TechCon® SE Asia 2017

Transformer Health Assessment

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OMICRON

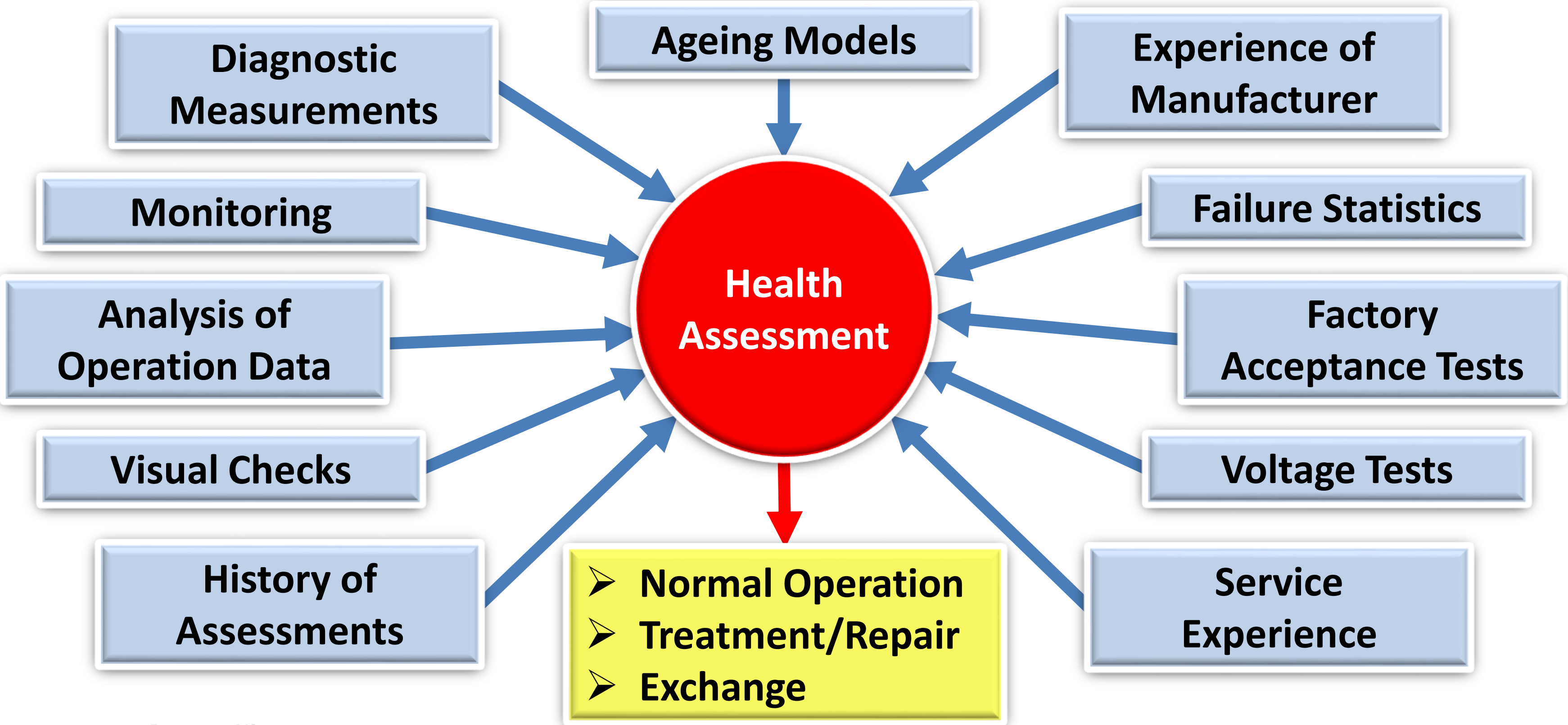
Transformer Health Assessment

- **Introduction**
- Diagnostic on Power Transformers
  - Oil
  - Main Insulation
  - Magnetic Core and Coil
  - Diagnostic of the Bushings
  - Diagnostic of the Tap Changer
- Case Study – Health Assessment of a Transformer

Work of Cigre - Transformer Health Assessment

Cigre WG	Topic	Brochure	Year
A2.18	Life Management Techniques for Power Transformers	227	2003
A2.27	Recommendations for Condition Monitoring and Conditioning Assessment for Transformers	343	2008
A2.34	Guide for Transformer Maintenance	445	2011
A2.37	Transformer Reliability Survey	642	2015
A2.43	Bushing Reliability		
A2.44	Intelligent Conditioning Monitoring Systems	630	2015
A2.45	Transformer Failure Investigation and Post-Mortem Analysis		
A2.49	Condition Assessment of Power Transformers		
A2.55	Life Extension of Oil Filled Transformers and Shunt Reactors		

Assessment of Transformer Health



Diagnostic Measurements

Ageing Models

Experience of Manufacturer

Monitoring

Failure Statistics

Analysis of Operation Data

Health Assessment

Factory Acceptance Tests

Visual Checks

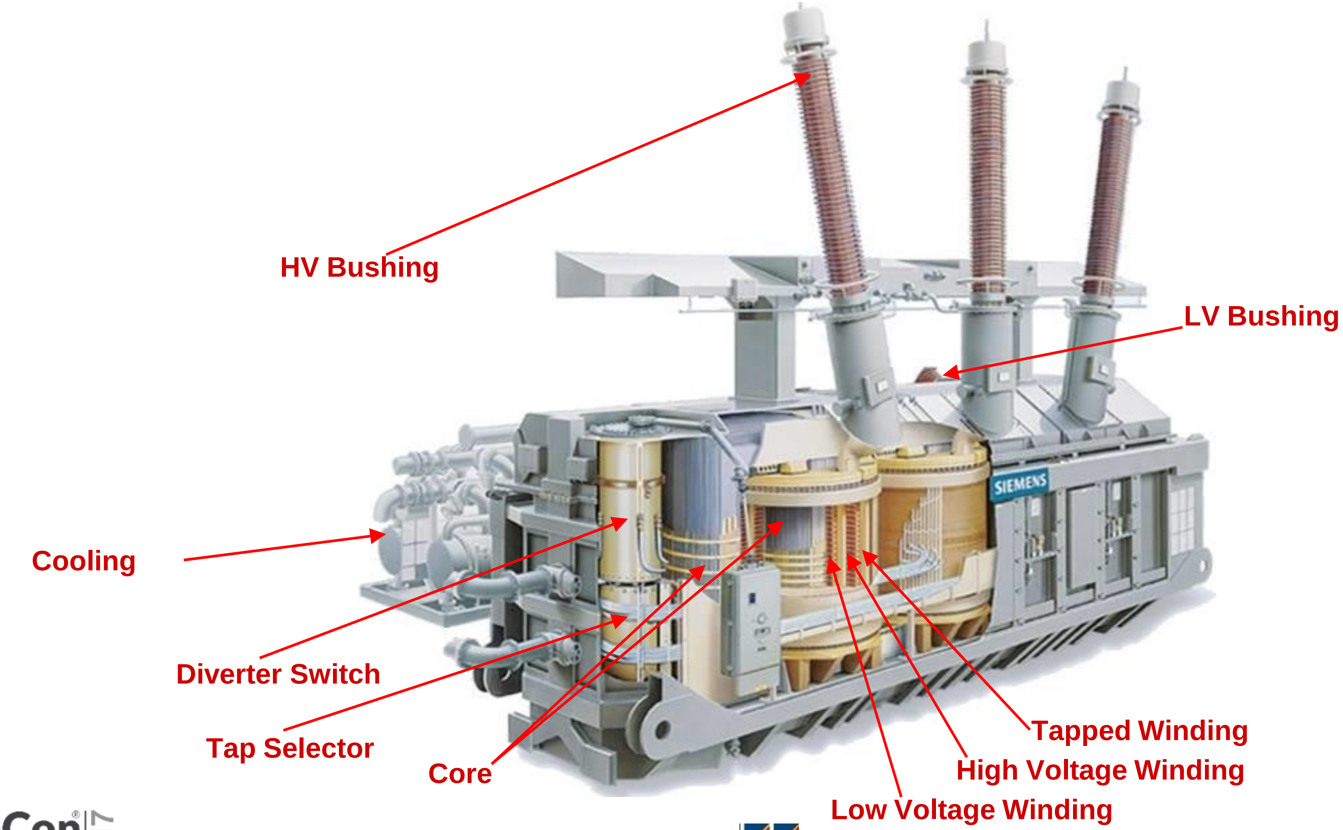
Voltage Tests

History of Assessments

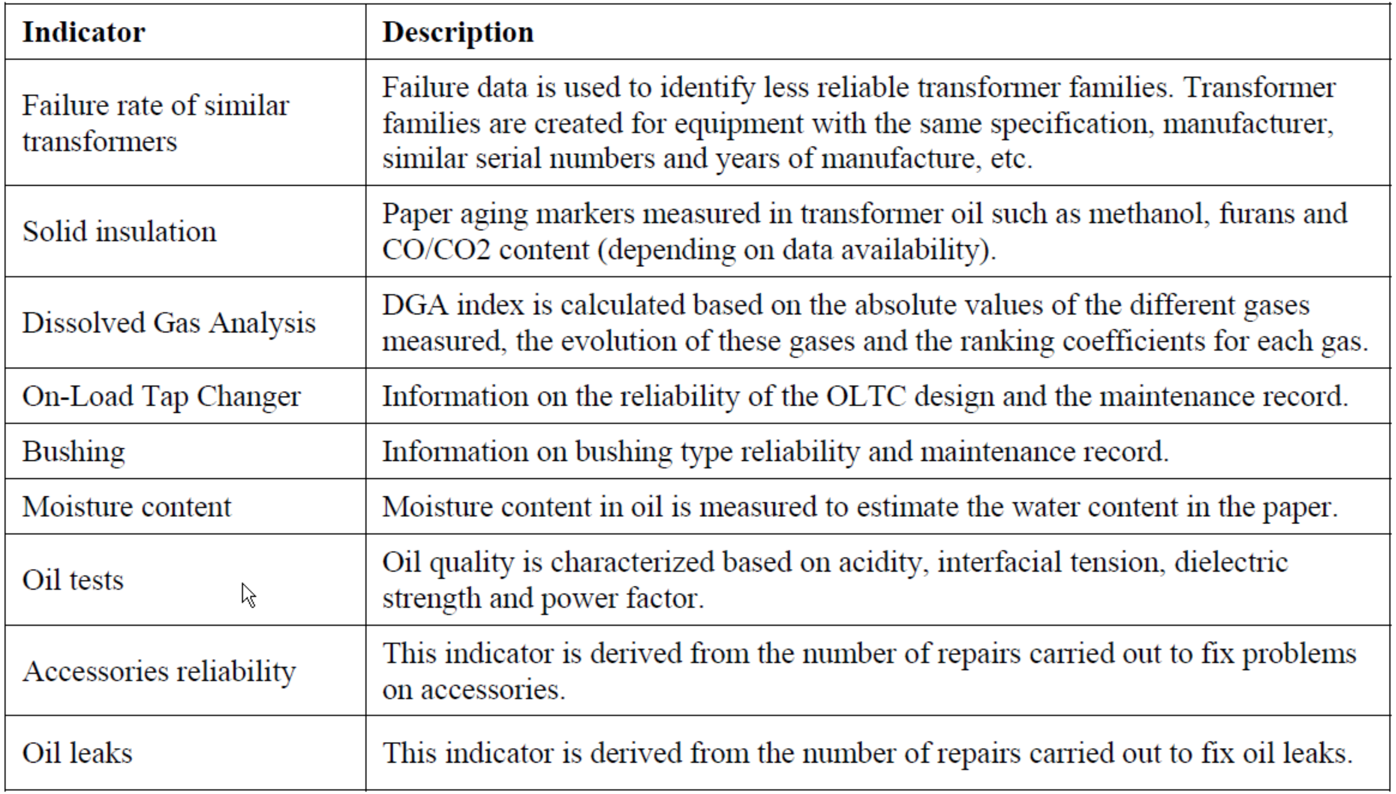
- Normal Operation
- Treatment/Repair
- Exchange

Service Experience

Components of a Generator Step-Up Transformer



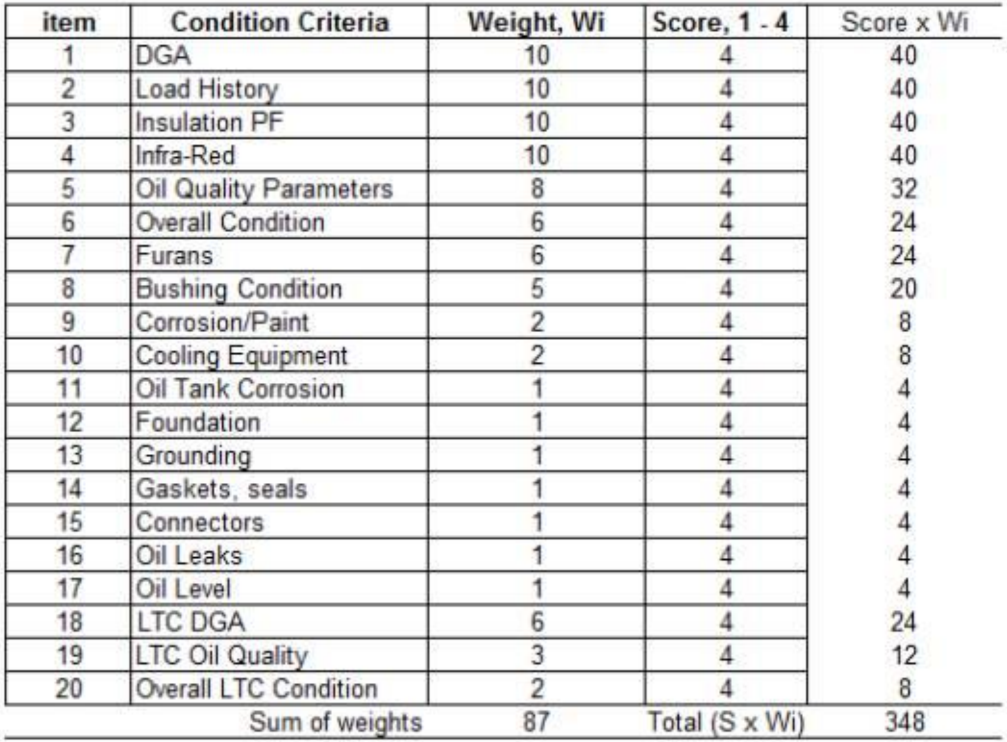
Indicators used to Estimate the Health Index



Indicator	Description
Failure rate of similar transformers	Failure data is used to identify less reliable transformer families. Transformer families are created for equipment with the same specification, manufacturer, similar serial numbers and years of manufacture, etc.
Solid insulation	Paper aging markers measured in transformer oil such as methanol, furans and CO/CO2 content (depending on data availability).
Dissolved Gas Analysis	DGA index is calculated based on the absolute values of the different gases measured, the evolution of these gases and the ranking coefficients for each gas.
On-Load Tap Changer	Information on the reliability of the OLTC design and the maintenance record.
Bushing	Information on bushing type reliability and maintenance record.
Moisture content	Moisture content in oil is measured to estimate the water content in the paper.
Oil tests	Oil quality is characterized based on acidity, interfacial tension, dielectric strength and power factor.
Accessories reliability	This indicator is derived from the number of repairs carried out to fix problems on accessories.
Oil leaks	This indicator is derived from the number of repairs carried out to fix oil leaks.

P. Picher et. al. „Use of Health and Reliability Dta for Transformer Condtioning Assessment and Fleet Ranking“, A2-101, Cigre Paris 2014

Assessment of Risks

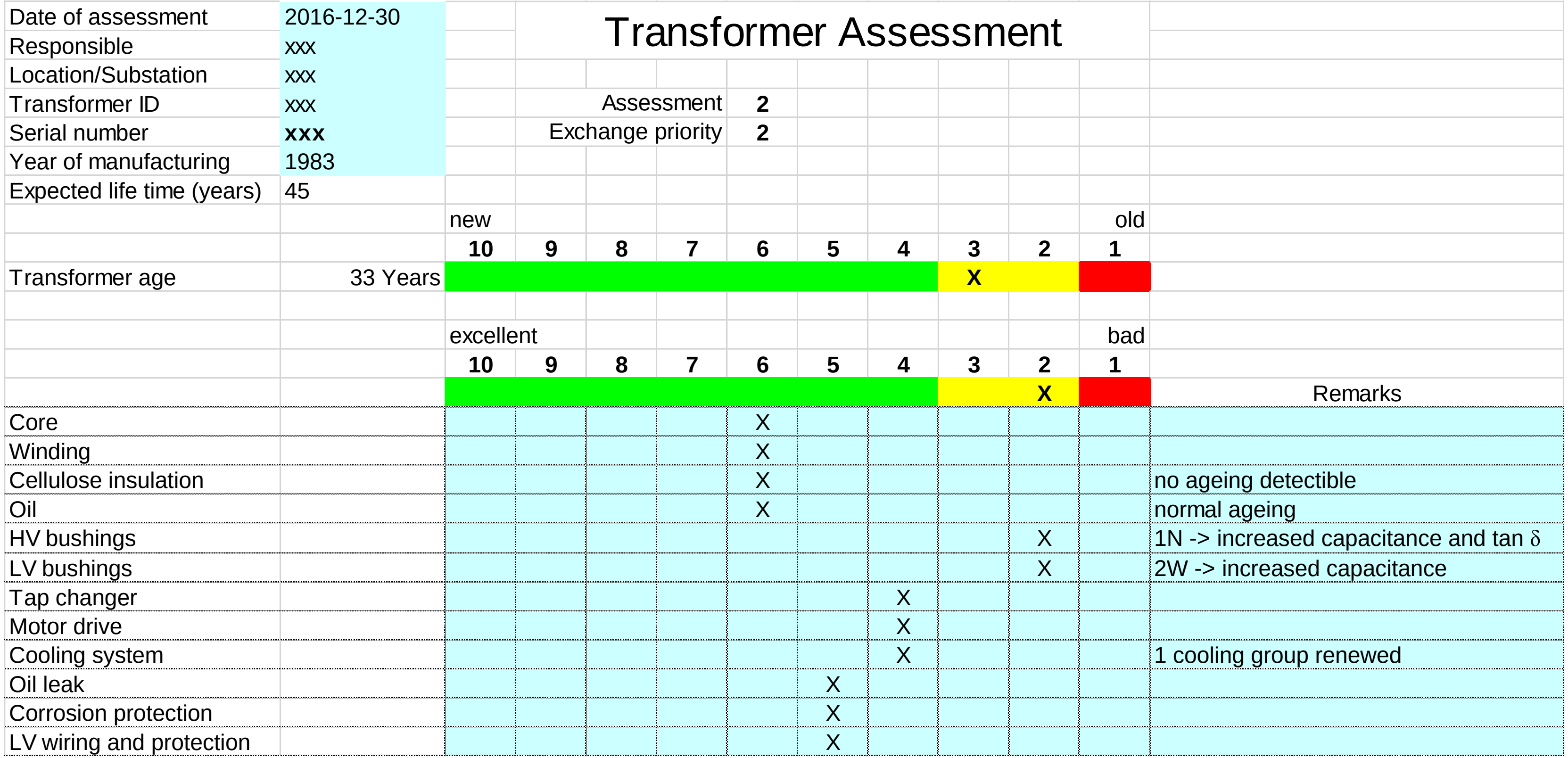


item	Condition Criteria	Weight, Wi	Score, 1 - 4	Score x Wi
1	DGA	10	4	40
2	Load History	10	4	40
3	Insulation PF	10	4	40
4	Infra-Red	10	4	40
5	Oil Quality Parameters	8	4	32
6	Overall Condition	6	4	24
7	Furans	6	4	24
8	Bushing Condition	5	4	20
9	Corrosion/Paint	2	4	8
10	Cooling Equipment	2	4	8
11	Oil Tank Corrosion	1	4	4
12	Foundation	1	4	4
13	Grounding	1	4	4
14	Gaskets, seals	1	4	4
15	Connectors	1	4	4
16	Oil Leaks	1	4	4
17	Oil Level	1	4	4
18	LTC DGA	6	4	24
19	LTC Oil Quality	3	4	12
20	Overall LTC Condition	2	4	8
	Sum of weights	87	Total (S x Wi)	348

$$H.I = \frac{\Sigma(Wi \times Si)}{\Sigma(W i \times Si\ max)}$$

H.I. = 100.0%

Transformer Assessment



Date of assessment	2016-12-30		Transformer Assessment									
Responsible	xxx											
Location/Substation	xxx											
Transformer ID	xxx				Assessment	2						
Serial number	**xxx**				Exchange priority	2						
Year of manufacturing	1983											
Expected life time (years)	45											
		new									old	
		10	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	
Transformer age	33 Years	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨 **X**	🟨	🟥	
		excellent									bad	
		10	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	
		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟨 **X**	🟥	Remarks
Core						X						
Winding						X						
Cellulose insulation						X						no ageing detectible
Oil						X						normal ageing
HV bushings										X		1N -> increased capacitance and tan δ
LV bushings										X		2W -> increased capacitance
Tap changer								X				
Motor drive								X				
Cooling system								X				1 cooling group renewed
Oil leak							X					
Corrosion protection							X					
LV wiring and protection							X					

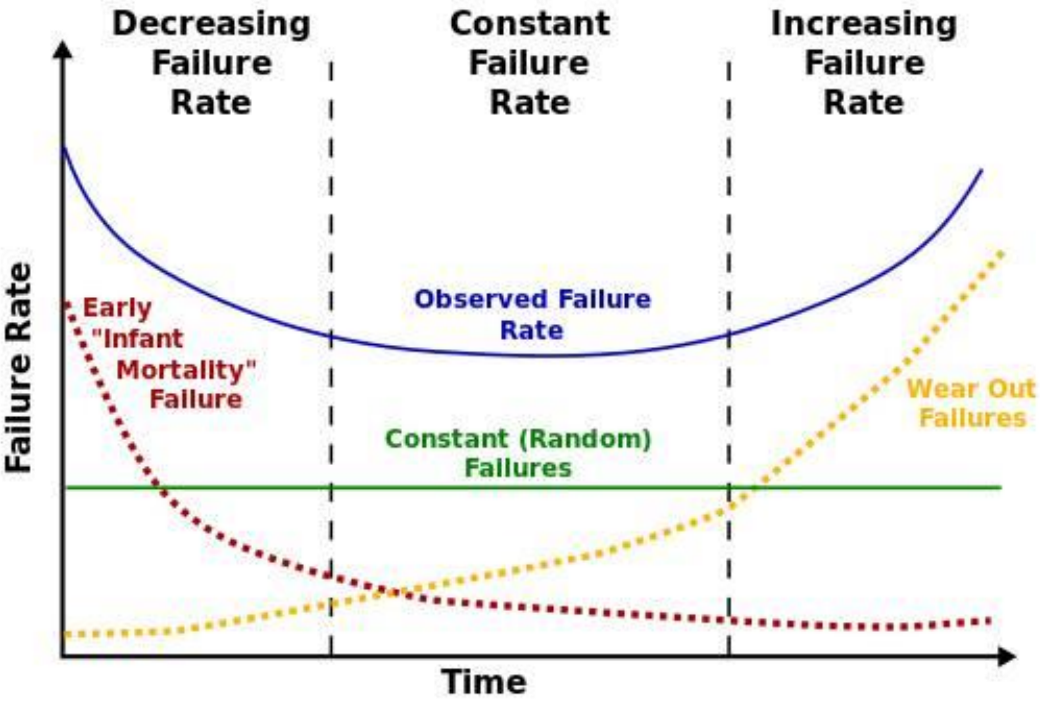
Source: VKW Bregenz Austria

Transformer Assessment

10	9	8	7	6
Excellent condition no diagnostic and repair measures in the long term **No recognizable defects exist**	**Excellent condition** long-term no diagnostic and repair measures **No notable defects exist**	**Very good condition** long-term no diagnostic and repair measures expected **Negligible deficiencies exist**	**Good condition** no immediate action required **Small deficiencies present, long term measures required**	**Satisfactory condition** no immediate action required **Major deficiencies exist, medium-term measures necessary**
5	4	3	2	1
Moderate condition no immediate action required **Major deficiencies exist, short-term measures necessary**	**Sufficient condition** partial repair necessary **Severe shortcomings, operation of the plant in the medium term with increased operational risk**	**Poor condition** partial repair necessary **Severe shortcomings, operation of the system in the short term with increased operational risk**	**Insufficient condition** partial repair necessary, increased operating risk **Safe operation of the system without online monitoring no longer ensured**	**Very bad condition** immediate general repair necessary **Safe operation of the system no longer ensured**

Source: VKW Bregenz Austria

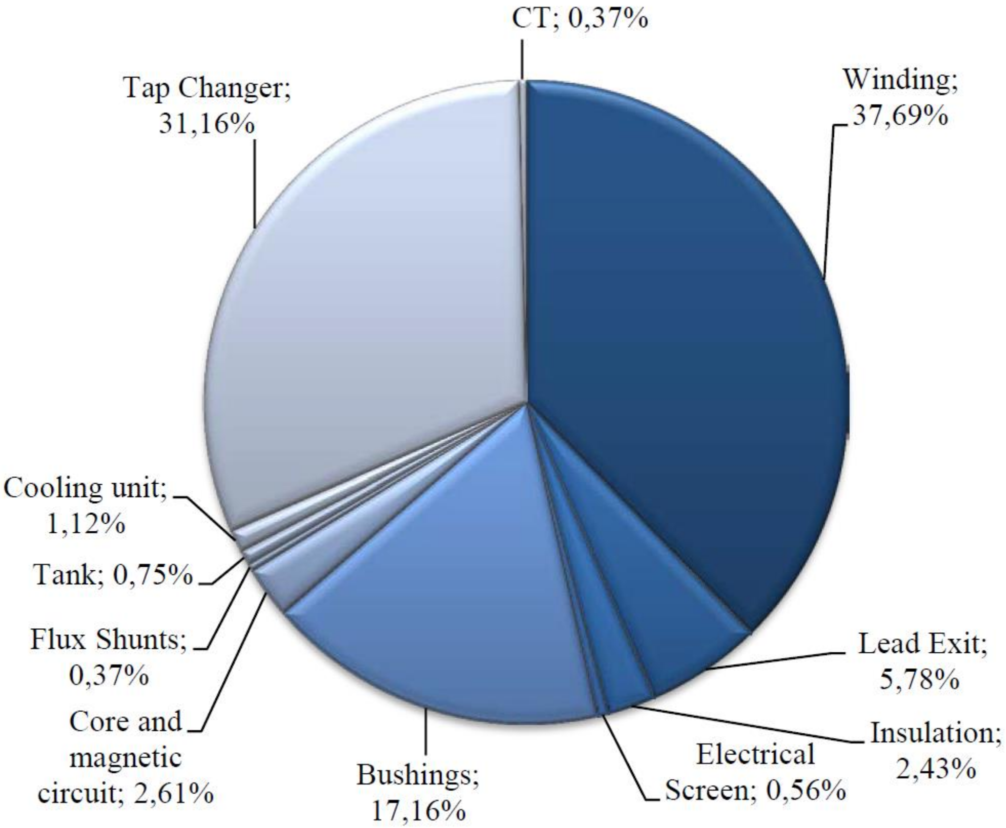
Bathtube Curve of Failure Rate



Source: Wikipedia Feb. 2014

Failure Locations

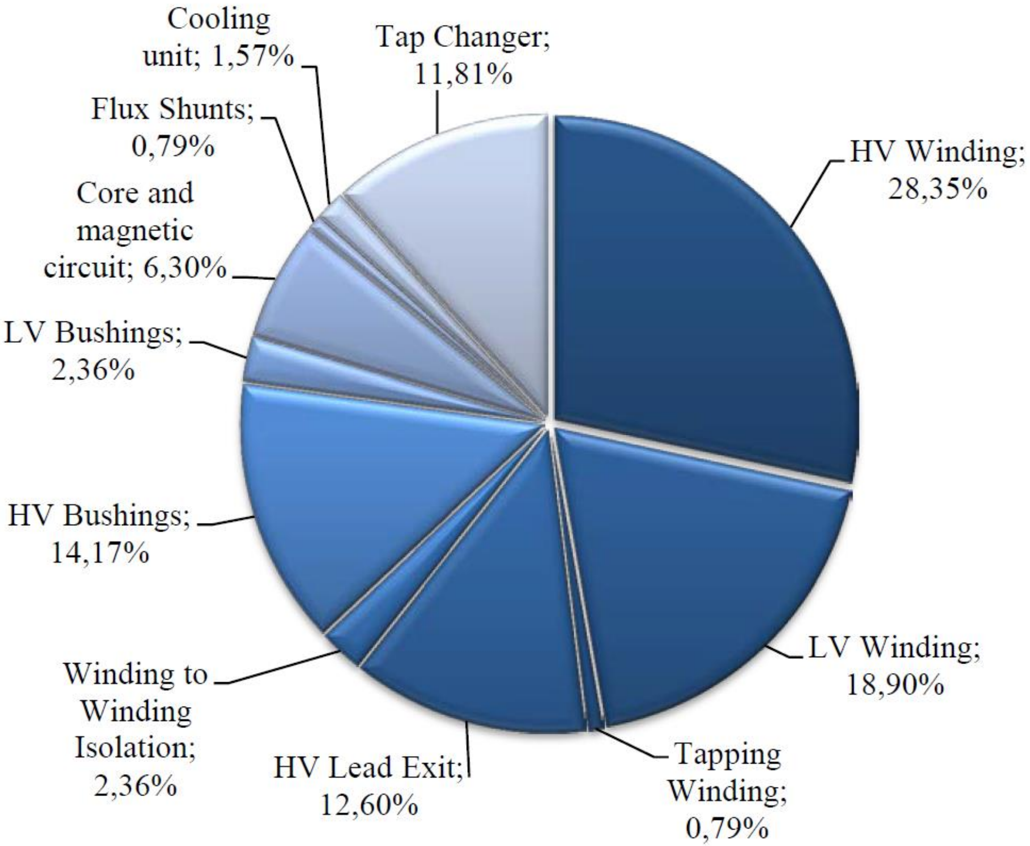
of Substation Transformers > 100kV



Source: Cigre WG A2.37 “Transformer Reliability“, Cigre Brochure 642

Failure Locations

of Generator Step-up Transformers > 100kV



Source: Cigre WG A2.37 “Transformer Reliability“, Cigre Brochure 642

Causes of Ageing

- Dielectric causes
- Electromagnetic causes
- Thermal causes
- Chemical causes

Electromagnetic Causes of Ageing

High currents (e.g. due to short circuits nearby the transformer) produce high mechanical forces

- Deformation of the winding
- Damage of the paper insulation (cracks) , particularly on aged parts
- Initiation of partial discharges
- Initiation of partial break-downs

Thermal Causes of Ageing

- Hysteresis losses in the magnetic core
- Shorted laminates
- Resistive losses in the windings
- Dielectric losses in the insulation
- Load changes will cause warming up and cooling down - negative influence on the lifetime of the insulation
- The ageing of the insulation is accelerated by a factor 2, if the temperature is increased by 7°C (valid for normal operation temperatures)

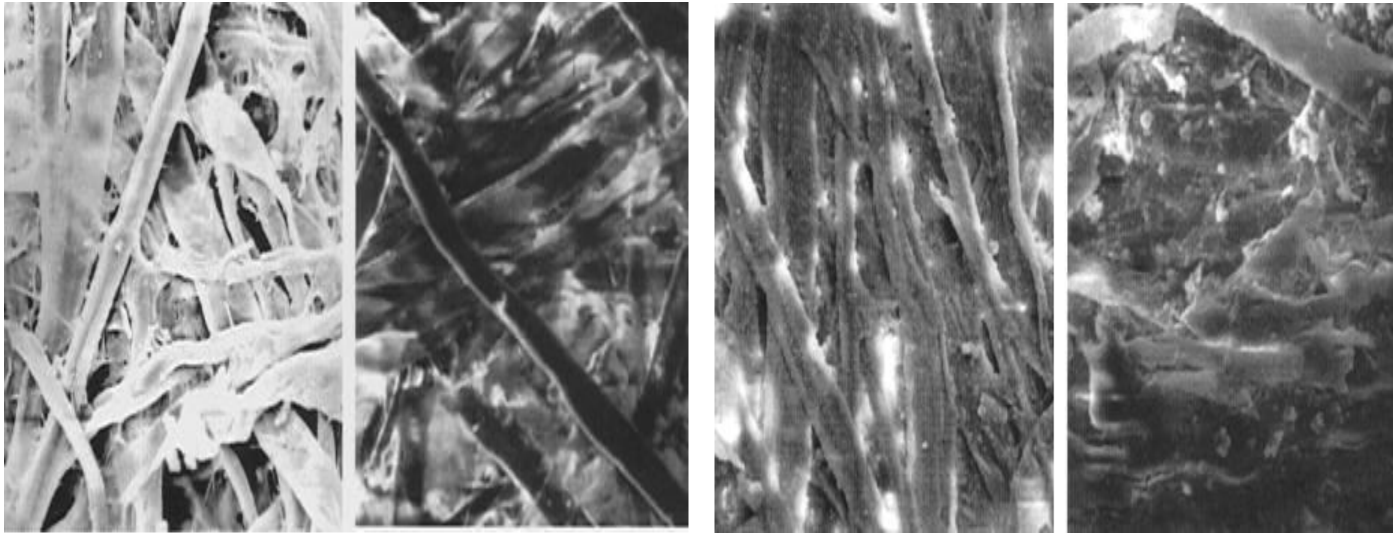
Chemical Causes of Ageing

Organic acids are produced as a result of ageing

- In particular, they affect the paper insulation
  -> accelerated ageing

- Metals like Copper, Iron, Aluminium and Zinc are behaving like catalysts
  -> accelerated ageing

Ageing of the Cellulose by Acids



Microstructure of paper with Neutralization Number [mg/kg]
(from left to right)   0.05   0.1   0.2   0.3

Ageing in the Cellulose

- Ageing of Cellulose is caused by:

- the influence of oxygen

  → Oxidation

- the influence of water

  → Hydrolysis

- the influence of heat

  → Pyrolysis

Ageing of Paper

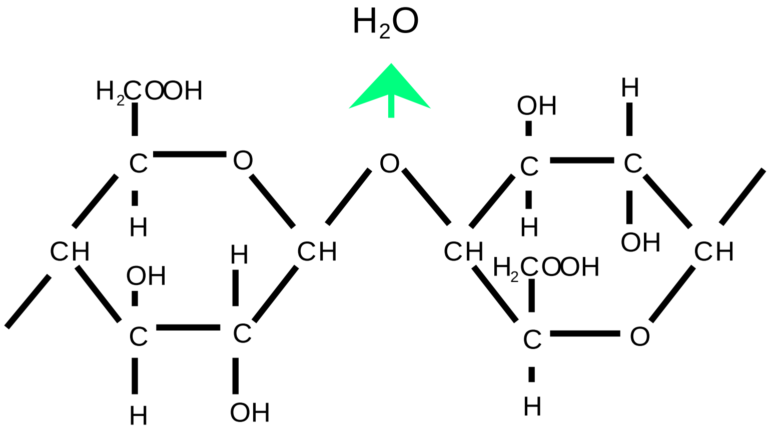
As the cellulose ages, the glucose ring chains break (depolymerisation). The following substances are produced:

Water

Gases (CO, CO2)

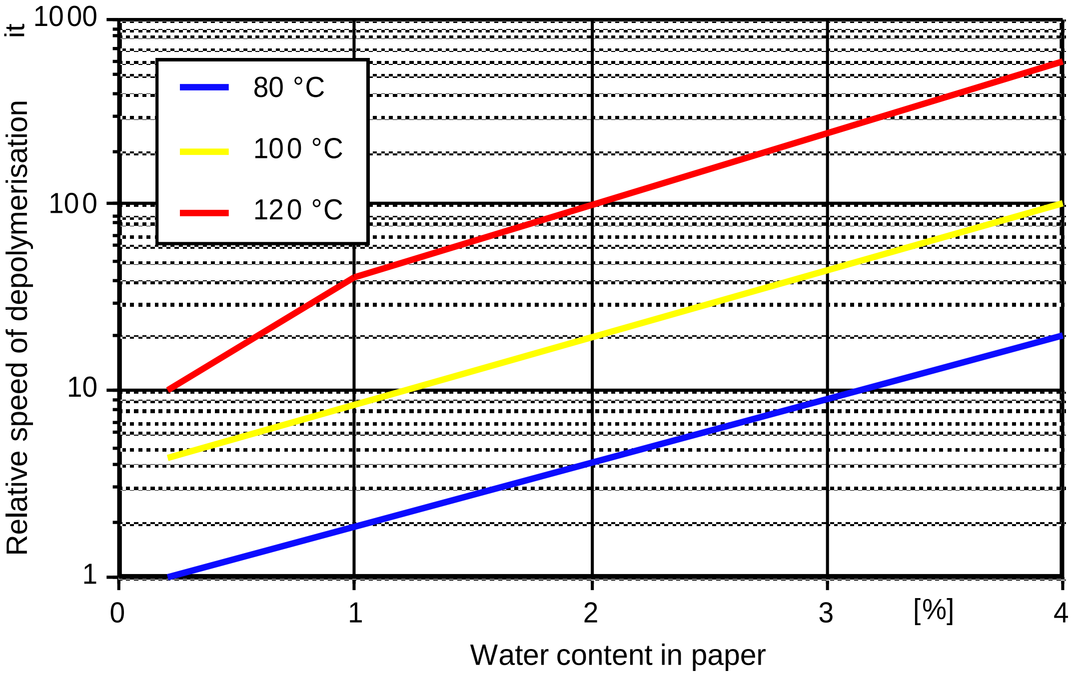
Furanes

Carboxyl Groups (organic acids)



Water as Ageing Factor

Water and heat accelerate the ageing of the Cellulose



➡ To extend the lifetime, the water has to be removed from the insulation!

