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Development and Engineering Mng
Corporative Executive Engineer

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High Voltage Power Transformers:
Short-Circuit – Stress, Strength, Design, Testing, Advanced Technologies and Recommendations
Short-Circuit in Power Transformers

Content

- introduction
- short-circuit in power transformers
  - overview
  - fault types and severity
  - reliability and failure rates
  - international standards
- short-circuit performance
  - thermal and mechanical capabilities
  - short-circuit current characterization and dynamic effect
  - short-circuit forces, failure modes, tap changers position, aging effects
  - residual pressing forces
- short-circuit and power transformer design
  - design steps (fault current; SC forces; SC stresses; design criteria)
  - experiences
- short-circuit full test
  - test needs, results and failure rates
  - reference list
- advanced materials and technologies
- conclusions
- recommendations
  - technical specification – Tender and Design
  - performance verification – Design Review and/or Full SC Test
- PPTR Power Transformers
  - power transformers up to 765kV
  - shunt reactors up to 765kV
  - heavy current industrial transformers
  - service (Eng Solution, Factory and Site Repairs, Monitoring Systems, TrServices)
  - insulation components
  - transformer components (Bushings, Tap Changers, etc)

- PPMV Medium Voltage, PPHV High Voltage
Context

Power Transformer Importance

Power Transformer: 50%...70% Substation Cost
Scenarios

Electric Power Existing Infra Structure Aging

FURNAS SE Tijuco Preto São Paulo ITAIPU HVAC 765 kV Transmission System

765/550kV banks Autos 1650MVA

765/345kV banks Autos 1500MVA

345kV capacitor banks

550kV yard

765kV yard

345kV yard

SE Tijuco Preto - Terminal HVAC ITAIPU - São Paulo
High Voltage Power Transformers:
Short Circuit - Overall
Economic environment can affect power transformers design and performance:

- there are now more strong temptations to save active material
- there are now more strong temptations to go closer to mechanical limits
- present tenders comparison process may be weak to compare short-circuit performance

Industry Standards to check the short-circuit mechanical strength and integrity of Power Transformers:

- existing standards, as an example IEC60076-5 3rd Ed 2006-02, establishes recommendations as
  a) Short-Circuit tests; or
  b) Design Review evaluation/verification (IEC proposes typical allowable, critical stresses)
Fault Occurrence

Utility experience

- line faults statistics more frequent than substation faults
- highest number of faults in systems rated up to 100kV
- single-phase faults are the most frequent >65% of all faults, typically due to lightning strokes

<table>
<thead>
<tr>
<th>Fault Type</th>
<th>Number of faults per 100 km/year (90-percentile value)</th>
<th>1-phase faults</th>
<th>2-phase faults</th>
<th>3-phase faults</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line faults</td>
<td></td>
<td>17,3</td>
<td>8,3</td>
<td>4,8</td>
</tr>
<tr>
<td>Substation faults</td>
<td></td>
<td>64</td>
<td>65</td>
<td>74</td>
</tr>
</tbody>
</table>

- line faults 1ph, 2ph, 3ph **not so severe** if far from transformer
- substation faults 1ph, 2ph, 3ph **are severe cases**, with highest fault current, not frequent

**Worst case:**
3 phases short-circuit caused by forgotten safety grounding devices after maintenance…
Short-Circuit in Power Transformers

Useful Life and Reliability

- **Useful Life and Reliability**
- **Failure Rate**
- **Time, years**
- **Acceptable Failure Rate**
- **New**
- **Normal Life**
- **End of Life**
- **Life Extension**
- **Infant Failures**
- **Normal Failures**
- **Aging Failures**

- **2-6 years**
- **20-30 yrs**
- **40-60 yrs**
- **70-80 yrs**

- **2-6 years**
- **40-60 yrs**
- **70-80 yrs**

- **Acceptable Failure Rate**
## Short-Circuit in Power Transformers

### Reliability and Failures

#### Overall

<table>
<thead>
<tr>
<th>Survey source</th>
<th>overall failure rate</th>
<th>mechanical failures (including short-circuit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIGRE ELECTRA #88.1988</td>
<td>~2 %</td>
<td>53 %</td>
</tr>
<tr>
<td>IEEE ANSI C57.91</td>
<td>~2 %</td>
<td>51 %</td>
</tr>
<tr>
<td>BRAZIL ELETROBRÁS GCOI 1998</td>
<td>~1.7 %</td>
<td>58 %</td>
</tr>
</tbody>
</table>

#### Short-Circuit Only

<table>
<thead>
<tr>
<th>Survey source</th>
<th>Period</th>
<th>Transf x Year</th>
<th>failure rate due to short-circuit only (ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIGRE TF WG12.19 1997</td>
<td>1993-1997, 5 yrs</td>
<td>-</td>
<td>0.0130 % (1.00 pu)</td>
</tr>
<tr>
<td>HYDRO-QUEBEC 1998</td>
<td>1993-1997, 5 yrs</td>
<td>117</td>
<td>0.0342 % (2.60 pu)</td>
</tr>
<tr>
<td></td>
<td>1970-1998, 28 yrs</td>
<td>10 167</td>
<td>0.1570 % (12.07 pu)</td>
</tr>
</tbody>
</table>
Short-Circuit in Power Transformers

