

## **Analysis of Short Circuit Withstand Capability of Power Transformers**

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### **SUMMARY**

The research commenced in the 1970ies resulted in a theory revealing the nature of development processes of deformations leading to all known damage kinds occurring in windings under short circuit. It is the basis for the respective calculation methods, criteria and norms for verification of short circuit withstand capability of power transformer windings. It contains no empirical dependencies or coefficients, thus has no limitations on values of parameters of the windings considered.

A comparison of these criteria and those put forth in the Informative Annex A of IEC 60076-5:2006 is given. The criterion of winding conductor strength in compression/tension is similar to the IEC criterion. The criterion limiting the residual radial displacements of winding conductors (rigidity criterion) is missing from Annex A. To verify winding withstand capability against buckling, the critical stress is calculated with regard to: conductor material yield strength; wire type; epoxy bonding of conductors and/or wires gluing with each other; initial bending strains; buckling form depending on winding type, radial supports absence/presence, radial gap inside the winding, spacers columns quantity, axial clamping. In contrast, Annex A only offers a set of empirical factors regarding wire type and epoxy bonding. The inconsistency of the winding conductors bending strength criteria in Annex A is demonstrated; instead a set of criteria based on the limiting state is suggested. Verification of winding conductor tilting withstand capability, strength analysis of winding elements under the action of axial internal short circuit forces is performed by criteria similar to those in Annex A. However, the values of acting internal forces and stresses are determined by a dynamic calculation of windings axial vibrations due to electromagnetic short circuit forces. The critical conductor tilting force is determined with regard to the same parameters as the critical buckling stress. The criterion of withstand capability against torsion (spiralling) for helical and layer windings is explicitly defined.

A comparison of calculation and tests results of 50 machines is given. The software implementing these calculation methods is used by over 30 transformers manufacturers worldwide. The transformers analyzed by JSC “VIT” with its application have passed short circuit tests on the first go, confirming the validity of the presented theory, calculation methods, norms and criteria, as well as the adopted approach to strength analysis of the clamping structure. The raising importance of strength analysis of the windings clamping structure is discussed and illustrated by examples. Measures for short circuit withstand capability improvement are listed. The ultimate importance of stringent quality control for delivery of short circuit safe transformer equipment is stressed.

### **KEYWORDS**

Transformers, short circuit, forces, buckling, tilting

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Starting from the 1970ies, JSC “VIT” has been performing research aimed at developing reliable calculation methods for short circuit withstand capability analysis of power transformer windings. Based on the laws and relations of deformable systems mechanics, there has been developed a theory that reveals the nature of the processes of development of deformations that lead to all known short circuit winding damage kinds. This theory does not contain any empirical dependencies or coefficients, thus it does not contain any limitations on values of parameters of the windings considered. Based on the theory, there were developed calculation methods, which were implemented as a software-methodical suite (SMS) “ELDINST”. This suite includes two software programs: 1) ELDINST (calculation of short circuit withstand capability of windings); 2) YokeBeam (calculation of a set of clamping structure parameters required for the ELDINST software). SMS “ELDINST” also includes a set of technical documentation.

Short circuit withstand capability of transformer windings according to SMS “ELDINST” is verified by 8 criteria described below.

**1.** Verification of winding conductors strength under the action of radial electromagnetic forces is similar to the approach accepted in the informative Annex A of IEC 60076-5:2006:

$$K1 = \frac{\sigma_{02}}{\sigma_w} \geq K1 \text{ min} , \quad (1)$$

where  $\sigma_{02}$  is conductor material yield strength;  $\sigma_w$  is the maximum hoop stress in the average conductor.

**2.** For the residual deformations of conductors after short circuit to have no critical influence upon insulating gaps and cooling conditions, the windings must meet the criterion of rigidity under the action of radial electromagnetic forces:

$$K2 = \frac{u_{ps}}{u_{pls}} \geq K2 \text{ min} , \quad (2)$$

where  $u_{ps}$  ,  $u_{pls}$  are the permissible and calculated residual radial displacements of conductors. This criterion is missing from the informative Annex A of IEC 60076-5:2006.

