Transformer Thermal Modeling

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Background

- EPRI recently completed a study to assess the effects of MHD-EMP (E3) on the U.S. Transformer Fleet.
- The tools and assessment procedure used in the study can be leveraged in GMD assessments.
  - Time-domain transformer model
  - Thermal model parameters
  - Assessment criteria (temperature limits)
Time-domain Thermal Model

Transformer Thermal Model

Electrical Response

Thermal Response

GIC

Hotspot Temperature Rise

Total Hotspot Temperature

Top Oil Temperature

Transformer Thermal Model (Impulse Response)

\[ X(z) \rightarrow H(z) \rightarrow Y(z) \]

Hotspot Temperature Rise

\[ GIC \]
Transformer Thermal Model

- Derivation of time-domain thermal model

**Step Response (time domain)**

\[ \Delta \theta_{HS}(t) = \Delta \theta_{SS} \left( 1 - e^{-\frac{t}{\tau}} \right) \]

**Unit Step Response (time domain)**

\[ g(t) = \frac{\Delta \theta_{SS}}{i_{dc}} \left( 1 - e^{-\frac{t}{\tau}} \right) \]

**Impulse Response (time domain)**

\[ h(t) = \frac{dg}{dt} = \frac{K}{\tau} e^{-\frac{t}{\tau}} \]

\[ K = \frac{\Delta \theta_{SS}}{i_{dc}} \]
Transformer Thermal Model

Impulse Response (time domain)

\[ h(t) = \frac{dg}{dt} = Ke^{-\frac{t}{\tau}} \]

\[ K = \Delta \theta_{ss}/i_{dc} \]

\[ H(s) = Ke^{\frac{1}{1+\tau s}} \]

Impulse Response (S domain)

\[ H(z) = K \left( \frac{1}{1+\tau z^{-1}} \right) \]

\[ s = \frac{2}{\Delta t} \left( 1 - z^{-1} \right) \]

\[ \frac{1 + z^{-1}}{1 + \frac{2\tau}{\Delta t} + \left( 1 - \frac{2\tau}{\Delta t} \right) z^{-1}} \]

Impulse Response (Z domain)

\[ h(t) = \frac{dg}{dt} = Ke^{-\frac{t}{\tau}} \]

\[ K = \Delta \theta_{ss}/i_{dc} \]

\[ H(z) = K \left( \frac{1}{1+\tau z^{-1}} \right) \]

asymptotic behavior

\[ y(k+1) = \left( \frac{K(k)}{1+\frac{2\tau}{\Delta t}} \right) (x(k+1) + x(k)) - \left( \frac{1 - \frac{2\tau}{\Delta t}}{1 + \frac{2\tau}{\Delta t}} \right) y(k) \]

thermal time constant

Effective GIC (current and previous time step)

hotspot rise current time step

hotspot rise previous time step

Total Hotspot Temperature

\[ THS(k+1) = \theta_{TO} + y(k+1) \]
# Transformer Thermal Models

- A total of 5 models were used in the study.

<table>
<thead>
<tr>
<th>Model</th>
<th>Model Type</th>
<th>Transformer Type</th>
<th>Thermal Time Constants (Seconds)</th>
<th>Transformer Details</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Heating</td>
<td>Cooling</td>
</tr>
<tr>
<td>A</td>
<td>Structural Part</td>
<td>Auto w/ tertiary</td>
<td>600</td>
<td>650</td>
</tr>
<tr>
<td>B</td>
<td>Structural Part</td>
<td>Conv.</td>
<td>780</td>
<td>780</td>
</tr>
<tr>
<td>C</td>
<td>Structural Part</td>
<td>Three-winding Conv.</td>
<td>800</td>
<td>500</td>
</tr>
<tr>
<td>D</td>
<td>Winding</td>
<td>Conv.</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>E</td>
<td>Winding</td>
<td>GSU</td>
<td>150</td>
<td>150</td>
</tr>
</tbody>
</table>
Transformer Model A (Structural Part)

- Single Phase 230kV:115kV 240 MVA Autotransformer
- Factory test and FEM simulation results were evaluated to determine the basis of the model.

Factory Test (Weak Source)

FEM Model (Strong Source)
Largest Simulated Temperature

~100°C

~130°C
Transformer Model A (Structural Part)

- To be conservative, the model for Transformer A was based on the FEM simulation results.

Model Validation

Hotspot temperature rise corresponding to various dc current levels

Heating: \( \tau_1 = 600 \) seconds  
Cooling: \( \tau_2 = 650 \) seconds
Transformer Model B (Structural Part)

- Single-phase 500kV:16.5kV 400 MVA conventional transformer

Model Validation

Hotspot temperature rise corresponding to dc current level of 5 Amps/phase

Heating: \( \tau_1 = 780 \) seconds
Cooling: \( \tau_2 = 780 \) seconds

Transformer Model C (Structural Part)

- 3-Phase 410 kV:120kV:21 kV GY-GY-D 400 MVA conventional transformer\(^1\)
- Model was based on the highest recorded hotspot temperature observed during the field test.

Transformer Model C (Structural Part)

Model Validation

Hotspot temperature rise corresponding to various dc current levels

Heating: $\tau_1 = 800$ seconds
Cooling: $\tau_2 = 500$ seconds
Transformer Model D (Winding)

- Single-phase 750 MVA 345kV:24.5kV transformer (winding)\(^1\)

Model Validation

Hotspot temperature rise corresponding to dc current of 60 Amps/phase

Heating: \(\tau_1 = 150\) seconds
Cooling: \(\tau_2 = 150\) seconds

Transformer Model E (Winding)

- Single-phase 1299 MVA 418.8kV:20.5kV GSU (Winding)

Model Validation

Hotspot temperature rise corresponding to dc current of 60 Amps/phase

Heating: $\tau_1 = 150$ seconds

Cooling: $\tau_2 = 150$ seconds

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Example Results

- Benchmark Waveform (GICpeak = 75 Amps/phase)
Large Scale Assessments

- Things to consider when performing large-scale, “planning-level” assessments
  - Initial temperature of structural parts and windings
  - Magnitude and duration of GIC are important → time-domain models
  - Transformer condition: temperature limits in IEEE C57.163 assume transformers are in new condition
  - Exceeding temperature limits ≠ transformer failure
  - Bubble formation is not instantaneous and does not guarantee failure (temperature limits are very conservative)

- Temperature limits used in the EPRI study were based on Condition-Based GIC Susceptibility Category:
  - PTX Condition Code (based on trends of dissolved gases)
  - Transformer age (proxy for moisture content)
  - Effect of transformer design is accurately accounted for in the thermal models
Assessment Criteria

Condition-based GIC Susceptibility Categories

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition-Based GIC Susceptibility Category</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I</td>
</tr>
<tr>
<td>Age</td>
<td>0–25</td>
</tr>
<tr>
<td>Power Transformer Expert (PTX) software</td>
<td></td>
</tr>
<tr>
<td>Abnormal Condition Code</td>
<td>1</td>
</tr>
</tbody>
</table>

Conservative Temperature Limits

<table>
<thead>
<tr>
<th>Condition-based GIC Susceptibility Category</th>
<th>Hotspot Temperature Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Structural Parts (°C)</td>
</tr>
<tr>
<td>I</td>
<td>180</td>
</tr>
<tr>
<td>II</td>
<td>160</td>
</tr>
<tr>
<td>III</td>
<td>140</td>
</tr>
</tbody>
</table>

For comparison, IEEE C57.163 limits are 200°C for structural parts and 180°C cellulose insulation (windings).
Example Results

- Benchmark Waveform (GICpeak = 75 Amps/phase)
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