High Temperature Insulation Systems and their use in Mobile Transformers

Myron B. Bell, PE
mbell@deltastar.com
Delta Star, Inc.
June 23rd 2015
Introduction
History of Delta Star

➢ 1908 – Delta Star founded in Chicago

➢ 1950 – Purchased by H.K. Porter and named Delta Star Electric Division

➢ 1959 – Delta Star purchased Hill Transformer located in San Carlos, CA

➢ 1961 – Built our Lynchburg, VA manufacturing facility

➢ 1976 – First mobile substation built for Withlacoochie Electric Coop

➢ 1988 – Delta Star became an Employee Owned Company (ESOP)

➢ 2003 – Delta Star received ISO 9001:2008 standing

➢ 2005 – Delta Star chosen by Congress to provide military mobile transformers

➢ 2008 – Delta Star celebrating 100 years in business

➢ 2009 – Delta Star plant modernization complete

➢ 2013 – Delta Star completes hi-bay expansion

➢ 2014 – Delta Star completes second vapor phase

➢ 2015 – Delta Star increases capacity.
Basic Transformer Design Variables
Mobile Transformer Design vs. Power Transformer Design
Thermal Limits of Conventional Insulation
Affects of Heat on Conventional Insulation Systems
Definitions from C57.154-2012 IEEE Standard
Hybrid Insulation Thermal Limits
Factory Thermal Testing
Purpose of C57.154-2012 IEEE Standard
Mobile Transformer construction and setup
Summary
Examples of mobile solutions
Q&A
# Basic Transformer Design

- **Nameplate Ratings**

## Transformer Specifications

<table>
<thead>
<tr>
<th></th>
<th>Class</th>
<th>ONAN/ONAF/ONAF</th>
<th>Three Phase</th>
<th>60 Hertz</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV</td>
<td>550</td>
<td>kV BIL</td>
<td>135000</td>
<td>GRDY/77945</td>
</tr>
<tr>
<td>LV</td>
<td>200</td>
<td>kV BIL</td>
<td>35500</td>
<td>GRDY/20497</td>
</tr>
<tr>
<td>TV</td>
<td>110</td>
<td>kV BIL</td>
<td>13200</td>
<td>VOLTS</td>
</tr>
<tr>
<td>Neutral H0</td>
<td>150</td>
<td>kV BIL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neutral X0</td>
<td>110</td>
<td>kV BIL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cont. Temp. Rise (HV,LV)</td>
<td>65</td>
<td>°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cont. Temp. Rise (TV)</td>
<td>65</td>
<td>°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impedance (H-X)</td>
<td>% AT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impedance (H-Y)</td>
<td>% AT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impedance (X-Y)</td>
<td>% AT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured Noise Level</td>
<td></td>
<td></td>
<td>135000-35500</td>
<td>VOLTS AND</td>
</tr>
<tr>
<td>All Windings Are Copper Wound</td>
<td></td>
<td></td>
<td>44.8</td>
<td>MVA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>135000-13200</td>
<td>VOLTS AND</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>35500</td>
<td>VOLTS</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>44.8</td>
<td>MVA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>dB(A)</td>
</tr>
</tbody>
</table>
Basic Transformer Design

- Details, details, details
  - Electric and Magnetic Fields
  - Current Density
  - Radial and Axial short circuit forces
  - Flux Density
  - Turns Ratio
  - Winding Resistance
  - Ampere turns
Basic Transformer Design

- **Items to consider**
  - What does the customer need?
  - Are there size limitations?
  - What is the intended usage?

- **Items most critical**
  - Voltage Ratio
  - Phase Angle
  - Impedance
  - MVA
Basic Transformer Design

**Forces:**
- Vectoral components, in axial and radial directions, seen by the windings.
- These forces are the mechanical stresses on the transformer.

\[ \vec{F} \propto \vec{B} \times \vec{J} \]

<table>
<thead>
<tr>
<th>Force</th>
<th>Flux Density</th>
<th>Current Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\propto$</td>
<td>$\times$</td>
<td>$X$</td>
</tr>
</tbody>
</table>

Delta Star Inc.
Basic Transformer Design

Forces:

\[ \mathbf{F} \propto \mathbf{B} \times \mathbf{J} \]

\[ \mathbf{B} \propto N \mathbf{I} \]

\[ \mathbf{J} = \frac{\mathbf{I}}{\text{area}} \]

By association

\[ \mathbf{F} \propto \frac{1}{\text{area}} \]

\[ \mathbf{F} \propto I^2 N \]
Forces:

\[ F \propto I^2 N \]

- Current is already determined by MVA and Voltage ratings.
- Now we need to determine the number of turns.
- What do turns affect, other than ratio?
Basic Transformer Design

**Impedance:** \(\% Z\)

**Impedance is affected by 2 main things.**

1. **Geometry** – Height and gap. Typically taller units will have a lower impedance.
   
