairs occurring in transformer windings, $fr \geq 0.2$, on average $fr = 0.3$. Under such friction coefficient values according to (14), winding torsion becomes possible at

$$F_r \geq 2\pi fr F_a \approx 2F_a. \quad (16)$$

The EM forces, the radial and axial components of which meet (16), are quite realistic for transformer windings. Thus, the F_r components of EM short circuit forces can cause windings torsion.

According to the presented data, $fr >> tg\theta$. Under such conditions, as it follows from (15), $M_c << M_{fr}$.This indicates that $\mathbf{F_c}$ demonstrably cannot overcome $\mathbf{F_{fr}}$ $(\mathbf{F_{fr}} = -\mathbf{F_c})$ acting against it, and cannot cause winding torsion.

One arrives at the same conclusion using the results of [2] regarding coiling and uncoiling deformations. The paper maintains that these damage kings are caused by tangent forces F_τ

$$F_\tau(\Delta y) = \pm[P(y) - P(y + \Delta y)] \cdot (H/\pi D)/w, \quad (17)$$

where H, w are the height and quantity of winding turns; $P(y)$ and $P(y + \Delta y)$ are the integral axial forces at the top and bottom boundaries of the considered winding part of Δy height.

Essentially, $[P(y) - P(y + \Delta y)]$ determines the axial force acting upon the considered winding part, and the factor $(H/\pi D)/w$ determines the average $tg\theta$ (3). Taking into account the transformer winding maximum height $H \approx 3000$ mm, the average diameter $D \approx 1000$ mm and the minimum amount of turns $w \approx 10$ (in tap windings), one obtains the maximum helix angle tangent $tg\theta_{max} \approx 0.1$. Thus, the maximum tangent force acting upon the considered winding part is determined by expression

$$F_\tau(\Delta y)_{max} = \pm[P(y) - P(y + \Delta y)] \cdot 0.1. \quad (18)$$

But the torsion of the considered winding part by the tangent force will be prevented by the friction forces on its boundaries. The maximum resultant force of these forces is calculated by formula

$$F_{fr} = \mp[P(y) + P(y + \Delta y)] \cdot fr. \quad (19)$$

The plus sign in square brackets of (19) due to the friction forces on both faces of the considered winding part being opposite to the tangent force.

Substituting into (19) $fr = 0.2$ one obtains the minimum friction force preventing torsion of the considered winding part,

$$F_{fr\,min} = \mp[P(y) + P(y + \Delta y)] \cdot 0.2. \quad (20)$$

Comparing (18) and (20) one will observe that the tangent force cannot overcome the friction forces on the boundaries of the considered part, even with the minus sign in the square brackets of (20); therefore it cannot cause winding torsion. Thus, here we have arrived at the same conclusion as in the analysis of (15).

Besides, paper [2] absolutely correctly maintains that the tangent forces in the own magnetic field always cause winding coiling. But the external transformer windings uncoil, which can only take place under the action of tensile radial EM forces. Thus, the results of tests and investigations presented above do not corroborate the statements of [2] regarding the role of tangent forces in windings torsion. They indicate that such damage kind is caused specifically by the uncompensated radial EM forces on winding faces (Fig. 5).

It must be pointed out, that according to (17) the parts of the LV winding of the 333 MVA 750 kV transformer that obtained deformations during tests were subjected to not the largest tangent forces. According to this formula, the tangent forces increase as the considered winding parts increase (as long as the radial flux density components do not change their sign), and therefore torsion deformations must span its larger parts if not the entire winding. Evidently, this contradicts tests results of the considered transformer, where torsion deformations took place only in the outermost quarters of the first and last winding turns.

Analysis of EM short circuit forces demonstrated that only the uncompensated radial components of these forces on the winding edges can cause their torsion. However, the question remained open as to why the action of these forces in coiling windings occurs only on the outermost turns, while in the uncoiling windings (Fig. 2) torsion spans the entire height. The cause of such deformation pattern lies in the following. The considered EM forces are external to the winding conductors. But besides, in the conductors take place internal forces caused by the initial bending strains ε_b, that occur during winding fabrication (Fig. 6, where: 1 is a conductor; 2 is a strip; 3 is a mandrel; b, ρ_k are the conductor radial dimension and curvature radius; $R = D/2$). The initial bending stresses σ_b corresponding to ε_b (Fig. 7, where σ_{pl}, ε_{pl} are the conductor material proportional limit and the corresponding strain) in every conductor cross section reduce to internal bending moments M_b. On the one hand, these prevent further conductor curvature increase; on the other hand, they tend to decrease conductor curvature. It was indicated earlier, that winding coiling is accompanied by increase of its conductors curvature, and the uncoiling – by its decrease. Thus, under the action of uncompensated radial forces causing coiling of turns, the moments M_b prevent propagation of coiling deformation throughout the entire winding height by preventing conductor curvature increase, thus localising coiling deformations on the winding edges. If there act uncoiling uncompensated radial forces, then the moments M_b lead to propagation of uncoiling deformations throughout the entire winding height by facilitating conductor curvature decrease.

