Transformer Overloading and Assessment of Loss-of-Life for Liquid-Filled Transformers

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Presentation Outline

• Introduction and Motivations
• Remaining Transformer (Insulation) Life, Transformer Thermal Model, IEEE Loading Guides
• Modeling and Economic Evaluation
• Simulation and Results
• Conclusions
Transformer Type and Nameplate Rating

- **Oil-Filled Transformer**
  - <500 kVA (distribution, OA)
  - 500 kVA - 100 MVA (distribution power) (OA, OA/FA, OA/FA/FA)
  - >100 MVA (transmission power) (OA/FA/FA and OA/FA/FOA)

- **65°C average winding temperature rise**
  (thermally-upgraded paper insulation)

- **55°C average winding temperature rise**
  (not thermally-upgraded paper, *kraft*)

- **30/40/50/56 MVA @55° / 65° C TR (OA/FA/FA)**

@55°C TR
Issues and Considerations

• Thermal Model
  - Design Consideration (Losses & Cooling)
  - Temperature (Top & Bottom Oil, Winding Hottest-Spot Temp.)
  - Insulation Degradation
  - Estimation of Transformer Remaining Life from Its Insulation

• Economic Model
  - Total Owning Cost (TOC)
  - Revenue Requirement
  - Other Models!!
Thermal Model
• Design
• Temperature
• Insulation
• Life

Optimization
(Minimum Cost & Optimum Sizing)
• New Design
• Retrofit Design
  - Replace now
  - Replace later
  - Add a second transf.
  - ??

Economical Model
Revenue Requirement

Uncertainties & Probability
Approach
• Future load growth projection
• Ambient temp.
• Transformer Failure
Loading Guide Standards

• **IEEE Std. C57.91-1995 (USA)**
  - Clause 7 (Classical Model)
  - Annex G (Detailed Model)

• **IEC 354-1991 (EUROPE, CANADA and Others)**

• **IEEE & IEC Comparisons**
  IEC is somewhat similar to IEEE Clause 7
Transformer Failure Modes

• **Long-term Failure Mode**
  – Mechanical and chemical properties of insulation deterioration
  – Dielectric strength reduction (approx. 10% over the transformer life)

• **Short-term Failure Mode**
  – Bubble formation (gassing), temporally dielectric strength reduction (30% impulse strength reduction @ 180 °C)
• The Tensile Strength (Mechanical) of cellulose insulation is used as a criteria for loss-of-life estimation.

• Recently, the Degree of Polymerization (DP) (Chemical) has also become a popular measurement of insulation life.

• If a sample of insulation near hot spot location is made available, the remaining life of the transformer could be approximately predicted based on specific criteria.
Remaining Life by Tensile Strength Method

The normalized remaining life by tensile strength method based on 20% remaining tensile strength (RTS) as end-of-life criteria, created by least square method.

\[ \text{Remaining Life} = 1 + 0.633 \ln \left( \frac{\text{RTS}}{97.05} \right) \]
The normalized remaining life by DP method based on remaining DP of 200 as end-of-life criteria, created by least square method

\[
\text{Remaining Life} = 1 + 0.881 \ln \left( \frac{RDP}{622} \right)
\]
IEEE Std. C 57.91-1995, Per-Unit Life

- Per-Unit Life
  \[ L = 9.80 \times 10^{-18} e^{\frac{15,000}{T_{HS}+273}} \]

- Relative Aging Factor
  \[ F_{AA} = \frac{dL}{dt} = e^{\frac{39.164 - 15,000}{T_{HS}+273}} \]

- Equivalent Aging
  \[ F_{EQA} = \frac{1}{T} \int_{0}^{T} F_{AA} \, dt \]

- % Loss-of-Life
  \[ = \frac{F_{EQA} \times T}{Normal \, Insulation \, Life} \times 100 \]

- Normal Insulation Life (20-30 Yrs.)
- Hottest-Spot Temperature \((T_{HS})\)
Hottest-spot temperature = ambient temperature ($T_A$) + top oil rise over ambient ($\Delta T_{TO}$) + hot spot rise over top oil ($\Delta T_G$)
Thermal Model (IEEE Clause 7)

Steady-State Equations

\[ T_{HS} = T_A + \Delta T_{TO} + \Delta T_G \]

\[ \Delta T_{TO} = \Delta T_{TOR} \left( \frac{K^2 R + 1}{R + 1} \right)^n \]

\[ \Delta T_G = \Delta T_{GR} \cdot \left( K^2 \right)^m \]

K = Per-Unit Loading (Actual Load/Rated (max) Load)

R = Loss Ratio (Load Loss @ Rated Load/No-Load Loss)

Exponent "n" and "m" depends on “Cooling”
Thermal Model (IEEE Clause 7)

Transient Equations

Oil

\[ \tau_{TO} \frac{d\Delta T_{TO}}{dt} = -\Delta T_{TO} + \Delta T_{TO,u} \]

\[ \Delta T_{TO,u} = \Delta T_{TOR} \cdot \left( \frac{K^2 R + 1}{R + 1} \right)^n \]