Failure - Step Up Transformer 3Ø, 440MVA, 16.5-16.5/500kV

Ifalta 46 kA
phase-to-ground fault

28 kA
It2
D1
G1

Ig1

440 MVA, 16.5-16.5/500kV

1.8 kA
Ired

LV1

46 kA

HV

1

network

500 GVA

LV2

It3

G2

ABB Brazil JCM A-11
Power Products Division
Power Transformers
External Short-Circuit at LV Side
Failure in the HV Regulating Winding HVR
### Characteristics:
- overall revision
- includes the alternative to prove the power transformer short-circuit withstand by calculation method based on similar transformer testing
- gives calculation guidance and criteria
IEEE:

- C57.12.00 section 7 – establishes requirements for short-circuit withstand of oil immersed power transformers
- C57.12.90 section 12 – established procedures for the short-circuit test of oil immersed power transformers, including approval criteria and diagnostics methods
High Voltage Power Transformers:
Short Circuit – Thermal and Mechanical Capabilities
Short-Circuit in Power Transformers

General

Power Transformers must be designed and built to withstand without damages:
- mechanical stresses; and
- thermal stresses

produced by external short-circuits events.

External short-circuits events include:
- 3-phase short-circuit
- 2-phase isolated short-circuit
- 2-phase to ground short-circuit
- 1-phase to ground short-circuit

faults on any one set of terminals at a time.

Overcurrent:
- symmetric component (rms) of short-circuit fault current
- asymmetric component (peak) of short-circuit fault current
High Voltage Power Transformers:
Short Circuit – Current and Dynamic Effect
Short-Circuit Current

Under an external short-circuit event:
- the first peak of the fault current over the transformer will increase to a multiple of the rated current.

The short-circuit fault current will depend on:
- pre-fault open circuit voltage
- source and transformer impedance
- instant of the fault onset (initial phase angle)
Short-Circuit in Power Transformers

Short-Circuit Current

\[ i(t) = \sqrt{2} \cdot I_{k_{\text{rms}}} \cdot \left[ \text{sen}(\omega t + \alpha - \phi) - e^{-t/\tau} \cdot \text{sen}(\alpha - \phi) \right] \]

\[ \tau = \frac{X}{\pi \cdot R} \]

1st peak of the instantaneous short-circuit current

\[ u(t) = \bar{U} \cdot \text{sen}(\omega t + \alpha) \]

\[ \alpha = 0, \phi = \pi/2, X/R = 30 \]

<table>
<thead>
<tr>
<th>Transf X/R</th>
<th>k</th>
<th>k \cdot \sqrt{2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤100</td>
<td>15</td>
<td>1.81</td>
</tr>
<tr>
<td>&gt;100</td>
<td>30</td>
<td>1.90</td>
</tr>
</tbody>
</table>

\[ \text{Imax} = I_k \cdot \sqrt{2} \cdot \left( 1 + e^{-\pi \frac{R}{X}} \right) = I_k \cdot \sqrt{2} \cdot k \]

\[ k = 1 + e^{-\pi \frac{R}{X}} \]

symmetric current peak factor

asymmetry factor
Short-Circuit in Power Transformers

Short-Circuit Current

Dynamic Effect

\[ i(t) = \sqrt{2} \cdot I_{k_{\text{rms}}} \cdot \left[ \text{sen}(\omega t + \alpha - \phi) - e^{-t/\tau} \cdot \text{sen}(\alpha - \phi) \right] \]

<table>
<thead>
<tr>
<th>( \alpha )</th>
<th>( \sqrt{2} \cdot k )</th>
<th>Short-Circuit Force Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.70</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>2.68</td>
<td>0.98</td>
</tr>
<tr>
<td>20</td>
<td>2.62</td>
<td>0.94</td>
</tr>
<tr>
<td>30</td>
<td>2.52</td>
<td>0.87</td>
</tr>
<tr>
<td>40</td>
<td>2.39</td>
<td>0.79</td>
</tr>
<tr>
<td>50</td>
<td>2.23</td>
<td>0.68</td>
</tr>
<tr>
<td>60</td>
<td>2.04</td>
<td>0.57</td>
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<tr>
<td>70</td>
<td>1.83</td>
<td>0.46</td>
</tr>
<tr>
<td>80</td>
<td>1.61</td>
<td>0.35</td>
</tr>
<tr>
<td>90</td>
<td>1.39</td>
<td>0.27</td>
</tr>
</tbody>
</table>
High Voltage Power Transformers:
Short Circuit – Electromagnetic Dynamic Forces
Short-Circuit in Power Transformers

Short-Circuit Forces

Dynamic Effect

- short-circuit pass through over current \((I_k, \text{rms} \text{ and } I_{\text{max}}, \text{peak})\)
- short-circuit current \(I_k\) establishes a Leakage Magnetic Field \(H_k = f(I_k)\) \(\text{Ampere Law}\)
- in a conductor with a short-circuit current \(I_k\) immersed in a leakage magnetic flux \(H_k\) is established a electromagnetic force \(F_k = f(I_k \times H_k)\) \(\text{Biot-Savat Law}\)
- means that the short-circuit Force is proportional to the square of the short-circuit-current

\[
I_k \rightarrow H_k = f(I_k) \rightarrow F_k = f(I_k, H_k) \rightarrow F_k = f(I_k^2)
\]