   *Assuming the same number of turns.

2. **The # of turns** – Impedance varies with the square of the turns.
Once we know our turns

- We can calculate our volts/turn

  Exactly as it sounds. The voltage drop across each turn in the windings.

Once established, this value is the same for all windings in the transformer. i.e. HV, LV, TV, RV, etc.
Basic Transformer Design

Example:

- 138,000 volts across an HV winding having 1380 turns equates to 100 volts/turn.
- 72 turns on the LV winding will produce \((72 \times 100) = 7200\) volts

What about a regulating winding?

**The lower the volts/turn, the smaller the iron core can be for a given flux density.**
Now we know Turns, Impedance, Volts/Turn, and Flux Density

The last item we need for our basic design is Current Density.

Remember, our forces are proportional to current density. A smaller conductor means a smaller coil, but higher forces and higher resistance.

What does a larger conductor do?
Adjustments to one variable typically affects other variables.

- Force
- Flux Density
- Ampere Turns
- Flux Density
- %Z
- \( \frac{N_1}{N_2} \)

Can you build it?
Basic Transformer Design

Are you bored yet?

- How is this related to high temperature insulation?
- What causes higher temperatures in transformers?
Heating:

- Generally caused by high losses, or reduced cooling. How are losses calculated?
- Losses are split into three categories, with the third having two subcategories.
  1) \( I^2R \) Losses from the copper in the winding
  2) No-Load losses for the iron in the core
  3) Stray losses consisting of Eddy and Hysteresis losses in the stray fields.
I^2R, or Copper Losses

Simple mathematic equation, the product of I^2R. The resistance of the winding multiplied by the square of the current.

These losses vary as the square of the MVA or current. Once measured, they can be scaled to any MVA for a given unit.

What did we discuss that affects the resistance?
No-Load Losses or Iron Losses

By using our core diameter and window height, we calculate the core weight. Also knowing the flux density allows us to calculate the no-load losses from performance curves of the electrical steel being used for the core.
No-Load Losses:

- M6 Grade
- 0.25 W/lb
- 50 Hz
- 60 Hz

AKSteel
M-6 Mill-Anneal GOES
0.014 in. Thick
CORE LOSS - 50 and 60 Hz
Test: Parallel; ASTM A343
Losses

No-Load Losses:

- 0.31 W/kg = 0.1409 W/lb
- 1.0 T = 10 kG
- 50 Hz
- 60 Hz
- H0-DR Grade
No-Load Losses:

From this example, by changing core steel grades from M6 to H0-DR, our loss values at the same flux density went from:

0.25 Watts/pound for M6 to
0.141 Watts/pound for H0-DR

Nearly 44% decrease!!!!!
Stray Losses:

These losses are calculated by evaluating finite element field plots for the design.
Now that we know our losses, how are we going to cool the unit?

Table 2—Cooling class designation

<table>
<thead>
<tr>
<th>Present designations</th>
<th>Previous designations</th>
</tr>
</thead>
<tbody>
<tr>
<td>ONAN</td>
<td>OA</td>
</tr>
<tr>
<td>ONAF</td>
<td>FA</td>
</tr>
<tr>
<td>ONAN/ONAF/ONAF</td>
<td>OA/FA/FA</td>
</tr>
<tr>
<td>ONAN/ONAF/OFAF</td>
<td>OA/FA/FOA</td>
</tr>
<tr>
<td>ONAN/OFAF</td>
<td>OA/FOA</td>
</tr>
<tr>
<td>ONAN/ODAF/ODAF</td>
<td>OA/FOA (^a)/FOA (^a)</td>
</tr>
<tr>
<td>ODAF</td>
<td>FOA(^a)</td>
</tr>
<tr>
<td>ODWF</td>
<td>FOW(^a)</td>
</tr>
</tbody>
</table>

