Transformer Applications & Eco Directive
Cast Resin & Oil Distribution Transformers

Anton Joseph & Enrique Palomares, Abril 2016
Agenda

- Distribution Transformers
- Transformer Fundamentals
- Manufacturing Process
- Transformer Specification
- Design Considerations
- Maintenance
- Eco Directive
Distribution Transformers
Electricity Distribution
Why HV

- Total 3 Phase Losses = $3 I^2 R$
- Active Power, $P = \sqrt{3} VI \cos \Phi$
- $I = P / (\sqrt{3} V \cos \Phi)$
- Losses = $P^2 R / (V^2 \cos^2 \Phi)$

Losses are inversely proportional to the square of Voltage & directly proportional to the square of the Active Power

- High system voltage reduces transmission losses
- Requires more expensive lines, cables & transformers
- Generator transformers are step up
- Distribution transformers are generally step down
  - Voltage taken down in several steps
  - Lower voltages closer to the consumers
Electricity Distribution
Interconnected Electricity System
Electricity Distribution
Distributed Generation
Electricity Distribution
Applications

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<th>Transformer Type</th>
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Transformer Types

- Up 10 MVA & up to 36 kV
- Pole Dry
- Dry 63 MVA 72.5 kV
- 50 – 10,000 kVA up to 36 kV
- 10 – 63 MVA up to 170 kV
- Up to 800 kV HVDC – 400 Tonnes
- Traction
Distribution Transformers

Introduction

- Receives energy from higher transmission voltages and transforms for distribution to lower voltage substations or directly to consumers
  - Typically from 11 to 0.4 kV in the UK
- Normal Oil & Dry transformer ratings
  - Up to 10 MVA & 36 kV
- Cast Resin Dry Transformers
  - up to 63 MVA
  - up to 72.5kV
Transformer Fundamentals
Transformer Fundamentals
Magnetic Circuit

- Faraday’s Law of Electromagnetic Induction
- $V_s / V_p = N_s / N_p$
- Step up or step down
- Isolate one circuit from the other
  - Harmonics are not isolated by the transformer
Transformer Fundamentals
Heat Loss

- Losses generate heat
- Removed through air ventilation or oil circulation

100% POWER  0.3%  99.7% POWER
VOLTAGE 1     0.3%     VOLTAGE 2

Three Phase
Transformer Fundamentals
Cooling of Dry Transformers

- In a dry transformer the heat generated by coils and core is dissipated to air

![Diagram of a dry transformer showing heat generation, transfer, and dissipation]

- Heat generated in coils and core are transferred by the air through convection
  - Hot air exit from the transformer
  - Cold air entrance from the ambient

- AN
- AN/AF
Transformer Fundamentals
Cooling of Oil Transformers

- Mineral or synthetic oil is used for cooling & insulation
  - O Mineral Oil with Flash Point ≤ 300°C,
  - K Flash Point > 300°C & biodegradable
- Heat dissipated to air in the radiator

- ONAN
- ONAF
- OFAF
- KNAN
- ……..

*Radiators with fans*

- The hot liquid, coming from coils and core, flows through the radiators
- The heat is transferred in the radiators to ambient air, cooling thereby the liquid
- The colder liquid flows back into the transformer tank
- The cycle starts again: heat is generated at coils and core and transferred to the liquid
Transformer Fundamentals
Windings and conductor materials

- Copper or aluminum conductor is used
- Cu has a higher conductivity ($1.7 \times 10^8 \Omega \text{m}$) than Al ($2.8 \times 10^8 \Omega \text{m}$), but a higher density
  \[\Rightarrow\] Transformers with windings made of Cu or somewhat more compact, but heavier than those made of Al
- Cu is more expensive than Al and more kg of metal is needed $\Rightarrow$ transformers with Cu windings are more expensive
- Specific markets or customers may require Cu windings
- LV and HV coils use mostly the same conductor material, but it can also be different
- Cu and Al can be used in the shape of wires or foils
Transformer Fundamentals