Transformer Health Assessment

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- Case Study – Health Assessment of a Transformer

Information from Oil Analysis

DGA

Information about the transformer

Chemical and Electrical Tests

Information about the oil

Furan Analysis
Methanol Analysis
Ethanol Analysis

Information about the ageing of the solid insulation

IEC 60422

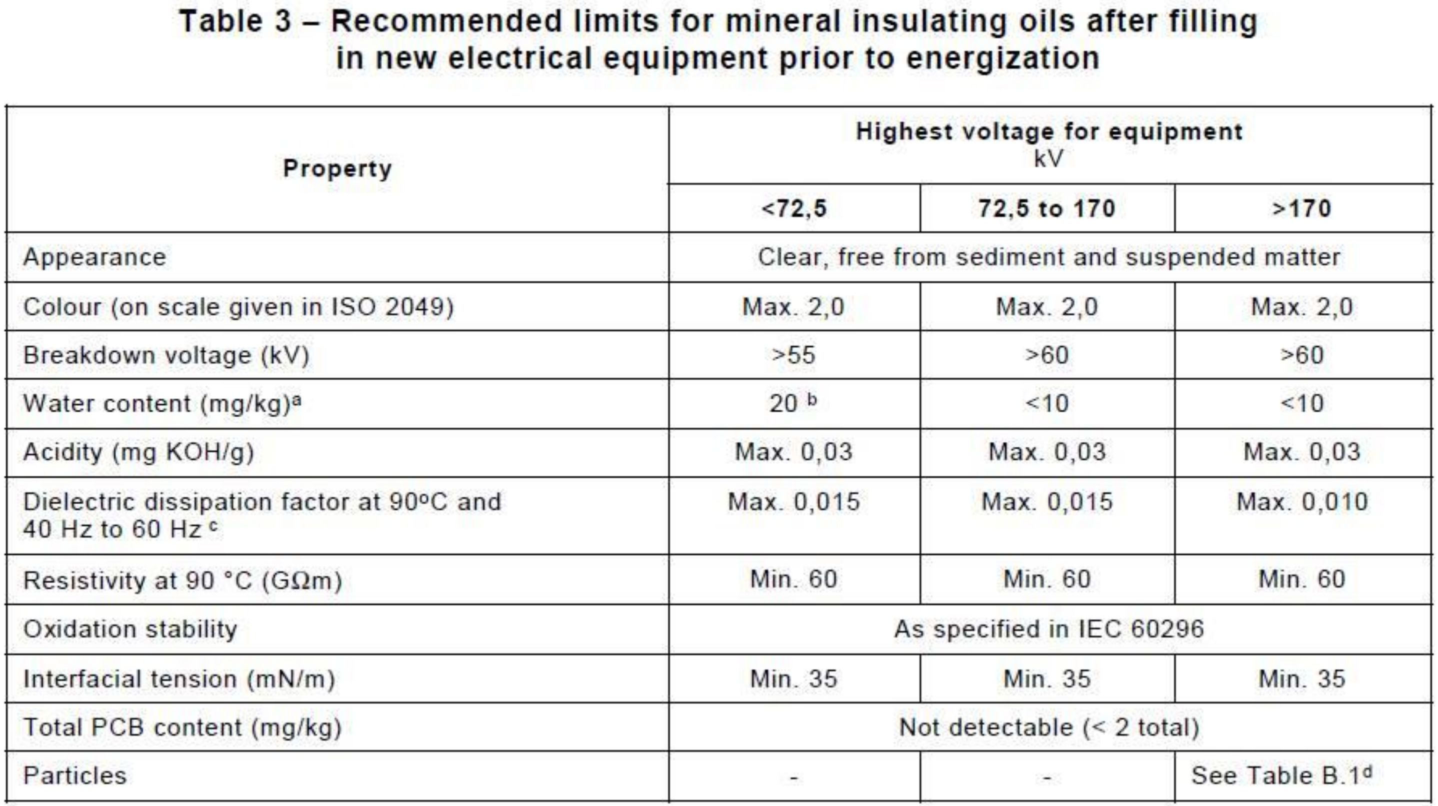


Table 3 – Recommended limits for mineral insulating oils after filling in new electrical equipment prior to energization

Property	**Highest voltage for equipment** kV		
	<72,5	**72,5 to 170**	**>170**
Appearance	Clear, free from sediment and suspended matter		
Colour (on scale given in ISO 2049)	Max. 2,0	Max. 2,0	Max. 2,0
Breakdown voltage (kV)	>55	>60	>60
Water content (mg/kg)[a]	20 [b]	<10	<10
Acidity (mg KOH/g)	Max. 0,03	Max. 0,03	Max. 0,03
Dielectric dissipation factor at 90°C and 40 Hz to 60 Hz [c]	Max. 0,015	Max. 0,015	Max. 0,010
Resistivity at 90 °C (GΩm)	Min. 60	Min. 60	Min. 60
Oxidation stability	As specified in IEC 60296		
Interfacial tension (mN/m)	Min. 35	Min. 35	Min. 35
Total PCB content (mg/kg)	Not detectable (< 2 total)		
Particles	-	-	See Table B.1[d]

IEC 60422

Water Saturation in Oil

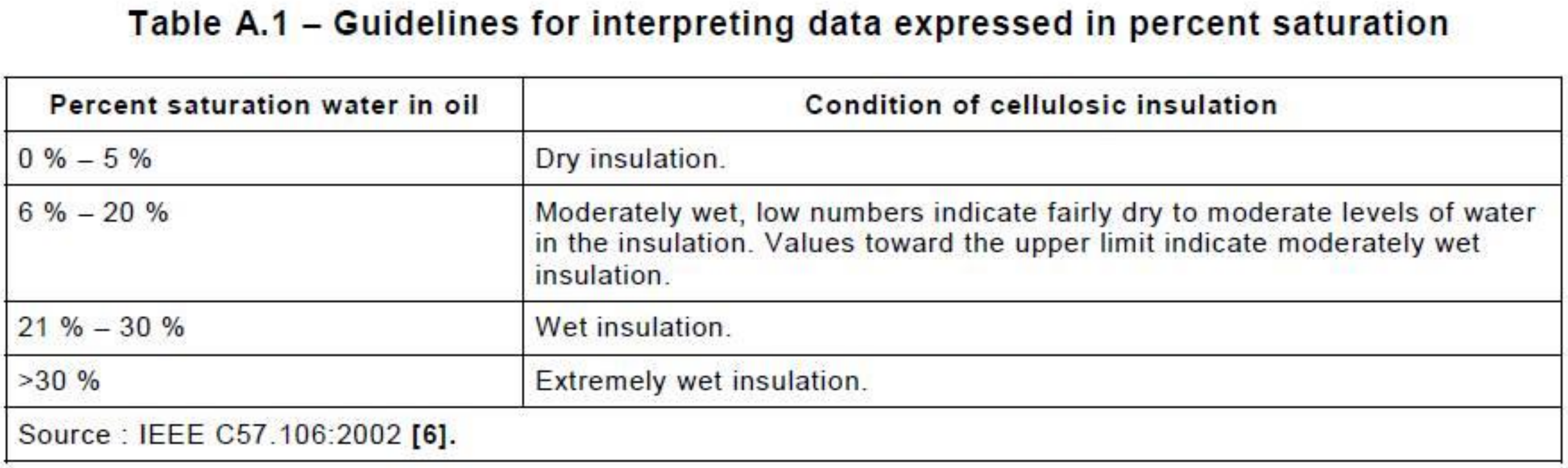
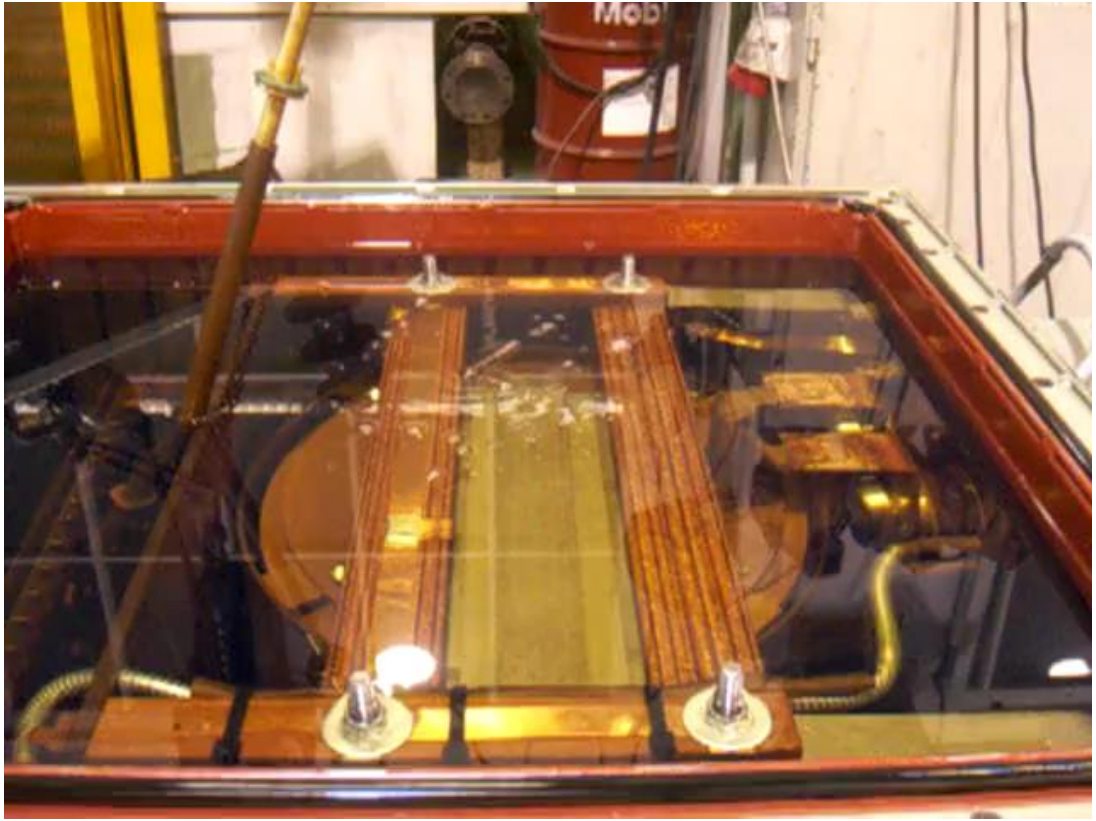


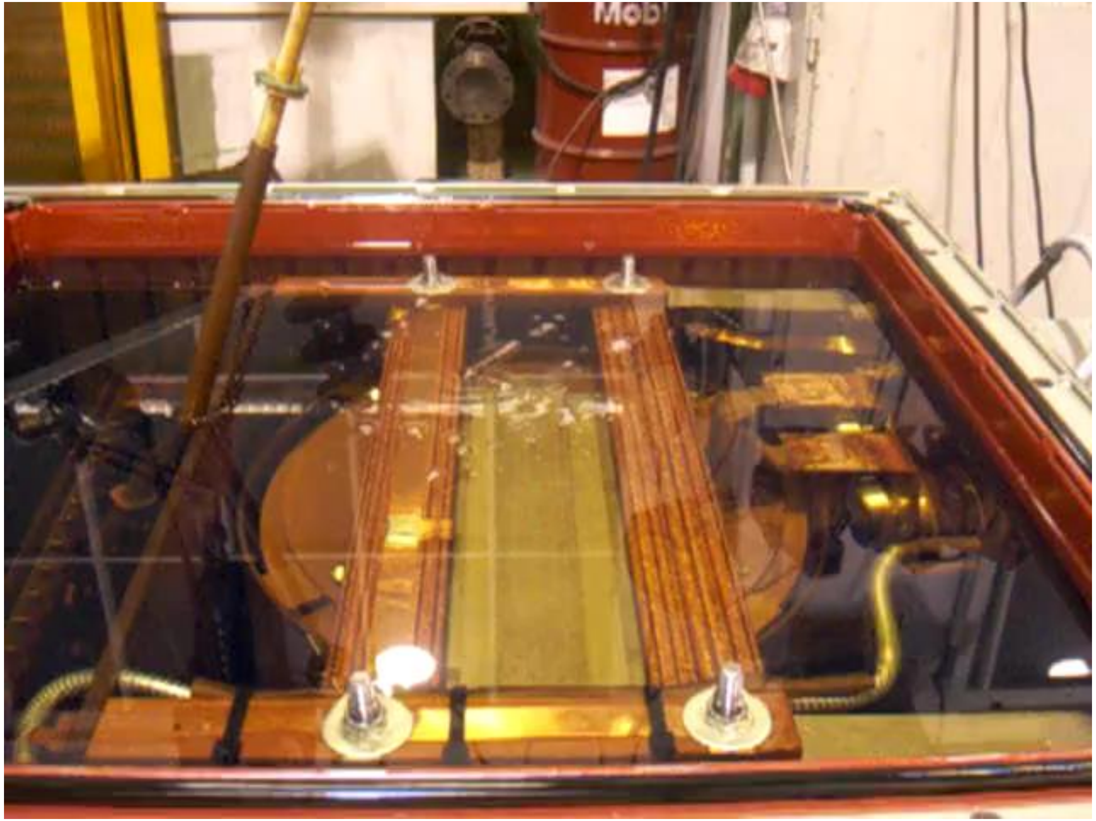
Table A.1 – Guidelines for interpreting data expressed in percent saturation

Percent saturation water in oil	Condition of cellulosic insulation
0 % – 5 %	Dry insulation.
6 % – 20 %	Moderately wet, low numbers indicate fairly dry to moderate levels of water in the insulation. Values toward the upper limit indicate moderately wet insulation.
21 % – 30 %	Wet insulation.
>30 %	Extremely wet insulation.
Source : IEEE C57.106:2002 **[6]**.	

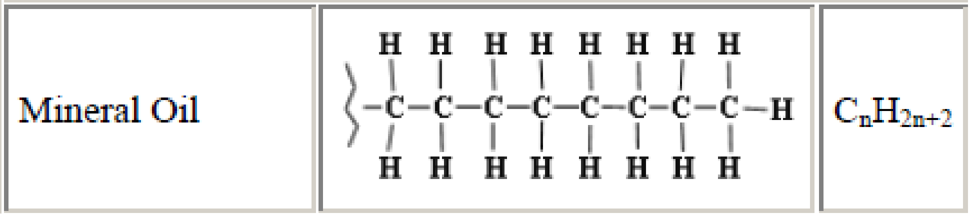
Gases in Oil caused by PD



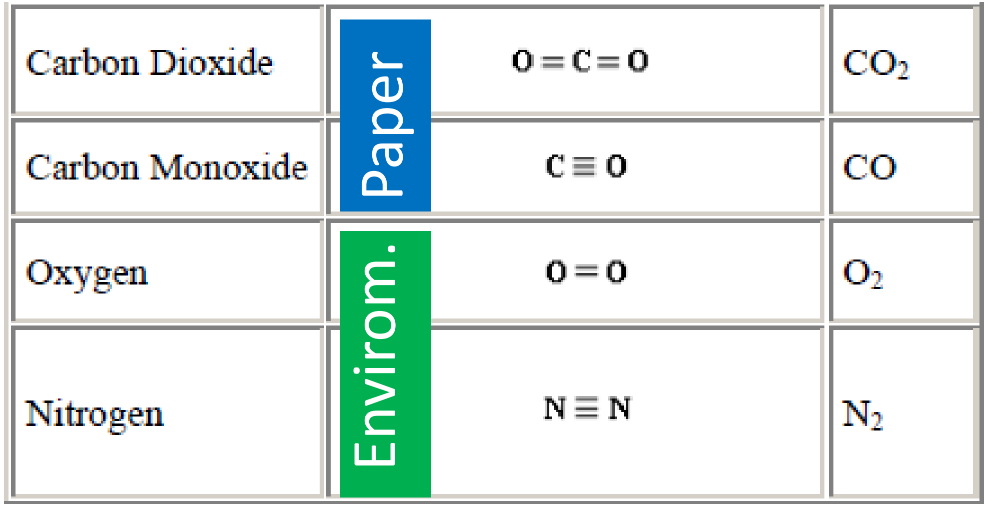
Gases in Oil caused by PD



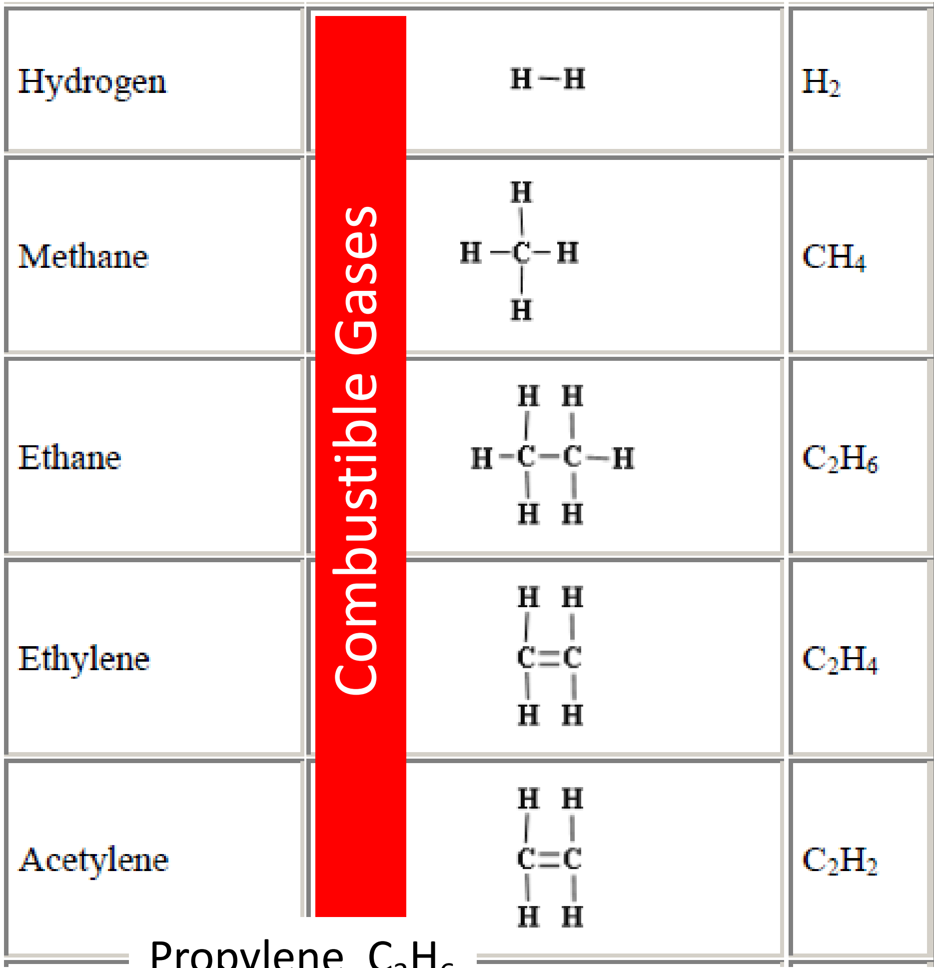
Gases



Mineral Oil	$\begin{array}{cccccccccc} & H & H & H & H & H & H & H & H & \\ & \vert & \vert & \vert & \vert & \vert & \vert & \vert & \vert & \\ \rangle - & C - & C - & C - & C - & C - & C - & C - & C - & H \\ & \vert & \vert & \vert & \vert & \vert & \vert & \vert & \vert & \\ & H & H & H & H & H & H & H & H & \end{array}$	C_nH_{2n+2}



Carbon Dioxide	Paper	$O=C=O$	CO_2
Carbon Monoxide		$C\equiv O$	CO
Oxygen	Envirom.	$O=O$	O_2
Nitrogen		$N\equiv N$	N_2



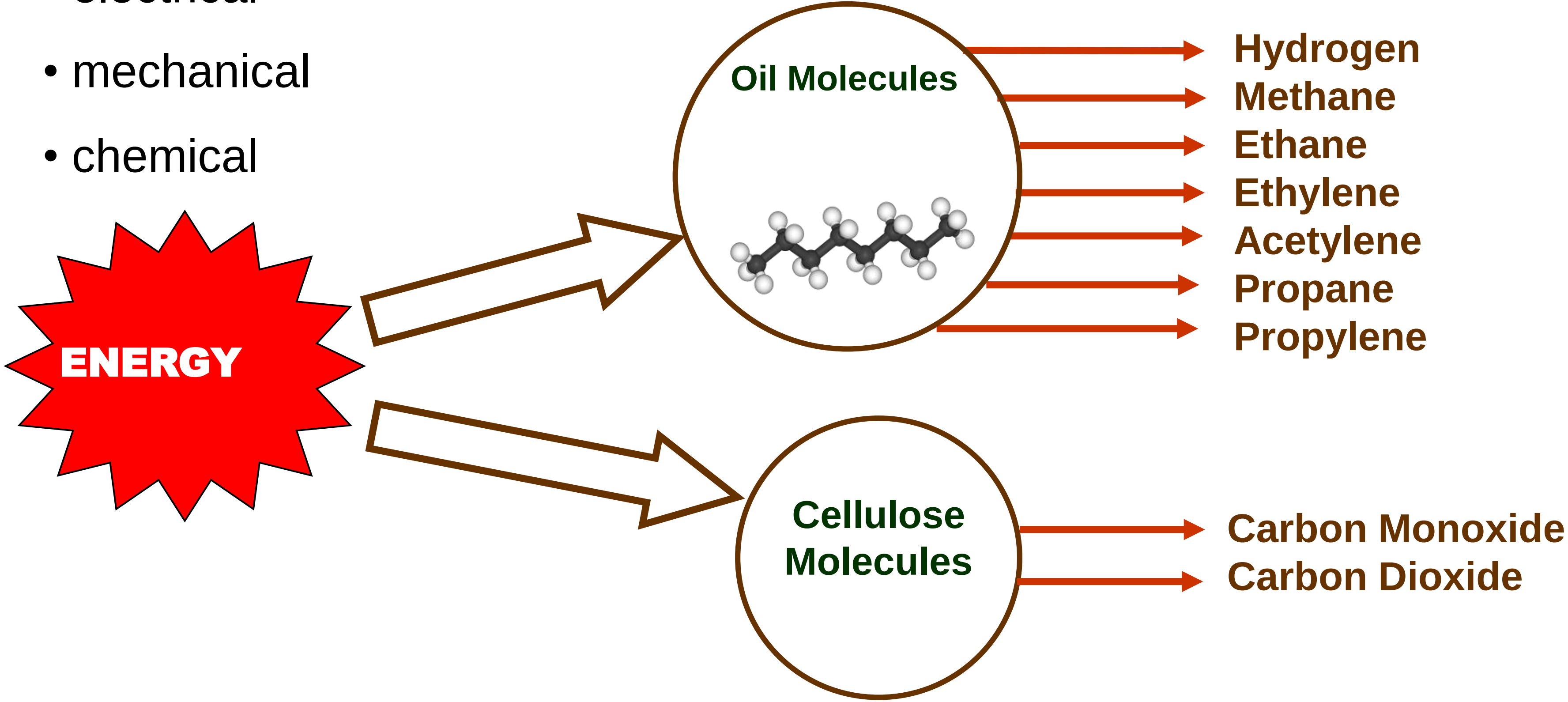
Hydrogen	Combustible Gases	$H-H$	H_2
Methane		$\begin{array}{ccc} & H & \\ & \vert & \\ H - & C & - H \\ & \vert & \\ & H & \end{array}$	CH_4
Ethane		$\begin{array}{cccc} & H & H & \\ & \vert & \vert & \\ H - & C - & C & - H \\ & \vert & \vert & \\ & H & H & \end{array}$	C_2H_6
Ethylene		$\begin{array}{cc} H & H \\ \vert & \vert \\ C = & C \\ \vert & \vert \\ H & H \end{array}$	C_2H_4
Acetylene		$\begin{array}{cc} H & H \\ \vert & \vert \\ C = & C \\ \vert & \vert \\ H & H \end{array}$	C_2H_2

Propylene C_3H_6

Propane C_3H_8

Fault Gas Formation

- thermal
- electrical
- mechanical
- chemical



ENERGY

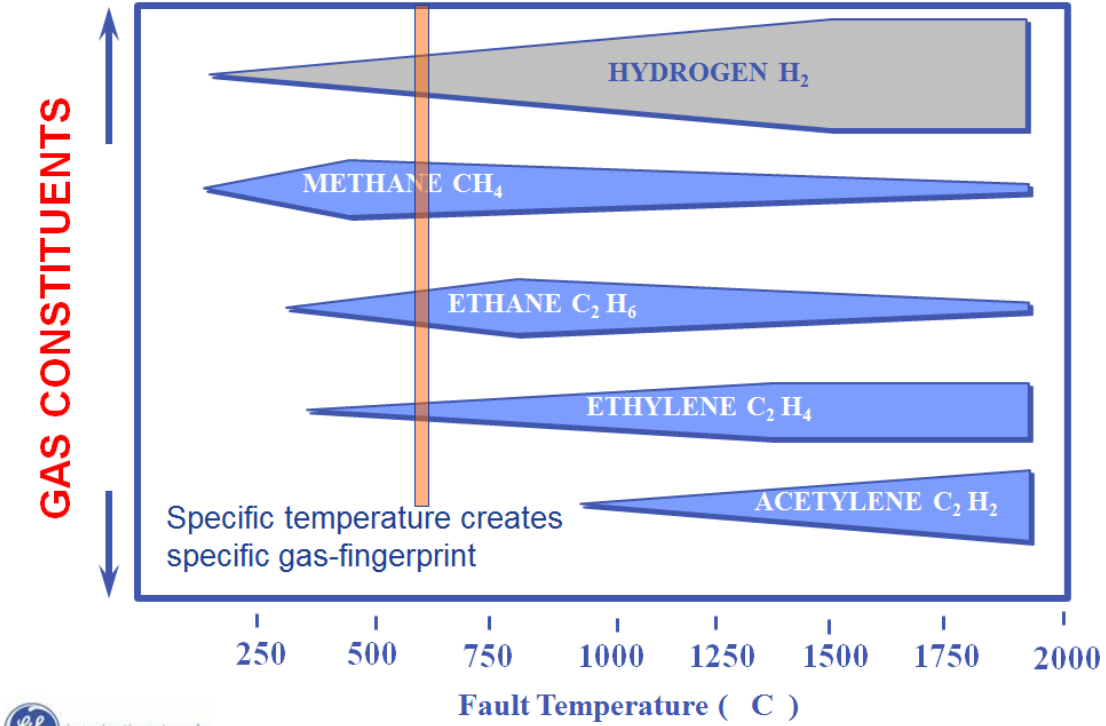
Oil Molecules

Hydrogen
Methane
Ethane
Ethylene
Acetylene
Propane
Propylene

Cellulose Molecules

Carbon Monoxide
Carbon Dioxide

Gas Formation from Oil Dependent on the Temperature

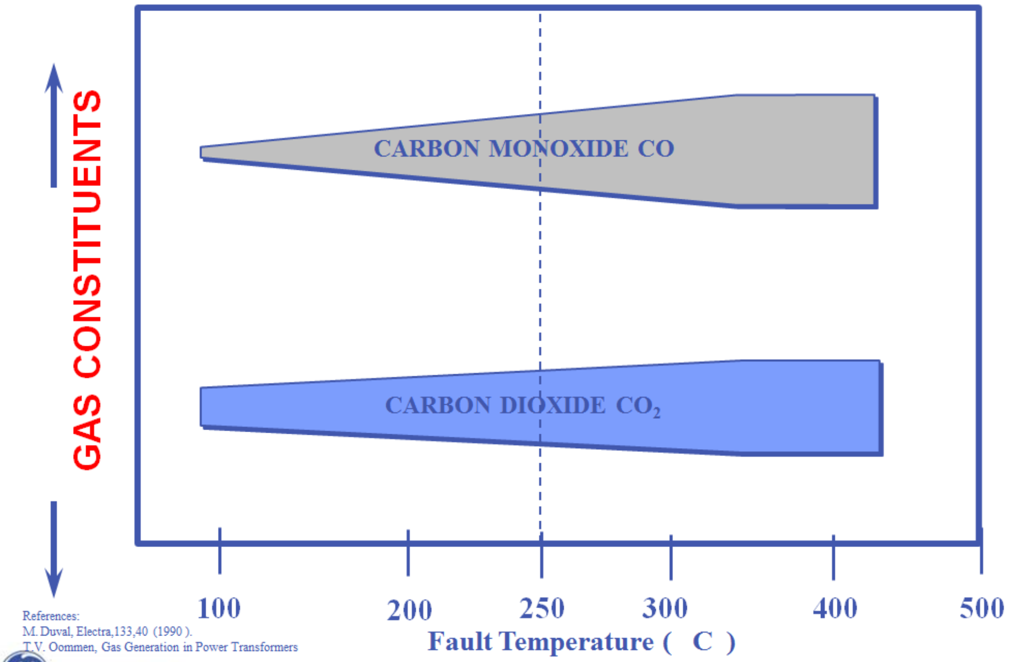


Specific temperature creates specific gas-fingerprint

imagination at work

Monitoring & Diagnostic Product Range – Feb. 2012

Gas Formation from Cellulose Dependent on the Temperature

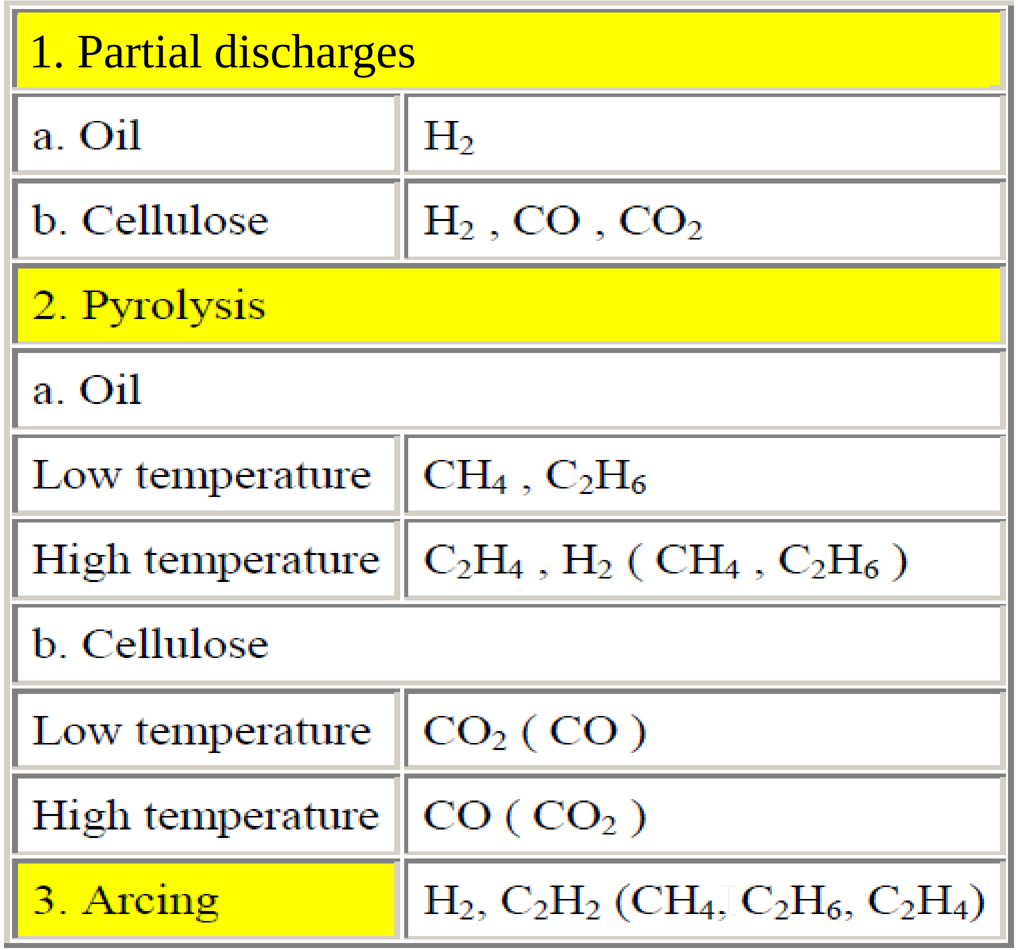


References:
M. Duval, Electra,133,40 (1990).
T.V. Oommen, Gas Generation in Power Transformers

imagination at work

Monitoring & Diagnostic Product Range – Feb. 2012

Key Gases



1. Partial discharges	
a. Oil	H_2
b. Cellulose	H_2 , CO , CO_2
2. Pyrolysis	
a. Oil	
Low temperature	CH_4 , C_2H_6
High temperature	C_2H_4 , H_2 (CH_4 , C_2H_6)
b. Cellulose	
Low temperature	CO_2 (CO)
High temperature	CO (CO_2)
3. Arcing	H_2, C_2H_2 (CH_4, C_2H_6, C_2H_4)

Cigre Brochure 296 – Typical Gas Values

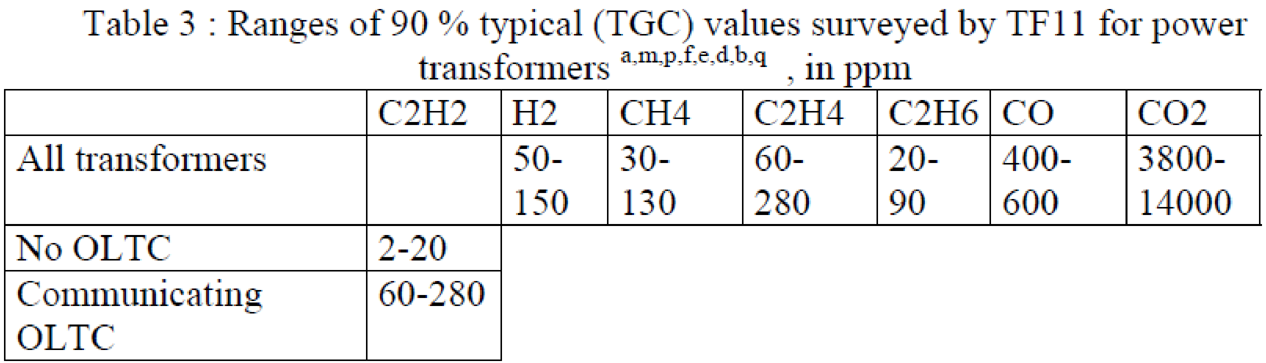


Table 3 : Ranges of 90 % typical (TGC) values surveyed by TF11 for power transformers [a,m,p,f,e,d,b,q] , in ppm