\(^a\) Indicates directed oil flow per preceding NOTE 2.
Cooling - ODAF

Oil flow - 2 parallel systems

Oil flow within the winding
Mobile Units
Applications

- Transformer failure - Emergency
  - Natural causes
  - Vandalism/Sabotage
  - Terrorism
  - EMP/GIC

- Routine maintenance
- Temporary power supply
- Power for a seasonal load
Types of mobile units

- Mobile transformer
Types of mobile units

- Mobile transformer
- Mobile substation
Types of Mobile Units

- Mobile Transformer
- Mobile Substation
- Portable Transformer
Types of mobile units

- Mobile transformer
- Mobile substation
- Portable transformer
- Skid mounted
Types of mobile units

All of these have something in common.

The need to be compact for the amount of MVA they deliver, in order to be quickly transported
Mobile versus Power unit
Mobile versus Power Unit

- Smaller size
- Lighter
- Delivered fully assembled to the site
- Short set up time
- Self contained - auxiliary power supply
- Must comply with DOT regulations
- May be equipped with HV and LV protection
- May be used outside substation if properly equipped

How to achieve it?
Mobile versus Power Unit

- High current densities and temperature rises – limited by short circuit withstand
- **Insulation – hybrid for 75, 95 and 95/115 C ratings**
- Impedance voltage specified at maximum rating
- Core – high permeability steel
- Oil preservation system – sealed tank, N2 system
- Cooling – ODAF, sound pressure level and source
- Tank – High strength steel
- Switches instead of boards
- Auxiliary power supply – external or internal
- Accessories and trailer design
Current densities for mobiles
- Restricted by short circuit withstand
- Higher losses

The unit protected by its own impedance only

Impedance restraints
- Regulation – affected by power factor
- Stray losses – affected by stray flux

Radial forces
- Compressive (buckling) on inner winding
- Outward force on outer winding

Axial forces
- Forces within the winding and on end structures
- Pre-compressing windings
- Compressive (buckling) forces on the inner winding (usually LV)
- Self supporting winding
- Outward forces on the outer winding (usually HV)
- Forces try to increase the main duct
Axial Forces

- Forces at the ends of windings
- Forces within windings created by taps
- Balancing windings
Axial Forces

- Forces within the windings
  - Bending forces
  - Pressing key spacers
  - Tilting forces
- Pre-compressing windings
- Pressing beams, rings and end insulation
3D Models

Model

• As Built
Mobiles typically generate 30%-50% more heat as a comparative power transformer, given the same MVA. 

- Due to:
  - Higher current density, flux density, and impedance.
  - Smaller tanks
  - Less oil
Factory Temperature Test

Meant to measure actual temperature for average winding and top oil during full load simulation. Hot spot can also be measured, if fiber optics are installed, if not, hot spot is calculated using the measured winding gradient and an empirical multiplier generated by the manufacturer.

Proving of the design!
Factory Temperature Test

• No-load and Load Losses are measured independently for the top rated MVA. We already discussed what affects these values.

• These losses are summed together and this simulated “Load” is forced upon the unit in test.

• Monitored variables include: Top Oil temp, Bottom and Top radiator temp, ambient temp, hot spot (if possible), Actual sourced kW, and actual sourced current.
Factory Temperature Test

- Continues until the top oil rise over ambient changes by less than 2.5% or 1°C for 3 consecutive hours.
- Load is reduced to rated current for the associated MVA for 1 hour.
- Source power is disconnected and winding resistance is measured for a 10 minute period in 15 second intervals.
Factory Temperature Test

• These resistance values are then plotted in a spreadsheet to extrapolate the resistance value at the time the source was disconnected, “time zero”

• This resistance value, when compared to the winding resistance at an ambient reference temperature, allows us to calculate the average winding temperature and winding gradient at the associated MVA.
Simplified formula according to
IEC 60076-7 (old IEC 354):

Hot Spot = Top oil + H * g * Ky

H = Hot-Spot Factor (empirical value of the transformer maker),
g = Gradient (calculated by the transformer maker),
K = Load factor (actual load/nominal load),
y = Winding exponent (depending on the cooling mode ONAN, ONAF;...)