**3.** Windings, compressed by radial electromagnetic short circuit forces, must satisfy the following criterion:

$$K3 = \frac{\sigma_{cr}}{\sigma_w} \geq K3 \text{ min} , \quad (3)$$

where  $\sigma_{cr}$  is the critical stress of buckling which is calculated on the basis of the following parameters:

- yield strength of conductor material  $\sigma_{02}$  ;
- wire type (simple/PICC; subdivided/bunch; CTC);
- epoxy bonding of conductors and/or wires gluing with each other;
- initial bending strains;
  - radial dimension of the average conductor (b);
  - average winding diameter (D);
- form of buckling which depends on:
  - winding type (disk, helical, layer);
  - absence or presence of radial supports;
  - radial clearance inside the winding;
  - quantity of spacers columns;
  - axial clamping.

The informative Annex A of IEC 60076-5:2006 does not consider a set of the aforementioned factors, and introduces a series of empirical factors to take into account the wire type and conductors epoxy bonding.

The main feature of the approach implemented in SMS “ELDINST” is taking into account initial bending strains when determining the critical stresses of buckling. In Fig. 1 are shown dependencies of critical stress v. slenderness ratio, where curve 1 is built in accordance with the theory

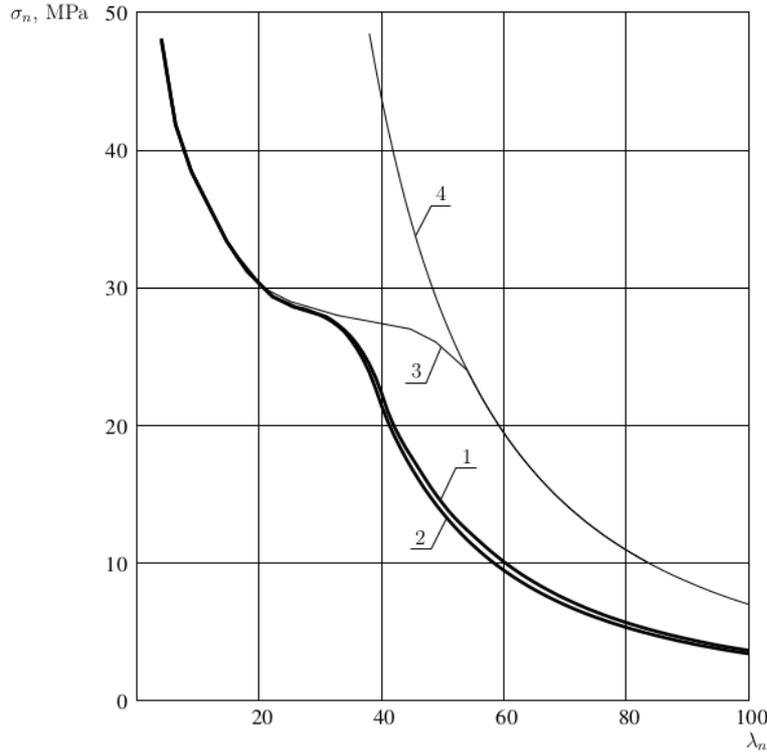


Fig. 1 : Critical stress v. slenderness ratio.

of SMS “ELDINST” at  $\kappa = \frac{b}{D} = 0.01$ , curve 2 – at  $\kappa = 0.04$ ; curve 3 corresponds to Shanley's concept, adopted in the works by del Vecchio; curve 4 is Euler-Timoshenko's dependency. Thus, calculation methods that do not take into account the initial bending deformations produce overestimated values of critical stresses of buckling.

Similar curves are calculated and used to verify buckling withstand capability of the windings with epoxy bonding and/or wires gluing.

