Insulation & Thermal Design
Winding Selection

Windings
Conductors: Paper Insulated **Flat Conductors**

If higher mechanical stability is required: Multiple conductors with Epoxy bonding. In this case, the individual strips are insulated from one another with enamel.

<table>
<thead>
<tr>
<th>SINGLE CONDUCTOR (FC)</th>
<th>MULTIPLE CONDUCTORS (MC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>flat conductor</td>
<td>radial twin conductor</td>
</tr>
<tr>
<td></td>
<td>radial triple conductor</td>
</tr>
<tr>
<td></td>
<td>radial quad conductor</td>
</tr>
<tr>
<td>axial twin conductor</td>
<td>2x2 quad conductor</td>
</tr>
</tbody>
</table>

![Diagram of conductor types]
Conductors: Continuously Transposed Conductors (CTC)

CTC Axial twin CTC

If higher mechanical stability is required:
- Strands with Epoxy bonding
- CTC with intermediate paper layer
Conductors: **Conductor Insulation**
- High electrical breakdown withstand
- Thermal stability
- Kraft Paper – made of long wood fibers, purified from resin material and lignin through a chemical process.
- The Degree of Polymerization (DP) measures the length of the fibers and is a measure for aging

<table>
<thead>
<tr>
<th></th>
<th>Density</th>
<th>Thermal Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose Paper</td>
<td>0.7-0.85 g/cm³</td>
<td>105</td>
</tr>
<tr>
<td>Cellulose Paper, Thermally upgraded</td>
<td>0.7-0.85 g/cm³</td>
<td>120</td>
</tr>
<tr>
<td>Calendered paper</td>
<td>0.95-1.1 g/cm³</td>
<td>105</td>
</tr>
<tr>
<td>Calendered Paper, Thermally upgraded</td>
<td>0.95-1.1 g/cm³</td>
<td>120</td>
</tr>
<tr>
<td>Meta Aramid (Nomex 410)</td>
<td>1 g/cm³</td>
<td>220</td>
</tr>
</tbody>
</table>
Example: **Net Covered CTC** for lower winding gradients
Insulation & Thermal Design
Insulation Materials

Solid Insulation Materials
Based on natural cellulose fibers – all materials can be impregnated with oil

Paper
very thin material (50 ... 200 μm)
electrical +++, mechanical –

Pressboard
thickness 0,5 ... 8mm
Sheet material, angle rings
snout segments
electrical ++, mechanical +
Solid Insulation Materials

**Laminated Pressboard**
Glued pressboard with Casein or Polyester
thickness 9 .... 120mm
electrical +, mechanical ++

**Laminated Wood**
glued veneer from beech (or birch) with Phenolharz
different direction of layers
thickness 10 ... 120mm
electrical -, mechanical +++
Solid Insulation Materials

Synthetic materials – cannot be oil impregnated

- Insulating varnish
- Nomex
- Glass fiber
Example
Field plot of a 123 kV transformer

Test: one phase induced

The green lines are equipotentials – they connect points of equal voltage. The electric field gradient cuts these at 90 degrees.
Insulation & Thermal Design
PD and breakdown considerations

**General cause** of partial discharge and/or a breakdown is **high electrical stress** according the following situations:

**Causes can be**
- Cavity not filled with oil
- Contamination (metal)
- Design (selection of material, failure in design)
- Mechanical damage
- Manufacturing outside of tolerance
- Sharp edges
Cavity not filled with oil (inside glue, glass fiber, ...)

- Electrical field strength higher than inside the material
  \[ E_{\text{cavity}} \sim 2 \ldots 5 \times E_{\text{material}} \]

- Breakdown voltage of cavity < Breakdown voltage of material
  - Start of partial discharge inside the cavity
  - Breakdown
Contamination (metal) inside material (pressboard, laminated pressboard, KP-wood, paper)

- High field strength at the edges of the metal part, local overload
- Partial discharge
- Breakdown possible (dependent on the size of the metal part)
Causes of Partial Discharge and Breakdown – Example

Manufacturing outside of tolerance

- High electrical field strength
  - partial discharge
  - breakdown

Cylinder

≥ 2 mm

HV-disc winding
Causes of Partial Discharge and Breakdown - Examples

- Deformed angle ring
- Soft paper insulation
Causes of Partial Discharge and Breakdown - Examples

Contamination with metal parts

Glue in the insulation arrangement
Source of conductor and core heating

Loss contribution:

**Load current**
- Ohmic resistance of winding conductor: \(I^2 \cdot R\) 60-90 %
- Eddy current losses in all metallic parts due to the magnetic stray flux of the windings < 20 %

**No-load voltage**
- Magnetic flux \(\Phi\) in core core steel ≈ 1 W/kg
- Exciting current < 1 % of rated current 10-30 %
## Cooling types