Winding

\[ \tau_{G} \frac{d\Delta T_{G}}{dt} = -\Delta T_{G} + \Delta T_{G,u} \]

\[ \Delta T_{G,u} = \Delta T_{GR} \cdot \left( K_u^2 \right)^m \]
Modified Transient Equations

\[
\tau_{TO} \frac{d\Delta T_{TO}}{dt} = -\Delta T_{TO} + \Delta T_{TO,u} + \Delta T_A
\]

\[
\Delta T_{TO}(s) = \frac{1}{1 + \tau_{TO}s} \cdot \Delta T_{TO,u}(s) + \frac{1}{1 + \tau_{TO}s} \cdot \Delta T_A(s)
\]
Thermal Block Diagram (IEEE Clause 7)
Aging Rate and % Loss-of-Life

- Loading cycle, Complex load growth
- Ambient temperature variation

\[
\text{Aging Rate} = e^{\left(\frac{15,000}{383} - \frac{15,000}{T_{HS} + 273}\right) \Delta t} \times 100
\]

\[
\%\text{loss of life} = e^{\left(\frac{15,000}{383} - \frac{15,000}{T_{HS} + 273}\right) \Delta t} \times 100
\]

\[
\frac{\text{Normal Life}}{\text{Life Normal}} = 100
\]
IEEE “Clause 7” & “Annex G” Comparisons

- **“Clause 7”** thermal model: Simple, Requires minimum information, uses **top-oil temperature**

- **“Annex G”** thermal model: More **complex**, Requires more information, Focus on duct oil temperature change, uses **bottom-oil temperature**
## “Clause 7” and “Annex G”

### Data Requirements

<table>
<thead>
<tr>
<th>IEEE Classical Model (Clause 7)</th>
<th>IEEE Detailed Model (Annex G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Top oil temperature rise at rated load</td>
<td>1. Top oil temperature rise at rated load</td>
</tr>
<tr>
<td>2. Hot spot temperature rise over top oil at rated load</td>
<td>2. Hot spot temperature rise at rated load</td>
</tr>
<tr>
<td>3. Loss ratio at rated load</td>
<td>3. Average winding temperature rise at rated load</td>
</tr>
<tr>
<td>4. Winding time constant</td>
<td>4. Bottom oil temperature rise at rated load</td>
</tr>
<tr>
<td>5. Oil time constant or</td>
<td>5. Losses data from test report</td>
</tr>
<tr>
<td>6. Type of cooling system</td>
<td>6. Weight of Core &amp; coil</td>
</tr>
<tr>
<td></td>
<td>7. Weight of tank &amp; fittings</td>
</tr>
<tr>
<td></td>
<td>8. Gallons of fluid</td>
</tr>
<tr>
<td></td>
<td>9. Type of cooling system</td>
</tr>
<tr>
<td></td>
<td>10. Type of cooling fluid</td>
</tr>
<tr>
<td></td>
<td>11. Type of winding material</td>
</tr>
<tr>
<td></td>
<td>12. Winding time constant</td>
</tr>
<tr>
<td></td>
<td>13. Location of hot spot</td>
</tr>
<tr>
<td></td>
<td>14. Per unit eddy current losses at hot spot location</td>
</tr>
</tbody>
</table>
IEEE Annex G & Clause 7 Thermal Model (Step Load Response)
Economic Evaluation
(Total Owning Cost)

Buying a New Transformer
Simplified Practice,

$$\text{TOC} = \text{IPP} + A \times \text{NLL} + B \times \text{LL}$$

Owner Specifies:
- Size (MVA)
- A & B Factors

Manufacturer Specifies:
- Initial purchase price (IPP)
- Losses (Winding & Core)
Economic Evaluation
(Revenue Requirement)

Revenue Requirement

• Daily load curves
• Daily ambient temp. variations
• Overloading & end-of-life
• Accurate energy loss
• Transformer replacement
• Refined & flexible method
• Detailed economic analysis

Applicable for
Investor Owned Utilities (IOU)
OPTIMIZATION

- NEW DESIGN
- RETROFIT APPLICATIONS
Optimization
(New Procurement)

- Daily load curve, Complex load growth
- Ambient temperature variation
- Economic data
  - discount rate, tax,
  - energy cost, etc.

Transformer Data → Thermal Model

Thermal Model → Life Expectancy

Life Expectancy → Economic Model

Economic Model → TOC
Optimization
(Retrofit Design)

Existing system

Estimate Remaining Life

Historical load and ambient temp. data

Present load
Load growth
Load shape
Ambient temp.
Economic data etc.

