Reduction of Losses in Distribution Transformers

Dr. Juan C. Olivares-Galvan, Professor
Universidad Autonoma Metropolitana

Invited lecture for IEEE Greece PES Chapter
4 November 2010, Athens, Greece
I. Introduction
II. Stray losses in distribution transformers
III. Dielectric losses
IV. Tank losses due to high currents of LV
V. Design parameters of wound cores
VI. Conclusions
I. Introduction

- Overheating
- Insulation design
- **Loss reduction**
- Noise
- Size and shape

- No-load test
- Load test
Objective

Reduce transformer losses

\[
P_{\text{no-load}} = P_e + P_h + P_d
\]

\[
P_{\text{load}} = P_{12R} + P_{EC} + P_{\text{stray}}
\]
### Why distribution transformers?

<table>
<thead>
<tr>
<th>Transformer type</th>
<th>Millions of kWh</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No-load losses</td>
<td>Load losses</td>
<td></td>
</tr>
<tr>
<td><strong>Generator step up</strong></td>
<td>18</td>
<td>89</td>
<td></td>
</tr>
<tr>
<td><strong>Bulk power substation</strong></td>
<td>67</td>
<td>138</td>
<td></td>
</tr>
<tr>
<td><strong>Distribution substation</strong></td>
<td>97</td>
<td>114</td>
<td></td>
</tr>
<tr>
<td><strong>Distribution</strong></td>
<td>328</td>
<td>127</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>510</td>
<td>468</td>
<td></td>
</tr>
</tbody>
</table>

Source: Electric Power Research Institute (EPRI)

5000-MW utility system
With reduction of losses Mexico will invest less in generation.
II. Stray losses in transformers

- 500 kVA, shell type
- Closed topology
- Eddy current cancelation
- Load test
Stray losses vs transformer rating

\[ P_{\text{stray}} = 0.0007(kVA)^2 + 0.9838(kVA) - 4.7359 \quad \text{W} \]

\[ P_{S/L} = 0.0393(kVA)^{0.2056} \]
Description of experiment

<table>
<thead>
<tr>
<th>Part of the transformer</th>
<th>Number of aluminum foils</th>
<th>Length of aluminum foils (mm)</th>
<th>Total volume (mm$^3$)</th>
<th>Total mass (gr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sides</td>
<td>209</td>
<td>780</td>
<td>28984956</td>
<td>78839.08</td>
</tr>
<tr>
<td>Top and bottom</td>
<td>66</td>
<td>1200</td>
<td>14081760</td>
<td>38302.39</td>
</tr>
</tbody>
</table>
Results of experiments

<table>
<thead>
<tr>
<th>Test</th>
<th>Stray losses at ambient temperature (W)</th>
<th>Percentage of reduction of the stray losses with respect of test without shield</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shield of 1.2 mm</td>
<td>504.139</td>
<td>0</td>
<td>99.09</td>
</tr>
<tr>
<td>Shield of 10 mm</td>
<td>416.99</td>
<td>20.9</td>
<td>99.12</td>
</tr>
</tbody>
</table>

\[
\delta = \sqrt{\frac{2}{\omega \sigma \mu_0 \mu_r}}
\]

<table>
<thead>
<tr>
<th>Material</th>
<th>(\mu_r)</th>
<th>(\sigma) (S/m)</th>
<th>(\delta) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>1</td>
<td>3.82x10^7</td>
<td>10.5</td>
</tr>
<tr>
<td>Iron</td>
<td>2000</td>
<td>1.03x10^7</td>
<td>0.484</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>1</td>
<td>1.1x10^6</td>
<td>23.4</td>
</tr>
<tr>
<td>Copper</td>
<td>1</td>
<td>5.80x10^7</td>
<td>8.53</td>
</tr>
<tr>
<td>Gold</td>
<td>1</td>
<td>4.10x10^7</td>
<td>10.1</td>
</tr>
<tr>
<td>Silicon steel</td>
<td>50000</td>
<td>2x10^6</td>
<td>0.205</td>
</tr>
</tbody>
</table>
Incident, reflected and transmitted fields near the surface of conductors

\[ J \]

\[ \sigma \text{ large} \]

\[ \text{Depth of penetration} \]

Incident H field

Reflected H field

Transmitted H field

\[ J_s \]
Present worth analysis

Transformer life

0

US$18

30

i = 10 percent

Cost of electromagnetic shield = 10%

TAELS = (30.50W)(8760 hours/year)($0.067/kWH) = US $18.00

Total Annual Energy Loss Saving = TAELS

\[ P = \frac{(1+i)^n - 1}{i(1+i)^n} \]

\[ P = \frac{(1+0.1)^{30} - 1}{0.1(1+0.1)^{30}} \]  

\[ ($18.00) = (9.43)($18.00) = US$169.74 \]
IV. Dielectric losses

No-load losses during three stages of transformer manufacturing

<table>
<thead>
<tr>
<th>No-load losses with a test coil of 12 turns (W)</th>
<th>No-load losses of the set core-winding (W)</th>
<th>No-load losses of the completed transformer (tank included) (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>102.84</td>
<td>121.3</td>
<td>118.3</td>
</tr>
<tr>
<td>107.16</td>
<td>121.0</td>
<td>114.5</td>
</tr>
<tr>
<td>106.84</td>
<td>123.1</td>
<td>118.0</td>
</tr>
<tr>
<td>100.36</td>
<td>121.3</td>
<td>119.5</td>
</tr>
</tbody>
</table>

\[ P_d = V^2 \omega \tan \delta \ C \]
Stages of transformer manufacturing
IV. Tank losses due to high currents of LV