	C2H2	H2	CH4	C2H4	C2H6	CO	CO2
All transformers		50-150	30-130	60-280	20-90	400-600	3800-14000
No OLTC	2-20						
Communicating OLTC	60-280						

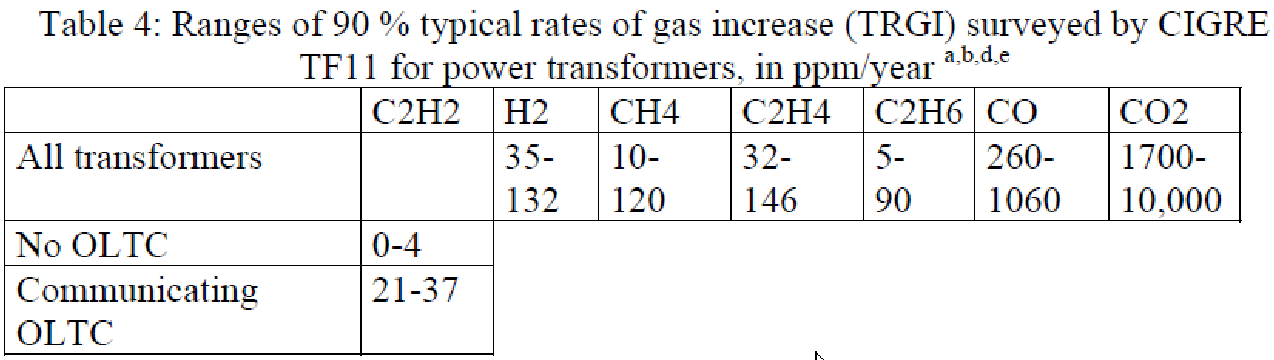
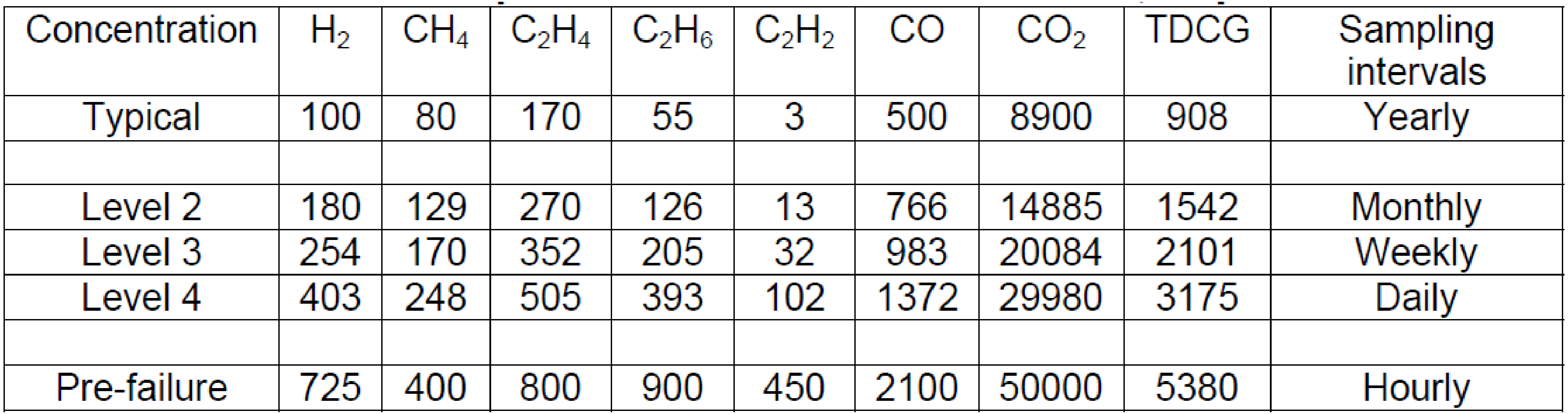


Table 4: Ranges of 90 % typical rates of gas increase (TRGI) surveyed by CIGRE TF11 for power transformers, in ppm/year [a,b,d,e]

	C2H2	H2	CH4	C2H4	C2H6	CO	CO2
All transformers		35-132	10-120	32-146	5-90	260-1060	1700-10,000
No OLTC	0-4						
Communicating OLTC	21-37						

Cigre Brochure 443

Oil Sampling Intervals versus Gas Concentrations



Concentration	H_2	CH_4	C_2H_4	C_2H_6	C_2H_2	CO	CO_2	TDCG	Sampling intervals
Typical	100	80	170	55	3	500	8900	908	Yearly
Level 2	180	129	270	126	13	766	14885	1542	Monthly
Level 3	254	170	352	205	32	983	20084	2101	Weekly
Level 4	403	248	505	393	102	1372	29980	3175	Daily
Pre-failure	725	400	800	900	450	2100	50000	5380	Hourly

IEEE Std C57.104

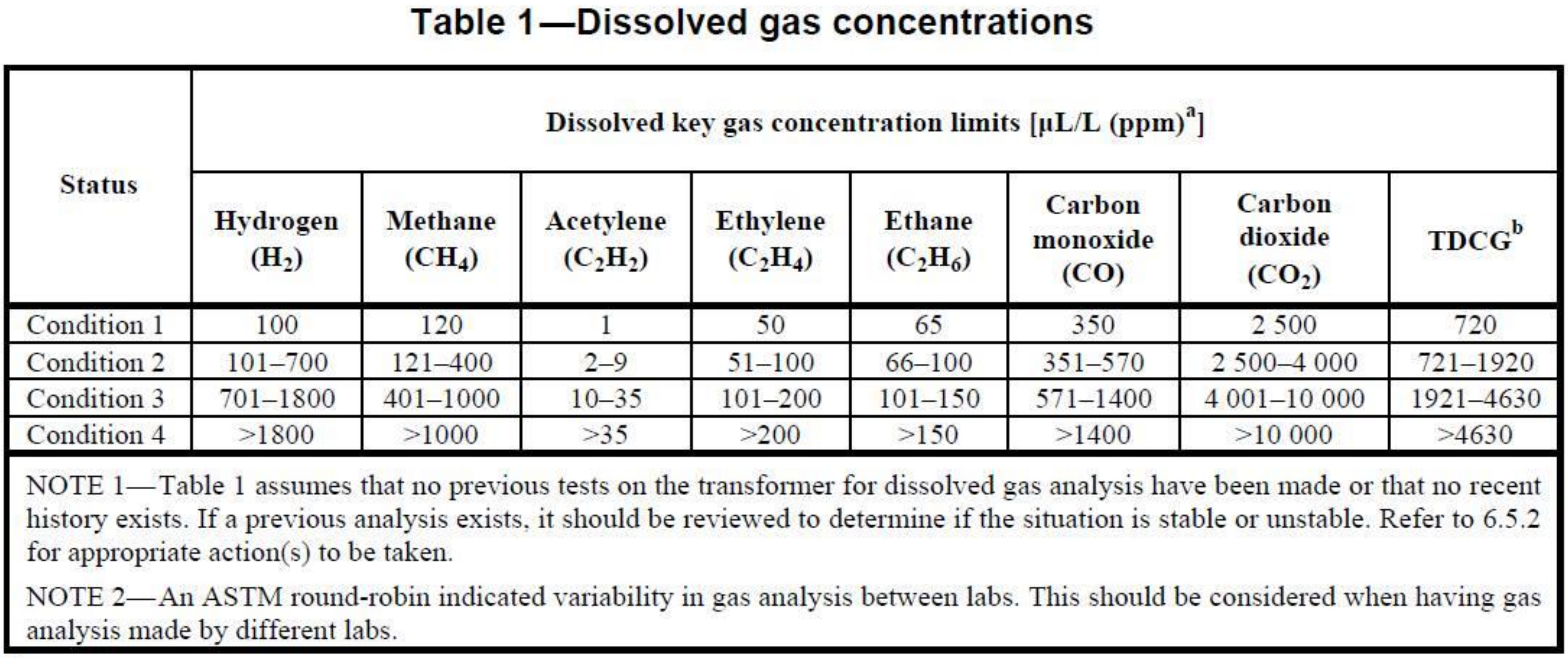


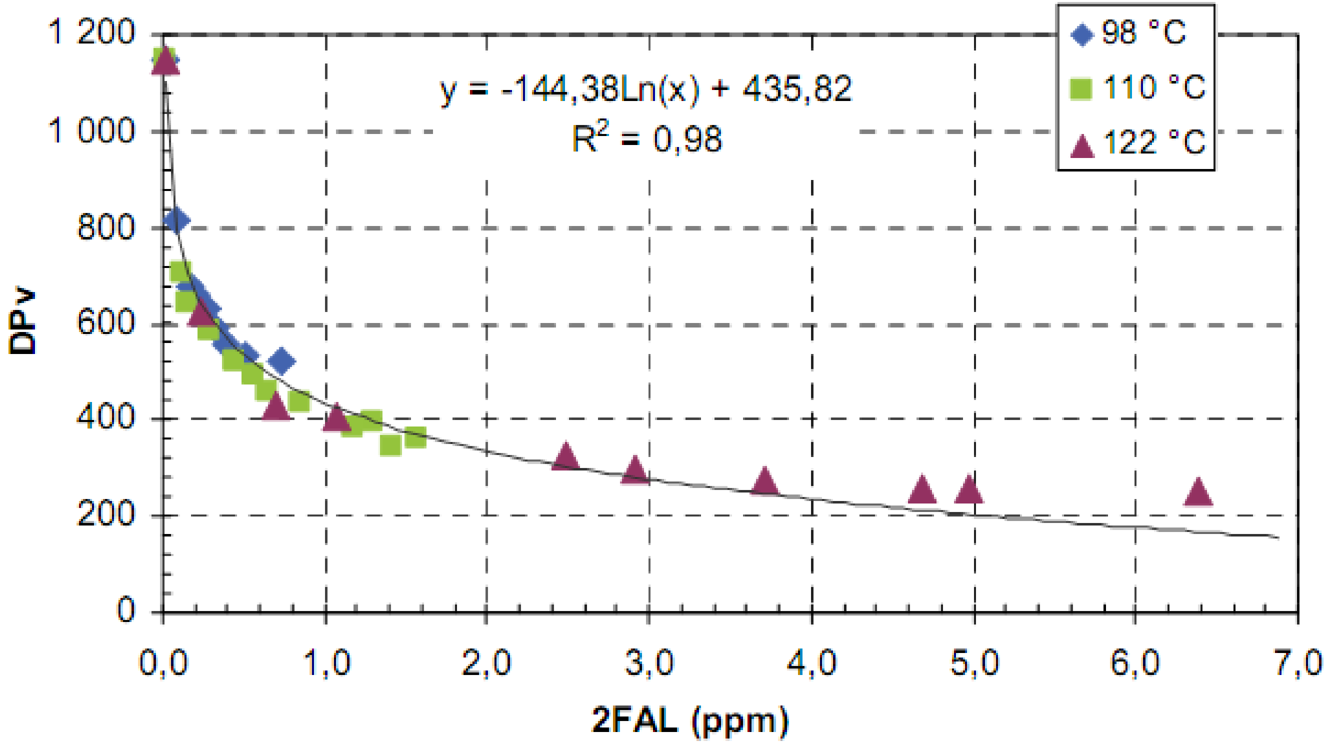
Table 1—Dissolved gas concentrations

Status	Dissolved key gas concentration limits [µL/L (ppm)[a]]							
	Hydrogen (H_2)	Methane (CH_4)	Acetylene (C_2H_2)	Ethylene (C_2H_4)	Ethane (C_2H_6)	Carbon monoxide (CO)	Carbon dioxide (CO_2)	TDCG[b]
Condition 1	100	120	1	50	65	350	2 500	720
Condition 2	101–700	121–400	2–9	51–100	66–100	351–570	2 500–4 000	721–1920
Condition 3	701–1800	401–1000	10–35	101–200	101–150	571–1400	4 001–10 000	1921–4630
Condition 4	>1800	>1000	>35	>200	>150	>1400	>10 000	>4630

NOTE 1—Table 1 assumes that no previous tests on the transformer for dissolved gas analysis have been made or that no recent history exists. If a previous analysis exists, it should be reviewed to determine if the situation is stable or unstable. Refer to 6.5.2 for appropriate action(s) to be taken.

NOTE 2—An ASTM round-robin indicated variability in gas analysis between labs. This should be considered when having gas analysis made by different labs.

Furane Analysis



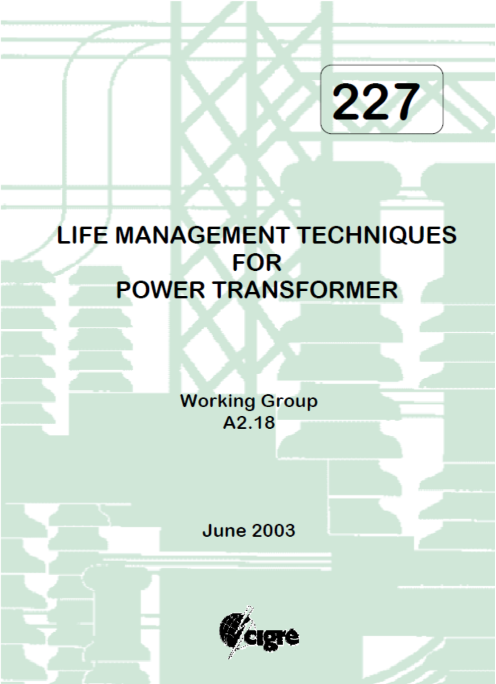
Source: B.Yves, et al.: “MV/LV distribution transformers: Research on paper ageing markers”, Cigre D1.103, 2012

Warning Levels

Paper Degradation

Cigre Brochure

227 - 2003

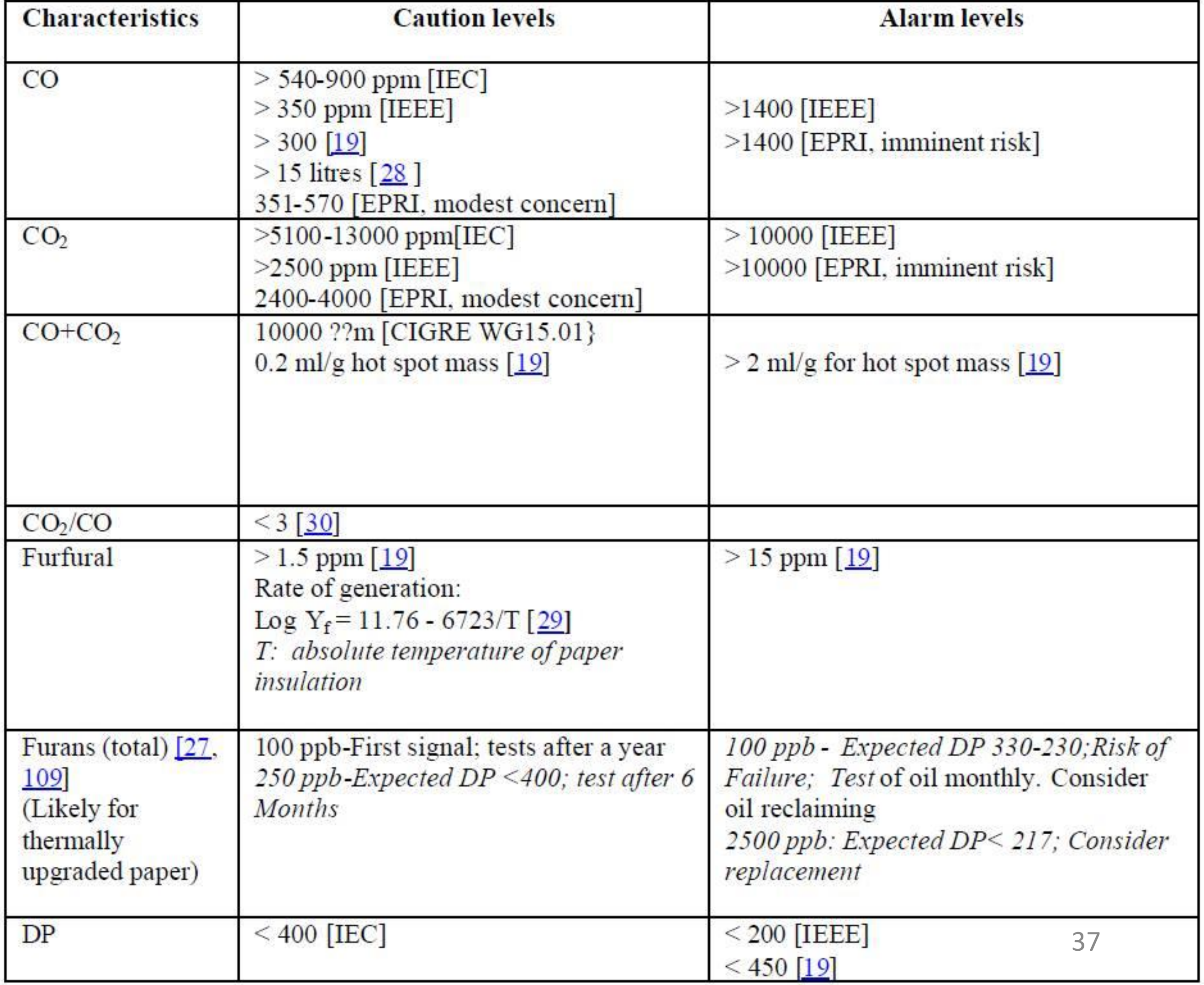

227

LIFE MANAGEMENT TECHNIQUES
FOR
POWER TRANSFORMER

Working Group
A2.18

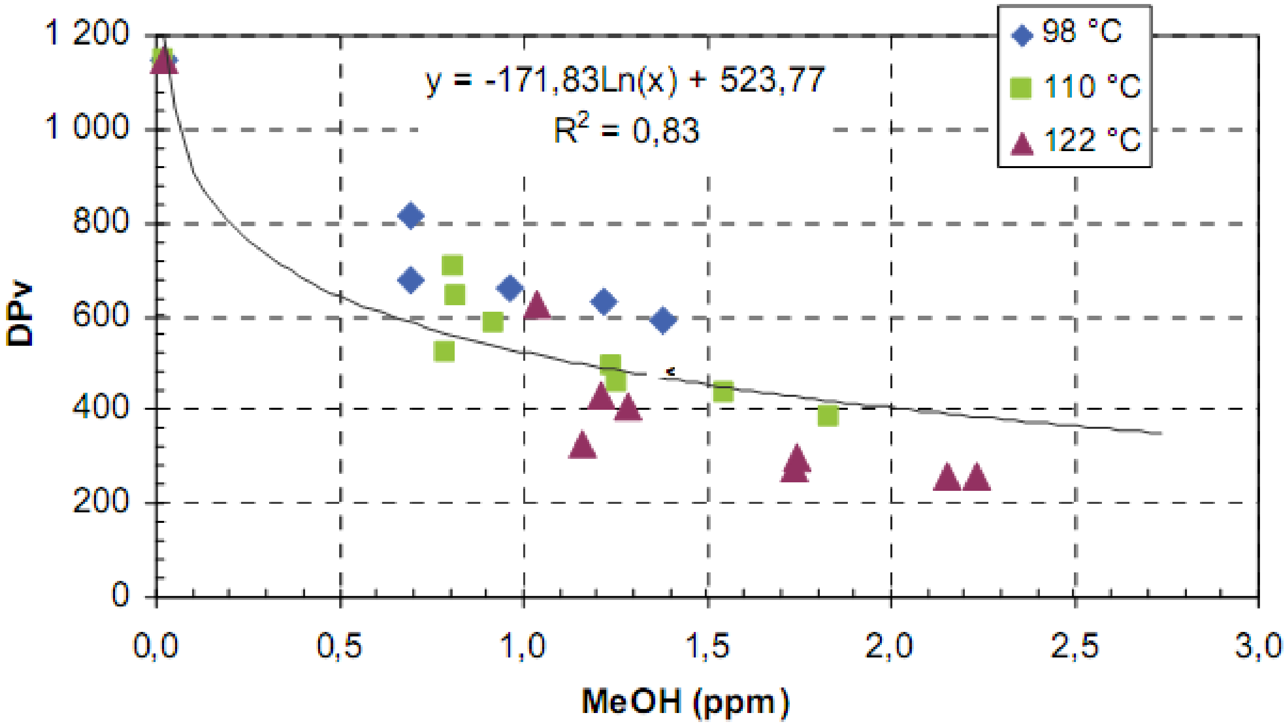
June 2003

cigre



Characteristics	Caution levels	Alarm levels
CO	> 540-900 ppm [IEC] > 350 ppm [IEEE] > 300 [19] > 15 litres [28] 351-570 [EPRI, modest concern]	>1400 [IEEE] >1400 [EPRI, imminent risk]
CO_2	>5100-13000 ppm[IEC] >2500 ppm [IEEE] 2400-4000 [EPRI, modest concern]	> 10000 [IEEE] >10000 [EPRI, imminent risk]
$CO+CO_2$	10000 ??m [CIGRE WG15.01} 0.2 ml/g hot spot mass [19]	> 2 ml/g for hot spot mass [19]
CO_2/CO	< 3 [30]	
Furfural	> 1.5 ppm [19] Rate of generation: Log Y_f = 11.76 - 6723/T [29] *T: absolute temperature of paper insulation*	> 15 ppm [19]
Furans (total) [27, 109] (Likely for thermally upgraded paper)	100 ppb-First signal; tests after a year *250 ppb-Expected DP <400; test after 6 Months*	*100 ppb - Expected DP 330-230;Risk of Failure; Test* of oil monthly. Consider oil reclaiming *2500 ppb: Expected DP< 217; Consider replacement*
DP	< 400 [IEC]	< 200 [IEEE] < 450 [19]

Methanole MeOH Analysis



Source: B.Yves, et al.: “MV/LV distribution transformers: Research on paper ageing markers”, Cigre D1.103, 2012

Transformer Health Assessment

- Introduction
- **Diagnostic on Power Transformers**
  - Oil
  - **Main Insulation**
  - Magnetic Core and Coil
  - Diagnostic of the Bushings
  - Diagnostic of the Tap Changer
- Case Study – Health Assessment of a Transformer

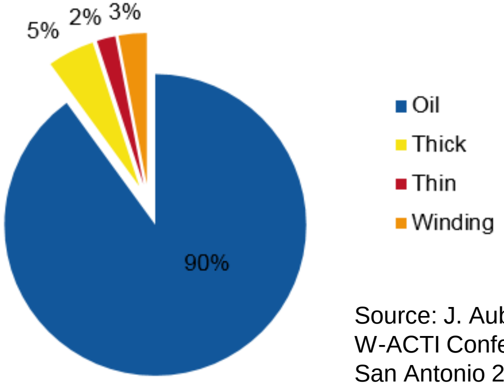
Main Insulation

- **Water Content Measurement with Dielectric Frequency Response**
- Insulation Resistance Measurement
- Capacitance and Dielectric Dissipation Factor Measurement
- Partial Discharge Measurement

Water Distribution in Transformers

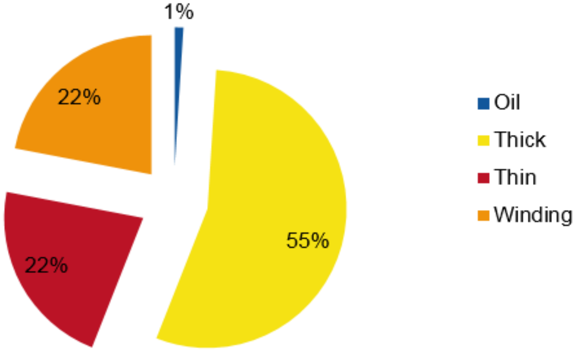
Source: Weidmann AG

Insulation Weight Distribution

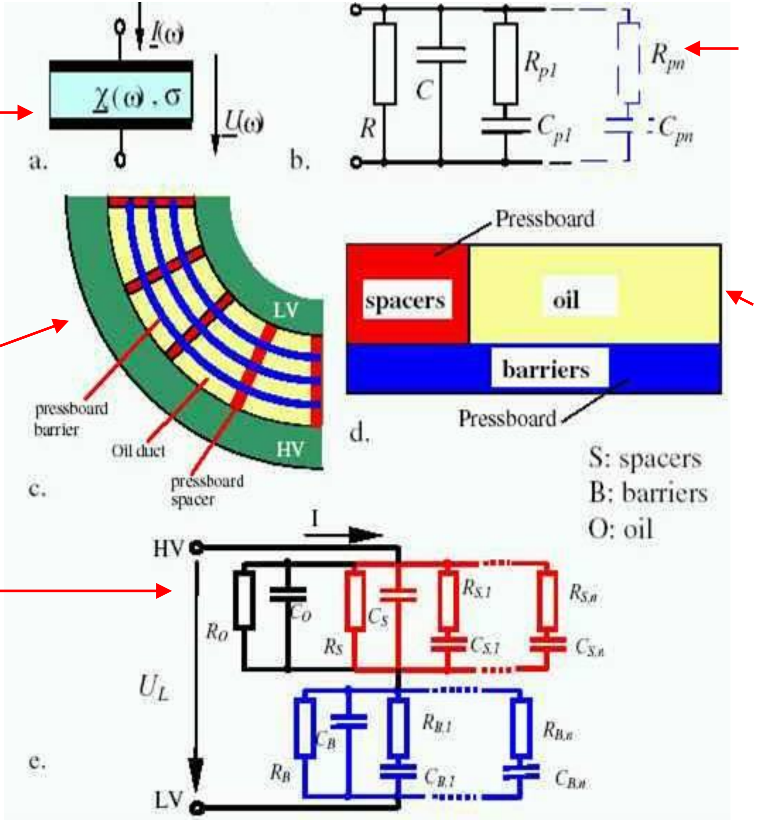


Source: J. Aubin
W-ACTI Conference
San Antonio 2005

Water Distribution



Equivalent Circuit Diagram



a. Plate condenser as a model for dielectric insulation

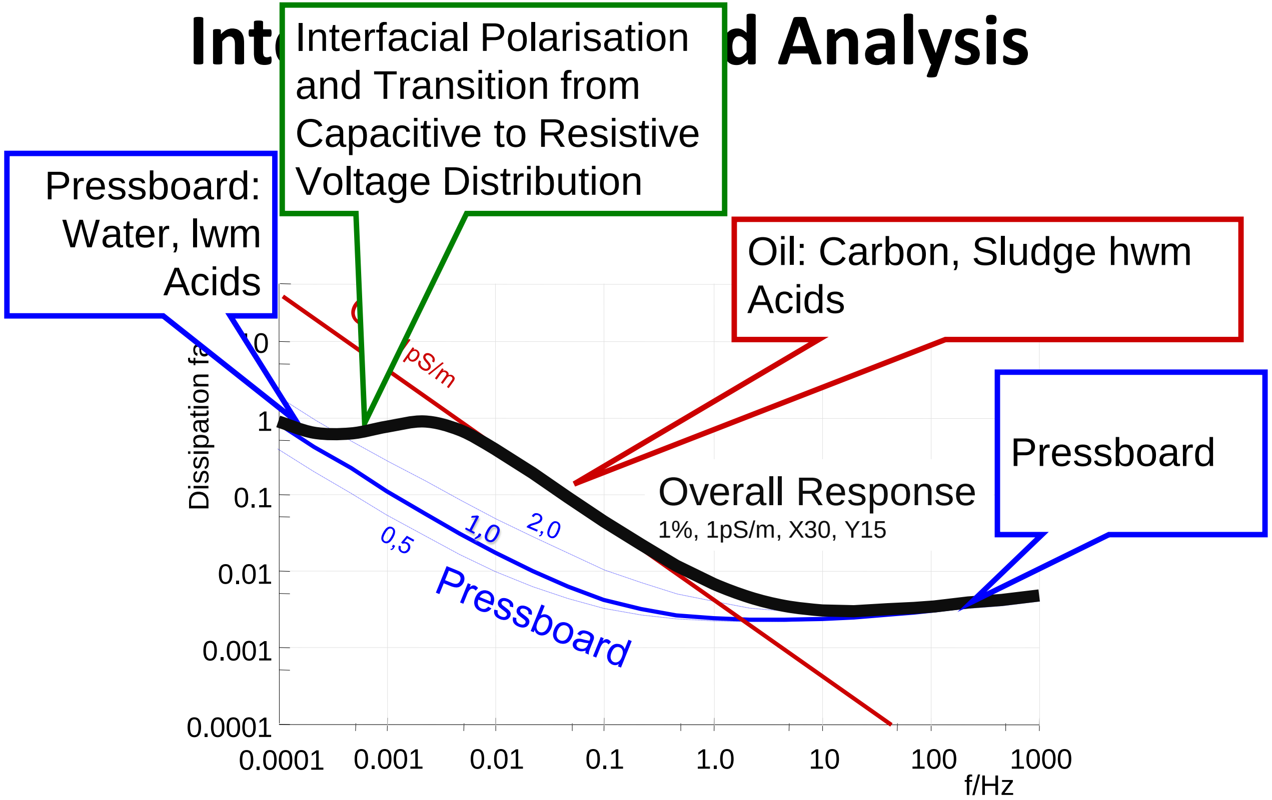
c. Part of the cross section of a power transformer main insulation system between HV and LV windings

e: Dielectric model for the insulation system of power transformers

b. Model for the behaviour of a dielectric with polarisation characteristic and conductivity

d. Simplified geometry model for the main components oil, barriers and spacers

Int d Analysis



Interfacial Polarisation and Transition from Capacitive to Resistive Voltage Distribution

Pressboard: Water, lwm Acids

Oil: Carbon, Sludge hwm Acids

Pressboard

Overall Response

1%, 1pS/m, X30, Y15

Analysis of the Water Content by Comparison to Model Results

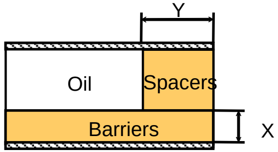
Measurement

Laboratory Results

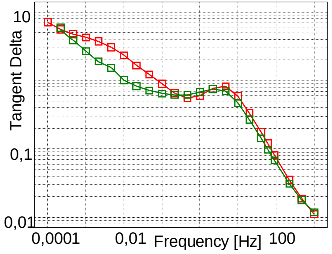
Temperature

Oil

XY-Model



Comparison
Fitting



Water Content
Oil Conductivity

Source: Weidmann

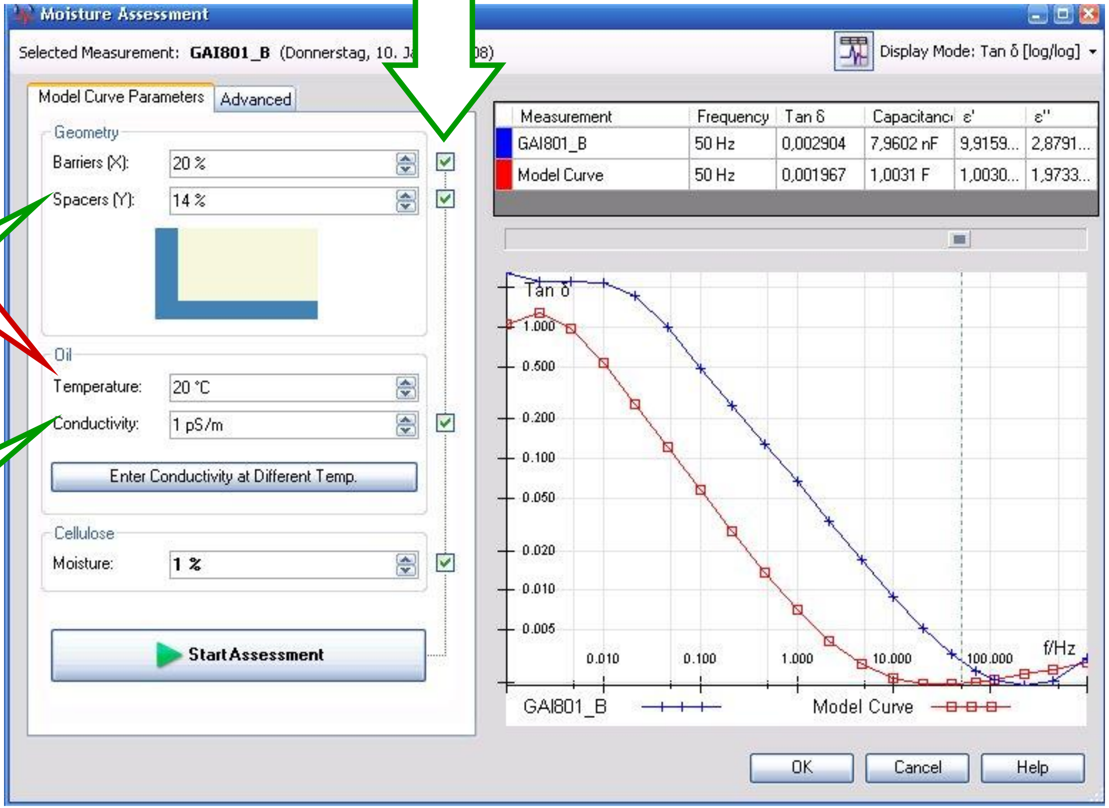
Assessment Settings

Check box:
Variable calculated by software

Required:
Oil temperature

Optional:
Geometry XY

Optional:
Oil conductivity



Selected Measurement: **GAI801_B** (Donnerstag, 10. Ja 08)

Display Mode: Tan δ [log/log]

Geometry

Barriers (X): 20 % ☑

Spacers (Y): 14 % ☑

Oil

Temperature: 20 °C

Conductivity: 1 pS/m ☑

Cellulose

Moisture: **1 %** ☑

	Measurement	Frequency	Tan δ	Capacitanc	ε'	ε''
🟦	GAI801_B	50 Hz	0,002904	7,9602 nF	9,9159...	2,8791...
🟥	Model Curve	50 Hz	0,001967	1,0031 F	1,0030...	1,9733...

