Power Transformer Diagnostics: Novel Techniques and their Application

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Transformers

Topics of Discussion

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

Transformer Considerations

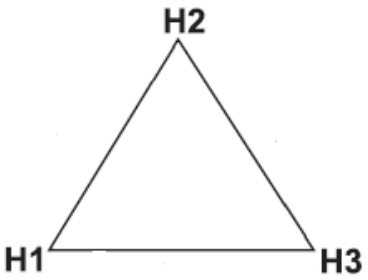
- Transformer Types and Classifications
- Transformer Configurations
- Vector Groups
- Oil Preservation Systems
- Insulating Materials and Fluids
- Construction Forms
- Core Steel
- Ratings
- Cooling Schemes
- Tap Changers (OLTC, DETC)
- Bushings
- Surge Arresters

Transformer Types and Classifications

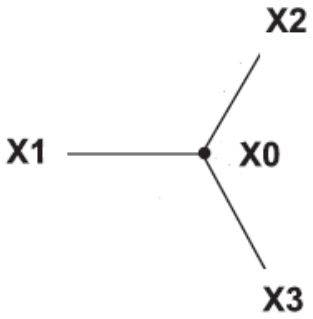
- Distribution
- Power
- Rectifier
- Arc-Furnace
- Network
- Regulating (Voltage Regulators)
- Phase Shifting
- Reactors*

Vector Groups

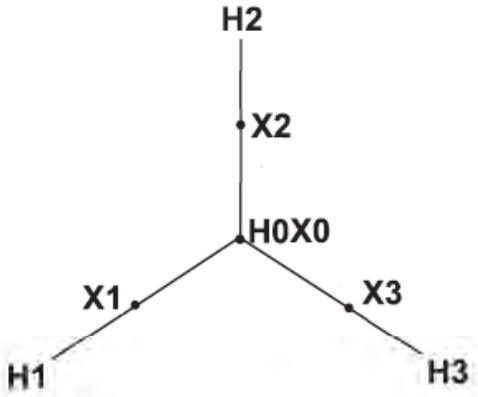
DELTA



WYE-STAR



AUTO



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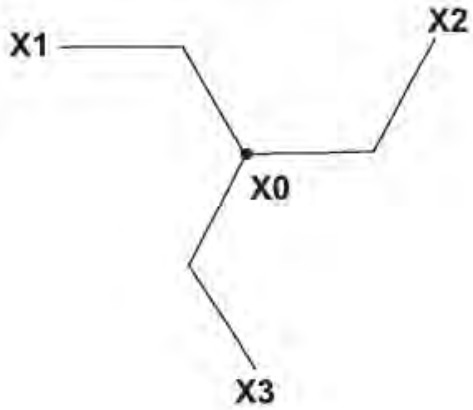
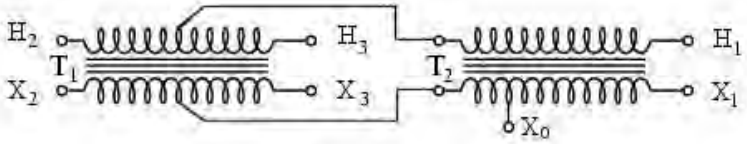


SCOTT-T



Winding Types

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

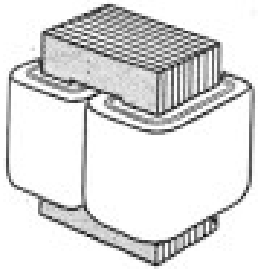
Courtesy of Delta Star, San Carlos, CA

Courtesy of Delta Star, San Carlos, CA

Construction Forms

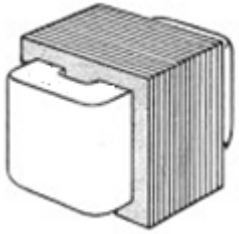
Core Form

- Concentric
- Less Iron
- More CU

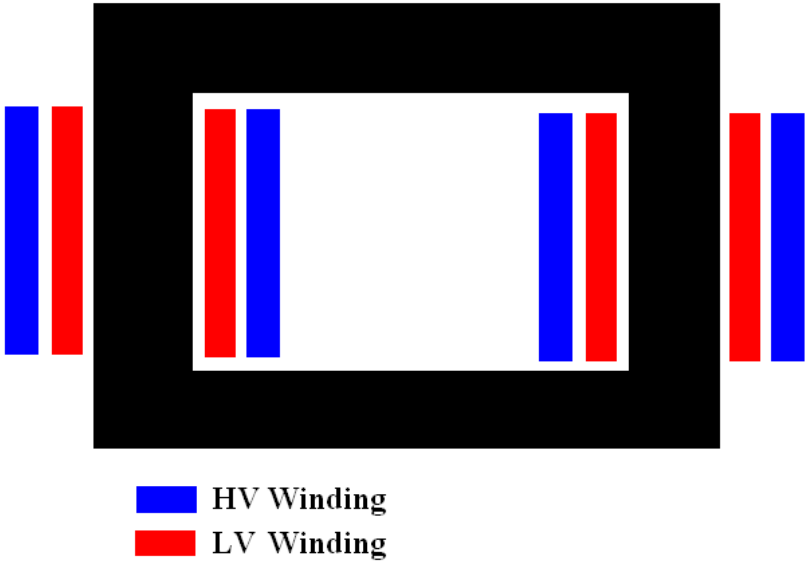


Shell Form

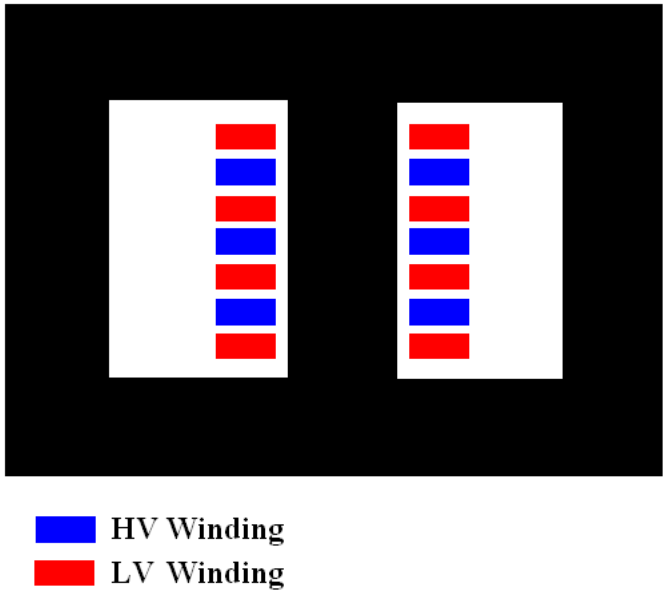
- Interleaved
- More Iron
- Less CU



Core Form



Shell Form



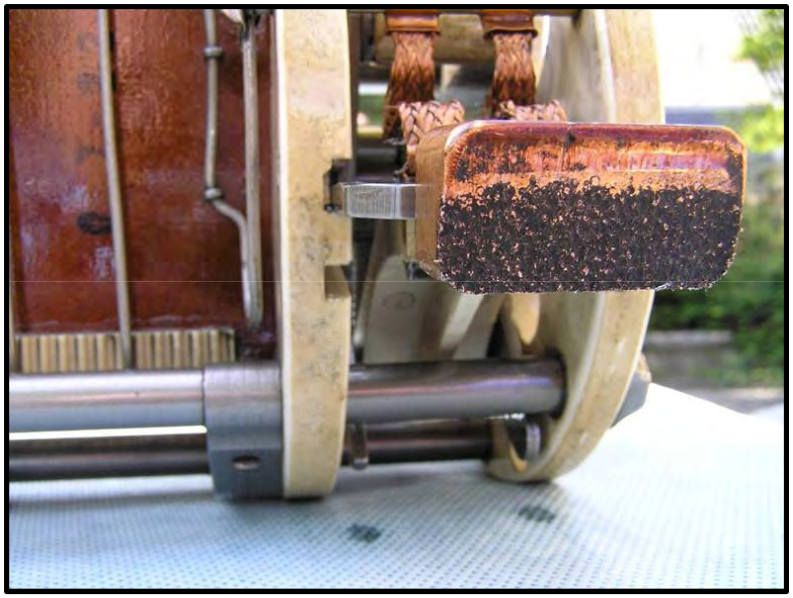
Life Expectancy

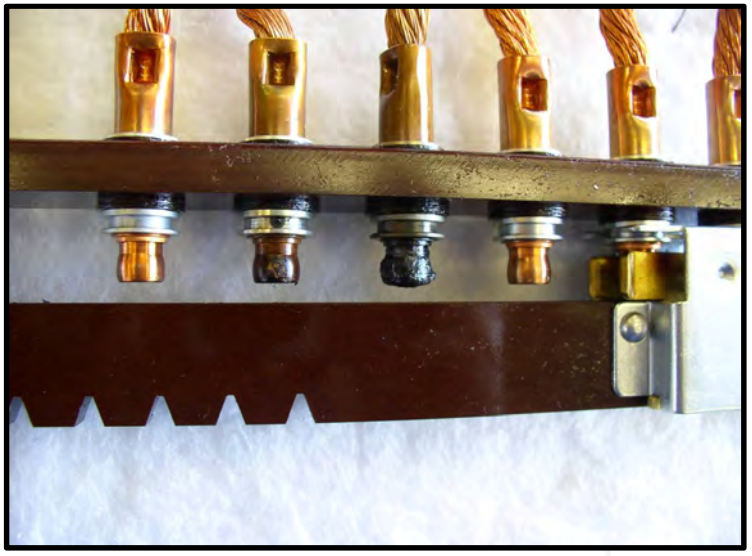
- 180,000 hrs or 20.55 years
- 110 °C Hottest Spot for 65 °C Temp Rise insulation
- Degree of Polymerization (200 -1200 DP)
- 1200 DP - New Paper
- 200 DP at 150,000 hrs (end of life)

  - Heat
  - Moisture
  - Oxygen

Failure Modes

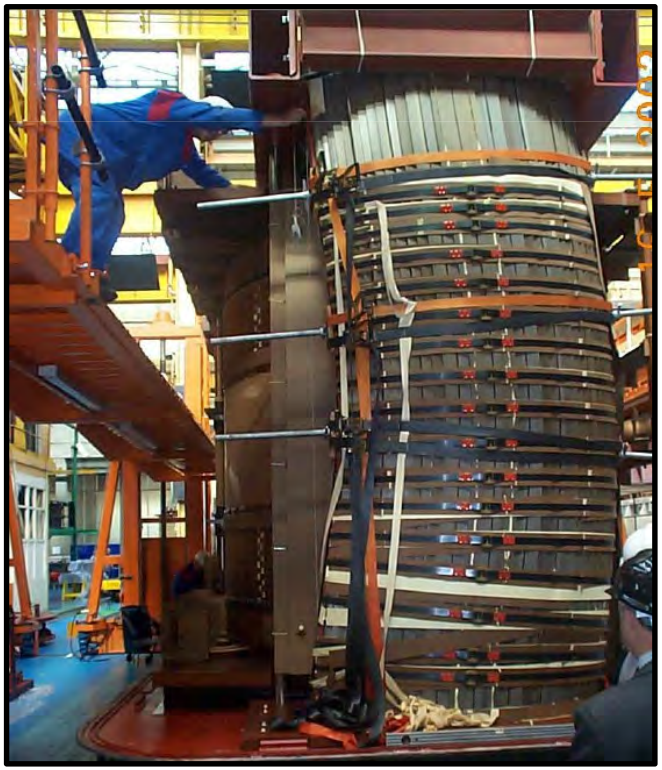
Failure Modes

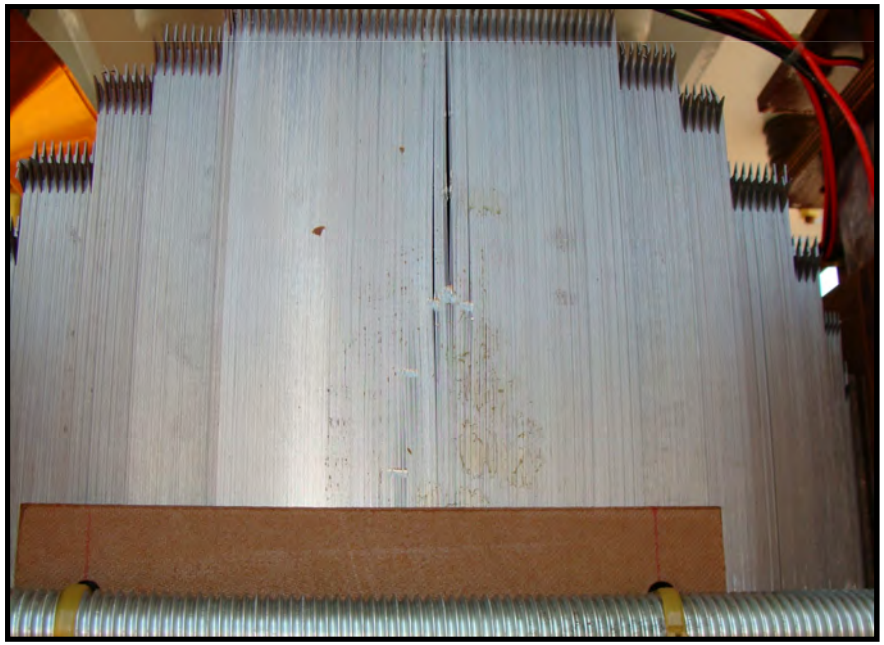




Core Failure Modes

- Over-Heating
- Bulk Movement
- Multiple Core Grounding
- Lamination Gaps
- Shorted Laminations
- Ungrounded Core





Oil Analysis – DGA and Oil Screen

- Hydrogen (H_2)
- Methane (CH_4)
- Ethane (C_2H_6)
- Ethylene (C_2H_4)
- Acetylene (C_2H_2)
- Carbon Monoxide (CO)
- Carbon Dioxide (CO_2)
- Oxygen (O_2)
- Nitrogen (N_2)

- Rate of Gas Generation
- Partial Discharge
- Arcing
- Electrical Heating
- Metal Heating
- Decomposition of Paper

Oil Analysis – DGA and Oil Screen

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

- Degree of Polymerization DP (Paper)
- Furans (Oil)

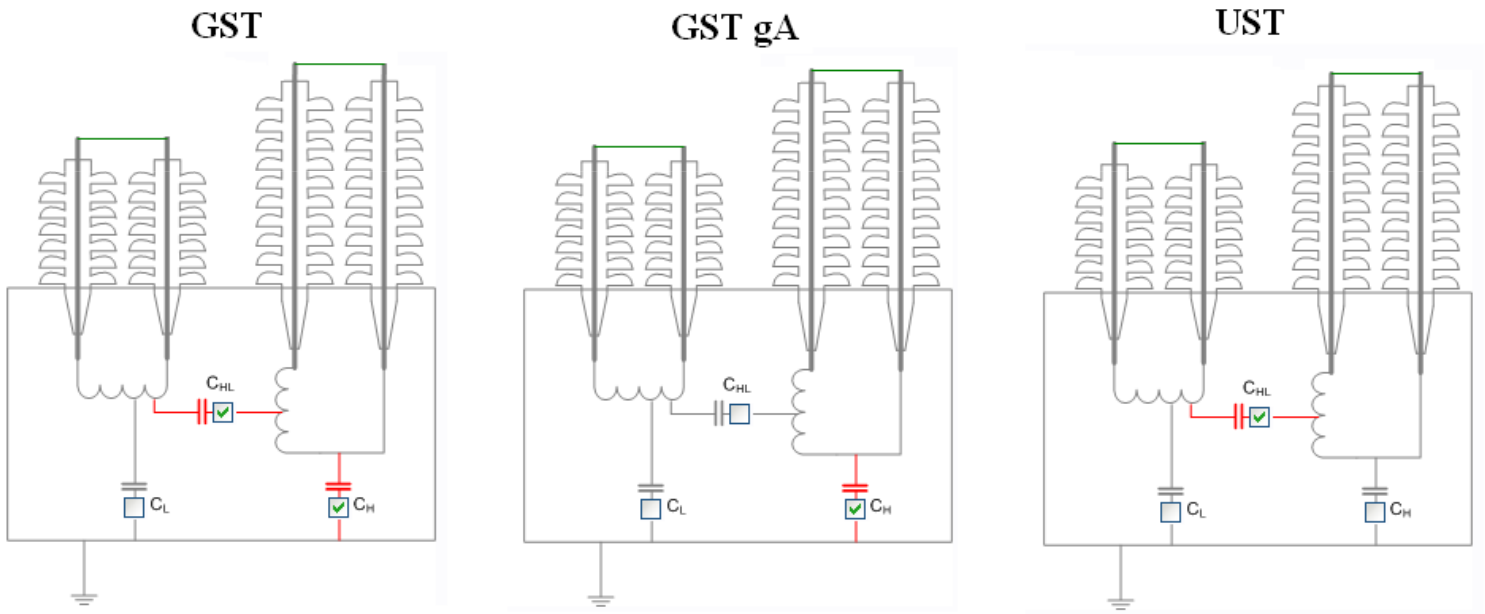
Transformer Tests

Dielectric	Thermal	Mechanical
DGA	DGA	SFRA
Oil Screen	Oil Screen	Leakage Reactance
PF/TD CAP	IR	PF/TD CAP
Exciting Ima	DC Winding RES	Exciting Ima
Turns Ratio Tests		DC Winding RES
DFR		
Insulation Resistance		