Insulation

- Transformer components need to be electrically insulated:
  - HV coil versus LV coil, phase versus phase, and coils versus core
- The majority of voltage and the electric field is taken up by air or oil
- The main purpose of the solid or paper insulation is:
  - dielectric insulation
  - avoidance of shorts between windings turns due to contamination
  - mechanical rigidity and protection for the coils
Transformers have 2 loss components:

- No-load loss in iron core:
  - due to hysteresis and eddy currents
  - independent of load

- Load loss in windings:
  - due to resistive and eddy currents
  - increases with square of load
  - load loss value is given for 100% load

Transformer efficiency can easily be calculated from the losses

- maximum efficiency is typically at 40-50% load
Transformer Fundamentals
Temperature reference for load loss

- Load loss:
  - Load losses must be always referred to the same temperature

- Reference temperature for oil transformers is $T=75^\circ$ and for dry transformers $T=120^\circ$. (F-class)

- Formula for recalculating the losses to any temperature:
  
  $P_{120^\circ} = P_{75^\circ} \times \frac{(234,5 +120)}{(234,5+75)}$
Transformer Fundamentals

No-load loss

- No-load losses do not depend on the temperature
- Oil transformers have lower no-load losses than dry transformers for the same rating because the core is smaller (air needs larger clearance).
Manufacturing Process
Manufacturing Process Design

Engineering design capabilities
Advanced Design Tools
Common Design System
Manufacturing Process Modelling

3D Modelling: PTC Creo 2.0
- Awarded 3D software that combines Parametric and Direct modeling.
- Maximize innovation while at the same time ensuring speed, flexibility, and faster time-to-market.

Finite Element Method Analysis (FEM)
- Optimize virtual prototypes in the design process.
- Improve product life cycle, achieving strong electrical and mechanical designs.

FEM Mechanical: MSC Nastran Structures
- Awarded structural analysis software used by our engineers to perform static and dynamic analyses: Vibrations, Seismic Conditions, Handling of special designs,..

FEM Electrical: MagNet, ThermNet & ElecNet
- Software specialized in magnetic and dielectric fields, which allows to calculate key electrical parameters: Impedances, losses, temperature rise & hot-spots, short-circuit forces, prediction of voltage breakdown...
Manufacturing Process
Robotic core stacking cell
Manufacturing Process
Robotic core stacking

- 52% reduction in stacking labor time compared with manual stacking.
- No load losses, noise level and no load current reduction compared with manual stacking.
- Improvement in finishing. Improvement of product quality perception by the customer.
- Decrease in accidents.
Manufacturing Process
High Voltage Coil

- High voltage winding consists of a foil winding in multiple disks.
- Each disk has several turns.
- High voltage coil is reinforced with fiberglass net.
High Voltage Coil
Random Winding

Wire is wound in random without any pattern
The adjacent wires in a random winding can have high potential differences, thus creating a large number of critical areas without sufficient insulation distances. This could cause problems with the insulation between turns leading to possible short circuits.
High Voltage Coil

Wire in Layers

Wire is wound in different layers, as shown.
The insulating space between two layers is modified progressively, with the aim to assure enough distance in critical areas.
Spaces between layers are progressively modified to increase distances between turns. However there will be high potential difference between layers.
This system consists of foil windings in multiple disk. Each disk has several turns.
The connection between two consecutive foil disk is made as shown.
There are critical areas localized between disks. We can allocate enough space during design to eliminate problems with insulation.
In a foil disk winding design, the safety insulating space, between critical turns, can be easily guaranteed compared to other winding methods.
High Voltage Coil
Foil Disk

The foil is wound in a special machine using laser for the correct positioning of disks.
High voltage coil
Winding
High Voltage Coil
Foil Disk

Foil disk winding before being encapsulated.
High Voltage Coil Moulding
In horizontal filling system, cavities don’t form between foils disks. This is because the air is pushed by the resin mixture in radial direction – from bottom to the top.

