Power transformer diagnostics and DC bias in transformers

Dennis Albert – A2 Power Transformers and Reactors

Webinar – 2024-06-26

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For power system expertise

Power Transformers

Transformer Digital Twin

State-of-the-Art Diagnostics

Transformer Modelling

Advances Diagnostics

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State-of-the Art in Transformer Diagnostics

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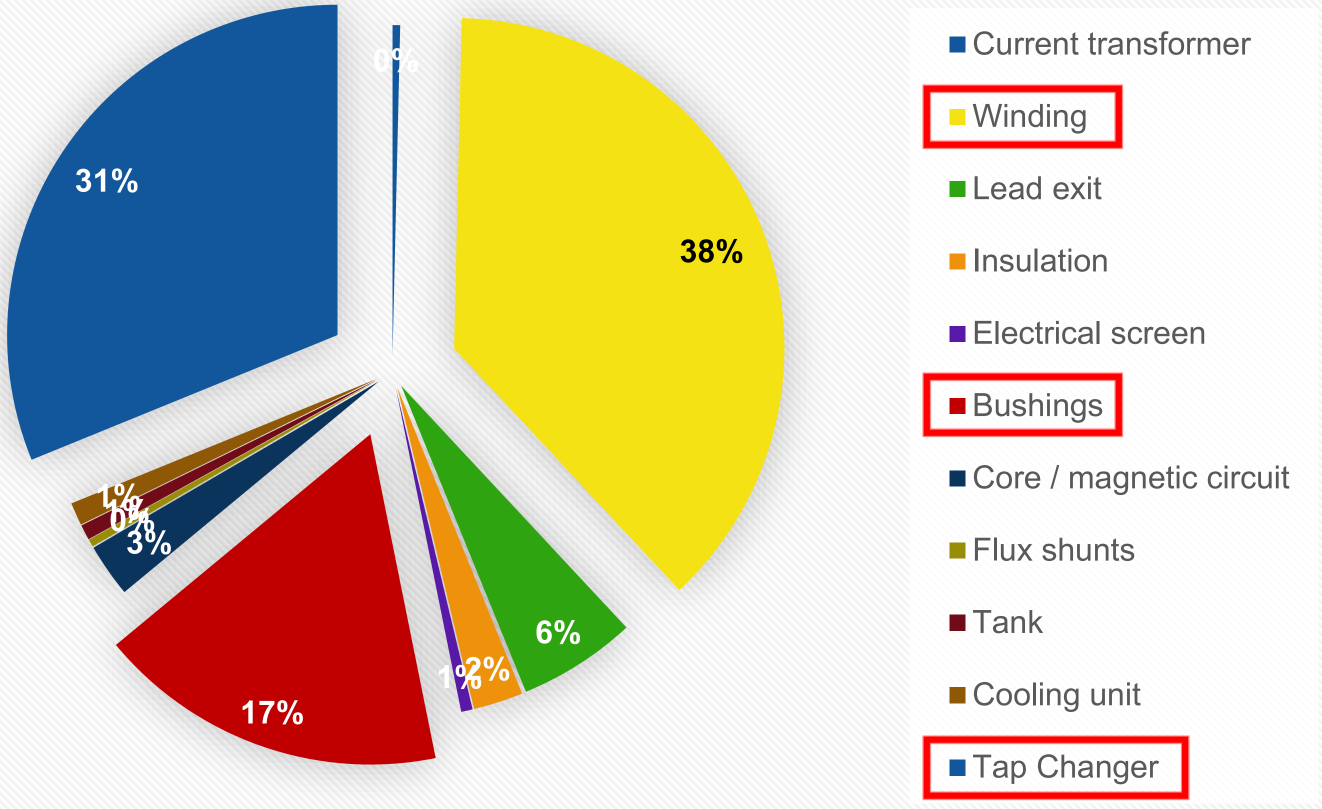
Diagnostics – Why?

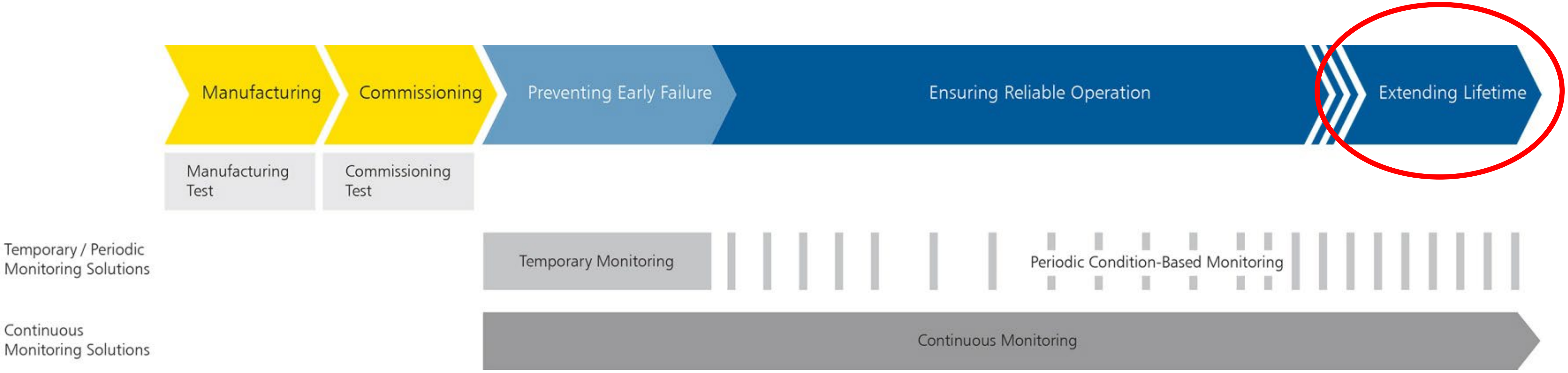


Source: DEVELOPMENT AND RESULTS OF A WORLDWIDE TRANSFORMER RELIABILITY SURVEY" CIGRE SC A2 COLLOQUIUM 2015, Shanghai

CIGRE WG A2.37: Transformer failure statistics

- 22.000 grid transformers
- 150.000 service years

Diagnostics – Why?



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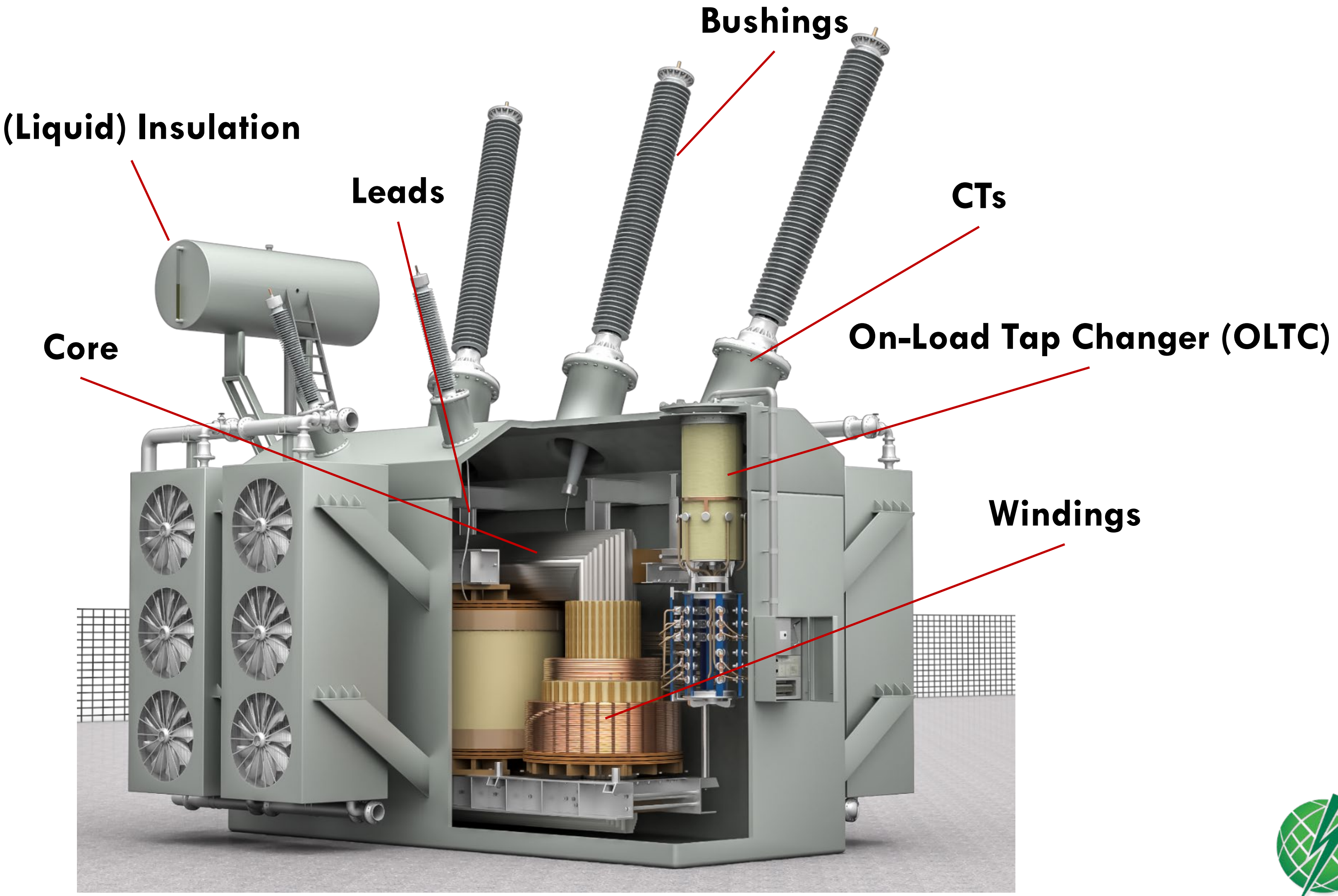
State-of-the-Art Diagnostics



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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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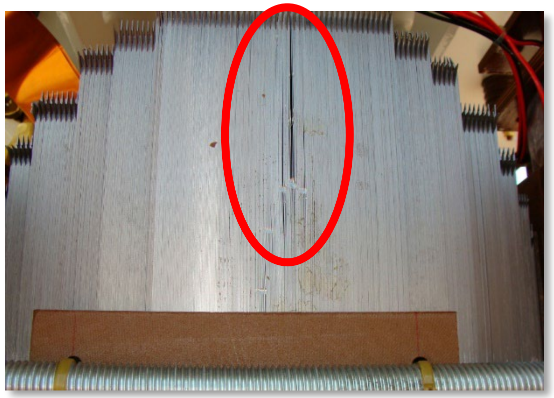
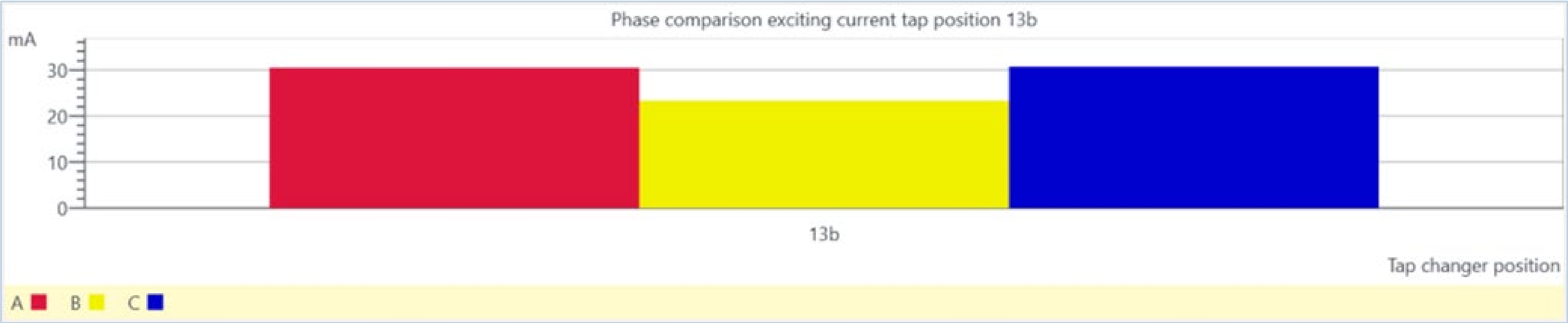
State-of-the-Art Diagnostics

Component	Detectable faults	Possible measurement methods															
		Capacitance and power factor/dissipation factor measurement:	at 50 Hz or 60 Hz	as tip-up test	with variable frequency	DC winding resistance measurement and OLTC verification	Transformer turns ratio (TTR) measurement	Exciting current measurement	Short-circuit impedance / leakage reactance measurement	Frequency response of stray losses (FRSL) measurement	Demagnetization	Dielectric (frequency) response analysis	Sweep frequency response analysis (SFRA)	Current transformer analysis	Partial discharge analysis	Partial discharge localization	Online dielectric condition monitoring
Bushings	Partial breakdown between capacitive graded layers, cracks in resin-bonded insulation		■		■							■			■		■
	Aging and moisture ingress		■		■							■					■
	Open or compromised measuring tap connection			■	■												■
	Partial discharges in insulation			■											■		■
CTs	Current ratio or phase error considering burden, excessive residual magnetism, non-compliance to relevant IEEE or IEC standard													■			
	Burden-dependent current ratio and phase displacement													■			
	Shorted turns													■			
Leads	Contact problems					■							■				
	Mechanical deformation												■				
Tap changer	Contact problems in tap selector and at diverter switch					■		■					■				
	Open circuit, shorted turns, or high resistance connections in the OLTC preventative autotransformer					■		■					■				
	Contact problems in the DETC					■		■					■				
Insulation	Moisture in solid insulation		■		■							■					
	Aging, moisture, contamination of insulation fluids		■		■							■					
	Partial discharges			■											■	■	■
Windings	Short-circuits between windings or between turns					■	■	■					■				
	Strand-to-strand short-circuits									■			■				
	Open circuits in parallel strands					■				■			■				
	Short-circuit to ground		■		■			■									
	Mechanical deformation		■		■				■				■				
	Contact problems, open circuits					■							■				
Core	Mechanical deformation		■		■								■				
	Floating core ground		■		■								■				
	Shorted core laminates							■					■				
	Residual magnetism							■			■		■				