Moisture Assessment

before fitting

T = 20°C

Barriers: 40 %

Spacers: 40 %

WC: 0,5 %

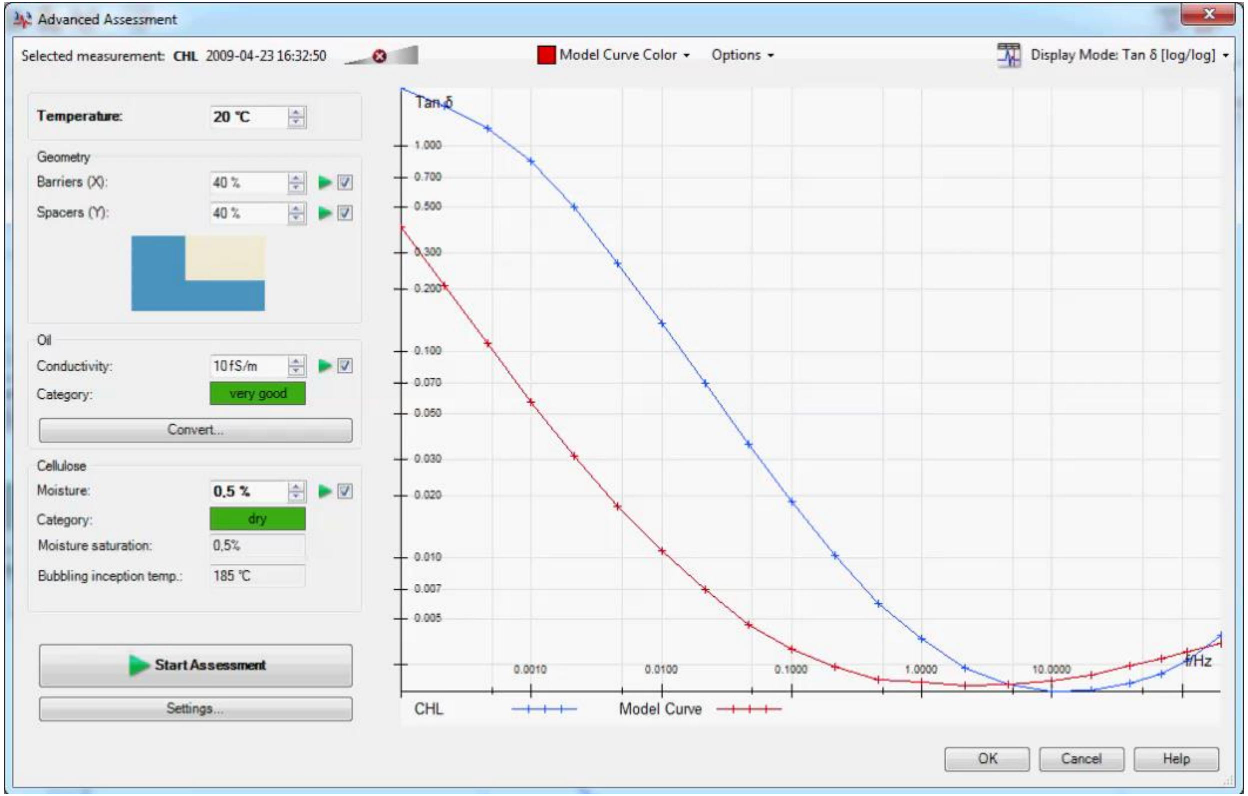
after fitting

T = 30°C

Barriers: 35 %

Spacers: 24 %

WC: 1,2 %



Advanced Assessment

Selected measurement: **CHL** 2009-04-23 16:32:50

Temperature: 20 °C

Geometry

Barriers (X): 40 % ▶ ☑

Spacers (Y): 40 % ▶ ☑

Oil

Conductivity: 10 fS/m ▶ ☑

Category: very good

Cellulose

Moisture: 0,5 % ▶ ☑

Category: dry

Moisture saturation: 0,5%

Bubbling inception temp.: 185 °C

DFR Measurement on a 200 MVA Transformer

Transformer

DFR Instrument (DIRANA)

DFR Measurement on a 200 MVA Transformer

Before Drying

Selected measurement: 🟥 CHL before drying

Model curve color: 🟨

Visible frequency range of the model curve: ● range used for moisture analysis ○ full range

Temperature 33 °C

Geometry

Barriers (X) 54 % ☑

Spacers (Y) 25 % ☑

☐ Use asset specific limits in moisture analysis

Insulation material

Mineral oil impregnated pressboard

Oil

Conductivity 7,9 pS/m ☑

Conductivity @ 20°C 4.0 pS/m

Category good

εr (50 Hz) 0

Compensation of aging byproducts ● yes ○ no

Cellulose

Moisture 2,5 % ☑

Category moderately wet

Moisture saturation 10.3 %

Bubbling inception temp. 147 °C

Automatic moisture analysis performed.

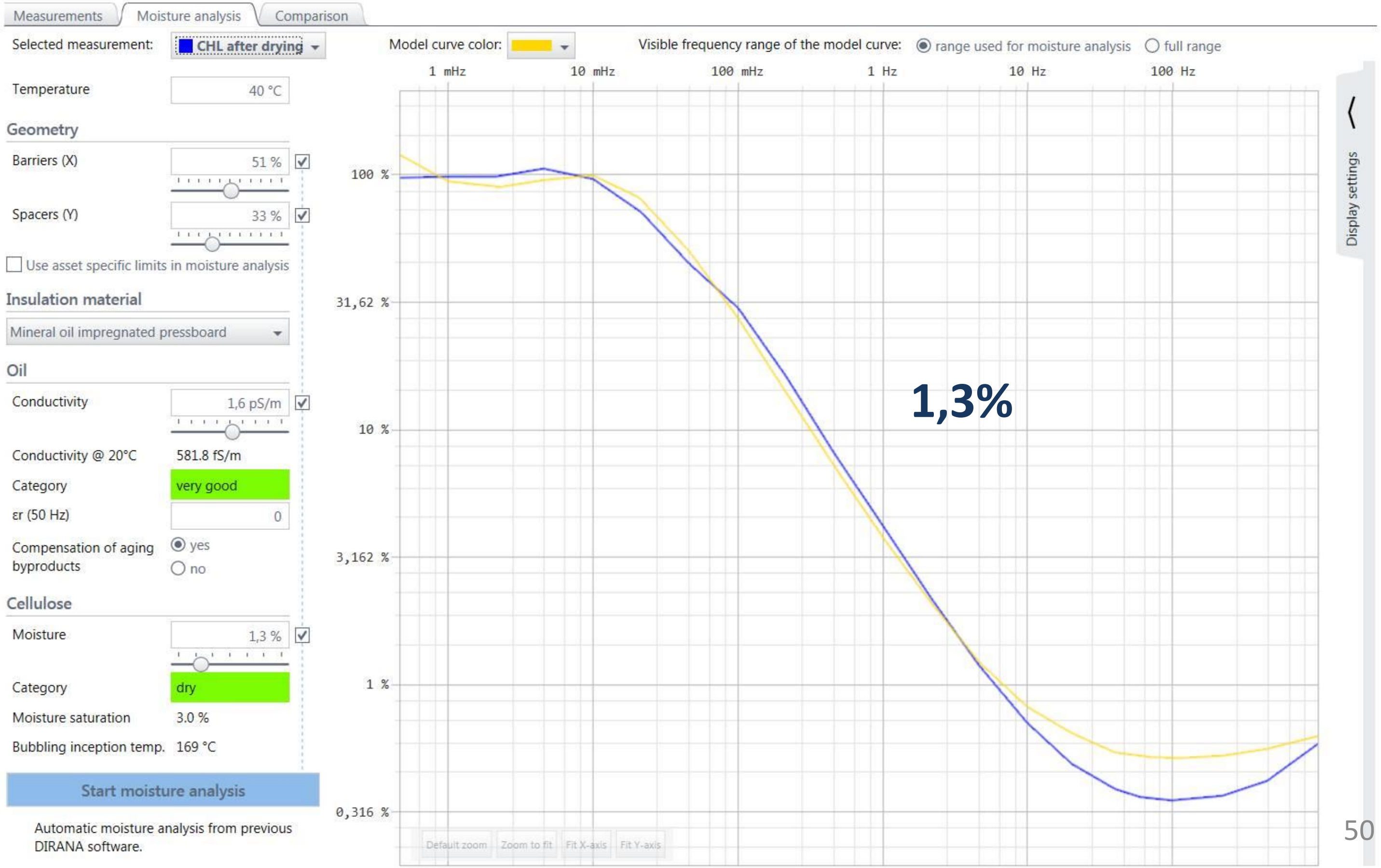
Measurement on a 200 MVA Transformer

Decision:

Drying of the transformer

DFR Measurement on a 200 MVA Transformer

After Drying



Selected measurement: CHL after drying

Visible frequency range of the model curve: ● range used for moisture analysis ○ full range

Temperature: 40 °C

Geometry

Barriers (X): 51 % ☑

Spacers (Y): 33 % ☑

☐ Use asset specific limits in moisture analysis

Insulation material

Mineral oil impregnated pressboard

Oil

Conductivity: 1,6 pS/m ☑

Conductivity @ 20°C: 581.8 fS/m

Category: very good

εr (50 Hz): 0

Compensation of aging byproducts: ● yes ○ no

Cellulose

Moisture: 1,3 % ☑

Category: dry

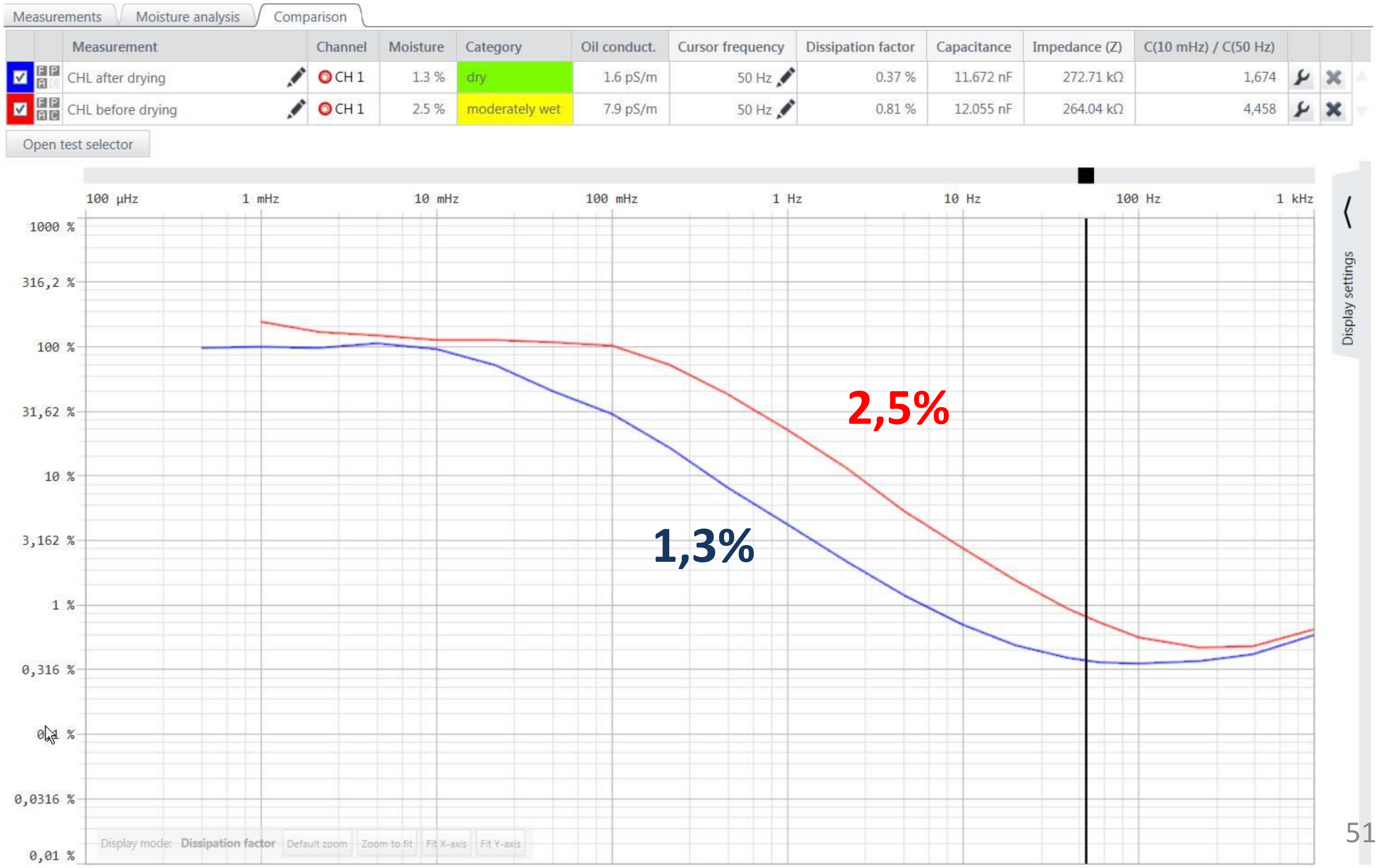
Moisture saturation: 3.0 %

Bubbling inception temp.: 169 °C

1,3%

Automatic moisture analysis from previous DIRANA software.

DFR Measurement Before and After Drying



	Measurement	Channel	Moisture	Category	Oil conduct.	Cursor frequency	Dissipation factor	Capacitance	Impedance (Z)	C(10 mHz) / C(50 Hz)
☑	CHL after drying	CH 1	1.3 %	dry	1.6 pS/m	50 Hz	0.37 %	11.672 nF	272.71 kΩ	1,674
☑	CHL before drying	CH 1	2.5 %	moderately wet	7.9 pS/m	50 Hz	0.81 %	12.055 nF	264.04 kΩ	4,458

Display mode: Dissipation factor

2,5%

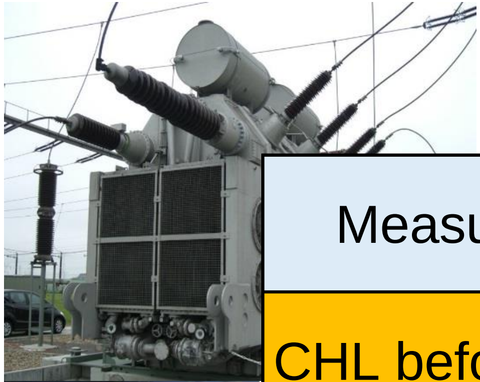
1,3%

Main Insulation

- Water Content Measurement with Dielectric Frequency Response
- **Insulation Resistance Measurement**
- Capacitance and Dielectric Dissipation Factor Measurement
- Partial Discharge Measurement

Insulation Resistance Measurement

220kV Transformer before and after Drying



Measurement	s	Ri	PI	DAR
CHL before drying	600 s	1,0212 GΩ	1,813	1,41
CHL after drying	600 s	6,5739 GΩ	3,947	1,45

Measurement	s	A	Ri	PI	DAR
CHL before drying	60 s	355,0379 nA	0,5633 GΩ	1,813	1,41
			1,6654 GΩ	3,947	1,45
			1,0481 GΩ	3,021	1,51
			2,1881 GΩ	4,977	1,61

			Ri	PI	DAR
			1,0212 GΩ	1,813	1,41
CHL after drying	600 s	30,4232 nA	6,5739 GΩ	3,947	1,45
CLT before drying	600 s	63,1595 nA	3,1666 GΩ	3,021	1,51
CLT after drying	600 s	18,3631 nA	10,8914 GΩ	4,977	1,61

Main Insulation

- Water Content Measurement with Dielectric Frequency Response
- Insulation Resistance Measurement
- **Capacitance and Dielectric Dissipation Factor Measurement**
- Partial Discharge Measurement

Capacitance and Dissipation Factor Measurement @ 50Hz

220kV Transformer Before and after Drying

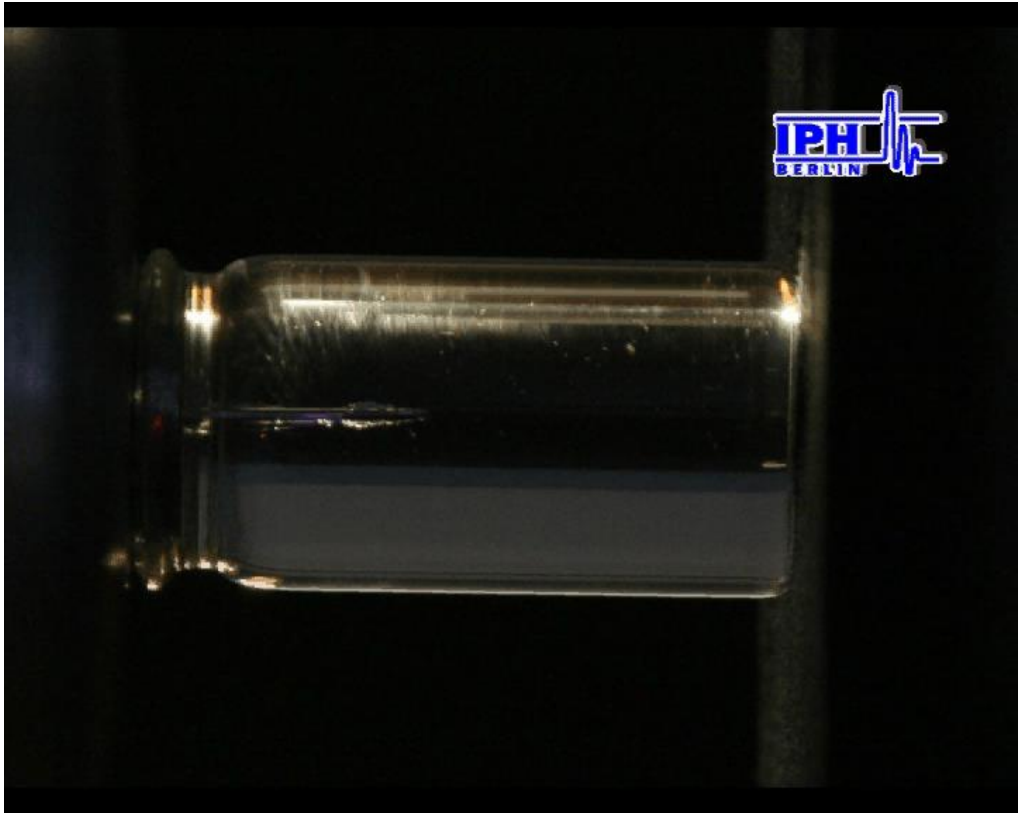
Measurement	Tan δ	C	C(10mHz) / C(50Hz)
CHL before drying	0,00811	12,0551 nF	4,4579
CHL after drying	0,00375	11,6719 nF	1,6735
CLT before drying	0,00779	14,0735 nF	3,8066
CLT after drying	0,00383	13,6873 nF	1,6937

Main Insulation

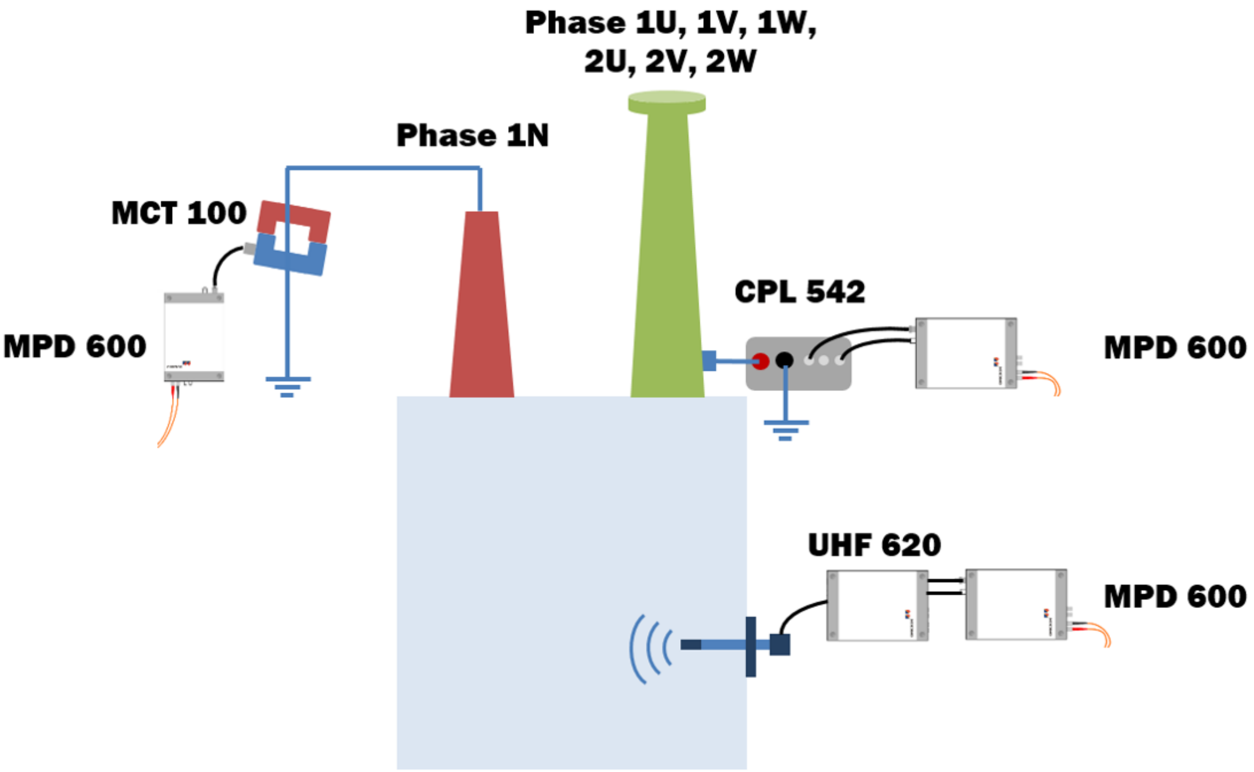
- Water Content Measurement with Dielectric Frequency Response
- Insulation Resistance Measurement
- Capacitance and Dielectric Dissipation Factor Measurement
- **Partial Discharge Measurement**

PD Damages

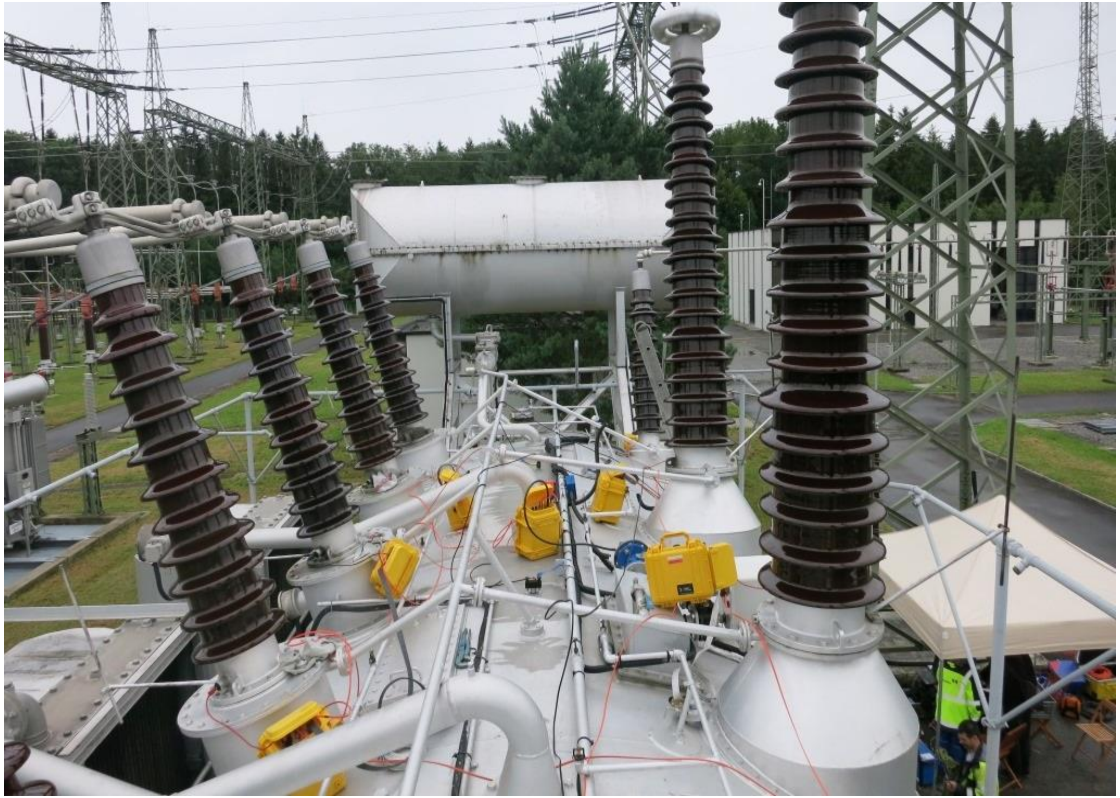
Electrical Treeing



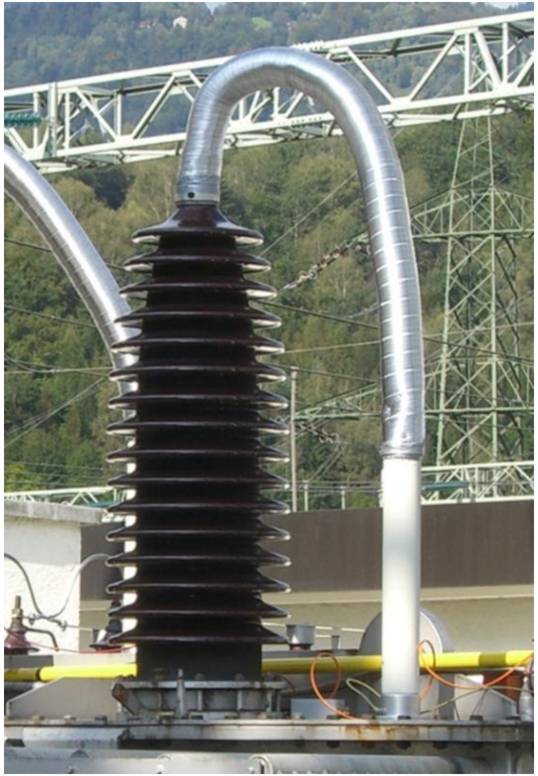
PD Coupling Possibilities



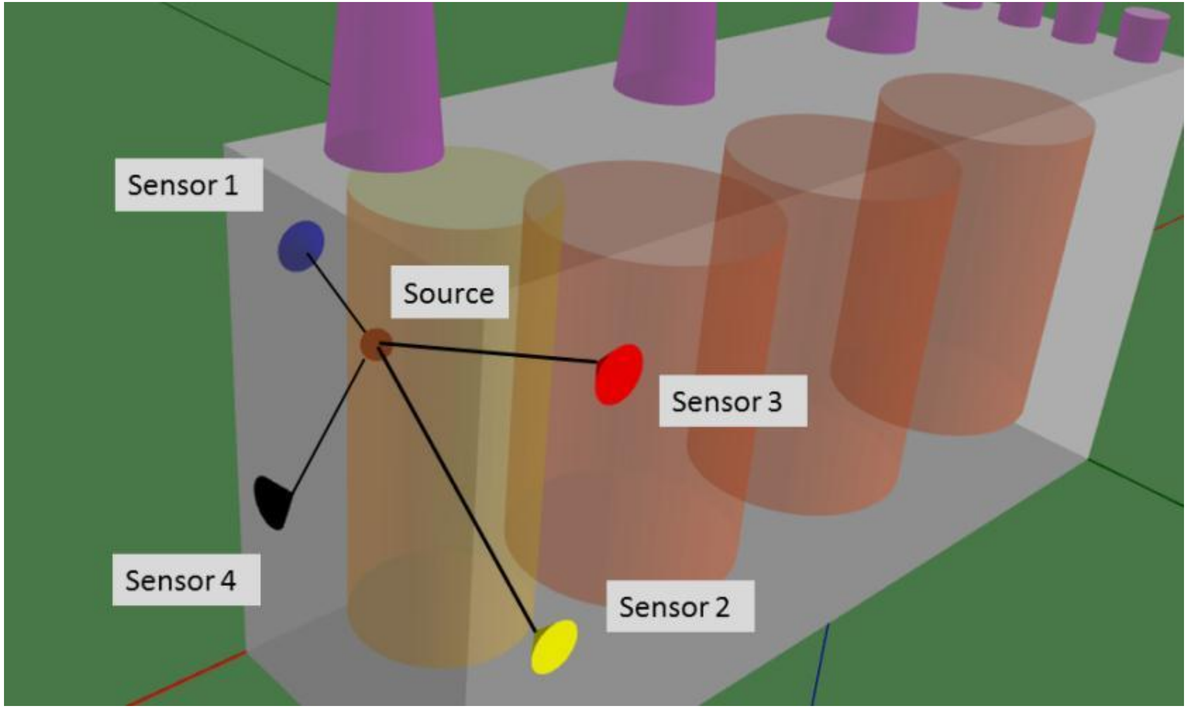
Measurement at the Bushing Taps



Measurement with Coupling Capacitors



Acoustical PD Location



PD Location

Piezo Sensors for the Acoustical PD Location

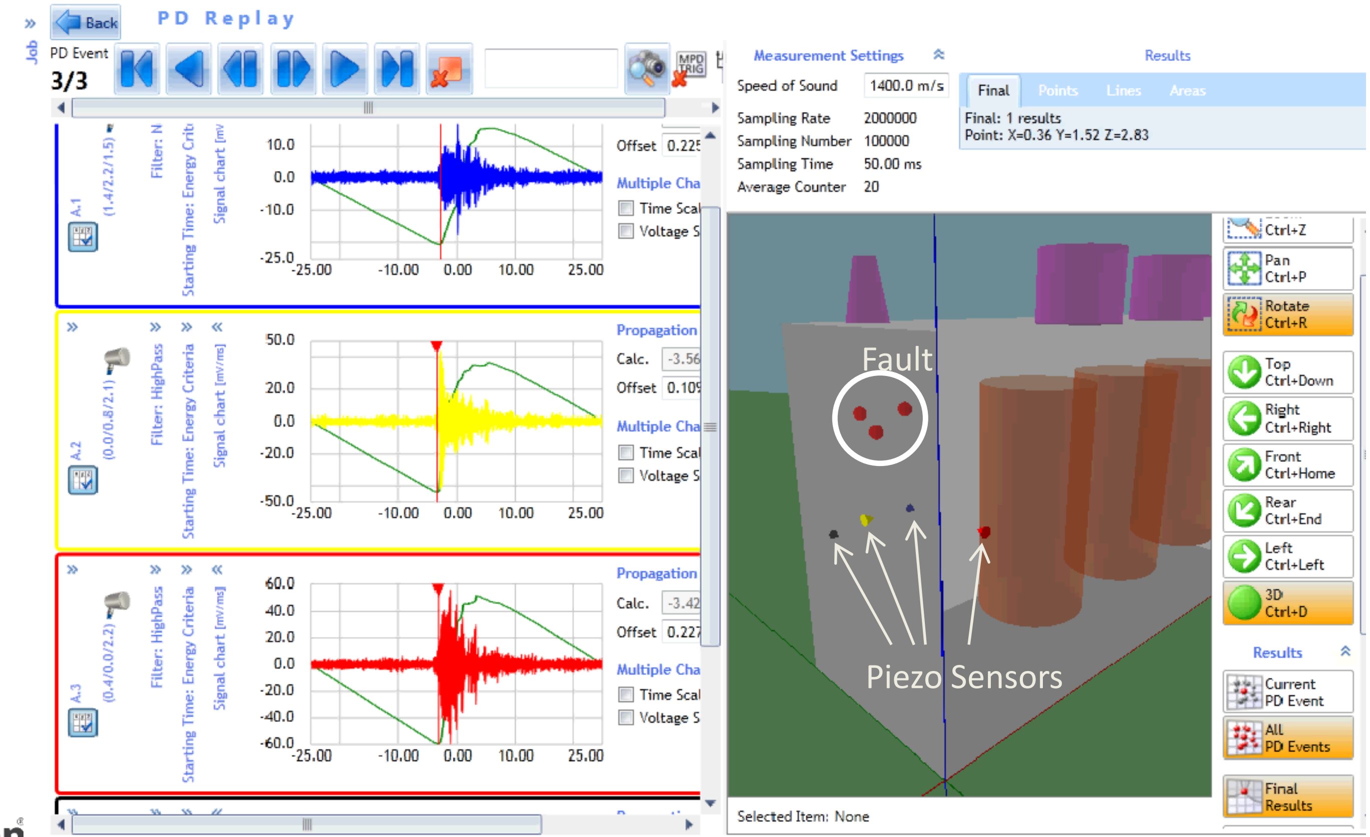
red

yellow

black

blue

Acoustical PD Location



PD Replay

PD Event 3/3

Measurement Settings

Speed of Sound 1400.0 m/s

Sampling Rate 2000000

Sampling Number 100000

Sampling Time 50.00 ms

Average Counter 20

Results

Final: 1 results

Point: X=0.36 Y=1.52 Z=2.83

Offset 0.225

Calc. -3.56

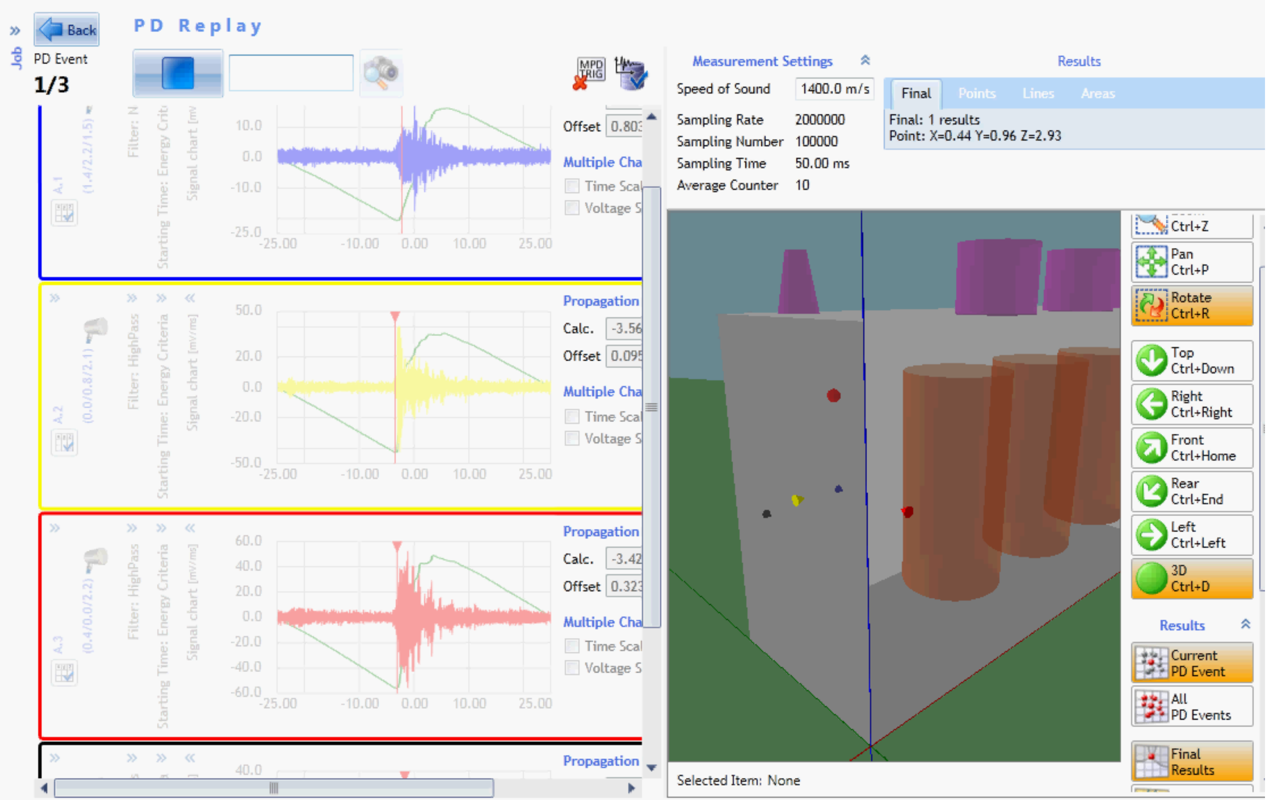
Offset 0.109

Calc. -3.42

Offset 0.227

Selected Item: None

Acoustical PD Location



Speed of Sound 1400.0 m/s
Sampling Rate 2000000
Sampling Number 100000
Sampling Time 50.00 ms
Average Counter 10