Verification of winding conductors strength in bending by radial and axial electromagnetic forces in the SMS “ELDINST” is radically different from the

approach suggested in the informative Annex A of IEC 60076-

5:2006. According to the Annex (cl. 3.3.3.2) one should use three strength conditions: the conditions of strength in compression-tension, in bending in the axial and radial directions, i.e.

$$\sigma_{t.act}^* \leq 0.9 \cdot R_{p0.2}, \quad (4)$$

$$\sigma_{br.act}^* \leq 0.9 \cdot R_{p0.2}, \quad (5)$$

$$\sigma_{ba.act}^* \leq 0.9 \cdot R_{p0.2}. \quad (6)$$

Obviously, with short circuit surge current being fed, the deformations of tension as well as bending in the radial and axial directions originate in conductors simultaneously. Therefore, conductor strength must be checked by the stress that corresponds to the maximum full strain, which is equal to the sum of strains of tension and bending in the radial and axial directions. Under the condition, that this sum doesn't exceed the yield limit of the conductor material, it can be defined as a sum of three stresses –  $\sigma_{t.act}^*$ ,  $\sigma_{br.act}^*$ ,  $\sigma_{ba.act}^*$ , i.e.

$$\sigma_{act}^* = \sigma_{t.act}^* + \sigma_{br.act}^* + \sigma_{ba.act}^*. \quad (7)$$

For conductor strength to be ensured, instead of the three conditions (4)–(6), the single condition below must be met:

$$\sigma_{act}^* \leq 0.9 \cdot R_{p0.2}, \quad (8)$$

in other terms

$$\sigma_{t.act}^* + \sigma_{br.act}^* + \sigma_{ba.act}^* \leq 0.9 \cdot R_{p0.2}. \quad (9)$$

Also, when it is taken into account that the conductors bend during winding manufacture, and significant bending strains and stresses arise in them (sometimes these stresses significantly exceed  $R_{p0.2}$ ), then all the strength conditions (4),–(6), (8), (9) are not correct and mustn't be used to check short circuit strength of windings.

With regard to the aforementioned, verification of winding conductors strength in bending by the axial and radial electromagnetic short circuit forces in the SMS “ELDINST” is performed by the limiting state. As such is accepted the state in which the stresses acting in every point of the dangerous cross section of the conductor are equal to the yield limit. The limiting state is shown in Fig. 2; it is

characterised by a pair of limiting bending moments due to the action of the stresses in areas 1 and 2 of the conductor cross section.

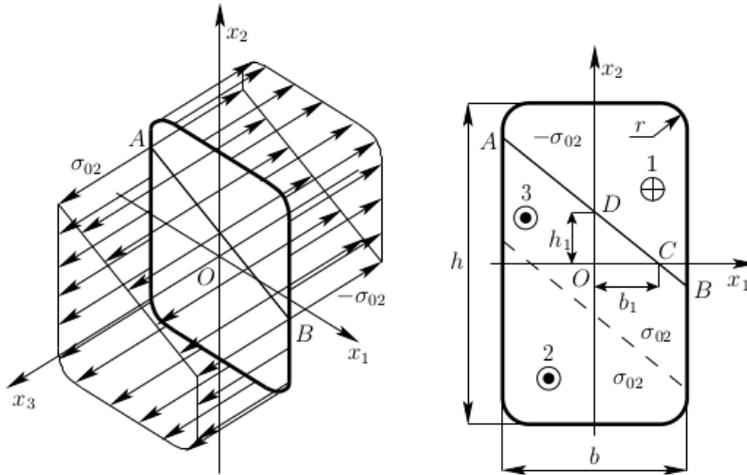


Fig. 2 : Limiting State

4. Thus, the maximum bending moment of the axial electromagnetic short circuit forces acting upon the span of the conductor between the supports (i.e. spacers columns) must not exceed the value of the respective limiting bending moment:

$$K4 = \frac{M_{1lim}}{M_{1max}} \geq K4_{min}, \quad (10)$$

where  $M_{1lim}$ ,  $M_{1max}$  are the limiting and maximum moments of bending in the axial direction.