Disks can’t move during the casting process. This ensures the insulating level between foils disks to remain constant.
In vertical filling system, the high voltage mold is filled in a vertical position in the casting chamber.

Cavities can form between the foil disks, due to air being pushed by the resin mixture in axial direction – from the bottom to the top.

Any air bubbles will lead to increased partial discharge.
Manufacturing Process
Low Voltage Coil
Manufacturing Process
Low Voltage Coil
Manufacturing Process
Low Voltage Coil - Curing

Option:
Low voltage
Sealed or Casted
Manufacturing Process
Oil Transformer Windings

- Windings are dried in an oven to attain below 1% of moisture content
- Epoxy resin coated paper provides adhesion of winding layers
- Filled with filtered and degassed transformer oil under vacuum
Manufacturing Process
Oil Transformer Windings

- Prevention of moisture from the ambient is achieved by
  - Hermetically sealed tank
  - Separating the tank with a conservator – outside air enters through a Silica Gel Breather
Assembly section

Firstly

Secondly
Assembly section

Sensors
PTC 130-150
Test laboratories

Two test rooms certificate ISO / IEC 17025 since 2001 according to ENAC

(general requirements for the competence of testing and calibration laboratories)
The final test
Routine and special tests

Routine and special Tests:
FAT
Temperature Rise Test
Lightning Impulse test
Sound level test
Other special tests...
Transformer Specification
Transformer Specification
Basic

- Rated Power in kVA
  - kW x Power Factor
- Primary Voltage (± 5% Tolerance)
- Secondary Voltage at no load
- Number of phases & Frequency (± 5% Tolerance)
- Impedance
  - `Resistance to AC circuit with magnitude & phase
- Altitude (< 1000 m a.s.l.) & ambient temperature (40°C)
- Cooling type
  - with AF, rating increases by up to 40%
- Losses
  - low loss transformers up to ~50% higher costs
- Winding Material
  - with Cu about 70% higher price
## Transformer Specification

### Electrical insulation system

- **Thermal Class**
  - It indicates the maximum temperature that a material can admit without changing its characteristics.
  - The temperature rise admitted in windings will depend on the insulation material thermal class.

<table>
<thead>
<tr>
<th>Thermal Class</th>
<th>Max. Temp. Admitted by the Insulation Material (°C)</th>
<th>Average Max. Temperature Rise in Windings (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A)</td>
<td>105</td>
<td>65</td>
</tr>
<tr>
<td>(B)</td>
<td>130</td>
<td>80</td>
</tr>
<tr>
<td>(F)</td>
<td>155</td>
<td>100</td>
</tr>
<tr>
<td>(H)</td>
<td>180</td>
<td>125</td>
</tr>
<tr>
<td>(C)</td>
<td>220</td>
<td>150</td>
</tr>
</tbody>
</table>

- **Oil**
- **Dry**
The allowed winding temperature rise depends on the insulation class, maximum ambient temperature and hot spot.

- Simple consideration: \( \text{max. ambient } T + \text{winding } T\text{-rise} \leq \text{max. } T\text{-rise admitted by the insulation class} \)

- **Example: oil transformer:**
  - Maximum ambient temperature: \(40^\circ C\)
  - Insulation class \((A) = 105^\circ C\)
  - Winding temperature rise admitted = \(105 - 40 = 65^\circ C\)
    
    \(\Rightarrow\) allowed average winding \(T\)-rise: \(60^\circ C\)

- **Example: dry transformer:**
  - Maximum ambient temperature: \(40^\circ C\)
  - Insulation class \((F) = 155^\circ C\)
  - Winding temperature rise admitted = \(155 - 40 = 115^\circ C\)
    
    \(\Rightarrow\) allowed average winding \(T\)-rise \(100^\circ C\)

- In practice the transformer is not continuously at 100% load and the temperature varies (day, month, year). This compensates for increased temperature during overload periods.
Transformer Specification
Tap Changer

