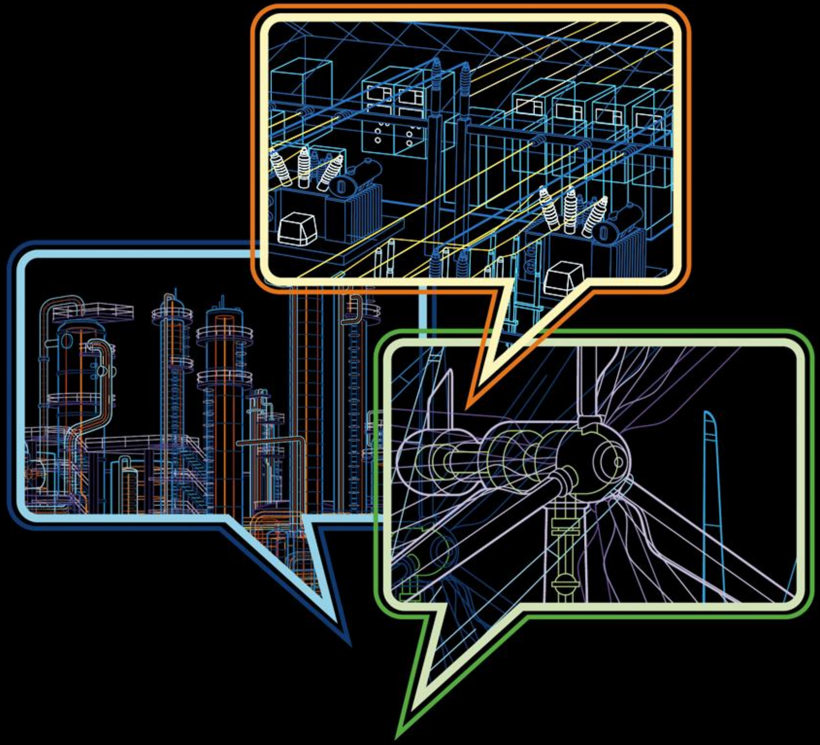


ABB Automation & Power World: April 18-21, 2011

WPO-100-1A&1B

Advanced diagnostics for detection and root cause analysis of problems in power transformers

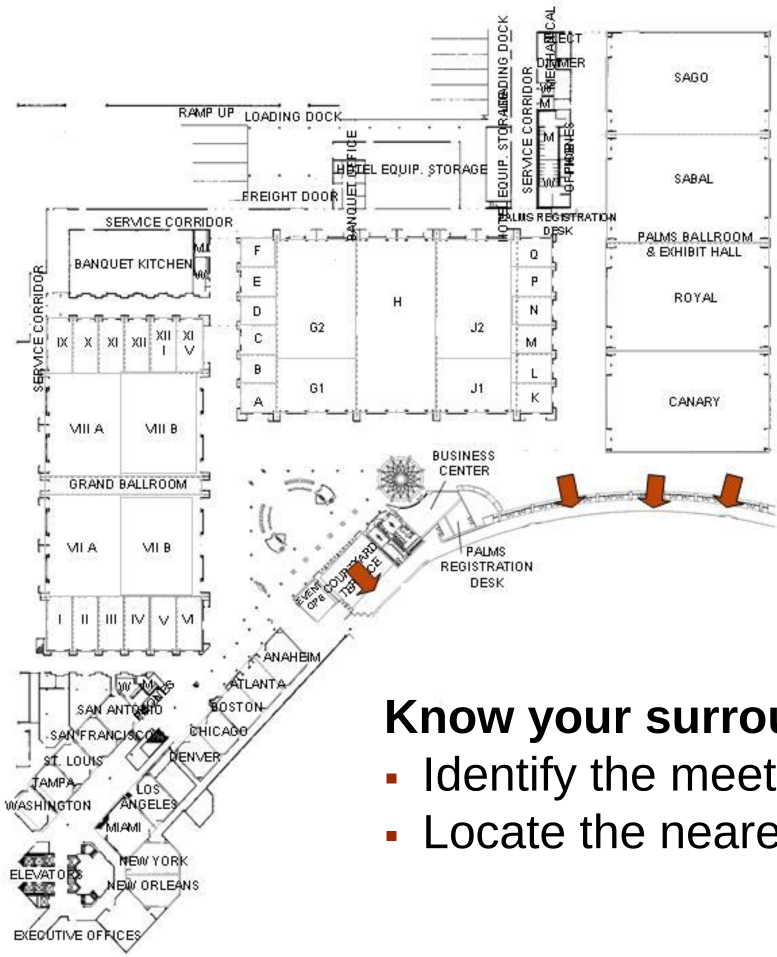
WCS-100-1A & 1B
Advanced diagnostics for detection and root cause analysis of problems in power transformers

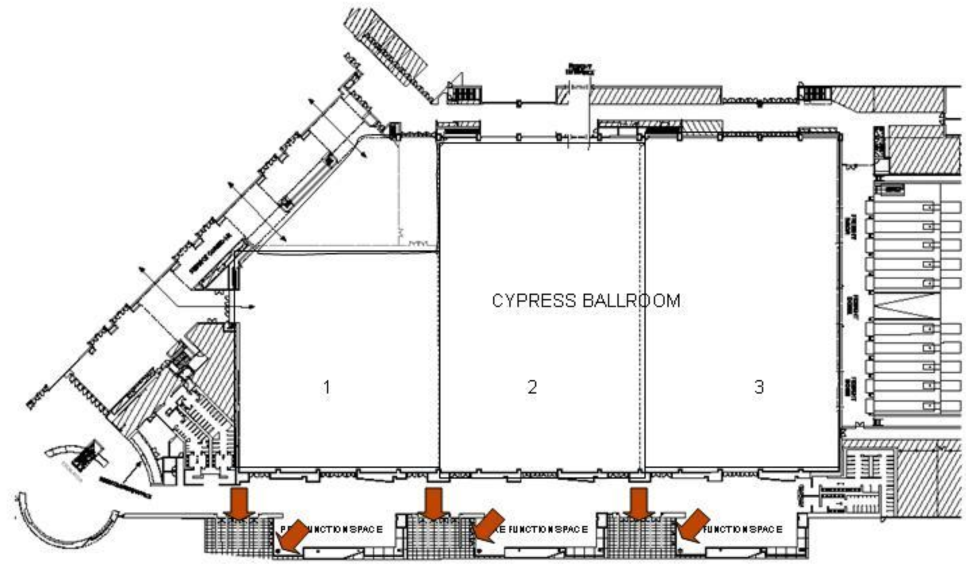
- Dr. Poorvi Patel
- Manager, TRES Engineering Solutions
- ABB
- St. Louis, MO

Your safety is important to us
Please be aware of these emergency procedures

- In the event of an emergency please dial ext. 55555 from any house phone. Do not dial 9-1-1.
- In the event of an alarm, please proceed carefully to the nearest exit. Emergency exits are clearly marked throughout the hotel and convention center.
- Use the stairwells to evacuate the building and do not attempt to use the elevators.
- Hotel associates will be located throughout the public space to assist in directing guests toward the closest exit.
- Any guest requiring assistance during an evacuation should dial “0” from any house phone and notify the operator of their location.
- Do not re-enter the building until advised by hotel personnel or an “all clear” announcement is made.

Your safety is important to us
Convention Center exits in case of an emergency





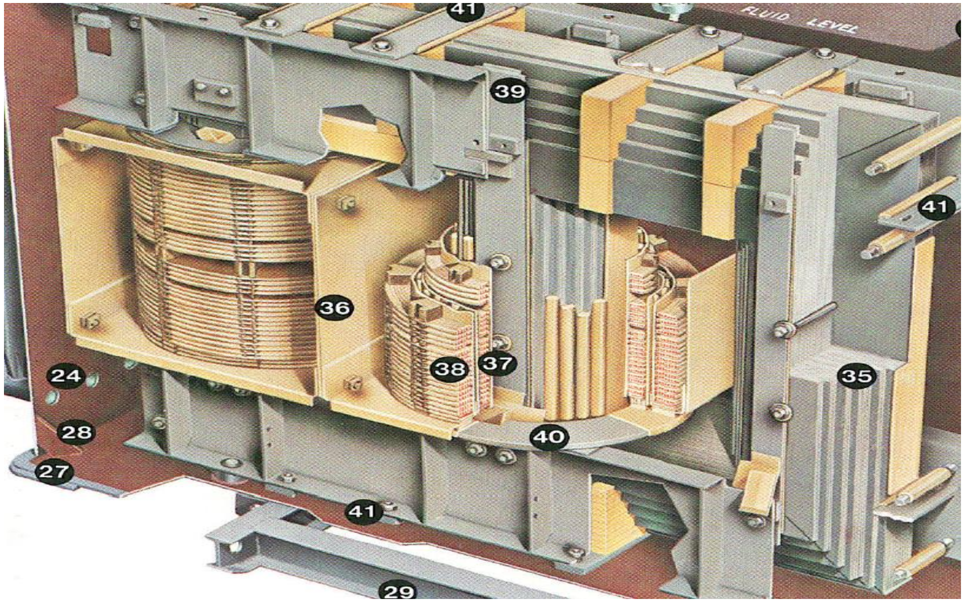
Know your surroundings:

- Identify the meeting room your workshop is being held in
- Locate the nearest exit

Advanced diagnostics for detection and root cause analysis of problems in power transformers

- What is DFR?
- DFR- Cases
- What is SFRA?
- FRA- Cases

.DFR- What is that ?



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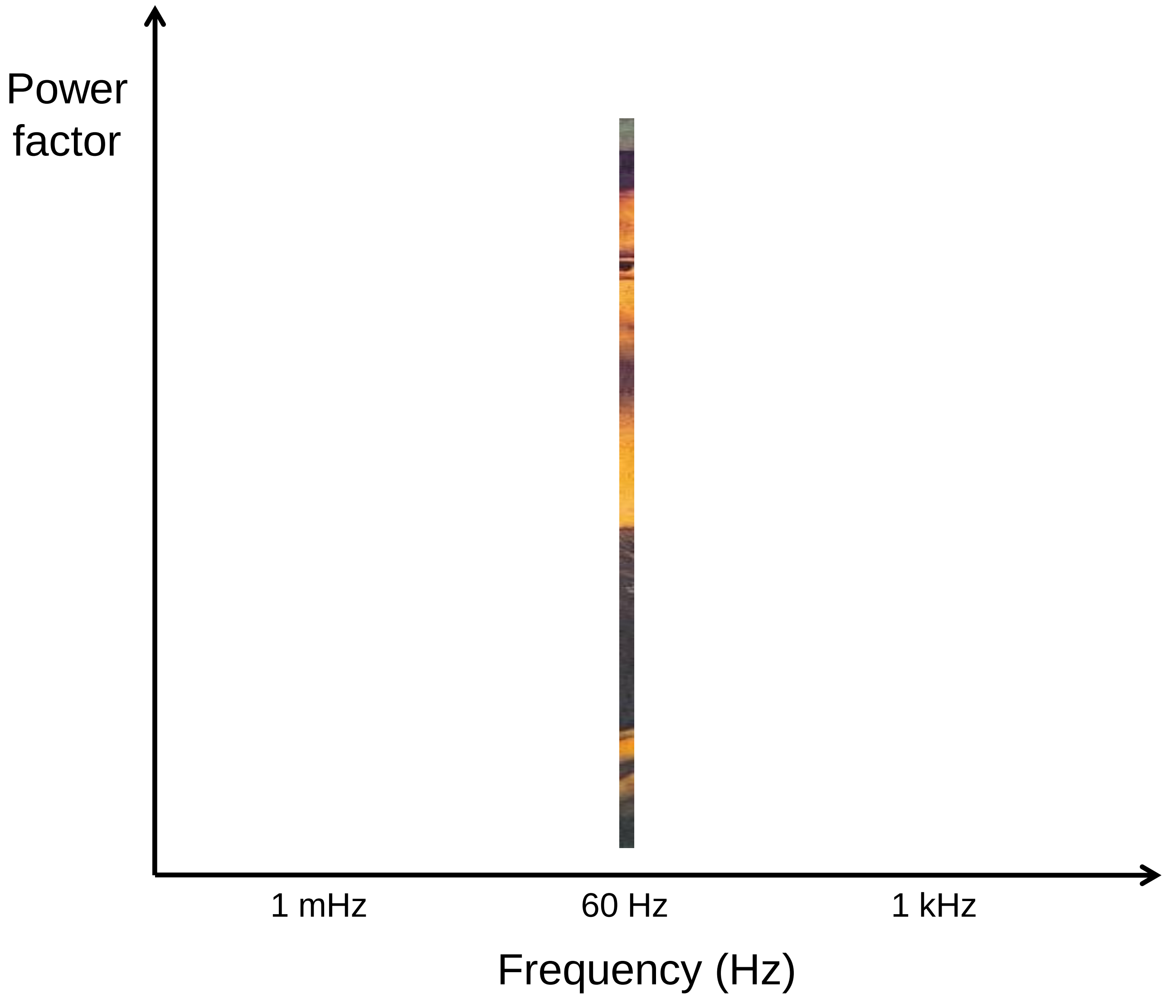
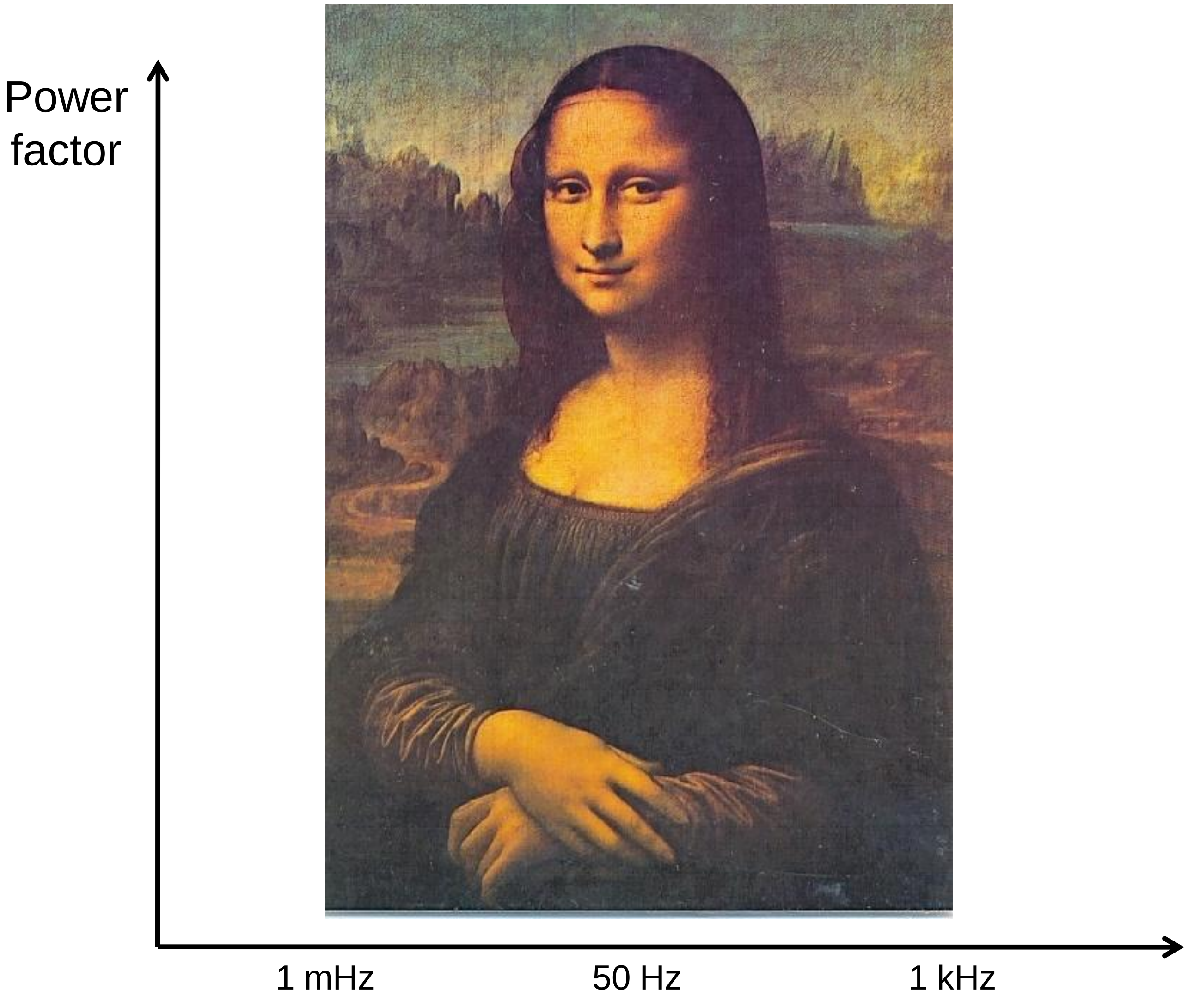
Why Dielectric Frequency Response?