- Pad-mounted transformers
- With and without stainless-steel plate
- $I_X = 590.49$ A, $I_H = 5.65$ A
- Plate thickness: 6.35 mm
- AISI 304
- Carbon steel: ASTM A36
Experimental results

- Test with and without stainless steel
- Same active element was used
- Tests without oil
Load losses vs primary current for a 225 kVA transformer
Simulations
Simulations in 3D of tank losses

Nodes: 12179
Elements: 90179
Magnetic field measurements around LV

\[ Gauss_{\text{peak}} = \frac{60 \cdot E_{\text{peak, mv}}}{15.2 \cdot f} \]
Magnetic field measurements

Peak magnetic flux density (milligauss)
Maximum values of electric field and magnetic flux density in public areas

ICNIRP: International Commission on Non-Ionizing Radiation Protection
CENELEC: Comité Européen de Normalisation Electrotechnique
IRPA: International Radiation Protection Association
NRPB-UK: UK National Radiation Protection Board

ICNIRP: 5 kV/m, 0.1 mT
CENELEC: 10 kV/m, 0.64 mT
NRPB: 12 kV/m, 1.6 mT
IRPA: 5-10 kV/m, 0.1-1 mT
Present-worth analysis

$$P = \frac{(1+i)^n - 1}{i(1+i)^n} A$$

Transformer life

US$41.87

P

Time

0 10 12 14 16 18 20 22 24 26 28 30

Loss cost as a Percentage of transformer cost

TAELS = $70.9 \times (8760 \text{ hours/year}) \times ($0.06739) = \text{US$41.87}$

i = 10 percent
V. Reduction of core losses

<table>
<thead>
<tr>
<th>Material</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical steel</td>
<td>32.5 ± 5.5</td>
</tr>
<tr>
<td>Copper and aluminum</td>
<td>22 ± 6</td>
</tr>
<tr>
<td>Insulation</td>
<td>14.1 ± 5.5</td>
</tr>
<tr>
<td>Carbon steel</td>
<td>16.4 ± 8.5</td>
</tr>
<tr>
<td>Fabricated parts</td>
<td>15 ± 9</td>
</tr>
</tbody>
</table>

The transformer price is reduced.

Less copper and insulation
Less insulating oil
A smaller tank
A smaller core
Core with step-lap joint

- Step or book ($n_s$).
- Air gap ($g$)
- Overlap ($L_o$)
- Lamination thickness ($d$)
- Insulation thickness ($T_i$)
Design of wound core

\[ E = \frac{A_e}{2D}, \quad W_{fe} = P_n \left( W_{kg} \right) F_e \]

\[ A_n = \frac{37513(V_{\text{turn}})}{B_m} \]
LHL windings

- Maximum tension
- Minimum tension

Thickness vs. Height

Winding tension (kg) vs. AWG size
Experiments with core parameters

<table>
<thead>
<tr>
<th>Sample</th>
<th>Longitud traslape (cm)</th>
<th>No load losses (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>49.01</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>47.49</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>44.24</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>46.61</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>55.38</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>51.42</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>53.58</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>50.18</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>48.98</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>55.11</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>50.88</td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>50.03</td>
</tr>
</tbody>
</table>
Simulations using FEM

Magnetic flux trajectories for an air gap of 3mm and overlap length of 1.0cm, a) Two laminations per step; b) Eight laminations per step
Emissions of power plants

**Typical emissions data for existing power plants (kg/MBTU)**

<table>
<thead>
<tr>
<th></th>
<th>Coal-Fired Steam</th>
<th>Combustion turbine</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>77</td>
<td>45.4</td>
</tr>
<tr>
<td>SO₅</td>
<td>1.54</td>
<td>0.05</td>
</tr>
<tr>
<td>NO₅</td>
<td>0.41</td>
<td>0.23</td>
</tr>
</tbody>
</table>

**Typical Emissions Reduction in metric tons over the 30-year life of the transformer**

<table>
<thead>
<tr>
<th></th>
<th>Reduced generation only at coal-fired steam plants</th>
<th>Reduced generation only at distillate oil combustion turbine plants</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>63756304,9</td>
<td>49866116</td>
</tr>
<tr>
<td>SO₅</td>
<td>1275126,1</td>
<td>54918,63</td>
</tr>
<tr>
<td>NO₅</td>
<td>339481,624</td>
<td>252625,698</td>
</tr>
</tbody>
</table>

(50,000,000 transformers)(6.43 W)(8760 hours/year)(30 years) = 84,490,200,000 kWh.

(84,490,200,000 kwh)(9800 BTU/kwh) = 828,003,960 MBTU
Present worth analysis

Transformer life

Time

\( P = \frac{(1+i)^n - 1}{i(1+i)^n} A \)

\( i = 10 \text{ percent} \)

TAELC = \((6.43) \times (8760 \text{ hours/years}) \times ($0.627/\text{kW} \cdot \text{h})\)

= \$34.92 \text{ (Mexican pesos)} = \$3.79 \text{ per year}
VI. Conclusions

- Reduction of losses in three key elements of transformers.
- Extensive measurements of the load-loss test and no-load test were carried out on the test transformers.
- Tank losses were reduced 90 W using electromagnetics shielding.
- Tanks losses were reduced 200 W using T plate of stainless steel in a pad-mounted transformer.
Conclusions

- Behaviour of no-load losses during the manufacturing of distribution transformer.
- Core losses were reduced when overlap distance were reduced from 2 cm to 1 cm.