Figure 1 – Thermal diagram
<table>
<thead>
<tr>
<th>TIME (SEC)</th>
<th>RESISTANCE (Ω)</th>
<th>COLD RESISTANCE TEMP.</th>
<th>COLD RESISTANCE</th>
<th>HOT RESISTANCE</th>
<th>TEMPERATURE RISE FOR HV WINDING</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.55025154</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>105</td>
<td>0.54806380</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>0.54710460</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>135</td>
<td>0.54619000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>0.54533980</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>165</td>
<td>0.54452660</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>180</td>
<td>0.54374990</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>195</td>
<td>0.54300870</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>210</td>
<td>0.54229120</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>225</td>
<td>0.54161720</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>240</td>
<td>0.54097530</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>255</td>
<td>0.54035230</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>270</td>
<td>0.53976300</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>285</td>
<td>0.53920160</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>0.53866000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>315</td>
<td>0.53813270</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>330</td>
<td>0.53763180</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>345</td>
<td>0.53715660</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>360</td>
<td>0.53669870</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>375</td>
<td>0.53624310</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>390</td>
<td>0.53581810</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>405</td>
<td>0.53540210</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>420</td>
<td>0.53500210</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>435</td>
<td>0.53460840</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>450</td>
<td>0.53420500</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>465</td>
<td>0.53386530</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>480</td>
<td>0.53351470</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>495</td>
<td>0.53316660</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>510</td>
<td>0.53282970</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>525</td>
<td>0.53250770</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>540</td>
<td>0.53218340</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>555</td>
<td>0.53187420</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>570</td>
<td>0.53157480</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>585</td>
<td>0.53128370</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>600</td>
<td>0.53099360</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

MVA: 64

TOP OIL TEMP AT TIME OF CUT BACK: 79.8
AVG. TOP RAD TEMP AT TIME OF CUT BACK: 79.6
AVG. BOT RAD TEMP AT TIME OF CUT BACK: 56.4
AVG. AMBIENT TEMP AT TIME OF CUT BACK: 32.6
AVG. OIL RISE AT TIME OF CUT BACK: 37.6
TOP OIL RISE AT TIME OF CUT BACK: 49.7
BOT OIL RISE AT TIME OF CUT BACK: 25.8
TOP OIL TEMP AT TIME OF SHUT-DOWN: 78.8
AVG. TOP RAD TEMP AT TIME OF SHUT-DOWN: 78.7
AVG. BOT RAD TEMP AT TIME OF SHUT-DOWN: 56.1
AVG. AMBIENT TEMP AT TIME OF SHUT-DOWN: 31.3
AVG. OIL RISE AT TIME OF SHUT-DOWN: 36.3
TOP OIL RISE AT TIME OF SHUT-DOWN: 47.6

WINDING GRADIENT:

WINDING RISE:

GUARANTEE:

Hot spot Multiplier: 1.03
Hot Spot 67.30

HV FA HOT RESISTANCE

y = 4.2107E-08x^2 + 6.2819E-05x - 5.5381E-01
Table 3—Maximum continuous temperature rise limits

<table>
<thead>
<tr>
<th></th>
<th>Conventional insulation system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum required high-temperature solid insulation thermal class</td>
<td>120</td>
</tr>
<tr>
<td>Top liquid temperature rise, (°C)</td>
<td>65</td>
</tr>
<tr>
<td>Average winding temperature rise, (°C)</td>
<td>65</td>
</tr>
<tr>
<td>Hottest spot temperature rise for solid insulation, (°C)</td>
<td>80</td>
</tr>
</tbody>
</table>

NOTE 1—The temperature rises shown are based on a 30 °C average cooling air temperature as defined in IEEE C57.12.00. If the specified cooling air temperature is different from 30 °C, the temperature rise limits shall be adjusted accordingly to meet the suggested limits of Table 5.
How to meet the limits using paper?

• ONAF?
  Radiators would be too big for a mobile application

• ODAF?
  More efficient and smaller than rads, but just not enough oil to keep the windings cool
What happens when paper overheats

• Insulation in a transformer has two properties; mechanical and electrical

• Overheating conventional insulation results in lowered degree of de-polymerization (mech), and decreased dielectric properties (elect).

• Decreased life, eventual failure!
What happens when paper overheats

The measure of the ageing of cellulose-containing parts of the insulation is the degree of de-polymerisation (DP). It describes the middle number of combined glucose-rings inside the cellulose. In the unaged state the cellulose has a DP of approx. 1200.