Transformer Test Protocol

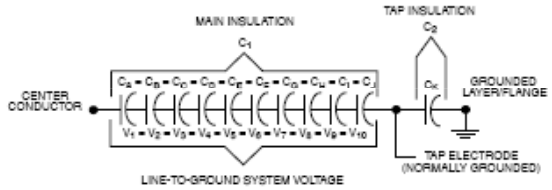
1. Overall Power Factor and Capacitance (Tip-Up, Variable Freq)
2. Bushings (C1, C2, Energized Collar) (Tip-Up, Variable Freq)
3. Exciting Current
4. Surge Arresters
5. Insulating Fluids
6. Leakage Reactance (Frequency Response of Stray Losses)
7. Turns Ratio Test
8. DC Winding Resistance (Slope, Ripple)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

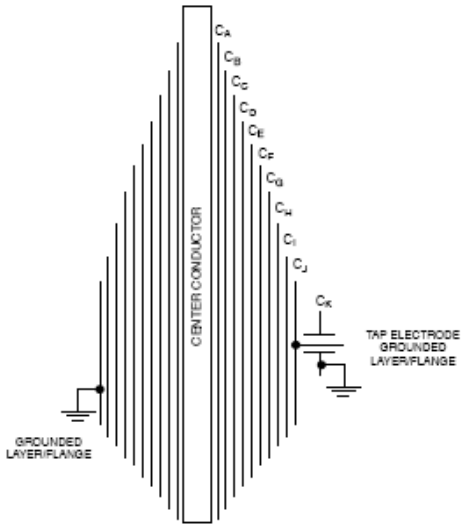
Overall PF and Capacitance



Bushings

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





Bushings

Bushings - NAMEPLATE

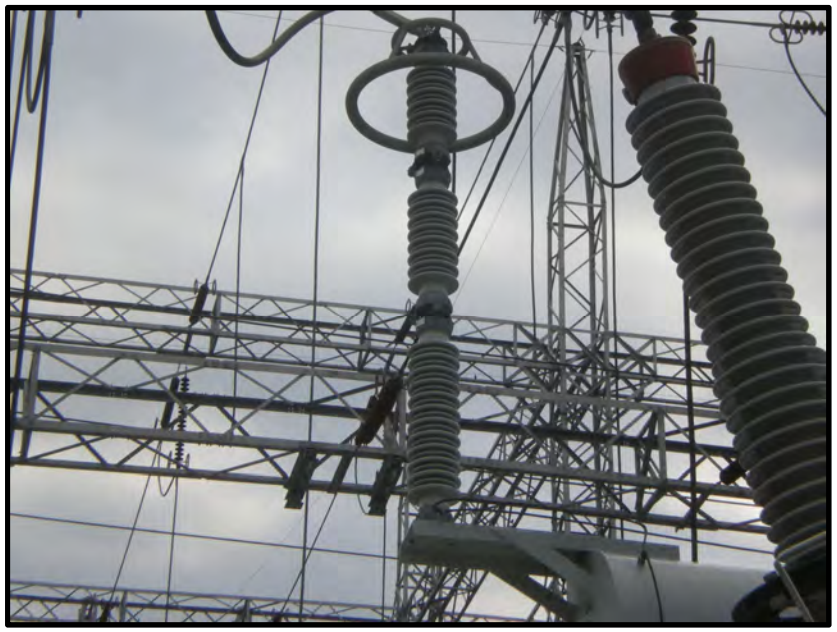
Bushing	Manufact.	Model/ Type	Year	Serial Number	Catalog Number	Drawing Number	BIL kV	kV Rating	A Rating	C1 PF[%]	C1 Cap (pF)	C2 PF[%]	C2 Cap (pF)
H1	ABB	O+C	1993				350	44.00	400	0.35	238		
H2	ABB	O+C	1993				350	44.00	400	0.26	240		
H3	ABB	O+C	1993				350	44.00	400	0.32	239		
H0													
X1	ABB	O+C	1993				150	25.00	2000	0.33	695		
X2	ABB	O+C	1993				150	25.00	2000	0.30	692		
X3	ABB	O+C	1993				150	25.00	2000	0.31	699		
X0	ABB	O+C	1993				150	25.00	2000	0.29	693		

Bushings - C1

Measurement Type: Ref@10 kV

Bushing	Energize	Ground	Guard	UST	Test kV	I mA	Cap pF	Watt Loss	PF [%] Measured	PF [%] Corrected	Correction Factor	Mode	Insulation Condition
H1	Conductor	-	-	Tap	10.022	0.891	236.25	0.020	0.22	0.00	1.00	UST A	PASS
H2	Conductor	-	-	Tap	10.014	0.896	237.67	0.021	0.23	0.00	1.00	UST A	PASS
H3	Conductor	-	-	Tap	10.022	0.896	237.68	0.021	0.24	0.00	1.00	UST A	PASS
H0	Conductor	-	-	Tap							1.00	UST A	
X1	Conductor	-	-	Tap	7.505	2.617	694.15	0.062	0.24	0.00	1.00	UST A	PASS
X2	Conductor	-	-	Tap	7.506	2.560	679.08	0.058	0.23	0.00	1.00	UST A	PASS
X3	Conductor	-	-	Tap	7.506	2.631	697.78	0.061	0.23	0.00	1.00	UST A	PASS
X0	Conductor	-	-	Tap	7.505	2.610	692.23	0.063	0.24	0.00	1.00	UST A	PASS

Surge Arresters



Surge Arrester - MEASUREMENTS

Measurement Type: Ref@10 kV

Winding/ Phase	Position	Energize	Ground	Guard	UST	Mode	Test kV	I mA	Watt Loss	Arrester Rating
H - A	1	MID 1/2	BOT 3	-	TOP 1	UST	9.999	0.258	0.052	PASS
H - A	2	MID 2/3	BOT 3	-	MID 1/2	UST	9.999	0.160	0.033	PASS
H - A	3	MID 2/3	BOT 3	MID 1/2	-	GST gA	9.999	0.302	0.046	PASS
H - B	1	MID 1/2	BOT 3	-	TOP 1	UST	10.003	0.257	0.053	PASS
H - B	2	MID 2/3	BOT 3	-	MID 1/2	UST	10.001	0.161	0.035	PASS
H - B	3	MID 2/3	BOT 3	MID 1/2	-	GST gA	10.001	0.304	0.049	PASS
H - C	1	MID 1/2	BOT 3	-	TOP 1	UST	10.000	0.257	0.051	PASS
H - C	2	MID 2/3	BOT 3	-	MID 1/2	UST	10.000	0.158	0.033	PASS
H - C	3	MID 2/3	BOT 3	MID 1/2	-	GST gA	9.999	0.305	0.047	PASS

- Analyzed on the basis of Watts

Advanced Diagnostics

1. **Advanced Power Factor**

   Tip-Up: Voids in Insulation

   Variable Frequency (15 Hz to 400 Hz): Moisture and Aging

2. **Advanced DC Winding Resistance**

   Ripple and Slope

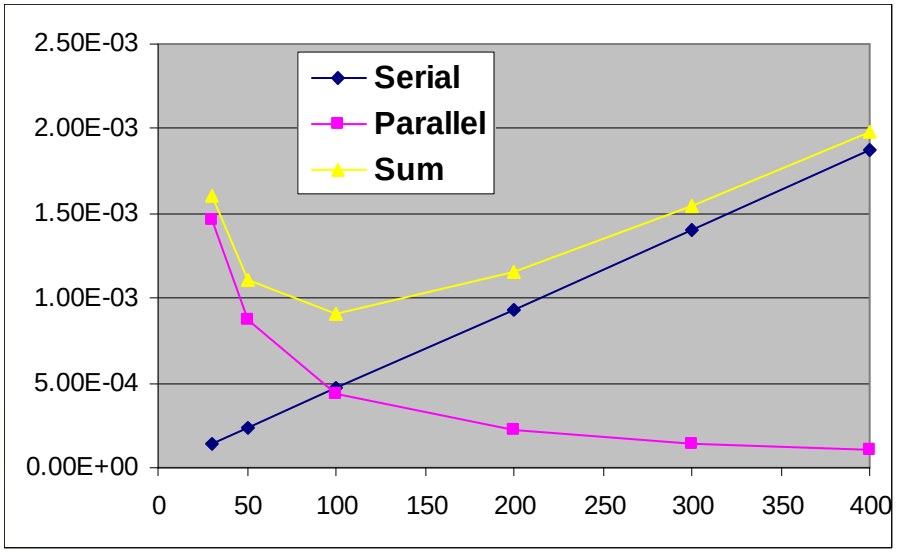
3. **Advanced Leakage Reactance**

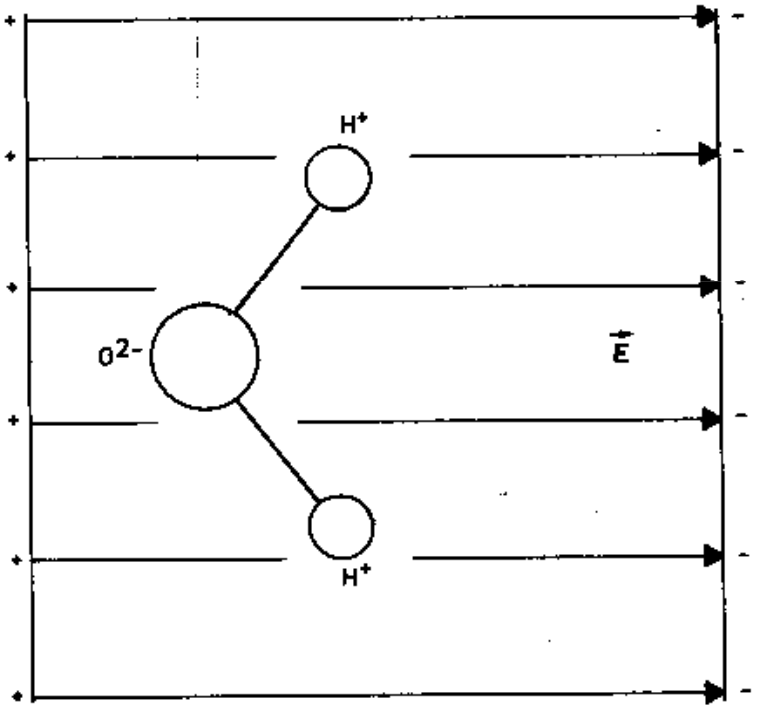
   FRSL (Frequency Response Stray Losses)

