Power transformer diagnostics and DC bias in transformers

Dennis Albert – A2 Power Transformers and Reactors
Webinar – 2024-06-26
Power Transformers

- Transformer Digital Twin
- Transformer Modelling
- State-of-the-Art Diagnostics
- Advances Diagnostics
State-of-the Art in Transformer Diagnostics
Diagnostics – Why?

### CIGRE WG A2.37: Transformer failure statistics

- 22,000 grid transformers
- 150,000 service years

Source: DEVELOPMENT AND RESULTS OF A WORLDWIDE TRANSFORMER RELIABILITY SURVEY” CIGRE SC A2 COLLOQUIUM 2015, Shanghai
Diagnostics – Why?
State-of-the-Art Diagnostics

- Bushings
- On-Load Tap Changer (OLTC)
- Core
- Windings
- Leads
- CTs
- (Liquid) Insulation
- CTs
State-of-the-Art Diagnostics

- **OFFLINE** tests: transformer de-energized
  - Conventional: turns ratio, winding resistance, short-circuit impedance
  - Capacitance & loss factor: C & dissipation/power factor (DF/PF)
  - Dielectric response: frequency domain spectroscopy (FDS) & PDC
  - Frequency response analysis: FRA
  - Partial Discharge (PD)
  - Dissolved Oil-in Gas Analysis (DGA)
  - Dynamic resistance measurement (DRM)
  - ...

- **ONLINE** tests: transformer in operation
  - temperature monitoring
  - Online-DGA
  - Partial Discharge
  - $\tan(\delta)/C$ on bushings
  - ...

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CIGRE Logo

For power system expertise
<table>
<thead>
<tr>
<th>Component</th>
<th>Detectable faults</th>
<th>Possible measurement methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bushings</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Partial breakdown between capacitive graded layers, cracks in resin-bonded insulation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aging and moisture ingress</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Open or compromised measuring tap connection</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Partial discharges in insulation</td>
<td></td>
</tr>
<tr>
<td>CTS</td>
<td>Current ratio or phase error considering burden, excessive residual magnetism, non-compliance to relevant IEEE or IEC standard</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Burden-dependent current ratio and phase displacement</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shorted turns</td>
<td></td>
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<tr>
<td>Leads</td>
<td>Contact problems</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mechanical deformation</td>
<td></td>
</tr>
<tr>
<td>Tap changer</td>
<td>Contact problems in tap selector and at diverter switch</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Open circuit, shorted turns, or high resistance connections in the OLTC preventative autotransformer</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Contact problems in the DETC</td>
<td></td>
</tr>
<tr>
<td>Insulation</td>
<td>Moisture in solid insulation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aging, moisture, contamination of insulation fluids</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Partial discharges</td>
<td></td>
</tr>
<tr>
<td>Windings</td>
<td>Short-circuits between windings or between turns</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Strand-to-strand short-circuits</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Open circuits in parallel strands</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Short-circuit to ground</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mechanical deformation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Contact problems, open circuits</td>
<td></td>
</tr>
<tr>
<td>Core</td>
<td>Mechanical deformation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Floating core ground</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shorted core laminates</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Residual magnetism</td>
<td></td>
</tr>
</tbody>
</table>

State-of-the-Art Diagnostics
State-of-the-Art Diagnostics | Excitation Current

- no-load current measurement with low voltage during turns ratio test or with 10 kV
- sensitive to remanence
- Detect: shorted core laminations, shorted turns, OLTC issues
State-of-the-Art Diagnostics | Excitation Current

Example

- Vector group: Yzn5
- TTR test passed

![Fingerprint 3-phase TTR 120 VAC](image1)

![Comparison of fingerprint with shorted turns](image2)

<table>
<thead>
<tr>
<th>Phase</th>
<th>Exciting Current [mA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>12.598 mA</td>
</tr>
<tr>
<td>B</td>
<td>9.169 mA</td>
</tr>
<tr>
<td>C</td>
<td>14.445 mA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Phase</th>
<th>Exciting Current [mA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>158.756 mA</td>
</tr>
<tr>
<td>B</td>
<td>146.202 mA</td>
</tr>
<tr>
<td>C</td>
<td>304.773 mA</td>
</tr>
</tbody>
</table>
State-of-the-Art Diagnostics | Leakage Impedance

