INSULATION IN TRANSFORMERS

13TH MAY 2016
Agenda

1. Introduction

2. Insulation
   1. Liquid Insulation
   2. Solid Insulation (Cellulose)
      1. Paper
      2. Board
   3. Insulation Life

3. Dielectric Stress/Design
WEIDMANN ELECTRICAL TECHNOLOGY

WEIDMANN is a leading specialist for high voltage insulation and world-wide technology partner for manufacturers and users of transformers.

We develop and produce insulation materials, components and systems and advise our customers in all aspects of transformer design and operation.
• Founded in 1877

• Employees 4000

• Worldwide supplier for engineered products in ELECTRICAL TECHNOLOGY and PLASTICS TECHNOLOGY

• Privately held
Modern Power Transformer

Insulation Systems
- Transformerboard
- Insulating Paper
- Laminated PB
- Laminated Wood
- Enamel – Wire
- Epoxy Coatings
- Paper Phenolic
- Dielectric Fluid
Cellulose insulation in transformers

- Cellulose insulation in transformers comprise just a small percentage of total transformer costs, yet have tremendous leverage over design, size & weight.
- It is the weakest link in the transformers and has the most influence during the ageing process.
## Large Power Transformer Materials

*(reference 250 MVA Transformer)*

<table>
<thead>
<tr>
<th>Material</th>
<th>Weight (kg)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Steel</td>
<td>67165</td>
<td>34</td>
</tr>
<tr>
<td>Sheet Steel</td>
<td>45573</td>
<td>22</td>
</tr>
<tr>
<td>Copper Wire</td>
<td>24228</td>
<td>12</td>
</tr>
<tr>
<td>Transformer Oil</td>
<td>48000</td>
<td>24</td>
</tr>
<tr>
<td><strong>Kraft - Cellulose</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressboard</td>
<td>5294</td>
<td>3.0</td>
</tr>
<tr>
<td>Paper</td>
<td>1479</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>200,000</strong></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>
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Purpose of the Dielectric Fluid

• Provide Sufficient Dielectric Strength

• Provide Sufficient Cooling/Heat Transfer

• Preserve the Core and Coil Assembly
  (By filling the insulating material voids)

• Minimize the contact of oxygen with cellulose and other materials susceptible to oxidation
Insulation Fluids

- Mineral Oil
  - Naphthenic
  - Paraffinic
  - High Molecular Weight

- Silicone Fluid

- Synthetic hydrocarbons
  - E.g. Polyalphaolefins

- Polyol Esters

- Natural Esters (seed oils)
  - BioTemp®, FR3®
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Role of Transformerboard in the Transformer’s Insulation Subsystem

- Only Two Components
  - Water
  - Cellulose

- Mechanical

- Dielectric

- Thermal Cellulose determines life and loading
  - Class “A” Insulation - 105°C class
Cellulose

Northern Softwood Conifer: long, thin fiber (3-6mm)
Electrical-Grade (kraft process) Paper and Pressboard

• Most electrical-grade pressboard and papers used in oil-filled apparatus are made from wood cellulose refined using the “kraft” process. (“kraft” = German word for “strong”).

• The usual pulp furnish for electrical grade papers is unbleached, kraft-process pulp made from spruce, fir, and pine tree species from northern latitudes. Why? \(\rightarrow\) cold climate = slower tree growth \(\rightarrow\) long fiber length = higher strength.

Cellulose Macromolecule
Transformerboard Production

Cellulose

Cellulose Enlargements
Purpose of Solid Insulation in Transformers

Mechanical

- Winding tool
- Support the windings during short circuit
- Deal with axial and radial forces
- Maintain sufficient tensile, elongation, tear and compression strength during ageing of insulation
- Maintain dielectric clearances
- Support leads and auxiliary equipment
Purpose of Solid Insulation in Transformers

Dielectric

- Insulation should be able to deal with various dielectric stresses
  - Oil gap stresses
  - Creep Stresses
  - Stress in solid insulation
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Paper Production
Pulp – Paper Flow

- Multiple wire-mesh assemblies allows for thicker material

- Paper is continually processed whereas Transformerboard is made one sheet at a time
Paper
Creped Material
Crepe Paper

- Provides extensibility (stretch) to the product
  - Allows the paper to fit tightly over curved surfaces without wrinkles or gaps
  - Resists tearing during coil winding
  - Low Tensile Energy Absorption (toughness)

- Can be calendared
  - Control thickness of creped material
  - Adds some TEA
Paper

Adhesives

• Single or double sided application

• B-stage epoxy creates a rigid structure after heat treatment

• Diamond pattern creates a small oil duct to allow for impregnation
Thermal Upgrading

- All insulations degrade, changing chemical composition and properties over time. Dielectric, Mechanical, and Chemical strength dissipates.