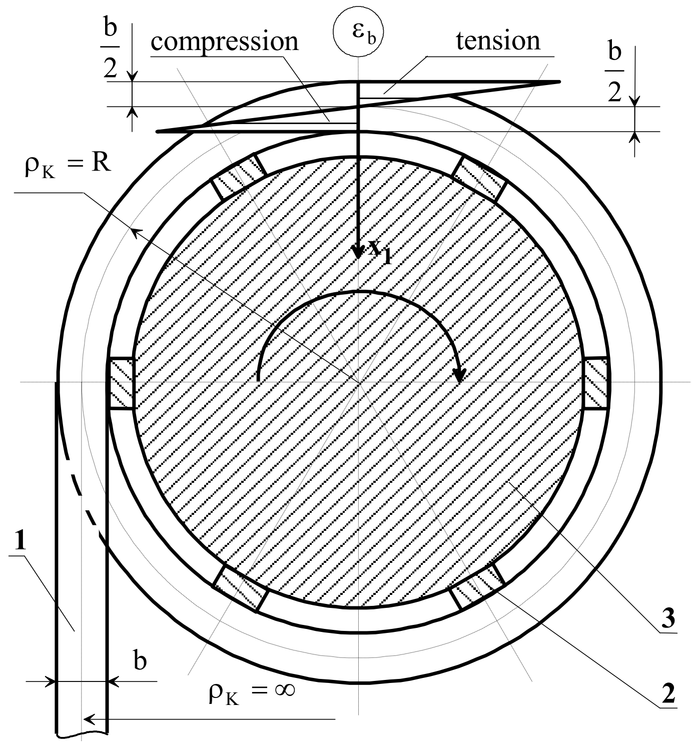

Fig. 6

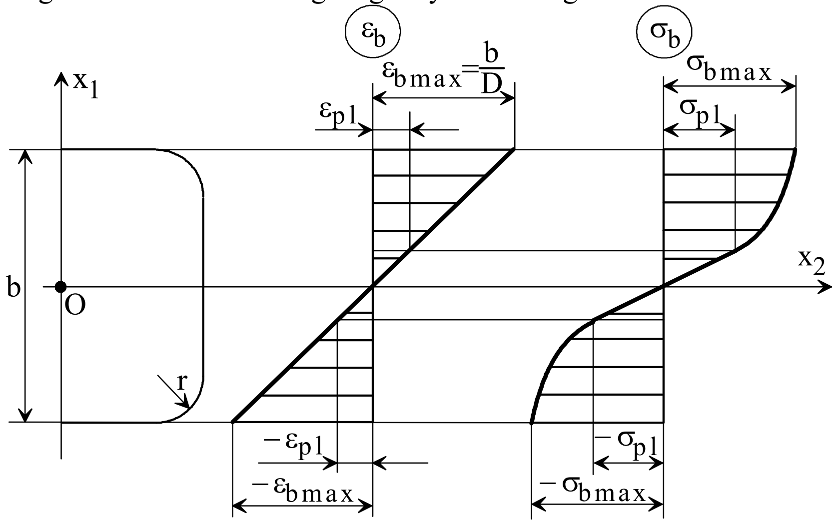

Fig. 7

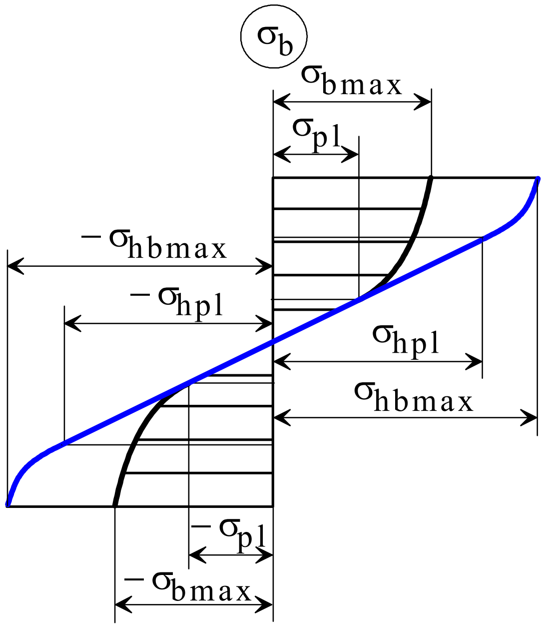

Fig. 8

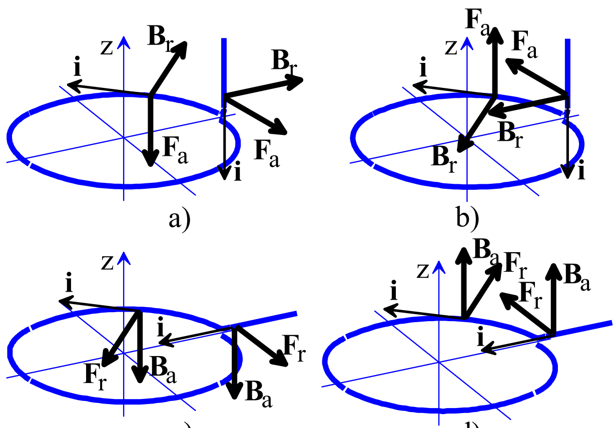

Fig. 9

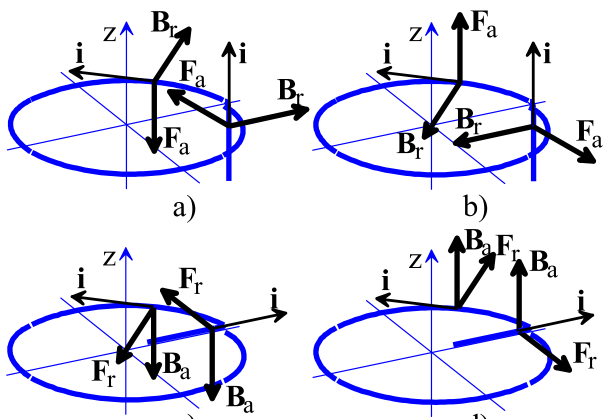

Fig. 10

It must be pointed out that under the same ε_b the stresses σ_b will be larger in hardened conductors (Fig. 8, where σ_{hpl}, $\sigma_{hb\,max}$ are the proportional limit and the maximum initial bending deformation of a hardened conductor). In this case the moments M_b will also be larger. For this reason utilisation of wires with hardened conductors must lead to a decrease of winding coiling and increase of uncoiling deformations.

In the analysis of EM forces on winding leads, in a first approximation let us consider that the flux density components on the leads are the same as on the outermost turns. In this case, on the vertical leads directed upward from the winding there will act EM forces caused by the radial flux density components $\mathbf{B_r}$ (Fig. 9, a, b), and equal to the $\mathbf{F_a}$ (2). If the axial forces compress the winding (Fig. 9, a), then the forces acting upon the vertical lead will coil the winding. Under the tensile axial forces (Fig. 9, b) the EM forces applied to the winding lead will uncoil the winding. On the horizontal leads directed away from the winding under the considered conditions there will act EM forces caused by the axial flux density components $\mathbf{B_a}$ (Fig. 9, c, d), and equal to $\mathbf{F_r}$ (1). Under the action of compressive radial forces upon the winding (Fig. 9, c) the EM forces applied to the horizontal lead will coil the winding. If the radial forces stretch the winding (Fig. 9, d), then the EM forces acting upon the horizontal lead will uncoil the winding. If the vertical leads are directed downward from the winding (Fig. 10, a, b), and the horizontal ones – inward (Fig. 10, c, d), the forces acting upon them under the considered conditions will invert their direction.

Generally, the EM forces on the leads can both prevent and facilitate winding torsion, which must be taken into account in short circuit withstand capability analysis. Obviously, in the winding shown in Fig. 1, the moments of the uncompensated radial forces and EM forces on the leads were unidirectional and overcame the moments due to initial bending and friction forces. As a result, the coiling deformations spanned the entire winding height.

