SELECTED PROBLEMS OF SHORT CIRCUIT WITHSTANDABILITY

Section II - POWER TRANSFORMER

28 - 30 October 2004, Vigo - Spain
Computing methods in the analysis of short circuit withstandability

The paper presents the following methods of calculation, taking into account deformation, the structure of the windings and physical properties of their materials:

- analytical method used for outer winding subjected to tensile radial forces,
- finite elements method used for winding loaded by compressive or tensile radial forces,
- deflation method for buckling stresses calculation,
- The analysis of axial forces, the coils vibration and critical axial pressure
Analytical method to analyse tensile radial forces

The general assumptions of the method:

- Winding coils consist of insulated rectangular conductors which are represented by concentric rings, sticking to each other (Fig. 1),

- Radial load of conductors are constant along circumference and can change in radial direction of the coil,

- Winding materials have non-linear mechanical characteristic. It can cause plastic deformation in conductors and accumulation effect of their deformation.
Analytical method to analyse tensile radial forces

Fig. 1. Electrodynamic conductor load $q_k$ and interaction on its adjacent turns and their insulation for stretched coils

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Analytical method to analyse tensile radial forces

Fig. 2 Strain/stress curves for: a) copper conductor - proof stress $\sigma_{0.2}=100\text{MPa}$, b) transformer-board (1) and paper (2)
Analytical method to analyse tensile radial forces

Fig. 3, 4 The cumulating effect of conductor permanent deformations and its approximation used in calculations for k-conductor.
Analytical method to analyse tensile radial forces

Fundamental equations:

\[
\sigma_k = \frac{(q_k + p_{k-1} - p_k) \cdot R_k}{s_c} \quad (1a)
\]

\[
\varepsilon_k \cdot R_k = \varepsilon_{k+1} \cdot R_{k+1} - \mu_k \cdot \delta_k \quad (1b)
\]

\[
p_0 = p_n \quad (2)
\]

\[
\sum_{i=2}^{1} \Delta \varepsilon_i = A \cdot (I - 1)^B \quad (3)
\]

\[
\sigma_m = \frac{q_0 \cdot R_m}{2 \cdot s_c} \quad (4)
\]
Analytical method to analyse tensile radial forces

Fig. 5 Distribution, along the width of the coil, of stresses in the coil conductors for different ratios $\sigma_m/\sigma_{0.2}$: 1-0.353, 2-0.9, 3-1.0, 4-1.1
a) at short-circuit state b) after short-circuit state Solid line - coil with inner axial ducts; dashed line – without axial ducts
Analytical method to analyse tensile radial forces

Fig. 7 Strains at short-circuit (solid lines) and permanent sets (dotted lines) of inner (1) and outer (2) coil conductors shown for the first (reference designation *) and 10th short-circuits (reference designation ⊗), as a function of the $\sigma_m/\sigma_{0.2}$ ratio.
Numerical method to analyse radial forces

The general assumptions of the method:

- Conductors are represented by curvilinear plan elements and coil insulation by spring elements. The elements have non-linear mechanic characteristic. The coil can have any shape.

- The radial load of coil conductors along the circumference and radial direction can be of any value and direction. It is possible to calculate the plastic deformation after short circuit states.

- Coil insulation can, in a typical situation, transfer only compressive forces.
Numerical method to analyse radial forces

Fig. 8. Discrete model of coil sector
1 – coil conductors, 2 – support strips, 3 – curvilinear elements representing coil conductor, 4 – springy elements
Numerical method to analyse radial forces

Fundamental equations:

\[ \left[ \mathbf{K}_{cp}^{(i)} + \mathbf{K}_\sigma^{(i)} \cdot (\sigma) \right] \cdot \Delta f^{(i+1)} = \Delta q^{(i+1)} \]  

(5)

\[ f^{(i)} = \sum_{j=1}^{i} \Delta f^{(j)} \]  

(5a)

\[ q^{(i)} = \sum_{j=1}^{i} \Delta q^{(j)} \]  

(5b)

\[ q_{ci}^{(i)} = \lambda \cdot q^{(i)} \]  

(6a)

\[ \left[ \mathbf{K}_{cp}^{(i)} + \lambda \cdot \mathbf{K}_\sigma^{(i)} \cdot (\sigma) \right] \cdot \mathbf{v} = 0 \]  