Final: 1 results
Point: X=0.44 Y=0.96 Z=2.93

Selected Item: None

Transformer Health Assessment

- Introduction
- Diagnostic on Power Transformers
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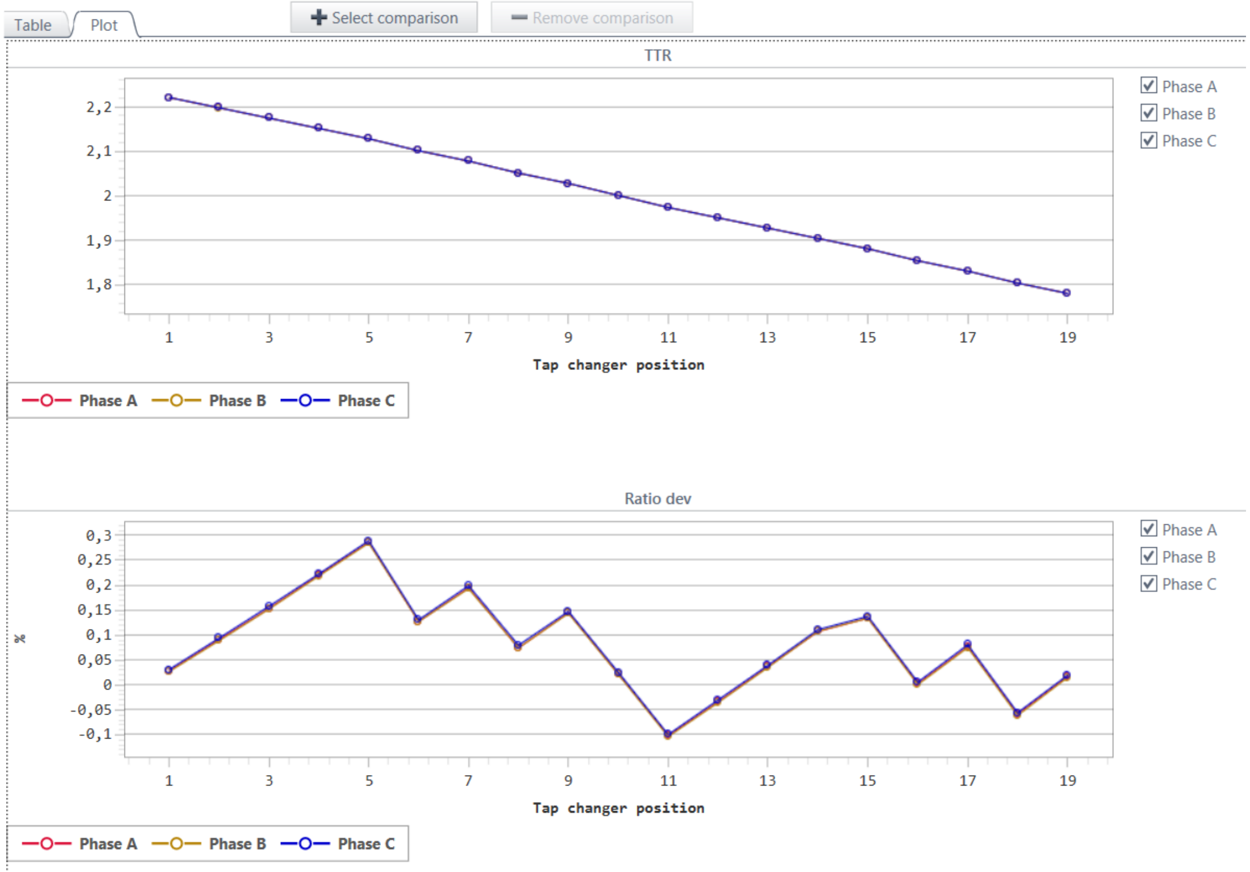
  - **Magnetic Core and Coil**
  - Diagnostic of the Bushings
  - Diagnostic of the Tap Changer
- Case Study – Health Assessment of a Transformer

Magnetic Core and Coil

- Insulation Resistance Measurement Core to Frame and Tank
- Ratio, Magnetising Current and Flux Balance Test
- Capacitance Measurement Coils to Ground
- Short Circuit Impedance
- Frequency Response Analysis

Ratio Measurement HV-LV



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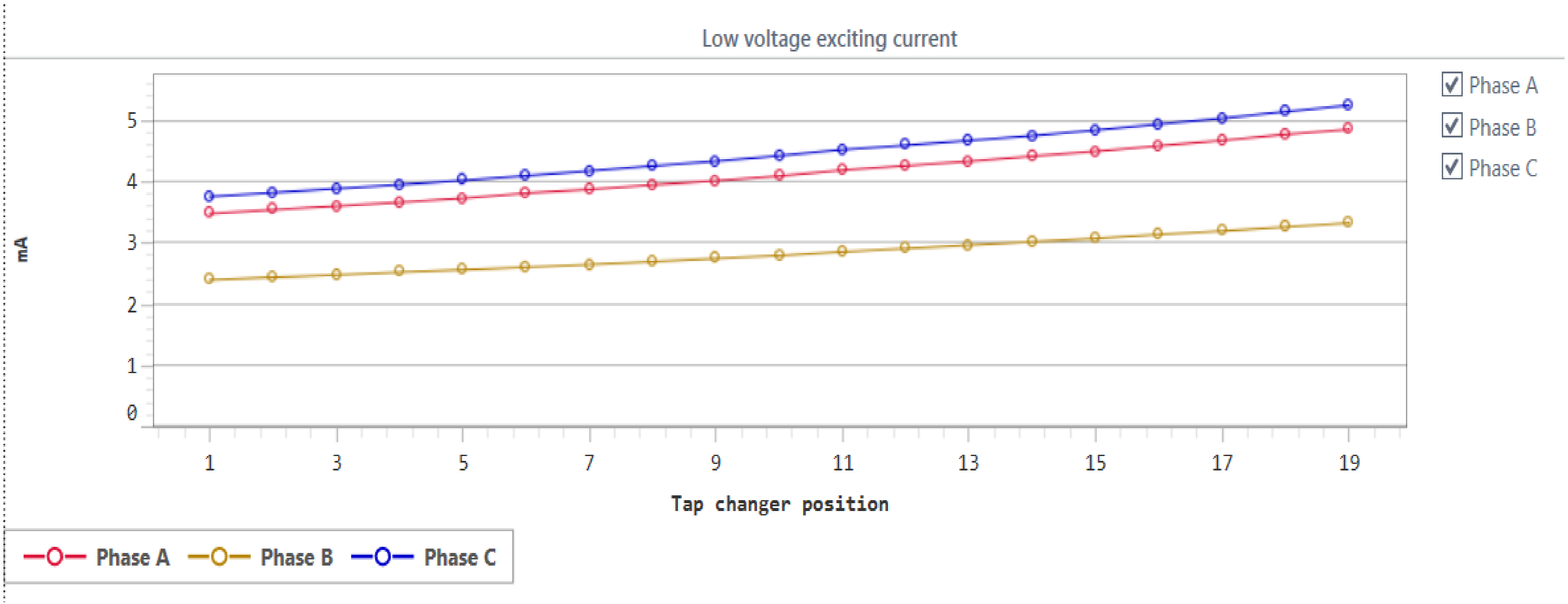
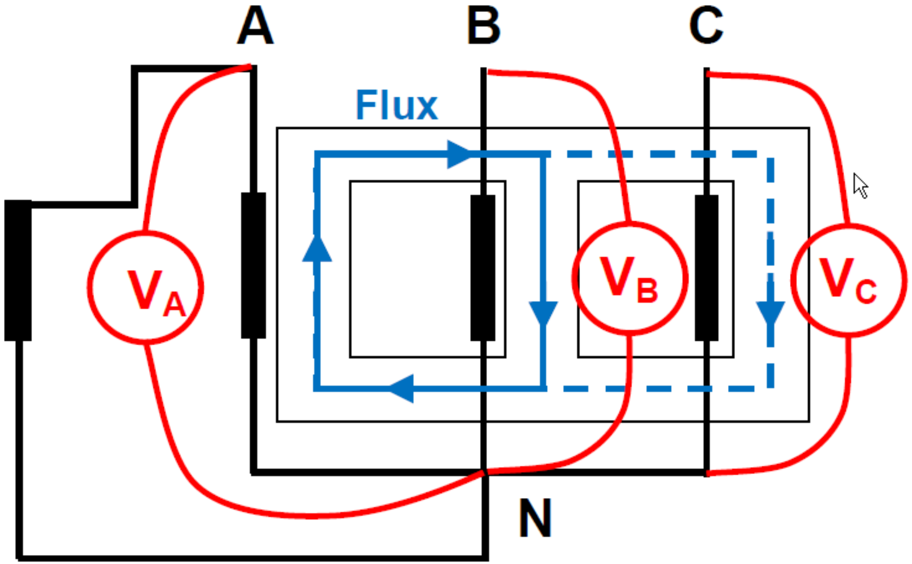
Magnetising Currents HV Side



Flux Balance Test

Expected Result (Voltages)

100%	-70%	-30%
-50%	100%	-50%
-30%	-70%	100%

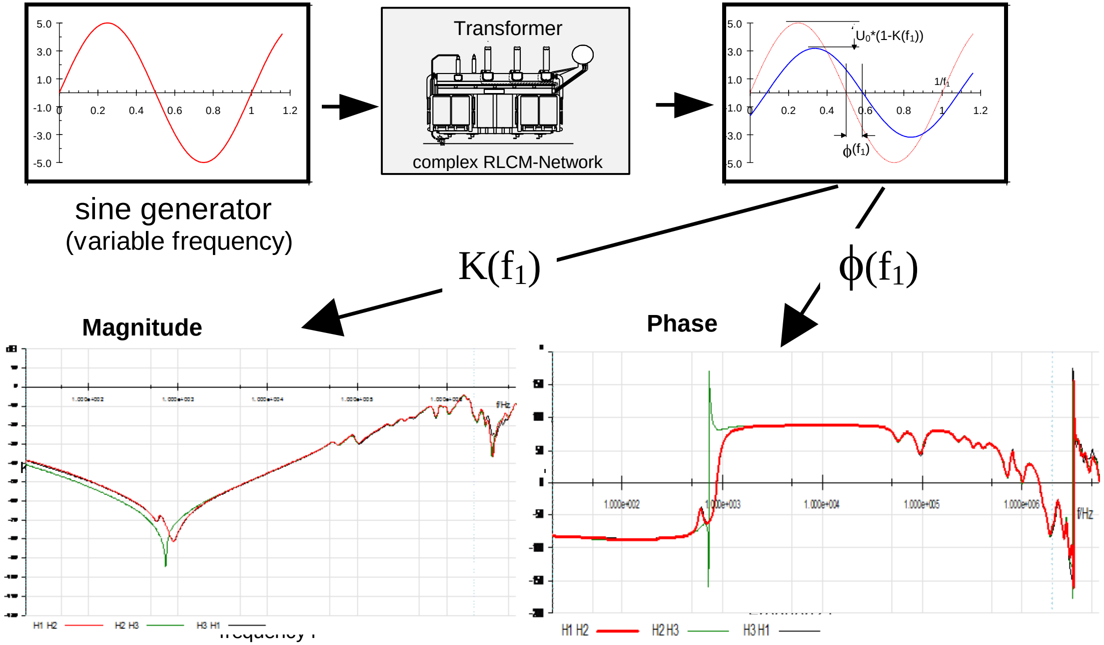


Test voltage on A-N, measured at B-N and C-N

Magnetic Core and Coil

- Insulation Resistance Measurement Core to Frame and Tank
- Ratio, Magnetising Current and Flux Balance Test
- Capacitance Measurement Coils to Ground
- Short Circuit Impedance
- **Frequency Response Analysis**

Swept Frequency Response Analysis (SFRA)



Transformer

complex RLCM-Network

sine generator
(variable frequency)

$K(f_1)$

$\phi(f_1)$

Magnitude

Phase

$$H(dB) = 20\log_{10}\left(\frac{V_{out}}{V_{in}}\right)$$

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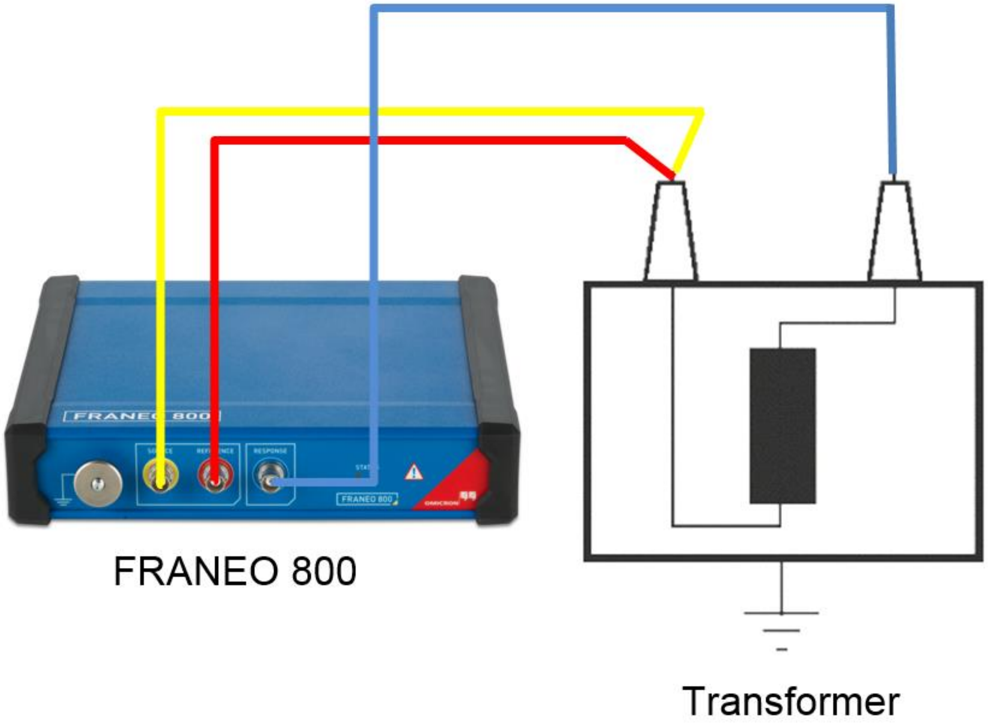
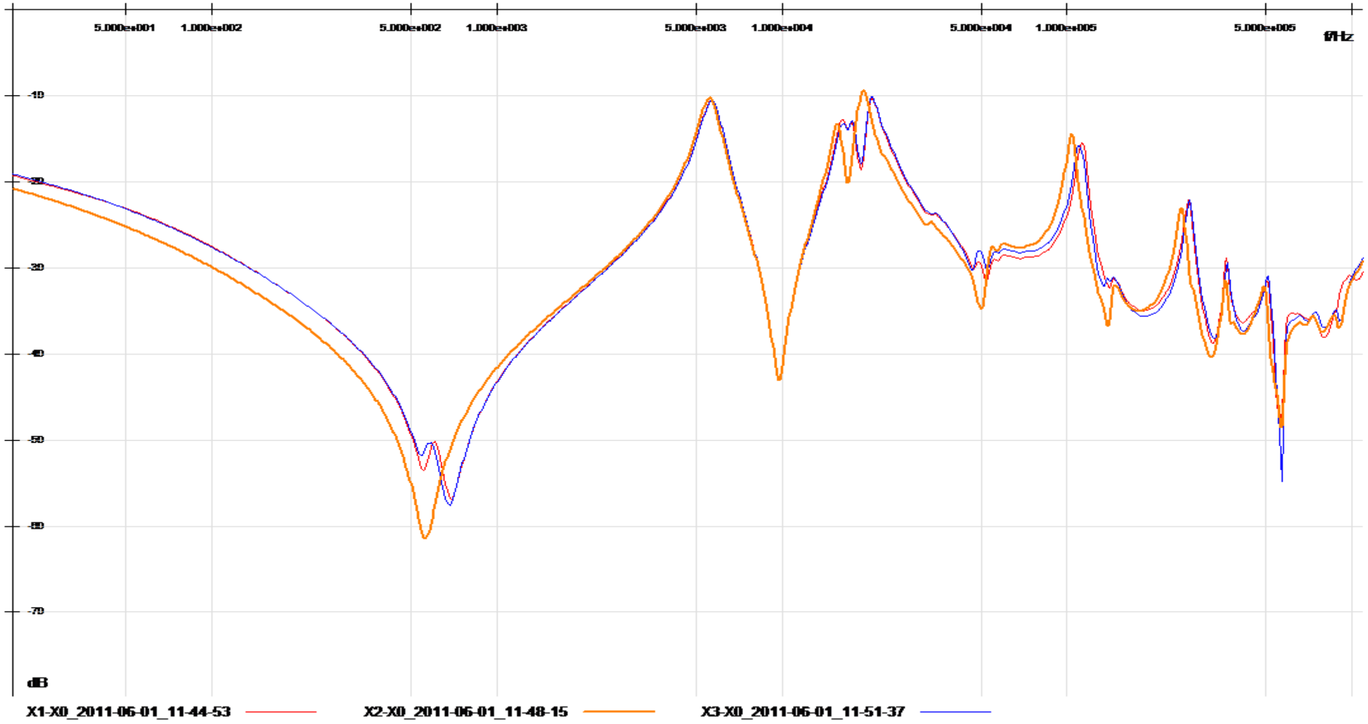
OMICRON

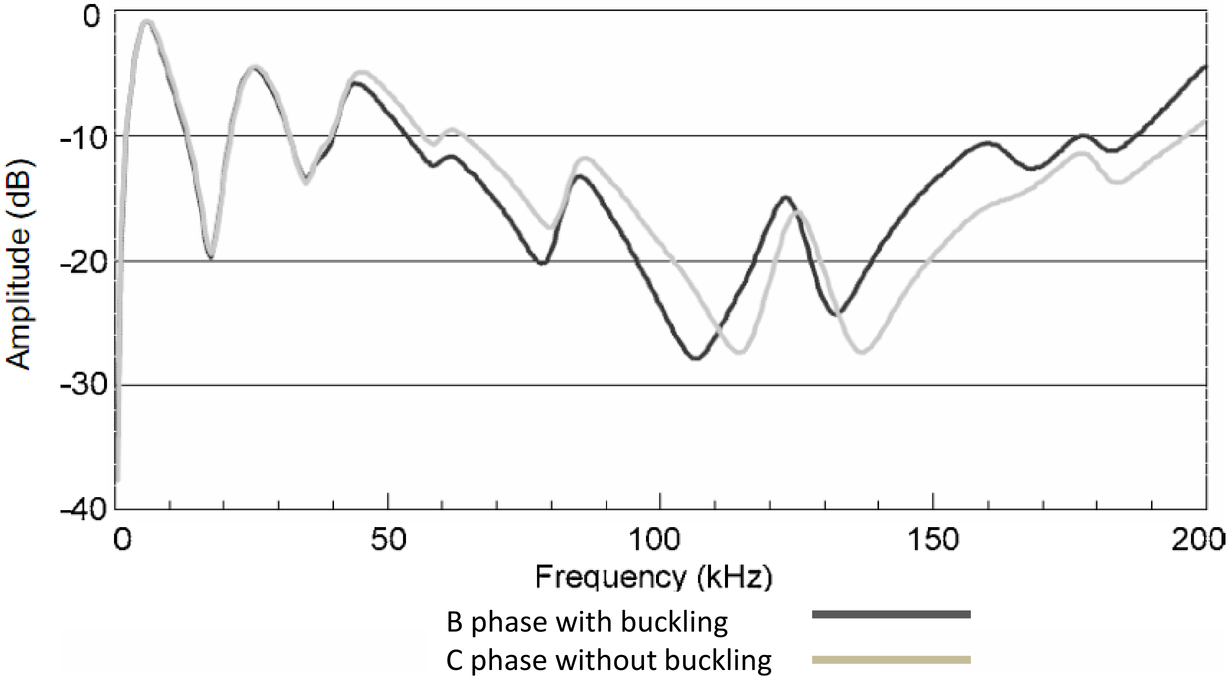
End to End FRA Measurement



FRA LV Winding – Comparison of the 3 Phases



Failure Modes due to Radial Forces



Source: Cigre Brochure 342 " MECHANICAL-CONDITION ASSESSMENT OF TRANSFORMER WINDINGS USING FREQUENCY RESPONSE ANALYSIS (FRA)"

Buckling

Transformer Health Assessment

- Introduction
- **Diagnostic on Power Transformers**
  - Oil
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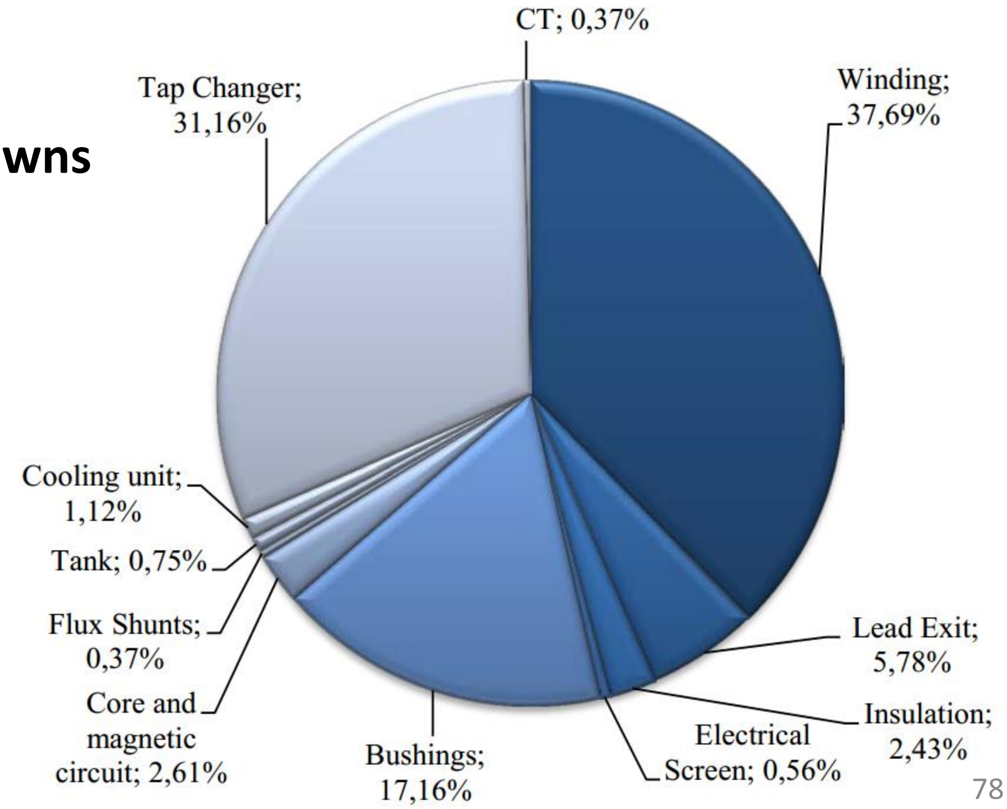
  - Magnetic Core and Coil
  - **Diagnostic of the Bushings**
  - Diagnostic of the Tap Changer
- Case Study – Health Assessment of a Transformer

Cigre A2.37 Transformer Failure Statistics

22.000 grid transformers with 150.000 sercice years

Causes for transformer breakdowns

Bushings = 17,16 %



Tenbohlen et. al.: „ DEVELOPMENT AND RESULTS OF A WORLDWIDE TRANSFORMER RELIABILITY SURVEY" CIGRE SC A2 COLLOQUIUM 2015, Shanghai

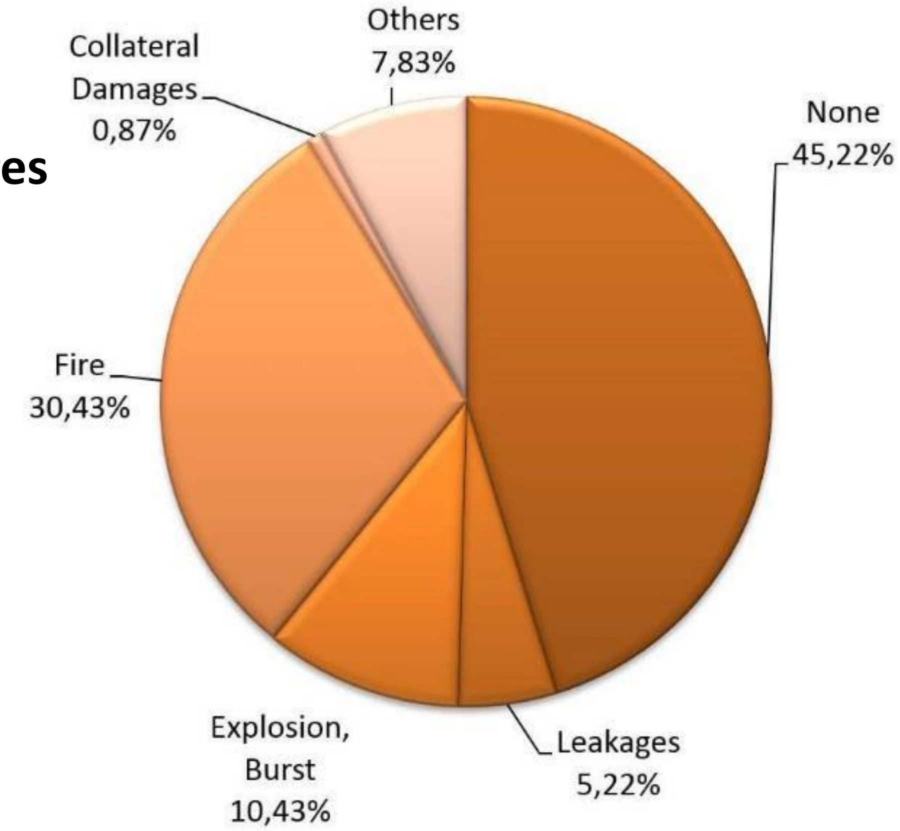
Cigre A2.37 Transformer Failure Statistics

External effects of bushing failures

Fire 30 %

Explosion, Burst 10 %

Tenbohlen et. al.: „ DEVELOPMENT AND RESULTS OF A WORLDWIDE TRANSFORMER RELIABILITY SURVEY” CIGRE SC A2 COLLOQUIUM 2015, Shanghai



Insulation Systems of High Voltage Bushings

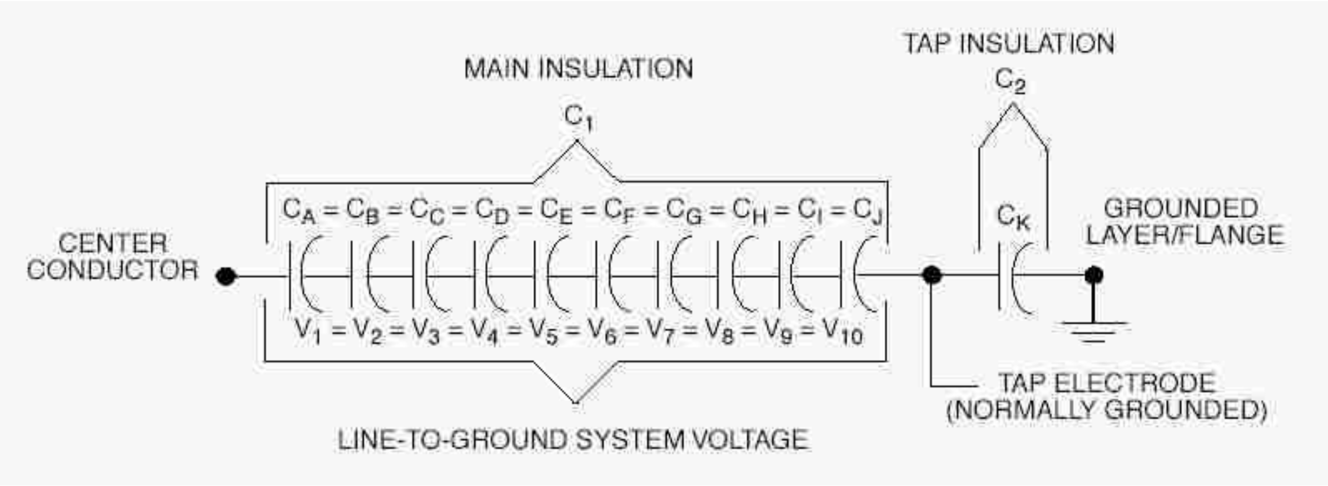
RBP Resin Bonded Paper

RIP Resin Impregnated Paper

OIP

Oil Impregnated Paper

Capacitive Bushings

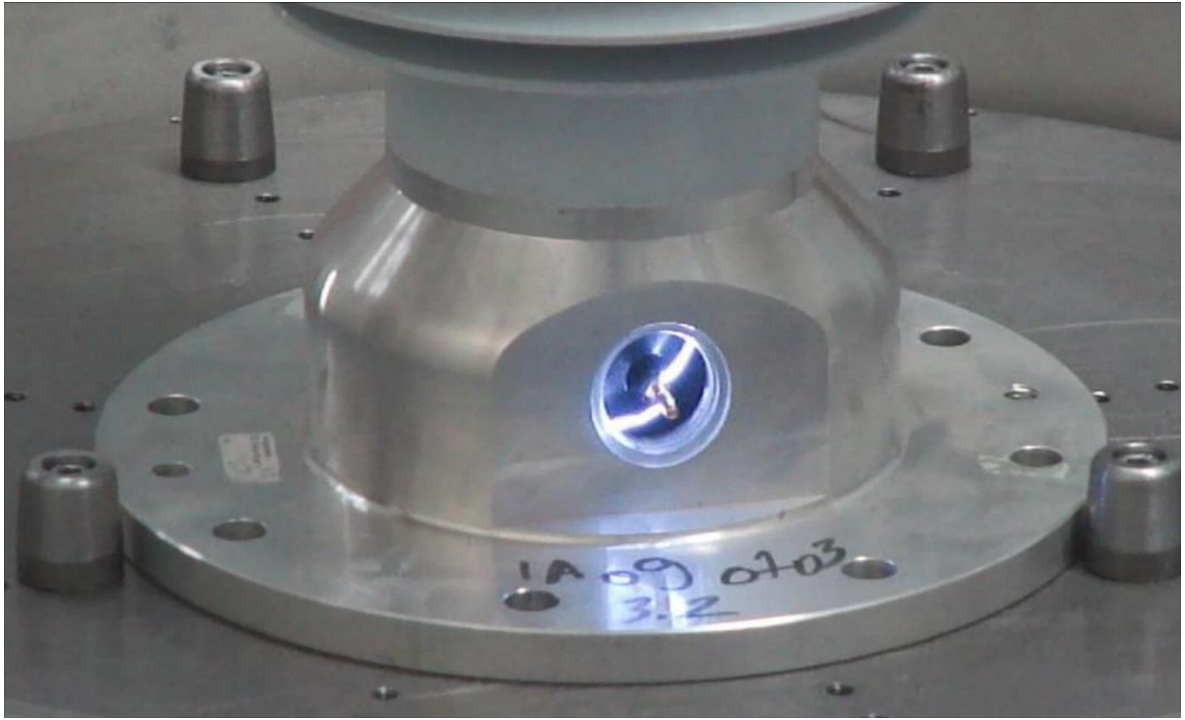


Current at the Measurement Tap

$$50Hz \;\rightarrow I_C = U\,\omega\,C \qquad = 10\;\ldots 100mA$$

$$BIL\ 1.2\mu s \;\rightarrow I_C = C\;dU/dt = 200A$$

Arcing at the Measurement Tap



Source: Norbert Koch „Diagnoseverfahren an Hochspannungsdurchführungen aus Herstellersicht“, HdT Essen 2013

Infrared Thermography

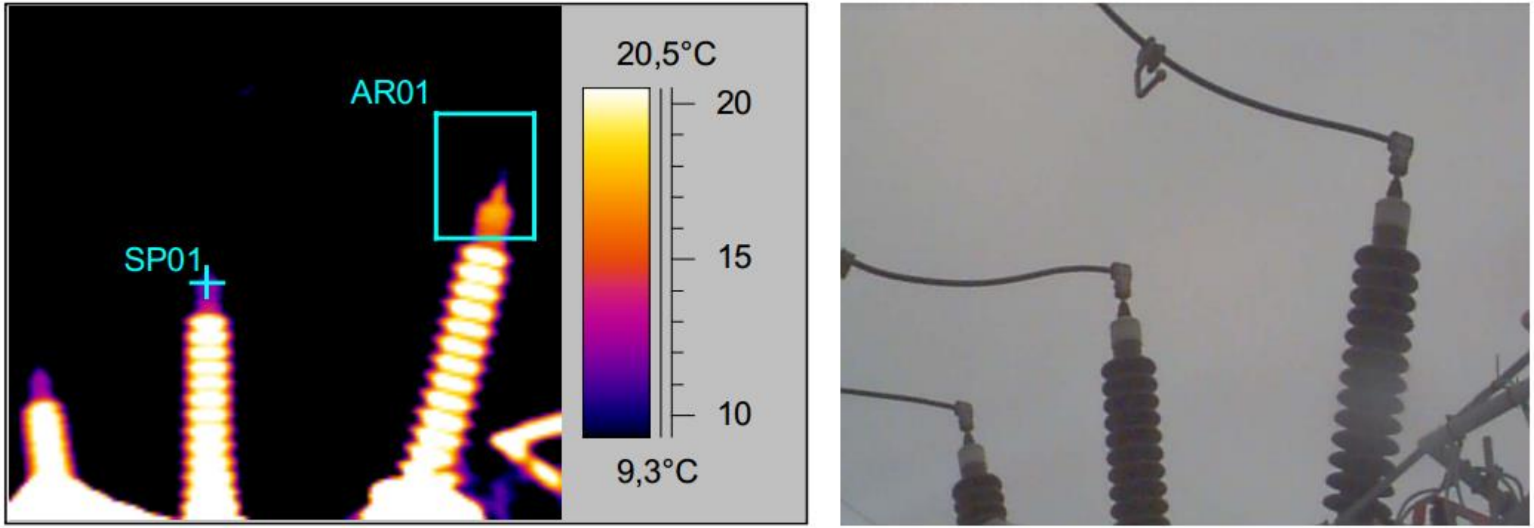
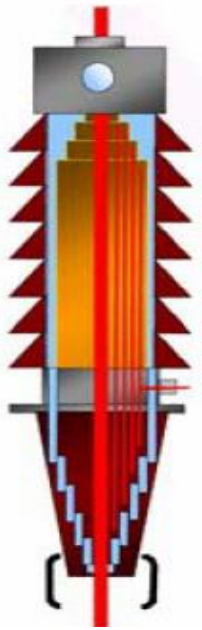


Fig.13. Measurement indicating poor current path between bushing inner and outer terminal.