- Match the transformer to the system
  - Variation in primary or secondary voltage
- Example + or - 5% Tap for a 11 to 0.4 kV transformer
  - Turns Ratio = 11 / 0.4 = 27.5
  - Increase in Turns Ratio = 1.05 * 27.5 = 28.875
  - Decrease in Turn Ratio = 0.95 * 27.5 = 26.125
- If Primary Voltage is constant, the secondary voltage at
  - +5% Tap – 11 / 28.875 = 380 V
  - -5% Tap – 11 / 26.125 = 412 V
- To keep the Secondary Voltage constant with the Primary Voltage changing
  - +5% Tap – 0.4 * 28.875 = 11.55 kV
  - -5% Tap – 0.4 * 26.125 = 10.45 kV
Transformer Specification
Off Line Tap Changer

- Discrete voltage regulation by varying the number of turns
- Distribution transformers are normally furnished with **off-load tap changers**
- The standard number of positions is 5 (+/-2x2.5%). More positions can be manufactured on request
- Connections are normally bolted for Dry Type
Transformer Specification
Off Line Tap Changer – Oil Type

- Tap changer located in the tank
Transformer Specification
On Line Tap Changer

- On-Load Tap Changer for frequently varying voltages
Transformer Specification
Vector Group

- Indicates winding configuration and difference in phase angle
  - D, Y, N, d, y, n, 1 to 11 (clock face) – Dyn11 (30° lead)
  - Example YNd11
Transformer Specification
Vector Group

- Example YNd1
Transformer Specification
Vector Group

- Some Vector Group are not available
  - Example YNd2

\[
\begin{array}{c}
A1 - A2 \\
B1 - B2 \\
C1 - C2
\end{array}
\]

\[
\begin{array}{c}
a1 - a2 \\
b1 - b2 \\
c1 - c2
\end{array}
\]
Transformer Specification
Environmental & Climatic Conditions – Dry Type

**Environmental Class:**
- **E0** Normal indoor installation, no condensation, no considerable pollution
- **E1** Limited pollution, occasional condensation e.g. off circuit periods
- **E2** Heavy pollution, frequent condensation

**Climate Class:**
- **C1** Lowest ambient temperatures:
  - operation – 5°C
  - storage and transport - 25°C
- **C2** Lowest ambient temperatures:
  - operation –25 °C
  - storage and transport at –25°C
Transformer Specification
Fire Resistance – Dry Type

Fire Class:

- **F0**  No special requirements except typical characteristics for dry-type transformers

- **F1**  Increased demands
  - All materials practically free of halogens
  - Limited formation of fumes
  - Limited contribution with calorific energy to the source of fire
  - Self extinguishing transformer fire
Cost drivers
Voltage class and impulse level (BIL)

The transformer must withstand the corresponding BIL level according to the voltage level – Induced Voltage (Separate Source Withstand) & Lightning Impulse Test

The different standards (IEC, ANSI, etc.) give more than one BIL level for the same voltage. For example in IEC:

<table>
<thead>
<tr>
<th>$U_M$</th>
<th>F.I. $kV_{ef}$</th>
<th>BIL List 1</th>
<th>BIL List 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,1</td>
<td>3</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>3,6</td>
<td>10</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>7,2</td>
<td>20</td>
<td>60</td>
<td>75</td>
</tr>
<tr>
<td>12</td>
<td>28</td>
<td>75</td>
<td>95</td>
</tr>
<tr>
<td>17,5</td>
<td>38</td>
<td>95</td>
<td>125</td>
</tr>
<tr>
<td>24</td>
<td>50</td>
<td>125</td>
<td>170</td>
</tr>
<tr>
<td>36</td>
<td>70</td>
<td>170</td>
<td>250</td>
</tr>
<tr>
<td>52</td>
<td>95</td>
<td>250</td>
<td>325</td>
</tr>
<tr>
<td>72,5</td>
<td>140</td>
<td>325</td>
<td></td>
</tr>
</tbody>
</table>

The lower the BIL-level for the same $U_M$, the lower is the price.
Transformer Specification
Enclosure and IP Classification