- This process is greatly accelerated by heat.

- If we increase the paper’s maximum “normal operating” temperature to a higher level, we can:
  - Run the transformer at a higher temperature, without degradation, and thus raise its capacity and productivity.
  - Run the transformer at the prior normal temperature, and extend its life.

- Normal paper is designed for a 55° “rise” (40° ambient + 55° rise = 95° total.)

- Thermally Upgraded paper can operate at a 65° “rise” (40° ambient + 65° rise = 105° total.)
HV Layer Type Windings

- Winding end fill strips
- Multiple turns of paper, DPP
- Aluminum or Copper Wire
LV Layer Type Windings

LV Winding

- Winding end insulation, typically Diamond Pattern Paper (DPP)
- Oil cooling gap (none to several), mainly Strips & Ladders
- Conductor typically copper or aluminum foil
- Layer insulation, typically DPP
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Other Insulation Products

Fixation Elements such as clamps and blocks

Transformerboard

Various paper products: DPP, Kraft paper, Crepe paper…

Copper conductor insulated by crepe paper tubes

Duct Strips for oil flow
SMART INSULATION™ – DIRECT MONITORING APPROACH

Insulation System with Embedded Sensors

- Winding Cylinder
- Conductor
- SmartSpacer® T Temperature
- SmartSpacer® M Moisture in Paper (in development)
- SmartSpacer® F Clamping Force (in development)

Sensors are integrated with eNameplate software.
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Transformerboard Production

Pulp - Transformerboard Flow

(Machine diagram for production of Transformerboard precompressed.)
Transformerboard Production

BM#1 – Low Density

BM#2 – High Density
Transformerboard Production

Types of Transformerboard

*Difference is due to final drying process

Pre-compressed – High Density
- Dried Under Pressure and Temperature
- Restrained between screened platens – PEEK wires

Calendared – Low Density, Formable
- Dried Unrestrained – no pressure
- Circulating Air Over ~ 100m long
- Calendared – roll press to obtain final density
Function
Components and their use

Angle Ring
Cap Ring
Washer Block Asmb
Keyspacers
Crossover Patch
Function

Components and their use

- Keyspacers
- CTC Ramp
- Dovetail Sticks
- Rectangular Sticks
- Cylinder
How is Pressboard used?

Clamping Ring (TX2)  Angle Ring (FormVal)  Radial Spacers (T4)  Axial Spacers (T4)

Winding Cylinder (T4)  Conductor Wrap (Paper)  HiLo Barriers (HiVal)  Washers (T4)

Static Ring (TX2 & Creped Paper)
WEIDMANN InsuLogix® Vault - the next step in SMART INSULATION™

- Bushing Monitors
- Transformer Oil Level, DGA
- Load Tap Changer
- Metrology
- Switchgear
- Cooling Control
- Thermal Devices
- Pressure Devices
Control Panel components that can be replaced with the VAULT

- Annunciator
- Tap counter
- Monitor
- Relays
- Monitor Modules
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Insulation Life

The thermal limit of transformer windings is the insulation on the conductor at the winding hot spot. The average winding rise is calculated as follows:

<table>
<thead>
<tr>
<th></th>
<th>55° C Rise</th>
<th>65° C Rise</th>
<th>75° C Rise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient (max ave.)</td>
<td>30°</td>
<td>30°</td>
<td>30°</td>
</tr>
<tr>
<td>Average Winding Rise</td>
<td>55°</td>
<td>65°</td>
<td>75°</td>
</tr>
<tr>
<td>Hot Spot Differential</td>
<td>10°</td>
<td>15°</td>
<td>15°</td>
</tr>
<tr>
<td>Hot Spot Temperature</td>
<td>95°</td>
<td>110° *</td>
<td>120° **</td>
</tr>
</tbody>
</table>

*Only attainable with thermally upgraded insulation.
** Only attainable with specialty cellulose insulation.

$+10° \ C \approx 12\% \ Increase \ in \ Transformer \ MVA$
Insulation Life

Aging Curves

Thermally upgraded paper TUK
Regular Kraft paper

(Paper severely aged below this line)

Source: Westinghouse/ABB Brochure on Insuldur®
Insulation Life
Degree of Polymerization

Measurement of intrinsic viscosity after dissolving the cellulose in a specific solvent.