<table>
<thead>
<tr>
<th>Oil Loop</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil Natural</td>
<td>ON</td>
</tr>
<tr>
<td>Oil Forced (pump)</td>
<td>OF</td>
</tr>
<tr>
<td>Oil Directed (pump, directed flow into main windings)</td>
<td>OD</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cooler Type</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Natural (radiator)</td>
<td>AN</td>
</tr>
<tr>
<td>Air Forced (radiator with fans, or cooler)</td>
<td>AF</td>
</tr>
<tr>
<td>Water Forced (cooling by water)</td>
<td>WF</td>
</tr>
</tbody>
</table>

- e.g. ONAN
- or one transformer with several conditions,
  e.g.: ONAN, ONAF, OFAF

former ANSI code: OA, FA, FOA
since 2006: ANSI = IEC
Oil flow in core type transformers:

- **ON**: Oil Natural
  - oil flow by heated parts (buoyant force)

- **OF**: Oil Forced
  - oil pumps: flow into tank

- **OD**: Oil Directed
  - oil pumps: flow directed into windings
Examples

ONAN / ONAF radiators with fans

ODAF
5 Coolers
Conventional Limits as per IEEE

<table>
<thead>
<tr>
<th>Limits as per IEEE C57.12.00-2010</th>
<th>Ambient Limit IEEE C57.12.00-2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Oil rise above ambient</td>
<td>Range</td>
</tr>
<tr>
<td>Winding rise above ambient</td>
<td>...+40° C oil: ≥ -20 ° C</td>
</tr>
<tr>
<td>Hotspot rise above ambient</td>
<td>Daily average</td>
</tr>
<tr>
<td></td>
<td>30 ° C</td>
</tr>
</tbody>
</table>

**Thermally upgraded paper** shall be used for insulation components that determine the minimum life expectancy, such as: winding insulation, layer to layer insulation, lead insulation.

- The allowed Hotspot Temperature of thermally upgraded paper insulation is 30+80=110° C.
- IEEE C57.91-2012 suggests that the expected lifetime at 110° C could be 15-20 years.
- The lifetime depends strongly on the moisture and oxygen content of the oil and insulation, therefore an oil preservation system is recommended.
Standard Model

A is the top-oil temperature derived as the average of the tank outlet oil temperature and the tank oil pocket temperature

B is the mixed oil temperature in the tank at the top of the winding (often assumed to be the same temperature as A)

C is the temperature of the average oil in the tank

D is the oil temperature at the bottom of the winding

E represents the bottom of the tank

g_r is the average winding to average oil (in tank) temperature gradient at rated current

H is the hot-spot factor

P is the hot-spot temperature

Q is the average winding temperature determined by resistance measurement

X axis indicates temperature rise

Y axis indicates relative vertical positions

■ measured point; ○ calculated point
Detailed simulation
Loss Distribution in individual parts of the windings can be calculated with very high precision

On this basis calculation of the Hotspot-Temperature is done, based on the calculated winding gradients, oil gradients and outer cooling system simulation.
### Hotspot distribution

<table>
<thead>
<tr>
<th>Insulation Type</th>
<th>Hot-spot rise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineral oil</td>
<td>69.8 K</td>
</tr>
<tr>
<td>Synthetic Ester</td>
<td>77.4 K</td>
</tr>
<tr>
<td>Natural Ester</td>
<td>80.2 K</td>
</tr>
</tbody>
</table>
Winding to oil gradient of a CTC

- Loss W/m²
- Enamel 0.8 K
- Oilfilm 1.5 K
- Paper Insulation 3.0 K
- Interface paper-oil 8.9 K
- Temp
- Distance

- 14.2 K
Oil Flow Concepts for the Windings
suitable for natural or directed oil flow

Layer Windings with Strips
Disc Windings without radial cooling ducts but with axial cooling ducts

Disc Windings with radial and axial cooling ducts
Increased cooling surface

Disc Windings with radial cooling ducts
The oil is guided by oil guide washers

Disc Windings with radial and axial cooling ducts
The oil is guided by oil guide washers

Very efficient for ON and OD cooling
Examples of temperature rises in oil and windings

(same windings, losses and radiators)

ON
- High longitudinal rise

OF
- Cooler top oil: low, but hotspot unchanged
- Not recommendable

OD
- Recommendable for larger transformers
- Limit: oil velocity to avoid electrostatical charging
Kurt Kaineder
Head of Engineering
Head of Electrical Design Global Technology Center MPT
Siemens AG Oesterreich
Transformers Linz
Kraussstraße 7
4020 Linz
Phone: +43 (5) 1707-71098
Fax: +43 (5) 1707-55391
Mobile: +43 (664) 615 4946
Mobile: +43 (664) 80117 71098
E-mail: kurt.kaineder@siemens.com

Siemens.com/transformers
James McIver
Principal Application Engineer
E T TR US
6860 Bermuda Road, STE 100
Las Vegas NV 89119
USA

Mobile: (702) 241-0157
E-mail: james.mciver@siemens.com

Siemens.com/transformers