- The “IP” classification describes the degree of protection provided by enclosures
- Explanation of numbers:  IP23
  - 1st number: protection against solid foreign objects: e.g. 2 corresponds to openings of max. 12.5 mm diameter (=finger).
  - 2nd number: protection against water: e.g. 3 provides protection against sprayed water

<table>
<thead>
<tr>
<th>First characteristic numeral</th>
<th>Protected from solids</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Not protected</td>
</tr>
<tr>
<td>1</td>
<td>50mm diameter</td>
</tr>
<tr>
<td>2</td>
<td>12.5mm diameter</td>
</tr>
<tr>
<td>3</td>
<td>2.5mm diameter</td>
</tr>
<tr>
<td>4</td>
<td>1.0mm diameter</td>
</tr>
<tr>
<td>5</td>
<td>Dust resistant</td>
</tr>
<tr>
<td>6</td>
<td>Dust tight</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Second characteristic numeral</th>
<th>Protected from water</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Not protected</td>
</tr>
<tr>
<td>1</td>
<td>Dripped vertically</td>
</tr>
<tr>
<td>2</td>
<td>Dripped at 15° angle</td>
</tr>
<tr>
<td>3</td>
<td>Sprayed</td>
</tr>
<tr>
<td>4</td>
<td>Splashed</td>
</tr>
<tr>
<td>5</td>
<td>Jet spray</td>
</tr>
<tr>
<td>6</td>
<td>Strong jet spray</td>
</tr>
<tr>
<td>7</td>
<td>Temporary immersion</td>
</tr>
<tr>
<td>8</td>
<td>Continuous immersion</td>
</tr>
</tbody>
</table>
Dry transformers - accessories
Enclosures

- Dry transformers can be used for indoor or outdoor installations
- For outdoor installations an enclosure is always necessary (so far)
- For indoor applications customer may want an enclosure due to:
  - Safety reasons (energized transformers are not allowed to be touched)
  - Ambient conditions (e.g. dust, water,..)
Dry transformers - accessories
Enclosures

IP-classification - Enclosures

A dry transformer is normally used for indoor operation with IP00 protection

BUT

Any kind of IP protection can be supplied with dry transformers
Dry transformers - accessories
Enclosure and cooling

- Ventilated and non-ventilated enclosures (for high IP) need to be distinguished
- In case of dirty or contaminated ambient, non-ventilated enclosures should be used
- Non-ventilated enclosures could need a heat exchanger
- Heat exchangers can be air-to-air or air-to-water heat exchangers
- Recently a more compact thermosiphon-based air-to-air heat exchanger was introduced
- Additionally the direct-water cooled technology is now available and allows to take out heat directly from the transformer without the need to pass via a heat exchanger
When a dry transformer is defined with enclosure, the temperature rise for windings needs to be lower than for IP00 transformers, because the air temperature inside the enclosure is higher.

A complete air temperature calculation is required. The larger the IP degree, the lower the winding temperature rise is permitted.

The winding temperature rise depends on the maximum ambient temperature.
Oil transformers - accessories
Buchholz Relay

- Protective device sensitive to effects of dielectric failure fitted to the conservator
  - Small accumulation of gas produced by decomposition of the insulating oil accumulates at the top providing a warning
    - Accumulated gases on the top can be analysed
  - Electric arc produces rapid oil flow providing a trip signal
Design Considerations
Design Considerations
Basic Requirements

- Primary & Secondary Voltages with tapping
  - Measure, Calculate and confirm
- Maximum Coincident Load + contingency for planned & unplanned growth
  - \( kVA = kV \times A \times 1.732 \) (square root of 3)
- Harmonics
  - < 5% THD
  - K Factors – weighting for harmonics
    - K 1 is linear load
    - K 4, 9 & 13 are common – transformer Is de-rated accordingly
- Harmonic Filtering
Design Considerations
Impedance Measurement