- leakage reactance or short-circuit test between two windings
- no coupling between the windings via core, only via air/oil gap
  ✓ assessment of the air/oil gap channel

![Diagram of a transformer with leakage impedance components](image)

Winding deformation (buckling) causing a change of leakage flux
State-of-the-Art Diagnostics | Leakage Reactance
Case Study

- 30 MVA YNyn6, 115 kV/34.5 kV transformer
- The transformer tripped out of service on a differential relay
  - DGA: hot spot involving cellulose

### Three-phase test

<table>
<thead>
<tr>
<th></th>
<th>I AC (A)</th>
<th>V AC (V)</th>
<th>Zk (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase A</td>
<td>1.100</td>
<td>67</td>
<td>61.04</td>
</tr>
<tr>
<td>Phase B</td>
<td>1.097</td>
<td>66</td>
<td>60.75</td>
</tr>
<tr>
<td>Phase C</td>
<td>1.115</td>
<td>64</td>
<td>57.77</td>
</tr>
</tbody>
</table>

Relative $Z_k$ = 6.79%

Nameplate $Z_k$ = 6.60%

Deviation = -2.85%

### Per-phase test

<table>
<thead>
<tr>
<th></th>
<th>I AC (A)</th>
<th>V AC (V)</th>
<th>Zk (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase A</td>
<td>1.00</td>
<td>29.1</td>
<td>29.11</td>
</tr>
<tr>
<td>Phase B</td>
<td>1.00</td>
<td>31.9</td>
<td>31.89</td>
</tr>
<tr>
<td>Phase C</td>
<td>0.99</td>
<td>28.8</td>
<td>28.81</td>
</tr>
</tbody>
</table>

Max. Deviation = ~10%
State-of-the-Art Diagnostics | Leakage Reactance

Case Study

Bulge on LV winding of Phase B
State-of-the-Art Diagnostics | Demagnetization

- several measurements/tests are sensitive to remanence
- Remanence increase inrush and mechanical force on reinforcements
- Methods for demagnetization:
  - heat up above Curie temperature
  - strong vibration force on the core
  - allying an opposing magnetic field

Grain oriented electrical steel sample placed inside an electromagnet. Magneto-optical images recorded with the CMOS-MagView; Source: Matesy GmbH
State-of-the-Art Diagnostics | Demagnetization
Power Transformers

- Transformer Digital Twin
- State-of-the-Art Diagnostics
- Transformer Modelling
- Advances Diagnostics
Advanced Diagnostics | Frequency Response of Stray Losses

- **Frequency Response of Stray Losses**
- frequency weep: 15 Hz – 490 Hz
- carried out per phase

- Shorted strands result in higher losses, particularly visible at higher frequencies
- Eddy losses are frequency dependent
- Such faults are not detectable by transformer ratio or winding resistance tests
Advanced Diagnostics | Frequency Response of Stray Losses

- Used to detect shorted parallel strands of continuously transposed conductors (CTC)
- CTC’s are used in transformers with higher power rating to reduce losses caused by skin effect and eddy currents
Assessment of FRSL measurements:

- Phase-to-phase comparison* or fingerprint
- $\Delta R_{\text{max}} = 15\%$
- $\Delta L_{\text{max}} = 2.5\%$

* CIGRE TB455, Guide for Transformer Maintenance, 2011
Advanced Diagnostics | Frequency Response of Stray Losses

- Case Study
  - 40 MVA Yd, 121 kV/12.85 kV transformer
  - Measurement triggered by gassing, indicating a hot spot
  - No other electrical standard test showed a fault

![Graph showing resistance vs. frequency for the 40-MVA transformer](image)
Advanced Diagnostics | Frequency Response Analysis

- **IFRA impulse FRA:**
  - derive frequency from a Fourier transformer of an impulse