Traditional Power Factor Testing



Dielectric Frequency Response



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Dielectric Response of Power Transformers

- Off-line diagnostics
- Oil and cellulose insulation system
- Dielectric properties are strongly affected by moisture and ageing.

➔ Dielectric response measurements can be used for diagnostic purposes.

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Why Dielectric Response

Purpose of measurement

- **Diagnostic test of insulation system**
  - **Moisture content**
  - **Oil Conductivity**
- **Diagnose defects in system**
  - **Diagnose high PF or tan δ**
  - **Contamination**
  - **Carbon Tracking**
  - **Resistance in core ground circuit**
- **Quality control test of Factory and/or Field processing**

Why Dielectric Response?

- Important to know the moisture level
  - Moisture and acids accelerates ageing
  - High moisture level can lead to bubble formation
- Oil conductivity is an ageing indicator
- Oil samples unreliable at low (off-line) temperatures

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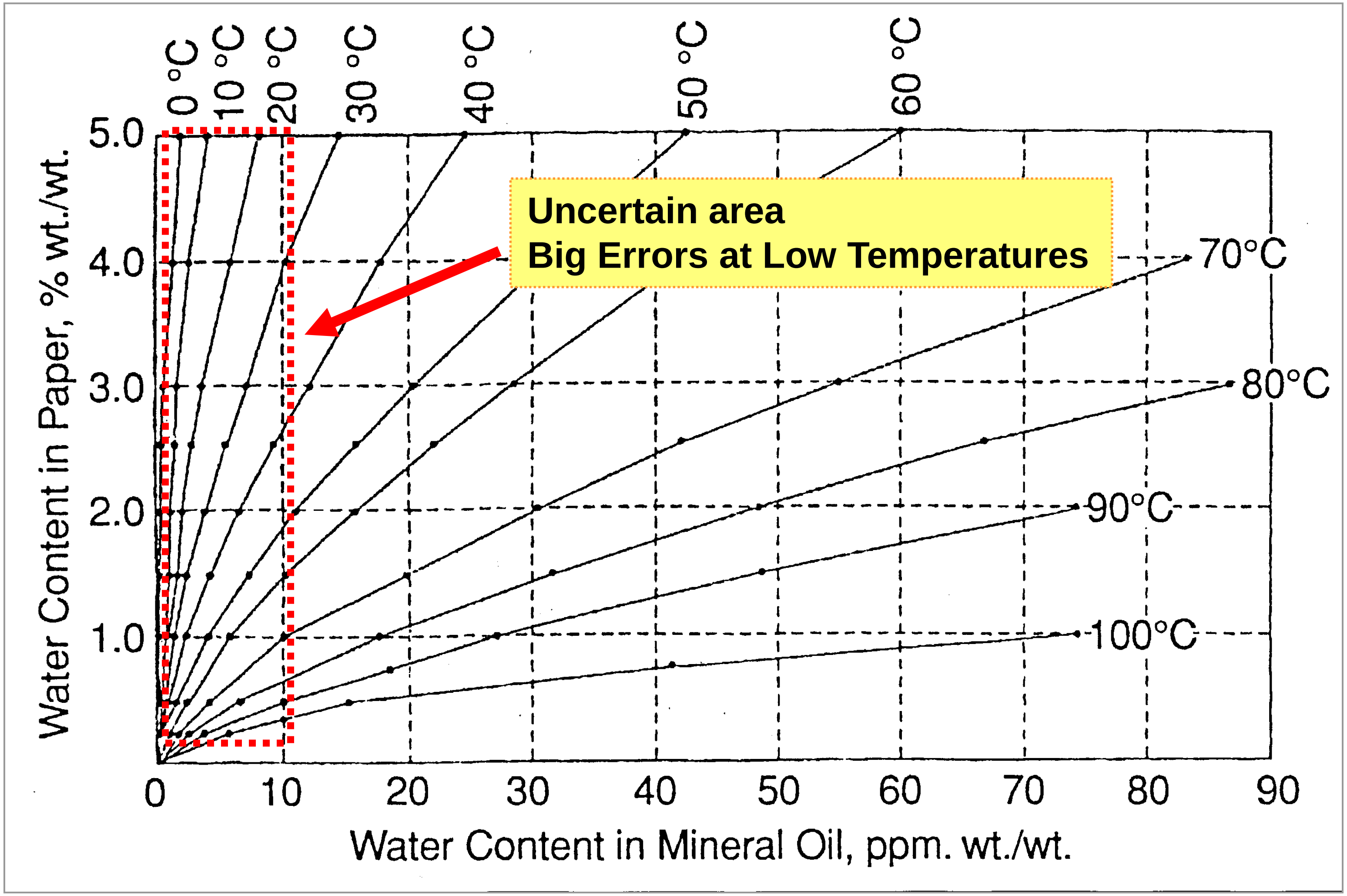
Cellulose Moisture from Oil Samples



From. P.J.Griffin, C. M. Bruce and J. D. Christie: *"Comparison of Water Equilibrium in Silicone and Mineral Oil Transformers"*, Minutes of the Fifty-Fifty Annual Conference of Double Clients, Sec. 10-9.1, 1988

Power Products where DFR is used

- **Transformer diagnostics**
  - **Power Transformers**
  - **Transformer Bushings**
  - **Instrument Transformers**

- **Cable diagnostics**
  - **XLPE cables**
  - **Oil/paper cables**

- **Manufacturing controlling system**
- **Trouble shooting electrical apparatus**
- **Material chacterization**

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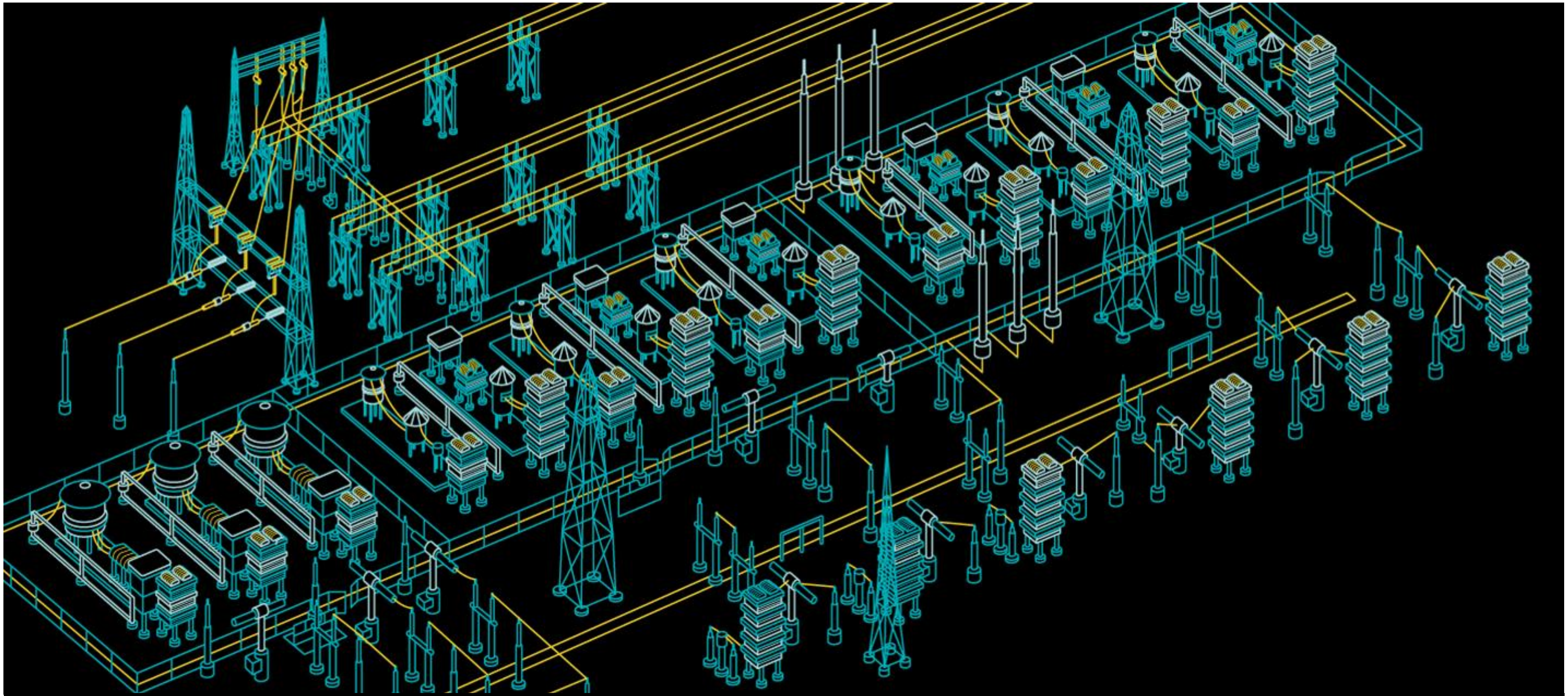
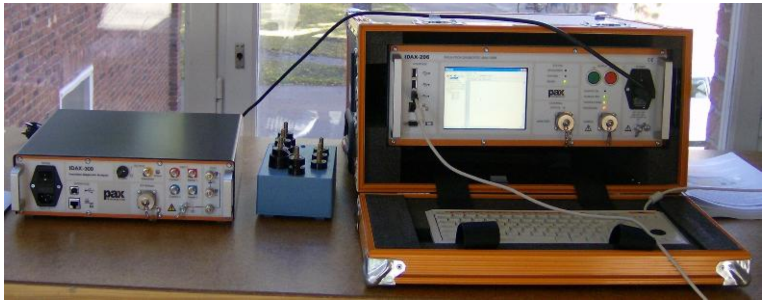


DFR-Measurements

Equipment Setup

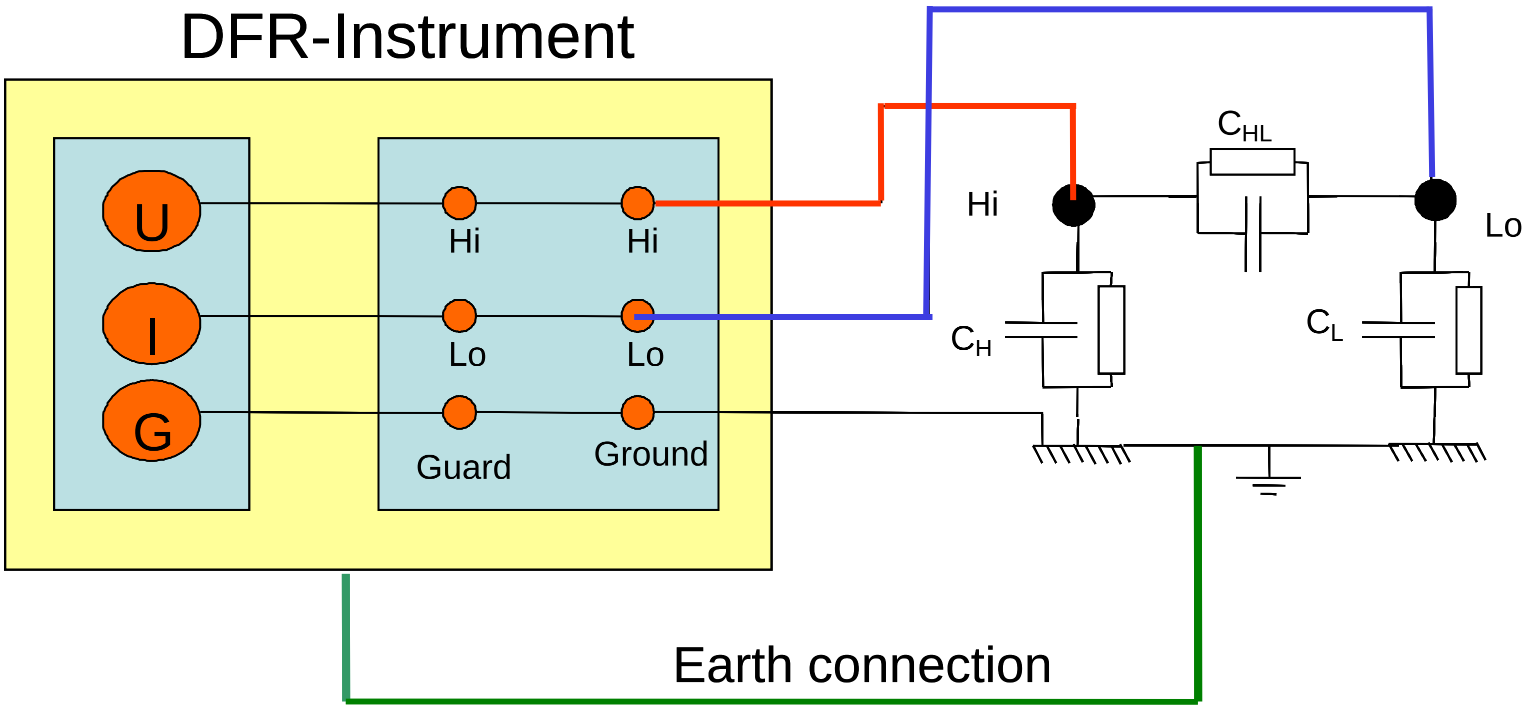
- **Sinusoidal signal of amplitude up to 200V peak**
- **Frequency sweep range**
  - **0.0001 – 10 kHz** maximum
  - .001 – 1000 Hz typical
  - 0.01-1000 Hz minimum