4. **SFRA - Sweep Frequency Response Analysis**

5. **DFR - Dielectric Frequency Response**

Variable Frequency Losses





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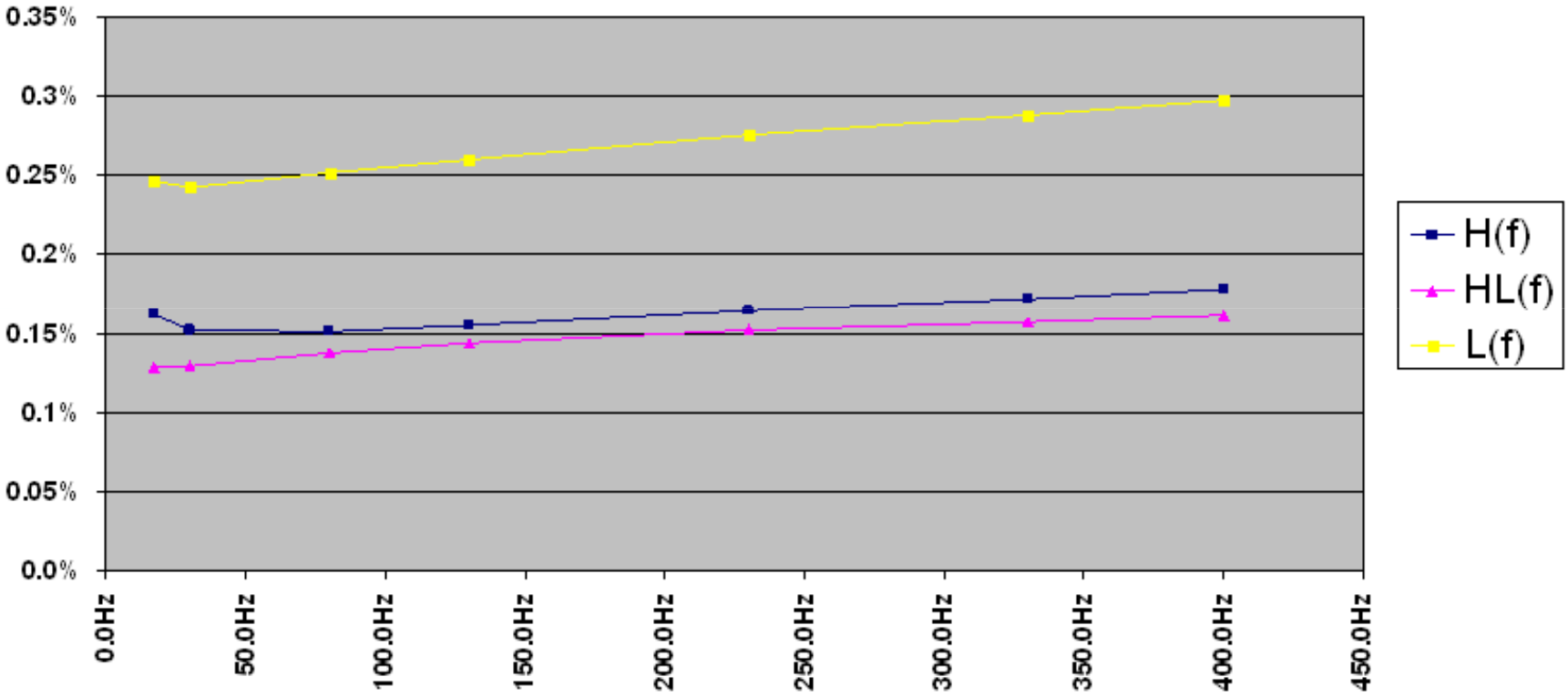
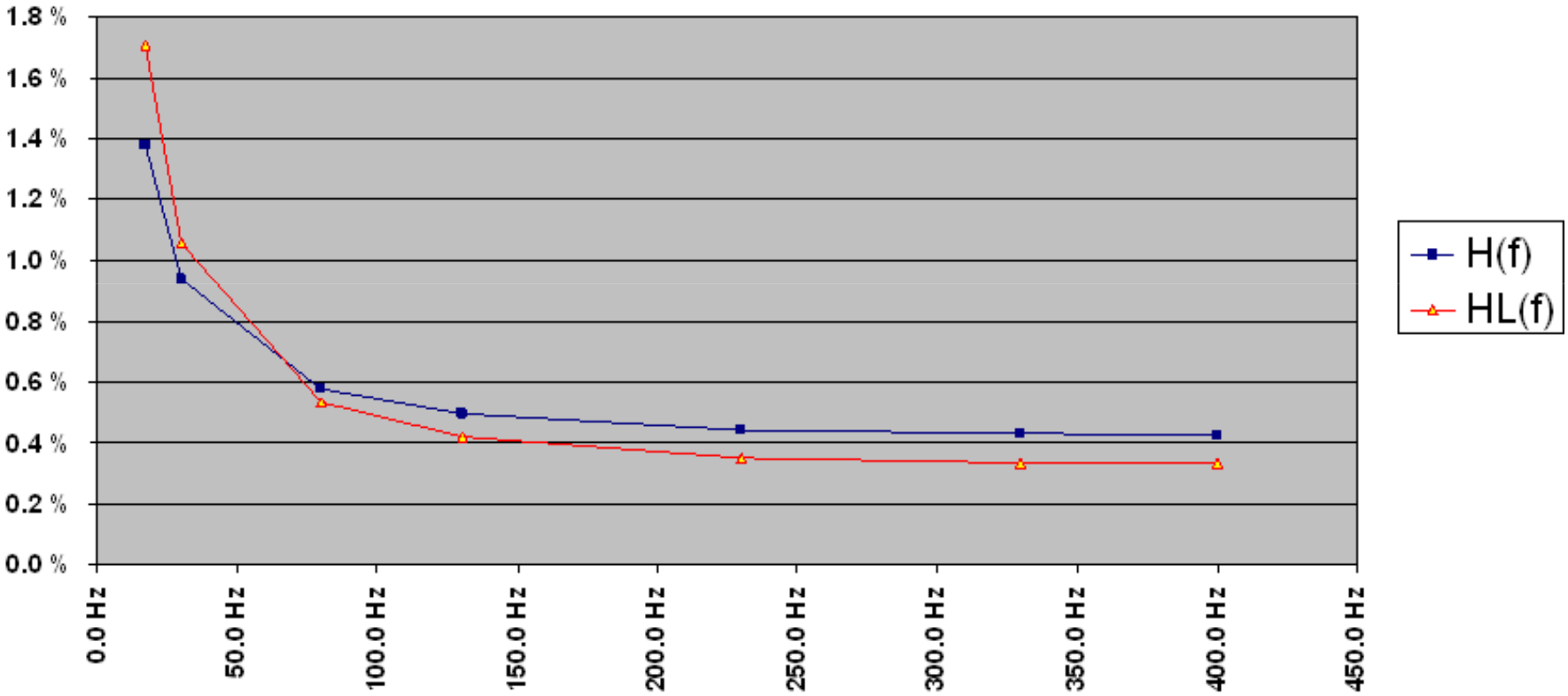
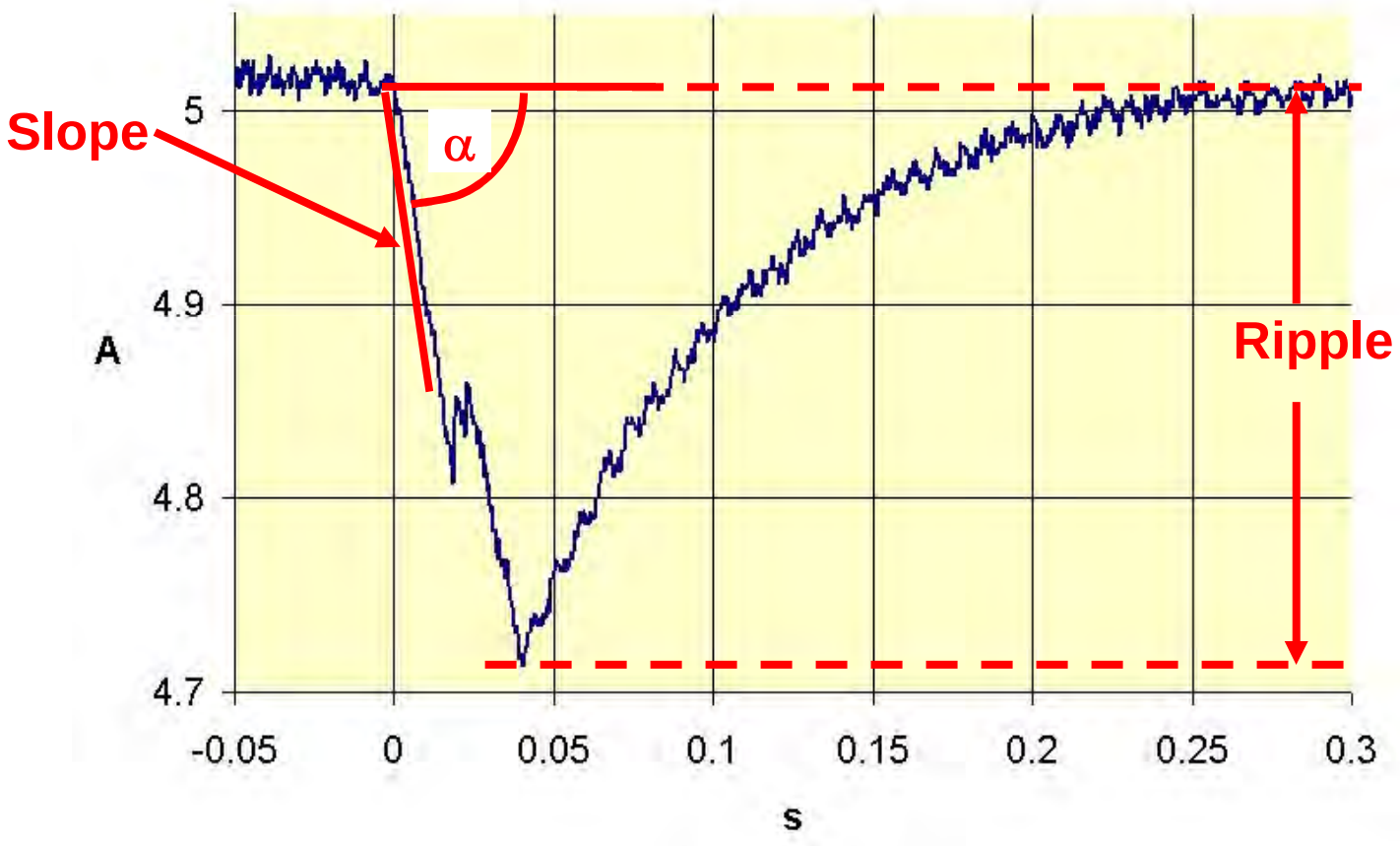
Normal Power Factor



Power Factor Influenced by Moisture



Slope and Ripple



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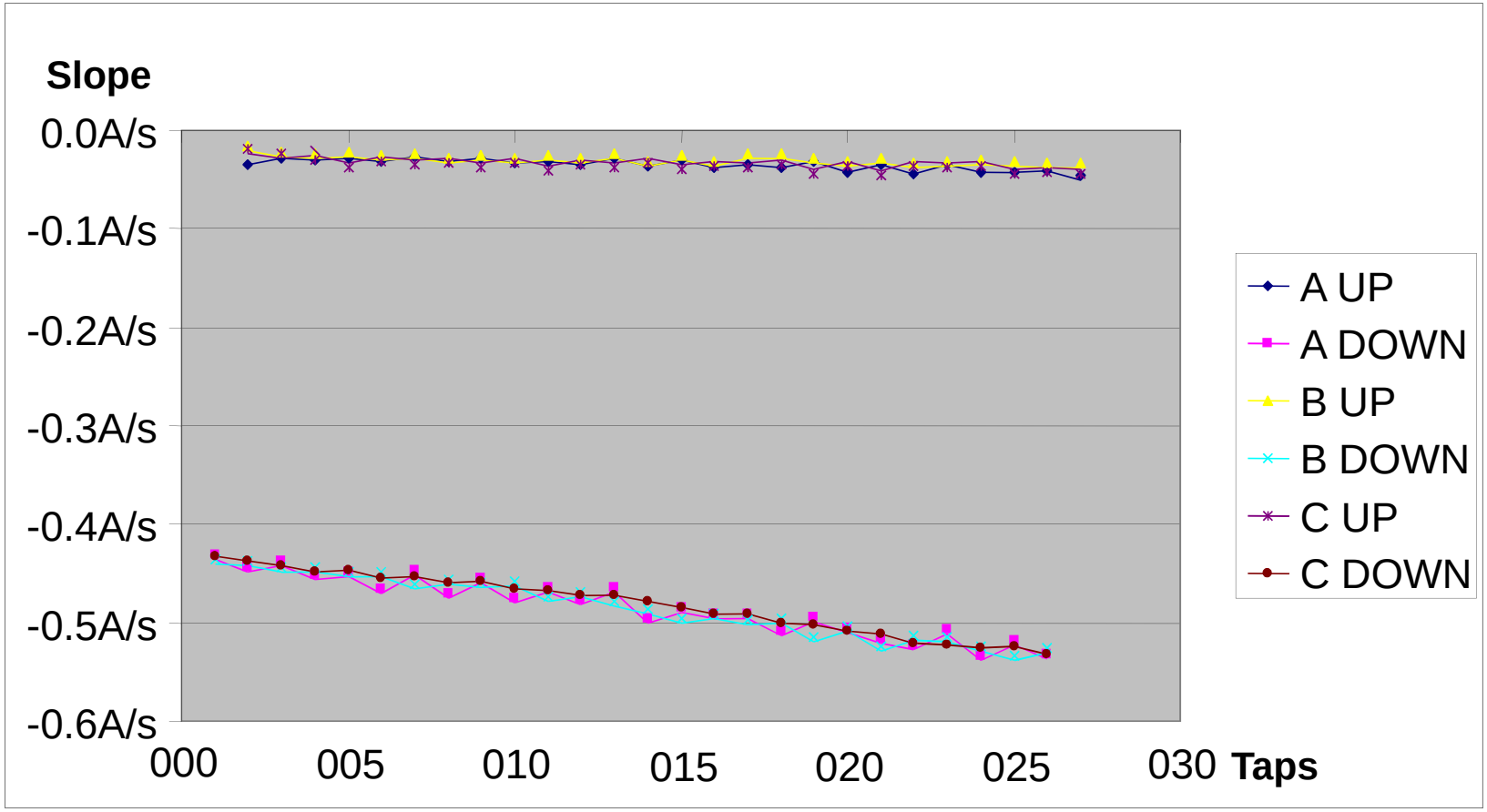
Advanced DC Resistance - Slope



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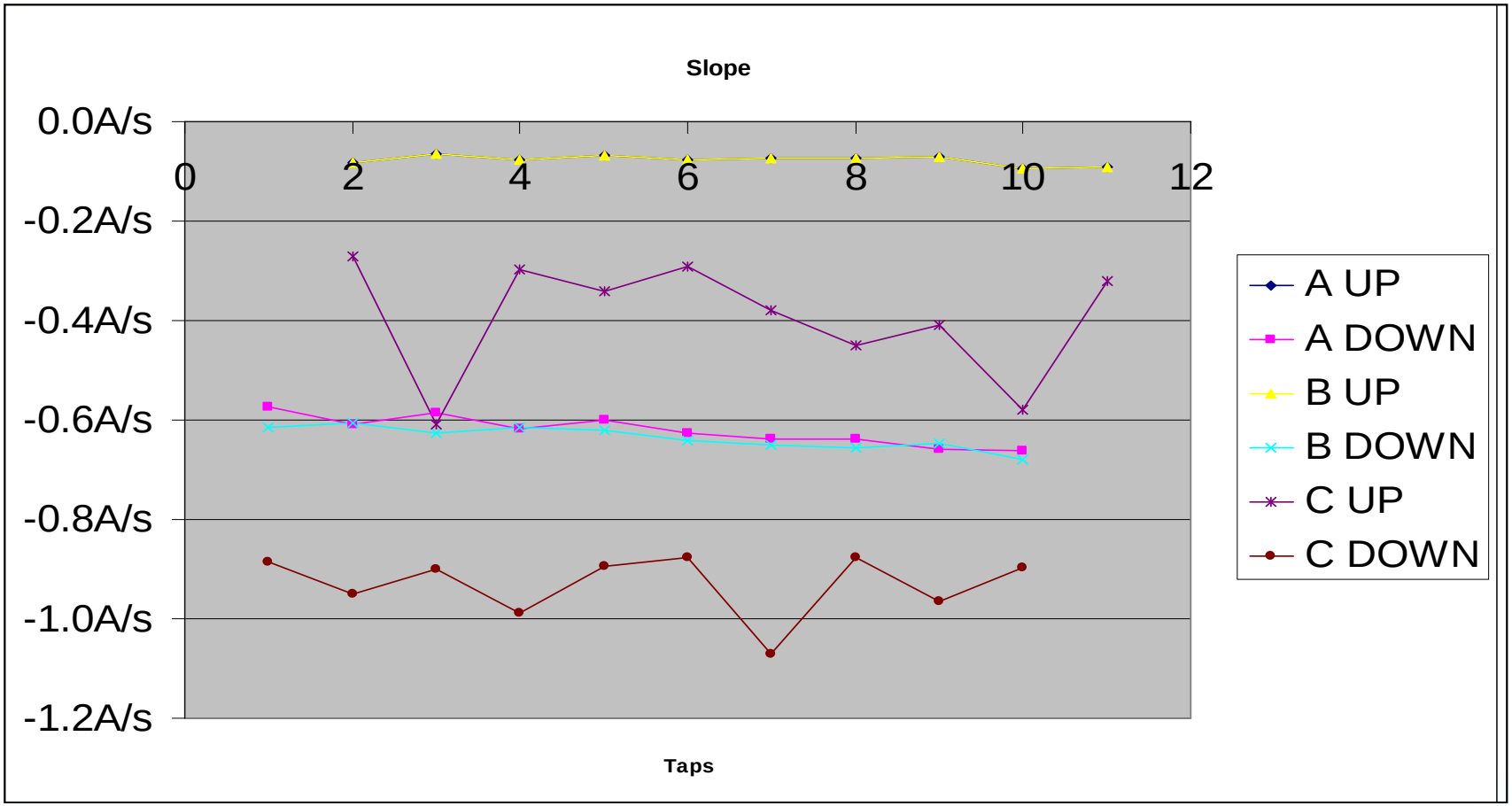
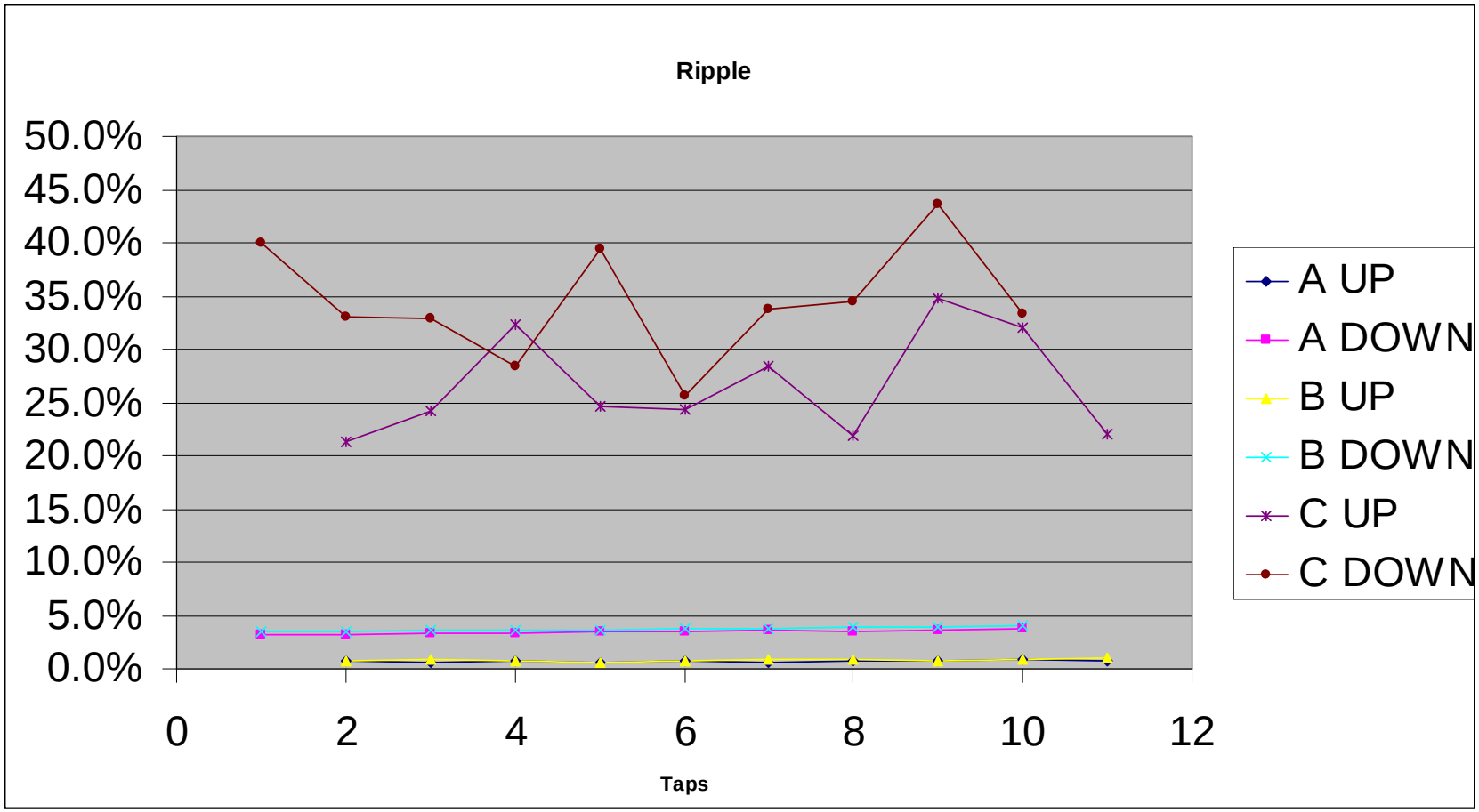
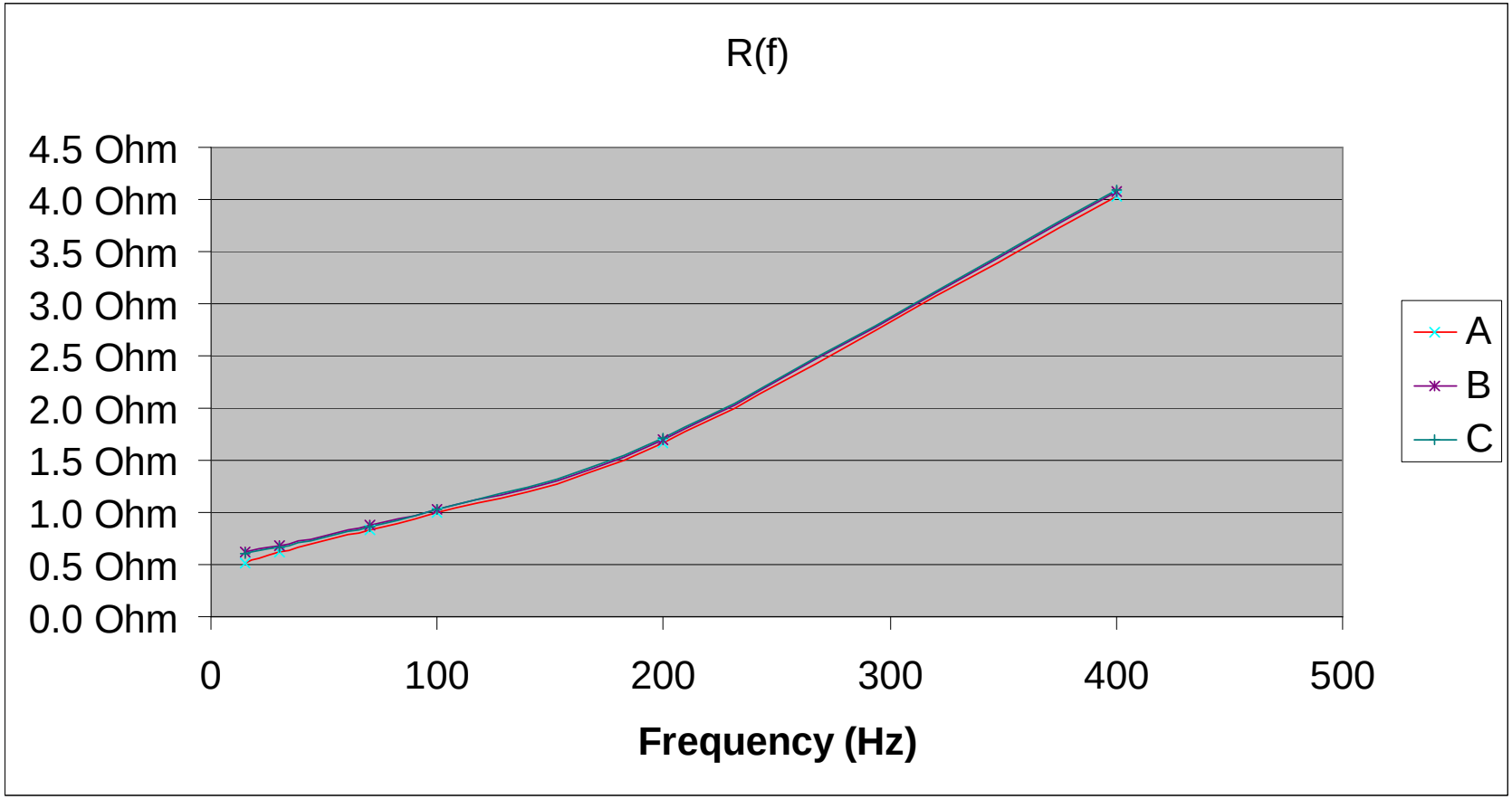
Advanced DC Resistance - Slope