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





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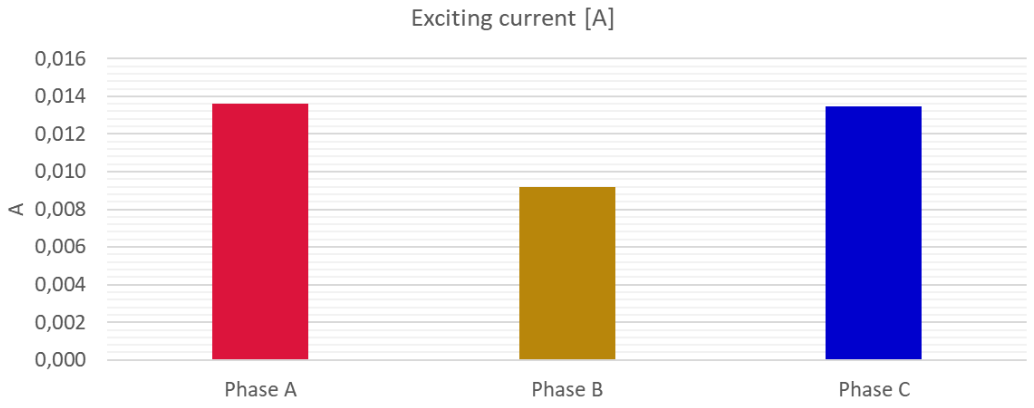
State-of-the-Art Diagnostics | Excitation Current

Example

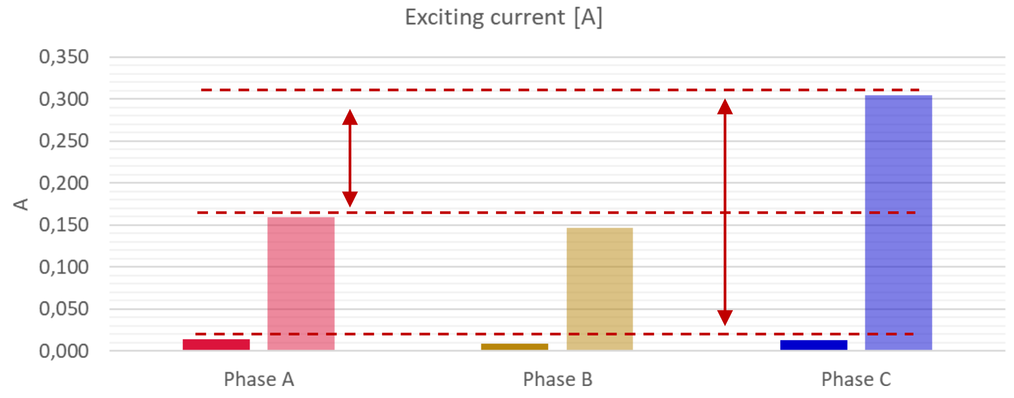
- Vector group: Yzn5
- TTR test passed

Fingerprint 3-phase TTR 120 VAC



12.598 mA **9.169 mA** **14.445 mA**

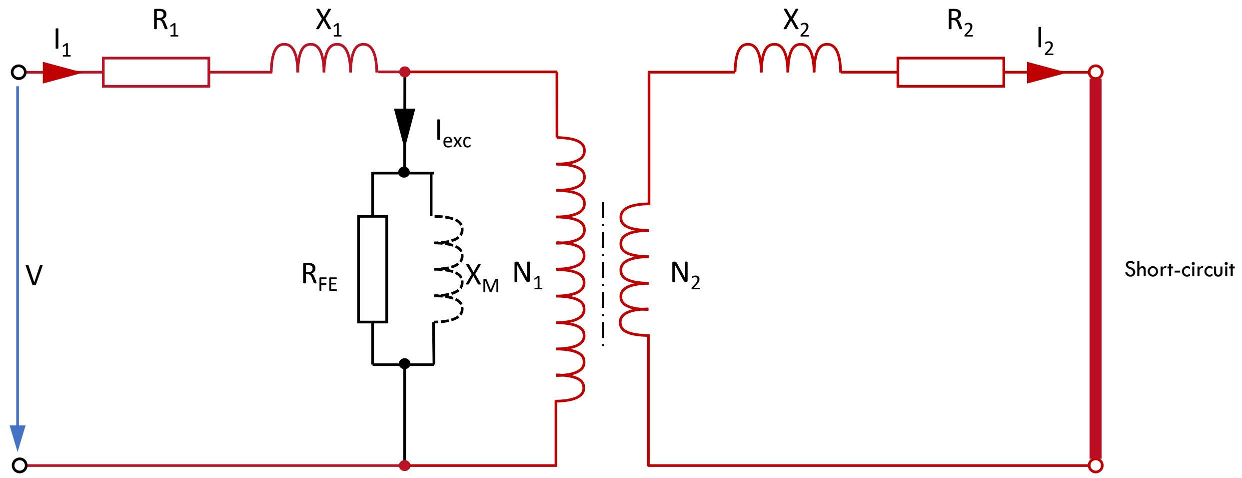
Comparison of fingerprint with shorted turns

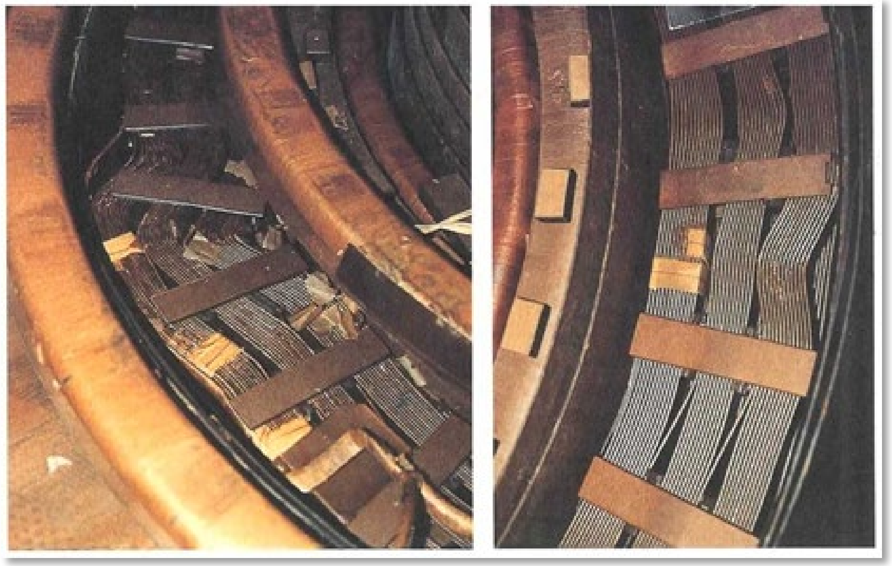


158.756 mA **146.202 mA** **304.773 mA**

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





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

	I AC (A)	V AC (V)	Z_k (Ω)
Phase A	1.100	67	61.04
Phase B	1.097	66	60.75
Phase C	1.115	64	57.77
Relative Z_k			6.79%
Nameplate Z_k			6.60%
Deviation			-2.85%

Per-phase test

	I AC (A)	V AC (V)	Zk (Ω)
Phase A	1.00	29.1	29.11
Phase B	1.00	31.9	31.89
Phase C	0.99	28.8	28.81
Max. Deviation			~10%

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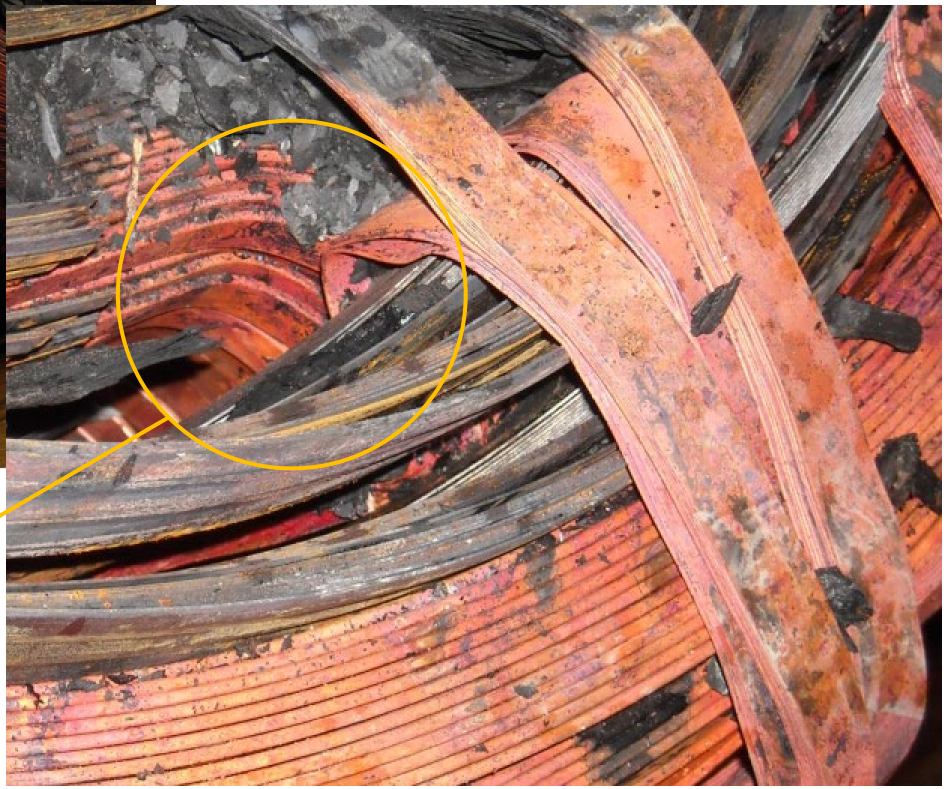
State-of-the-Art Diagnostics | Leakage Reactance

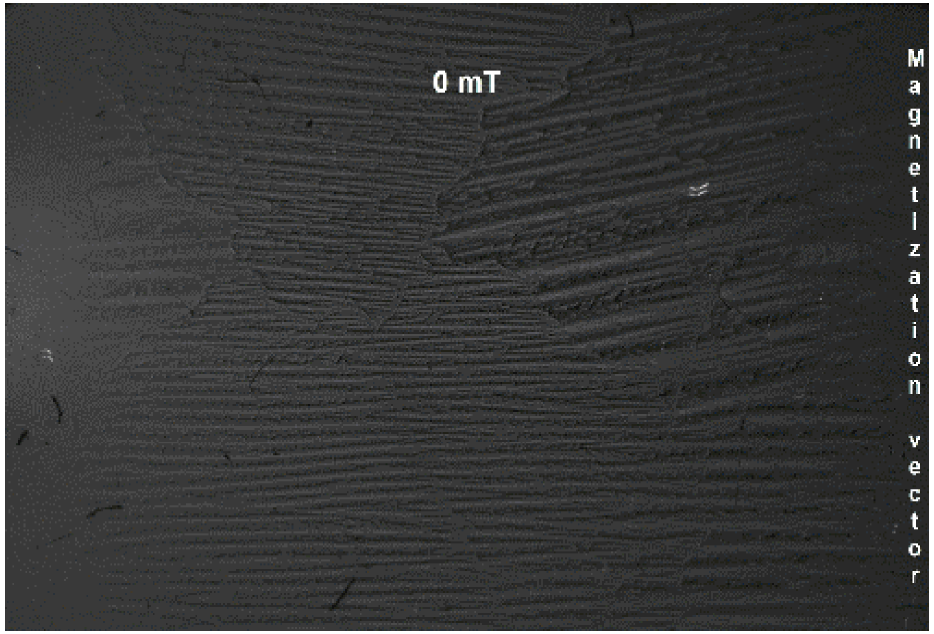
Case Study



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

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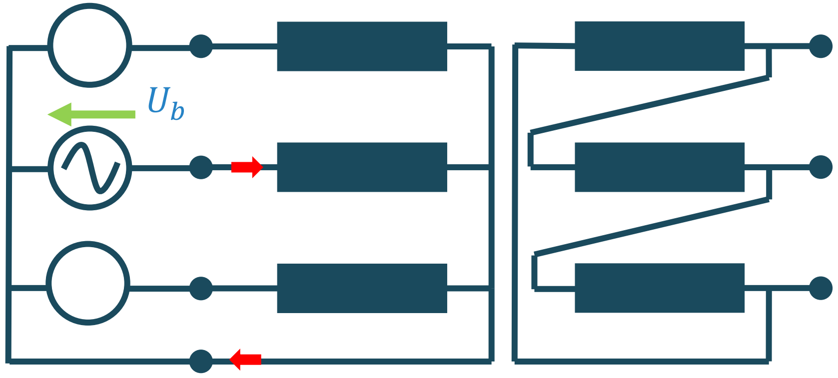
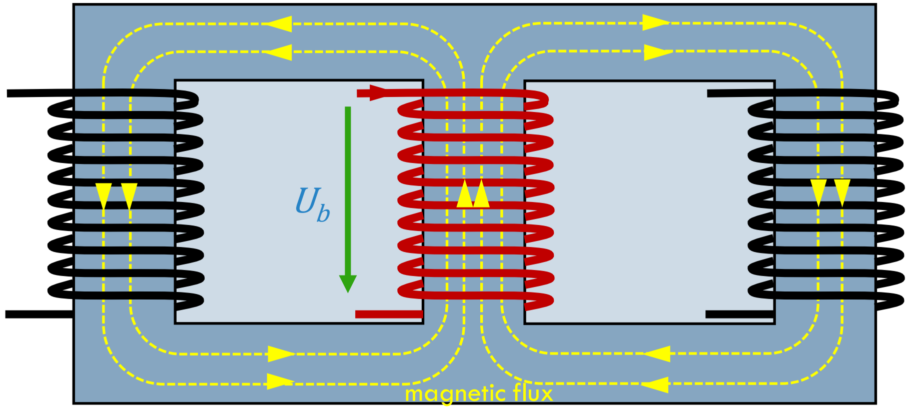
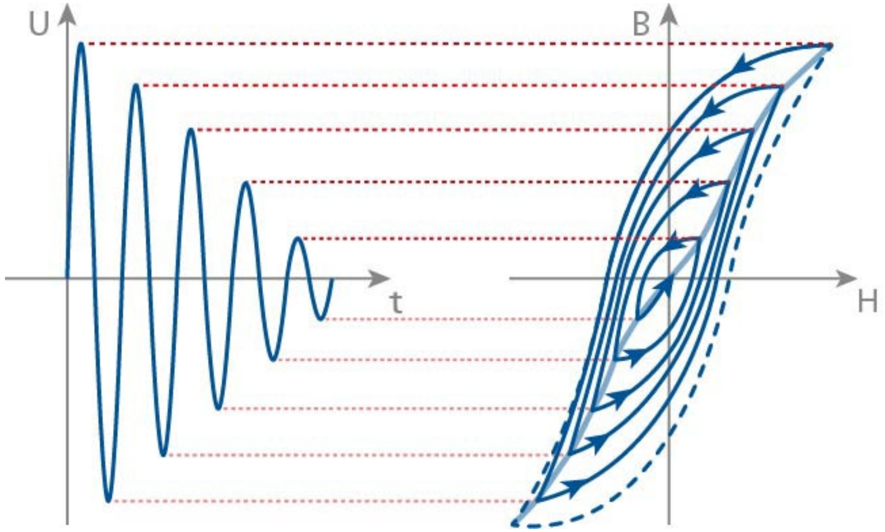
State-of-the-Art Diagnostics | Demagnetization