- Short circuit secondary windings
- Increase voltage on primary windings until full load current flows on the secondary
  - Impedance Voltage is due to winding resistance and leakage current
- \( Z \) in \% - \( \frac{\text{Impedance Voltage}}{\text{Rated Voltage}} \)
- Short circuit Impedance is the percentage of drop in Voltage due to winding resistance and leakage reactance to the rated Voltage
Design Considerations
Impedance

- Typical values 4 to 6% depending on the transformer size
  - Impedance is specified at 100% load
  - For ANAF rating it is at AN rating & not at AF
- Determines the maximum value of current under fault conditions
  - Impacts on the design of the protection system
  - Impedance increases with the number of turns and the thickness of the coil
  - Impedance reduces with core area and the height of the transformer
- Design is a compromise between losses and impedance
Design Considerations
Parallel Operation

- Centralised or Distributed
  - Redundancy
- Distributed with parallel operation
  - Same Voltage ratios, frequency, phase sequence and polarity
  - Transformer should have the same phase displacement between primary & secondary voltages
    - Example – Dyn11 & Yd11
- Same Impedance
  - A tolerance of 10% between the transformers
  - Load is shared in proportion to the MVA ratings
  - Unequal impedance will cause the lower impedance transformer to be overloaded
- Power Ratio of maximum 2:1 defined in IEC 676-8
Design Considerations

Size

- Space constraints
  - Eco Directive transformer are bigger and heavier
  - No specific advantage between Al or Copper
  - Cu transformers are shorter, fatter and heavier but more expensive

<table>
<thead>
<tr>
<th>Winding</th>
<th>Length</th>
<th>Width</th>
<th>Height</th>
<th>Weight</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>1,700</td>
<td>801</td>
<td>2,076</td>
<td>3,105</td>
<td>100%</td>
</tr>
<tr>
<td>Copper</td>
<td>1,850</td>
<td>1,010</td>
<td>1,850</td>
<td>4,300</td>
<td>175%</td>
</tr>
<tr>
<td>%</td>
<td>109%</td>
<td>126%</td>
<td>89%</td>
<td>138%</td>
<td></td>
</tr>
</tbody>
</table>

- It may be possible to change the design to accommodate size constraints
Design Considerations
Location

- Outdoor / Indoor, Dusty, Salty
  - Indoor – preferably dry transformers
    - Self extinguishing and environmentally friendly
    - Lower maintenance
  - Outdoors
    - Dry transformers can be installed with IP44 enclosure
      - C4H painting, Sealing of low voltage coil and space heaters
  - Oil transformers are suitable for external installation with harsh environmental conditions
Design Considerations
Spillage & Fire Containment

- Storage of more than 200 litres of oil
  - 500 kVA ONAN 11 to 0.4 kV transformer contains around 500 to 900 litres
- Additional guidance required if it is less than 10 m away from any inland freshwater or coastal waters or less than 50 m away from a well or borehole – Source Protection Zones
- Secondary Containment System Storage capacity should not be than 110%
- Minimum height of bund wall 150 mm to allow for rainfall and firefighting foam
- Equipped with oil separation and pump to remove rainwater
- Fire Risk Assessment
  - Separation, Fire Extinguishing Systems, Barriers
Maintenance
Maintenance
Dry Transformers

- Low maintenance
- Annual or quarterly for harsh environments such as dust or fumes or exposed to vibrations
  - Check for tightness of screws and bolts
  - Clean dusty surfaces with vacuum clearer or with dry air / Nitrogen
- Insulation Resistance Test
If the insulation of a winding has a defect, partial discharge appears.

In a vacuum cast transformer this defect can originate from an air bubble generated during the resin filling process.

This air cavity creates small electrical discharges, e.g. due to the potential difference between two turns. With time it destroys the insulation.