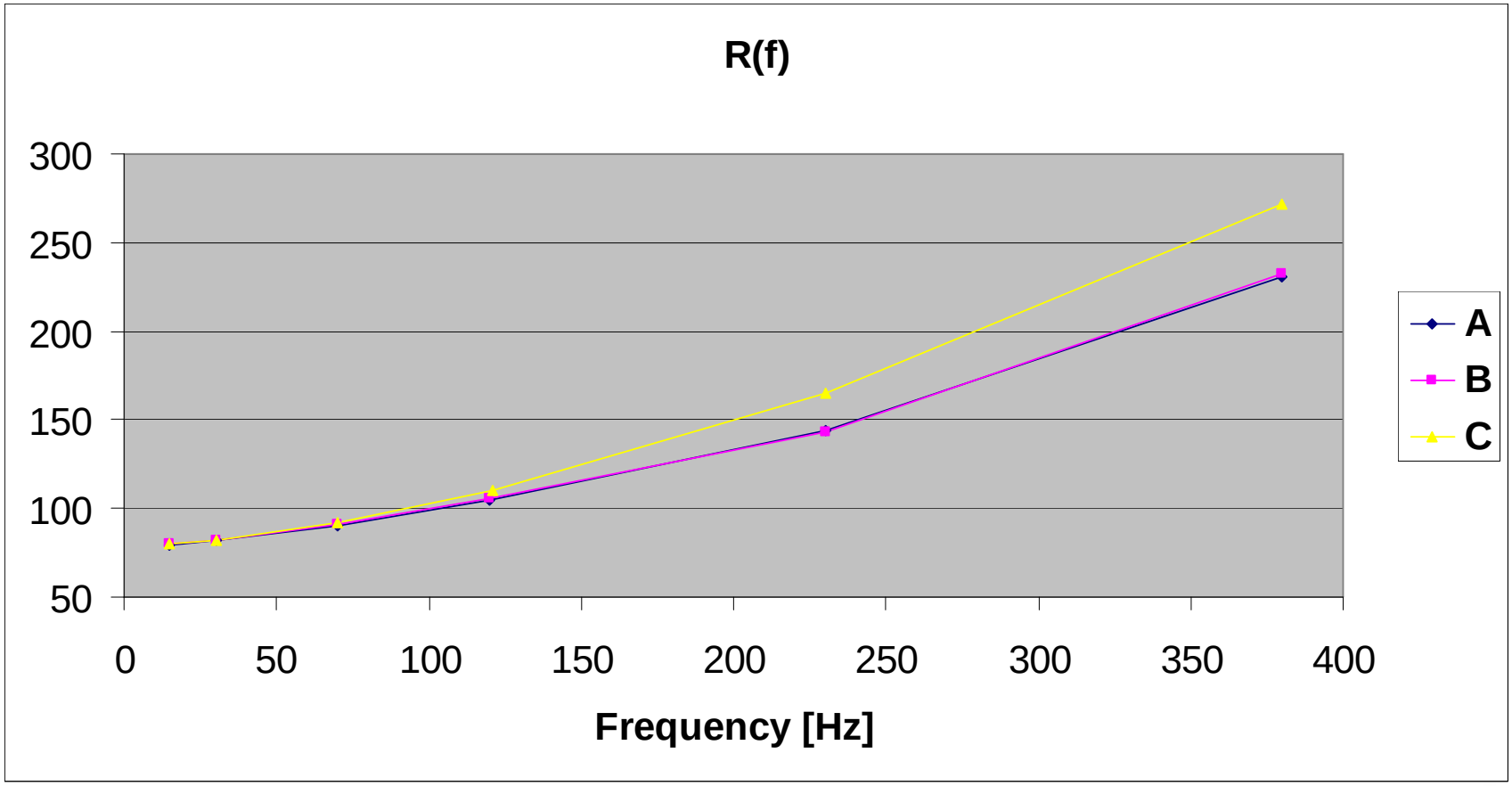
Advanced DC Resistance - Ripple



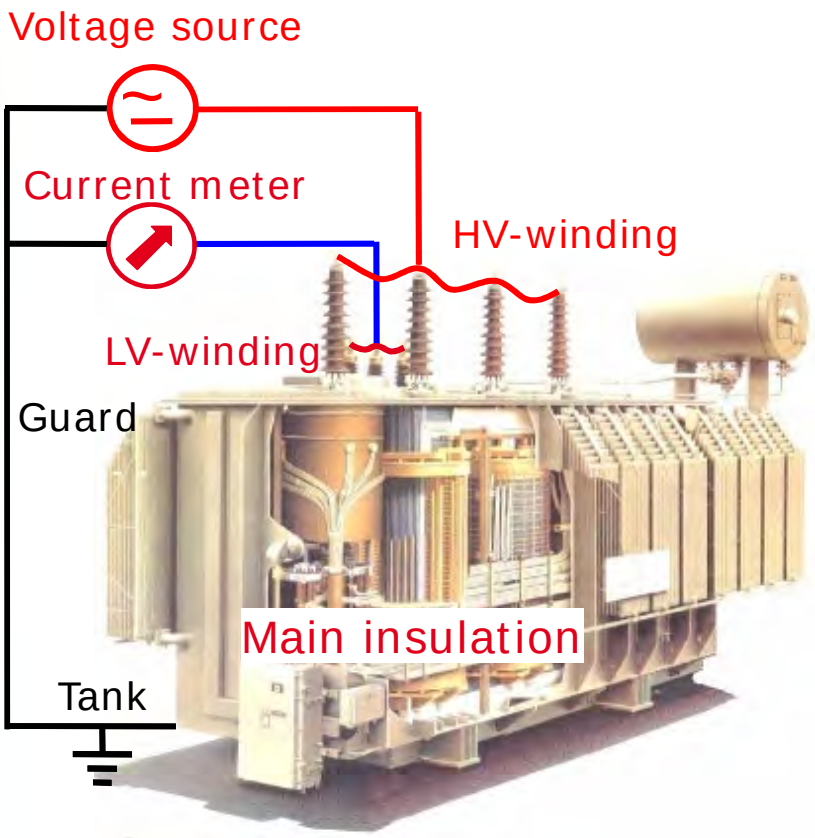
FRSL - Good


R(f)
4.5 Ohm
4.0 Ohm
3.5 Ohm
3.0 Ohm
2.5 Ohm
2.0 Ohm
1.5 Ohm
1.0 Ohm
0.5 Ohm
0.0 Ohm
0
100
200
300
400
500
Frequency (Hz)
A
B
C

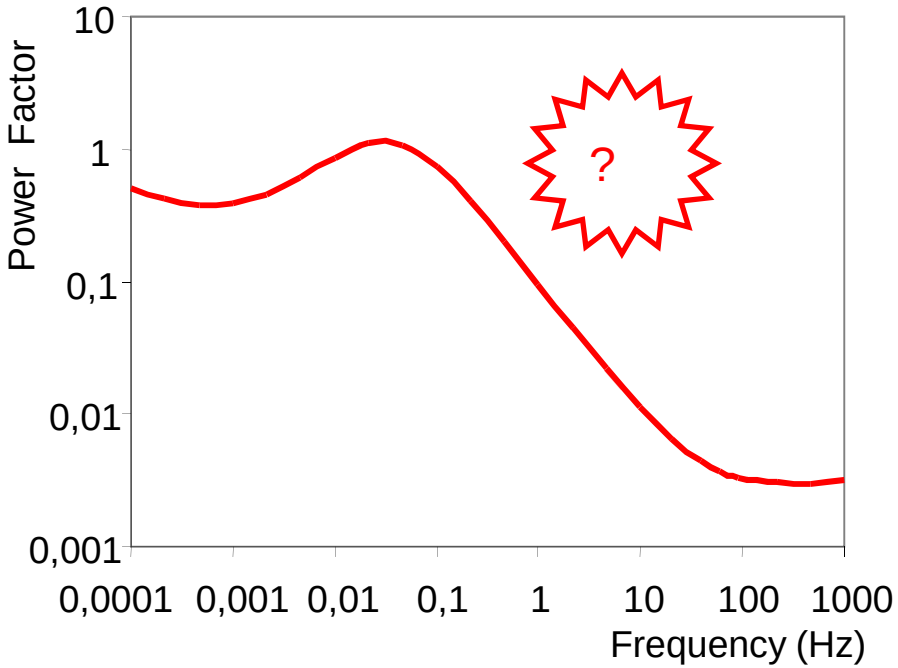
FRSL – Poor Result
Short-Circuit Between Parallel Strands



Dielectric Frequency Response (DFR)



Power Factor in Frequency Domain



Moisture in Transformers

1. Reduces Dielectric Strength
2. Promotes the Formation of Bubble
3. Ages Insulation with Heat and Oxygen

Moisture Terminology – Paper, Pressboard, and Oil

1. Water Content
    - Pressboard & Paper (percentage of total mass)
    - Oil (PPM)
2. Moisture Saturation – P,P,O (Relative, Humidity)

Moisture Fact in Transformers

1. If mass of oil equals paper-pressboard, then at equilibrium the water content is (2000:1)
2. In transformers there is 10X more oil mass than paper and pressboard, so the water content is (200:1)

Oil Ratio to Paper : Pressboard

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

Water content at 60 °C:
40 ppm

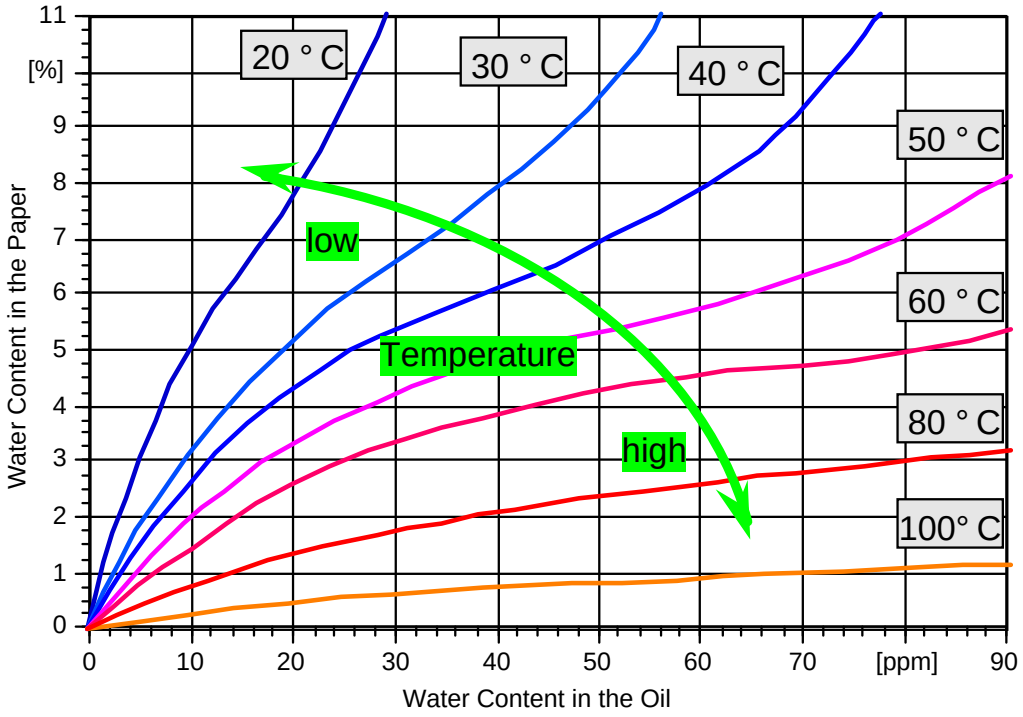
Mass of the water, dissolved in the oil:
4 kg = 8.8 Lbs