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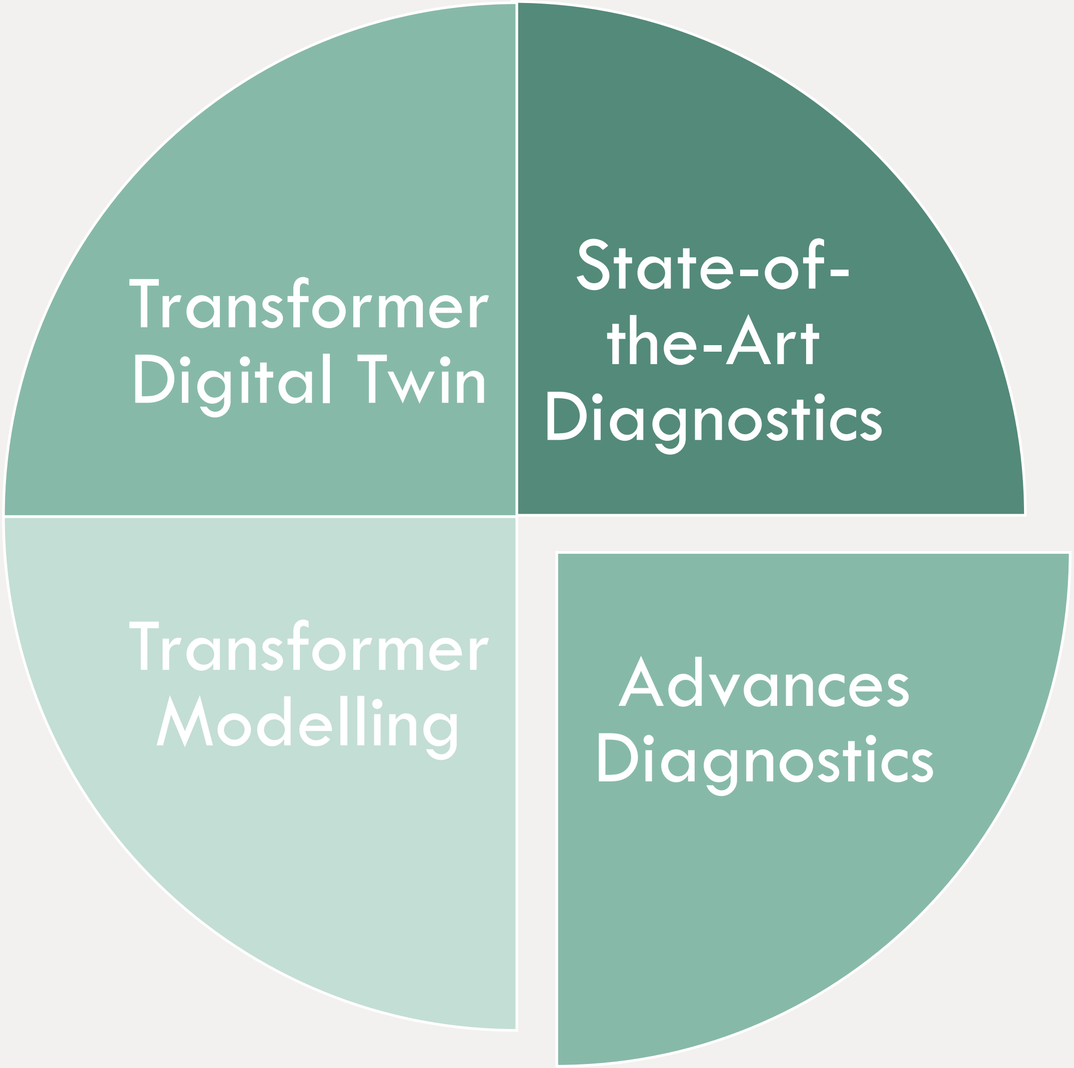
Power Transformers



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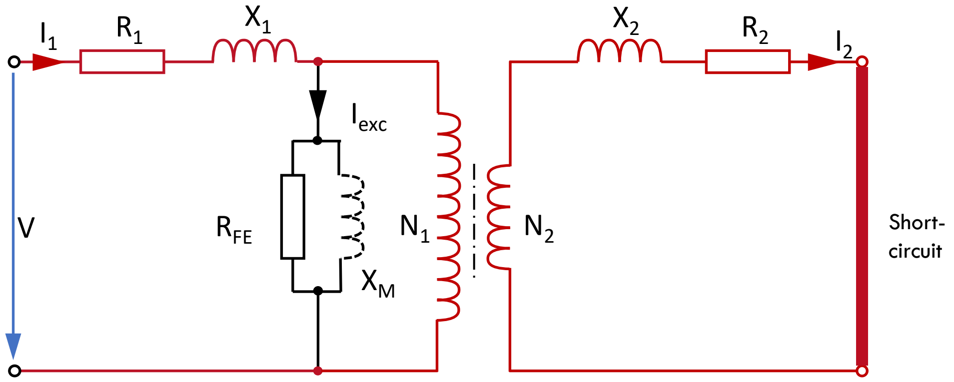
Advanced Diagnostics | Frequency Response of Stray Losses

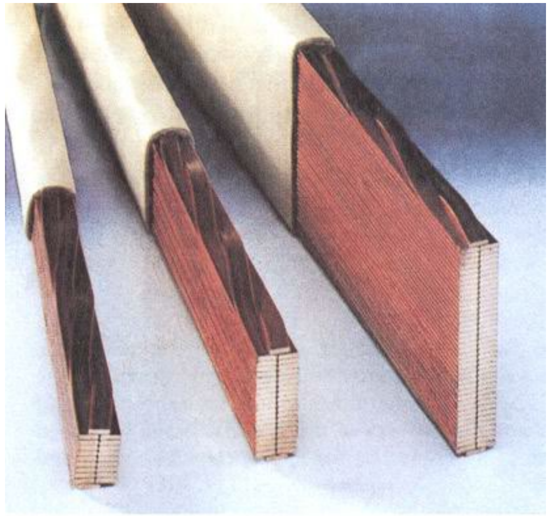
- **F**requency **R**esponse of **S**tray **L**osses
- frequency weep: 15 Hz – 490 Hz
- carried out per phase



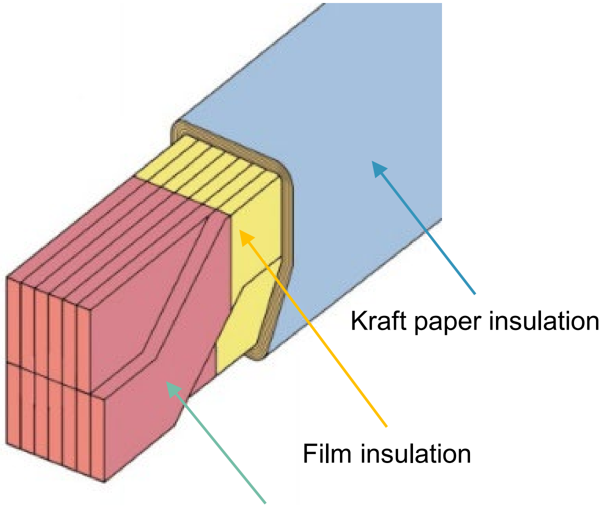
- Shorted strands result in higher losses, particularly visible at higher frequencies
- Eddy losses are frequency dependent
- Such faults are not detectable by transformer ratio or winding resistance tests

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

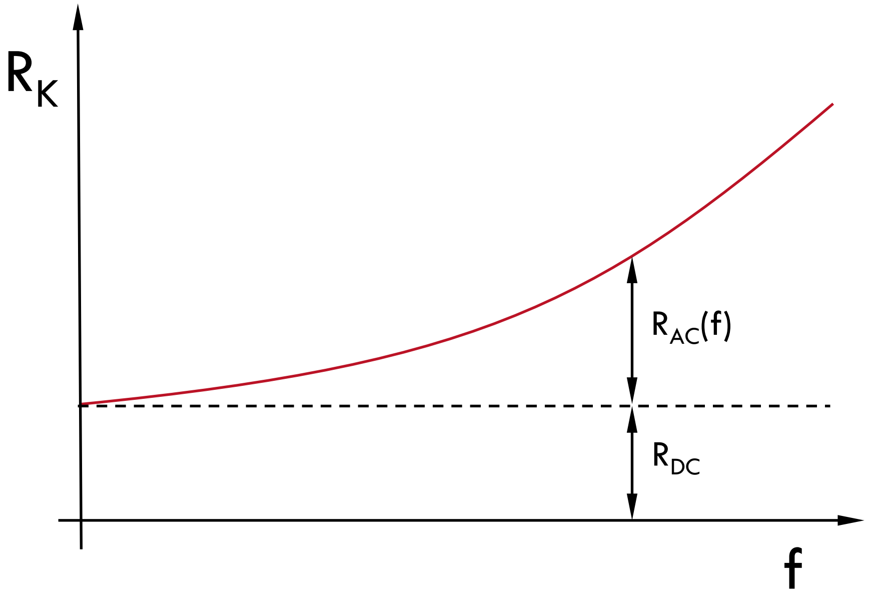


Example of CTC conductors



Advanced Diagnostics | Frequency Response of Stray Losses

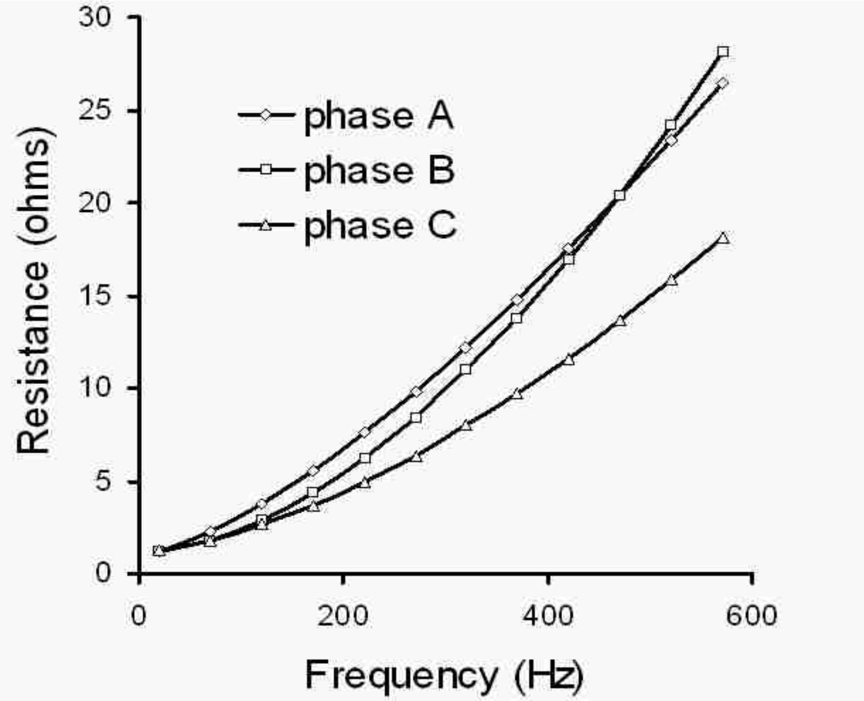
- Assessment of FRSL measurements:
  - ✓ **Phase-to-phase comparison* or fingerprint**
  - ✓ $\mathbf{\Delta R_{max} = 15\ \%}$
  - ✓ $\mathbf{\Delta L_{max} = 2.5\ \%}$



* CIGRE TB455, Guide for Transformer Maintenance, 2011

Advanced Diagnostics | Frequency Response of Stray Losses

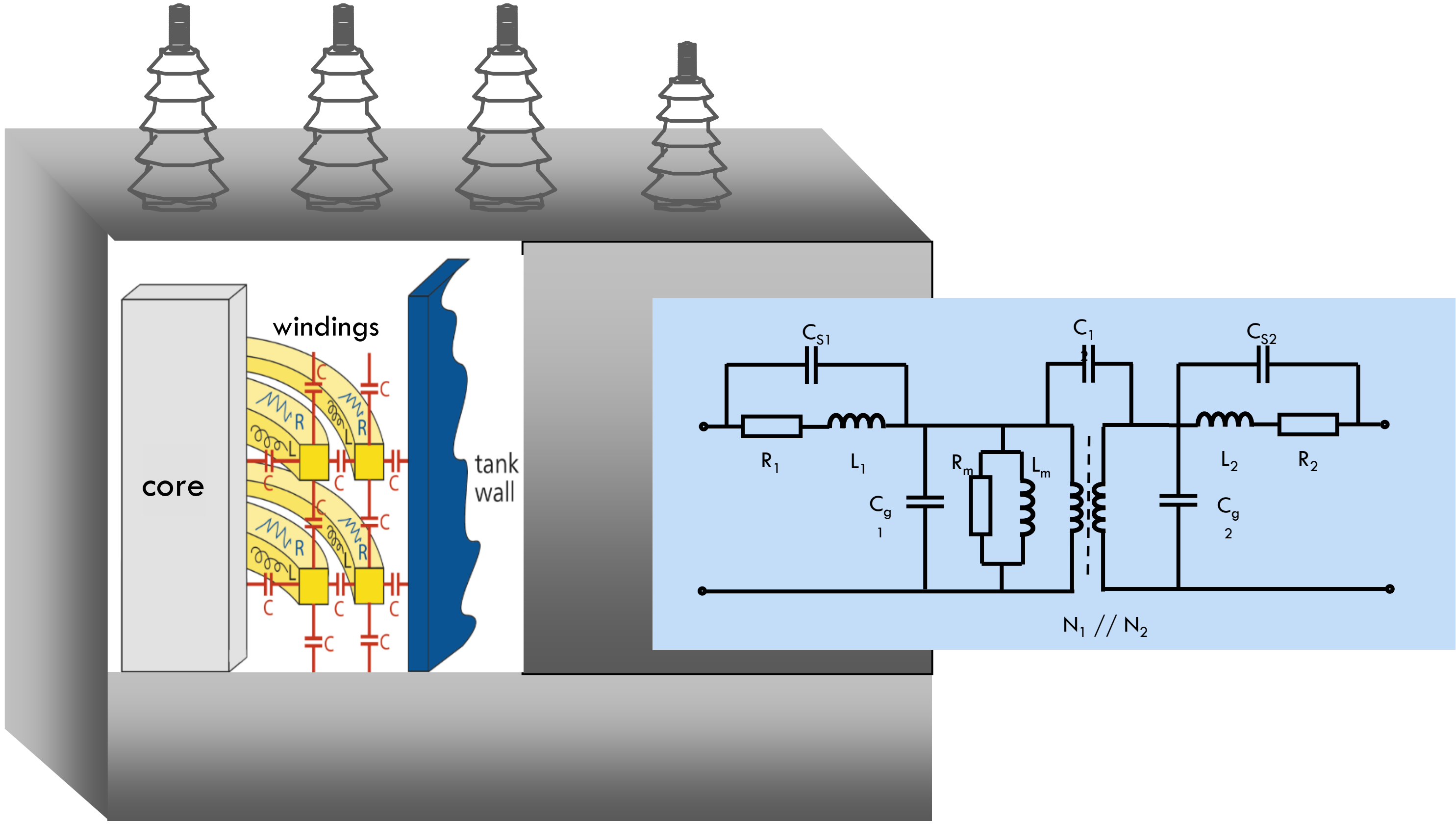
- Case Study
  - ✓ 40 MVA Yd, 121 kV/12.85 kV transformer
  - ✓ measurement triggered by gassing, indicating a hot spot
  - ✓ no other electrical standard test showed a fault