Replace with new transformer now

Overload existing transf. and replace with new one later

Add a 2nd transformer
Complete Method Block Diagram

Probability Tree Structure

<table>
<thead>
<tr>
<th>Path</th>
<th>Levelized Revenue Requirement</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$134,000</td>
<td>0.0016</td>
</tr>
<tr>
<td>81</td>
<td>$101,000</td>
<td>0.0016</td>
</tr>
</tbody>
</table>

Transformer Thermal Model

Economic Data
- Energy and Demand Charge Escalation Rate

Historical Data
- Ambient Temperature and Load Profiles
- Estimated Remaining Life

New Transformer Sizing Criteria
- End-of-Life

Transformer Data Size, Losses, Cost
- Thermal Data, Electrical Losses

Cost of Transformer
Cost of Losses

Equivalent Levelized Revenue Requirement (ERR)

Utility's Financial Model
- Debt Ratio
- Equity Return
- Borrowed Money Rate
- Tax Rate
- Depreciation Method
- Book Life

Random Failure Model
SIMULATION CASE STUDIES AND RESULT

- Case #1 - New Design
- Case #2 - Retrofit Applications
Case #1: New Design

Example Data

• Buy new transformer for a new project
• Initial peak load = 20 MVA
• Load growth in first 4 years (Probability)
  - High growth = 2.00%
  - Moderate growth = 1.75%
  - Low growth = 1.00%
• Load growth after the 4th year is 2.00%
Case #2: Retrofit Design

Example Data

• Existing transformer rating = 18 MVA
• In service for 25 years
• Estimated remaining life = 0.25 pu.
• Initial peak load = 20 MVA
• Load growth in first 4 year (Probability)
  - High growth = 2.00%
  - Moderate growth = 1.75%
  - Low growth = 1.00%
• Load growth after 4th year is 2.00%
• Replace with new unit now or continue overload ..and replace later?
Windows Based Computer Program

- Graphic interface, Load, Save, Print, and Copy
- Transient Loading Analysis (Daily load)
- Life Cycle Study (with load growth from table)
- Optimize Transformer Size
- Delay Replacement or Replace now Analysis
Screen Shot (1), Main Menu
### IEEE Annex G Input

#### Test Data

<table>
<thead>
<tr>
<th>Description</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>kVA Base for Testing</td>
<td>28000</td>
<td>kVA</td>
</tr>
<tr>
<td>Winding Temperature</td>
<td>75.0</td>
<td>C</td>
</tr>
<tr>
<td>I^2R loss</td>
<td>51690</td>
<td>watts</td>
</tr>
<tr>
<td>Winding Eddy Losses</td>
<td>0</td>
<td>watts</td>
</tr>
<tr>
<td>Stray Losses</td>
<td>21078</td>
<td>watts</td>
</tr>
<tr>
<td>Core Losses</td>
<td>36986</td>
<td>watts</td>
</tr>
</tbody>
</table>

#### Losses at one per unit loading

<table>
<thead>
<tr>
<th>Description</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Losses</td>
<td>297726</td>
<td>watts</td>
</tr>
</tbody>
</table>

Update

Exit
Screen Shot (3), Load Profile Input

24hrs Load Profile Editor

24 hrs Load and Ambient Temperature Profile

Note: To delete a row and the following rows, enter "0" or BLANK in Time column and press Update button.
Screen Shot (4), Load Growth Input
Screen Shot (5), Temperatures Plot

Temperature Profile Plots (IEEE Annex G Thermal Model)

- Hot spot
- Top oil
- Winding
- Bottom oil
- Ambient
- Loading

Time (hr) vs Temperature (°C) vs Loading (Per unit)
Screen Shot (6), Life Cycle Charts

- Loss of Transformer Life (in years)
  - Annual LOF
  - Acc. LOF

- Remaining Degree of Polymerization (DP)
  - Remain DP
  - Acc. Loss of Life (yrs)

- Remaining Tensile Strength
  - Remain TS
  - Acc. LOF

- Hot Spot and Top Oil Temperature
  - Hot Spot
  - Top Oil
Screen Shot (8), Economic Data Input

[Image of a financial data input interface]

- Minimum Transformer Size: 20.0 MVA
- Maximum Transformer Size: 40.0 MVA
- Load Growth Rate after 4th year: 2.00%
- Return on Equity Rate: 16.00%
- Borrowed Money Rate: 5.00%
- Debt Ratio: 0.50
- Tax Rate: 50.00%
- Market Value Rate: 10.00%
- Inflation Rate: 0.00%
- Book Life: 30 years

- Energy Price: 0.035 $/kwh
- Energy Escalation Rate: 2.00%
- Demand Charge: 120 $/kw
- Demand Charge Escalation Rate: 2.00%
- Peak Responsibility Factor: 0.80
- Random Failure Rate: 0.50%

- Existing Transformer Size: 18.00 MVA
- Years in Service: 25 years
- Remaining Life: 0.25 per unit
- Transformer Price: 340000 $
- Market Value Rate: 10.00%
Conclusions

• Developed an Optimization Model for the “Best Utilization” of a transformer:
  – Transformer replacement strategy (retrofit design)
  – Optimum transformer sizing (new design)

• Computer program is written to facilitate long and complex calculations

• Windows based computer program

• Asset management tools
Future Work

• New programming is required for faster optimization computation

• The different depreciation method (economic model) shall be explored

• Loss-of-life and hottest-spot calculation shall be updated when more real data is made available

• Other financial model shall be explored

• Sensitivity analysis on Loss Ratio (R)
Now publicly available on the PSERC Website

PSERC Project Report:
Transformer Overloading and Assessment of Loss-of-Life for Liquid-Filled Transformers

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