Gives an average measurement of the number of glucose units per molecular chain = Average fiber length

- DP Incoming Kraft Pulp \( \sim 1400 \)
- DP of Insulation Components prior to processing \( \sim 1200 \)
- DP of Insulation Components following processing \( \sim 1000 \)
- DP level considered as “over-processed” \( \sim 800 \)
- DP level considered end of life \( \sim 200 \)
Insulation Life

Degree of Polymerization

Degree of Polymerization = measurement of “n”

Quantity of uninterrupted molecules is indicative of structural stability
Insulation Life

Degree of Polymerization

**Paper Insulation Aging in Mineral Oil**

<table>
<thead>
<tr>
<th>DP</th>
<th>DP</th>
<th>DP</th>
<th>DP</th>
<th>DP</th>
<th>DP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>733</td>
<td>549</td>
<td>405</td>
<td>309</td>
<td>181</td>
</tr>
</tbody>
</table>

Progressive aging with time

**End of mech str.**

**Brittle & dark**

**Effects of aging:**
- darkening of color
- loss of electrical and mechanical strength; trans. Failure
- shortening of cellulose chains – DP lowered
- paper becomes wetter, and acidic
- by-products contaminate the oil

Source: ABB Power Technologies, Inc.
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FAILURE!
**Dielectric Stress**

**Theoretical Failure Model**

1. **Situation without field**
   - double layer
   - unstructured condition
   - barrier

2. **Influence of increasing field strength**
   - current flow
   - increasing conductivity
   - drift of particles
   - structuring

3. **"Initial" process (microscopic)**
   - generation of micro-cavities ("bubbles")
   - approx at 1000 kV/mm (local field)

4. **Generation of streamers**
   - radial propagation of low-density structures

5. **Stepwise propagation of streamers**
   - successive steps of streamer propagation as sequence of ignition, extinction, re-ignition, etc

6. **Influence of barriers**
   - charge transfer
   - transfer of electrode potential
   - surface discharge
   - local field enhancement
   - breakthrough
   - stress to the next oil duct

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**Insulation in Transformers**

13 May 2016 / JM & JB
Dielectric Stress
Predicting Failures

Finite Element Analysis (FEA) allows us to predict where areas of high dielectric stress could occur. We can then arrange Transformerboard in a manner that reduces the likelihood of discharges propagating.
Dielectric Stress
Predicting Failures – Local Stress

New FEA tools allow us to simulate designs and stresses much quicker

Stress Profile Between 4th & 5th Top HV Sections = 10.9 kV/mm.
Dielectric Stress

WEIDMANN Reference Curves - Oil

![Graph showing partial discharge inception field strength vs oil duct width for degassed oil with non-insulated and insulated electrodes.]
Dielectric Stress

Predicting Failures – Oil Gaps

Using the WRCs we’re able to determine a “safety margin” for the oil based on a Weibull distribution.
INSULATION SPECIFICATION GUIDE

WHY DID WE CREATE IT?

- Overall lack of concern in transformer specifications related to insulation requirements
- If insulation is specified, typically the verbiage is very general or outdated
- WEIDMANN Guide provides support/data for specifying insulation materials
- Ultimately provides an important barrier to potential offshore suppliers
- Bring awareness about differences in insulation materials currently available on the market and its effect on transformer performance, reliability and longevity
## INSULATION SPECIFICATION GUIDE
### WHY TRANSFORMER OWNERS SHOULD SPECIFY INSULATION MATERIALS

<table>
<thead>
<tr>
<th></th>
<th>Transformer Manufacturer</th>
<th>Transformer Owner / End User</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Insulation Cost</strong></td>
<td>2-8% of Transformer Selling Price</td>
<td>Negligible % of Cost of Substation or Generating Plant where the transformer is located</td>
</tr>
<tr>
<td><strong>Risk</strong></td>
<td>Test Floor or In-Service Failure within Warranty</td>
<td>In Service Failure &amp; Resulting Cost</td>
</tr>
<tr>
<td><strong>Capital at Risk</strong></td>
<td>Cost of rework or replacement</td>
<td>Partial or total loss of Substation or Generation plant 7 – 10 X Transformer Cost</td>
</tr>
<tr>
<td><strong>Duration of Risk</strong></td>
<td>Transformer Production and Warranty Period</td>
<td>Transformer operational life 20 – 30 years</td>
</tr>
</tbody>
</table>
### Example 1: Solid Insulation Transformerboard

<table>
<thead>
<tr>
<th></th>
<th>General</th>
<th>Directed</th>
<th>Specific</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solid Insulation</strong></td>
<td>Solid insulation within the windings and clamping structure shall be of a suitable cellulosic or aramid material and shall comply with current applicable industry standards for dielectric integrity, short circuit, thermal requirements, loss of life, and emergency loading.</td>
<td>Solid insulation within the windings and clamping structure shall be of a suitable cellulosic or aramid material supplied by a manufacturer with a proven history (15 or more years experience supported by technical development and testing) and shall comply with current applicable industry standards for dielectric integrity, short circuit, thermal requirements, loss of life, and emergency loading.</td>
<td>Transformer to be manufactured using only WEIDMANN Transformerboard for solid, non-paper insulation components.</td>
</tr>
</tbody>
</table>