- in a transformer design the short-circuit current **Dynamic Effect** is considered:
  - peak value of the asymmetric current \((I_{\text{max}}, \text{peak})\)
  - instantaneous value of the voltage is at its zero value \((\alpha = 0 \text{ deg} \text{ and } \phi = 90 \text{ deg})\)
  - asymmetry factor \(k = f(R/X)\)
  - peak factor \(k_p = \sqrt{2} \cdot k\)
- means that the short-circuit **Dynamic Force** is proportional to the square of the peak value of the asymmetric component of the short-circuit-current

\[
I_k \rightarrow I_{\text{max}} = \sqrt{2} \cdot I_k \rightarrow I_{\text{max}} = k \cdot \sqrt{2} \cdot I_k
\]

\[
F_d = f(I_{\text{max}}^2) \rightarrow F_d = f((\sqrt{2} \cdot k \cdot I_k)^2)
\]
Short-Circuit in Power Transformers

Electromagnetic Forces: Two (2) Single Conductors

Ampere Law
\[ \oint \mathbf{H} \cdot d\mathbf{l} = I \]
\[ \mathbf{B} = \mu \cdot \mathbf{H} \]

Bio-Savart
\[ d\mathbf{F} = dq \cdot \mathbf{v} \wedge \mathbf{B} = i \cdot d\mathbf{l} \wedge \mathbf{B} = \mathbf{B} \cdot d\mathbf{l} \cdot i \cdot \text{sen} \theta \]

\[ F_1(I_2) = \frac{\mu_0}{2 \cdot \pi} \frac{I_1 \cdot I_2}{d} \cdot \ell \quad [N] \]
Electromagnetic Forces: Two (2) Winding – Magnetic Stray Leakage Flux

A Two Windings Transformer:

- 2D plot
- magnetic stray field lines
- Radial direction
- Axial direction
- the magnetic stray flux has components in axial and in radial direction
- there are field components outside the windings
Electromagnetic Forces: Two (2) Windings

The direction of forces:
- is always directed perpendicular to the magnetic field lines

Forces usually are split into the two components
- Radial forces
- Axial forces

Electromagnetic forces tend to:
- reduce radius of inner winding (compression)
- increase radius of outer winding (tensile)
- reduce winding height (compression)
- increase the main insulation duct
- increase existing un-symmetries.
Electromagnetic Forces and its Four (4) Components

Force Components:
- **F1** – single direction and constant force
- **F2** – single direction and exponentially damped force
- **F3** – un-damped alternated double power frequency force
- **F4** – damped alternated power frequency force
Short-Circuit in Power Transformers

Electromagnetic Forces: Two (2) Winding

\[
B_{\text{axial}} \quad \text{AXIAL component}
\]

\[
B_{\text{radial}} \quad \text{RADIAL component}
\]

\[
\Phi_{\text{leak}}
\]

\[
I_1 \quad I_2
\]

\[
F_{\text{load}}
\]

\[
Z_{\text{load}}
\]

\[
F_{\text{axial}} = f(B_{\text{axial}})
\]

\[
F_{\text{radial}} = f(B_{\text{radial}})
\]

\[
I_1 = I_2 = Z_{\text{load}}
\]

\[
B_a
\]

\[
B_r (I_1)
\]

\[
B_r (I_2)
\]
Short-Circuit in Power Transformers

Electromagnetic Forces in Winding: Radial

\[ \mathbf{F}_{\text{radial}} \]

- **Transf \leq 100 \text{MVA}** ⇒ \( k \cdot \sqrt{2} = 2.55 \)
- **Transf > 100 \text{MVA}** ⇒ \( k \cdot \sqrt{2} = 2.69 \)

\[
\begin{align*}
B_{\text{ax}} &= \mu_0 \cdot \frac{N_2 \cdot I_2}{H_{\text{enr}}} \\
F_{\text{rad}} &= \frac{B_{\text{ax}} \cdot N_2 \cdot I_2 \cdot D_{\text{med}}}{2} \\
\sigma_{\text{rad}} &= \frac{F_{\text{rad}}}{N_2 \cdot A_{\text{cond}}} 
\end{align*}
\]

- tensile stress and elongation of outer winding
- compression stress and buckling of inner winding
- deterioration of cellulose insulation
Short-Circuit in Power Transformers

Electromagnetic Forces in Winding: Axial

- Conduits tilting
- Winding axial collapse
- Telescoping with axial displacement of conductors
- Axial bending deflection of conductors between spacers
- Influenced by winding asymmetries
- Deterioration of cellulose insulation
- Lower upper winding end supports
- Core frame and winding pressing mechanical structure

\[ F_{axial} = 2\pi \cdot \frac{D_{med}}{2} \cdot \frac{N_2 \cdot I_2}{H_{enr}} \cdot \int_{z_0}^{z} B_{rad}(z) \cdot dz \]

\[ \sigma_{ax} = \frac{F_{ax}}{\pi \cdot D_{med} \cdot B_{enr}} \]
Short-Circuit in Power Transformers