To prevent torsion due to EM forces and internal forces occurring in the winding itself, the following steps can be taken.

Winding clamping to prevent torsion at the expense of friction between turns. Under such clamping force, compressive internal forces take place in the winding under short circuit, such that the maximum static friction forces are greater than the forces causing torsion. The required axial compressive internal forces can be determined on the basis of (8), (13). But calculation results with regard to windings axial vibrations demonstrate that in order to create the required axial compression often very high axial clamping forces are necessary. First of all, it concerns tap windings with multiple plexes (Fig. 2). The conceptual side of the mentioned is demonstrated by Fig. 11 schematically showing windings with a single plex and four plexes, through which flows a current $\mathbf{i}_1$. It is perfectly obvious that, the rest of conditions being equal, to hold four plexes from uncoiling one needs four times greater friction forces between turns than the same to hold one plex. And in order to obtain four times greater friction forces, one must increase by the same factor the compressive internal forces between the turns. In such cases, a stronger and thus more expensive clamping structure is necessary. Therefore, in order to prevent winding torsion other measures are more efficient, namely:

Winding ends (leads) fixation. In the case of compressive radial forces causing winding coiling one can decrease the radial gap between the winding and the element inside it (a magnetic system leg, another winding). With a zero radial gap, the element located inside the winding acts a radial support for it. It was demonstrated above that, at the expense of the internal bending moments M_b coiling deformations cannot propagate throughout the entire height of a radially compressed winding. Thus, in order to prevent coiling of such a winding, it is sufficient to provide radial supports only to the extreme turns.