5. To verify conductor strength in bending by the radial electromagnetic short circuit forces, a similar criterion is used:

$$K5 = \frac{M_{2lim}}{M_{2max}} \geq K5_{min}, \quad (11)$$

where  $M_{2lim}$ ,  $M_{2max}$  are the limiting and maximum moments of bending in the radial direction.

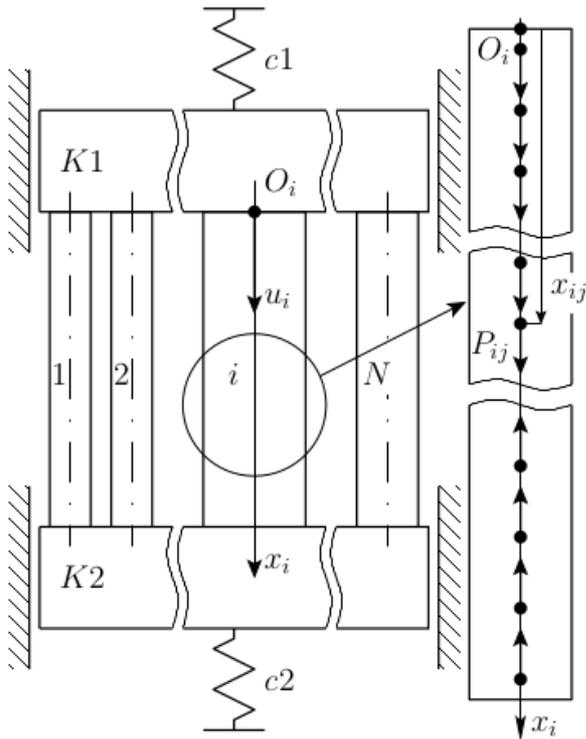


Fig. 3 : Model for calculation of windings axial vibrations under short circuit.

In order to analyse strength of winding elements, winding conductors tilting withstand capability and to calculate the internal forces acting upon the clamping structure, a calculation of windings axial vibrations is performed according to the model presented in Fig. 3, where  $1, \dots, N$  are linearly elastic rods simulating the windings;  $K1$ ,  $K2$  are the masses simulating the top and bottom clamping rings with the yoke beams connected to them;  $c1$ ,  $c2$  are the inertialess springs simulating the top and bottom clamping structures;  $x_{i,j}$  are the axial coordinates of the winding coils (turns);  $P_{i,j}$  are the time functions of the axial electromagnetic forces applied to the coils (turns).

The presented dynamic calculation differs from the static approach suggested in the informative Annex A of IEC 60076-5:2006. It allows to reliably determine axial internal forces

arising in the windings and applied to the clamping structure.

6. Based on the axial vibrations calculation results, windings withstand capability against conductors tilting is determined according to the criterion:

$$K6 = \frac{P_{cr}}{N_{max}} \geq K6_{min}, \quad (12)$$

where  $P_{cr}$  is critical conductor tilting force;  $N_{max}$  is the maximum internal compressive force in the winding.

The calculation of  $P_{cr}$  takes into account not only the contribution of the conductors with regard to their epoxy bonding, but also the contribution of deformable spacers columns, elements of insulation between coils, as well as deformations of locking strips.

7. The criterion of winding elements strength under short circuit adopted in SMS “ELDINST” is similar to that in the informative Annex A of IEC 60076-5:2006, the difference being that the acting stress is determined in accordance with the aforementioned dynamic calculation:

$$K7 = \frac{|\sigma_{perm}|}{[\sigma_{max}]} \geq K7_{min}, \quad (13)$$

where  $\sigma_{perm}$  is the permissible stress of the material of a winding element (i.e. conductor, spacer, paper insulation);  $\sigma_{max}$  is the maximum acting stress in the respective winding element.