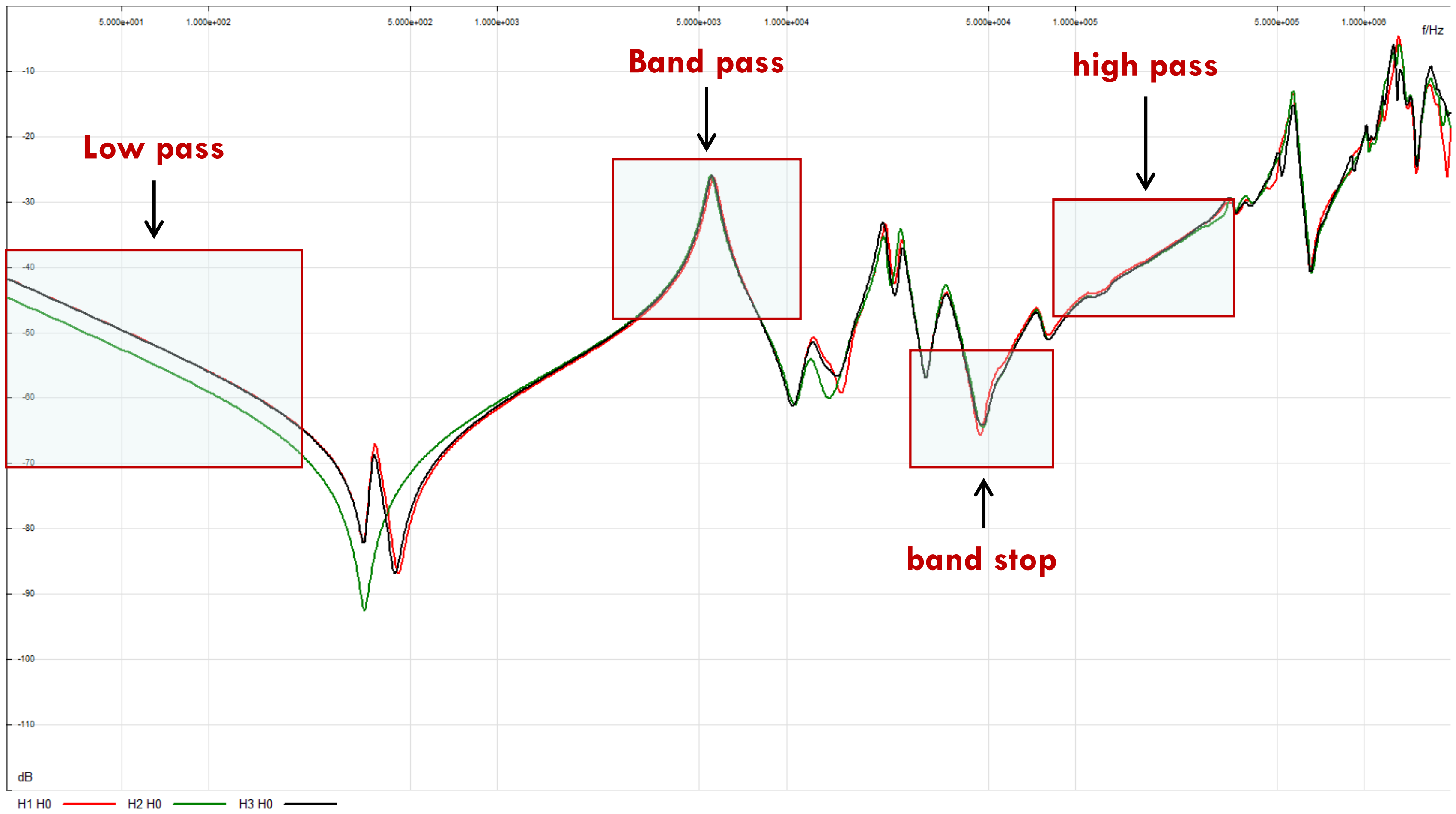
Resistance vs. frequency for the 40-MVA transformer

Advanced Diagnostics | Frequency Response Analysis

- **I**FRA **impulse** FRA:
  - ✓ derive frequency from a Fourier transformer of an impulse
- **S**FRA **sweep** FRA
  - ✓ use sinusoidal signal with variable frequency



Advanced Diagnostics | Frequency Response Analysis



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

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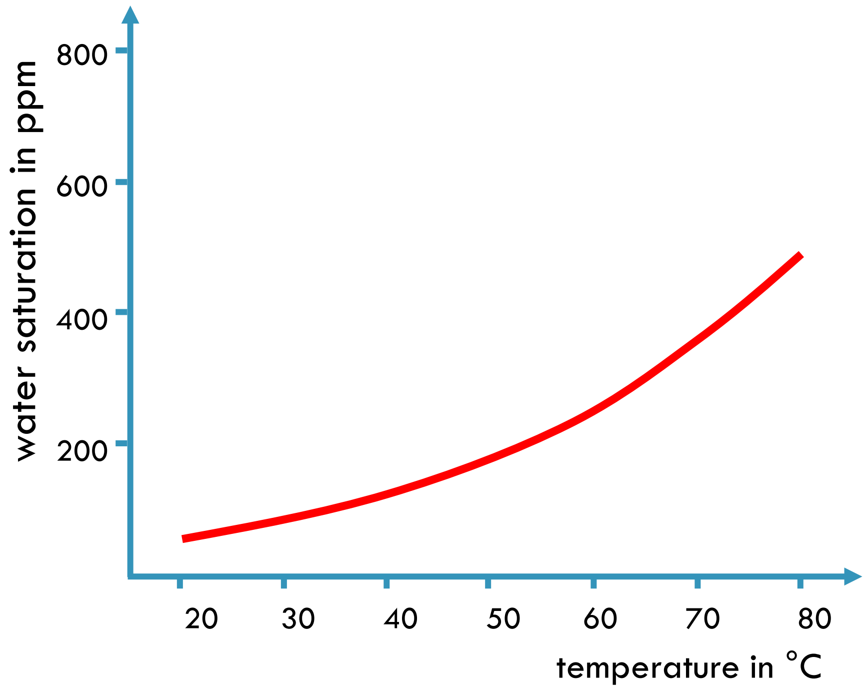
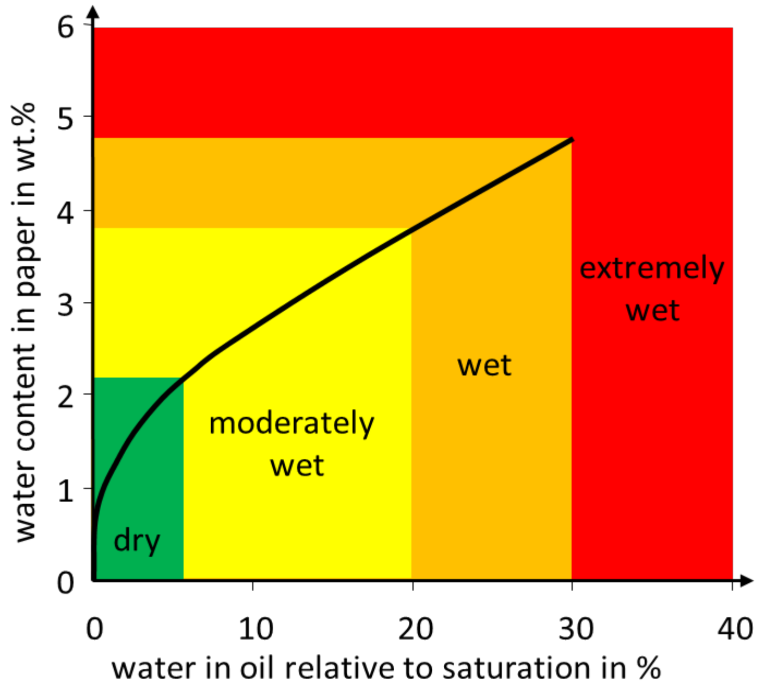
Advanced Diagnostics | Moisture Analysis

- **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(δ)
  - ✓ frequency range: 10 µHz – 5 kHz @ 200 V_{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

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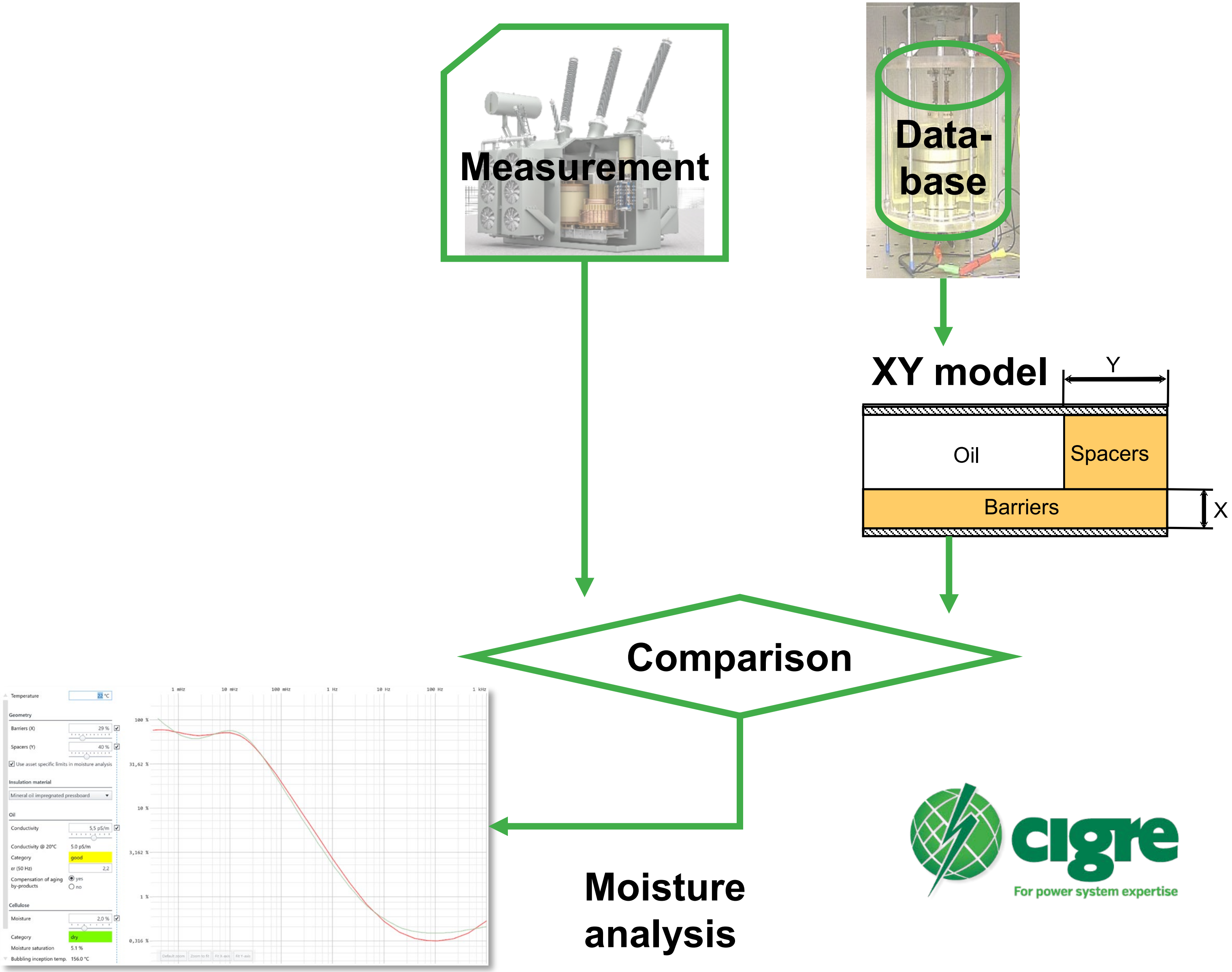