Partial discharges must be measured. Standard values are below 10 pC.
Maintenance Oil Transformers

- Check oil leaks and oil level at regular intervals
- Oil including Midel are hygroscopic – will absorb atmospheric moisture
  - Maintenance of Silica Gel Breather - monthly
- Annual Oil Sampling
  - Increase frequency if highly loaded
  - Serviceability of oil – dielectric strength & water content
  - Insulation system – deterioration of oil & paper produces combustible gases – Dissolved Gas Analysis
- Maintenance of accessories
Maintenance
Oil Reclamation

Oil Inlet
Gate Valve

Inlet Pump

Filter

Degassing Chamber

Heating

Vacuum Pump

Vacuum Gauge

Discharge Pump

Oil Outlet
Gate Valve
Eco Directive
## Eco Directive

### Oil Transformers

Table I.1: Maximum load and no-load losses (in W) for three-phase **liquid-immersed** medium power transformers with one winding with $U_{n} \leq 24$ kV and the other one with $U_{n} \leq 1.1$ kV

<table>
<thead>
<tr>
<th>Rated Power (kVA)</th>
<th>Tier 1 (from 1 July 2015)</th>
<th>Tier 2 (from 1 July 2021)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum load losses $P_{k}$ (W) (*)</td>
<td>Maximum no-load losses $P_{a}$ (W) (*)</td>
</tr>
<tr>
<td>$\leq 25$</td>
<td>$C_{k}$ (900)</td>
<td>$A_{a}$ (70)</td>
</tr>
<tr>
<td>50</td>
<td>$C_{k}$ (1 100)</td>
<td>$A_{a}$ (90)</td>
</tr>
<tr>
<td>100</td>
<td>$C_{k}$ (1 750)</td>
<td>$A_{a}$ (145)</td>
</tr>
<tr>
<td>160</td>
<td>$C_{k}$ (2 350)</td>
<td>$A_{a}$ (210)</td>
</tr>
<tr>
<td>250</td>
<td>$C_{k}$ (3 250)</td>
<td>$A_{a}$ (300)</td>
</tr>
<tr>
<td>315</td>
<td>$C_{k}$ (3 900)</td>
<td>$A_{a}$ (360)</td>
</tr>
<tr>
<td>400</td>
<td>$C_{k}$ (4 600)</td>
<td>$A_{a}$ (430)</td>
</tr>
<tr>
<td>500</td>
<td>$C_{k}$ (5 500)</td>
<td>$A_{a}$ (510)</td>
</tr>
<tr>
<td>630</td>
<td>$C_{k}$ (6 500)</td>
<td>$A_{a}$ (600)</td>
</tr>
<tr>
<td>800</td>
<td>$C_{k}$ (8 400)</td>
<td>$A_{a}$ (650)</td>
</tr>
<tr>
<td>1 000</td>
<td>$C_{k}$ (10 500)</td>
<td>$A_{a}$ (770)</td>
</tr>
</tbody>
</table>
### Eco Directive

### Dry Transformers

Table 1.2: Maximum load and no-load losses (in W) for three-phase dry-type medium power transformers with one winding with \( U_m \leq 24 \text{ kV} \) and the other one with \( U_m \leq 1.1 \text{ kV} \).

<table>
<thead>
<tr>
<th>Rated Power (kVA)</th>
<th>Tier 1 (1 July 2015)</th>
<th>Tier 2 (1 July 2021)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum load losses ( P_k ) (W) (*)</td>
<td>Maximum no-load losses ( P_o ) (W) (*)</td>
</tr>
<tr>
<td>( \leq 50 )</td>
<td>( B_k ) (1 700)</td>
<td>( A_o ) (200)</td>
</tr>
<tr>
<td>( 100 )</td>
<td>( B_k ) (2 050)</td>
<td>( A_o ) (280)</td>
</tr>
<tr>
<td>( 160 )</td>
<td>( B_k ) (2 900)</td>
<td>( A_o ) (400)</td>
</tr>
<tr>
<td>( 250 )</td>
<td>( B_k ) (3 800)</td>
<td>( A_o ) (520)</td>
</tr>
<tr>
<td>( 400 )</td>
<td>( B_k ) (5 500)</td>
<td>( A_o ) (750)</td>
</tr>
<tr>
<td>( 630 )</td>
<td>( B_k ) (7 600)</td>
<td>( A_o ) (1 100)</td>
</tr>
<tr>
<td>( 800 )</td>
<td>( A_k ) (8 000)</td>
<td>( A_o ) (1 300)</td>
</tr>
<tr>
<td>( 1 000 )</td>
<td>( A_k ) (9 000)</td>
<td>( A_o ) (1 550)</td>
</tr>
</tbody>
</table>
## Eco Directive
### Tier 1 vs Tier 2