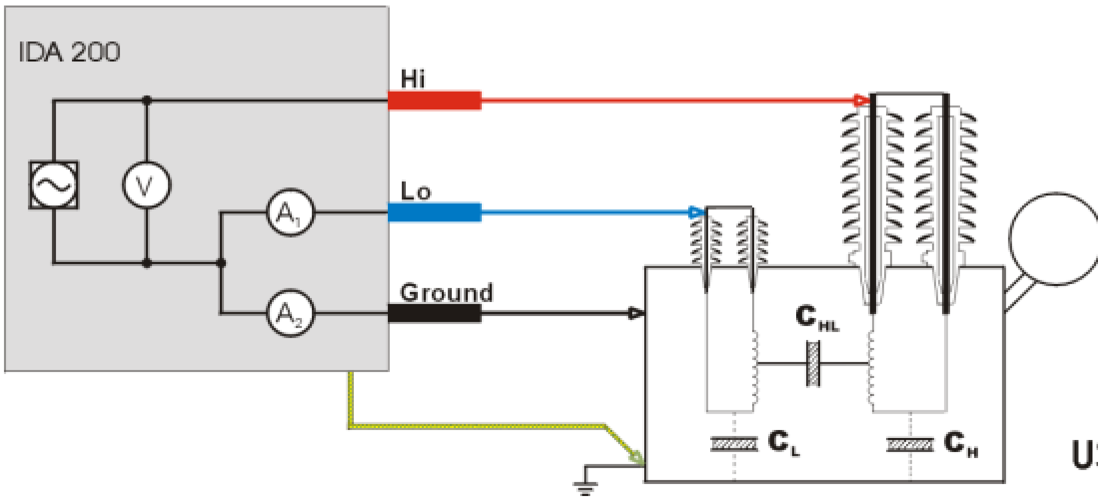
- **Three-electrode set up: the voltage electrode “Hi”, the current sense electrode “Lo” and the ground**
  - **UST**
  - **(GST)**
  - **GST-g**

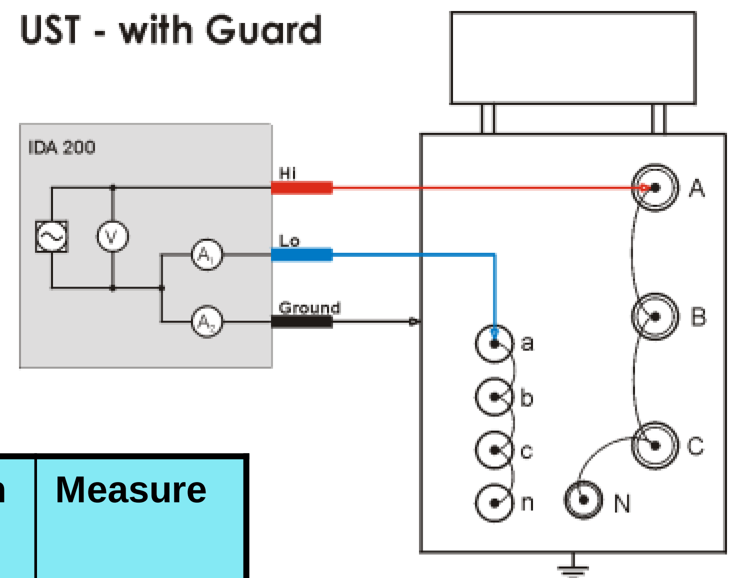
UST Setups

Ungrounded specimen test, UST, with guard



Two winding transformer

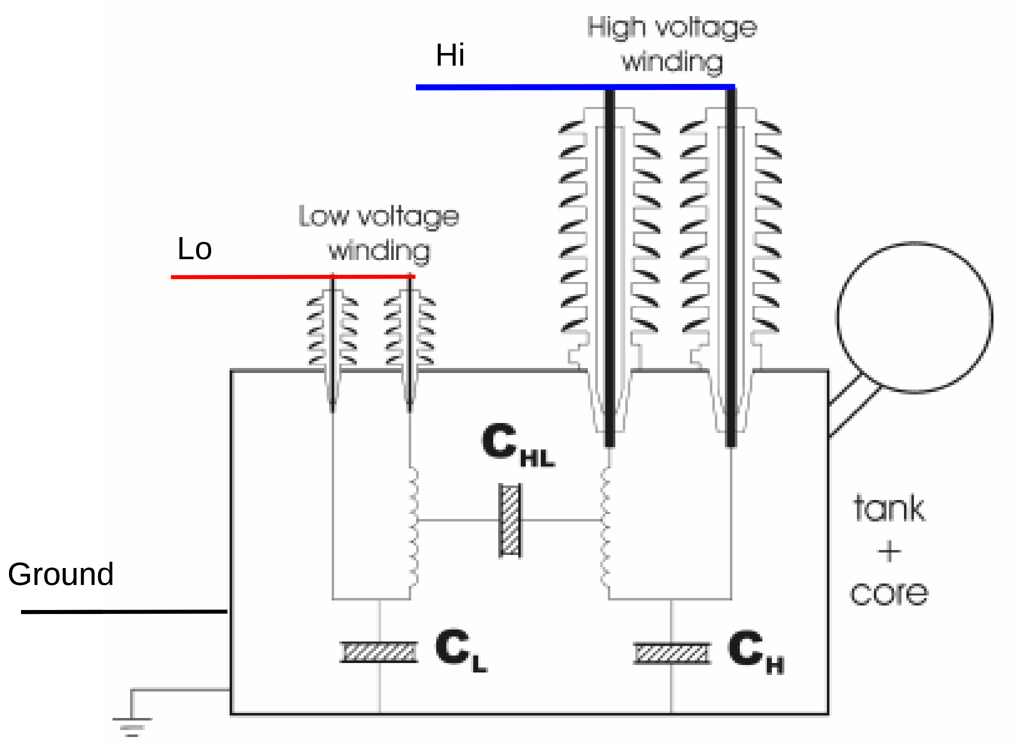




With this lead connection the following measurement could be performed

No	Mode	Hi (Red)	Lo (Blue)	Ground (Black)	Configuration	Measure
1	UST	High	Low	Tank	UST	CHL
2	GST	High	Low	Tank	GST-Guard	CH

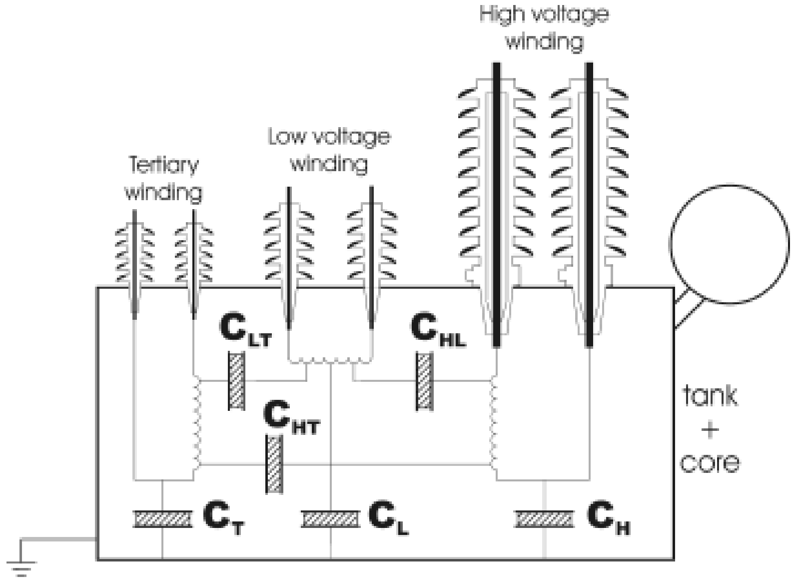
Two winding transformer



With this lead connection the following measurement could be performed

No	Mode	Hi (Red)	Lo (Blue)	Ground (Black)	Configuration	Measure
1	GST	Low	High	Tank	GST-Guard	CL

Three winding transformer



List of measurement set-ups for three winding power transformer using IDA 200

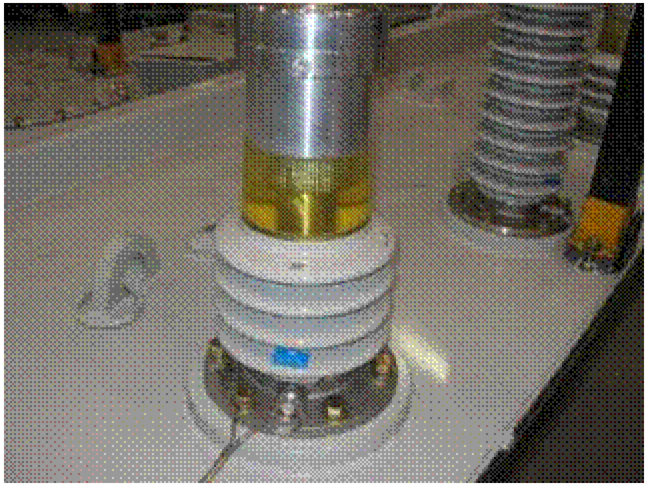
No	Mode	Hi (red)	Lo (blue)	Ground (black)	Configuration	Measure	Measurement Template
1	UST	High	Low	Tert+Tank	UST	C_{HL}	3W-CHL
2	UST	High	Tert	Low+Tank	UST	C_{HT}	3W-CHT
3	UST	Low	Tert	High+Tank	UST	C_{LT}	3W-CLT
4	GST	High	Low+Tert	Tank	GST-Guard	C_H	3W-CH
5	GST	Low	High+Tert	Tank	GST-Guard	C_L	3W-CL
6	GST	Tert	High+Low	Tank	GST-Guard	C_T	3W-CT

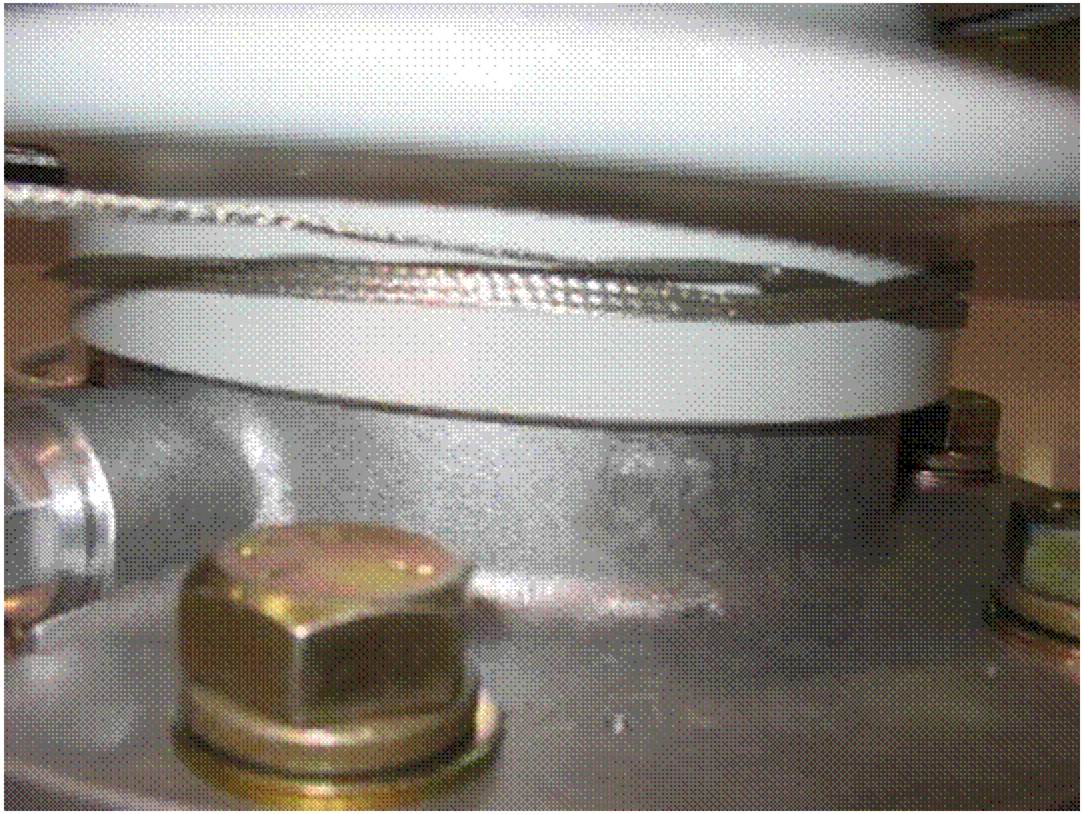
Rainy days

- Instrument is sensitive to water
  - Can cause failure of electronics if the instruments gets soaked
  - Keep instrument under shelter if rain threatens
- Water on bushings affects readings
  - Try guarding the bushing porcelain
- UST test between windings usually unaffected.