- **SFRA sweep FRA**
  - use sinusoidal signal with variable frequency
Advanced Diagnostics | Frequency Response Analysis

Low pass

Band pass

High pass

Band stop
Advanced Diagnostics | Frequency Response Analysis

- frequency weep: 20 Hz – 2 MHz
- voltage amplitude: 10 V_{pp}
- 4 different tests
  - end-to-end open circuit
  - end-to-end short-circuit
  - end-to-end capacitive
  - end-to-end inductive
- detect mechanical deformations
- Fingerprint method
- Sister unit comparison & phase comparison can be used with caution
Advanced Diagnostics | Moisture Analysis

- **Moisture in transformers:**
  - reduced PD inception voltage
  - reduced breakdown voltage
  - bubble evolution from wet paper
  - Accelerated aging of cellulose due to depolymerization by hydrolysis

- more water in cellulose than in oil
  - temperature increase causes release of water from cellulose into oil
  - 150 MVA, 7 t cellulose, 70 t mineral oil, 20° C, 3%wt. → **210 kg water**
**Advanced Diagnostics | Moisture Analysis**

- **dielectric spectroscopy**
  - ✓ capacitance & \( \tan(\delta) \)
  - ✓ frequency range: 10 µHz – 5 kHz @ 200 \( V_{\text{peak}} \)

- **moisture analysis**
  - ✓ comparing measurement data with a database
  - ✓ model curve close to measurement curve with help of oil conductivity and geometry data

According to IEC 60422.
**Advanced Diagnostics | Moisture Analysis**

- **moisture analysis**
  - comparing measurement data with a database
  - model curve close to measurement curve with help of oil conductivity and geometry data

![Diagram showing moisture analysis process](image.png)
Advanced Diagnostics | Capacitance & Power Factor

- e.g. two windings create a capacitance together with the insulation
- capacitances can be measured from terminals (include bushings!)

![Diagram of capacitance measurement](image-url)
**Dissipation Factor & Power Factor**

- $\tan \delta = \frac{I_R}{I_C}$
- $\cos \phi = \frac{I_R}{I_{\text{test}}}$
# Advanced Diagnostics | Capacitance & Power Factor

<table>
<thead>
<tr>
<th>Capacitance</th>
<th>Windings</th>
<th>Transformer core</th>
<th>Dissipation / Power factor (DF/PF)</th>
<th>Insulation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>o Short circuit to ground</td>
<td>o Mechanical deformation</td>
<td>o Mechanical deformation</td>
<td>o Moisture in solid insulation</td>
</tr>
<tr>
<td></td>
<td>o Mechanical deformation</td>
<td>o Change of the geometry between winding</td>
<td>o Floating core to ground</td>
<td>o Ageing products, moisture, contamination of insulation fluids</td>
</tr>
<tr>
<td></td>
<td>o Displacement</td>
<td>o Change of the geometry between winding</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

[Image: CIGRE logo]
Advanced Diagnostics | Capacitance & Power Factor

Case Study: 220 kV Bushing stored outside

![Graph showing dissipation and power factor over different frequencies and time periods after removing from TR, 3 months and 6 months after removing]
Advanced Diagnostics | PD Measurement

- on dry-type transformers with cast-resin insulation are available exceeding 50 kV
- DF/PF has very limited use for dry-type transformers, due to the leakage currents on the insulation surface.
- Reliable diagnostic measurement so far: partial discharge (PD) measurement
- Induced voltage (IVPD) test at higher frequencies (mitigate saturation)
- Single-phase excitation with mobile test equipment
Advanced Diagnostics | PD Measurement

Measurement Setup

- Induced Voltage Test with Partial Discharge Measurement (IVPD)
  - ✔ factory: 3-phase
  - ✔ on-site: 1-phase
- Advantage of IVPD: stress turn-to-turn insulation
  - ✔ caution: not over stress line-to-ground insulation

\[1.05 \cdot U_R = 242 \text{ V}_{L-N}\]