<table>
<thead>
<tr>
<th>Type</th>
<th>Tier 1</th>
<th>Tier 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Load</td>
<td>No Load</td>
</tr>
<tr>
<td>Oil</td>
<td>11,000</td>
<td>950</td>
</tr>
<tr>
<td>Dry</td>
<td>11,000</td>
<td>1,800</td>
</tr>
</tbody>
</table>

Size & weight between Tier 1 & Tier 2: 5 to 10% impact
Calculation methods

The methodology for calculating the Peak Efficiency Index (PEI) for medium and large power transformers is based on the ratio of the transmitted apparent power of a transformer minus the electrical losses to the transmitted apparent power of the transformer.

\[
PEI = 1 - \frac{2(P_0 + P_{c0})}{S_r \sqrt{\frac{P_0 + P_{c0}}{P_k}}}
\]

Where:

\(P_0\) is the no load losses measure at rated voltage and rated frequency, on the rated tap
\(P_{c0}\) is the electrical power required by the cooling system for no load operation
\(P_k\) is the measured load loss at rated current and rated frequency on the rated tap corrected to the reference temperature
\(S_r\) is the rated power of the transformer or autotransformer on which \(P_k\) is based
# Eco Directive

## Peak Efficiency Index

Table I.5: Minimum Peak Efficiency Index (PEI) values for **dry type** medium power transformers

<table>
<thead>
<tr>
<th>Rated Power (kVA)</th>
<th>Tier 1 (1 July 2015)</th>
<th>Tier 2 (1 July 2021)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3,150 &lt; S_r \leq 4,000$</td>
<td>99.348</td>
<td>99.382</td>
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<tr>
<td>5000</td>
<td>99.354</td>
<td>99.387</td>
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<tr>
<td>6300</td>
<td>99.356</td>
<td>99.389</td>
</tr>
<tr>
<td>8000</td>
<td>99.357</td>
<td>99.390</td>
</tr>
<tr>
<td>$\geq 10,000$</td>
<td>99.357</td>
<td>99.390</td>
</tr>
</tbody>
</table>
Eco Directive
ANAF

- Up to 40% increase in power with fans for emergency operation only
  - Increase in load is not part of normal duty cycle
  - Temporary increase in load due to failure of another transformer
    - N-1 operation mode
  - Transformer will comply with Eco Directive at AN rating and not on AF rating
- If the increased load is part of the normal duty cycle, then AF rating losses should be complied with
### Eco Directive

#### ANAF

<table>
<thead>
<tr>
<th>Power</th>
<th>NLL</th>
<th>LL120</th>
</tr>
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<tbody>
<tr>
<td>2000</td>
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<td>16000</td>
</tr>
<tr>
<td>2800</td>
<td>3423</td>
<td>20384</td>
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### Table

<table>
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<th>No load losses</th>
<th>Load Losses</th>
<th>Load (kVA)</th>
<th>No load losses</th>
<th>Load Losses</th>
<th>Load (kVA)</th>
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<th>Load Losses</th>
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<td>160</td>
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Comply at AN: 2000
Comply at AF: 2800
Comply at AN/AF: 2000.6

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<th>Load Losses</th>
<th>Load (kVA)</th>
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<th>Load Losses</th>
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</table>

Course Ref: 382T1
Eco Directive
ANAF

![Graph showing power losses for different kVA levels]

<table>
<thead>
<tr>
<th>Power</th>
<th>NLL</th>
<th>LL120</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
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</table>
Thank you for your attendance
Power and productivity for a better world™