(6b)

\[ q_{cr} = \sum_{j=1}^{n} q_{cr}^{(j)} \]  

(6c)
Numerical method to analyse radial forces - examples

Fig. 9 The winding deformation of the distribution transformer with rectangular legs at three phase fault
Numerical method to analyse radial forces - examples

Fig. 10 HV layer winding deformation of large power GSU Transformer, caused by short-circuit tensile radial forces (black line – the winding without deformation, red line - deformed winding). a) at the amplitude of short-circuit current, b) after short-circuit state.
Numerical method to analyse radial forces - examples

Fig. 11 The stresses in HV winding conductors of large power GSU Transformer, caused by short-circuit tensile radial forces.
Numerical method to analyse buckling stresses

General basis of deflation method:

- making the analysis of coil deformation (it’s uses only static equations (5)),
- the calculation takes into account physical and geometrical non-linearity,
- finding the step of load, at which the shape of coil is rapidly changing.
Numerical method to analyse buckling stresses - examples

Fig. 12 Deformations of the unsupported ring for different steps of radial load (blue line: step 80 - $\sigma_m = 8.8$ MPa, step 105 - $\sigma_m = 11.55$ MPa, step 110 - $\sigma_m = 12.1$ MPa, step 111 - $\sigma_m = 12.21$ MPa, black line: unsupported ring)
Numerical method to analyse buckling stresses - examples

Fig.13 Radial displacement of chosen knots of the calculation ring model in function of loading, defined with average compressive stresses $\sigma_m$.

(position of knots on the ring is shown in Fig.12)
Buckling stresses, the simple formulas

- **Critical radial load for unsupported ring:**
  \[ \sigma_{cr} = \frac{E}{4} \left( \frac{h}{R} \right)^2 \]  
  (7)
  
  - E-modulus of elasticity, \( h \)-radial dimens. of the ring, \( R \)-the ring radius

- **Critical radial load for coils, according to Fischer’s formula [7]:**
  \[ \sigma_{cr} = \frac{E}{48} \cdot z^2 \cdot \left( \frac{h}{R} \right)^2 \]  
  (8)
  
  - \( z \)-number of supports on winding circumference
Numerical method to analyse buckling stresses - examples

Table 2 Critical load $\sigma_{kr}$ for unsupported ring

<table>
<thead>
<tr>
<th>Pattern of buckling</th>
<th>Value of critical load $\sigma_{crr}$ [MPa] calculated according:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Deflection method representing</td>
</tr>
<tr>
<td></td>
<td>$\frac{1}{4}$ of the circumference</td>
</tr>
<tr>
<td>1</td>
<td>14,96</td>
</tr>
<tr>
<td>2</td>
<td>15,18</td>
</tr>
<tr>
<td>3</td>
<td>no data</td>
</tr>
</tbody>
</table>
Numerical method to analyse buckling stresses - examples

Table 3 Value of Buckling Stresses for Selected Models [6]

<table>
<thead>
<tr>
<th>Symbol of Models</th>
<th>Test results in [MPa]</th>
<th>Calcul. results in [MPa], accor. to:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Deflect. method</td>
</tr>
<tr>
<td>MR32</td>
<td>74,4</td>
<td>70,4</td>
</tr>
<tr>
<td>M16B</td>
<td>50,5</td>
<td>56,6</td>
</tr>
<tr>
<td>Del Vecch.1</td>
<td>88,4</td>
<td>109,0</td>
</tr>
<tr>
<td>Del Vecch.2</td>
<td>90,4</td>
<td>99,0</td>
</tr>
</tbody>
</table>

1) model was made of ctc conductor [2], [6]
2) Del Vecchio’s model tests [5]
Numerical method to analyse buckling stresses - examples

Fig. 14 Test and calculation results of model MR32 [6]

a) Model after a destructive dynamic test
b) Calculated instability form (dotted line) for inner turn of coil.
Numerical method to analyse buckling stresses - examples

Fig. 15 Test and calculation results of model M16B [2,6]
a) Model after a destructive dynamic test, b) Calculated instability form for inner turn of coil.
The analysis of axial forces and the coils vibration

The general assumptions of the method:

- the coils, on which time variable axial electrodynamics forces act, are in state of vibration. The friction, static compressive and inertia forces also have an effect on the vibration,

- the windings are represented by concentrated mass of coils and the insulation between coils by springy elements (see Fig. 17),
The analysis of axial forces and the coils vibration