Source: ABB Brochure „Bushing diagnostics and conditioning“, 2750 515-142 en

Fault Mechanisms and Diagnosis

- Partial breakdowns
    - Measurement of capacitance
    - TanDelta measurement
    - PD measurement
- Voids, cracks
    - Measurement of capacitance (RBP)
    - PD measurement
- Contact problems on measurement taps
    - Tan Delta voltage sweep (tip-up test)
- Ageing, moisture
    - Dielectric response measurements
    - TanDelta

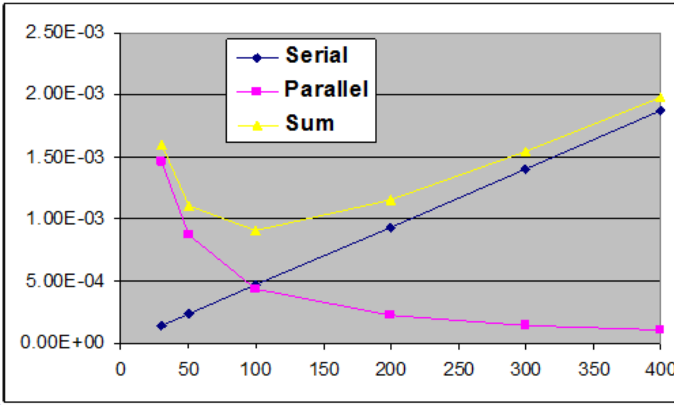


Voltage [kV]	No. of layers	% change
123	14	7.1
245	30	3.3
420	40	2.5
550	55	1.8

Definitions of Dielectric Losses

Dielectric losses are caused by

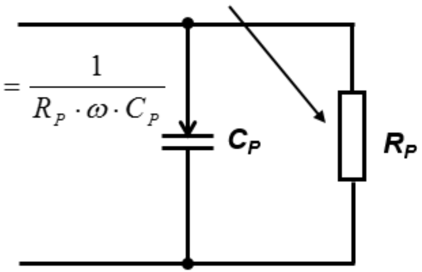
- **Conductive losses**
- **Polarization losses**
- Partial discharges



Parallel circuit

$$\text{DF}: \quad \tan\delta = \frac{|I_{RP}|}{|I_{CP}|} = \frac{1}{R_P \cdot \omega \cdot C_P}$$

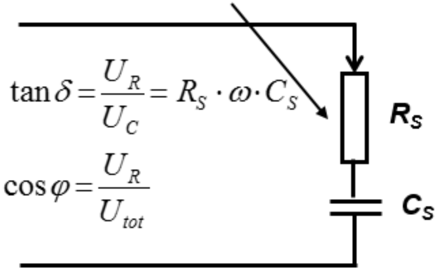
$$\text{PF}: \quad \cos\varphi = \frac{|I_{RP}|}{|I_{tot}|}$$



Serial circuit

$$\text{DF}: \tan\delta = \frac{U_R}{U_C} = R_S \cdot \omega \cdot C_S$$

$$\text{PF}: \cos\varphi = \frac{U_R}{U_{tot}}$$

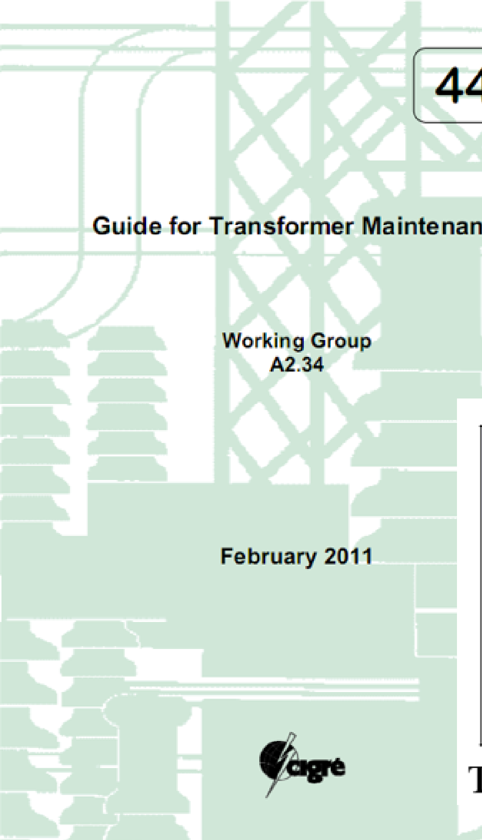


Standards

Type	RIP	OIP	RBP
Main insulation	Resin impregnated paper	Oil impregnated paper	Resin bonded paper
DF / tan delta (20°C, IEC60137)	< 0.7 %	< 0.7 %	< 1.5 %
PF cos phi (20°C, IEEE C57.19.01)	< 0.85 %	< 0.5 %	< 2 %
Typical new values	0.3-0.4 %	0.2-0.4 %	0.5-0.6 %
PD (IEC60137) at U_m **$1.5\ U_m/\sqrt{3}$** **$1.05\ U_m/\sqrt{3}$**	< 10 pC < 5 pC < 5 pC	< 10 pC < 5 pC < 5 pC	 < 300 pC

Cigre WG A2.34 Brochure 445

Guide for Transformer Maintenance



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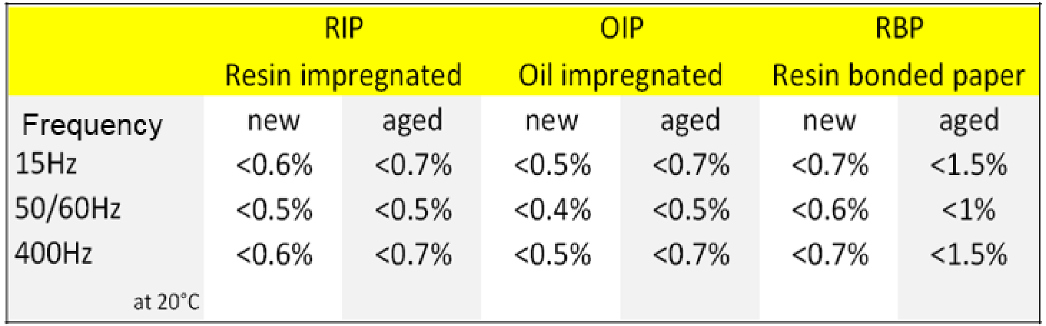
Guide for Transformer Maintenance

Working Group
A2.34

February 2011

www.e-cigre.org



	RIP Resin impregnated		OIP Oil impregnated		RBP Resin bonded paper	
Frequency	new	aged	new	aged	new	aged
15Hz	<0.6%	<0.7%	<0.5%	<0.7%	<0.7%	<1.5%
50/60Hz	<0.5%	<0.5%	<0.4%	<0.5%	<0.6%	<1%
400Hz	<0.6%	<0.7%	<0.5%	<0.7%	<0.7%	<1.5%
at 20°C						

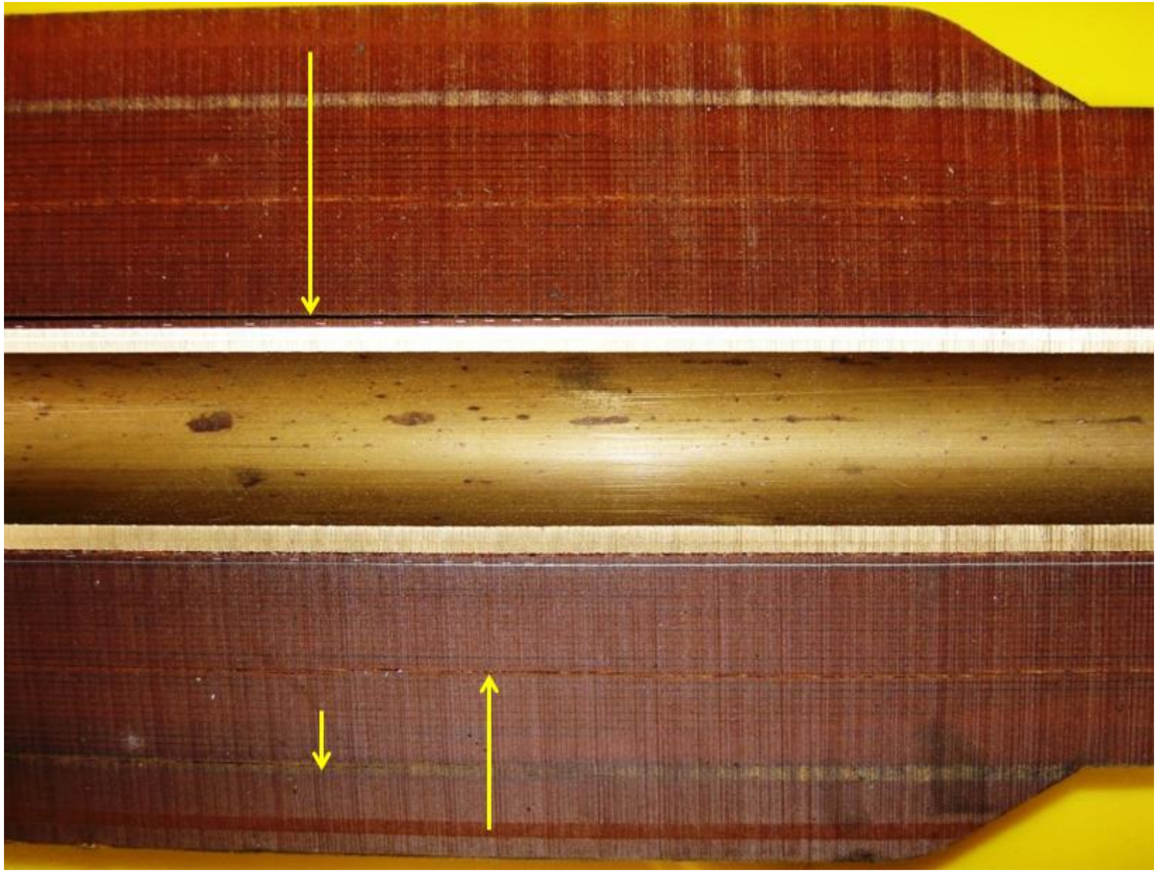
Table 40: Indicative DF/PF Limit Values for Condenser Bushings

RBP Bushing Oil-Filled Cracks

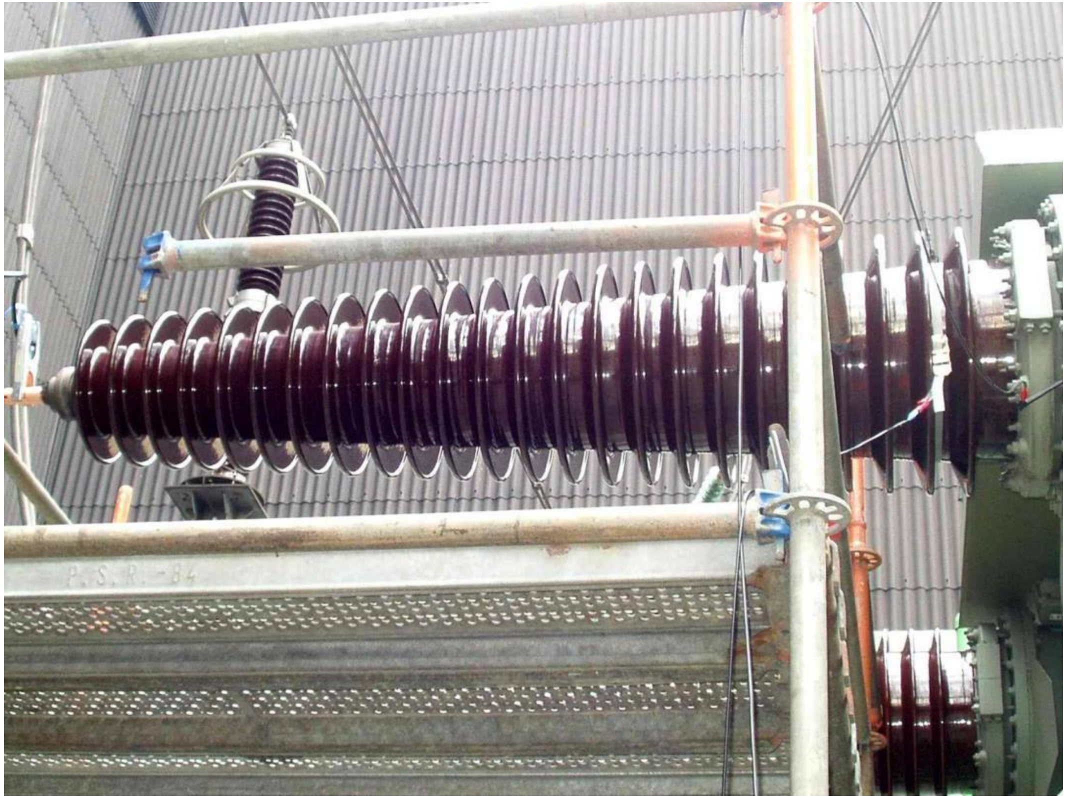
Oil Ingress by Capillare Effect

RBP – Bushings

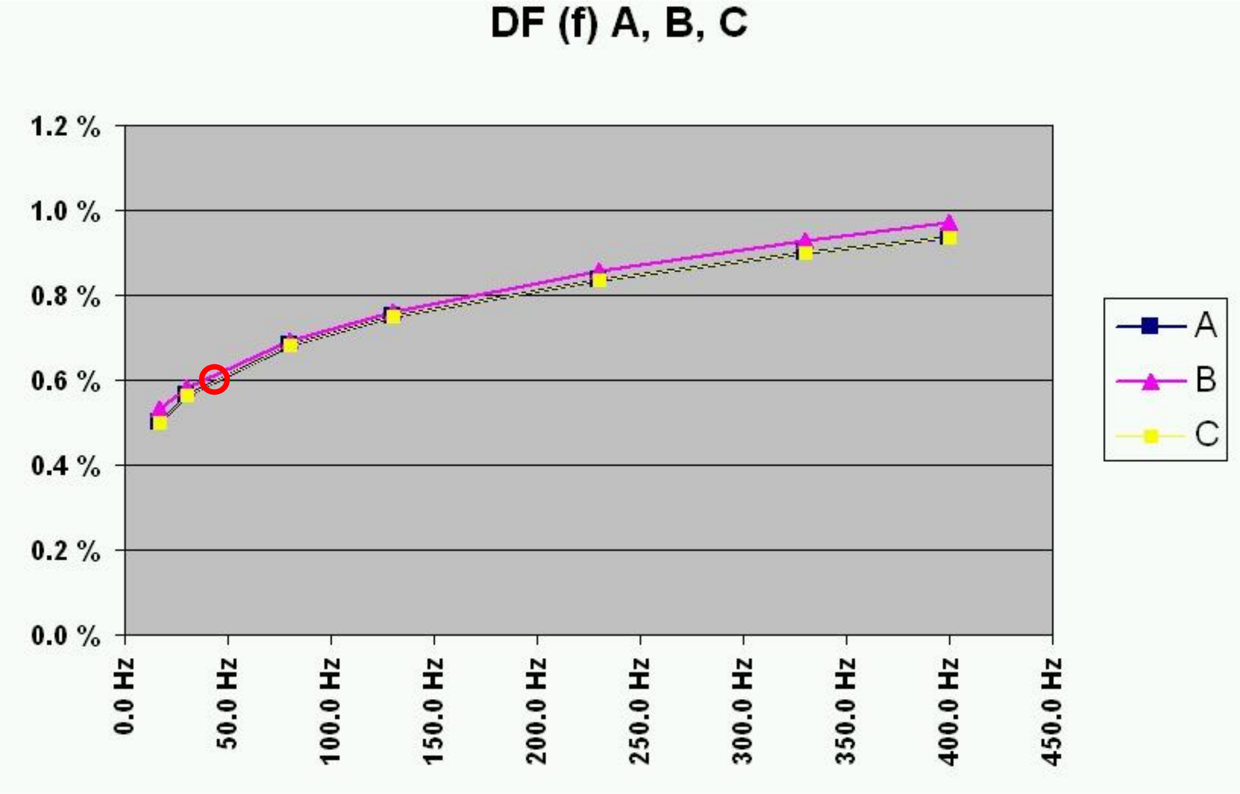
Cracks in the Insulation



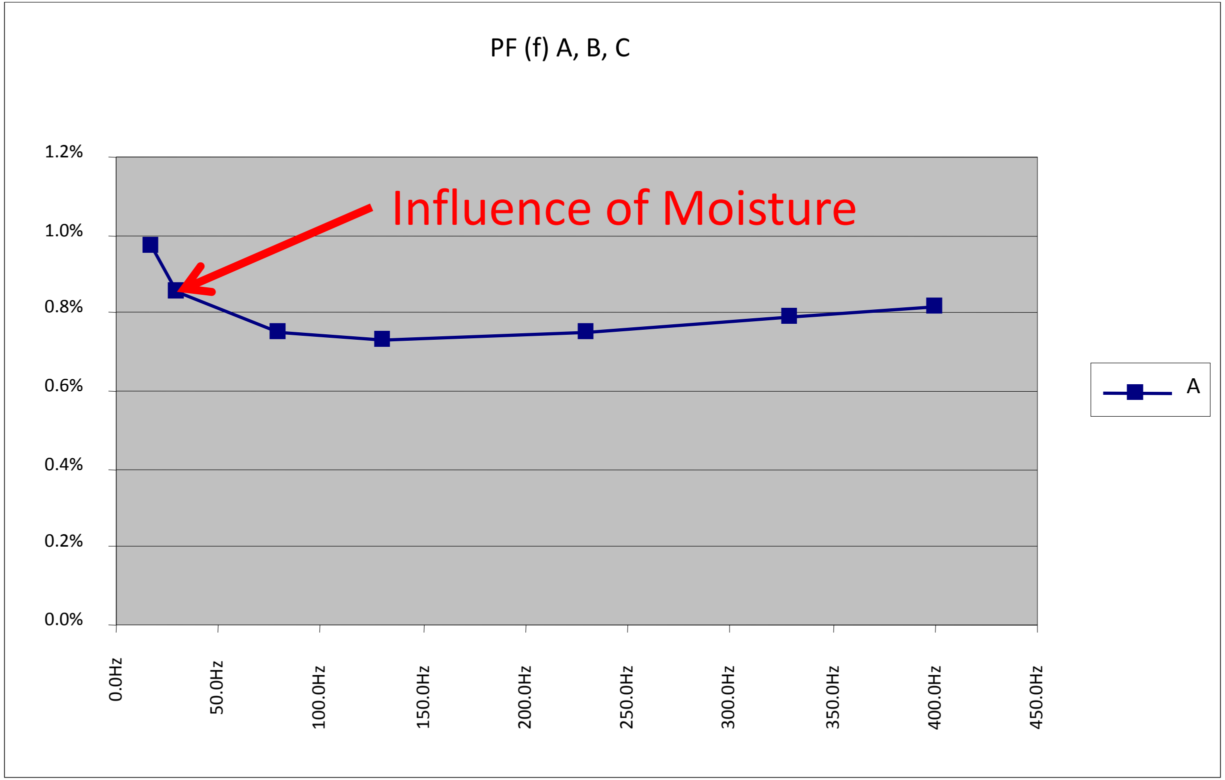
Measurement on 220kV RBP Bushings (1971)



TanDelta 15-400Hz



RBP Bushing 123kV (1963)



OIP Bushings

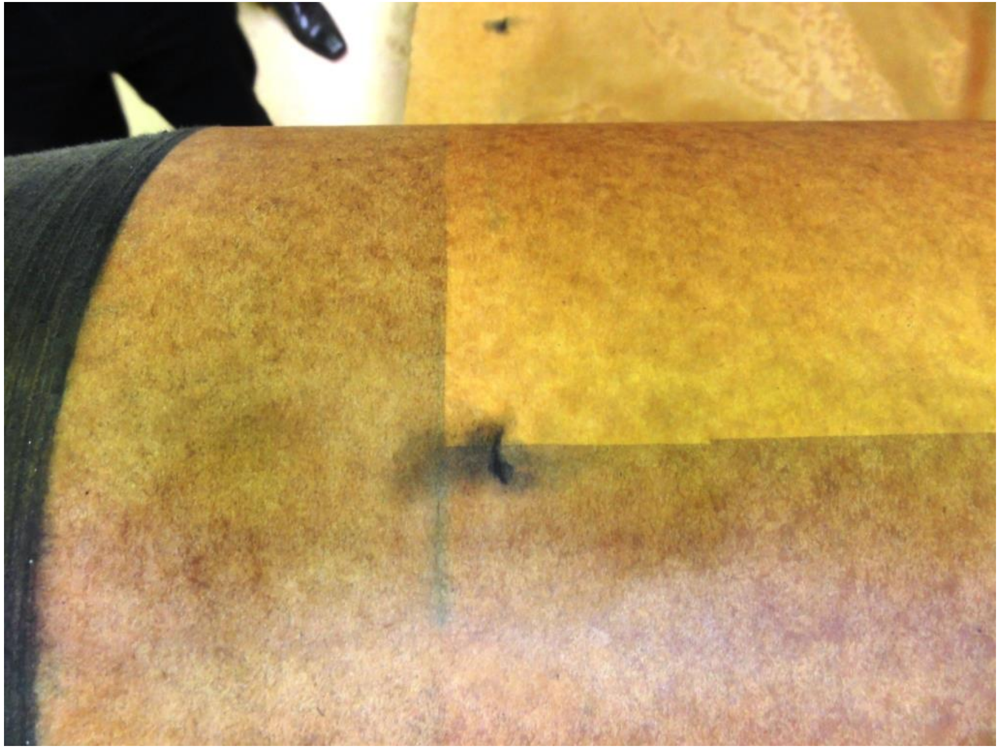
- Paper of the OIP bushings ages particularly at high temperatures

- Through aging the dielectric losses will increase
  -> this increases the dissipation factor

- Temperature dependent aging decomposes the paper and produces additional water
  -> this accellerates the aging

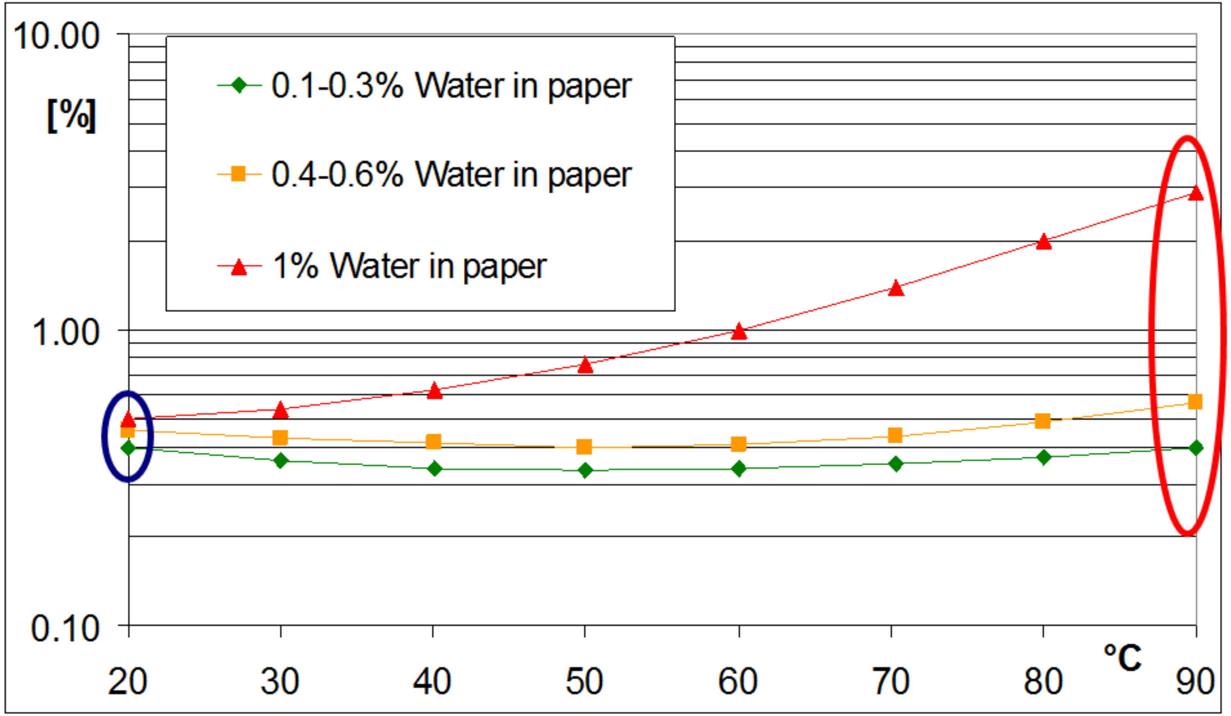
OIP Bushing

Breakdown at the Sharp Edge of the Foil



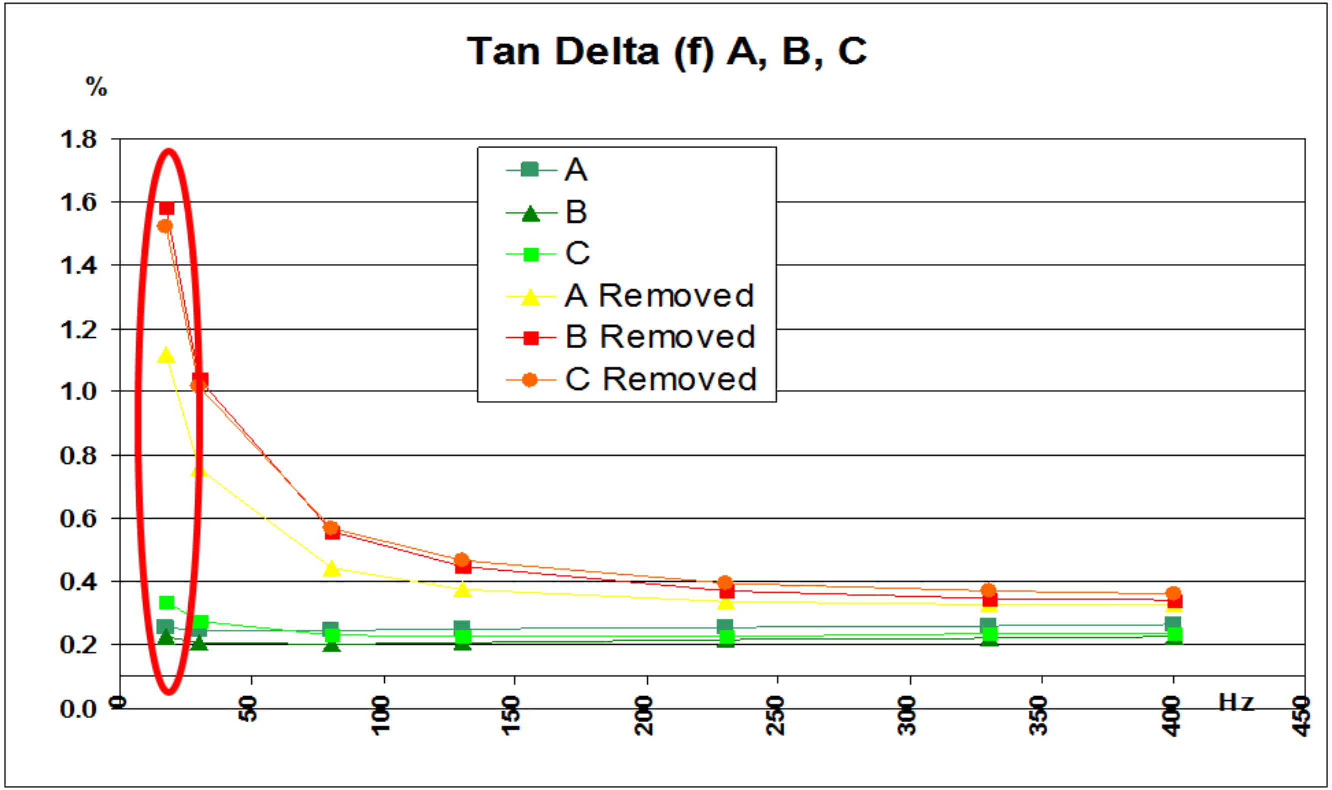
Source: Hubert Goebel GmbH

Tan Delta (T) at 50Hz (OIP DF)

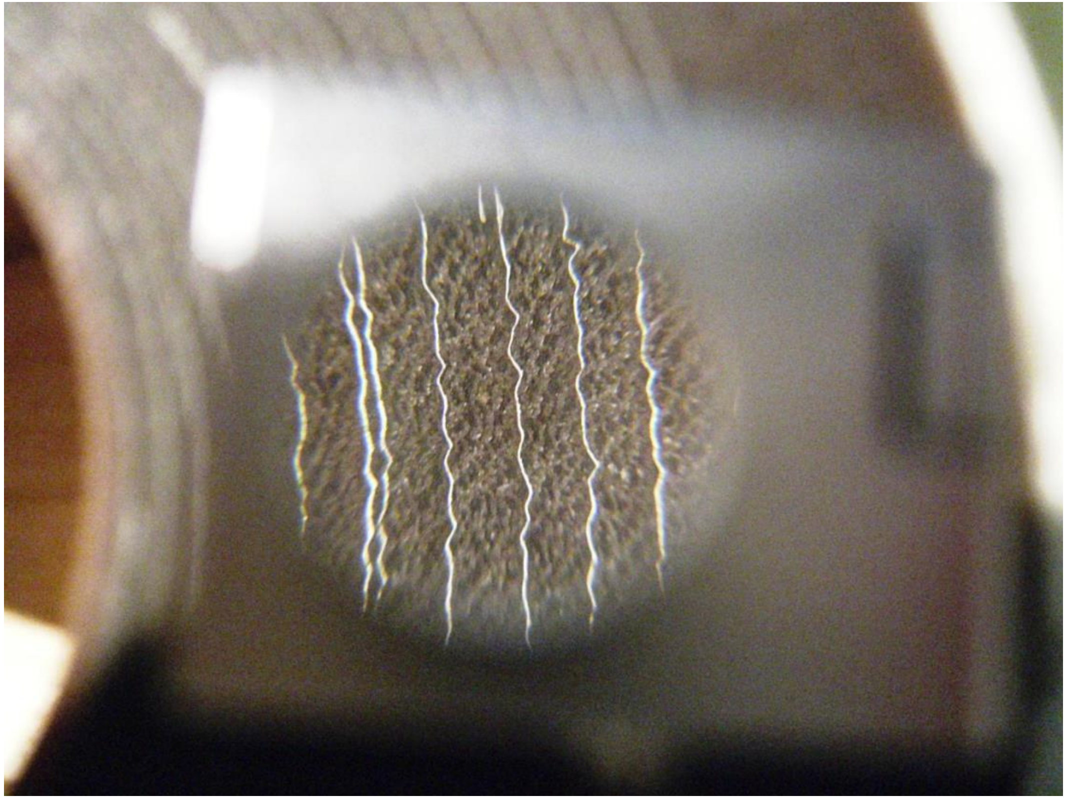


Source: ABB, Bushing diagnostics and conditioning

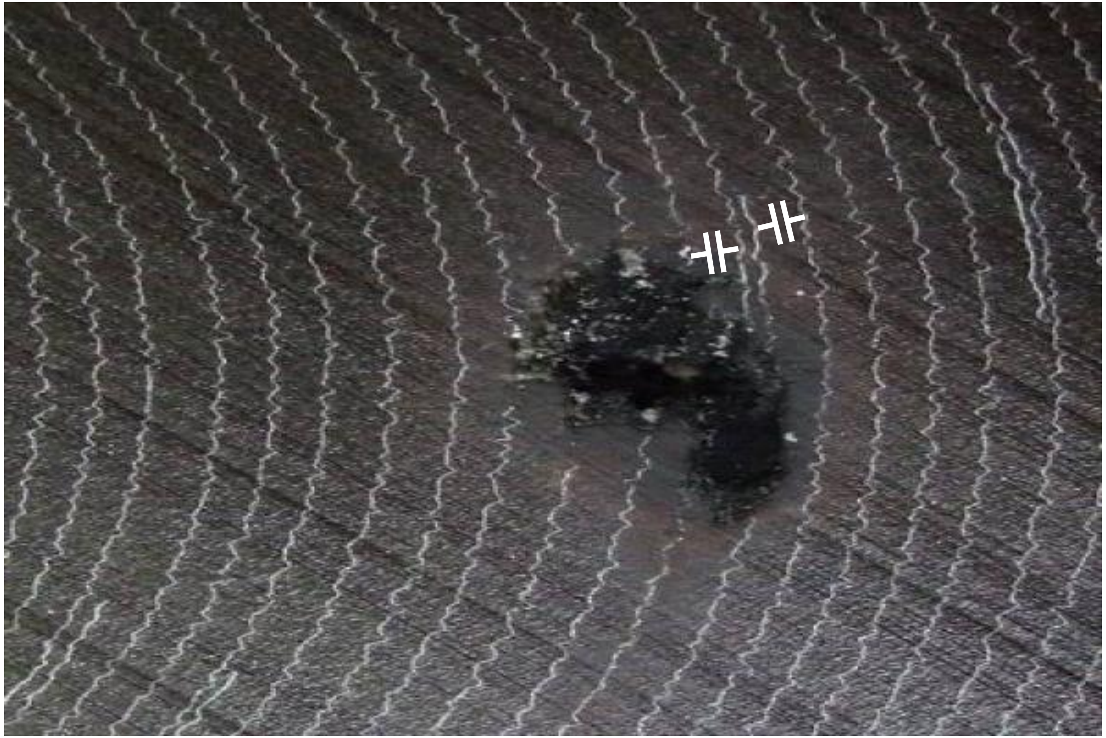
Tan Delta (f) at 30°C (33kV OIP DF)



RIP Bushings

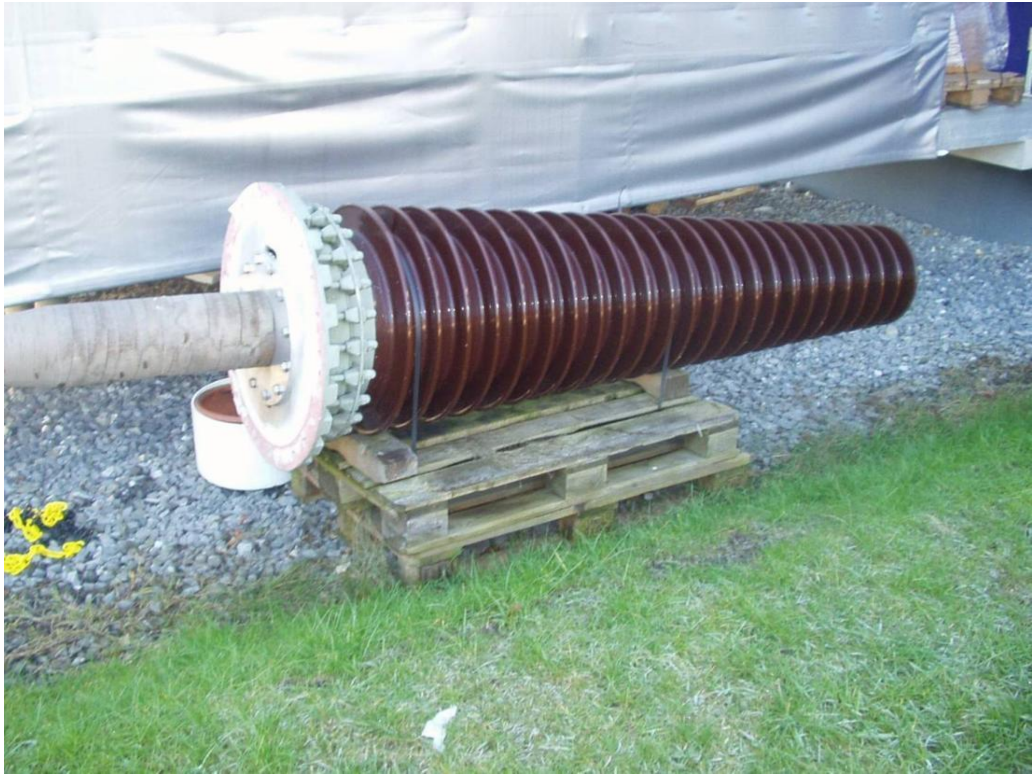


Partial Breakdown on a RIP Bushing

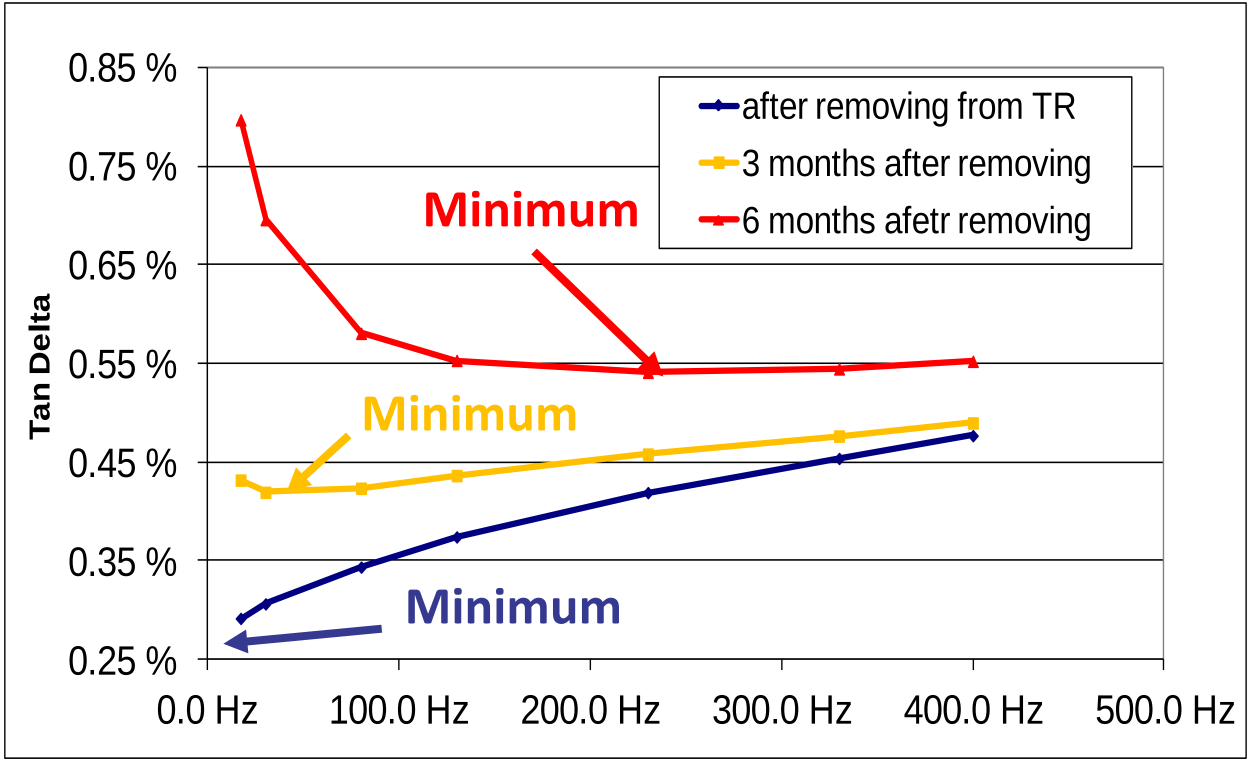


Source: B. Heil, „Diagnose und Bewertung von Durchführungen”, OMICRON AWT Germany 2010