Minimize Influence of contaminated Bushing insulation

GST-g and GST with small low voltage bushings or wet or dirty bushings, recommend guarding the bushing insulation to minimize the influence of contamination





High Capacitance Transformers

- Current at 1000 Hz and even 470 Hz may be too high
  - Instrument will not measure point
  - Reduce voltage so the 1000 Hz point is measured
  - Make 2 measurements
    - 1 at reduce voltage with 1-1000 Hz
    - 1 with full voltage from 0.001 Hz to 470 Hz
  - Add the 1000 Hz data to make a complete .001 – 1000 Hz file
    - Use text editor program like notepad

Low Capacitance Measurement

- Instrument may stop and display error message.
- Determine the reason for the low capacitance
  - Check nameplate connection
  - Check for inner-winding shields
- Change the minimum capacitance value on the C file
- Make the measurement
- Look for unusual results

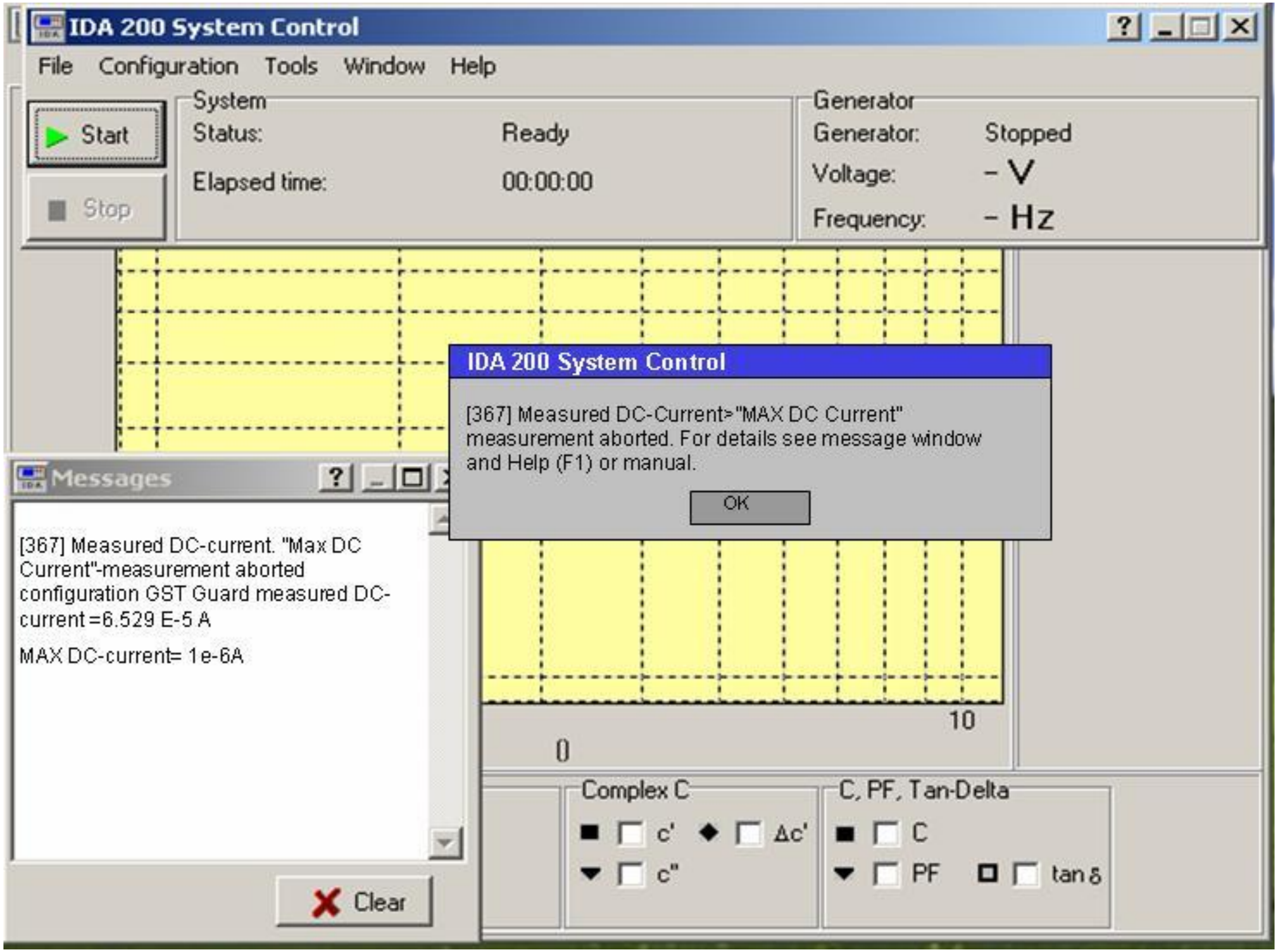
Noise

- Noise is any signal that is not produced by the applied voltage or the response of the transformer
- **AC Noise**
  - Overhead power lines
  - Nearby energized transformers
  - Improper grounds
  - Harmonics
- **DC Noise**
  - Ground currents
  - Dissimilar metals
  - Industrial processes

DC Noise

- Problems
  - Causes Error Signal and Halts Test
  - Can cause error if DC current is large
- Solution
  - Increase DC current limit in C file
  - Check Grounding Connections
  - Record DC current levels for future reference

Error Message – High dc current



Oil & Air Temperature

-**Top and Bottom Oil Temperature**

- **Air Temperature**

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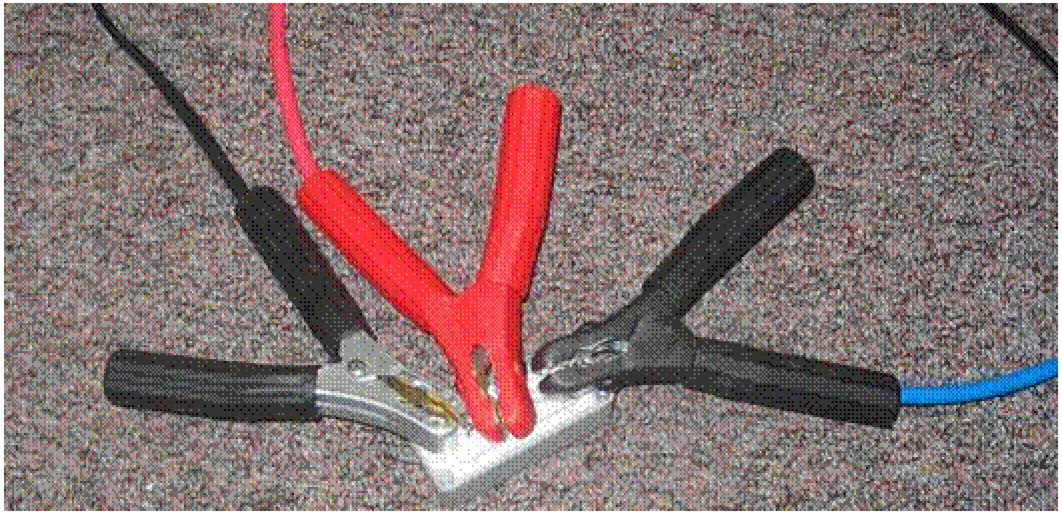
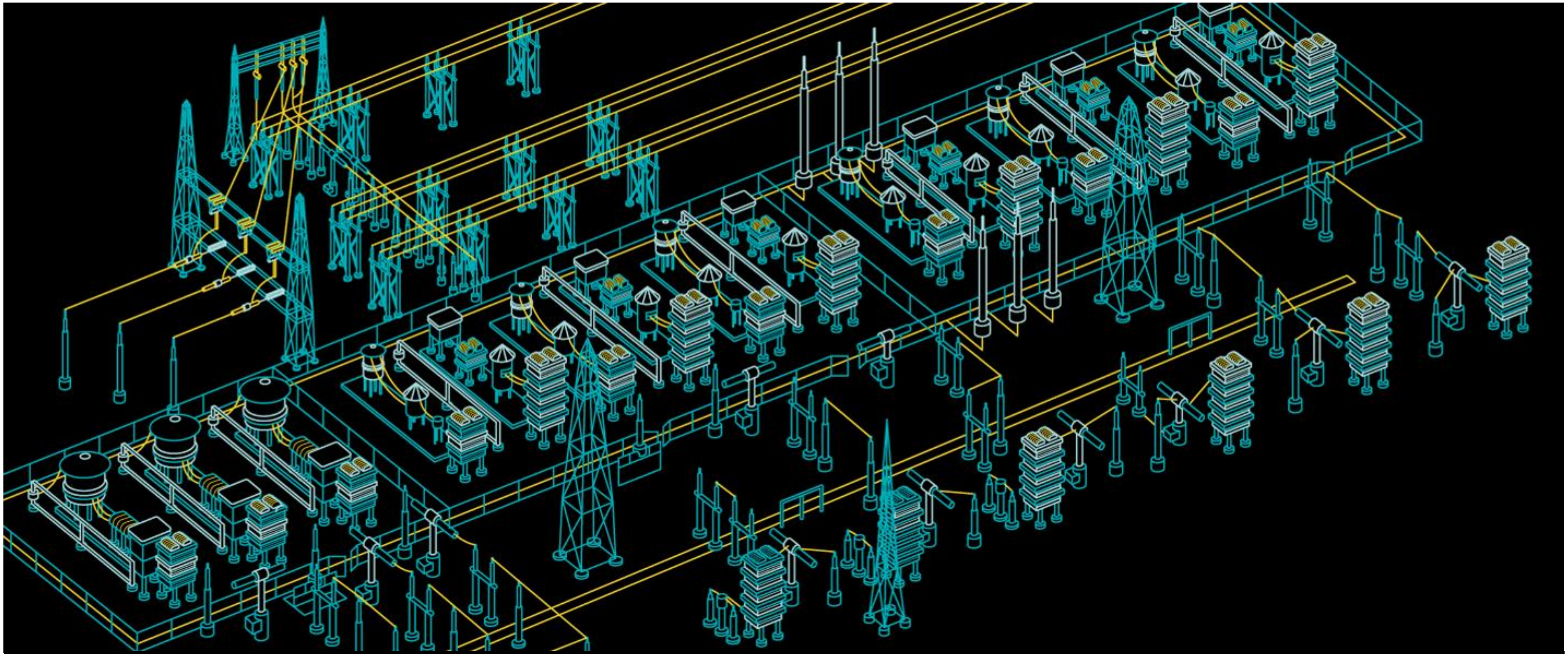
Oil Conductivity Measurement

Check the DFR- Instrument before testing



1) Red on 1, blue on 2 and black on 0 – UST – C_{12}
2) Red on 1, blue on 2 and black on 0 – GSTg – C_{10}
3) Red on 2, blue on 1 and black on 0 – GSTg – C_{20}



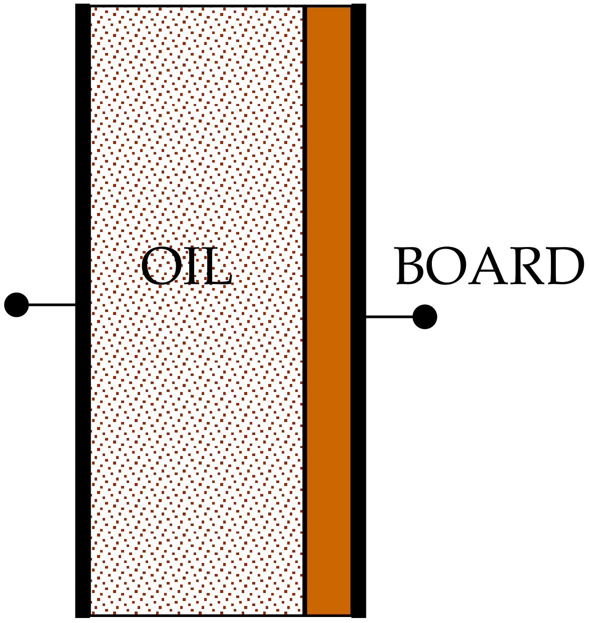
DFR-
Analysis

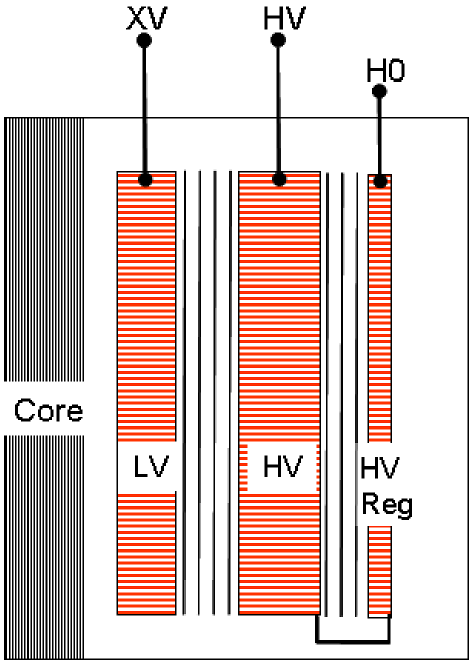
Dielectric Response of a Power Transformer

Dielectric response of a power transformer depends on:

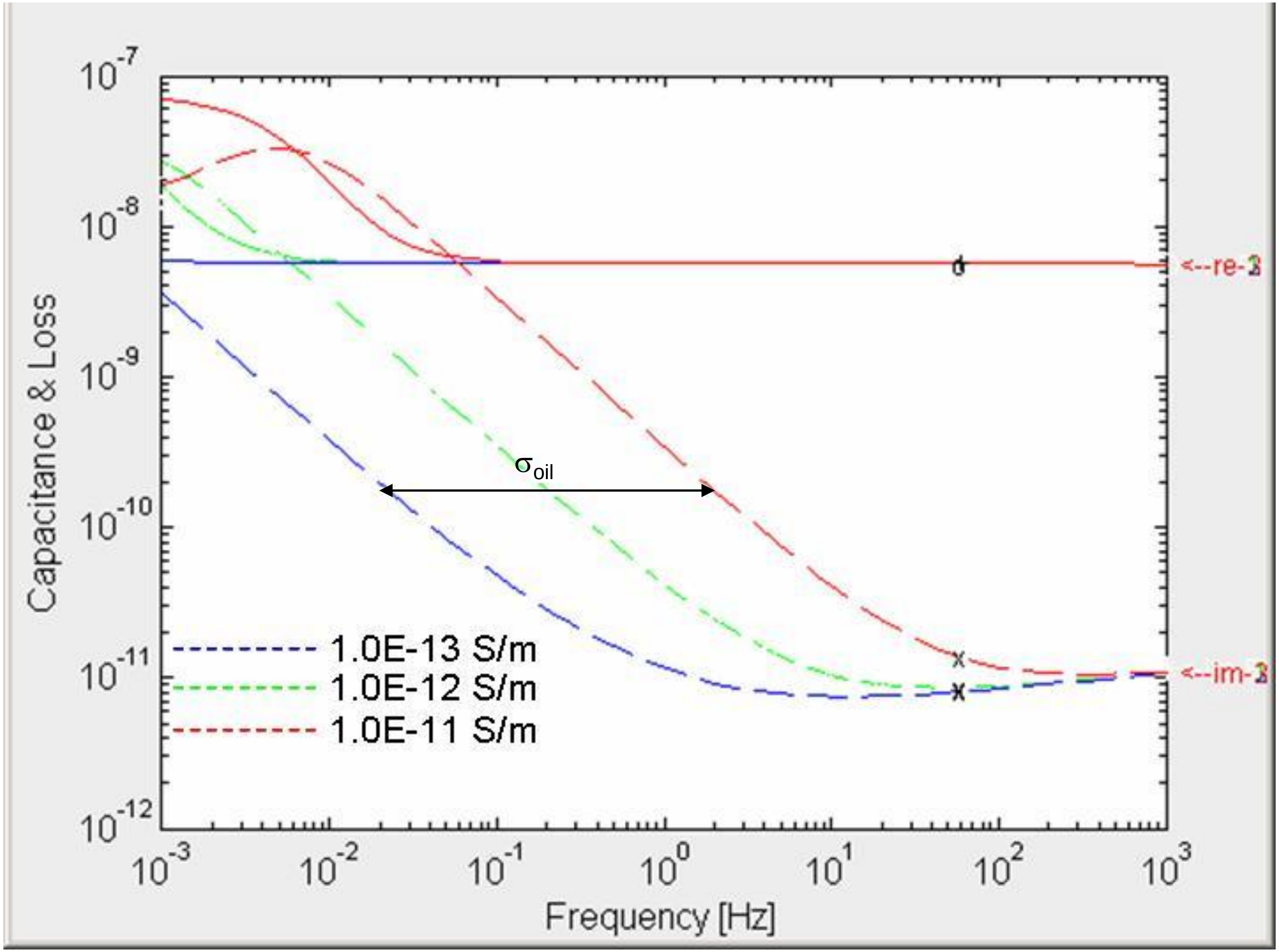
- **The dielectric response of the constituent materials**
- The structure/geometry of the constituent material

Oil and Pressboard in Series

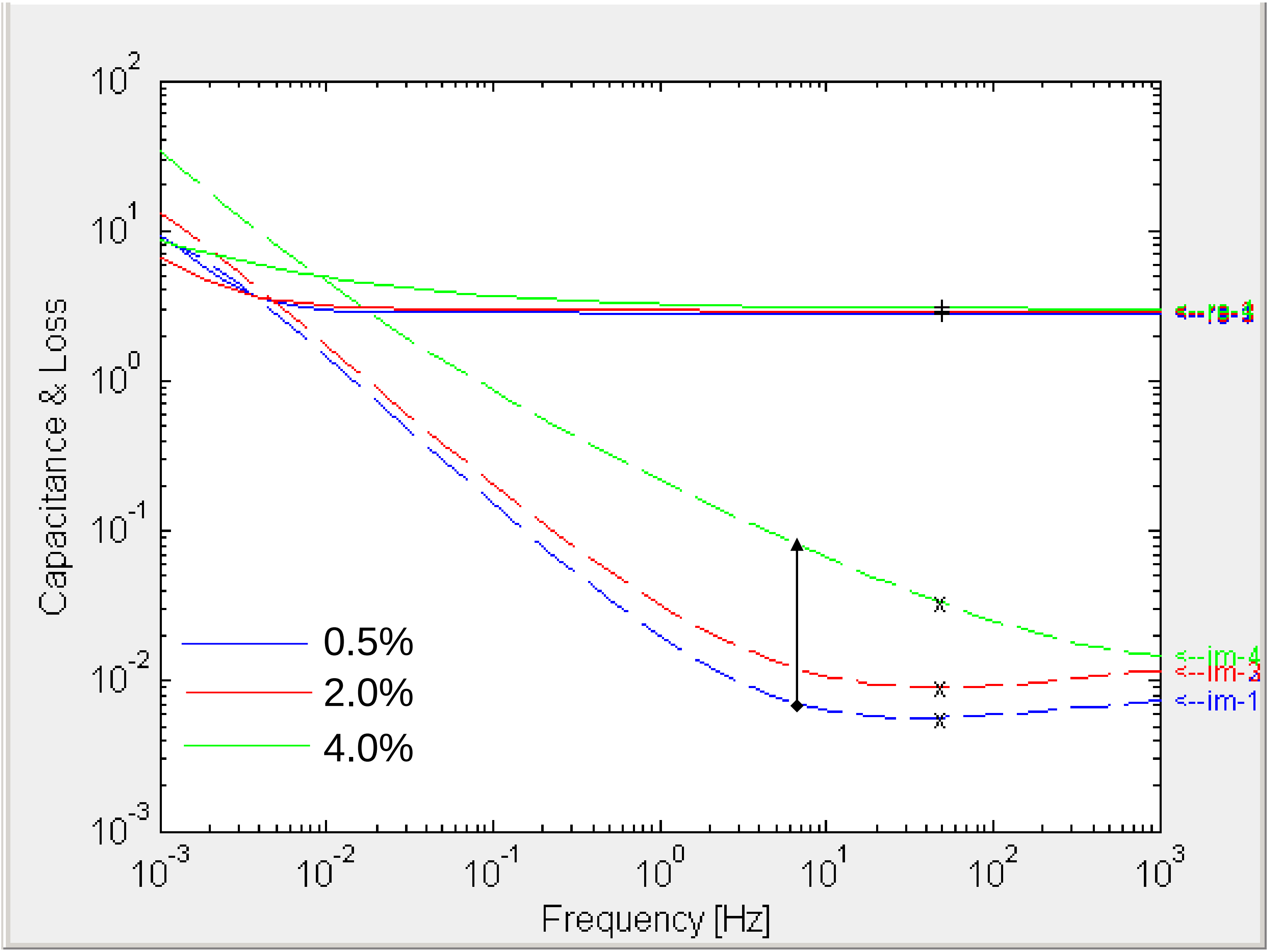




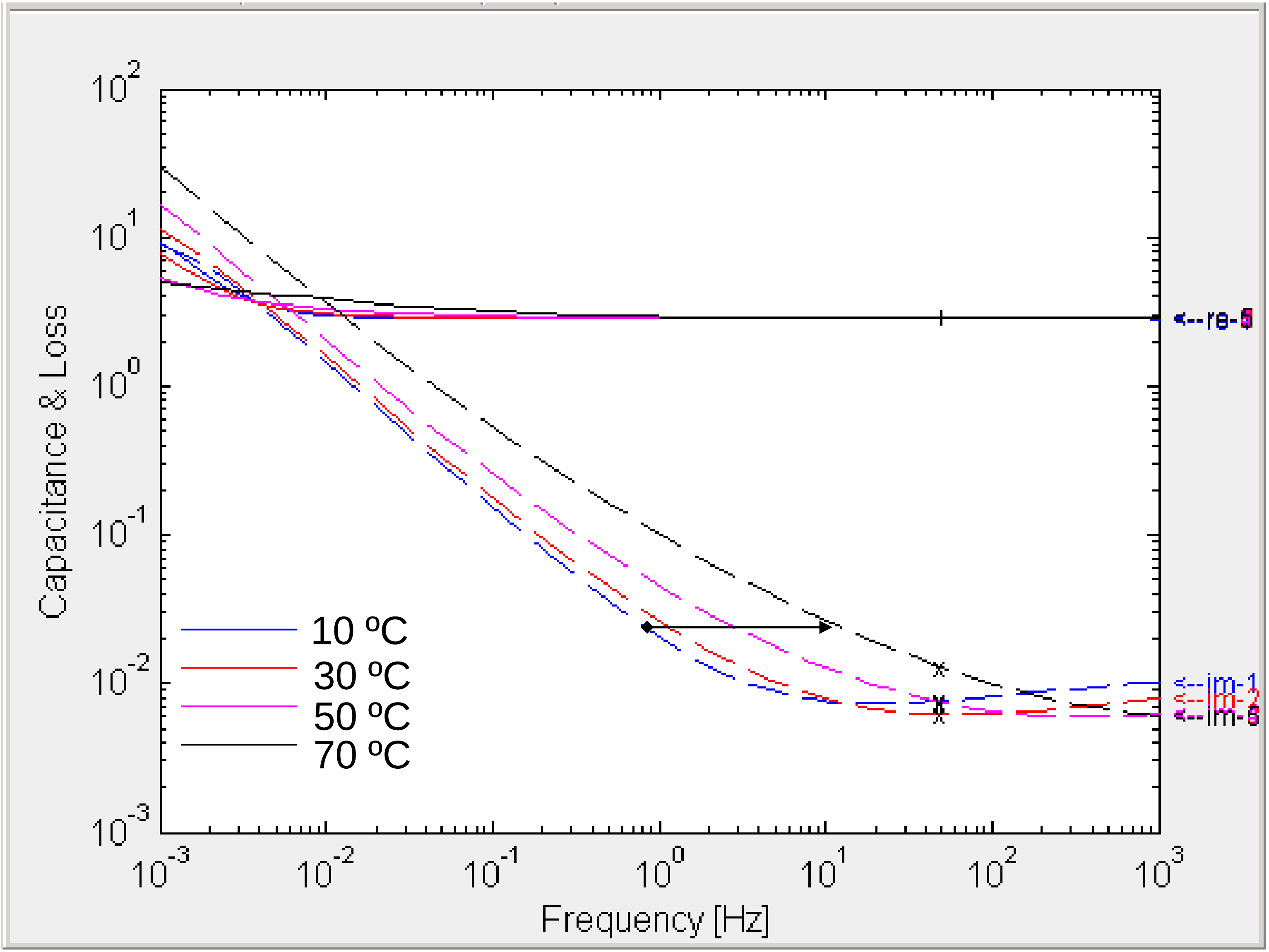
Dielectric Response - Insulation Oil



Dielectric Response of Moisture Content



DR of Oil Impregnated Pressboard, Temperature Dependence

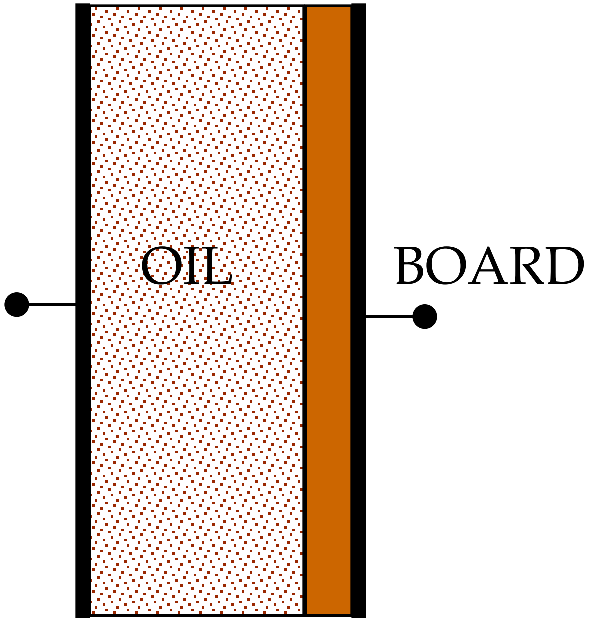


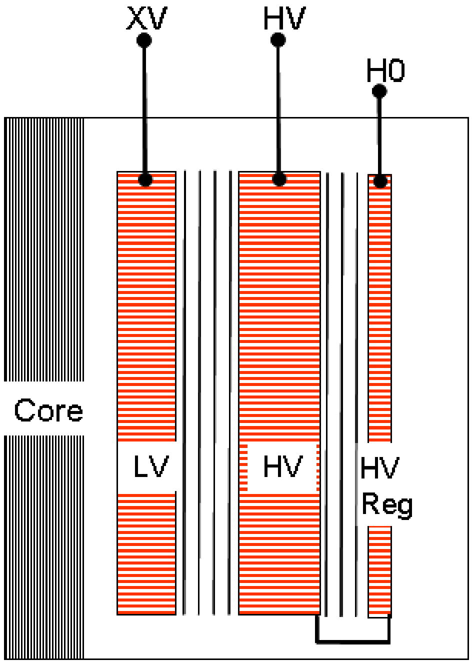
Dielectric Response of a Power Transformer

Dielectric response of a power transformer depends on:

- The dielectric response of the constituent materials
- **The structure/geometry of the constituent material**