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

Water content at 60 °C:
4 %

Mass of the water contained in the paper:
520 kg = 1200 Lbs

Karl Fischer Titration and Equilibrium Curves



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

Water Content Recommendations

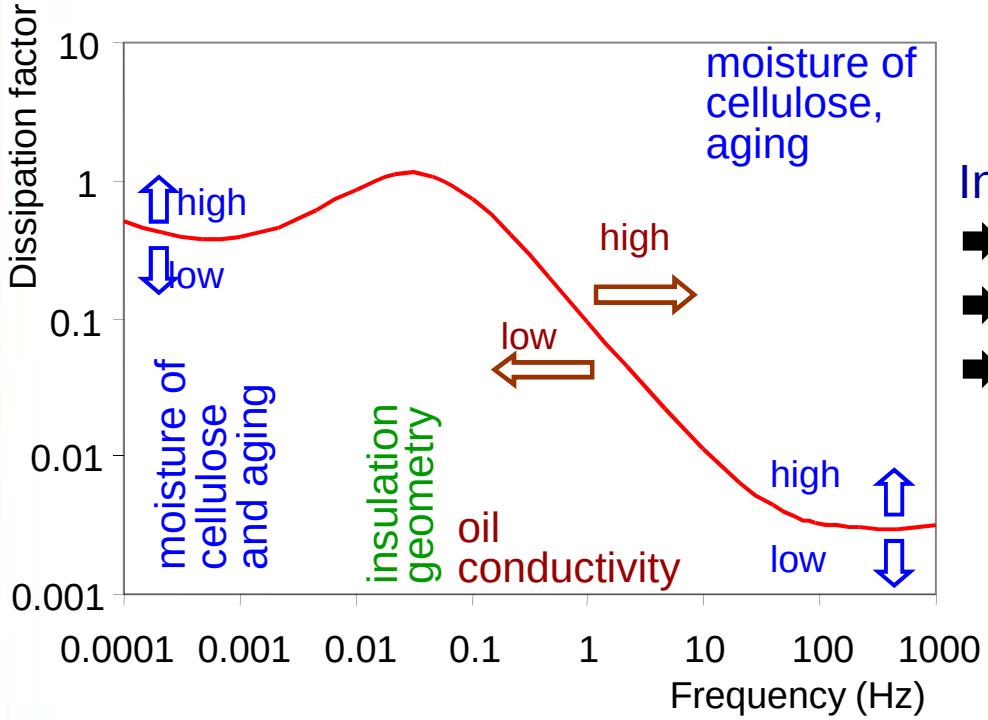
Category Moisture content in %

- Dry below 2.2
- Moderately wet 2.2-3.7
- Wet 3.7-4.8
- Extremely wet above 4.8

Measurement Characteristics

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

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

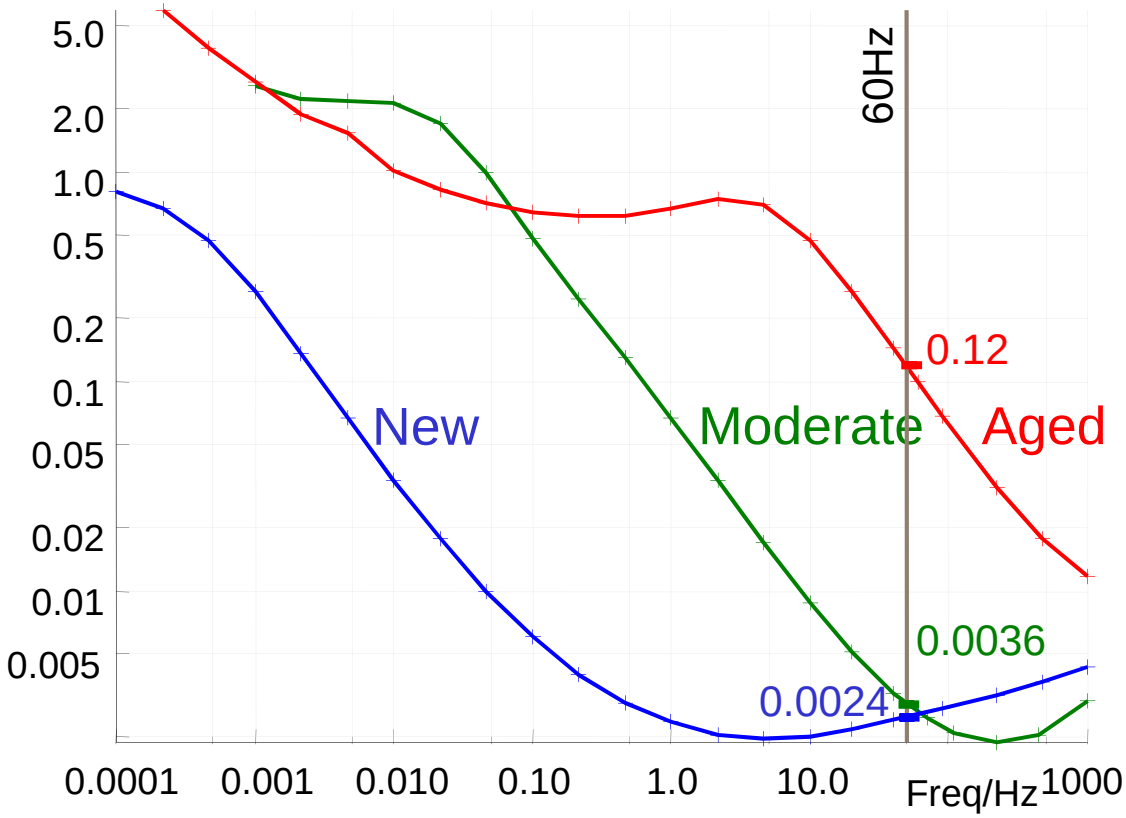


- Current in wide frequency range,
  e.g. 1 mHz – 1 kHz
- Display as dissipation factor or complex capacitance or complex permittivity

Interpretation

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

Measurement Examples



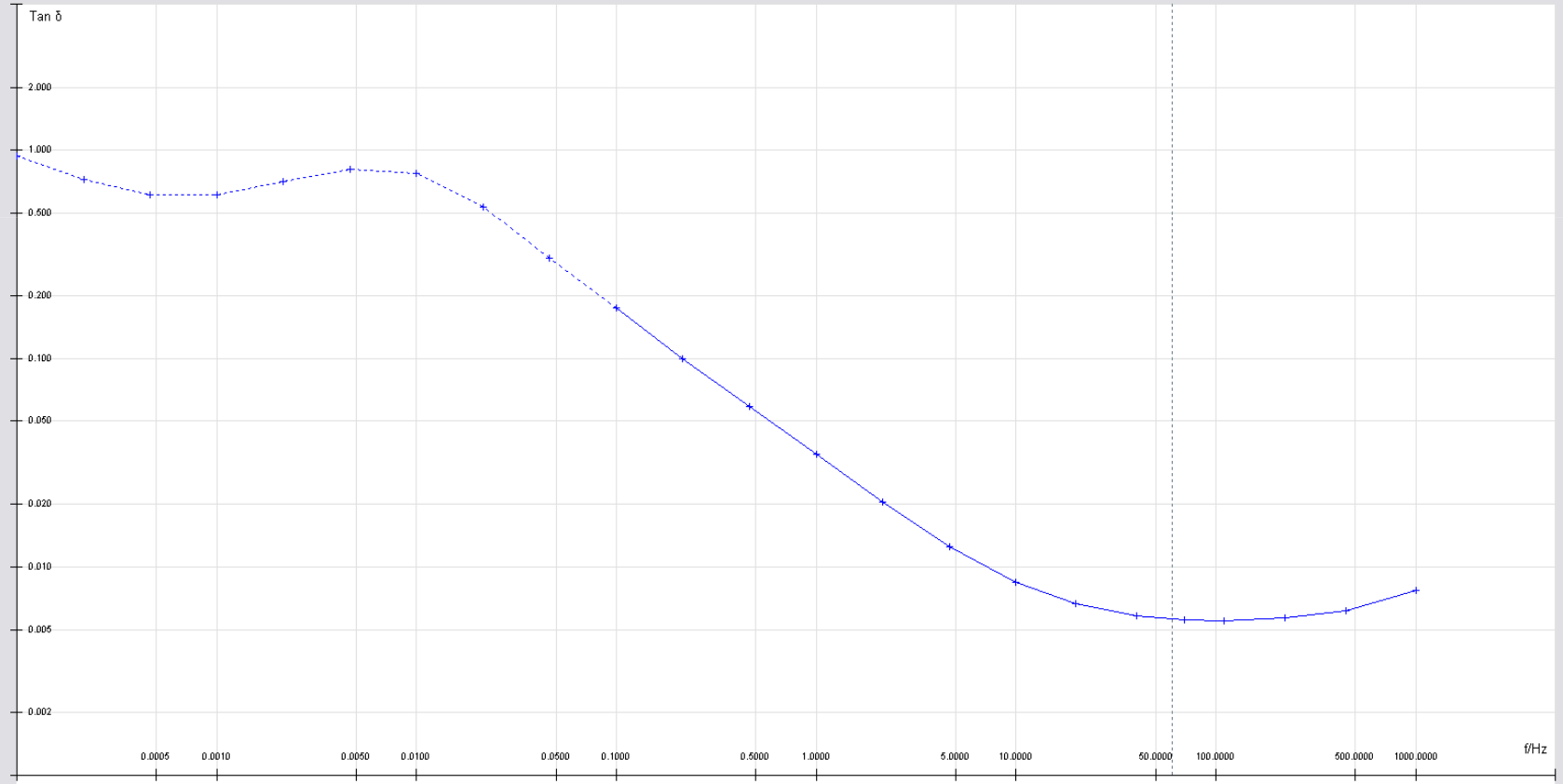
New, dry, cold: 1kHz - 0.1 mHz

Moderate: 1kHz - 1 mHz

Very aged: 1kHz - 10 mHz

3.1 % at 9 °C – Oil Sample Yielded 5.0%

Measurement	Frequency	Tan δ	Capacitance (C)	Resistance (R)	Impedance (Z)	ε'	ε''	Power Factor
CHL	60.514 Hz	0.005609	45.6565 nF	10.27 MΩ	57.604 kΩ	1.00745E+000	5.65075E-003	0.005609



What is SFRA?