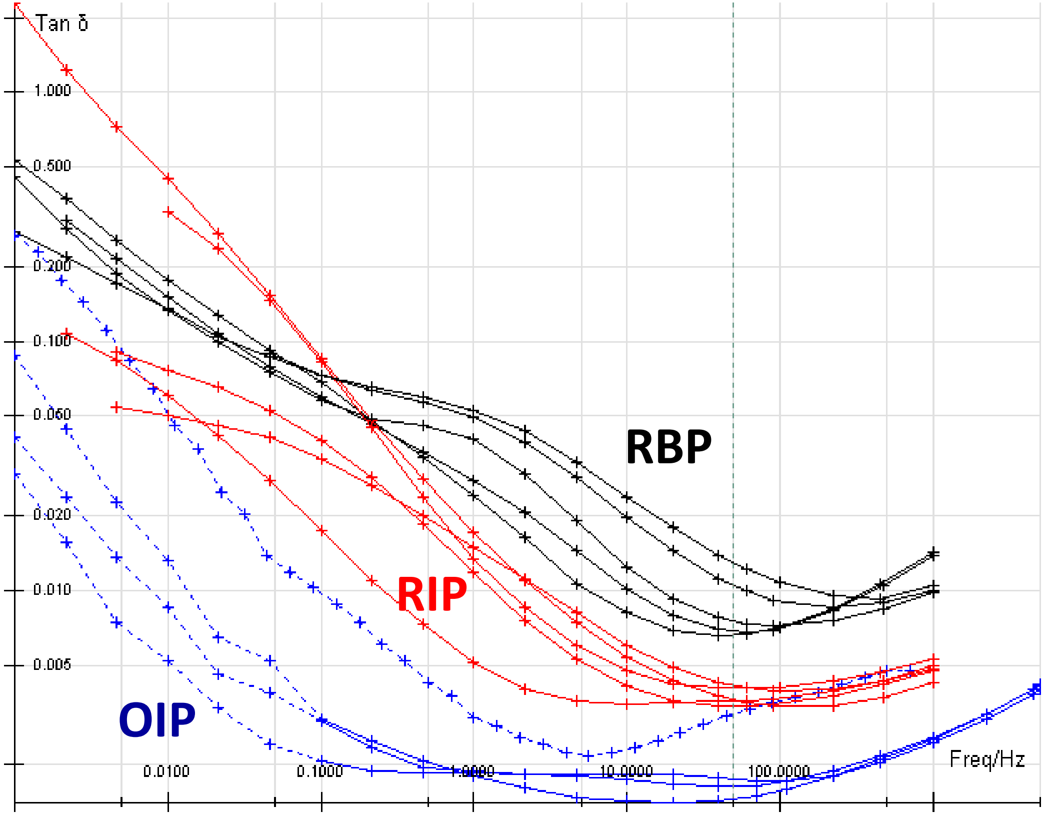
220kV RIP Bushing, Stored Outside



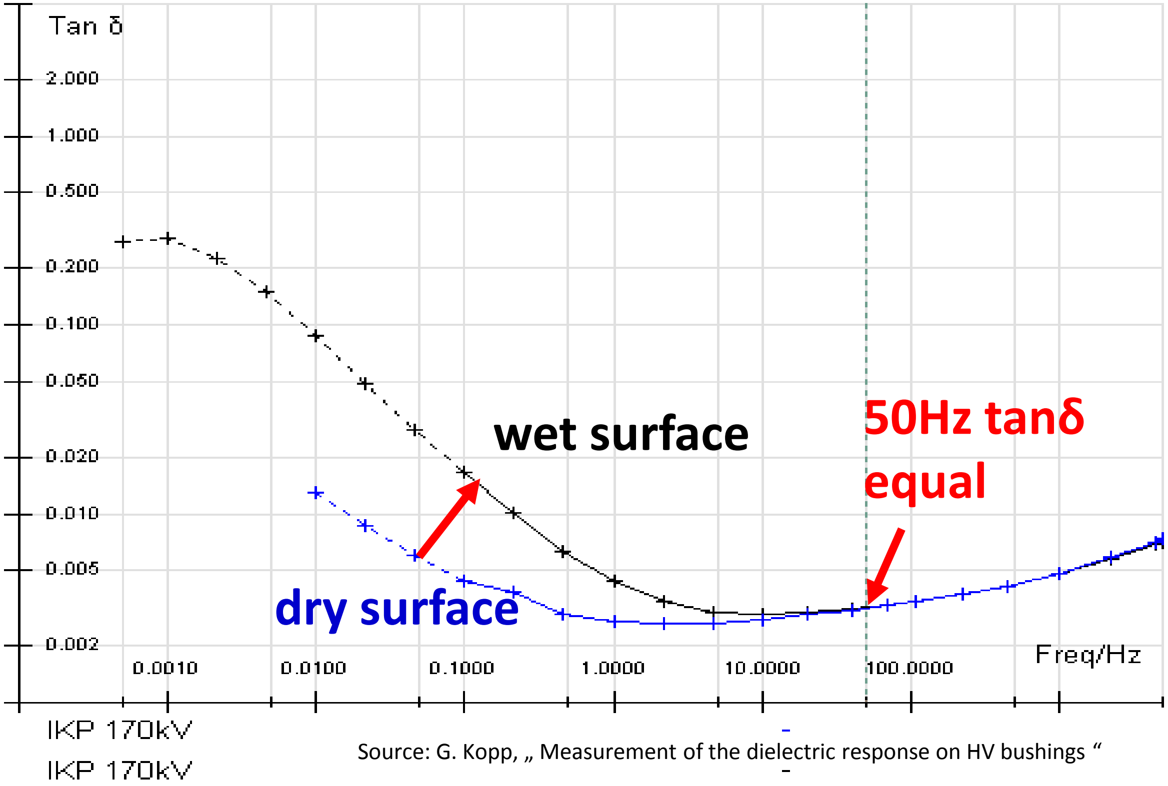
220kV RIP Bushing, Stored Outside



Dielectric Response on RIP, RBP and OIP Bushings



Dielectric Response with Dry and Wet Surface



wet surface

dry surface

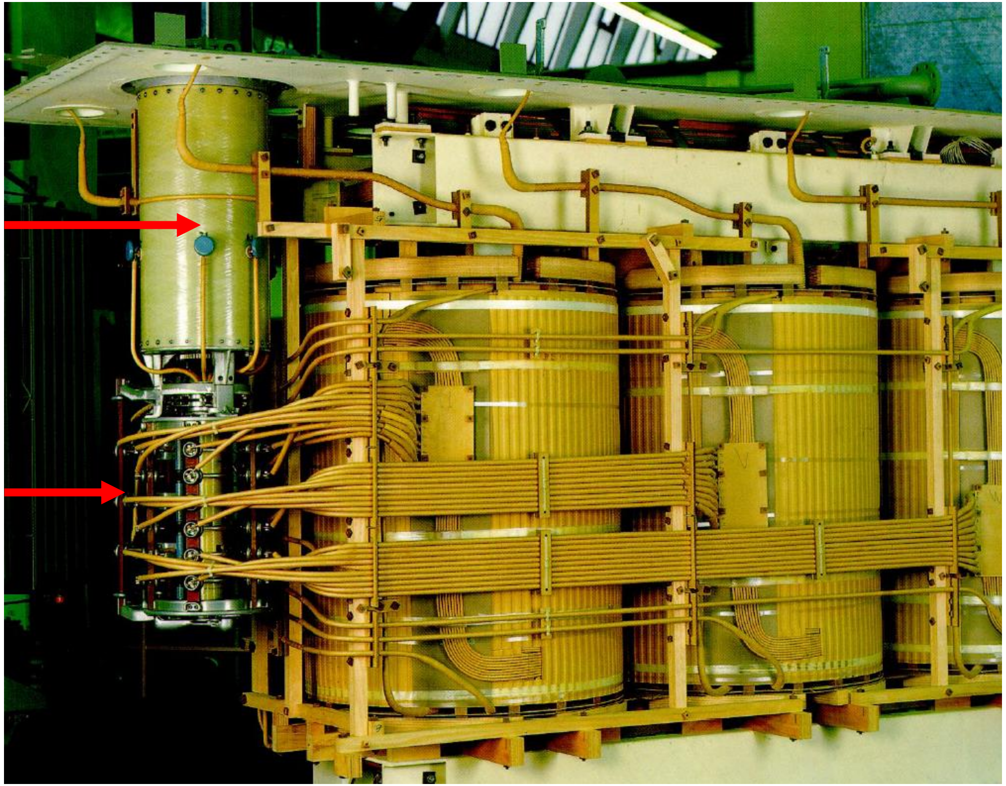
50Hz tanδ equal

Source: G. Kopp, „ Measurement of the dielectric response on HV bushings “

Transformer Health Assessment

- Introduction
- **Diagnostic on Power Transformers**
  - Oil
  - Main Insulation
  - Magnetic Core and Coil
  - Diagnostic of the Bushings
  - **Diagnostic of the Tap Changer**
- Case Study – Health Assessment of a Transformer

On Load Tap Changers



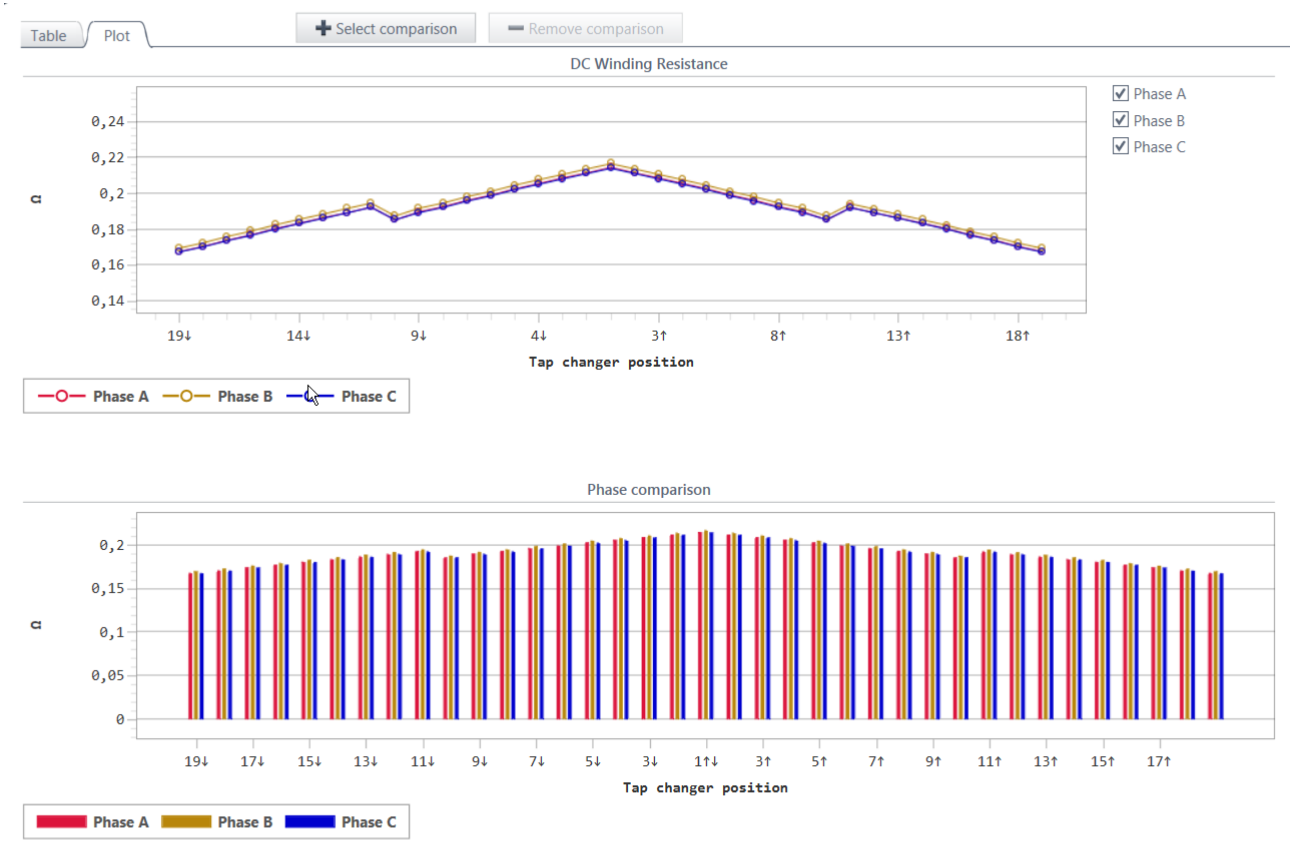
Diverter Switch

Tap Selector

Maschinenfabrik Reinhausen

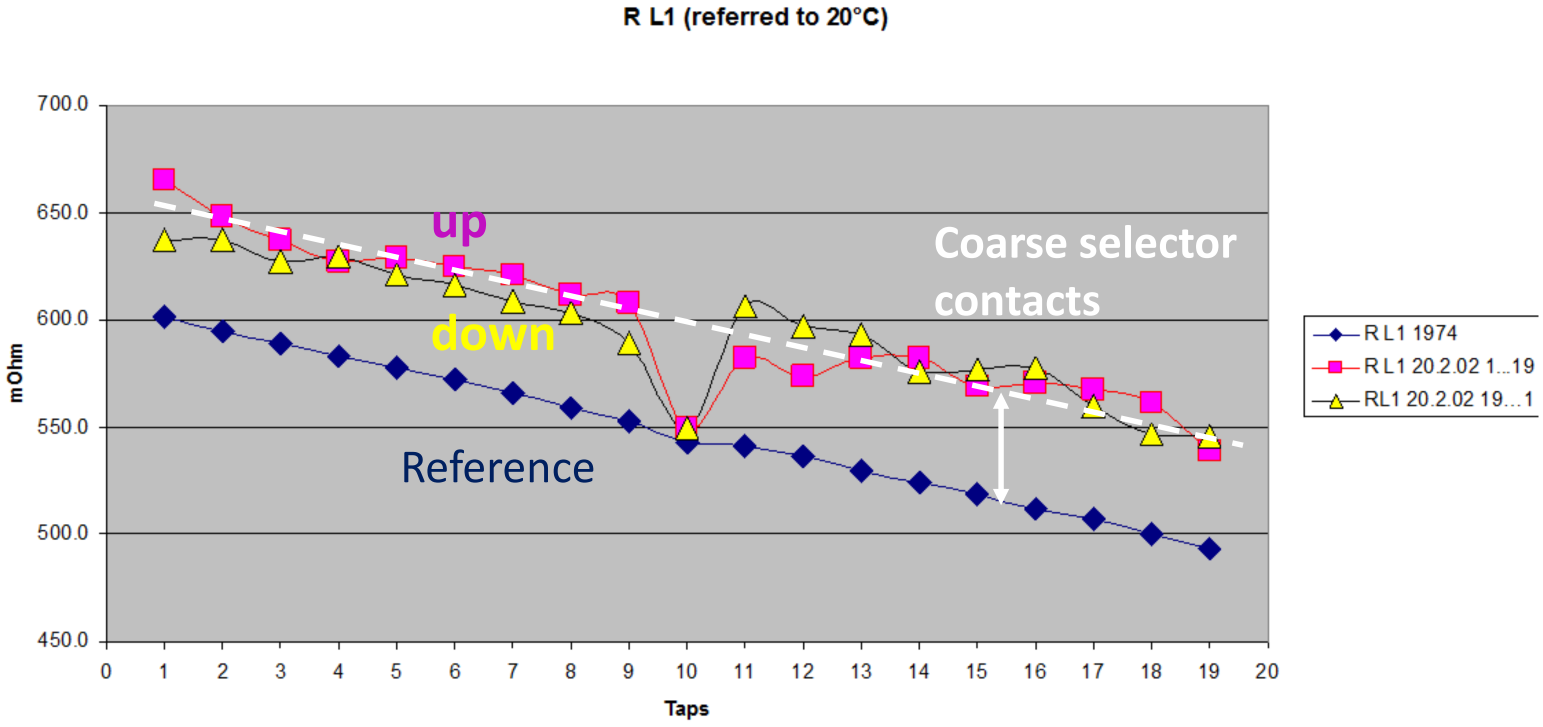
Static Winding Resistance Measurement HV on all Taps

for Tap Selector Diagnosis



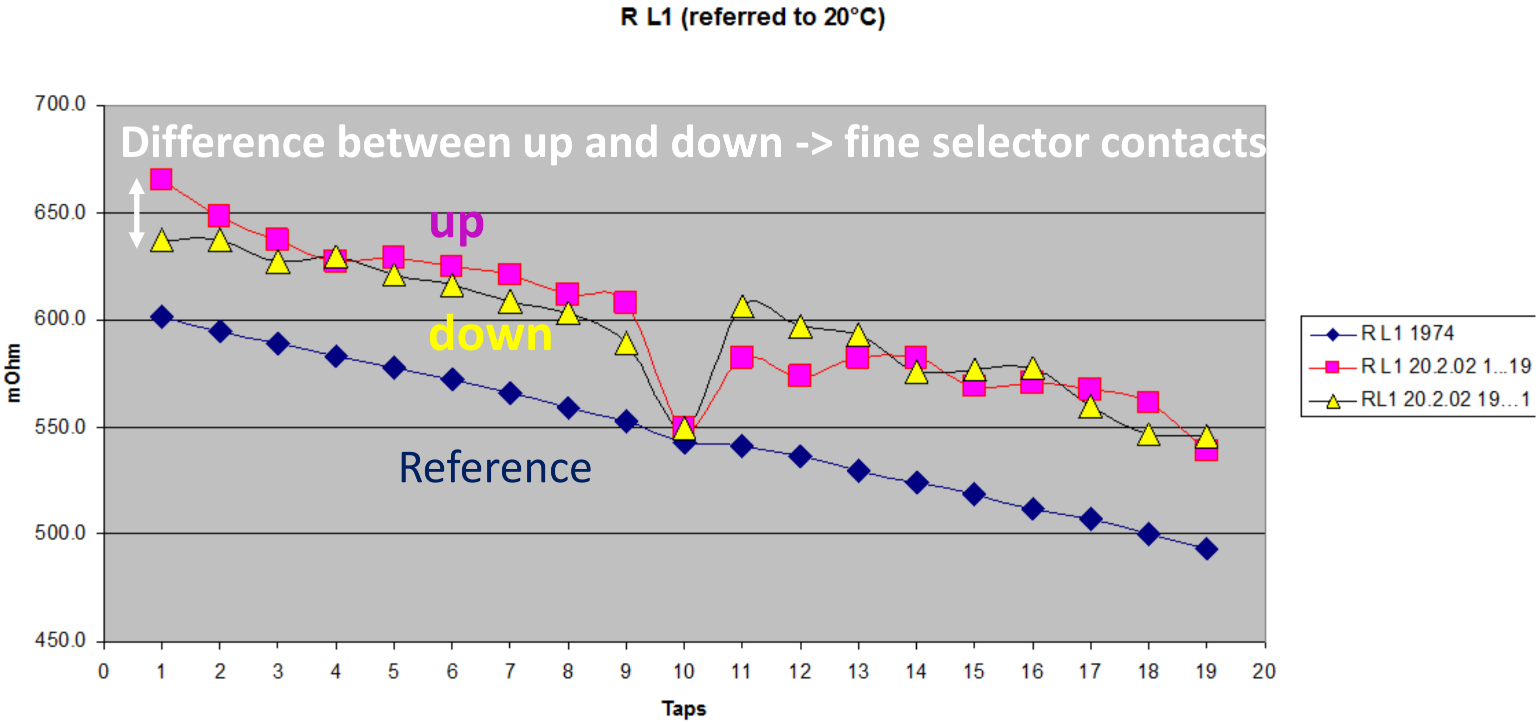
Static Winding Resistance Measurement HV on all Taps

for Tap Selector Diagnosis



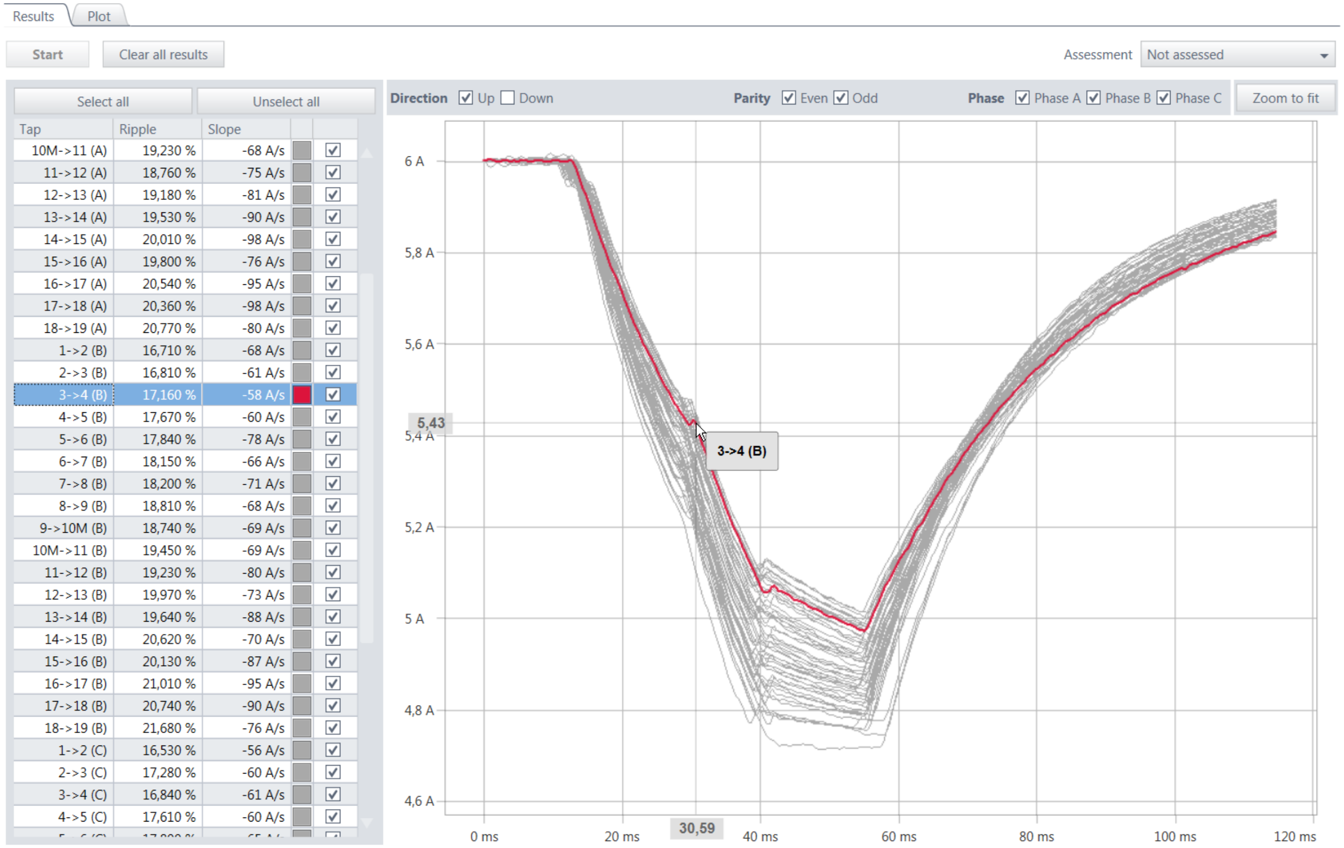
Static Winding Resistance Measurement HV on all Taps

for Tap Selector Diagnosis



Dynamic Winding Resistance Measurement HV 1-19

for Diverter Switch Diagnosis

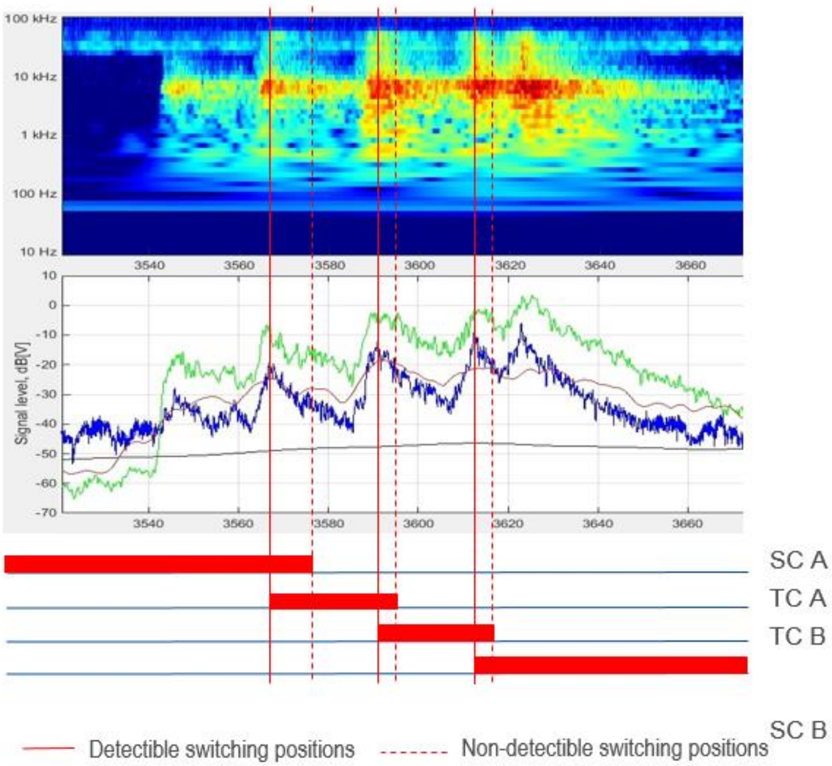


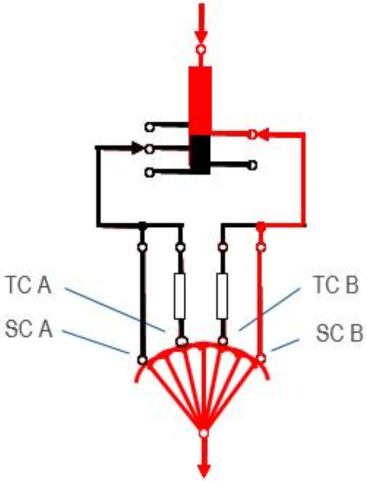
Assessment: Not assessed

Direction ☑ Up ☐ Down **Parity** ☑ Even ☑ Odd **Phase** ☑ Phase A ☑ Phase B ☑ Phase C

Tap	Ripple	Slope		
10M->11 (A)	19,230 %	-68 A/s	▨	☑
11->12 (A)	18,760 %	-75 A/s	▨	☑
12->13 (A)	19,180 %	-81 A/s	▨	☑
13->14 (A)	19,530 %	-90 A/s	▨	☑
14->15 (A)	20,010 %	-98 A/s	▨	☑
15->16 (A)	19,800 %	-76 A/s	▨	☑
16->17 (A)	20,540 %	-95 A/s	▨	☑
17->18 (A)	20,360 %	-98 A/s	▨	☑
18->19 (A)	20,770 %	-80 A/s	▨	☑
1->2 (B)	16,710 %	-68 A/s	▨	☑
2->3 (B)	16,810 %	-61 A/s	▨	☑
3->4 (B)	17,160 %	-58 A/s	🟥	☑
4->5 (B)	17,670 %	-60 A/s	▨	☑
5->6 (B)	17,840 %	-78 A/s	▨	☑
6->7 (B)	18,150 %	-66 A/s	▨	☑
7->8 (B)	18,200 %	-71 A/s	▨	☑
8->9 (B)	18,810 %	-68 A/s	▨	☑
9->10M (B)	18,740 %	-69 A/s	▨	☑
10M->11 (B)	19,450 %	-69 A/s	▨	☑
11->12 (B)	19,230 %	-80 A/s	▨	☑
12->13 (B)	19,970 %	-73 A/s	▨	☑
13->14 (B)	19,640 %	-88 A/s	▨	☑
14->15 (B)	20,620 %	-70 A/s	▨	☑
15->16 (B)	20,130 %	-87 A/s	▨	☑
16->17 (B)	21,010 %	-95 A/s	▨	☑
17->18 (B)	20,740 %	-90 A/s	▨	☑
18->19 (B)	21,680 %	-76 A/s	▨	☑
1->2 (C)	16,530 %	-56 A/s	▨	☑
2->3 (C)	17,280 %	-60 A/s	▨	☑
3->4 (C)	16,840 %	-61 A/s	▨	☑
4->5 (C)	17,610 %	-60 A/s	▨	☑

Vibroacoustic Measurements on OLTC





U. Seltsam, „Vibroacoustic Measurements on OLTC“, CEPED Dubai, 2016

Transformer Health Assessment

- Introduction
- Diagnostic on Power Transformers
  - Oil
  - Main Insulation
  - Magnetic Core and Coil
  - Diagnostic of the Bushings
  - Diagnostic of the Tap Changer
- **Case Study – Health Assessment of a Transformer**

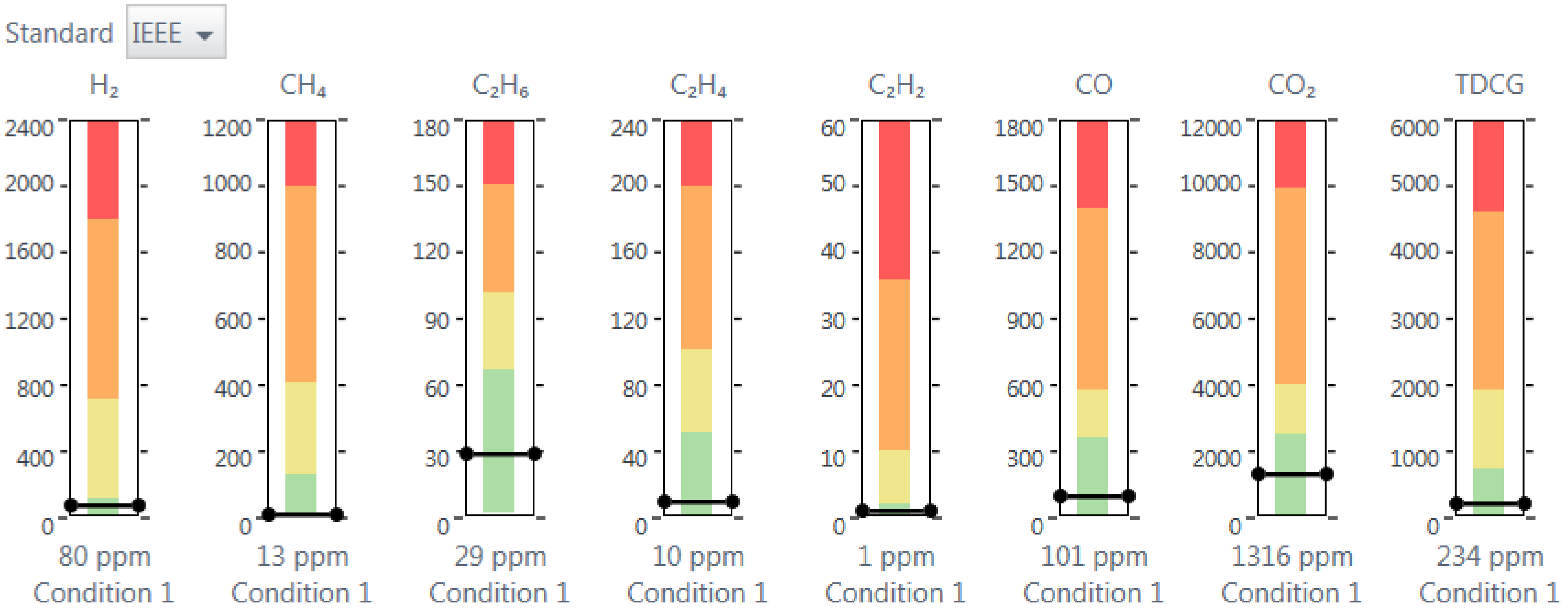
Health Assessment of a 220 kV / 300 MVA Transformer

Man. Year	**1993**
Counter OLTC	**39.414**

Health Assessment of a 220 kV / 300 MVA Transformer

- **Oil Analysis**
- Measuement of the Moisture in the solid Insulation
- Capacitance and tan δ Measurement of the Bushings
- Measurement of Turns Ratio and the Magnetising Currents
- Winding Resistance Measurements of the HV Windings on all Taps
- Measurement of the Short Circuit Impedance

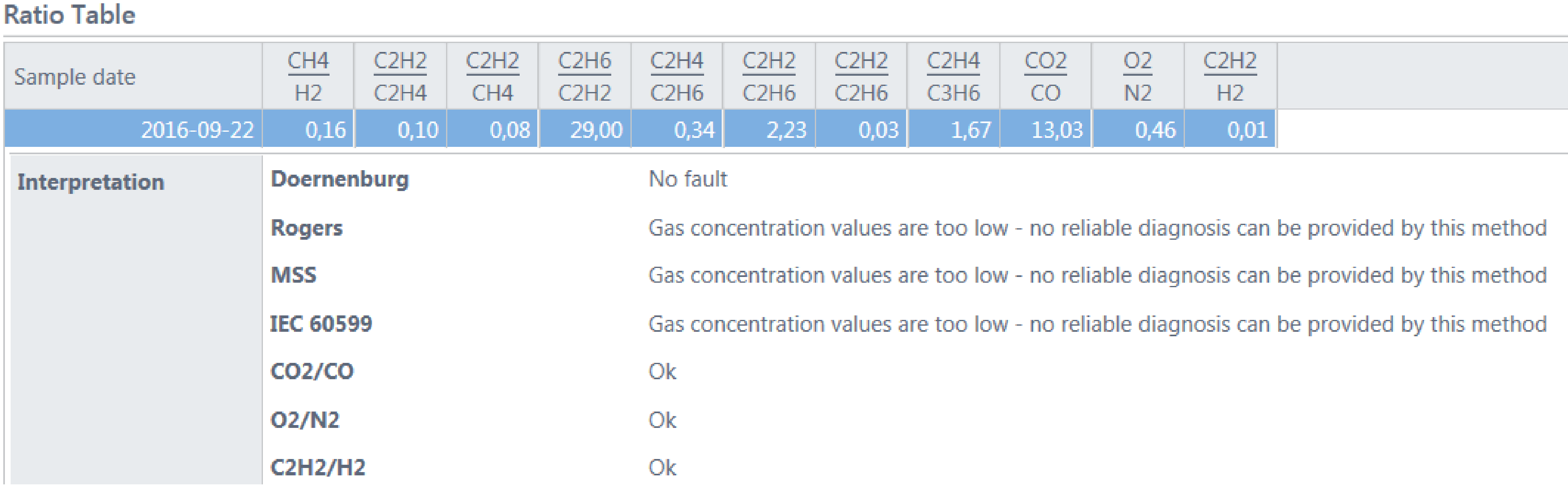
DGA 2016



Standard IEEE

H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO	CO_2	TDCG
80 ppm	13 ppm	29 ppm	10 ppm	1 ppm	101 ppm	1316 ppm	234 ppm
Condition 1	Condition 1	Condition 1	Condition 1	Condition 1	Condition 1	Condition 1	Condition 1