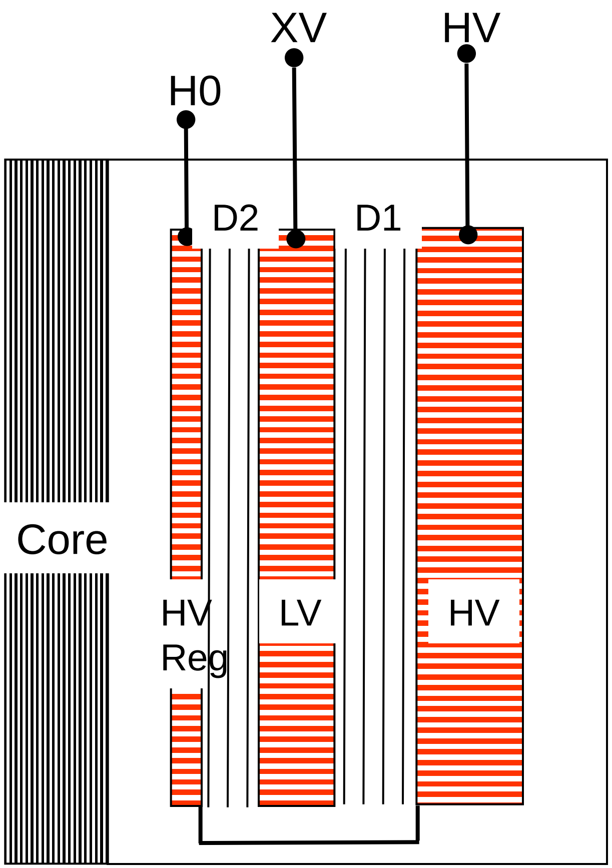
Oil and Pressboard in Series



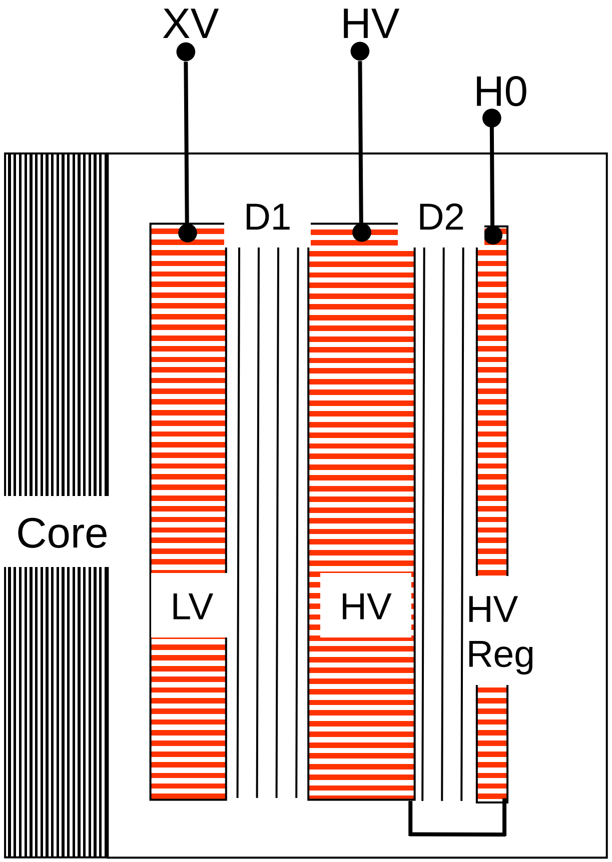


Measurement considerations

Winding configurations



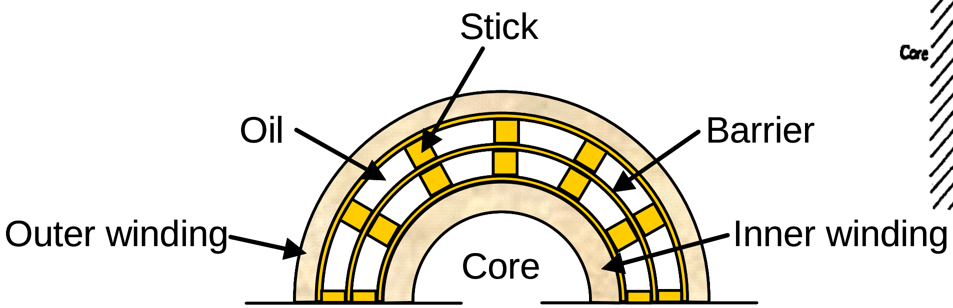
CHL => meas. D1//D2

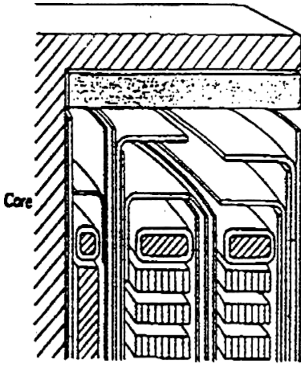


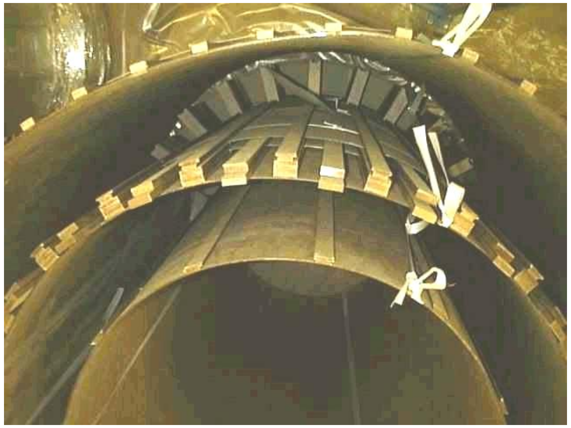
CHL => meas. D1

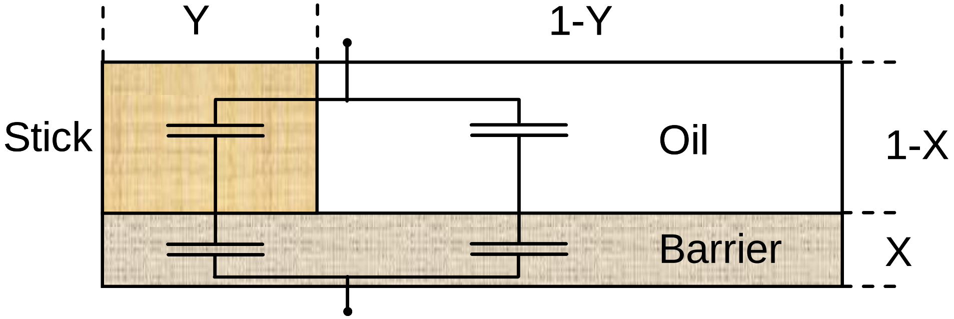
Power Transformer Insulation: Oil & Cellulose

Segment of insulation in main duct
• Cylindrical barriers
• Axial spacers







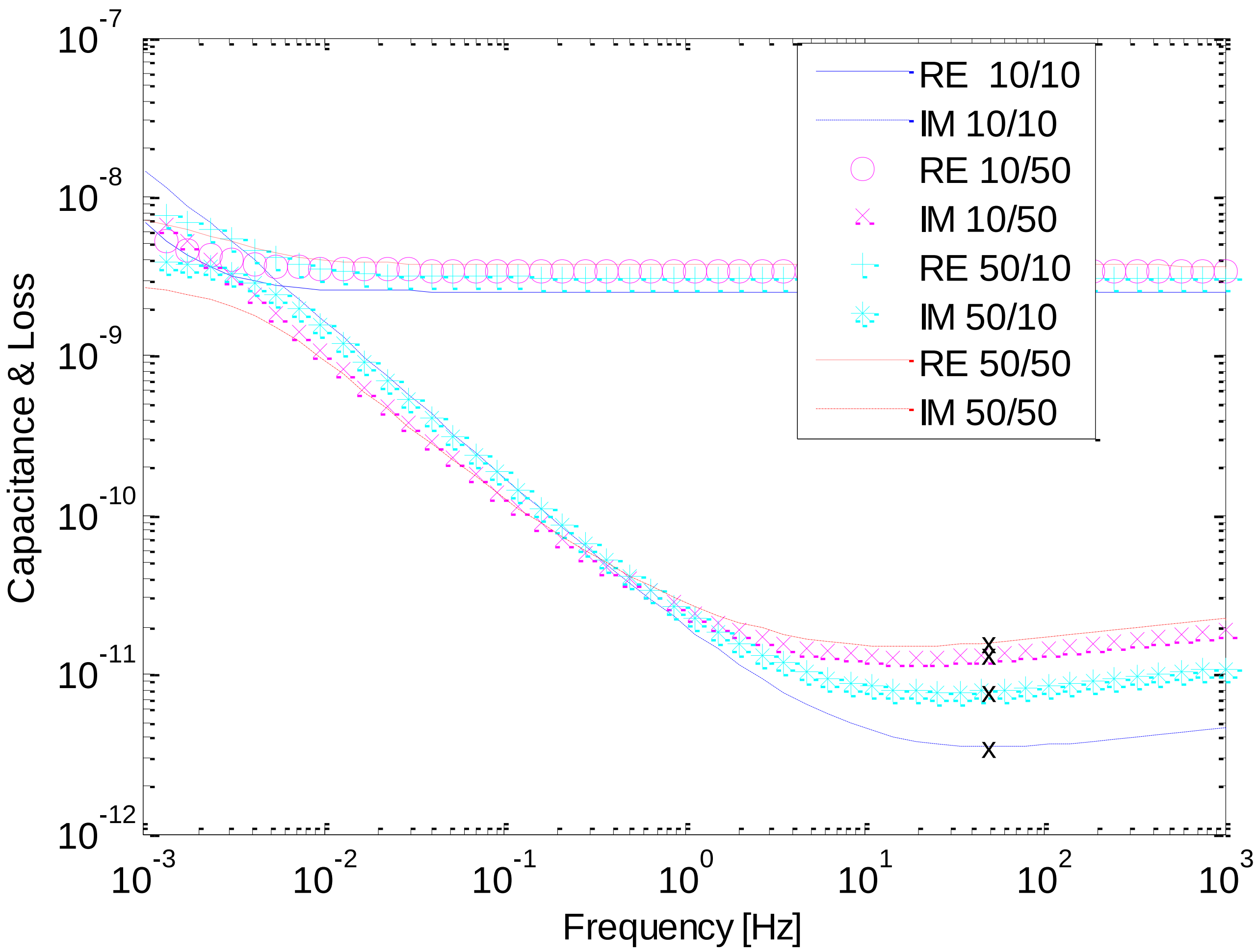


Simplified geometry for modelling:

The X-Y model

- Relative proportion of barriers, X
- Relative proportion of Sticks, Y

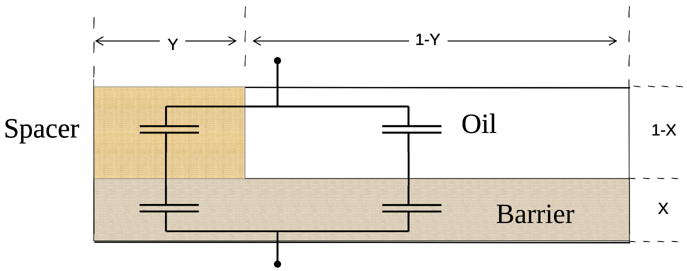
Influence of Geometry



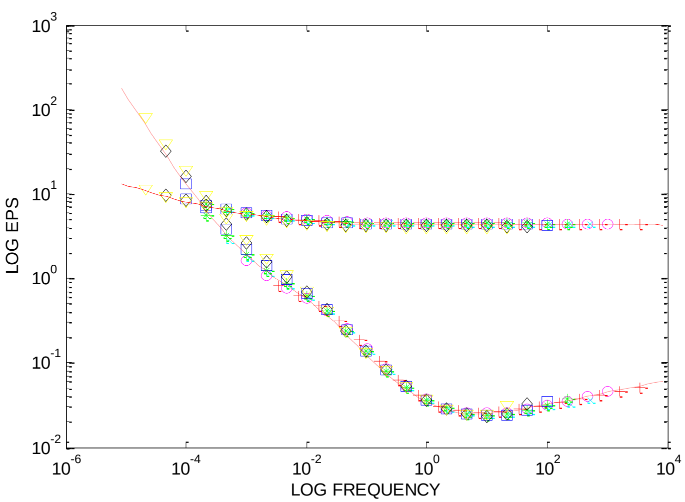
Influence of the insulation design on the dielectric response. The notation in the legend is such that "RE 10/10" means (real) capacitive part, X=10% and Y=10% etc.