*Ansgar Hinz
Messko GmbH
What happens when paper overheats

*Ansgar Hinz
Messko GmbH
C57.154 Definitions

◆ Conventional – temp rise limits, insulation materials or insulation systems operating at temperatures within normal thermal limits of IEEE C57.12.00
  ▪ 65°C avg winding rise, 80°C Hot Spot Rise, 110°C Hotspot temp, and 65°C top oil rise

◆ High Temperature – A description applied to temp-rise limits, insulation materials or insulation systems operating at higher temps than conventional

◆ Hybrid Insulation System – High temp solid insulation operating above conventional temps, combined with conventional solid insulation.

◆ Mixed Hybrid Insulation Winding – A winding composed of conventional solid insulation with high temp insulation used only selectively to allow higher than conventional hottest spot temps, with conventional avg temps.

◆ Full Hybrid Insulation Winding – A winding composed of conventional solid insulation with high temp insulation used in areas in contact with the winding conductor to allow higher avg winding and hot spot temps.
High Temp Insulation

The Primary High-Temperature Insulation used in the United States in Nomex® by Dupont

• Aramid based material
• Suitable for continuous operation at 220°C
• Retains dielectric strength from 0 - 95% relative humidity
• Once oil impregnated, significantly better dielectric strength than kraft paper of the same thickness
## Temperature Rises
(from IEEE C57.154)

### Table 3—Maximum continuous temperature rise limits for transformers with hybrid insulation systems

<table>
<thead>
<tr>
<th></th>
<th>Conventional insulation system</th>
<th>Hybrid insulation systems</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mixed hybrid insulation winding</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Full hybrid insulation winding&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Minimum required high-temperature</td>
<td>120</td>
<td>130</td>
</tr>
<tr>
<td>solid insulation thermal class</td>
<td></td>
<td>130</td>
</tr>
<tr>
<td>Top liquid temperature rise, (°C)</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>Average winding temperature rise, (°C)</td>
<td>65</td>
<td>75</td>
</tr>
<tr>
<td>Hottest spot temperature rise for</td>
<td>80</td>
<td>90</td>
</tr>
<tr>
<td>solid insulation, (°C)</td>
<td></td>
<td>90</td>
</tr>
</tbody>
</table>

**NOTE 1**—The temperature rises shown are based on a 30 °C average cooling air temperature as defined in IEEE C57.12.00. If the specified cooling air temperature is different from 30 °C, the temperature rise limits shall be adjusted accordingly to meet the suggested limits of Table 5.

**NOTE 2**—The conventional insulation system is shown for comparison purposes.

<sup>a</sup> Essentially oxygen-free applications where the liquid preservation system effectively prevents the ingress of air into the tank.
C57.154 standard

The purpose is to **standardize** the development of liquid-immersed transformers that use high-temperature insulation and operate at temperatures that exceed the normal thermal limits of C57.12.00 under continuous load, in the designed ambient, and at rated conditions.

Create rules that apply to all manufacturers for using insulation above conventional levels.
Avg Winding temp : Conventional Limits
Winding Hot Spot temp : Higher than conventional
Avg Winding temp : Higher than conventional
Winding Hot Spot temp : Higher than conventional

Figure 2—Illustration of a full hybrid insulation winding
# C57.154 standard

## Table 2—Insulation winding/system comparison

<table>
<thead>
<tr>
<th>Type of insulating component&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Conventional insulation system</th>
<th>Hybrid insulation systems</th>
<th>High-temperature insulation system&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C or H</td>
<td>C or H</td>
<td>H</td>
</tr>
<tr>
<td>Wire insulation</td>
<td>C</td>
<td>C &amp; H combination</td>
<td>H</td>
</tr>
<tr>
<td>Spacers/strips</td>
<td>C</td>
<td>C &amp; H combination</td>
<td>H</td>
</tr>
<tr>
<td>Barrier solid</td>
<td>C</td>
<td>C</td>
<td>C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Insulating component application temperature</th>
<th>Conventional insulation system</th>
<th>Hybrid insulation systems</th>
<th>High-temperature insulation system&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top liquid rise</td>
<td>C</td>
<td>C</td>
<td>H</td>
</tr>
<tr>
<td>Average winding rise</td>
<td>C</td>
<td>C</td>
<td>H</td>
</tr>
<tr>
<td>Hottest spot winding rise</td>
<td>C</td>
<td>H</td>
<td>H</td>
</tr>
</tbody>
</table>

<sup>a</sup> Only basic winding components are shown and other high-temperature insulation may be required depending on the results of the thermal mapping.