23.57 kV_{L-N} | rated: 13.6 kV_{L-N}
**Advanced Diagnostics | PD Measurement**

**Measurement Setup**

- **Advantage of IVPD:** stress turn-to-turn insulation
  - **CAUTION:** not overstress line-to-ground insulation
  - **Best practice:** use other two coils as voltage dividers

\[ 1.3 \cdot U_R = 300 \, V_{L-N} \]

\[ 14.64 \, kV_{L-N} \mid \text{rated: } 13.6 \, kV_{L-N} \]

(Engstler et al. 2024)
Power Transformers

- Transformer Digital Twin
- State-of-the-Art Diagnostics
- Transformer Modelling
- Advances Diagnostics
Transformer Modelling | Motivation

- **Origin of DC in the power grid**
  - power electronics (e.g. HVDC, STATCOM, Inverters)
  - geomagnetically induced currents (GICs)
  - corrosion protection systems
  - DC-powered public transportation system

- **Effects of DC on transformers**
  - increased sound
  - increased losses → heating

- **Mitigation of DC**
  - consider DC during the design stage
  - DC blocker in the transformer neutral
  - DC flux compensation system
Transformer Modelling | Motivation

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  - consider DC during the design stage
  - DC blocker in the transformer neutral
  - DC flux compensation system
## Transformer Modelling | Model Overview (I)

<table>
<thead>
<tr>
<th>Types</th>
<th>Physical-based</th>
<th>Data-based</th>
<th>Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal</td>
<td></td>
<td>Machine Learning</td>
<td>physics-informed neural network (PINN)</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td></td>
<td>Rule-based Systems</td>
<td>proper orthogonal decomposition (POD) method with finite element (FE)</td>
</tr>
<tr>
<td>Mechanical</td>
<td></td>
<td>Evolutionary Algorithms</td>
<td></td>
</tr>
<tr>
<td>Dielectric</td>
<td></td>
<td>Knowledge Graphs</td>
<td></td>
</tr>
<tr>
<td>Sound</td>
<td></td>
<td>Fuzzy Logic</td>
<td>artificial neural network (ANN)</td>
</tr>
<tr>
<td>Multi-physical</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Usage

- **Internal/external (over-) voltages**
- **Network studies**
- **Design optimization**
- **Lifespan forecasting**
- **Maintenance** (condition-based, predictive, replacement planning)
- **Risk Assessment**
- **Load Forecasting**
- **Fault Diagnostic**
- **Condition Assessment**
- **Load Forecasting**
- **Increasing robustness**
## Transformer Modelling | Physical-based Models

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Frequency Range</th>
<th>Application</th>
<th>Required Information</th>
<th>Simulation Time &amp; Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEM</td>
<td>Design Study</td>
<td>Design data (high)</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>White Box</td>
<td>500-800 kHz</td>
<td>System interaction &amp; internal overvoltage's</td>
<td>Design data (medium)</td>
<td>High</td>
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<tr>
<td>Grey Box</td>
<td>DC-500 kHz</td>
<td>System interaction</td>
<td>Design data (low) &amp; Measurements</td>
<td>Small/High</td>
</tr>
<tr>
<td>Black Box</td>
<td>&lt; 2 MHz</td>
<td>System interaction</td>
<td>Measurements</td>
<td>Small</td>
</tr>
</tbody>
</table>

### Transient Phenomena

<table>
<thead>
<tr>
<th>Transient Phenomena</th>
<th>Slow</th>
<th>Switching</th>
<th>Fast</th>
<th>Very Fast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Range</td>
<td>DC – 1 kHz</td>
<td>50/60 Hz – 10 kHz</td>
<td>10 kHz – 1 MHz</td>
<td>100 kHz – 50 MHz</td>
</tr>
</tbody>
</table>
Transformer Modelling | Grey-Box Models

- **Model components**: only common components (inductor, resistor, capacitor, ideal transformer,...)
- **Model structure**: derived with the principle of duality between magnetic and electric circuits
Transformer Modelling | Model Structure
Transformer Modelling | DC Hysteresis Test