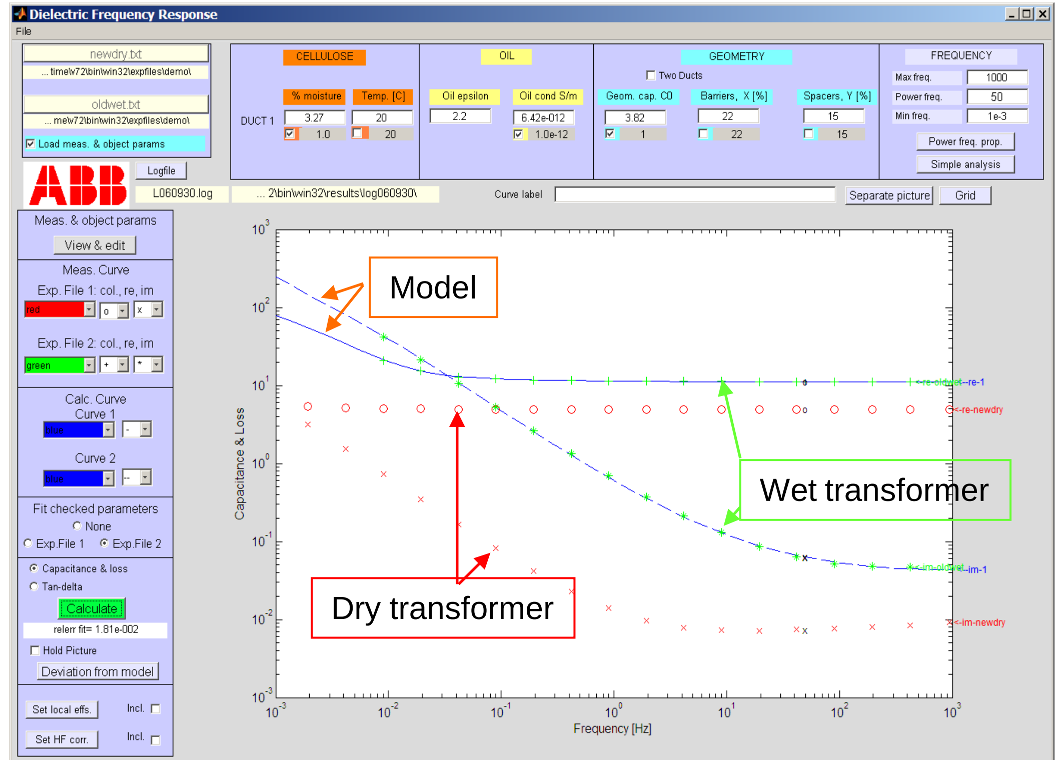
The X-Y model - Tool for Analysis

Simplified geometry



Materials characteristics





Insert the materials in the geometry

The X-Y model - Tool for Analysis

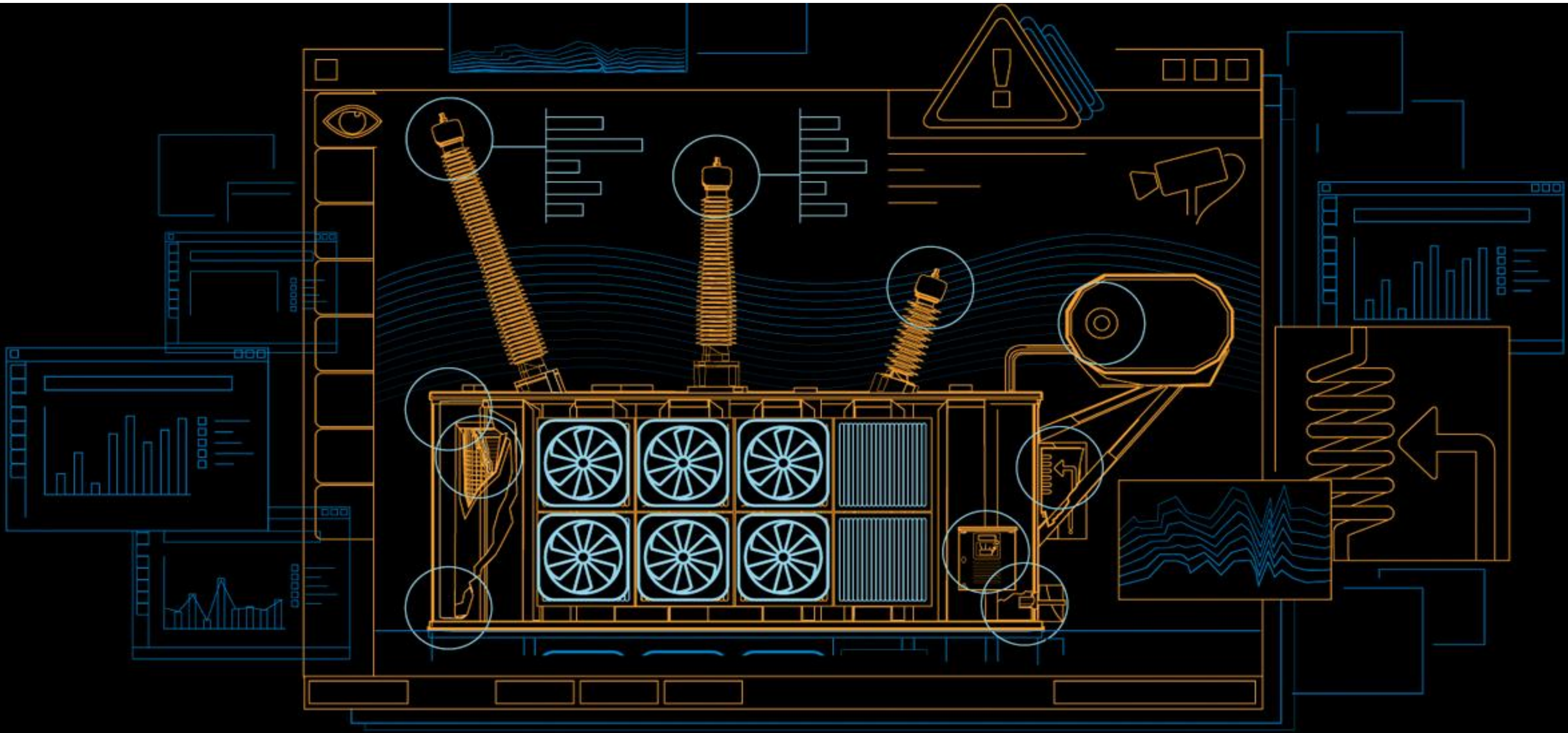
General Input Parameters

- X & Y for the XY-model
- Temperature (ºC)
- DFR measurements data

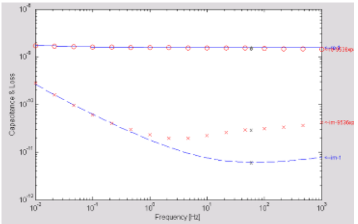
General Output Parameters
for the analysis tool

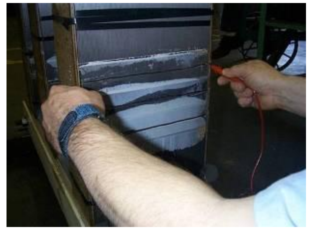
- % moisture,
- Oil conductivity

- Amount of contamiantion
- High Core ground resistance
-
-

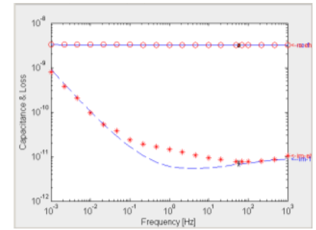


DFR- Cases



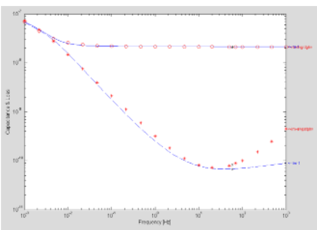


Preventive Auto issue

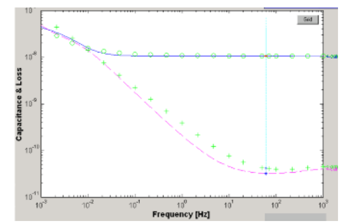


Contamination

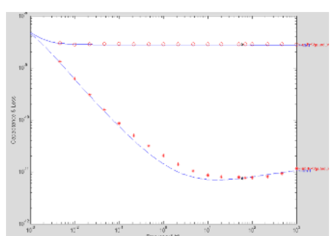
.DFR Cases



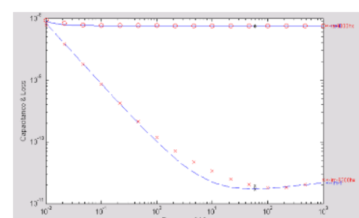
Resistor in the core ground



Pump Bearing Failure



Bushing Shield Problem



Carbon tracking

Case #1 – New Transformer

- HV kV: 220 kV (Y- connection)
- XV kV : 72.5 kV (Y- connection)
- TV kV: 12.0 kV (Δ- connection)
- Top rating MVA: 125 MVA at 50 Hz
- Cooling Class: ONAN/ONAF/ONAF

- Average oil temperature : 20 °C

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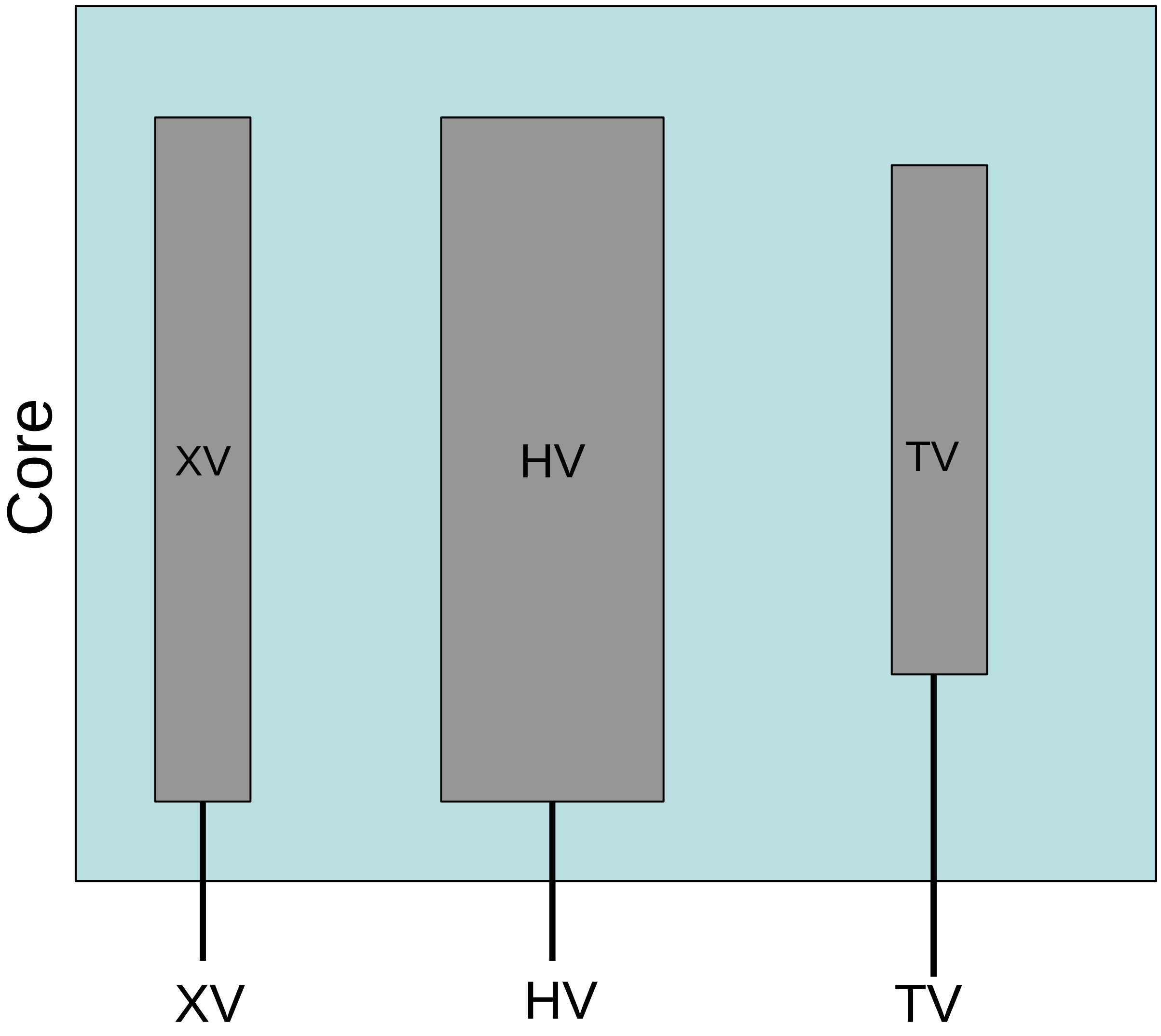
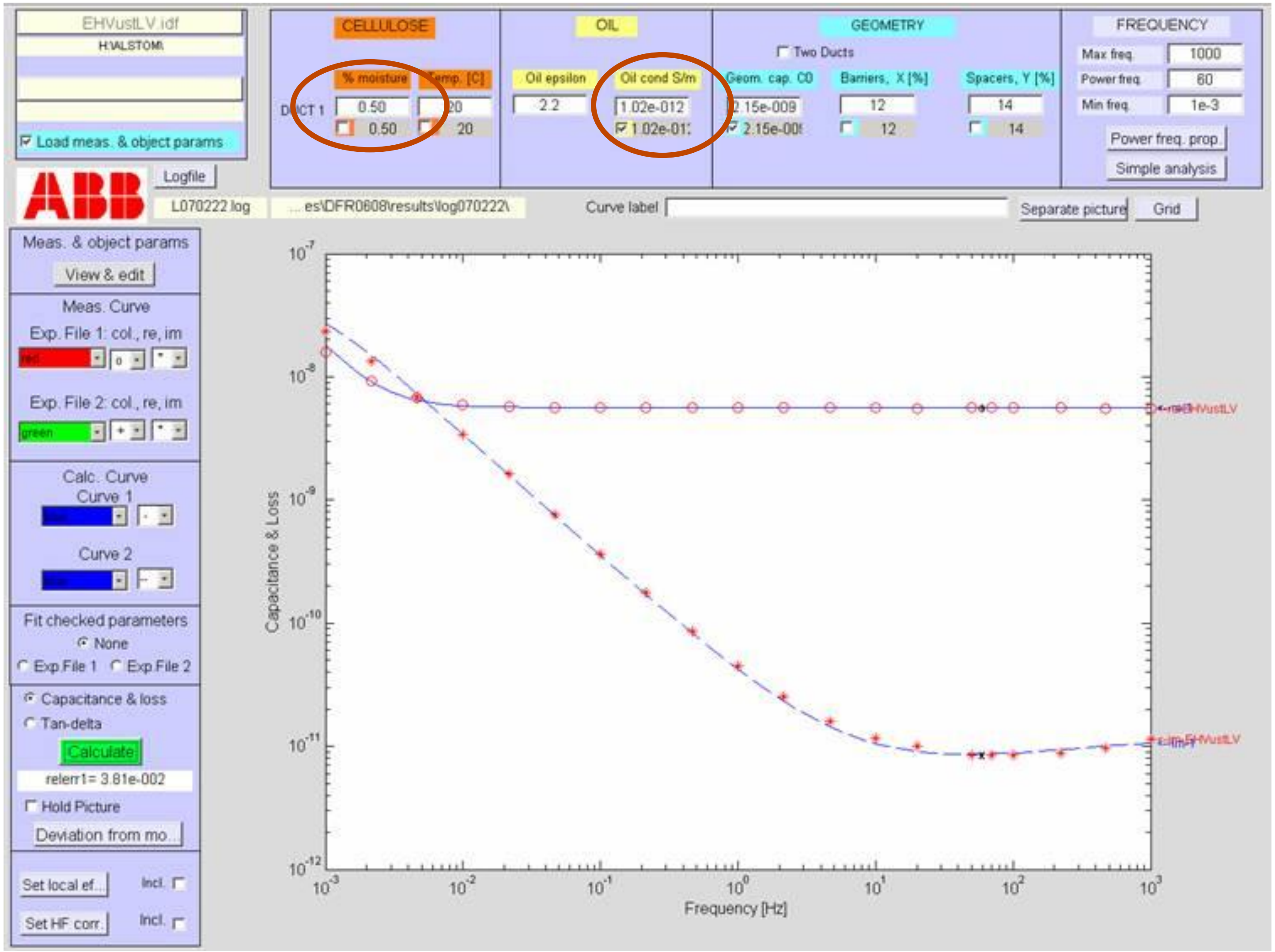
Case #1 – New Transformer – Test Configurations