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

- Measurement of the transfer function over a wide frequency range

Diagnostic Category

- **Dielectric**
- **Thermal**
- **“*Mechanical*”**

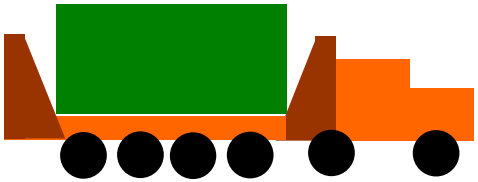
- **Use SFRA:**

1. **Transportation**
2. **Post Fault**

Life Cycle

Manufacturer Workshop

- Quality Assuring
- After Short Circuit Test
- Failure Investigation



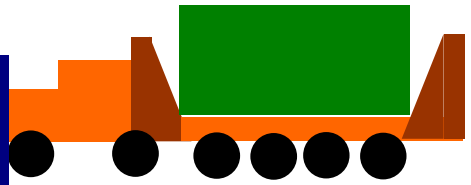
Truck Transport 1

Delivery Port

- Transport Checking

Ship Transport

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

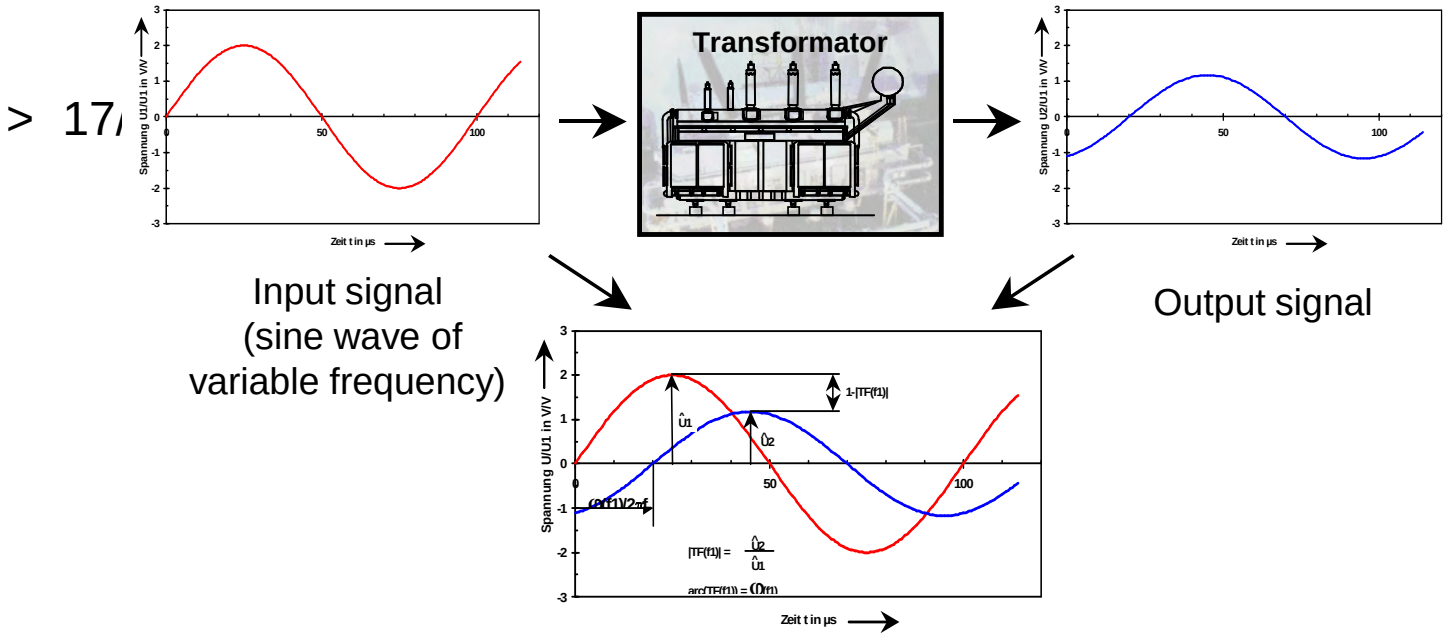


Truck Transport 2

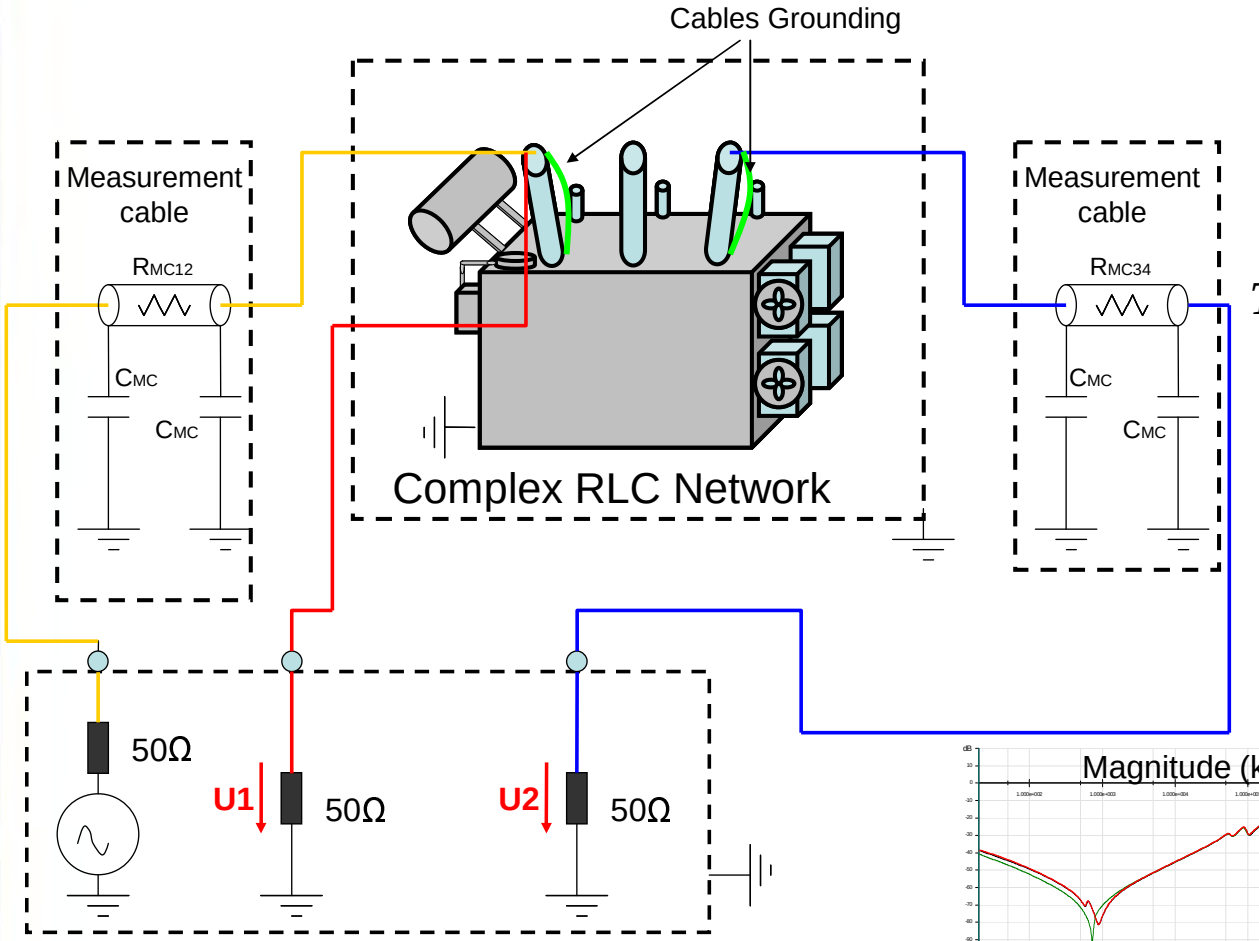
Reception Port

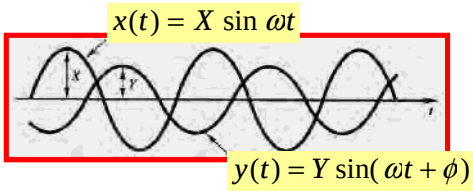
- Transport Checking

The SFRA Measurement Principle



Theoretical Background

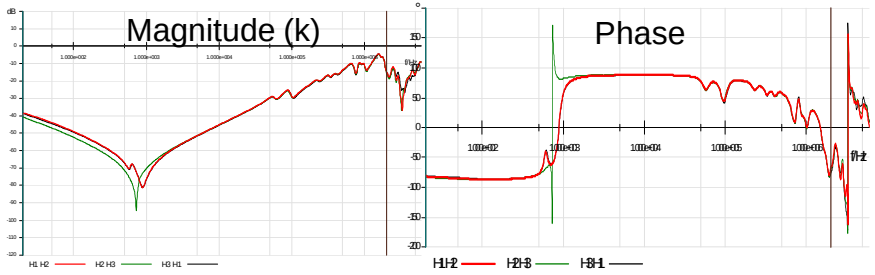




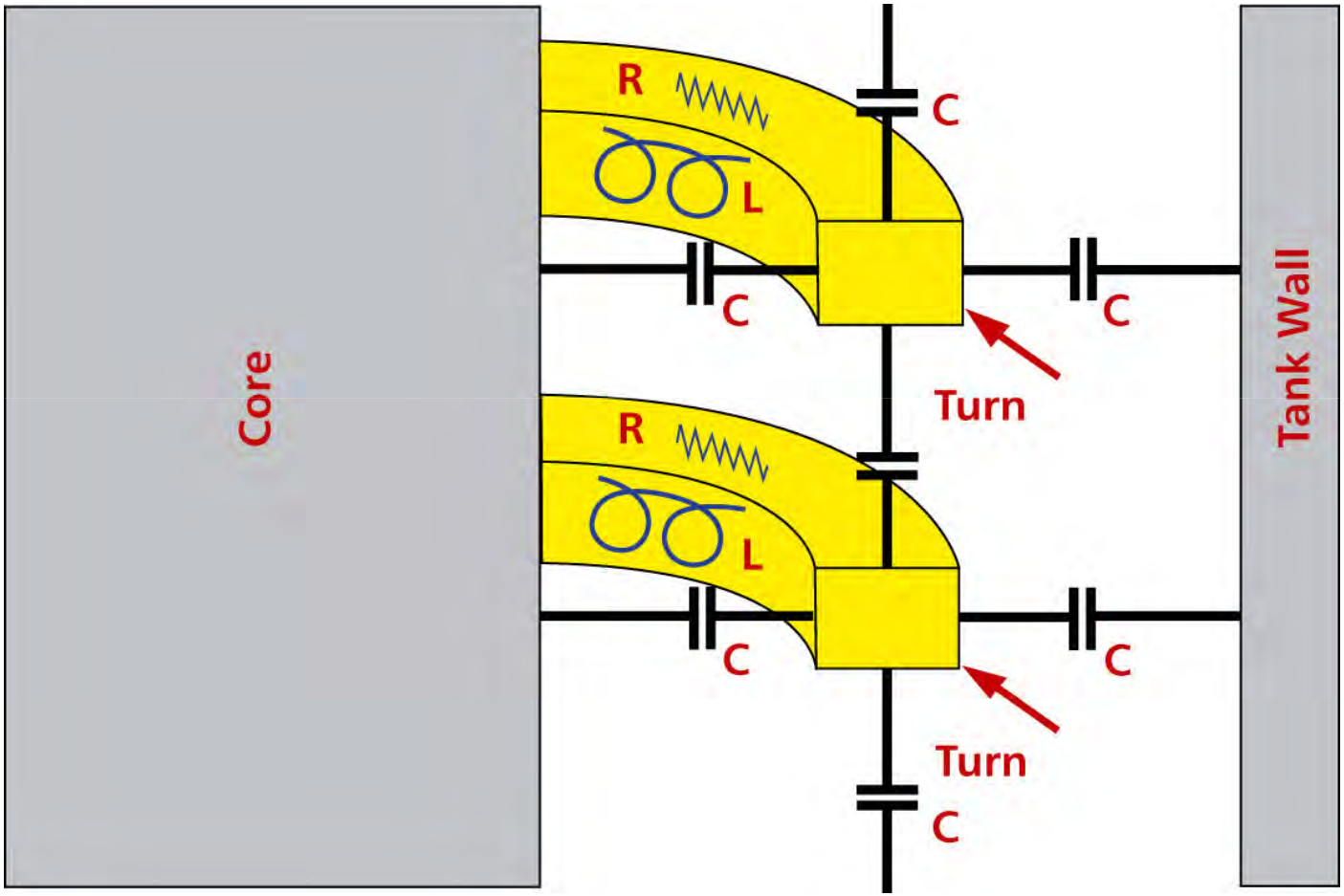
$$TF = \frac{U_2(s)}{U_1(s)} = \frac{R_m}{R_m + Z_{specimen}}$$

$$k = 20\log_{10}(U_2 / U_1)$$

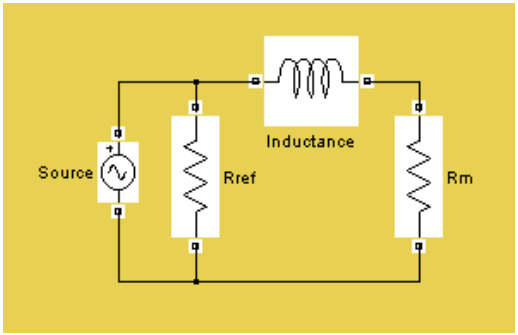
$$\varphi = \tan^{-1}(\angle U_2 / \angle U_1)$$

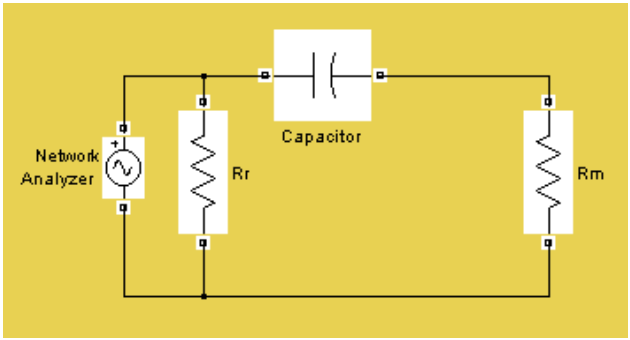


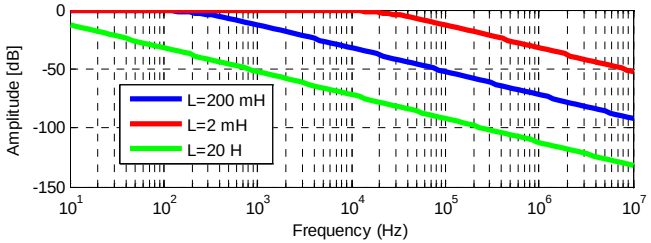
Passive Components

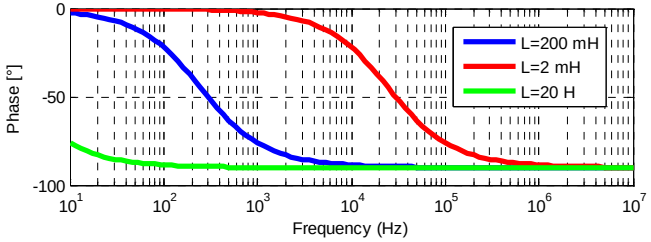


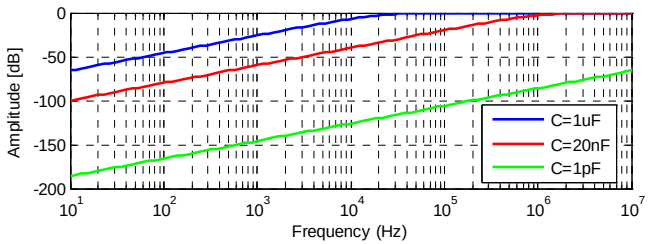
RLC Characteristics

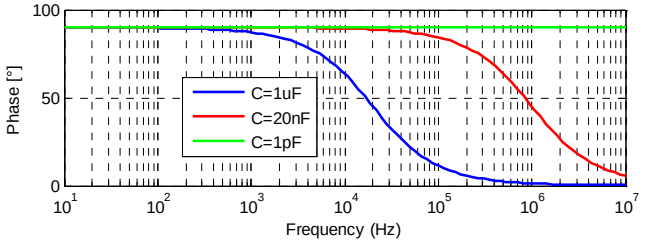




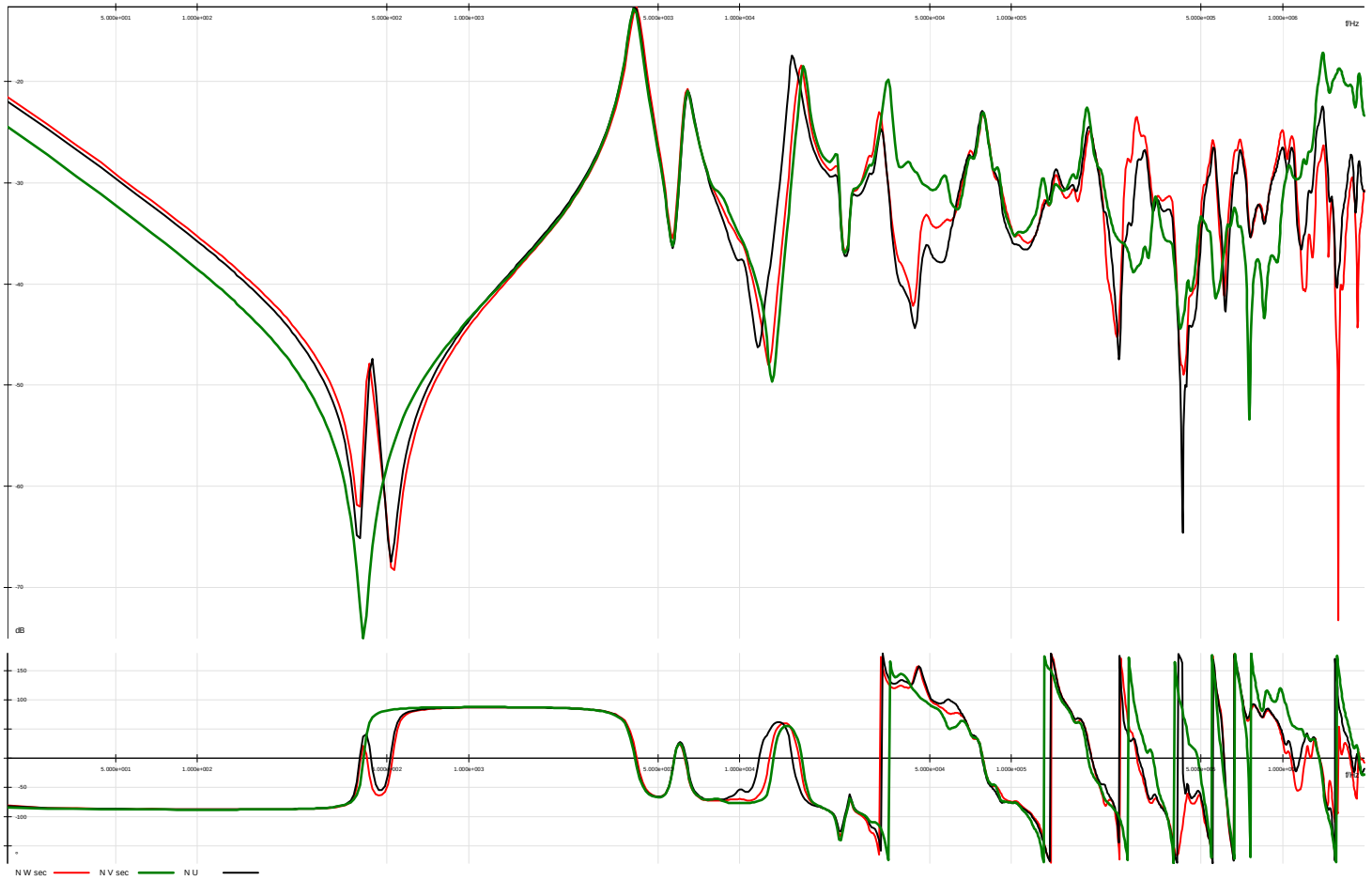








Typical Results

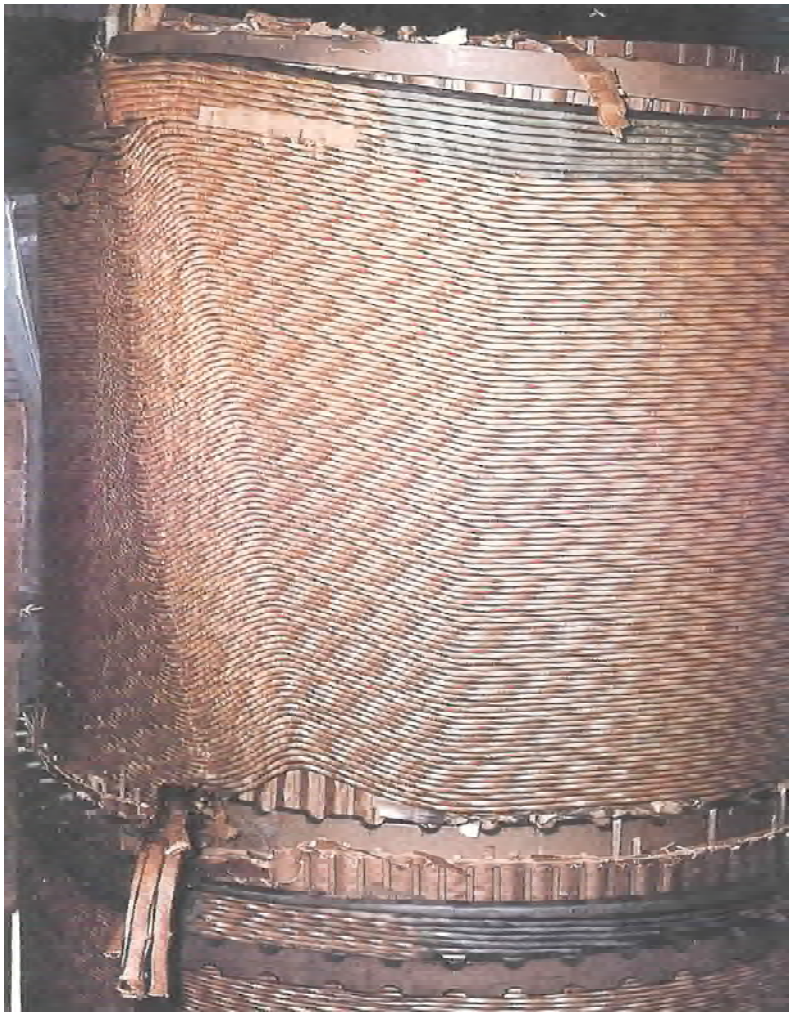


Failure Modes

- Radial “Hoop Buckling” Deformation
- Axial Winding Elongation “Telescoping”
- Overall- Bulk & Localized Movement
- Winding Turn-to-Turn Short Circuit
- Open Circuited Winding