Electromagnetic Forces: Two (2) Winding Transformer - 3Ph, 20MVA, 138/13.8kV

RADIAL Forces:
- radial forces:
  - LV compression: 3054 kN
  - HV traction: 4384 kN

AXIAL Forces:
- axial asymmetry: 5 mm
- inner axial force:
  - LV compression: 97 kN
  - HV compression: 138 kN
  - LV+HV total: 235 kN
- axial force to core yoke: 31 kN
Short-Circuit in Power Transformers

Radial Forces Failure Modes

Buckling of Inner Winding

<table>
<thead>
<tr>
<th>With Radial Support</th>
<th>Without Radial Support</th>
</tr>
</thead>
</table>

Radial Stresses Failure Modes:
- compression of inner winding
  buckling, mechanical instability, excessive deformations, etc
- traction of outer winding
  diameter increase, elongation & rupture of conductors, etc

Mechanical Strength:
- material elasticity limit – $\sigma_{0.2}$
- safety factor
**Radial Forces Failure Modes – Spiraling of Helical Winding Exits**

**SPIRALING:** tangential displacement of end turns of a Helical Winding

**Radial Mechanical Force in a Helical Winding Exit:**
- rotating reaction force of winding mass acceleration
- radial compression stress (buckling) of inner winding (N/mm²)
- radial tensile stress (elongation) of the outer winding (N/mm²)
- total cross section area of the winding exit (mm²)

**Failure Modes:**
- axial deformation and winding rotation
- mechanical instability of the winding

**Equation:**

\[ F_s = \sigma_s \cdot S_s [N] \]

**Symbols:**
- \( F_s \): Exit force
- \( \sigma_s \): Radial stress (buckling) [N/mm²]
- \( S_s \): Exit cross area [mm²]
Axial Forces Failure Mode:
- axial collapse by excessive axial compression
- winding conductors mechanical instability
- telescoping and axial displacement of conductors
- conductors tilting
- axial bending of conductors and excessive deflection
- solid insulation rupture – spacers, end insulation, core clamps
Axial Forces Failure Modes – Winding Compression and Axial Collapse

**Axial Collapse:**
- axial collapse typical in layer windings
- axial displacement of winding turns
- conductors elongation
- free radial displacement
- rupture of conductors paper insulation
- turn-to-turn failure

**Axial Excessive Compression:**
- winding inner excessive compression
- winding excessive axial deformation
- lower and/or upper winding end supports mechanical instability, rupture and/or collapse
- winding insulation damage and/or rupture
- electromagnetic forces increasing

**Axial Bending:**
- disc and helical type windings
- excessive axial bending of conductors
- damage and/or rupture of conductors insulation paper
Peripheral Displacement of Conductors and Supports:
- spiral compression of inner winding
- rupture of conductors insulation paper
- axial misalignment of supports and mechanical instability

Distortion in Discontinuities:
- inadequate support in one direction leading to mechanical instability in the opposite direction
- inner connections, winding conductors crossing, winding conductors transpositions
- inadequate support
- inadequate traction force and fixing
- spiraling of helical winding exits
Tap Changers (on-load OLTC and no-load DETC) Position

- magnetic stray flux distribution and intensity is depending on **OLTC** and/or **DETC** position

- changing **OLTC** and/or **DETC** position changes short-circuit force amplitude

- power transformer must be short-circuit designed for the most critical **OLTC** and/or **DETC** position (maximum force)

- while in operation, transformer may operates under a more favorable **OLTC** and/or **DETC** position, reducing short-circuit forces and stresses
Short-Circuit in Power Transformers

Short-Circuit Forces

Auto Transformer with OLTC at MV side and separate Regulating Winding

Leakage Flux
500/253 kV - max

Leakage Flux
500/207 kV - mín
**Short-Circuit Forces**

**Auto Transformer with OLTC at MV side and separate Regulating Winding**

### Leakage Flux - 500/253 kV - max

<table>
<thead>
<tr>
<th>Winding</th>
<th>Force on top yoke (kN)</th>
<th>Force on bottom yoke (kN)</th>
<th>Compressive force (max) (kN)</th>
<th>Strand stress (max) (MN/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TERC</td>
<td>15.2</td>
<td>9.9</td>
<td>16.0</td>
<td>-8.3</td>
</tr>
<tr>
<td>REGUL</td>
<td>0.0</td>
<td>188.9</td>
<td>1535.2</td>
<td>-46.7</td>
</tr>
<tr>
<td>MT</td>
<td>0.0</td>
<td>70.7</td>
<td>2319.1</td>
<td>98.6</td>
</tr>
<tr>
<td>AT</td>
<td>0.0</td>
<td>78.6</td>
<td>1795.7</td>
<td>92.7</td>
</tr>
</tbody>
</table>