The general assumptions of the method (continuation):

- mechanical characteristics of springy elements are non-linear,
- static compressive forces along winding height are computed from percentage compression of winding insulation height,
- the breaking contact between the coil and adjacent inter coil spacers is assumed as the criteria of winding destruction.
The analysis of axial forces and the coils vibration

Fig. 17 Winding model for dynamic analysis [9]. a) base diagram of coil arrangement, b) calculated forces acting on i-coil and its insulation
The analysis of axial forces and the coils vibration

Fundamental equations:

The equation of the static balance for computing static compressive forces distribution -

\[ K^{i}(\delta) \cdot \Delta Z^{(i+1)} = F_{pr} - (S^{i} + T^{i}) \]  \hspace{1cm} (9)

- \( K^{i}(\delta) \)-matrix of stiffness, \( \delta \)-coil displacement, \( \Delta Z^{(i+1)} \)-increment of displacement vector, \( F_{pr} \)-vector of pressing forces, \( S^{i} \)-vector of flexibility forces, \( T^{i} \)-vector of friction forces.

The matrix equation for computing parameters of vibration -

\[ M \cdot Z'' + C \cdot Z' + K(\delta) \cdot \Delta Z = F_{ed} - (S + T) \]  \hspace{1cm} (10)
The analyse of axial forces and the coils vibration

Fundamental equations (continuation) :

\[ M, C, F, Z, Z', Z'' \]

The criterion of breaking mechanical contact between the coil and the adjacent spacers in process the of coil vibration -

\[ S_n < 0 \quad (9a) \]
The axial forces and the coils vibration - examples

Presented calculation results were obtained for two technological variants, namely:

1. High static pressing degree of the insulation - about 9% of its height, by using rigid supports at the winding ends, coils wound with low tension

2. Limited static pressing degree of the insulation - about 7% of its height, less rigid ends supports and coils wound with higher tension
The axial forces and the coils vibration - examples

Fig 16 Axial electrodynamic forces acting on the end coils of LV winding of large power GSU transformer [10]
The axial forces and the coils vibration - examples

Fig. 18  Stress distribution in the insulation of the winding at static pressing, the technology covering version (1) and (2)
The axial forces and the coils vibration - examples

Fig. 19 Forces in end insulation of the winding as functions of time for variants 1 (a) and 2 (b)
The axial forces and the coils vibration - examples

Fig. 20 Axial displacement of end coils for version 1 (a) and 2 (b)
The axial forces and the coils vibration - examples

Fig. 21 Pressure in intercoil spacers at half of the winding height, version 2 [9], [10]
The critical axial forces - tilting effect

New draft document of IEC 60076-5 presents the following formula for critical axial forces of core-type transformers windings:

\[ F_{\text{tilt}} = \left[ K_1 \cdot E_0 \cdot \frac{n \cdot b_{eq} \cdot h^2}{D_{mw}} + K_2 \cdot \frac{n \cdot X \cdot b_{eq}^3 \cdot \pi \cdot D_{mw} \cdot \gamma}{h} \right] \cdot K_3 \cdot K_4 \]

were: \( E_0 \) - modulus of elasticity, \( n \) - number of strand in the winding radial width, \( b \) - equivalent radial width of strand, \( D_{mw} \) - average diameter of winding, \( h \) - strand height of conductor, \( K_1, K_2, K_3, K_4, X, \gamma \) - experimental data defined in the Draft Document.
The critical axial forces - tilting effect

Typical coil conductors deformation at tilting effect
Fig. 22 Arrangement with hydraulic press for static evaluation of critical axial forces at tilting
Testing the critical axial forces at tilting

Fig. 23 Arrangement for dynamic evaluation of critical axial forces. Supply coils and model after testing.
CONCLUSION

- the average stresses in the coil conductors $\sigma_m$ and their proof stress $\sigma_{0.2}$ are the most essential parameters determining withstandability of these windings to radial short circuit forces.

- The relation of the above stresses which should be considered as completely safe is $\sigma_n / \sigma_{0.2} \leq 0.7$.  

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CONCLUSION (continuation)

- The presented numerical calculation method of buckling stresses gives good results in comparison with tests, better than other simplified calculation formulas.

- The analysis of the axial component of short circuit forces and coils vibration, allowed for assessment of withstandability taking in account physical properties of winding materials, coil displacements and static compression forces.
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