DGA 2016

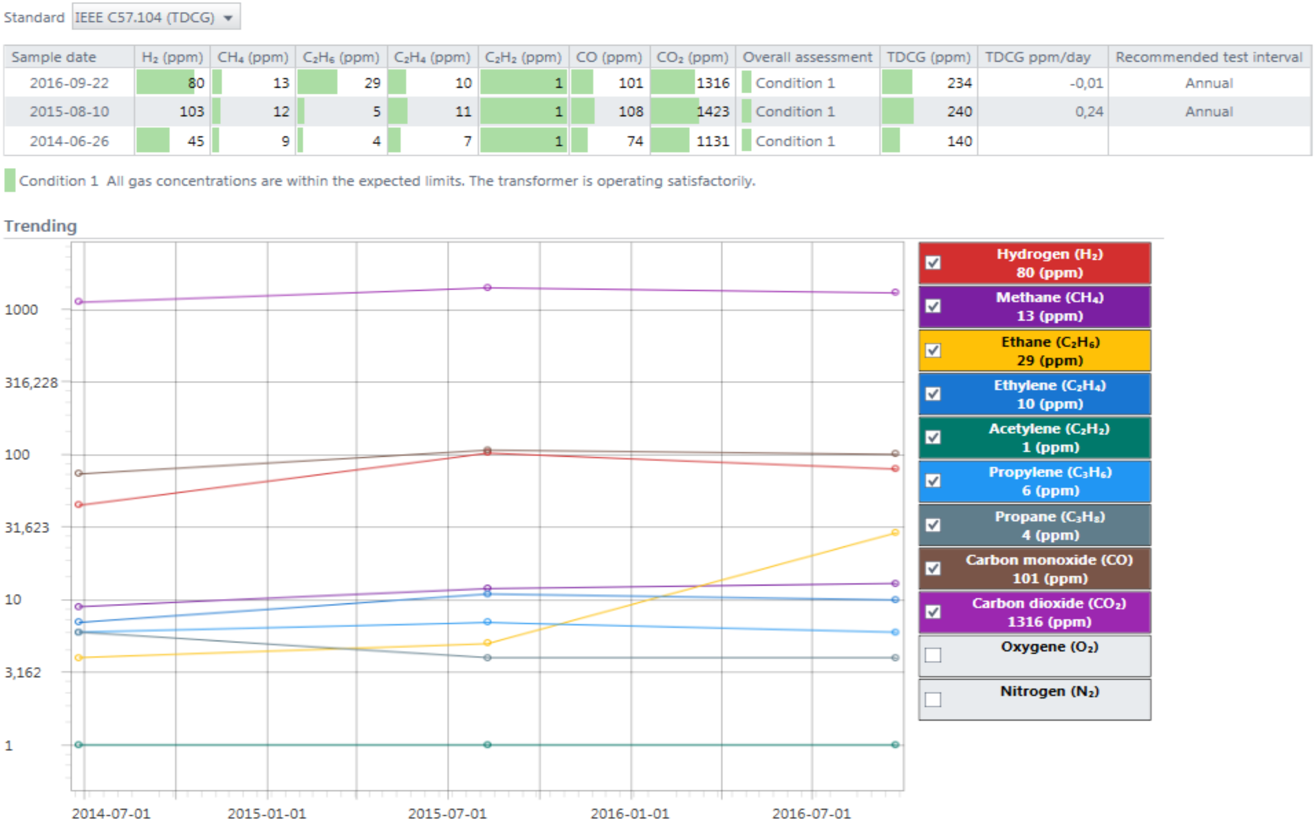


Ratio Table

Sample date	$\frac{CH_4}{H_2}$	$\frac{C_2H_2}{C_2H_4}$	$\frac{C_2H_2}{CH_4}$	$\frac{C_2H_6}{C_2H_2}$	$\frac{C_2H_4}{C_2H_6}$	$\frac{C_2H_2}{C_2H_6}$	$\frac{C_2H_2}{C_2H_6}$	$\frac{C_2H_4}{C_3H_6}$	$\frac{CO_2}{CO}$	$\frac{O_2}{N_2}$	$\frac{C_2H_2}{H_2}$
2016-09-22	0,16	0,10	0,08	29,00	0,34	2,23	0,03	1,67	13,03	0,46	0,01

Interpretation		
	Doernenburg	No fault
	Rogers	Gas concentration values are too low - no reliable diagnosis can be provided by this method
	MSS	Gas concentration values are too low - no reliable diagnosis can be provided by this method
	IEC 60599	Gas concentration values are too low - no reliable diagnosis can be provided by this method
	CO2/CO	Ok
	O2/N2	Ok
	C2H2/H2	Ok

DGA Trend from 2014 to 2016



Standard IEEE C57.104 (TDCG)

Sample date	H_2 (ppm)	CH_4 (ppm)	C_2H_6 (ppm)	C_2H_4 (ppm)	C_2H_2 (ppm)	CO (ppm)	CO_2 (ppm)	Overall assessment	TDCG (ppm)	TDCG ppm/day	Recommended test interval
2016-09-22	80	13	29	10	1	101	1316	Condition 1	234	-0,01	Annual
2015-08-10	103	12	5	11	1	108	1423	Condition 1	240	0,24	Annual
2014-06-26	45	9	4	7	1	74	1131	Condition 1	140		

🟩 Condition 1 All gas concentrations are within the expected limits. The transformer is operating satisfactorily.

Trending

☑ Hydrogen (H_2) 80 (ppm)
☑ Methane (CH_4) 13 (ppm)
☑ Ethane (C_2H_6) 29 (ppm)
☑ Ethylene (C_2H_4) 10 (ppm)
☑ Acetylene (C_2H_2) 1 (ppm)
☑ Propylene (C_3H_6) 6 (ppm)
☑ Propane (C_3H_8) 4 (ppm)
☑ Carbon monoxide (CO) 101 (ppm)
☑ Carbon dioxide (CO_2) 1316 (ppm)
☐ Oxygene (O_2)
☐ Nitrogen (N_2)

Health Assessment of a 220 kV / 300 MVA Transformer

- Oil Analysis
- **Measuement of the Moisture in the Solid Insulation**
- Capacitance and tan δ Measurement of the Bushings
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Measurement of the Relative Moisture in Oilr

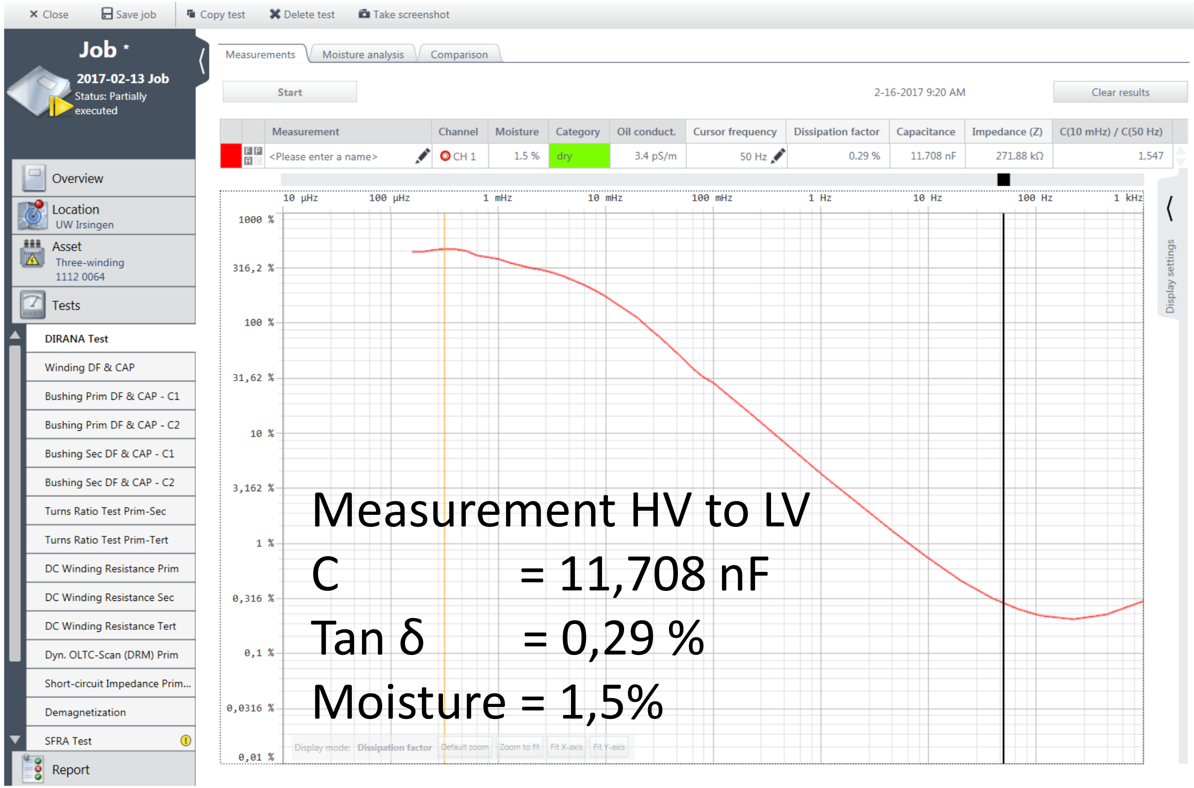
T = 47,8°C

RH = 6,3 %

Water Content

	RH	WC_{Cell}
New	1-2	0,5
Fair	5-10	1,5-2
Wet	10-15	3-4,5

Measurement of the Moisture in the Solid Insulation



2017-02-13 Job
Status: Partially executed

2-16-2017 9:20 AM

Measurement	Channel	Moisture	Category	Oil conduct.	Cursor frequency	Dissipation factor	Capacitance	Impedance (Z)	C(10 mHz) / C(50 Hz)
<Please enter a name>	CH 1	1.5 %	dry	3.4 pS/m	50 Hz	0.29 %	11.708 nF	271.88 kΩ	1,547

Measurement HV to LV

C = 11,708 nF

Tan δ = 0,29 %

Moisture = 1,5%

Health Assessment of a 220 kV / 300 MVA Transformer

- Oil Analysis
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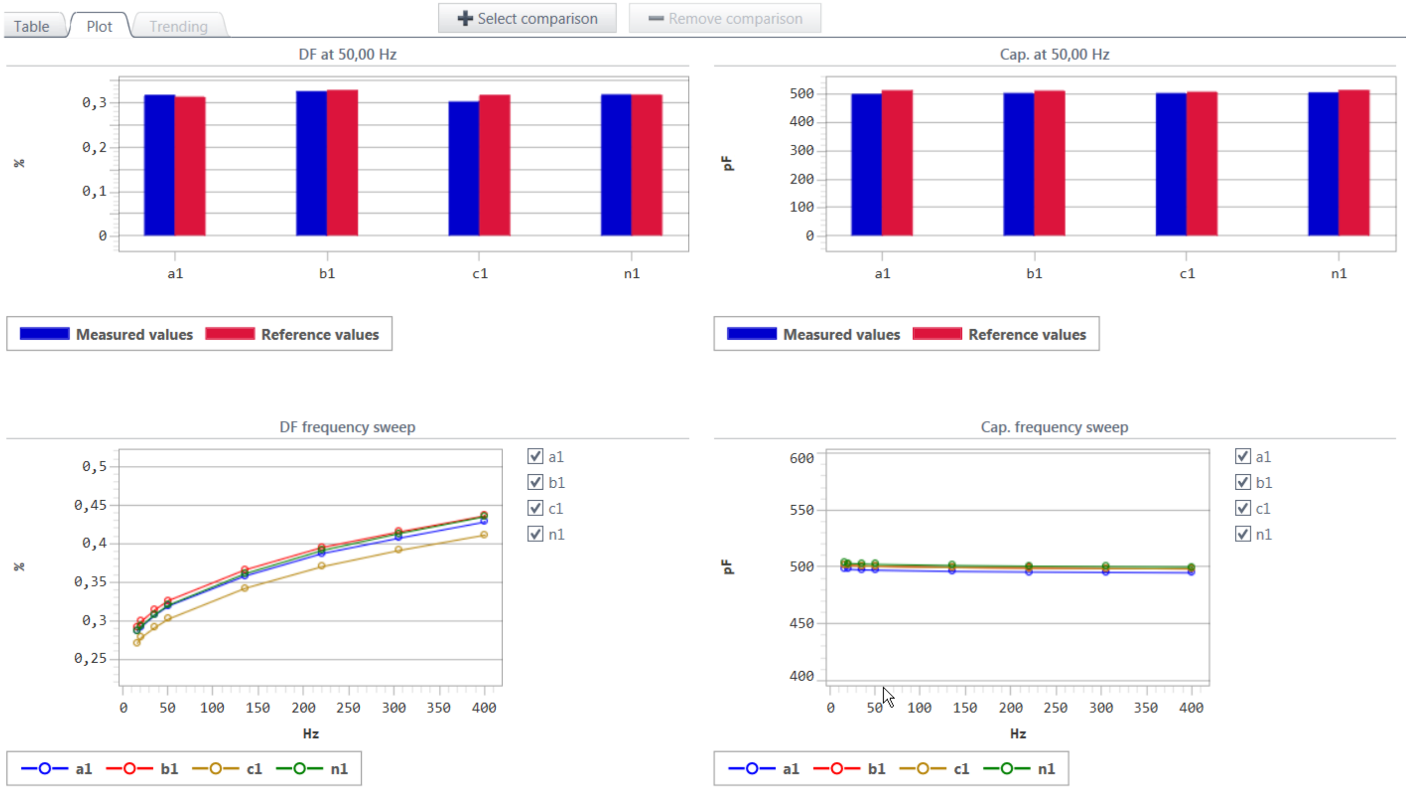
C- und Tan δ of the HV Bushings

C- und Tan δ of the LV Bushings



Health Assessment of a 220 kV / 300 MVA Transformer

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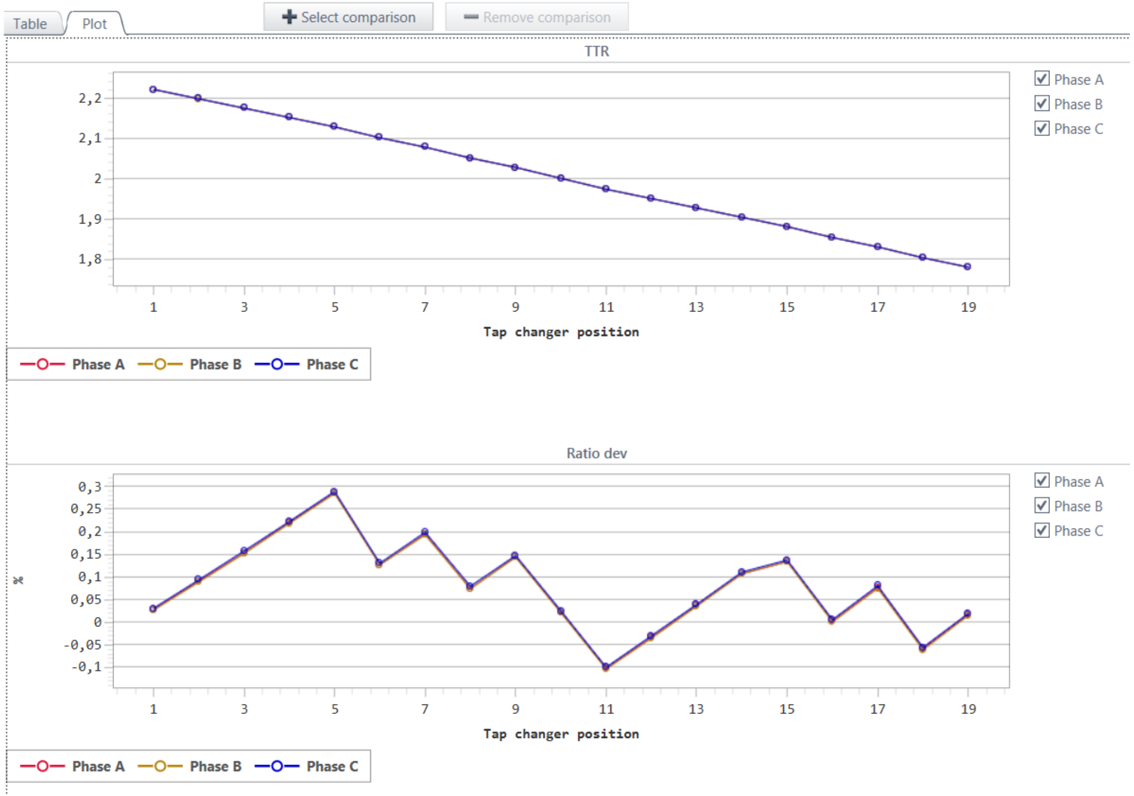
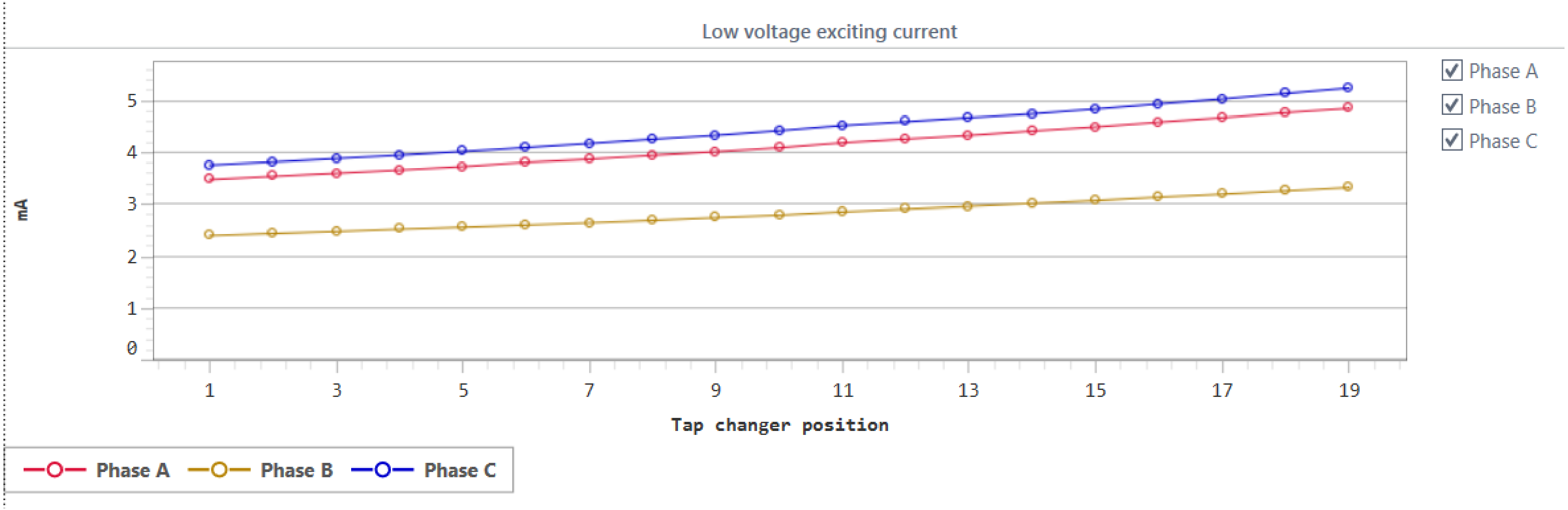
Ratio Measurement HV - LV



Magnetising Current HV



Health Assessment of a 220 kV / 300 MVA Transformer

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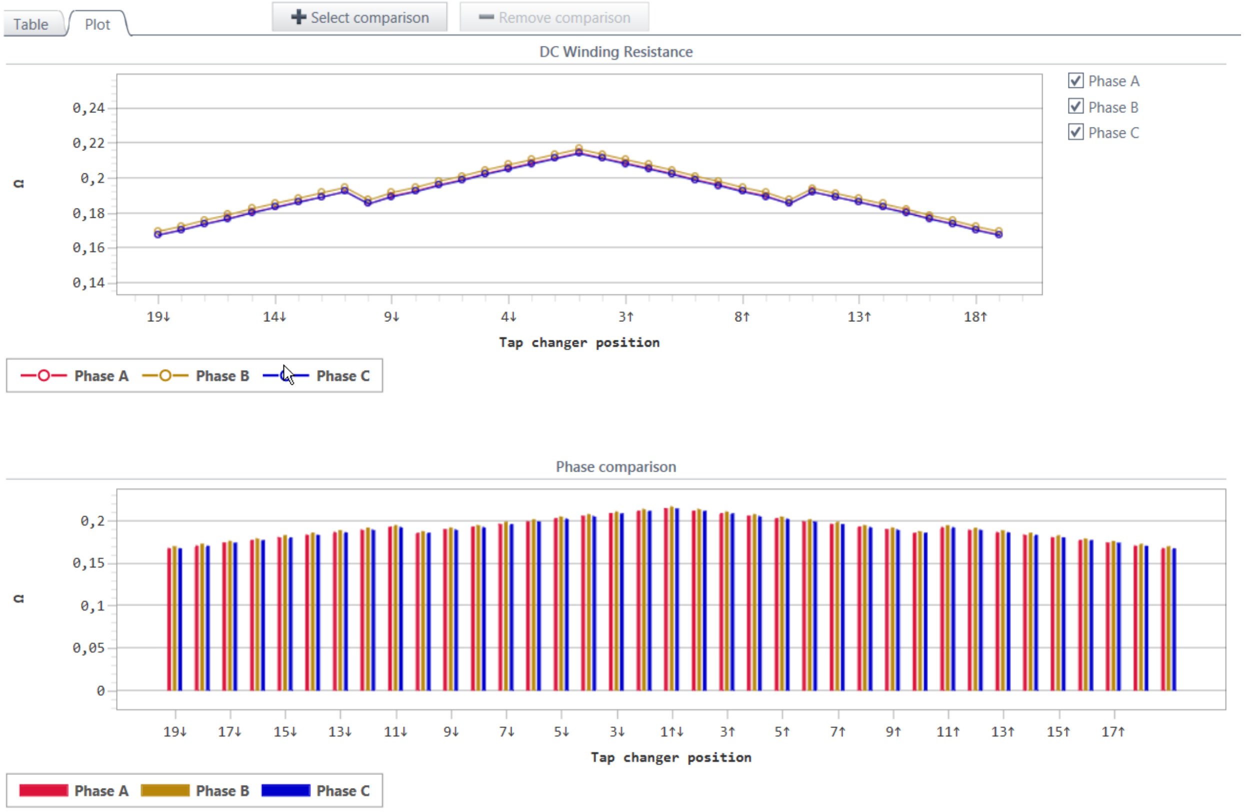
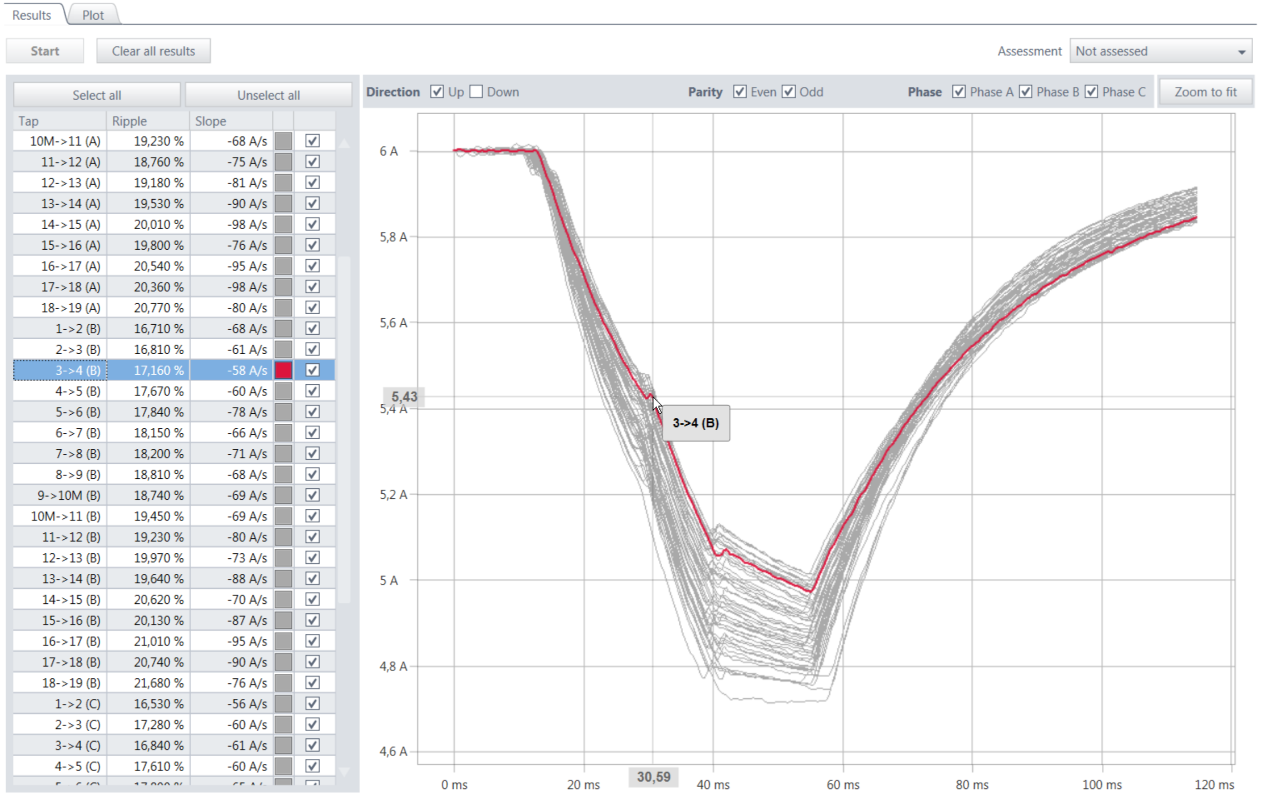
Static Winding Resistance Measurement HV



Dynamic Winding Resistance Measurement HV



Assessment: Not assessed

Direction ☑ Up ☐ Down **Parity** ☑ Even ☑ Odd **Phase** ☑ Phase A ☑ Phase B ☑ Phase C

Tap	Ripple	Slope		
10M->11 (A)	19,230 %	-68 A/s	▨	☑
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10M->11 (B)	19,450 %	-69 A/s	▨	☑
11->12 (B)	19,230 %	-80 A/s	▨	☑
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Health Assessment of a 220 kV / 300 MVA Transformer

- Oil Analysis
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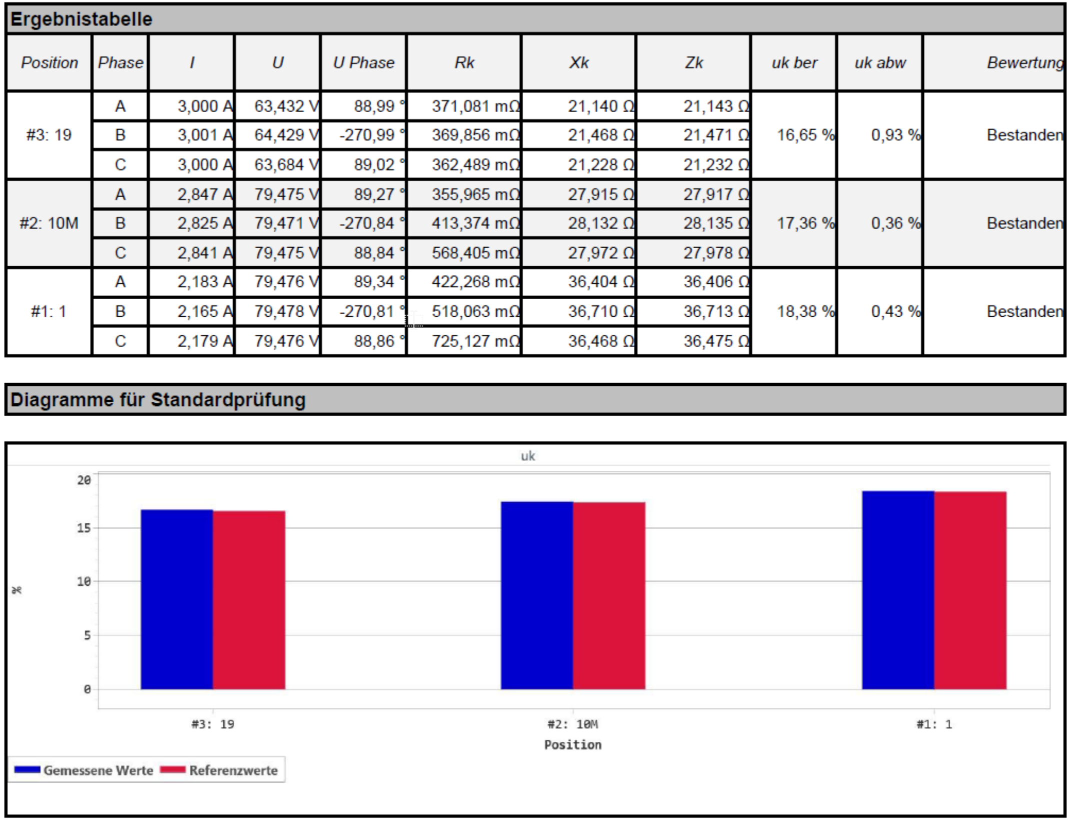
- **Measurement of the Short Circuit Impedance**

Short Circuit Impedance

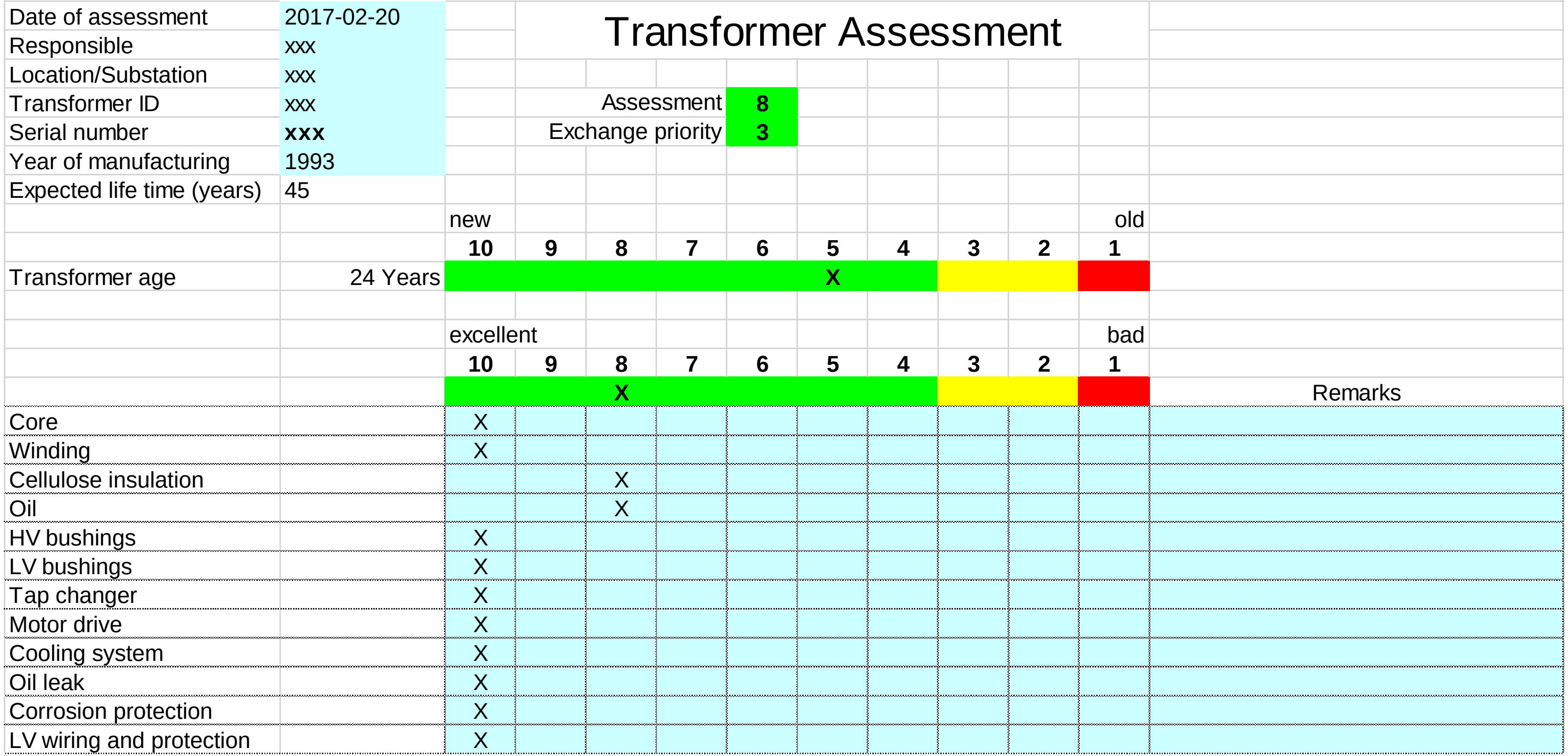


Ergebnistabelle

Position	*Phase*	*I*	*U*	*U Phase*	*Rk*	*Xk*	*Zk*	*uk ber*	*uk abw*	*Bewertung*
#3: 19	A	3,000 A	63,432 V	88,99 °	371,081 mΩ	21,140 Ω	21,143 Ω	16,65 %	0,93 %	Bestanden
	B	3,001 A	64,429 V	-270,99 °	369,856 mΩ	21,468 Ω	21,471 Ω			
	C	3,000 A	63,684 V	89,02 °	362,489 mΩ	21,228 Ω	21,232 Ω			
#2: 10M	A	2,847 A	79,475 V	89,27 °	355,965 mΩ	27,915 Ω	27,917 Ω	17,36 %	0,36 %	Bestanden
	B	2,825 A	79,471 V	-270,84 °	413,374 mΩ	28,132 Ω	28,135 Ω			
	C	2,841 A	79,475 V	88,84 °	568,405 mΩ	27,972 Ω	27,978 Ω			
#1: 1	A	2,183 A	79,476 V	89,34 °	422,268 mΩ	36,404 Ω	36,406 Ω	18,38 %	0,43 %	Bestanden
	B	2,165 A	79,478 V	-270,81 °	518,063 mΩ	36,710 Ω	36,713 Ω			
	C	2,179 A	79,476 V	88,86 °	725,127 mΩ	36,468 Ω	36,475 Ω			

Diagramme für Standardprüfung

Transformer Assessment



Date of assessment	2017-02-20		Transformer Assessment									
Responsible	xxx											
Location/Substation	xxx											
Transformer ID	xxx				Assessment	**8**						
Serial number	**xxx**				Exchange priority	**3**						
Year of manufacturing	1993											
Expected life time (years)	45											
		new									old	
		10	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	
Transformer age	24 Years	🟩	🟩	🟩	🟩	🟩	**X**	🟩	🟨	🟨	🟥	
		excellent									bad	
		10	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	
		🟩	🟩	**X**	🟩	🟩	🟩	🟩	🟨	🟨	🟥	Remarks
Core		X										
Winding		X										
Cellulose insulation				X								
Oil				X								
HV bushings		X										
LV bushings		X										
Tap changer		X										
Motor drive		X										
Cooling system		X										
Oil leak		X										
Corrosion protection		X										
LV wiring and protection		X										

Source: VKW Bregenz Austria

Thank You !

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