<sup>b</sup> Some conventional insulation is acceptable in locations where conventional temperatures are maintained.
C57.154 standard

- High Temp Insulation System - An insulation system used throughout the transformer, except for some minor insulation in lower temp areas, together with high-temp insulating liquid operating at higher than conventional levels.

<table>
<thead>
<tr>
<th>Liquid type</th>
<th>Ester</th>
<th>Ester</th>
<th>Ester</th>
<th>Ester</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum required high-temperature solid insulation thermal class</td>
<td>130</td>
<td>140</td>
<td>155</td>
<td>180</td>
</tr>
<tr>
<td>Top liquid temperature rise, (°C)</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Average winding temperature rise, (°C)</td>
<td>75</td>
<td>85</td>
<td>95</td>
<td>115</td>
</tr>
<tr>
<td>Hottest spot temperature rise, (°C)</td>
<td>90</td>
<td>100</td>
<td>115</td>
<td>140</td>
</tr>
<tr>
<td>Silicone</td>
<td>130</td>
<td>140</td>
<td>155</td>
<td>180</td>
</tr>
<tr>
<td>Top liquid temperature rise, (°C)</td>
<td>115</td>
<td>115</td>
<td>115</td>
<td>115</td>
</tr>
<tr>
<td>Average winding temperature rise, (°C)</td>
<td>75</td>
<td>85</td>
<td>95</td>
<td>115</td>
</tr>
<tr>
<td>Hottest spot temperature rise, (°C)</td>
<td>90</td>
<td>100</td>
<td>115</td>
<td>140</td>
</tr>
</tbody>
</table>

The temperature rises shown are based on a 30 °C average cooling air temperature as defined in IEEE Std C57.12.00. If the specified cooling air temperature is different from 30 °C, the temperature rise limits shall be adjusted accordingly to meet the suggested limits of Table 6.

Essentially oxygen-free applications where the liquid preservation system effectively prevents the ingress of air into the tank.

The high-temperature insulation may include different temperature classes, all above conventional.
### Table A.1—Typical properties of solid insulation materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal class (°C)</th>
<th>ASTM standard reference</th>
<th>Relative permittivity at 25 °C</th>
<th>Dissipation factor (%) At 25 °C</th>
<th>Moisture absorption (%)</th>
<th>Density (g/cm³)</th>
<th>Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose-based</td>
<td>105</td>
<td>D1305</td>
<td>3.3 – 4.1</td>
<td>0.4</td>
<td>7.0</td>
<td>0.97 – 1.2</td>
<td>Paper</td>
</tr>
<tr>
<td>Cellulose-based thermally-upgraded</td>
<td>120</td>
<td>D1305</td>
<td>3.3 – 4.1</td>
<td>0.4</td>
<td>7.0</td>
<td>0.97 – 1.2</td>
<td>Paper</td>
</tr>
<tr>
<td>Cellulose-based</td>
<td>105</td>
<td>D4063 [B8]</td>
<td>2.9 – 4.6</td>
<td>0.4</td>
<td>7.0</td>
<td>0.8 – 1.35</td>
<td>Board</td>
</tr>
<tr>
<td>Polyphenylene sulfide (PPS)</td>
<td>155</td>
<td></td>
<td>3.0</td>
<td>0.06</td>
<td>0.05</td>
<td>1.35</td>
<td>Film</td>
</tr>
<tr>
<td>Polyester glass</td>
<td>130 – 200</td>
<td></td>
<td>4.8</td>
<td>1.3 – 7.0</td>
<td>0.2 – 1.1</td>
<td>1.8 – 2.0</td>
<td>Sheet</td>
</tr>
<tr>
<td>Polyester glass</td>
<td>130 – 220</td>
<td></td>
<td>n/a</td>
<td>n/a</td>
<td>0.16 – 0.28</td>
<td>1.8 – 2.0</td>
<td>Shapes</td>
</tr>
<tr>
<td>Polyimide</td>
<td>220</td>
<td></td>
<td>3.4</td>
<td>0.2</td>
<td>1.0 – 1.8</td>
<td>1.33 – 1.42</td>
<td>Film</td>
</tr>
<tr>
<td>Aramid</td>
<td>220</td>
<td></td>
<td>1.6 – 3.2</td>
<td>0.5</td>
<td>5.0</td>
<td>0.66 – 1.10</td>
<td>Paper</td>
</tr>
<tr>
<td>Aramid</td>
<td>220</td>
<td></td>
<td>1.7 – 3.5</td>
<td>0.5</td>
<td>5.0</td>
<td>0.52 – 1.15</td>
<td>Board</td>
</tr>
</tbody>
</table>