Advanced Diagnostics | Moisture Analysis

Temperature 22 °C

Geometry

Barriers (X) 29 %

Spacers (Y) 40 %

☑ Use asset specific limits in moisture analysis

Insulation material

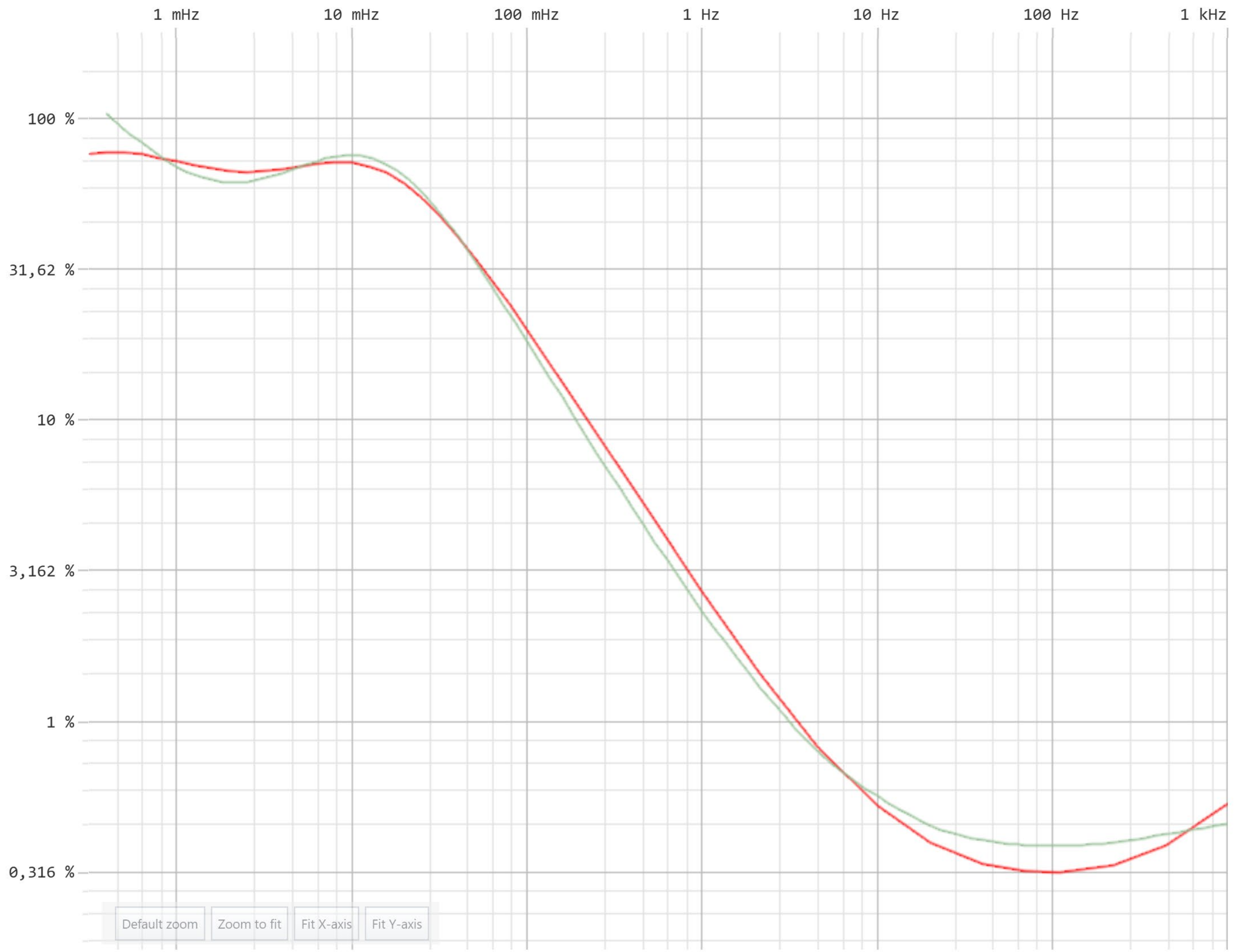
Mineral oil impregnated pressboard

Oil

Conductivity	5,5 pS/m
Conductivity @ 20°C	5.0 pS/m
Category	good
εr (50 Hz)	2,2
Compensation of aging by-products	◉ yes ◯ no

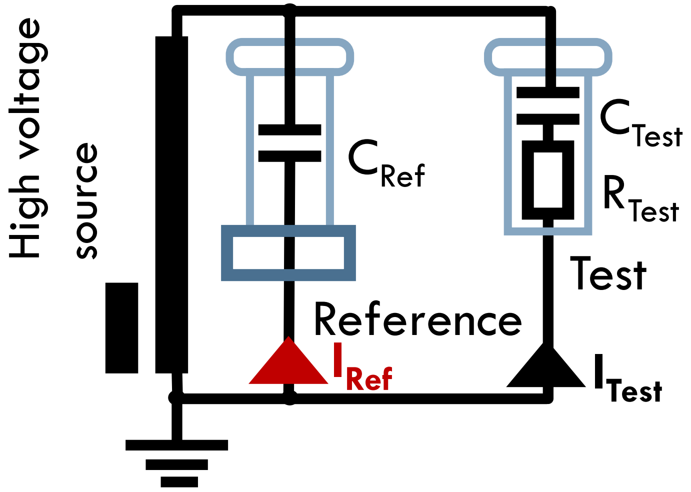
Cellulose

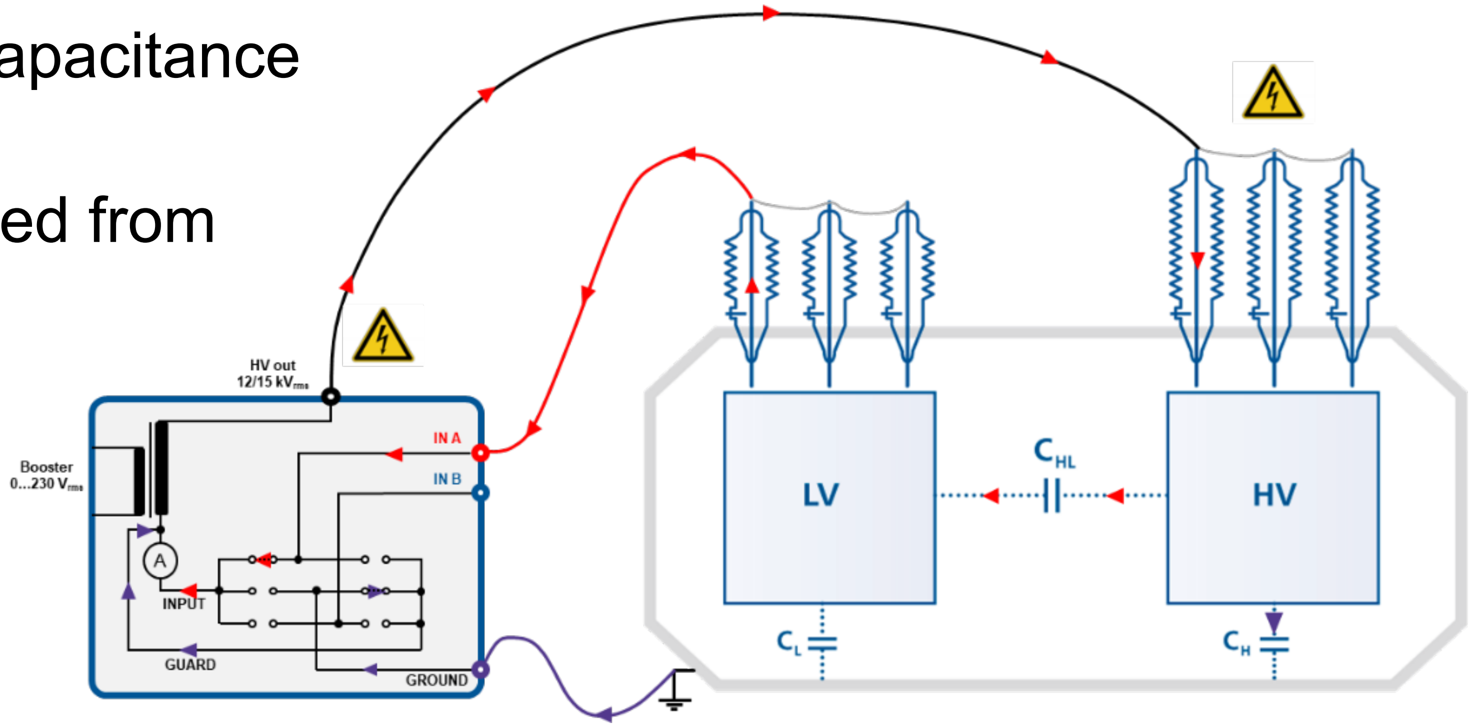
Moisture	2,0 %
Category	dry
Moisture saturation	5.1 %
Bubbling inception temp.	156.0 °C



Advanced Diagnostics | Capacitance & Power Factor

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



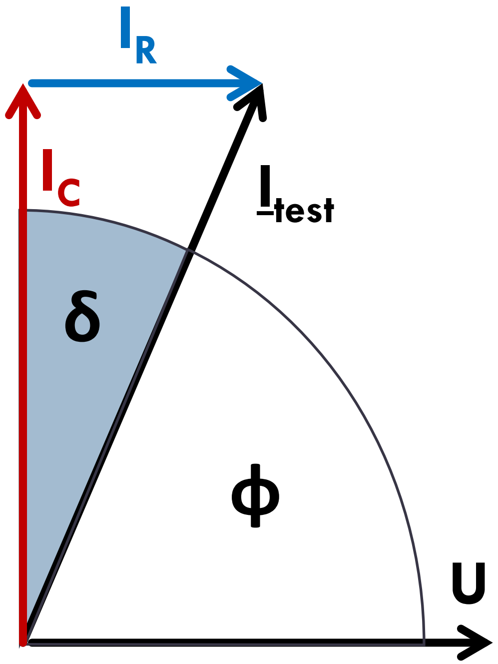


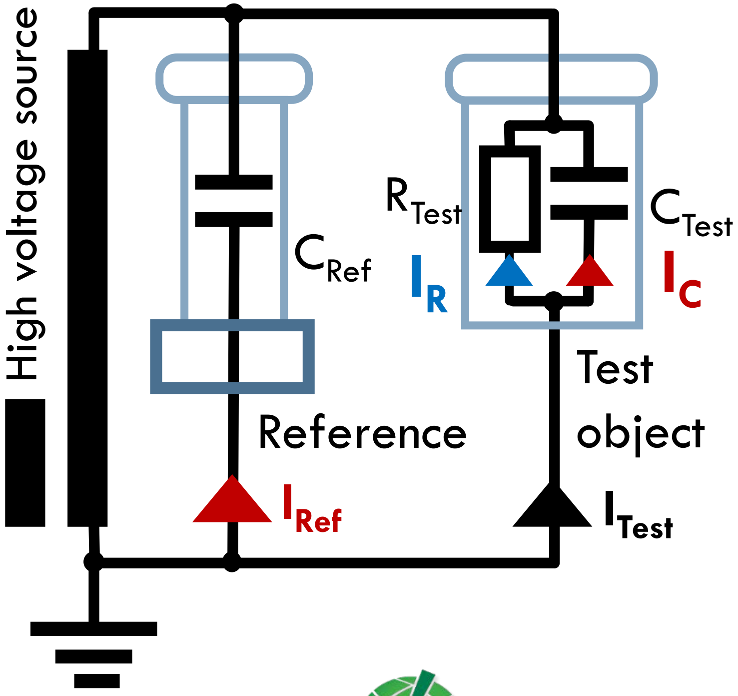
Advanced Diagnostics | Capacitance & Power Factor

- **Dissipation Factor & Power Factor**

$$\tan\delta = \frac{I_R}{I_C}$$

$$\cos\varphi = \frac{I_R}{I_{test}}$$





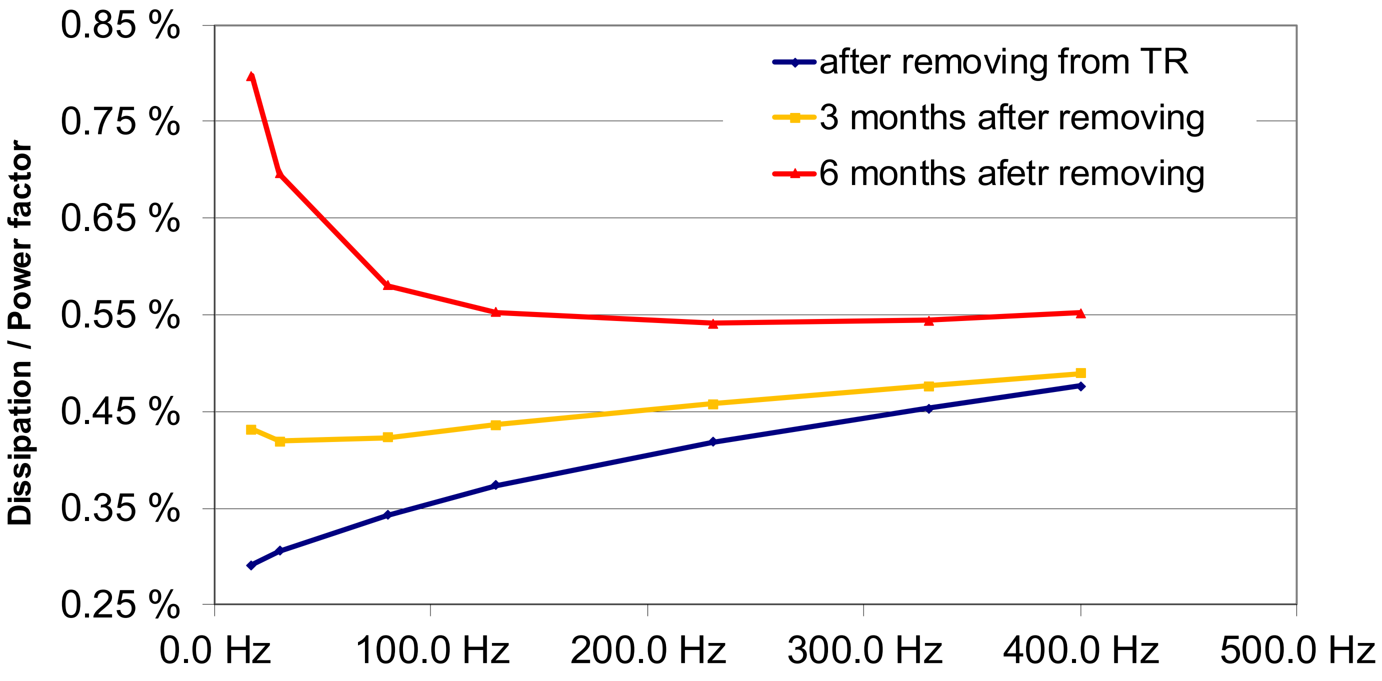
Advanced Diagnostics | Capacitance & Power Factor

Capacitance	
Windings	○ Short circuit to ground ○ Mechanical deformation ○ Change of the geometry between winding ○ Displacement
Transformer core	○ Mechanical deformation ○ Floating core to ground
Dissipation / Power factor (DF/PF)	
Insulation	○ Moisture in solid insulation ○ Ageing products, moisture, contamination of insulation fluids