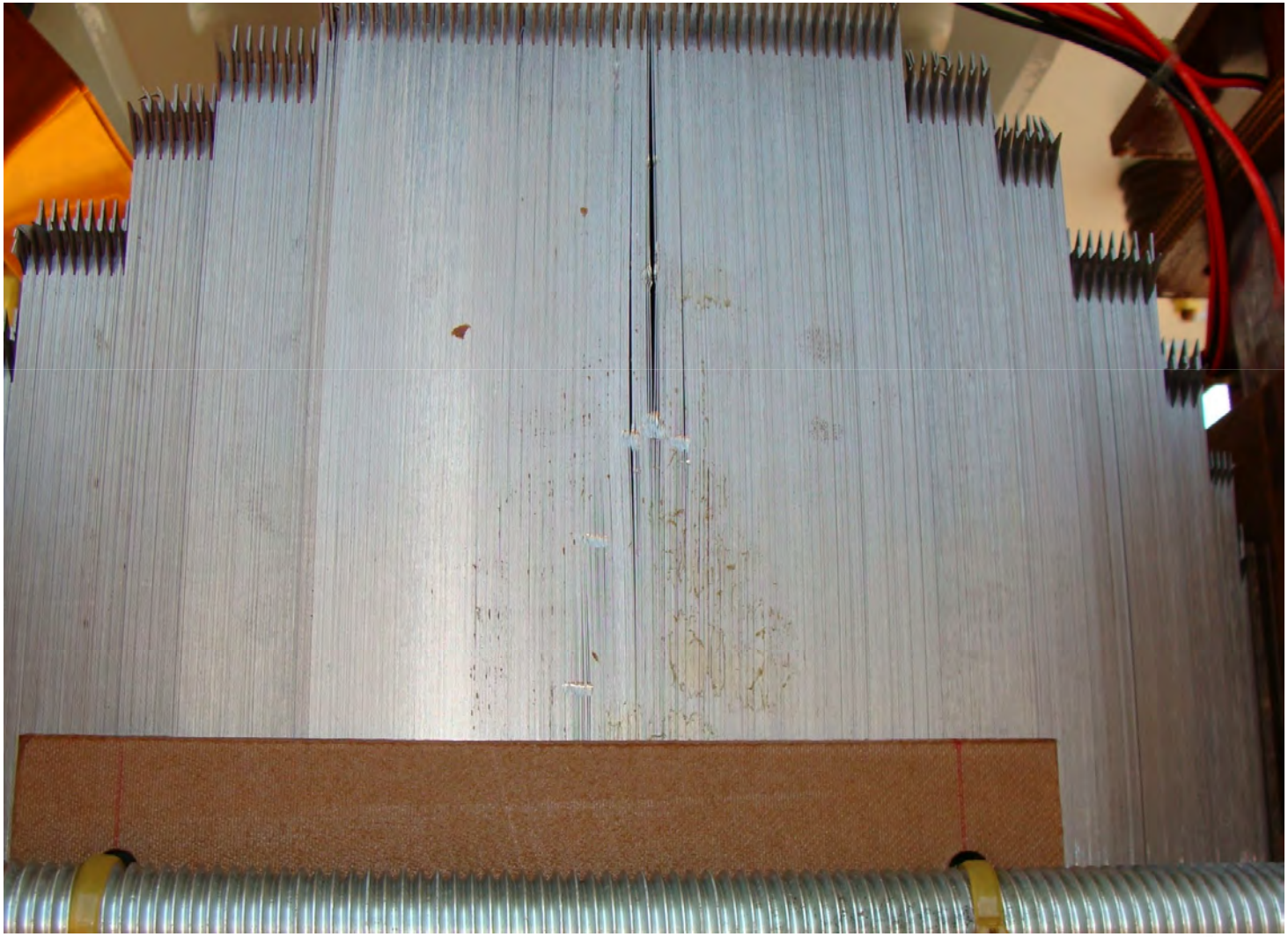
Radial Failure

Axial Failure



Conductor Tilting

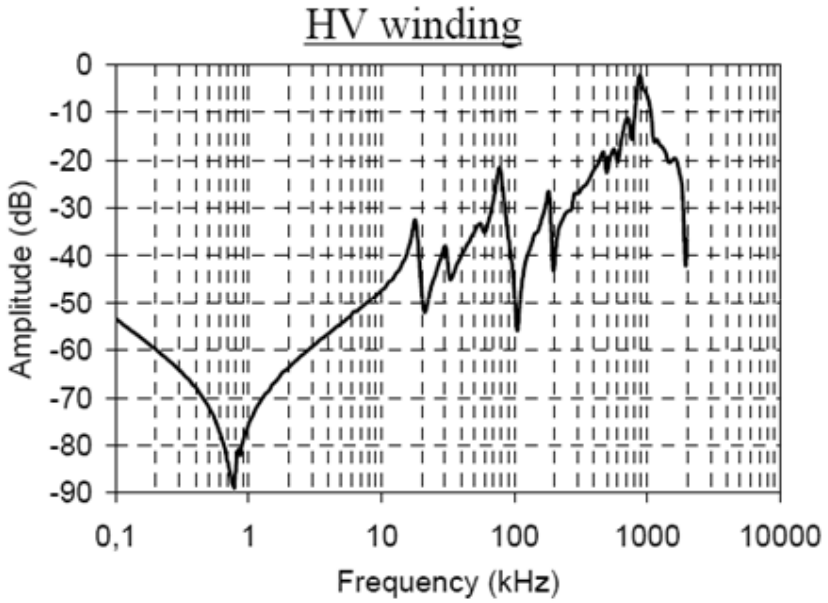
Core Faults

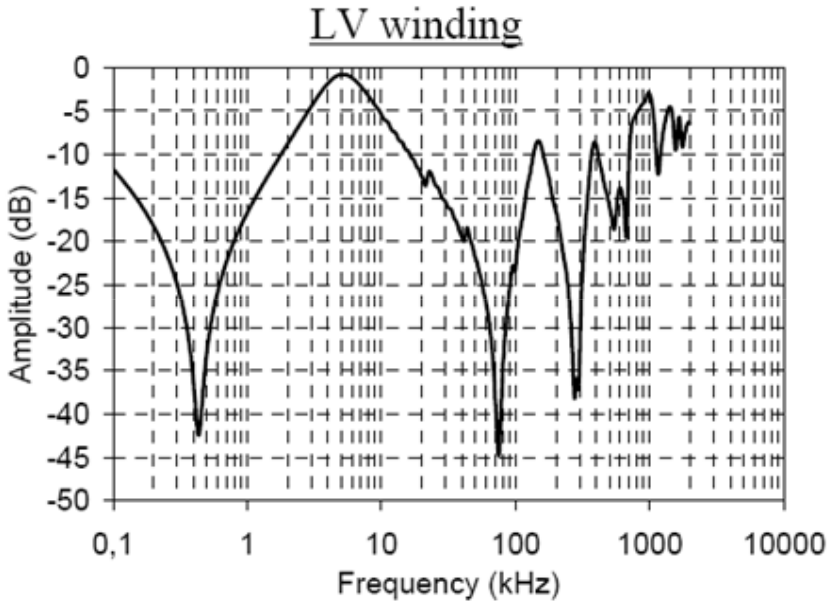


Measurements Types

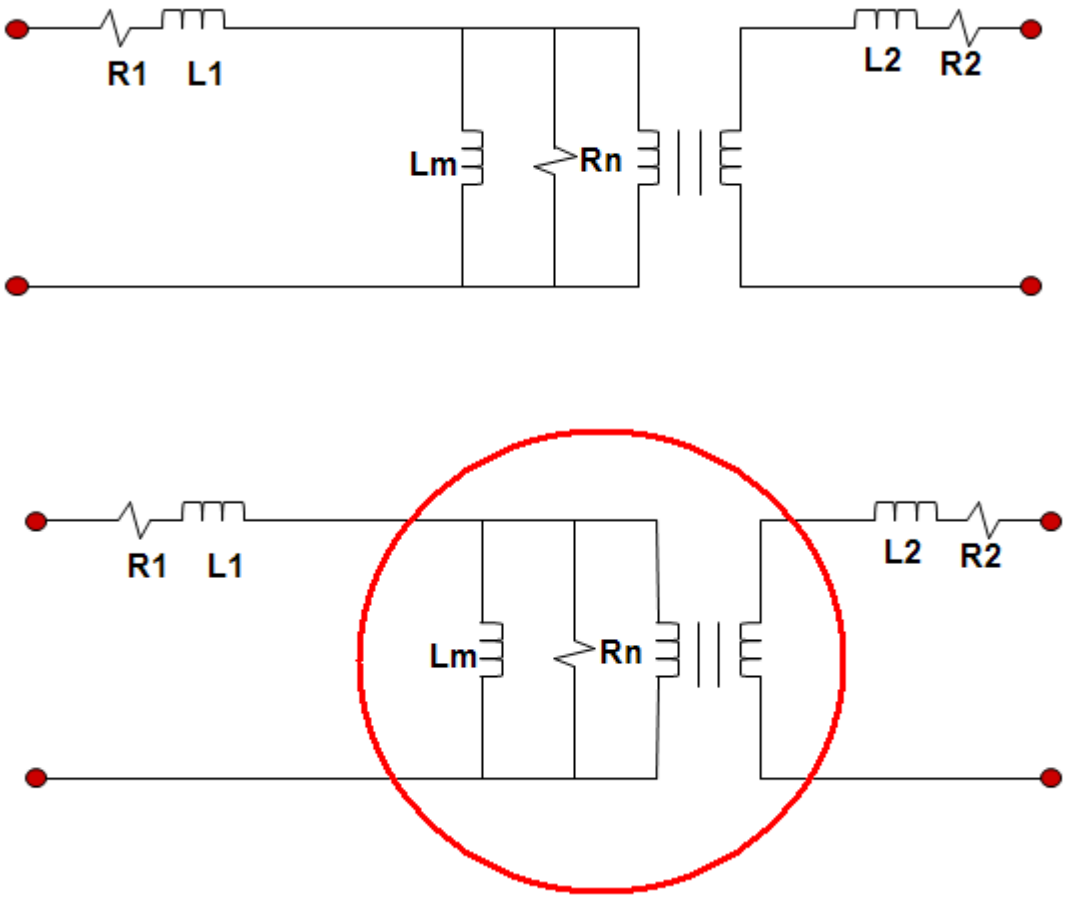
- Open Circuit - Exciting Ima
- Short Circuit - Leakage Reac
- Interwinding - CAP
- Transfer Voltage - TTR