AC Saturation Test

DC Hysteresis Test
Transformer Modelling | Model Optimization

-30 -20 -10 0 10 20 30

current in A

-8
-6
-4
-2
0
2
4
6
8

in Vs

T3Sa DC Hys
T3Sa AC Sat

-0.5 0 0.5

-5
0
5
10

-3

-50
0
50

voltage in V

time in s

0 20 40 60 80 100 120

-15
-10
-5
0
5
10

15

50

current in A

0 20 40 60 80 100 120

-50
0
50

-15
-10
-5
0
5
10

15

voltage in V

time in s

-30 -20 -10 0 10 20 30

current in A

-8
-6
-4
-2
0
2
4
6
8

X 10^-3

-5
0
5
10

X 10^-3

-0.5 0 0.5

5

0

-5

T3Sa DC Hys
T3Sa AC Sat

cigre

For power system expertise
Transformer Modelling | Use-Case 50 kVA Transformer

<table>
<thead>
<tr>
<th></th>
<th>Calc.</th>
<th>Dev. in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>S in VA</td>
<td>650.8</td>
<td>0.01</td>
</tr>
<tr>
<td>P in W</td>
<td>165.7</td>
<td>-7.07</td>
</tr>
</tbody>
</table>
Transformer Modelling | Use-Case 786 MVA Transformer

<table>
<thead>
<tr>
<th></th>
<th>Calc.</th>
<th>Dev. in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$ in kVA</td>
<td>231.3</td>
<td>+24.8</td>
</tr>
<tr>
<td>$P$ in kW</td>
<td>186.5</td>
<td>+12.6</td>
</tr>
</tbody>
</table>
Transformer Modelling | Use-Case 786 kVA Transformer

Saturation Curve vs. Hysteresis Model
Power Transformers

- Transformer Digital Twin
- State-of-the-Art Diagnostics
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- Advances Diagnostics
Transformer Digital Twin

- **Definition**
  - virtual dynamic representation of a physical artefact or system
  - automized bidirectional data exchange between the digital twin and physical asset
  - twin entails data of all phases of the entire product lifecycle

- JGW A2/D2.65 – Evaluate state-of-the art
- VDE Working Group for Digital Twins in energy sector in general

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Credit: CIGRE WG A2/D2.65 Transformer Digital Twin
Transformer Digital Twin | Realization & Aspects

- **Sensors**: DGA, busing tap, vibration, partial discharge, voltage, current,...

- **Data Acquisition**: data integrity, store, pre-process, data quality,...

- **Communication Infrastructure**: robust, near real-time

- **Modelling, Simulation, Data Analytics**: validation, update models, algorithms

- **Visualization & User Interface**: comprehensive, charts, dashboard, alarms, actions
Transformer Digital Twin | Model Types

- Physics-based models
  - electromagnetic
  - mechanic
  - thermal
  - dielectric & degradation

- Data-driven models
  - artificial intelligence based for complex situations

- Hybrid models combining data-driven and physics-based models
Transformer Digital Twin | Applications & Bottle Necks

- Anomaly detection
- Diagnosis
- Prognosis
- Predictive maintenance

- Standardization of interfaces/data exchange
- Data quality validation

Credits: www.byjusfutureschool.com
Let’s sum up...

- **Diagnostics**
  - **Standard Tests:** Excitation, Leakage, Demagnetization
  - **Advance Tests:** FRSL, SFRA, Moisture, C/PF, IVPD

- **Transformer electromagnetic modelling**
  - Transformer no-load current calculation requires hysteresis models to accurately reproduce the (measured) line currents
  - Modelling approach inherently in cooperates uncertainties by the optimization of the hysteresis model parameters

- **Transformer Digital Twin**
  - Standardization required
  - Data validation and quality
Thanks for listening ;)

Dennis Albert | dennis.albert@omicronenergy.com
Webinar – 2024-06-26
Literature


(Engstler et al. 2024) Engstler, B., Engelen, C., Application Note: Diagnostic of MW Transformers, OMICRON electronics GmbH, 2024

(IEC 2018) IEC, 60076-11, Power Transformers Part 11: Dry-type transformers, 2018

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