### Leakage Flux - 500/207 kV - min

<table>
<thead>
<tr>
<th>Winding</th>
<th>Force on top yoke (kN)</th>
<th>Force on bottom yoke (kN)</th>
<th>Compressive force (max) (kN)</th>
<th>Strand stress (max) (MN/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TERC</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>REGUL</td>
<td>0.0</td>
<td>1.7</td>
<td>184.2</td>
<td>-9.3</td>
</tr>
<tr>
<td>MT</td>
<td>0.0</td>
<td>81.4</td>
<td>1795.7</td>
<td>-46.5</td>
</tr>
<tr>
<td>AT</td>
<td>0.0</td>
<td>78.6</td>
<td>1734.0</td>
<td>92.7</td>
</tr>
</tbody>
</table>
Short-Circuit in Power Transformers

Transformer with DETC in HV Winding with Taps in the Winding

- **Leakage Flux 550/13.8 kV - max**
- **Leakage Flux 500/13.8 kV - min**
Short-Circuit in Power Transformers

Short-Circuit Forces

Transformer with DETC in HV Winding with Taps

Leakage Flux - 550/13.8 kV - max

<table>
<thead>
<tr>
<th>Winding</th>
<th>Force on top yoke (kN)</th>
<th>Force on bottom yoke (kN)</th>
<th>Compressive force (max) (kN)</th>
<th>Strand stress (max) (MN/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BT</td>
<td>0.0</td>
<td>128.4</td>
<td>3351</td>
<td>-90.1</td>
</tr>
<tr>
<td>AT</td>
<td>0.0</td>
<td>906.1</td>
<td>1608.9</td>
<td>113.9</td>
</tr>
</tbody>
</table>

Leakage Flux - 500/13.8 kV - min

<table>
<thead>
<tr>
<th>Winding</th>
<th>Force on top yoke (kN)</th>
<th>Force on bottom yoke (kN)</th>
<th>Compressive force (max) (kN)</th>
<th>Strand stress (max) (MN/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BT</td>
<td>0.0</td>
<td>137.7</td>
<td>2578.8</td>
<td>-88.6</td>
</tr>
<tr>
<td>AT</td>
<td>51.7</td>
<td>947.5</td>
<td>3477.6</td>
<td>123.0</td>
</tr>
</tbody>
</table>
Short-Circuit in Power Transformers

Short-Circuit Forces

Auto Transformer 1Ph
Short-Circuit at MV Side
500/230/13.8 kV

Auto Transformer 3Ph
Short-Circuit at TV Side
500/230/13.8 kV

Auto Transformer SC Phase-to-Ground at MV Side and SC Three-Phase at TV Side
Short-Circuit in Power Transformers

Short-Circuit Forces

### Auto Transformer SC Phase-to-Ground at MV Side and SC Three-Phase at TV Side

#### Auto Transf. 1Ph SC at MV 500/230/13.8 kV

- **Steady state short circuit winding current**
  - Terminal H1: 2640 A
  - Terminal X1: -6768 A
  - Terminal Y1: 19790 A

<table>
<thead>
<tr>
<th>Winding</th>
<th>Force on top yoke (kN)</th>
<th>Force on bottom yoke (kN)</th>
<th>Compressive force (max) (kN)</th>
<th>Strand stress (max) (MN/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TERC</td>
<td>195.3</td>
<td>164.3</td>
<td>208.8</td>
<td>-13.9</td>
</tr>
<tr>
<td>REGUL</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>MT</td>
<td>0.0</td>
<td>246.5</td>
<td>2313.5</td>
<td>-39.2</td>
</tr>
<tr>
<td>AT</td>
<td>0.0</td>
<td>31.5</td>
<td>1483.8</td>
<td>86.0</td>
</tr>
</tbody>
</table>

#### Auto Transf. 3Ph SC at TV 500/230/13.8 kV

- **Steady state short circuit winding current**
  - Terminal H1: 106 A
  - Terminal X1: 1588 A
  - Terminal Y1: -35040 A

<table>
<thead>
<tr>
<th>Winding</th>
<th>Force on top yoke (kN)</th>
<th>Force on bottom yoke (kN)</th>
<th>Compressive force (max) (kN)</th>
<th>Strand stress (max) (MN/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TERC</td>
<td>17.9</td>
<td>0.0</td>
<td>1193.0</td>
<td>-42.1</td>
</tr>
<tr>
<td>REGUL</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>MT</td>
<td>0.0</td>
<td>34.9</td>
<td>229.9</td>
<td>15.3</td>
</tr>
<tr>
<td>AT</td>
<td>0.0</td>
<td>1.4</td>
<td>22.2</td>
<td>0.1</td>
</tr>
</tbody>
</table>
High Voltage Power Transformers:
Short Circuit – Aging and Deterioration Effects
Short-Circuit in Power Transformers

Solid Insulation Aging

\[ N = \frac{GP_0}{GP} - 1 \]

Cellulose molecule

O2 chemical bond
Short-Circuit in Power Transformers

Solid Insulation Aging and Mechanical Strength Reduction

Insulation Paper
Polymerization Degree DP

- **New Paper - DP 1050 ... 1300**
  tensile strength of a new paper

- **Half Life Paper - DP 380 ... 450**
  residual tensile strength of a half-life paper
  is about 50% of the one of a new paper