HV and LV Open Circuit

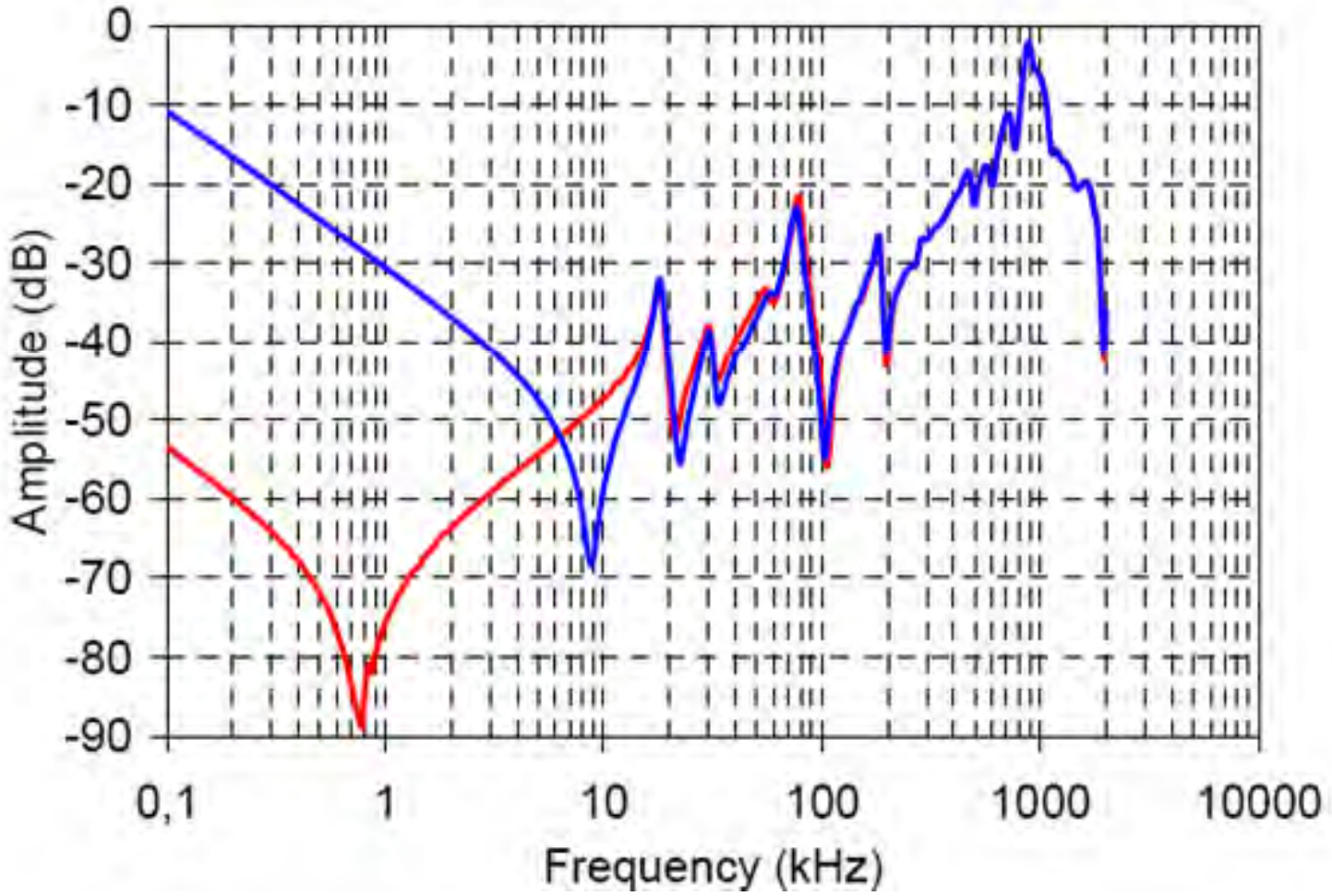




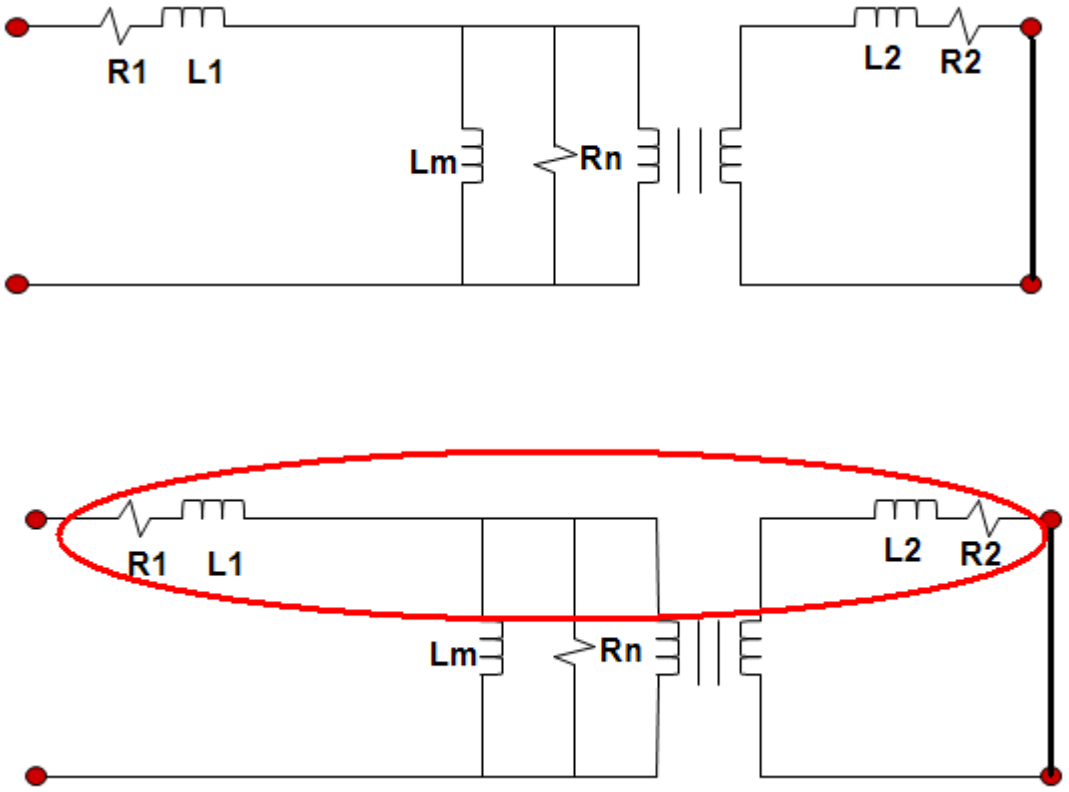
Open Circuit Tests



Open Circuit vs. Short Circuit



Short Circuit Tests



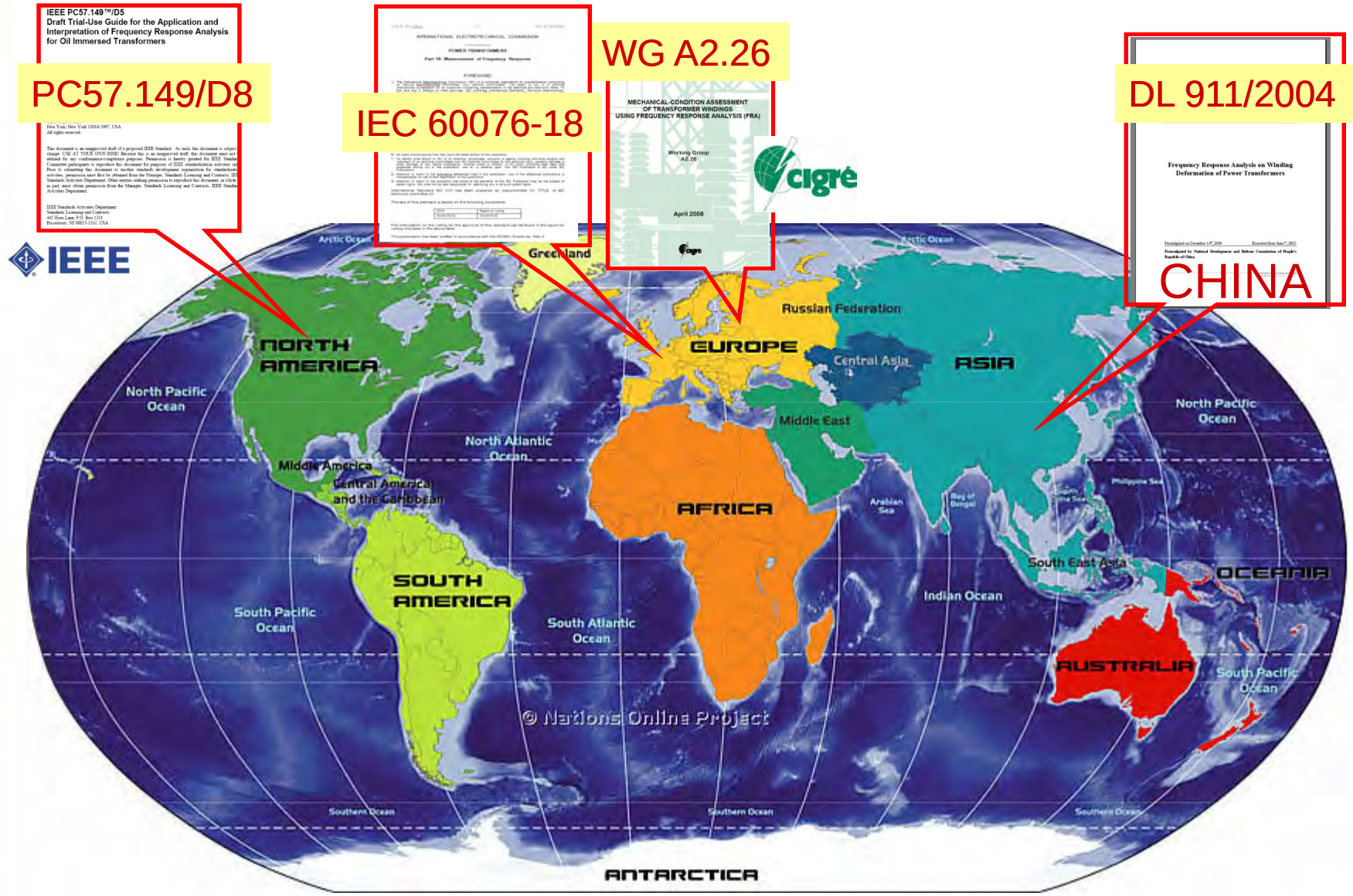
Analysis Strategies

- Baseline
- Similar Unit
- Phase Comparison

FRA Industry Groups

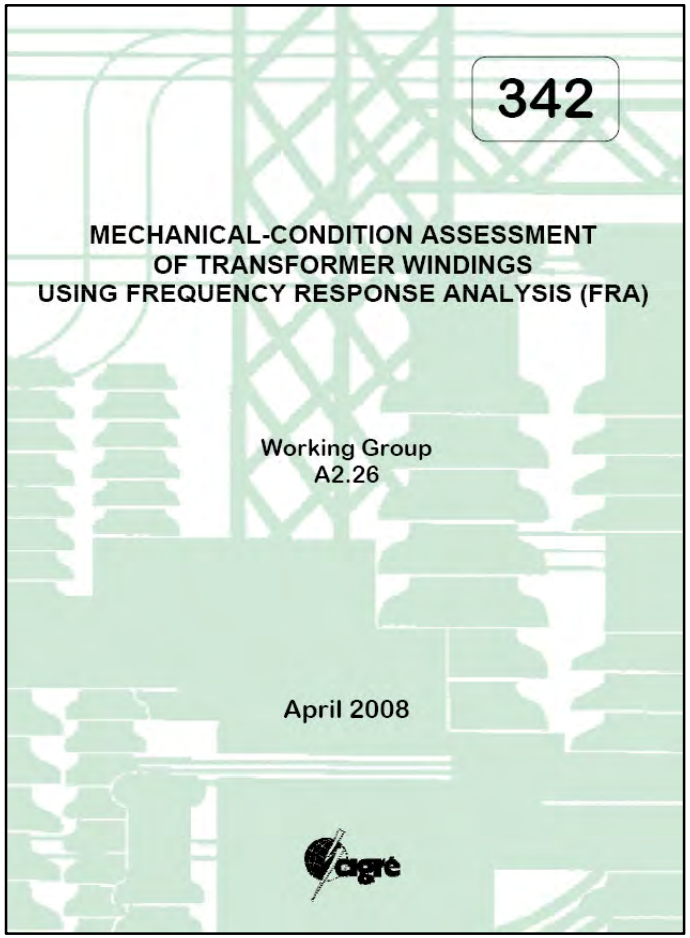
- CIGRE WG A2.26 (Guide)
- DL 911/2004 (Standard)
- IEC 60076-18 (Draft)
- IEEE WG PC57.149 (Guide) D8

Standardization in the World

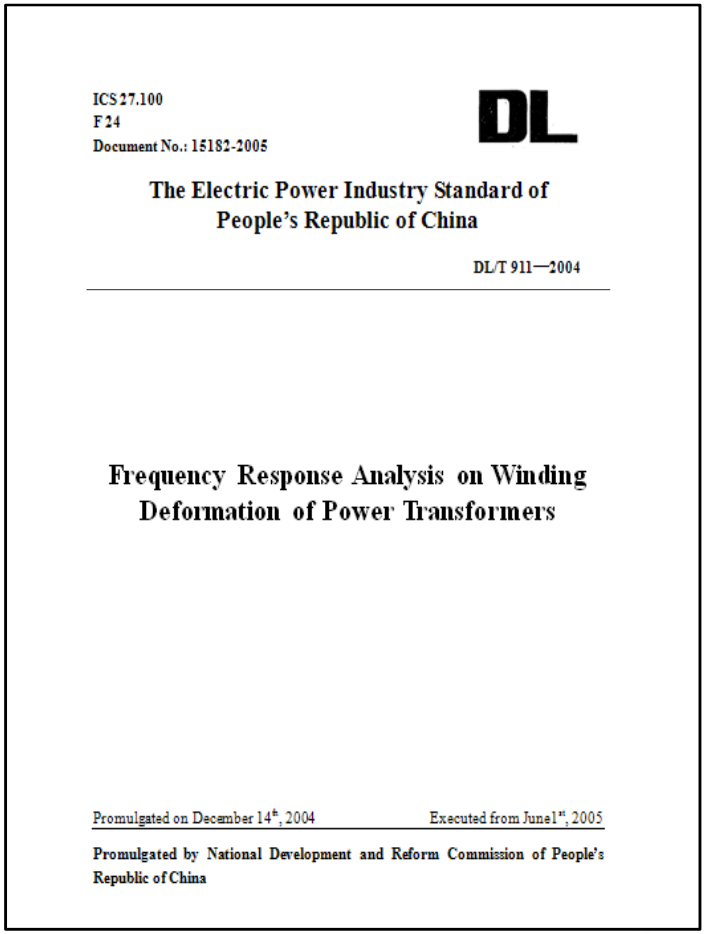


Available Documents

Cigré Brochure 342

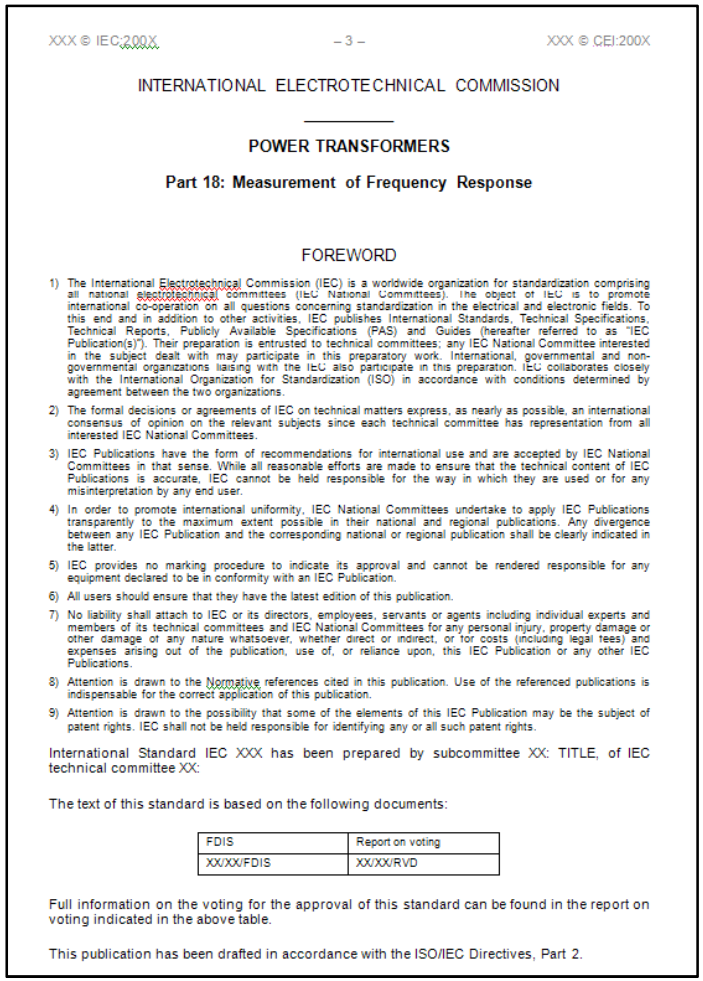


DL 911/2004



Available Documents

IEC 60076-18



INTERNATIONAL ELECTROTECHNICAL COMMISSION

POWER TRANSFORMERS

Part 18: Measurement of Frequency Response

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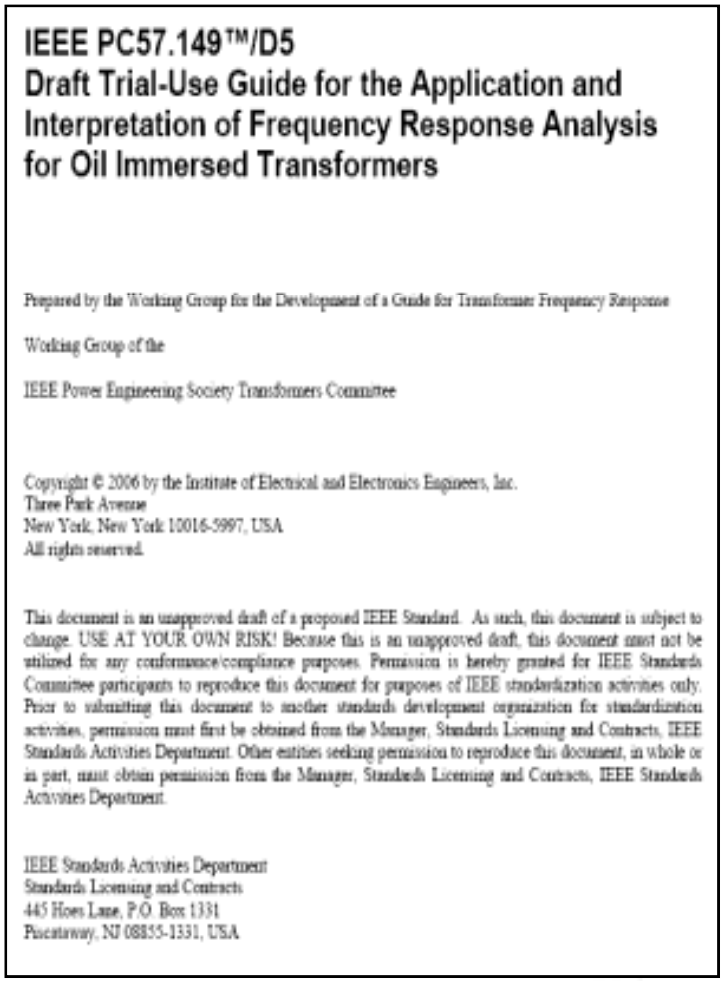
The text of this standard is based on the following documents:

FDIS	Report on voting
XX/XX/FDIS	XX/XX/RVD

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

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

IEEE PC57.149



IEEE PC57.149™/D5
Draft Trial-Use Guide for the Application and Interpretation of Frequency Response Analysis for Oil Immersed Transformers

Prepared by the Working Group for the Development of a Guide for Transformer Frequency Response

Working Group of the

IEEE Power Engineering Society Transformers Committee

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