For power system expertise

Advanced Diagnostics | Capacitance & Power Factor

Case Study: 220 kV Bushing stored outside



Advanced Diagnostics | PD Measurement

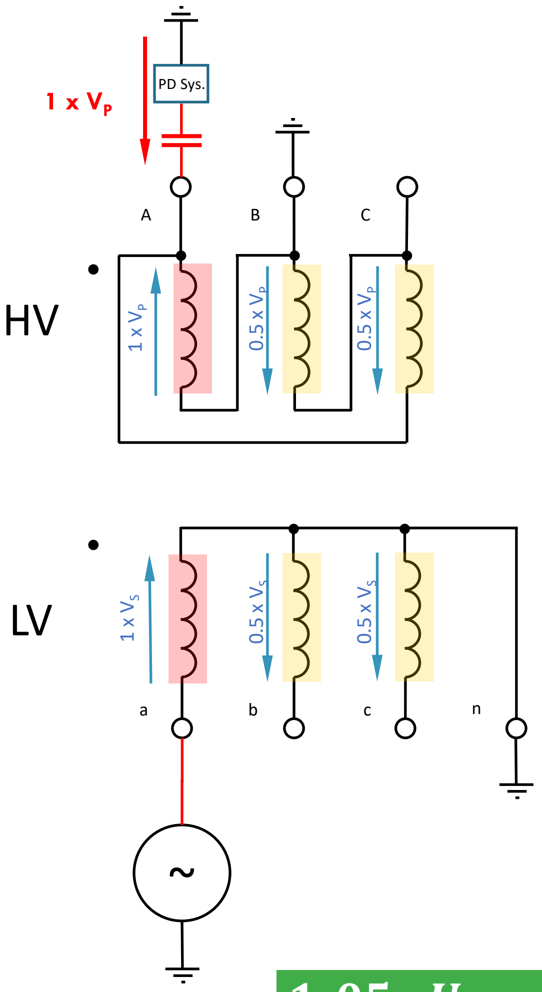
- on dry-type transformers with cast-resin insulation are available exceeding 50 kV
- DF/PF has very limited use for dry-type transformers, due to the leakage currents on the insulation surface.
- Reliable diagnostic measurement so far: partial discharge (PD) measurement
- Induced voltage (IVPD) test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

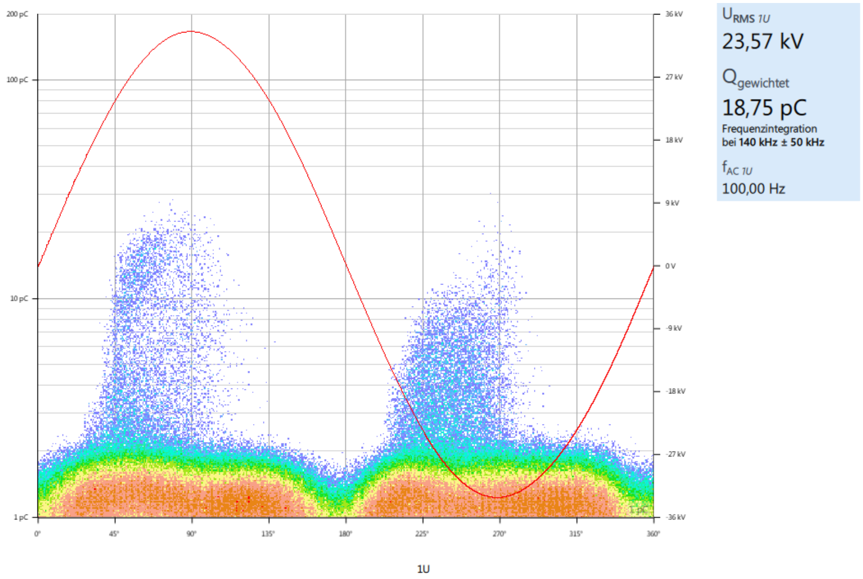
Advanced Diagnostics | PD Measurement

Measurement Setup

$23.57\ \mathrm{kV_{L-N}}$ | rated: $13.6\ \mathrm{kV_{L-N}}$

- 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 overstress line-to-ground insulation





$1.05 \cdot U_R = 242\ \mathrm{V_{L-N}}$

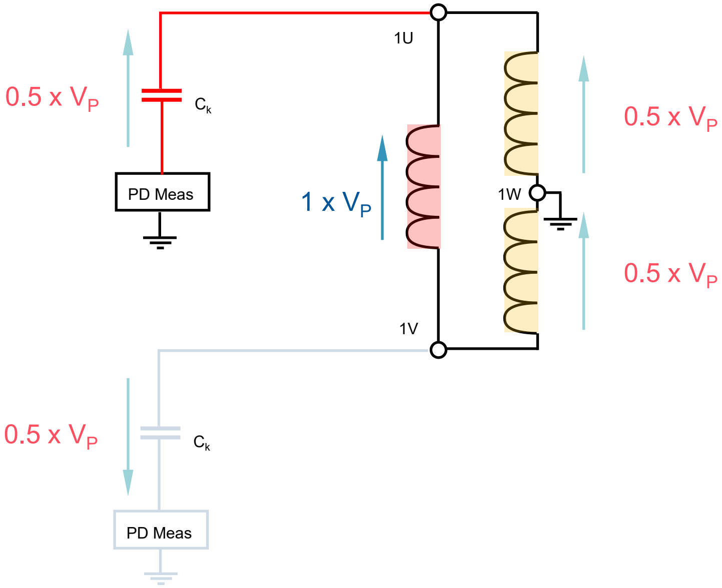
(IEC 2018, IEEE 2001, Engstler *et al.* 2024)

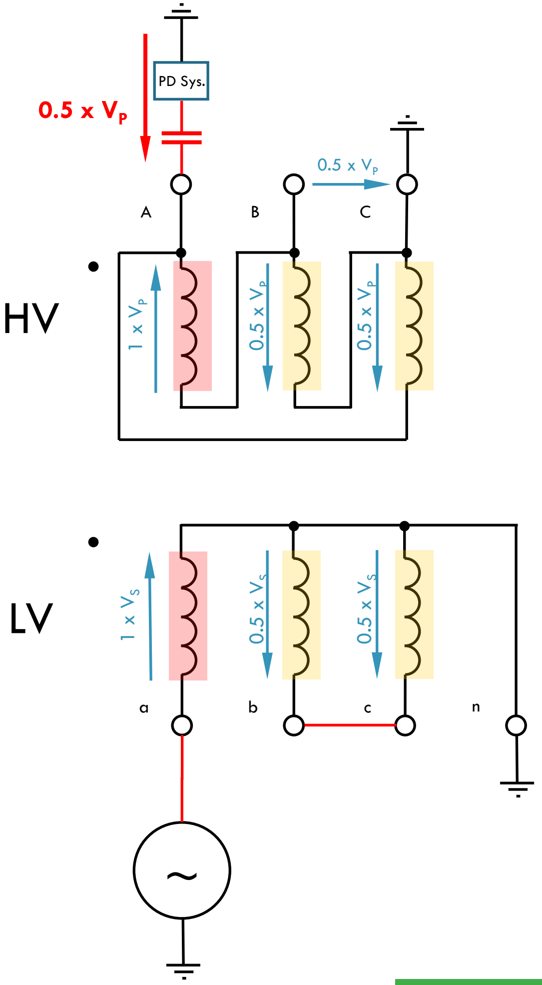
Advanced Diagnostics | PD Measurement

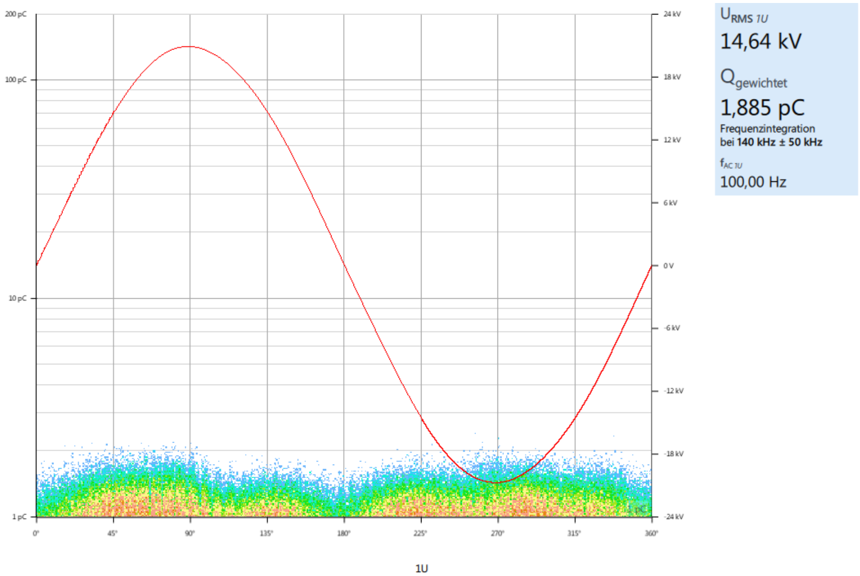
Measurement Setup

$14.64\ \mathrm{kV_{L-N}}$ | rated: $13.6\ \mathrm{kV_{L-N}}$

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







$1.3 \cdot U_R = 300\ V_{L-N}$

(Engstler *et al.* 2024)

Power Transformers

Transformer Digital Twin

State-of-the-Art Diagnostics

Transformer Modelling

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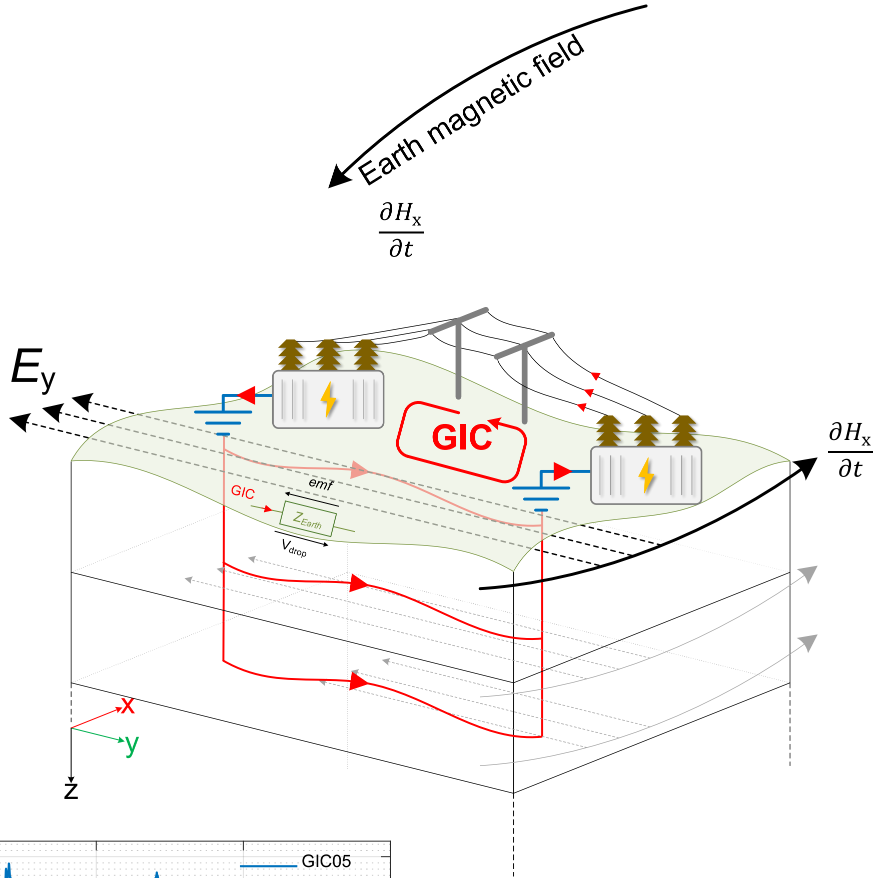
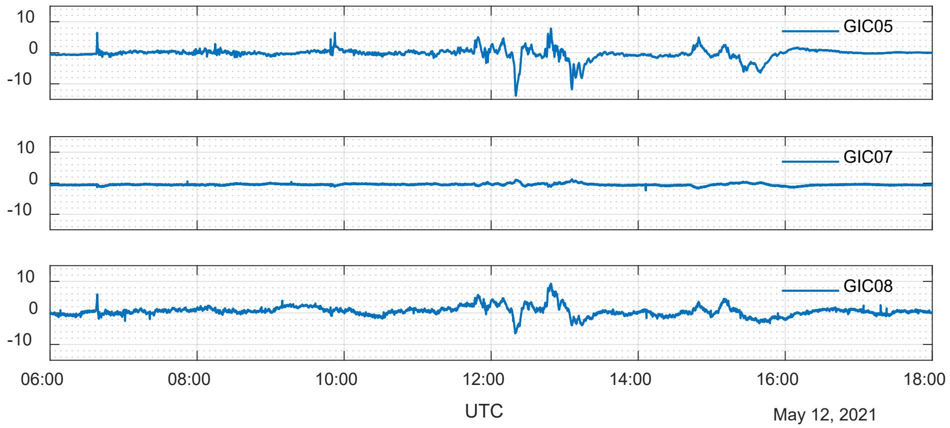
Transformer Modelling | Motivation



- **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



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Transformer Modelling | Motivation

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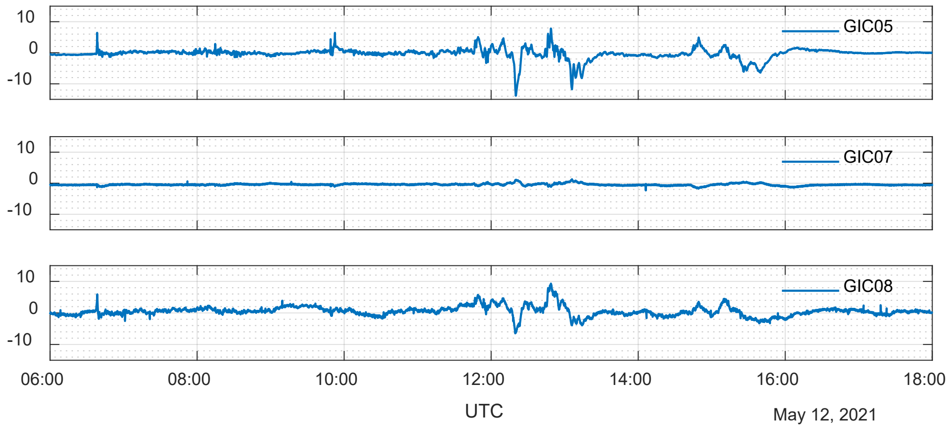

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Transformer Modelling | Model Overview (I)

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

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Transformer Modelling | Physical-based Models

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

Transient Phenomena	Slow	Switching	Fast	Very Fast
Frequency Range	DC – 1 kHz	50/60 Hz – 10 kHz	10 kHz – 1 MHz	100 kHz – 50 MHz