**NOTE 1**—All data has been taken from measurements in air.

**NOTE 2**—Relative permittivity and dissipation factor data are referenced to 50/60 Hz

**NOTE 3**—Moisture data is based on conditions of 50% relative humidity at a temperature of 23 °C
Typical Mobile Transformer construction
- High temperature material minimum 155 °C
- Wire insulation on all designs
- Key spacers on 95°C rise units
- Vertical strips on 95°C rise units
- Insulation in contact with metal parts temperature over 120°C

- Pressboard (low- and high density) for areas in contact with oil only where temperature is up to 105°C
HV Switch
LV Switch
Setting up mobile units
<table>
<thead>
<tr>
<th>Setting up units</th>
<th>Power</th>
<th>Mobile</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unit in storage</td>
<td>Unit in storage</td>
</tr>
<tr>
<td></td>
<td>Move on truck with crane</td>
<td>------</td>
</tr>
<tr>
<td></td>
<td>Move to location</td>
<td>Move to location</td>
</tr>
<tr>
<td></td>
<td>Move to pad with crane</td>
<td>------</td>
</tr>
<tr>
<td></td>
<td>Set on pad</td>
<td>Set mobile</td>
</tr>
<tr>
<td></td>
<td><strong>Install rads., bushings, SA</strong></td>
<td>------</td>
</tr>
<tr>
<td></td>
<td>Wire control cabinet</td>
<td>------</td>
</tr>
<tr>
<td></td>
<td>Check and set controls</td>
<td><strong>Check and set controls</strong></td>
</tr>
</tbody>
</table>
## Setting up units

<table>
<thead>
<tr>
<th>Power</th>
<th>Mobile</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Vacuum fill unit</td>
<td>----</td>
</tr>
<tr>
<td>- Waiting time after filling</td>
<td>----</td>
</tr>
<tr>
<td>- Test unit</td>
<td>Test unit</td>
</tr>
<tr>
<td>- Energize unit</td>
<td>Energize unit</td>
</tr>
<tr>
<td>- DGA</td>
<td>DGA</td>
</tr>
<tr>
<td>- Load unit</td>
<td>Load unit</td>
</tr>
<tr>
<td>- DGA</td>
<td>DGA</td>
</tr>
<tr>
<td>- Set up time – 4-6 days longer than for mobile unit</td>
<td></td>
</tr>
</tbody>
</table>
Summary

- Transformer Design is FUN!
- Changes to one variable affects others
- Substantial differences in Mobile vs. Power
- High temperature insulation has made it possible to push more MVA out of smaller size
- Read IEEE C57.154 for more detailed information
Examples of Mobile Substations and Mobile Products
Enclosed 10 MVA 34400 – 4800 x 2400
Enclosed 7 MVA, 25 kV Class Substation
HV 69 kV on the Gooseneck
70 MVA, 230 kV - 34.5 kV
50 MVA, 230 kV - 69 kV
45 MVA, 115 kV - 12 kV
40 MVA, 115 kV - 69 kV
30 MVA, 138 kV - 13 kV
HV PASMO Breaker
HV Transrupter
Transformer + LV and HV Breaker Trailer
Portable Autotransformer
Skid with Removable Wheels
Skid mounted Substation

Ready for transport

Under the test

Visible shock absorbers
Skid Unit
With LV switchgear, HV breaker, cooling
Transrupter with Switch Trailer
LV Breaker Trailer
Cable Trailers
Conceptual Design of
400 MVA Autotransformer
345 kV – 230 kV, 15 kV TV
on three trailers
Connections and Weights
THANK YOU