Also, in the calculation of axial vibrations are determined minimum internal compressive forces in the windings. These results are used to determine critical stresses of buckling  $\sigma_{cr}$ .

8. By the minimum internal compressive forces is also checked windings withstand capability against torsion (spiralling) according to the criterion

$$K8 = \frac{P_{pr}}{P_{tmin}} \geq K8_{min}, \quad (14)$$

where  $P_{pr}$  is the minimum internal axial compressive force of the winding;  $P_{tmin}$  is the minimum permissible internal axial compressive force of the winding for torsion (spiralling) prevention.

The recommended values of the minimum safety factors  $Ki_{min}$  are:

$$Ki_{min} = 1.0, \dots, 1.2; (i = 1, 2, \dots, 8). \quad (15)$$

As a result of axial vibrations calculations by ELDINST software, the maximum forces are determined that act upon the clamping structure as a whole and upon the yoke beams and yokes in particular. Strength of the clamping rings and clamping structure elements is verified with ANSYS software in JSC “VIT”

SMS “ELDINST” found wide application in the practice of transformer engineering. Currently, it is used by over 30 transformer manufacturers from various countries. Some of these manufacturers performed and continue to perform short circuit tests of transformers. The results of SMS “ELDINST” application to analysis of such transformers are presented in Tables 1, 2. Table 1 lists the transformers that were designed without using SMS “ELDINST”. The transformers listed in Table 2 were designed with direct application of this suite and tested for short circuit withstand capability. The tables demonstrate that calculation results match test and service data in all the cases. This proves validity of SMS “ELDINST” calculation methods, criteria and norms for verification of windings short circuit withstand capability

All the transformers that were designed with application of SMS “ELDINST” (Table 2) passed short circuit withstand capability tests on the first go. Theoretical research for improvement of windings short circuit withstand capability calculation and for expanding the features of SMS “ELDINST” continue to date. The results of the research into the problem are mainly covered in publications [1—18].

Co-operation is carried out with a series of manufacturers regarding preparation of transformers for short circuit tests (design review, manufacturing technology audit), participation in the tests, analysis of test results. Thus, to verify the calculation methods, experimental data are used that have been acquired from various test laboratories for the transformers of various manufacturers. The accumulated experience demonstrates that not only reliable methods for windings short circuit withstand capability analysis are required, but also similarly reliable methods for strength analysis of the windings clamping structure. On multiple occasions it was observed that a transformer would

sustain several short circuit experiments and fail afterwards. Further analysis would indicate that in such cases strength of the winding clamping structure had not been ensured. After introducing necessary improvements into the design, subsequent short circuit tests would complete successfully.

Table 1 : Transformer analysis and test results (retrospective)

№	Transformer (country, date of calculation)	Rated power, MVA	Country where tests were performed	Conclusion on calculation results	Test results
1	ODCNP-175000/750 (USSR, 15.01.1999)	175 (1 ph)	USSR	Buckling of PW winding	Buckling of PW winding
2	TDC-400000/220 (USSR, 22.01.1999)	400 (3 ph)	USSR	Buckling of LV winding	Buckling LV winding
3	TC-667000/500 (USSR, 15.12.1999)	667 (3 ph)	USSR	Conductors tilting in HV winding	Conductors tilting in HV windings of all phases
4	TRDN-80000/110 (USSR, 27.11.2001)	80 (3 ph)	USSR	Conductors tilting in HV winding	Conductors tilting in HV winding
5	TRDN-40000/161 (USSR, 09.09.2004 got damaged in service)	40 (3 ph)	USSR	Insufficient strength of the clamping structure of LV winding	Deformations of the clamping ring, clamping screws and LV winding itself
6	ONDCNP-320000/750/500 (Ukraine, 19.08.2003)	320 (1 ph)	USSR	Short circuit withstand capability is ensured	Passed the tests (deformations of windings were not detected)
7	TDN-63000/154 (Ukraine, 05.10.1999)	63 (3 ph)	Netherlands		
8	TM-400/10 (Ukraine, 09.03.2006)	0.4 (3 ph)	Ukraine		
9	TM-1000/10 (Ukraine, 22.03.2006)	1.0 (3 ph)	Ukraine		
10	70MVA 400/13.8kV (France, 08.12.2009)	70 (1 ph)	Netherlands		
11	10MVA 66kV (India, 07.10.2012)	10 (3)	India		
12	7.5MVA, 66kV, autotransformer (India, 08.10.2012; got damaged in service)	7.5 (1)	India	Insufficient strength of the clamping structure	Deformations of the pressing ring