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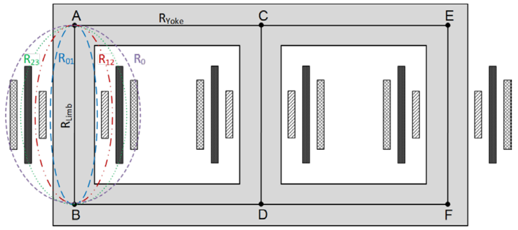
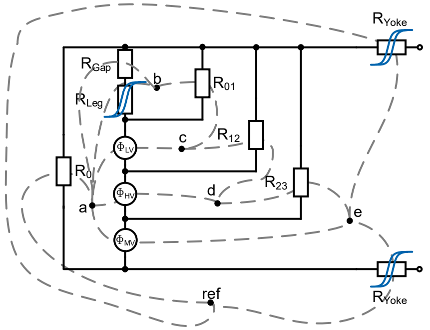
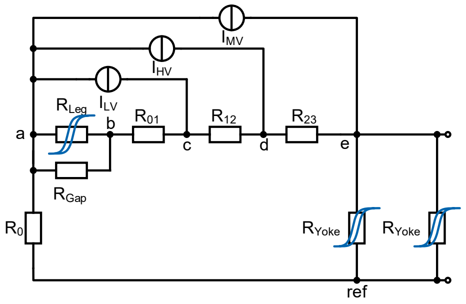
Transformer Modelling | Grey-Box Models

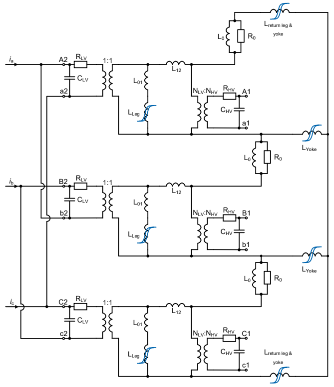
- **Model components**: only common components (inductor, resistor, capacitor, ideal transformer,...)
- **Model structure:** derived with the **principle of duality** between magnetic and electric circuits

Step 1
Transformer
Design

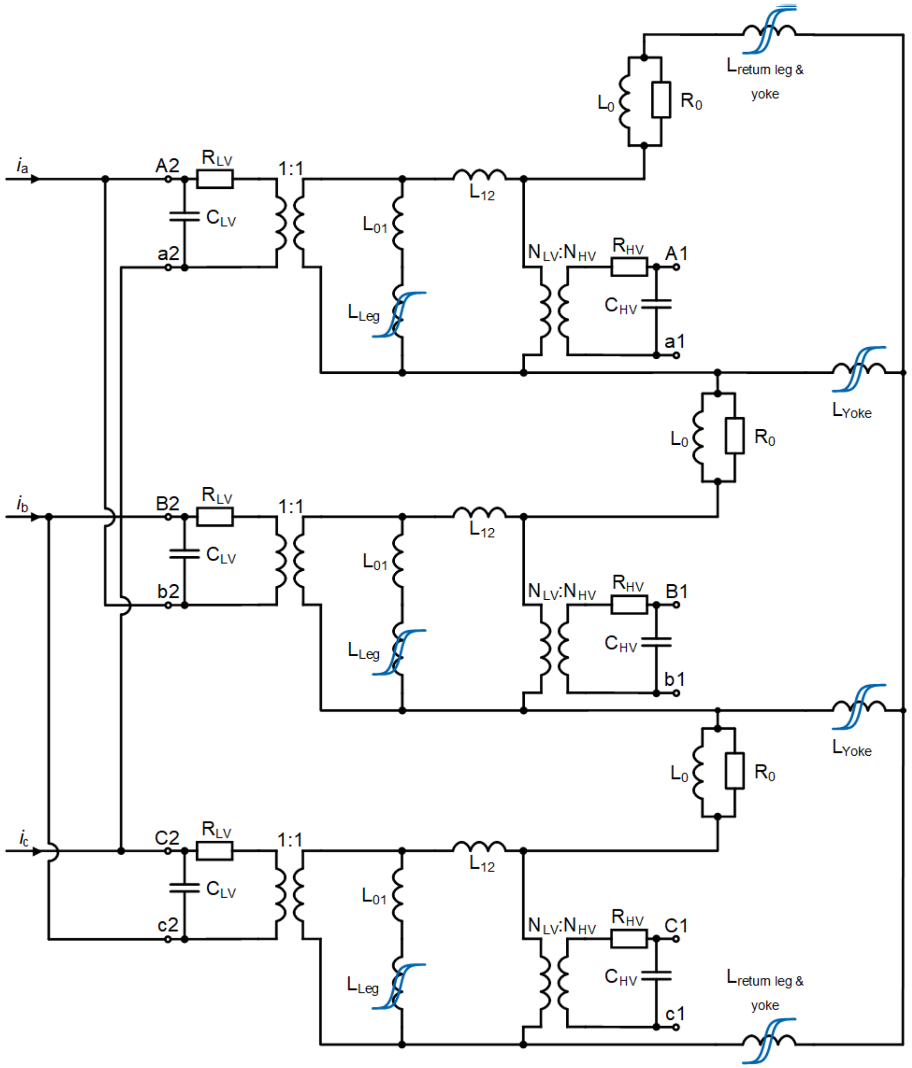




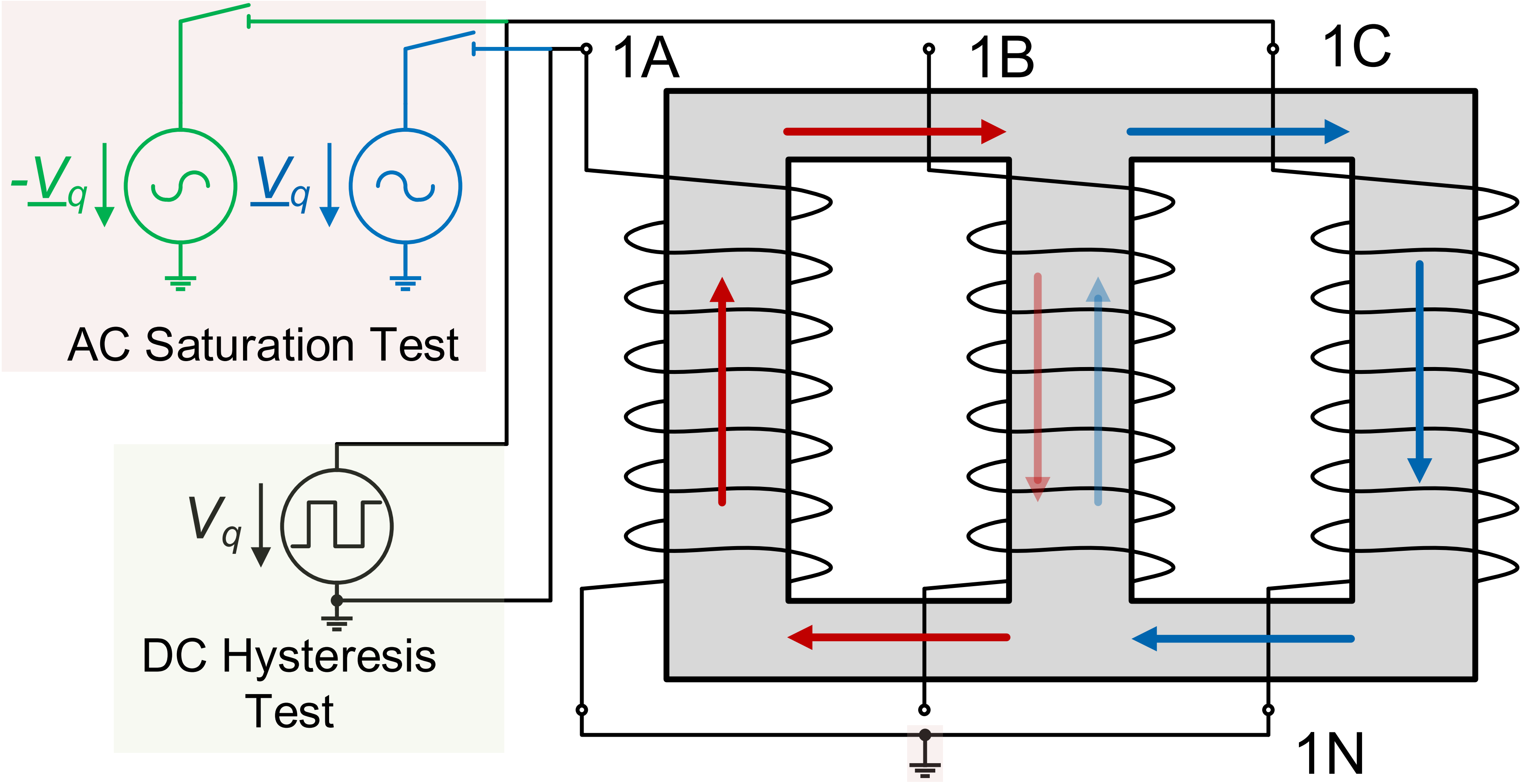


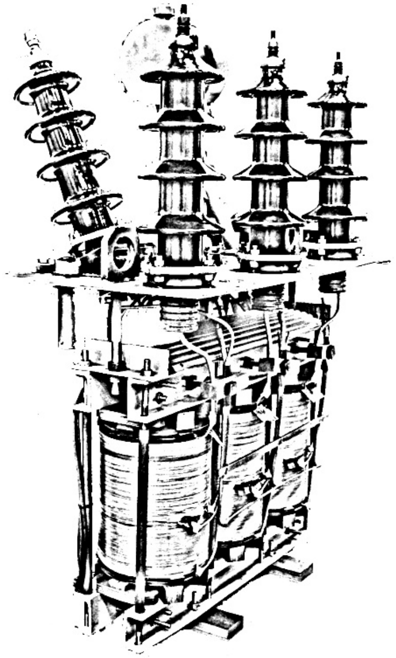


Transformer Modelling | Model Structure



Transformer Modelling | DC Hysteresis Test





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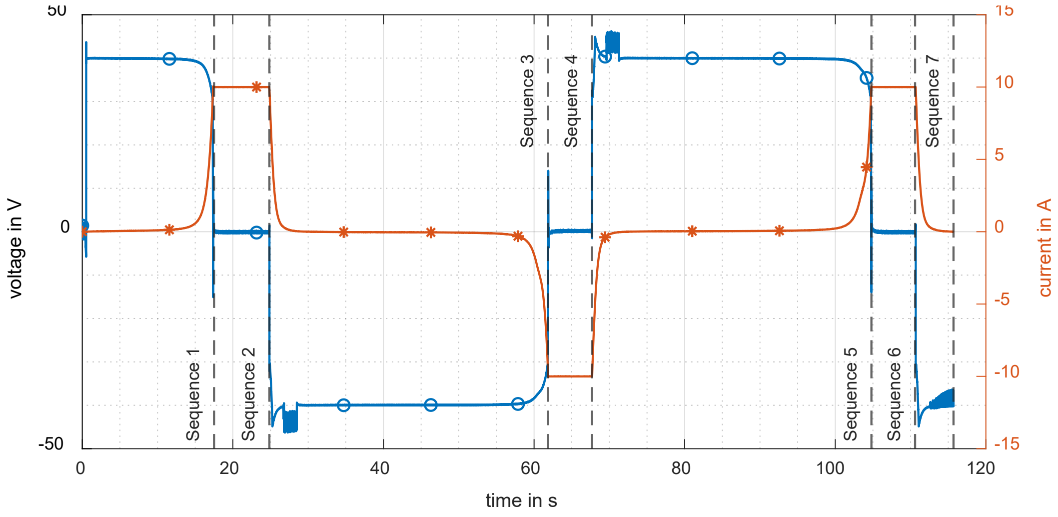
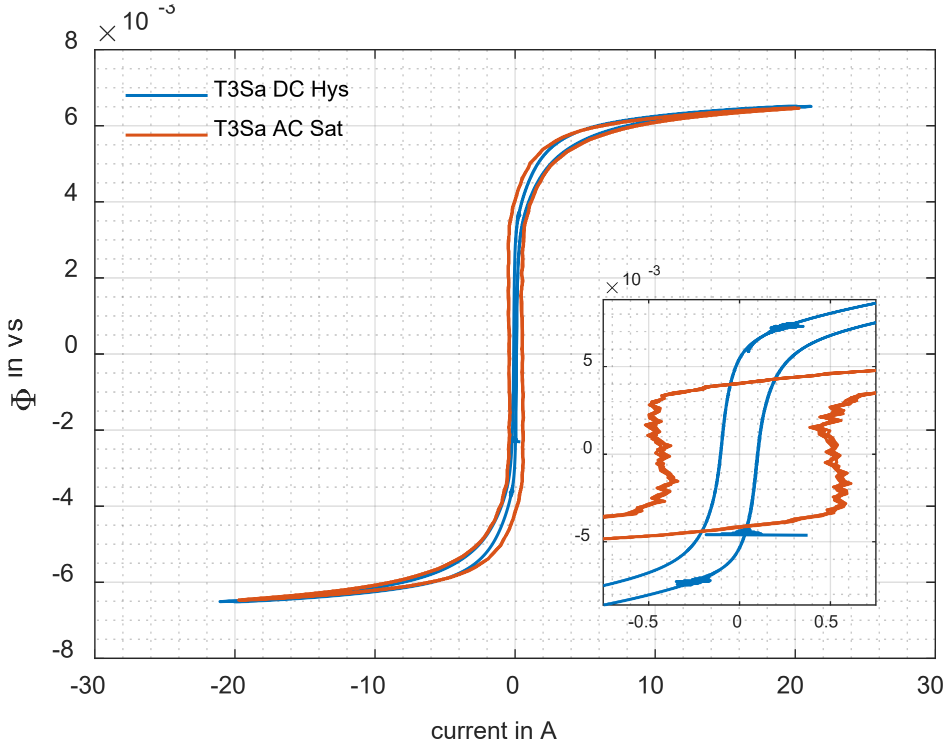
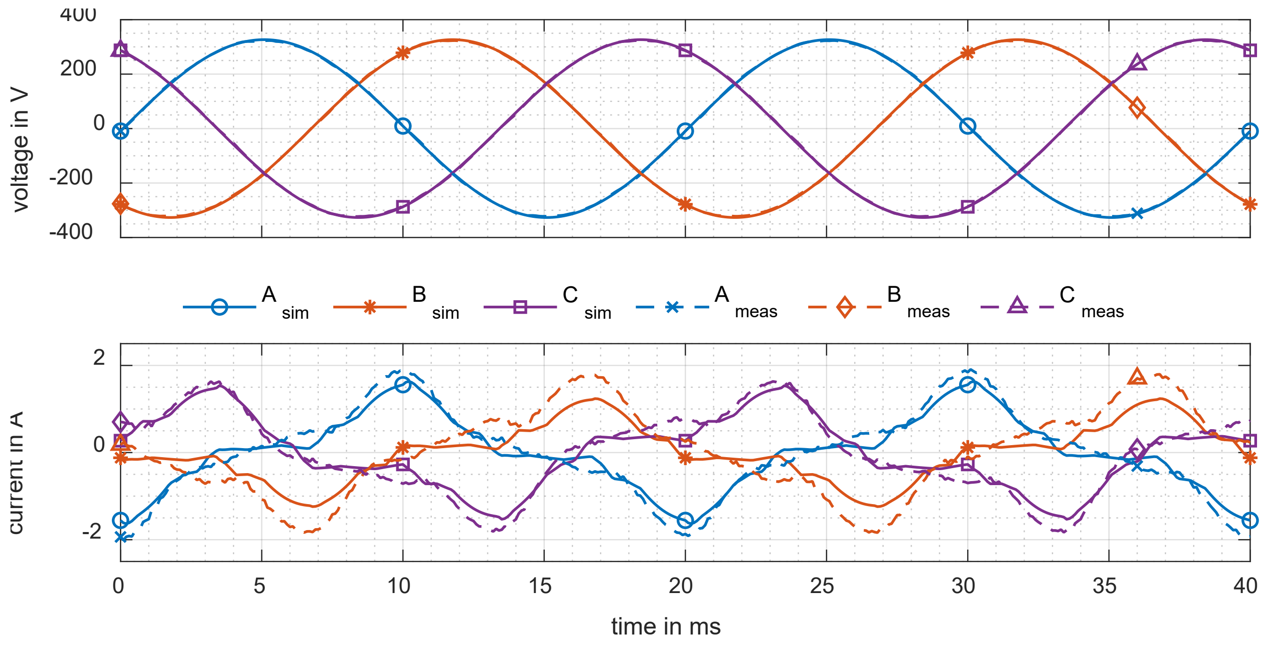
Transformer Modelling | Model Optimization

