Power Transformer Diagnostics: Novel Techniques and their Application

Charles Sweetser
Technical Service Manager
Transformers
Topics of Discussion

- Introduction to Power Transformers
- Life Expectancy
- Failure Modes
- Diagnostic Characteristics
- Diagnostic Measurements
- Standard Measurements
- Advanced Measurements
- SFRA - Sweep Frequency Response Analysis
- DFR - Dielectric Frequency Response
Transformer Considerations

- Transformer Types and Classifications
- Transformer Configurations
- Vector Groups
- Oil Preservation Systems
- Insulating Materials and Fluids
- Construction Forms
- Core Steel
- Ratings
- Cooling Schemes
- Tap Changers (OLTC, DETC)
- Bushings
- Surge Arresters
Transformer Types and Classifications

- Distribution
- Power
- Rectifier
- Arc-Furnace
- Network
- Regulating (Voltage Regulators)
- Phase Shifting
- Reactors*
Vector Groups

DELTA

H2

H1

H3

WYE-STAR

X2

X0

X3

AUTO

H0 X0

H1

H3

ZIG-ZAG

X1

X0

X3

SCOTT-T

H2

T1

X2

T2

X0

H3

X3

H1
Winding Types

1. Disk Winding
2. Pancake Winding
3. Helical Winding
4. Cylindrical or Layer Winding
Construction Forms

Core Form
- Concentric
- Less Iron
- More CU

Shell Form
- Interleaved
- More Iron
- Less CU
Life Expectancy

• 180,000 hrs or 20.55 years
• 110 °C Hottest Spot for 65 °C Temp Rise insulation
• Degree of Polymerization (200 -1200 DP)
• 1200 DP - New Paper
• 200 DP at 150,000 hrs (end of life)

➢ Heat
➢ Moisture
➢ Oxygen
Failure Modes
Failure Modes
Core Failure Modes

- Over-Heating
- Bulk Movement
- Multiple Core Grounding
- Lamination Gaps
- Shorted Laminations
- Ungrounded Core
Oil Analysis – DGA and Oil Screen

- Hydrogen (H₂)
- Methane (CH₄)
- Ethane (C₂H₆)
- Ethylene (C₂H₄)
- Acetylene (C₂H₂)
- Carbon Monoxide (CO)
- Carbon Dioxide (CO₂)
- Oxygen (O₂)
- Nitrogen (N₂)

- Rate of Gas Generation
- Partial Discharge
- Arcing
- Electrical Heating
- Metal Heating
- Decomposition of Paper
Oil Analysis – DGA and Oil Screen

- Dielectric Breakdown
- IFT
- Color
- Acidity
- Power Factor
- Moisture
- Specific Gravity
- Viscosity

- Degree of Polymerization DP (Paper)
- Furans (Oil)
# Transformer Tests

<table>
<thead>
<tr>
<th>Dielectric</th>
<th>Thermal</th>
<th>Mechanical</th>
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<tbody>
<tr>
<td>DGA</td>
<td>DGA</td>
<td>SFRA</td>
</tr>
<tr>
<td>Oil Screen</td>
<td>Oil Screen</td>
<td>Leakage Reactance</td>
</tr>
<tr>
<td>PF/TD CAP</td>
<td>IR</td>
<td>PF/TD CAP</td>
</tr>
<tr>
<td>Exciting Ima</td>
<td>DC Winding RES</td>
<td>Exciting Ima</td>
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<tr>
<td>Turns Ratio Tests</td>
<td></td>
<td>DC Winding RES</td>
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<tr>
<td>DFR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulation Resistance</td>
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</table>
Transformer Test Protocol

1. Overall Power Factor and Capacitance *(Tip-Up, Variable Freq)*
2. Bushings (C1, C2, Energized Collar) *(Tip-Up, Variable Freq)*
3. Exciting Current
4. Surge Arresters
5. Insulating Fluids
6. Leakage Reactance *(Frequency Response of Stray Losses)*
7. Turns Ratio Test
8. DC Winding Resistance *(Slope, Ripple)*
9. Insulation Resistance
Overall PF and Capacitance
Bushings

- Test Taps kV < 72 kV (C1 and C2)
- Potential Taps kV > 72 kV (C1 and C2)
- No Tap – Use Energized Collar at 10 kV
## Bushings

### Bushings - NAMEPLATE

<table>
<thead>
<tr>
<th>Bushing</th>
<th>Manufact.</th>
<th>Model/Type</th>
<th>Year</th>
<th>Serial Number</th>
<th>Catalog Number</th>
<th>Drawing Number</th>
<th>BIL kV</th>
<th>kV Rating</th>
<th>A Rating</th>
<th>C1 PF[%]</th>
<th>C1 Cap (pF)</th>
<th>C2 PF[%]</th>
<th>C2 Cap (pF)</th>
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<td>O+C</td>
<td>1993</td>
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<td>350</td>
<td>44.00</td>
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### Bushings - C1