Table 2 : Transformer analysis and test results (application)

№	Transformer(country, date of calculation or test)	Rated power, MVA	Country where tests were performed
1	154kV.GIT – gas filled, 20 MVA with two limbs (South Korea, 26.05.1998)	20 (1 ph)	South Korea
2	70MVA, 220kV (India, 17.04.2002)	70 (3 ph)	India
3	154kV.GIT – gas filled, 20 MVA with a single limb (South Korea, 03.09.2002)	20 (1 ph)	South Korea
4	25/31.5MVA, 132/32kV (India, 15.08.2003)	31.5 (3 ph)	India
5	SFFZ10-31500/110 (ATDTN) (PRC, 20.02.2004)	31.5 (3 ph)	PRC
6	SFZ-50000/110 (PRC, 20.02.2004)	50 (3 ph)	PRC
7	TRMGT-1000/10 (Ukraine, 16.05.2005)	1.0 (3 ph)	Ukraine
8	26MVA, 132/11.5kV (Iran, 26.09.2005)	26 (3 ph)	Netherlands
9	40/50MVA, 132/66kV (India, 25.09.2007)	50 (3 ph)	India

№	Transformer(country, date of calculation or test)	Rated power, MVA	Country where tests were performed
10	25MVA, 132/33kV (India)	25 (3 ph)	India
11	35MVA, 220kV (India, 03.04.2008)	35 (3 ph)	India
12	50MVA, 132/33kV (India)	50 (3 ph)	India
13	102MVA, 400/16kV (India, 09.06.2007)	102 (1 ph)	Netherlands
14	25MVA, 420/11kV (India, 15.01.2009)	25 (1 ph)	India
15	32MVA, 220/11kV (India, 15.01.2009)	32 (1 ph)	India
16	17.5MVA, 132/11kV (India, 20.10.2008)	17.5 (1 ph)	India
17	315MVA, 400/220/33kV, AT (India, 22.08.2007)	315 (3 ph)	Netherlands
18	80MVA, 400/11.5kV (India, 20.07.2009)	80 (3 ph)	India
19	200MVA, 420/21kV (India, 03.09.2009)	200 (1 ph)	Netherlands
20	45MVA, 21/11.5kV (India, 21.09.2009)	45 (3 ph)	India
21	82MVA, 15/420/ $\sqrt{3}$ kV (India, 13.04.2009)	82 (1 ph)	Netherlands
22	200 MVA, 400/132 kV, AT (India, 2010)	200 (3 ph)	Netherlands
23	250 MVA, 420/ $\sqrt{3}$ / 20 kV (UK– France, 2009 – 2010)	250 (1 ph)	Netherlands
24	315MVA, 400/220/33kV, AT (India, 15.01.2010)	315 (3 ph)	Netherlands
25	40MVA, 230/121/10.5kV, AT (India, 15.09.2008)	40 (1 ph)	India
26	105 MVA, 400/220/33kV, AT (India, 24.09.2011)	105 (1 ph)	Netherlands
27	15 MVA, 66/11kV, (India, 05.10.2012)	15 (3 ph)	India
28	TRDN-40000/110, (Russia, April 2012)	40 (3 ph)	Czech Republic
29	27MVA, 132/27kV, traction-feeding (India, July 2013)	27 (1 ph)	India
30	50MVA, 132/33kV (India, May 2014)	50 (3 ph)	India
31	5MVA, 66/11.55kV (India, August.2014)	5 (3 ph)	India
32	315MVA, 400/220/33kV, AT (India, July, 2014)	315 (3 ph)	Netherlands
33	130MVA, 500/150/31.5kV, AT (South Korea, 2014)	130 (1)	Netherlands
34	TRDN-40000/110, (Russia, February 2015)	40 (3 ph)	Russia
35	40 MVA, 60/31.5kV, (India, 2016 – 2017, 3 units)	40 (3)	Netherlands
36	40 MVA, 60/10.5kV, (India, 2016)	40 (3)	Netherlands
37	40 MVA, 60/31.5kV, (India, 2017)	40 (3)	India
38	40 MVA, 110kV, (Poland, 19.04.2018)	40 (3)	Czech Republic