- **End of Life Paper - DP 150 ... 200**
  residual tensile strength of a half-life paper
  is about 25% of the one of a new paper

Dielectric Strength at end-of-life is reduced just about ~ 10% of its original new paper value
High Voltage Power Transformers:
Short Circuit – Winding Residual Pressing Forces
Short-Circuit in Power Transformers

Electromagnetic Forces: Winding Dynamic Responses

Visco-Elastic Model

Material Elasticity: $E_{\text{Nomex}} > 4 \times E_{\text{Celulose}}$

- axial stiffness ($G_{mj}$) depending on temperature, characteristics and dimensions of:
  - insulation material inside the windings
  - insulation material outside in the windings distances
- ratios between applied force and winding system elastic-inertial response:
  - large range of variations
  - depending on of design and forces distribution
  - winding amplification (resonances) and reduction (damping) of local forces
Benefits of Residual Pressing Forces:
- increase mechanical stiffness of the windings
- increase mechanical natural frequencies of the windings
- reduction of short-circuit oscillatory forces in the insulation
- reduction of the axial displacement between windings

Modern Manufacturing Processes:
- drying process of the windings
- winding mechanical stabilization of the windings
- winding dimension stabilization of the windings
- Active Part drying under a Vapor Phase process
- final pressing of the windings

- guarantee and maintain the insulation mechanical stability
- maintain over time the residual pressing force
High Voltage Power Transformers: Short Circuit – Design Transformers to Withstand Short-Circuit Forces
Short-Circuit in Power Transformers

Designing Transformers to Withstand Short-Circuit Forces

Step 1 – Short-Circuit Fault Currents Calculation

Covering all external fault modes:
- three phase fault on HV, LV and Tertiary side
- line-to-line to line fault on HV, LV and Tertiary side
- line-to-ground fault on HV and LV side

Boundaries Conditions to Consider
- the network impedance in line with the Standard or with the Specification
- the pre-fault open-circuit voltage (Standard or Specification
- the different tap changer positions
- that impedances are subject of tolerances
- that current limiting reactors may show saturation effects
Step 2 – Short-Circuit Forces and Stresses Calculation

- **Radial forces and**
  - copper stresses in all windings

- **Spiraling forces and**
  - copper stresses on the winding exits

- **Axial compression forces and**
  - bending stresses in the cables
  - compression stresses on the papers of the winding conductors
  - critical tilting stresses of the winding conductors

- **Axial forces on the end supports and**
  - compression and bending stresses in the mechanical support structure

**Remark:**

The highest fault current will not always lead to the highest forces in a winding. Superimposed fields of other windings may create higher stresses!
Designing Transformers to Withstand Short-Circuit Forces

Step 3 – Design Criteria

Design to Radial Forces
- all windings are radially self supporting
- inner windings are subject to “free buckling”
  - a dynamic phenomenon
  - no radial support
  - strength is determined by Cu hardness (yield point) and conductor geometry
- outer windings are subject to tension
  - strength is determined by Cu hardness
- spiraling on windings exits
  - strength is determined by Cu hardness

Design to Axial Forces
- axial forces are calculated by FEM considering
  - axial displacement due to workshop tolerance
  - axial displacement due to Layer or Helical winding pitch when applicable
- windings are dimensioned for maximum compression forces
  - dynamic effects are considered by dynamic factors on the forces
- winding ends are dimensioned for
  - maximum unbalance forces and
  - a part of the maximum compression force (“Bounce Back”)
  - windings are radially self supporting
Designing Transformers to Withstand Short-Circuit Forces

Step 4 – Design Practices

Design practices

- focus on axial ampere-turn balancing optimization of all windings

- select the
  - cable dimensions
  - copper yield strength
  - epoxy bonding

to meet the stresses

- require close manufacturing tolerances

- provide solid clamping of the windings

- provide safe fastening of the winding exits
- provide safe fastening of the connection leads
Simplifications are applied during design:

- the forces alternate with the square of the current. During design only the peak force is calculated and considered as a static force. A dynamic factor may be used to consider the dynamic effects.

- core and Windings are a 3D arrangement. The routine field calculations are ran with 2D programs.

- layer and helical windings have a pitch creating variable displacements. It depends on the manufacturer’s rules which displacement is considered.

- forces calculation on the winding exits is based on a simplified model.

- mechanical withstand limits of helical windings against spiraling forces are based on limited number of experiments.
Short-Circuit in Power Transformers

Designing Transformers to Withstand Short-Circuit Forces

Improvements achieved over the last 20 years:

- Computer programs run fault current and force calculations for all fault conditions and all winding connections automatically.
- 3D magnetic tools have been applied for R&D work.
- Epoxy bonding of winding conductors has become available and the application became a standard practice.
- Hard and very hard drawn copper is applied more frequently.
- Pre-compressed pressboard is exclusively used.
- There is more focus on the short circuit strength during the design stage.
- More experience has been gained in the field and by testing.
Remarkable overall observations:

- designing for short-circuit strength has been of increased demand over last 20-30 years

- past power transformer short-circuit performance was not high with frequent failures by:
  - winding radial buckling
  - winding axial collapsing
  - broken press rings and end supports