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<th>Ref @ 10 kV</th>
<th>Bushing</th>
<th>Energize</th>
<th>Ground</th>
<th>Guard</th>
<th>UST</th>
<th>Test kV</th>
<th>I mA</th>
<th>Cap pF</th>
<th>Watt Loss</th>
<th>PF [%] Measured</th>
<th>PF [%] Corrected</th>
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<th>Mode</th>
<th>Insulation Condition</th>
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<td>Conductor</td>
<td>-</td>
<td>-</td>
<td>Tap</td>
<td>10.022</td>
<td>0.891</td>
<td>236.25</td>
<td>0.020</td>
<td>0.22</td>
<td>0.00</td>
<td>1.00</td>
<td>UST A</td>
<td>PASS</td>
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<tr>
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Surge Arresters

<table>
<thead>
<tr>
<th>Phase</th>
<th>Position</th>
<th>Energize</th>
<th>Ground</th>
<th>Guard</th>
<th>UST</th>
<th>Mode</th>
<th>Test kV</th>
<th>I mA</th>
<th>Watt Loss</th>
<th>Arrest Rating</th>
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<tbody>
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<td>MID 1/2</td>
<td>BOT 3</td>
<td>-</td>
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<td>-</td>
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<td>UST</td>
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<td>MID 2/3</td>
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<td>0.304</td>
<td>0.049</td>
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<td>MID 1/2</td>
<td>BOT 3</td>
<td>-</td>
<td>TOP 1</td>
<td>UST</td>
<td>10.000</td>
<td>0.257</td>
<td>0.051</td>
<td>PASS</td>
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<tr>
<td>H - C</td>
<td>2</td>
<td>MID 2/3</td>
<td>BOT 3</td>
<td>-</td>
<td>MID 1/2</td>
<td>UST</td>
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<td>0.158</td>
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<tr>
<td>H - C</td>
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<td>MID 1/2</td>
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<td>9.999</td>
<td>0.365</td>
<td>0.047</td>
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</table>

- Analyzed on the basis of Watts
Advanced Diagnostics

1. Advanced Power Factor
   Tip-Up: Voids in Insulation
   Variable Frequency (15 Hz to 400 Hz): Moisture and Aging

2. Advanced DC Winding Resistance
   Ripple and Slope

3. Advanced Leakage Reactance
   FRSL (Frequency Response Stray Losses)

4. SFRA - Sweep Frequency Response Analysis

5. DFR - Dielectric Frequency Response
Variable Frequency Losses

<table>
<thead>
<tr>
<th>Serial</th>
<th>Parallel</th>
<th>Sum</th>
</tr>
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<tbody>
<tr>
<td>0.00E+00</td>
<td>5.00E-04</td>
<td>1.00E-03</td>
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<tr>
<td>1.50E-03</td>
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</tbody>
</table>

Graph:

- Serial (blue diamond line)
- Parallel (pink square line)
- Sum (yellow triangle line)

Graph axes:
- X-axis: 0 to 400
- Y-axis: 0.00E+00 to 2.50E-03

Diagram:
- H⁺
- O²⁻
- E

Graph legend:
- Serial
- Parallel
- Sum
Normal Power Factor
Power Factor Influenced by Moisture

The graph shows the variation of power factor with frequency from 0.0 Hz to 450.0 Hz. Two lines are plotted: H(f) (blue) and HL(f) (red). The power factor decreases significantly with increasing frequency, especially at lower frequencies.
Slope and Ripple

![Graph showing slope and ripple analysis.](image)
Advanced DC Resistance - Slope
Advanced DC Resistance - Slope
Advanced DC Resistance - Ripple

![Graph showing advanced DC resistance - ripple](image)

- A UP
- A DOWN
- B UP
- B DOWN
- C UP
- C DOWN
FRSL - Good

![Graph showing frequency response with Ohm values for different frequencies.]
FRSL – Poor Result
Short-Circuit Between Parallel Strands

![Graph showing R(f) vs Frequency [Hz]]
Dielectric Frequency Response (DFR)

Power Factor in Frequency Domain

Voltage source | Guard | Main insulation | HV-winding | LV-winding | Current meter

Tank
Moisture in Transformers

1. Reduces Dielectric Strength

2. Promotes the Formation of Bubble

3. Ages Insulation with Heat and Oxygen
Moisture Terminology – Paper, Pressboard, and Oil

1. Water Content
   - Pressboard & Paper (percentage of total mass)
   - Oil (PPM)

2. Moisture Saturation – P,P,O (Relative, Humidity)
Moisture Fact in Transformers

1. If mass of oil equals paper-pressboard, then at equilibrium the water content is (2000:1)

2. In transformers there is 10X more oil mass than paper and pressboard, so the water content is (200:1)
Oil Ratio to Paper : Pressboard

Mass of the oil: 100,000 kg = 220,000 Lbs

Water content at 60 °C: 40 ppm

Mass of the water, dissolved in the oil: 4 kg = 8.8 Lbs

Mass of the solid insulation: 13,000 kg = 20,000 Lbs

Water content at 60 °C: 4 %

Mass of the water contained in the paper: 520 kg = 1200 Lbs
Karl Fischer Titration and Equilibrium Curves