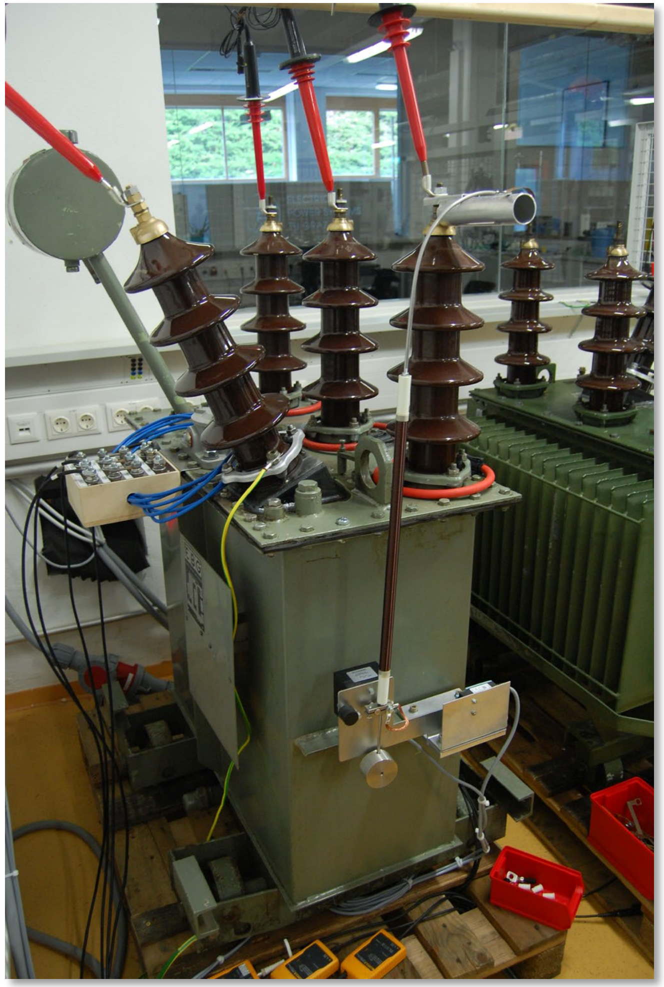




Transformer Modelling | Use-Case 50 kVA Transformer



	Calc.	Dev. in %
S in VA	650.8	0.01
P in W	165.7	-7.07



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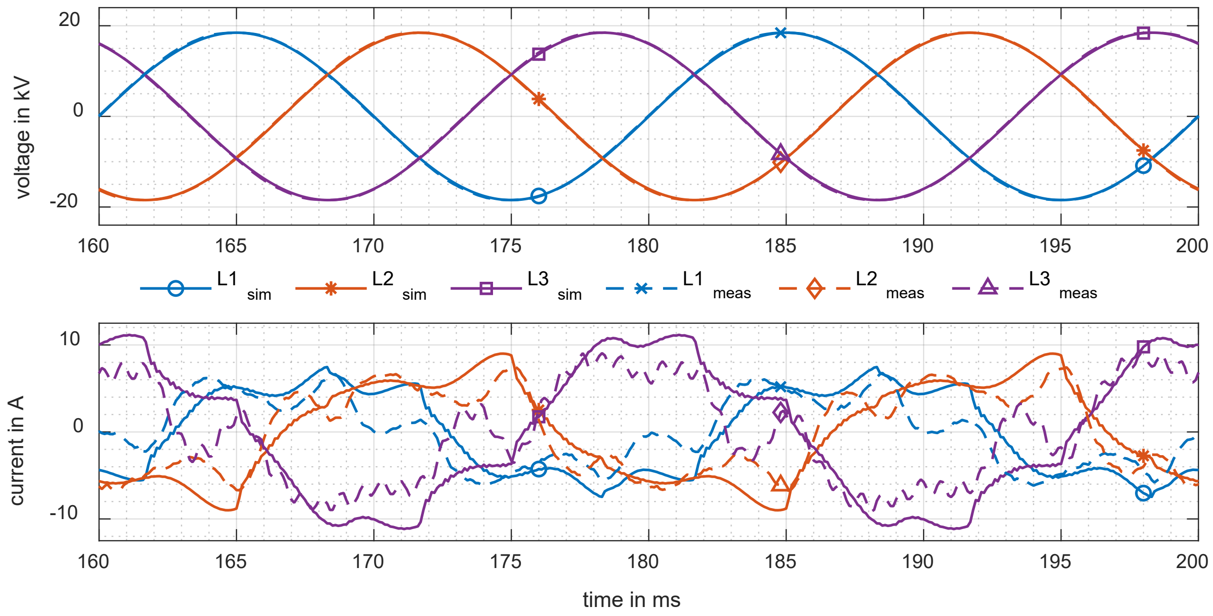
Transformer Modelling | Use-Case 786 MVA Transformer



	Calc.	Dev. in %
S in kVA	231.3	+24.8
P in kW	186.5	+12.6

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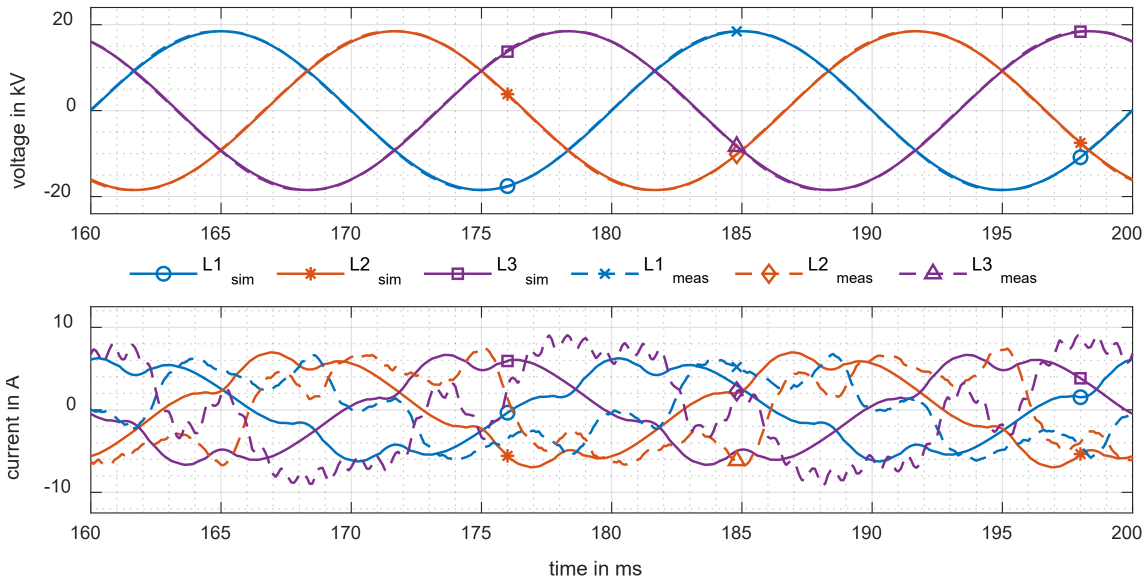
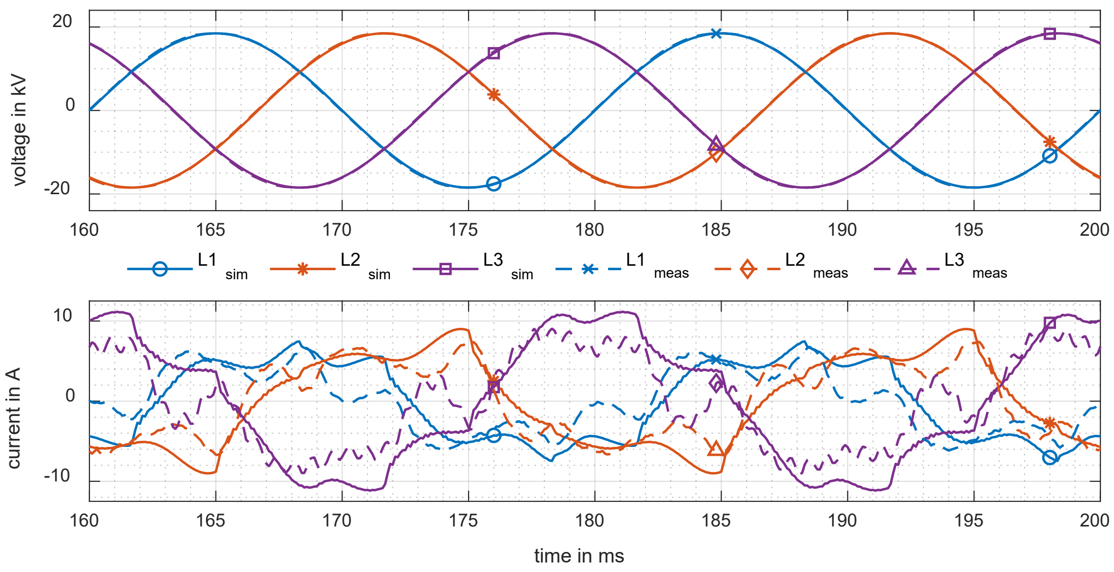
Transformer Modelling | Use-Case 786 kVA Transformer

Saturation Curve vs. Hysteresis Model





Power Transformers

Transformer Digital Twin

State-of-the-Art Diagnostics

Transformer Modelling

Advances Diagnostics

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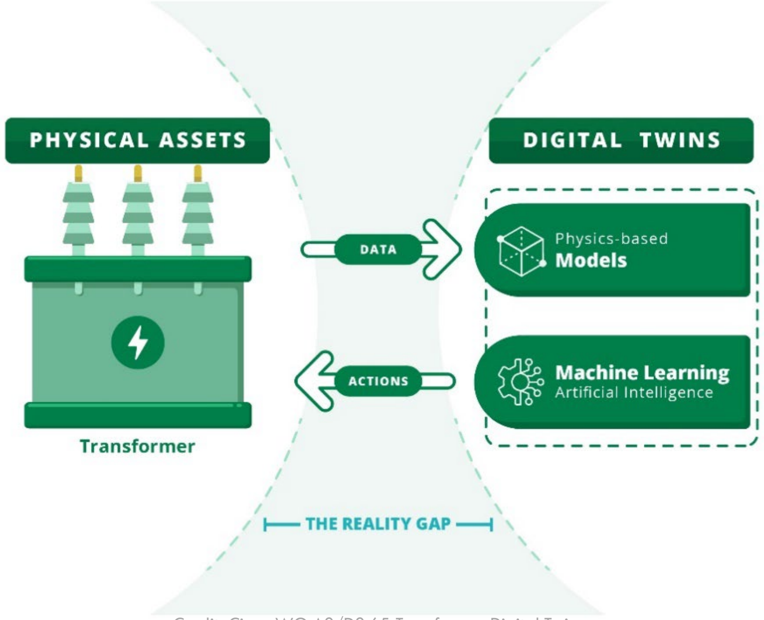
Transformer Digital Twin

- **Definition**[1]
  - ✓ 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



Credit: Cigre WG A2/D2.65 Transformer Digital Twin

[1] Trauer J, Schweigert-Recksiek S, Engel C, Spreitzer K, Zimmermann M. WHAT IS A DIGITAL TWIN? – DEFINITIONS AND INSIGHTS FROM AN INDUSTRIAL CASE STUDY IN TECHNICAL PRODUCT DEVELOPMENT. *Proceedings of the Design Society: DESIGN Conference*. 2020;1:757-766. doi:10.1017/dsd.2020.15

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

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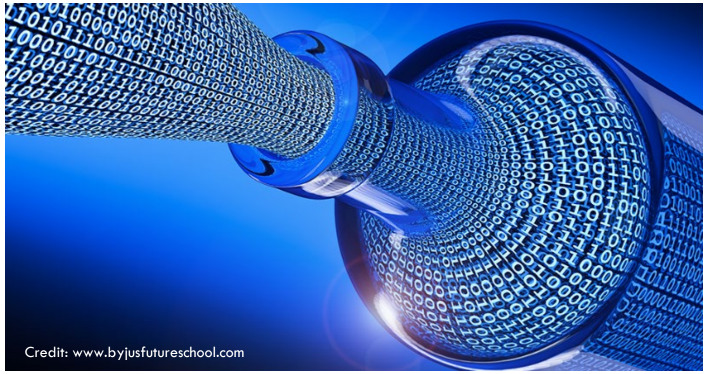
Transformer Digital Twin | Applications & Bottle Necks

- Anomaly detection
- Diagnosis
- Prognosis
- Predictive maintenance



- Standardization of interfaces/data exchange
- Data quality validation

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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

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Thanks for listening ;)

Dennis Albert | dennis.albert@omicronenergy.com

Webinar – 2024-06-26

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

(IEEE 2001) IEEE, C57.12.91, IEEE Standard Test Code for Dry-Type Distribution and Power Transformers, 2001

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