- design philosophy has changed
  - more experience has been gained, mainly after performing tests,
  - calculation tools were improved
  - there are better design rules
  - there are better materials to strengthen windings and winding supports

- power transformer short-circuit performance has increased over the last decades
  - no winding radial buckling
  - no winding axial collapsing
  - no winding axial conductors tilting indication
  in a transformer designed during that period.
High Voltage Power Transformers: Short Circuit – Short-Circuit Full Tests
Aspects to Consider

Technical aspects:
- mandatory for distribution transformers (≤ 500kVA)
- test may be not possible for large units (>400 MVA). Only few laboratories are able to test units rated over 100MVA.
- transformer application (normal substation, GSU, interconnections between two systems (phase-shifter or HVDC), etc.)

Economical aspects:
- Testing costs (including transport costs) and associated risks (project delays in case of a failure);
- Evaluation of revenue losses, mainly for bulk power applications like interconnections, generating power stations, large industrial plants, etc.;
- Large number of units to be ordered e.g. distribution transformers

Composite evaluation of all technical and economical aspects:
Costs of performing a short-circuit test series shall then be compared with the costs, inconveniences and risk of having a failure in service.
Benefit and risk of testing

- test results are an important feedback and a valuable source for improvements. Due to the high cost and the limited number of power test facilities the number of tests will remain limited

- submitting a transformer to a short-circuit test is always connected to high expenses for the purchaser. In case of a failure the expenses become very high for purchaser and manufacturer

- a short-circuit test therefore involves a risk for both parties

Why do transformers fail under a short-circuit testing

- due to design weakness because:
  - the rules did not fully cover the case
  - there are effects which have not been considered

- due to shortcomings during manufacturing

- due to transportation issues or poor test preparations
KEMA Netherlands Power Lab:
- 77 large transformers (25 - 440 MVA, 20 - 500 kV), 11 years of testing
- 31% failure rate during tests (mostly because an unacceptable increase in reactance)

CIGRE SC12 1998:
- worldwide survey with high-power 12 labs
- 12% average failure rate during tests (rated power > 40 and < 100 MVA)
- 42% average failure rate during tests (rated power > 100 MVA)

ABB 1997-2013:
- 59 TrafoStar power transformers tested (18 units with voltage 400 kV or above)
- 10% average failure rate during
Short-Circuit in Power Transformers

Tested and Proved Strength:

- short-circuit failures reduction of power transformers
- 199 units tested and approved in 45 yrs period 1968-2013
- 94 units tested and approved in 16 yrs period 1997-2013
- 10....1070MVA, 69...420kV, 1ph & 3ph, NLTC & OLTC
- 1 regulating down 40MVA unit manufactured by ABB Brazil
- test power labs KEMA, CESI and IREQ
# Short-Circuit in Power Transformers

## Short-Circuit Test Performance

### 1968-2013:
- 199 units tested
- up to 420kV
- step-up transf. up to 775MVA
- auto transf. up to 360MVA

### 1997-2013 TrafoStar:
- 94 units tested
- 59 TrafoStar & 35 SPT
- 18 units at 400kV or above

### 1998 South America:
- to CADAFE VE
- 1 unit from ABB Brazil
- 36MVA 3Ph, 115/13.8kV
- tested at CESI IT

## Table: Short-Circuit Test Performance

<table>
<thead>
<tr>
<th>Year</th>
<th>Serial No.</th>
<th>Rated Power (MVA)</th>
<th>Voltage Ratio (kV)</th>
<th>Short-Circuit Impedance at Rated Power (%)</th>
<th>Type of Regulation</th>
<th>Customer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1968</td>
<td>1572001</td>
<td>20</td>
<td>132/11kV</td>
<td>12/9/6.1%</td>
<td>ON-LAOD</td>
<td>OTE-Italy</td>
</tr>
<tr>
<td>1981</td>
<td>110-73054</td>
<td>20</td>
<td>132/13.5/10kV</td>
<td>12/9.1%</td>
<td>ON-LAOD</td>
<td>ENEL-Italy</td>
</tr>
<tr>
<td>1998</td>
<td>11977-01</td>
<td>102/60-42</td>
<td>240/22x2.5/14,6/14,11/14,11</td>
<td>12.0 (%) 11.65%</td>
<td>OFF-LAOD</td>
<td>ENEL-Canada</td>
</tr>
<tr>
<td>2008</td>
<td>12035-001</td>
<td>60</td>
<td>132/14.2 x 1.28/66</td>
<td>12.7%</td>
<td>Unknown</td>
<td>PSB-India</td>
</tr>
</tbody>
</table>

## Notes:
- ABB Short-Circuit Tested Transformers

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ABB Brazil  JCM A-62  
Power Products Division  
Power Transformers
High Voltage Power Transformers:
Short Circuit – Advanced Materials and Technologies
<table>
<thead>
<tr>
<th>Insulating Oil Impregnated Spacer</th>
<th>Dynamic Modulus of Elasticity - Ratio, pu</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dynamic Stress Low ± Px, N/mm²</td>
</tr>
<tr>
<td></td>
<td>50Hz</td>
</tr>
<tr>
<td>Pressboard</td>
<td>1.00</td>
</tr>
<tr>
<td>Nomex</td>
<td>0.80</td>
</tr>
</tbody>
</table>