For a set of transformers listed in Table 2 (it. 13 – 25, 33, 34, 38) there were performed calculations by the methods of SMS “ELDINST” as well as strength analysis of the clamping structure using ANSYS. The positive results of the tests of these machines attest to the validity of the strength analysis of the clamping structure performed by JSC “VIT”.

The transformers of medium and high capacity presented in Table 2 had common clamping rings; conductors epoxy bonding and hardening were used in their windings. Thus, the calculation methods, criteria and norms for short circuit withstand capability verification of SMS “ELDINST” have been proven by tests of the transformers of the old design (Table 1) as well as new design (Table 2).

The transformers presented in Table 2 differ in: 1) active part design and materials; 2) manufacturing equipment; 3) manufacturing technology; 4) quality control system; 5) staff skill and experience.

Such differences notwithstanding, successful tests of these transformers demonstrate that the main factor for ensuring windings short circuit withstand capability was the validity of calculation methods, verification criteria and norms of SMS “ELDINST”.

Generally, the analysis of SMS “ELDINST” application and tests allows to list the most widely applicable measures for solving a set of problems related to ensuring short circuit withstand capability of windings:

1. For prevention of buckling: a) conductors epoxy bonding; b) conductors hardening; c) installation of windings on the leg and on each other without clearances in the radial direction;
2. For ensuring conductors strength in bending by electromagnetic short circuit forces: a) conductors epoxy bonding; b) conductors hardening;
3. For prevention of conductors tilting: a) conductors epoxy bonding;
4. For prevention of torsion (spiralling) of helical and cylindrical (layer) windings: a) installation of radially compressed internal windings on the leg and on each other without clearances in the radial direction; b) applying fibreglass bands to the external windings.

With utilisation of the measures above, the main kind of damage becomes failure of the clamping structure elements. Thus, it is absolutely necessary to perform strength analysis of the clamping structure elements under the action of the maximum dynamic forces occurring under short circuit.

A series of cases were documented, when transformers would successfully pass short circuit tests due to utilisation of conductors epoxy bonding. However, in the machines delivered to the grid, conductors epoxy bonding would not be ensured. That is, to guarantee the quality of the machines delivered to the network a reliable quality control system is required, especially when wires with conductors epoxy bonding are used.

**Conclusions.** Positive experience of practical application of SMS “ELDINST” serves as confirmation of validity of its calculation methods, criteria and norms for verification of windings short circuit withstand capability.

Utilisation of conductors epoxy bonding and hardening, installation of windings on the magnetic system leg and upon each other without gaps, as well as using external fibreglass bands on radially stretched helical and cylindrical windings allow to solve the problem of ensuring windings short circuit withstand capability. The main problem becomes providing strength of the clamping structure under the action of short circuit forces. For the delivery of reliable transformers to the grid, verification of their short circuit withstand capability must be performed by windings short circuit withstand capability analysis and strength analysis of the clamping structure carried out in accordance with valid methods, or by test results. In addition, a reliable quality control system of production and materials used is necessary for manufacturers.

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