- Curves are only valid for new oil and new paper, for aged oil/paper different curves are necessary.
- Balance between water content in the paper and in oil needs constant temperatures over a long period.
- Only average measurement.
## Water Content Recommendations

<table>
<thead>
<tr>
<th>Category</th>
<th>Moisture content in %</th>
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<tbody>
<tr>
<td>Dry below</td>
<td>2.2</td>
</tr>
<tr>
<td>Moderately wet</td>
<td>2.2-3.7</td>
</tr>
<tr>
<td>Wet</td>
<td>3.7-4.8</td>
</tr>
<tr>
<td>Extremely wet above</td>
<td>4.8</td>
</tr>
</tbody>
</table>
Measurement Characteristics

\[ I(\omega) = j \omega C_0 \left\{ \varepsilon(\infty) + \chi'(\omega) - j \left[ \frac{\sigma_0}{\varepsilon_0 \omega} + \chi''(\omega) \right] \right\} U(\omega) \]

\[ \tan \delta(\omega) = \frac{C''(\omega)}{C'(\omega)} = \frac{\varepsilon''(\omega)}{\varepsilon'(\omega)} = \frac{\frac{\sigma_0}{\varepsilon_0 \omega} + \chi''(\omega)}{\varepsilon(\infty) + \chi'(\omega)} \]

- Current in wide frequency range, e.g. 1 mHz – 1 kHz
- Display as dissipation factor or complex capacitance or complex permittivity

Interpretation
- Slope - oil conductivity
- Hump - insulation geometry
- Low frequencies
  - moisture and aging
  - long test duration
Measurement Examples

New, dry, cold: 1kHz - 0.1 mHz
Moderate: 1kHz - 1 mHz
Very aged: 1kHz - 10 mHz
3.1 % at 9 °C – Oil Sample Yielded 5.0%
What is SFRA?

- Powerful and sensitive tool to assess the mechanical and electrical integrity of power transformers active part

- Measurement of the transfer function over a wide frequency range
Diagnostic Category

- Dielectric
- Thermal
- “Mechanical”

- Use SFRA:
  1. Transportation
  2. Post Fault
Life Cycle

Manufacturer Workshop

- Quality Assuring
- After Short Circuit Test
- Failure Investigation

- Routine Measurement
- After Transients/Overcurrents
- Failure Investigation (DGA)

Delivery Port

- Transport Checking

Reception Port

- Transport Checking
The SFRA Measurement Principle

Input signal (sine wave of variable frequency)

Transformator

Output signal

Magnitude

Phase
Theoretical Background

Measurement cable

CMC

RMC12

RMC34

Complex RLC Network

Cables Grounding

\[ x(t) = X \sin \omega t \]

\[ y(t) = Y \sin(\omega t + \phi) \]

\[ TF = \frac{U_2(s)}{U_1(s)} = \frac{R_m}{R_m + Z_{\text{specimen}}} \]

\[ k = 20 \log_{10}\left( \frac{U_2}{U_1} \right) \]

\[ \phi = \tan^{-1}(\angle U_2 / \angle U_1) \]
Passive Components
RLC Characteristics

![RLC Circuit Diagram]

Amplitude [dB] vs. Frequency (Hz)

- L=200 mH
- L=2 mH
- L=20 H

Phase [°] vs. Frequency (Hz)

- C=1uF
- C=20nF
- C=1pF
Typical Results
Failure Modes

- Radial “Hoop Buckling” Deformation
- Axial Winding Elongation “Telescoping”
- Overall- Bulk & Localized Movement
- Winding Turn-to-Turn Short Circuit
- Open Circuited Winding
Radial Failure
Axial Failure
Conductor Tilting
Core Faults
Measurements Types

- Open Circuit - Exciting Ima
- Short Circuit - Leakage Reac
- Interwinding - CAP
- Transfer Voltage - TTR
HV and LV Open Circuit

**HV winding**

**LV winding**
Open Circuit Tests
Open Circuit vs. Short Circuit
Short Circuit Tests
Analysis Strategies

- Baseline
- Similar Unit
- Phase Comparison
FRA Industry Groups

- CIGRE WG A2.26 (Guide)
- DL 911/2004 (Standard)
- IEC 60076-18 (Draft)
- IEEE WG PC57.149 (Guide) D8
Standardization in the World

- PC57.149/D8
- IEC 60076-18
- WG A2.26
- DL 911/2004
- CHINA
Available Documents

Cigré Brochure 342

MECHANICAL-CONDITION ASSESSMENT
OF TRANSFORMER WINDINGS
USING FREQUENCY RESPONSE ANALYSIS (FRA)

Working Group A2.26

April 2008

DL 911/2004

The Electric Power Industry Standard of
People’s Republic of China

Frequency Response Analysis on Winding
Deformation of Power Transformers

Prepared by National Development and Reform Commission of People’s Republic of China
INTERNATIONAL ELECTROTECHNICAL COMMISSION

POWER TRANSFORMERS
Part 18: Measurement of Frequency Response

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The text of this standard is based on the following documents:

FDIS

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Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

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