ABB Brazil JCM A-64
Power Products Division
Power Transformers
Short-Circuit in Power Transformers

Short-Circuit R&D and Advanced Materials

Paper Insulated Conductor Impact Test:

Stress Condition:
- Impact height is increased to the rupture of the insulation paper

![Diagram showing comparison of different materials under impact stress]

Legend:
- Green: Paper without rupture
- Red: Paper with rupture

allowable
Allowable Tensile Stress of Winding Conductor Insulation Paper

withstand > 2 × allowable
Advanced Simulation Capability

Dynamic Short-Circuit Calculation Response of a Helical Winding

Axial Compressive Force on Spacers [N]

Axial Vibration Amplitude [m]

CTF, CTF3
(Avg: 75%)

-107E+03
-96E+03
-85E+03
-75E+03
-64E+03
-54E+03
-43E+03
-32E+03
-22E+03
-11E+03
-739E+00
10E+03
20E+03

ABB Brazil  JCM A-66
Power Products Division
Power Transformers
Simulation, Analysis and Design Capability:

- complete set of design rules
- design criteria based on short-circuit tests
- technology experience from ASEA, BBC, GE, ANSALDO
- 2D & 3D advanced simulation tools
- adequate material selection
Short-Circuit in Power Transformers

Short-Circuit R&D and Advanced Applications

Advanced Materials and Application

Nomex®
ESCELSA – 3Ph, 300MVA, 230/138-138/13.8kV

ABB Brazil JCM A-68
Power Products Division
Power Transformers
High Voltage Power Transformers: Short Circuit – Conclusions and Recommendations
Short-Circuit in Power Transformers

Conclusions

Short-Circuit withstand capability

- short-circuit failures represent only a few percentage of total transformer failures but do generally result in catastrophic failures

- power transformer ability to withstand the dynamic effects of a short-circuit can be verified by:
  - a full short-circuit test at a certified power lab; or
  - a Design Review and detailed theoretic evaluation supported by Standard as IEC60076-5 3rd Ed 2006-02.
  - ABB is applying high values of asymmetry factor to calculate maximum peak of asymmetric short circuit current (asymmetry factor $k \cdot \sqrt{2} = 1.9 \cdot \sqrt{2} = 2.69$ resulting maximum worst case Dynamic Peak of the SC current)
  - ABB is applying 2D and 3D advanced FEM simulation tools to calculate Short-Circuit forces and stresses
  - ABB is applying advanced material with controlled Short-Circuit stresses
  - ABB has high demanding manufacturing control on winding related dimensions and processes

- power transformer short-circuit full test:
  - is the only method to guaranty the ability of a transformer to withstand a short-circuit
  - there are large differences in the number of Short-Circuit test failures among manufacturers
  - not all manufacturers submitted small-medium-large size transformers to a Short-Circuit full test
  - are expensive and a technical, economical and risk evaluation should be performed before requiring a test
  - adequate diagnostic methods, active part inspection and final type and routine tests at 100% of the rated levels are needed to insure that a short-circuit test did not damage the transformer.
  - ABB has tested 199 units 1968-2013 (94 units 1997-2013) with small failure rate compared to others Mnf
  - ABB applying continuously tests feedback and experience to improve transformers design and reliability
TENDER Step:

- to include new IEC60076-5 3rd Ed 2006-2 in tender documentation as a Standard for short-circuit strength verification of power transformers

- always to require manufacturer’s stresses compared with their allowed or critical values, deviations to IEC60076-5 3rd Ed 2006-2 Standard to be commented

- Design Reviews to be required and specified

- mention in the Transformer Specification that customer considers the rights to ask for SC tests one month after the order signature.
Recommendation

**DESIGN Step:**

- short-circuit strength evaluation as per IEC60076-5 3rd Ed 2006-2 Standard

- theoretical evaluation of a power transformer ability to withstand the dynamic effect of a short circuit either by:
  - **Design Review** where forces and stresses are compared with a short-circuit tested Reference Transformer from the manufacturer
  - **Design Review** by checking actual design stresses against the manufacturer design rules for short-circuit stresses
  - **Stress limit** overall guidance:
    a) stress shall **not exceed** manufacturers allowable stresses; or
    b) stress shall **not exceed 80% of the critical material stress value**; or
    c) stresses shall be compared to the stress guidance in the new IEC60076-5 3rd Ed 2006-2 Standard.
Short-Circuit in Power Transformers

**Recommendation**

**Short-Circuit Test:**

- important GSU Generator Step Up transformers
- important Auxiliary units in Power Plants

- key feeding transformers at Power Plants Substations or huge load centers
- strategic Intertie Transformers - 3 winding system transformers (Tertiary), Autos
- power transformers with helical windings
- power transformers with axial split winding connections

- one unit out from a Large Group of transformers with same/similar design

- transformers connected to networks known for many faults and high fault currents

- track feeding transformers
Power and productivity for a better world™