Fibreglass bands can be applied in order to prevent uncoiling of a radially tensile winding. At that, it is insufficient to apply the bands only to the extreme winding turns, because the internal bending moments M_b will uncoil the other turns. Thus, the bands must be applied uniformly along the entire winding height.

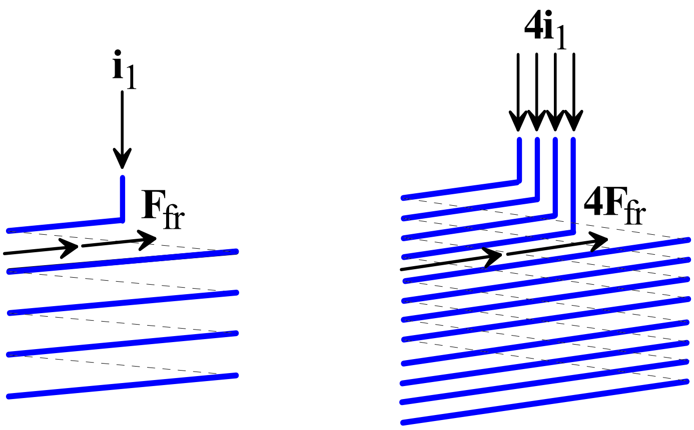

Fig. 11

Winding torsion due to the EM force acting on the leads can be prevented by fixing the latter. A device for leads fixation must be strong enough to sustain the EM forces acting upon it under short circuit. If no steps are taken to prevent winding torsion by the EM forces originating in it, as well as by the internal bending moments, then the leads fixation device must also sustain the uncompensated circumferential force on the winding end:

$$Fh = Sgm \cdot Spl \cdot zi\,, \tag{21}$$

where Sgm is the average stress due to the radial EM forces on conductors (determined in windings short circuit withstand capability analysis); Spl is plex cross section area; zi is plexes quantity.

The fibreglass band cross-section area can be calculated by the expression:

$$Sb = \frac{Fh}{[\sigma b]}\,, \tag{22}$$

where $[\sigma b]$ is the fibreglass band permissible tensile stress.

In tap windings with multiple plexes, the bands quantity can be taken equal to the winding turns quantity.

In the paper [2] and other publications [3, 4] an incorrect approach is taken – the components $\mathbf{F_a}$, $\mathbf{F_c}$, $\mathbf{F_r}$ of the same EM force $\mathbf{F}$ are regarded without proof as separate, independent and acting at different time. In the investigation of action of one of these components, the other components are not taken into account. For example, according to Annex A of publication [4] verification of conductor strength is performed by permissible stresses. At that, three strength conditions are used: in compression/tension as well as in bending in the radial and axial directions:

$$\sigma^*_{t,act} \leq 0.9 \cdot R_{p0.2}; \quad (23)$$

$$\sigma^*_{br,act} \leq 0.9 \cdot R_{p0.2}; \quad (24)$$

$$\sigma^*_{ba,act} \leq 0.9 \cdot R_{p0.2}, \quad (25)$$

where $\sigma^*_{t,act}$, $\sigma^*_{br,act}$, $\sigma^*_{ba,act}$ are conductor stresses due to deformations of compression/tension, bending in the radial and axial directions corresponding to the maximum surge current; $R_{p0.2}$ is conductor material yield strength.

Expressions (23) – (25) imply existence of three independent stresses that originate in the conductor from three different forces at different time, even though $\sigma^*_{t,act}$ and $\sigma^*_{br,act}$, are caused by $\mathbf{F_r}$ and cannot be independent. It is perfectly obvious that with the maximum short circuit surge current flowing, a single full stress σ^* originates in the conductor. This stress corresponds to the full strain ε^* caused by tension/compression, bending in the axial and radial directions due to the action of the EM force $\mathbf{F}$ as well as due to the initial bending during winding fabrication (Fig. 5, 6). At that, in many cases, already the initial bending deformations (Fig. 6) surpass the conductor yield strength. That is, (24) does not hold for them even without regard to the EM forces. However, these conductors sustain significant EM forces without detectable deformations. This means that with the initial plastic strains strength verification by permissible stresses is not correct.

Papers [2, 3] did not take into account the axial component F_a of the EM force F in their treatment of windings torsion, thus their results and conclusions require correction

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