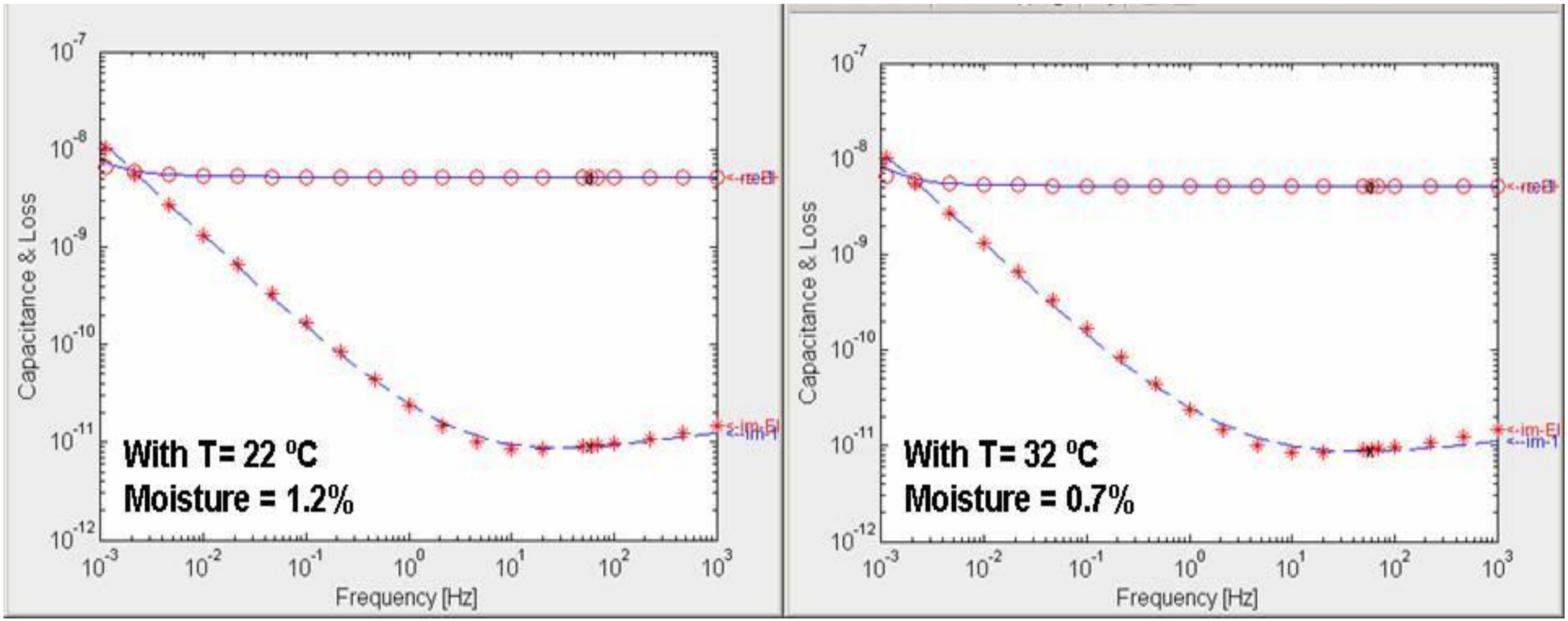


- HV UST XV
- HV UST TV
- XV to ground
- HV to ground
- TV to ground

Case #1 – New Transformer – HV UST XV

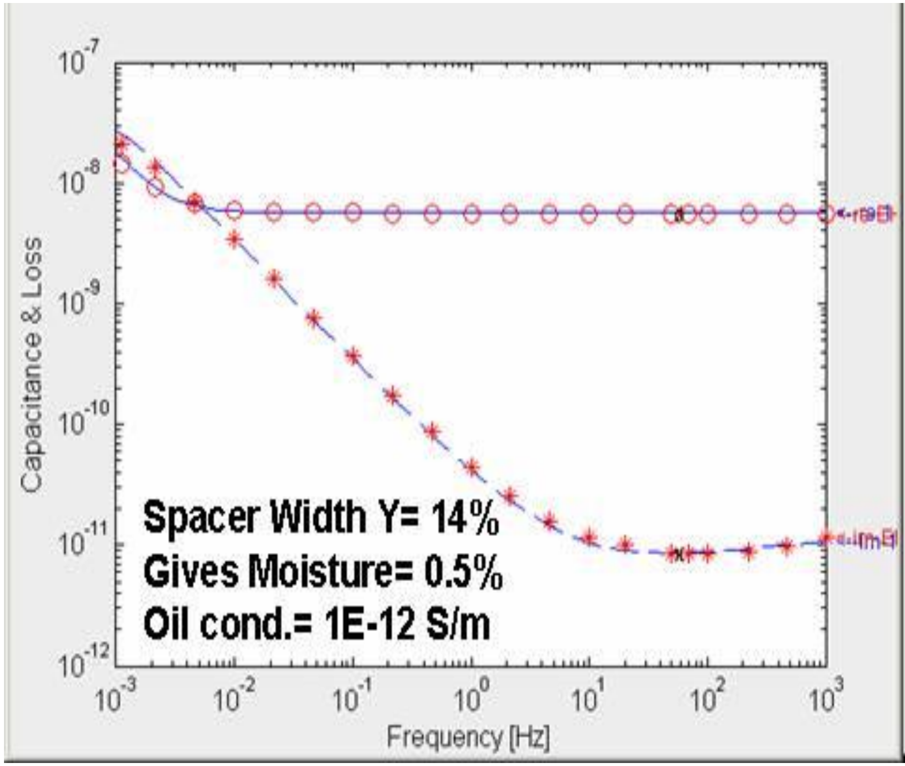


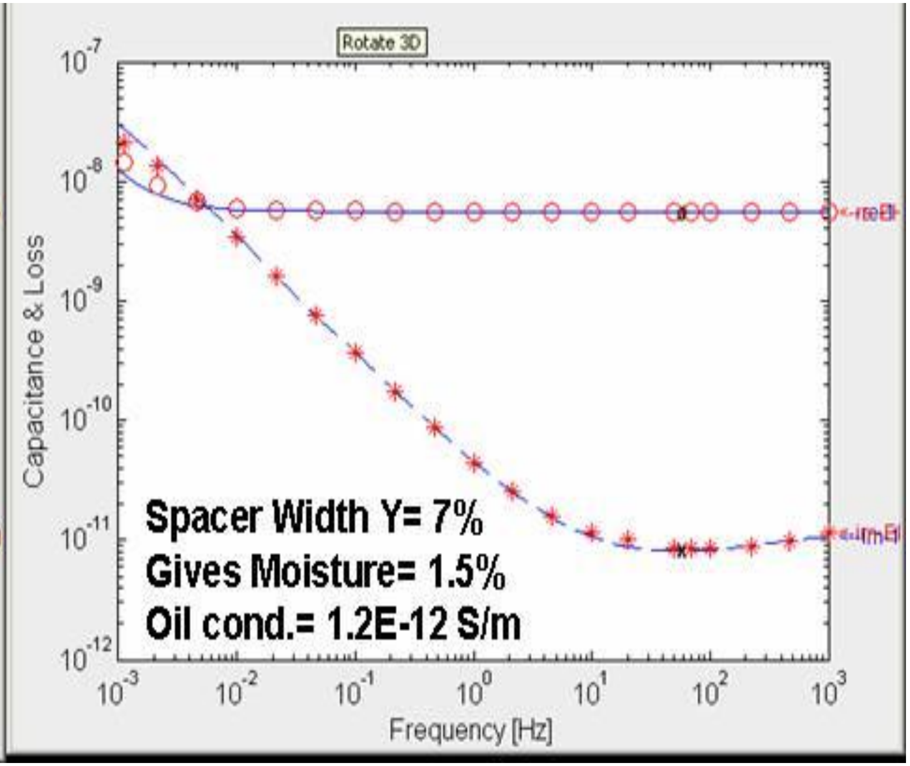
Case #1 – Temperature influence



An Error in Temperature can affect the estimate of moisture in the insulation

Case #1 – New Transformer – Geometrical prop.





An Error in %X and %Y can affect the accurcy of the results

-Case 2- Unit Gassing in the field!!

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Case #3: Unit Gassing in Operation

HV:	525 kV
XV:	15 kV
MVA:	236 MVA
Coolant:	Mineral oil

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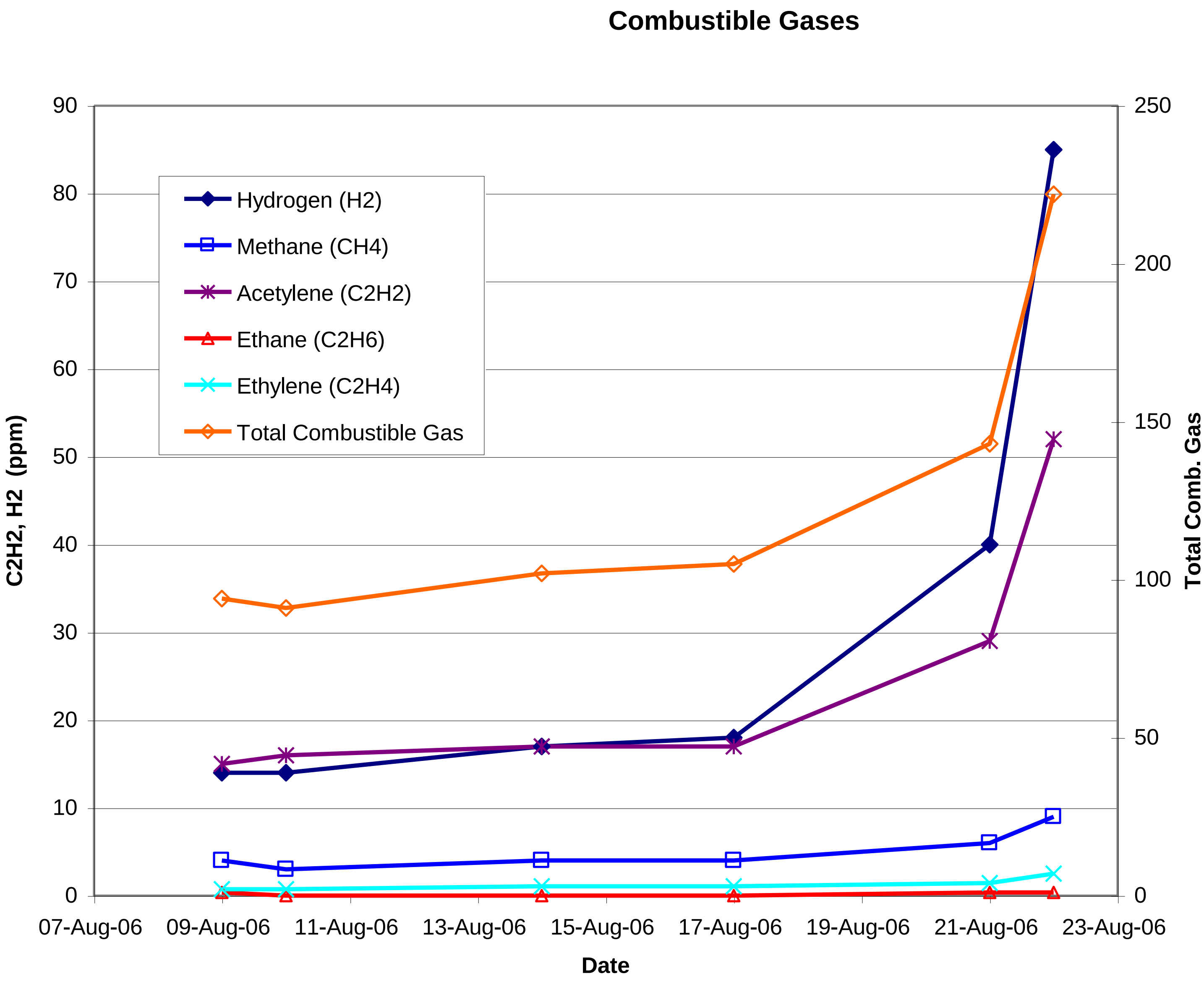
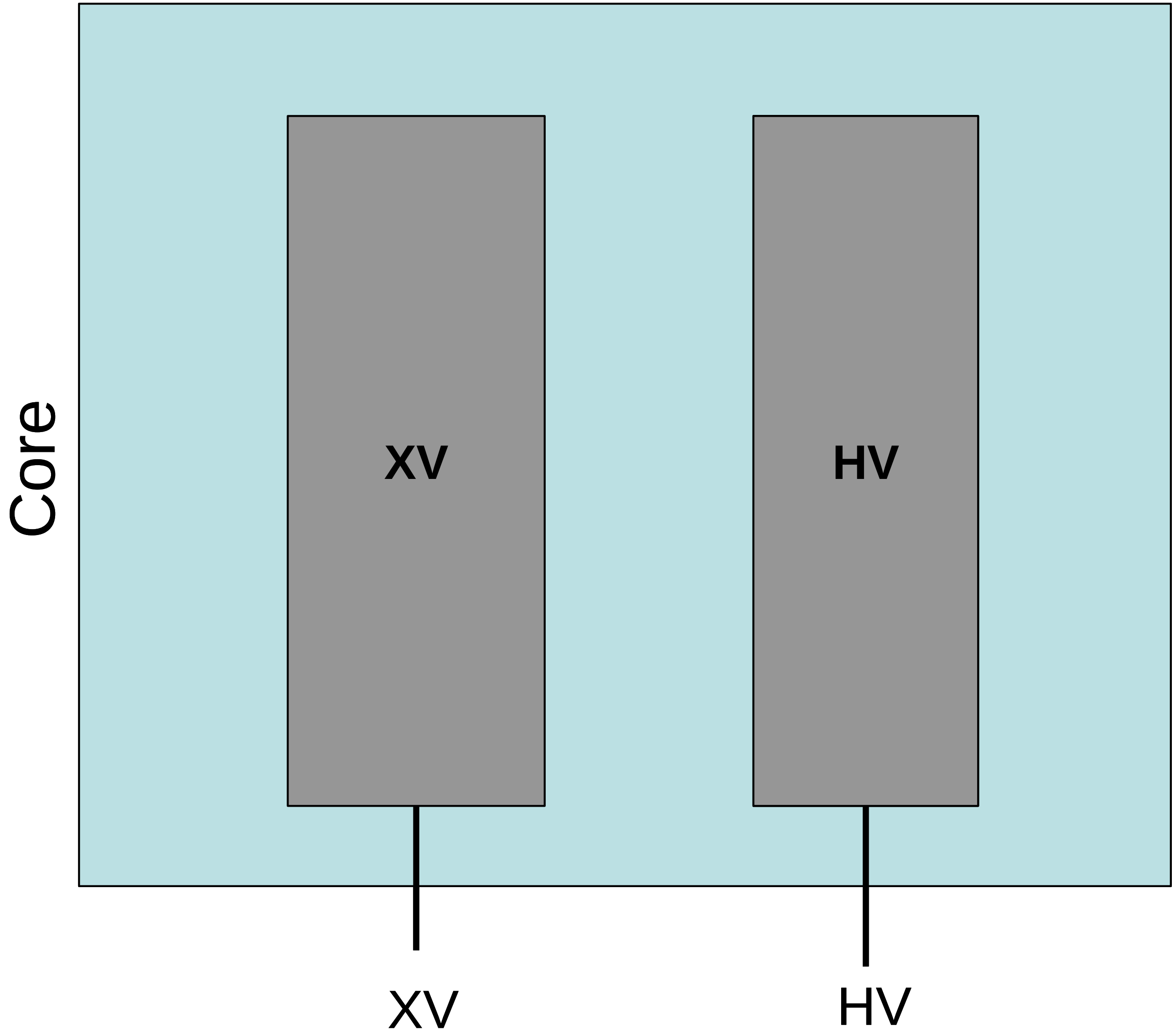
Case #3: Unit Gassing in Operation

- The unit was producing combustible gasses. No obvious fault could be detected.
- Customer performed routine tests, and all were normal
- DFR- measurements were done as a last resort to help locate the source so the unit could be repaired in the field without returning it to the factory.
- ABB performed H-ground, X-ground and H-X DFR tests

Case #3: Unit Gassing in Operation



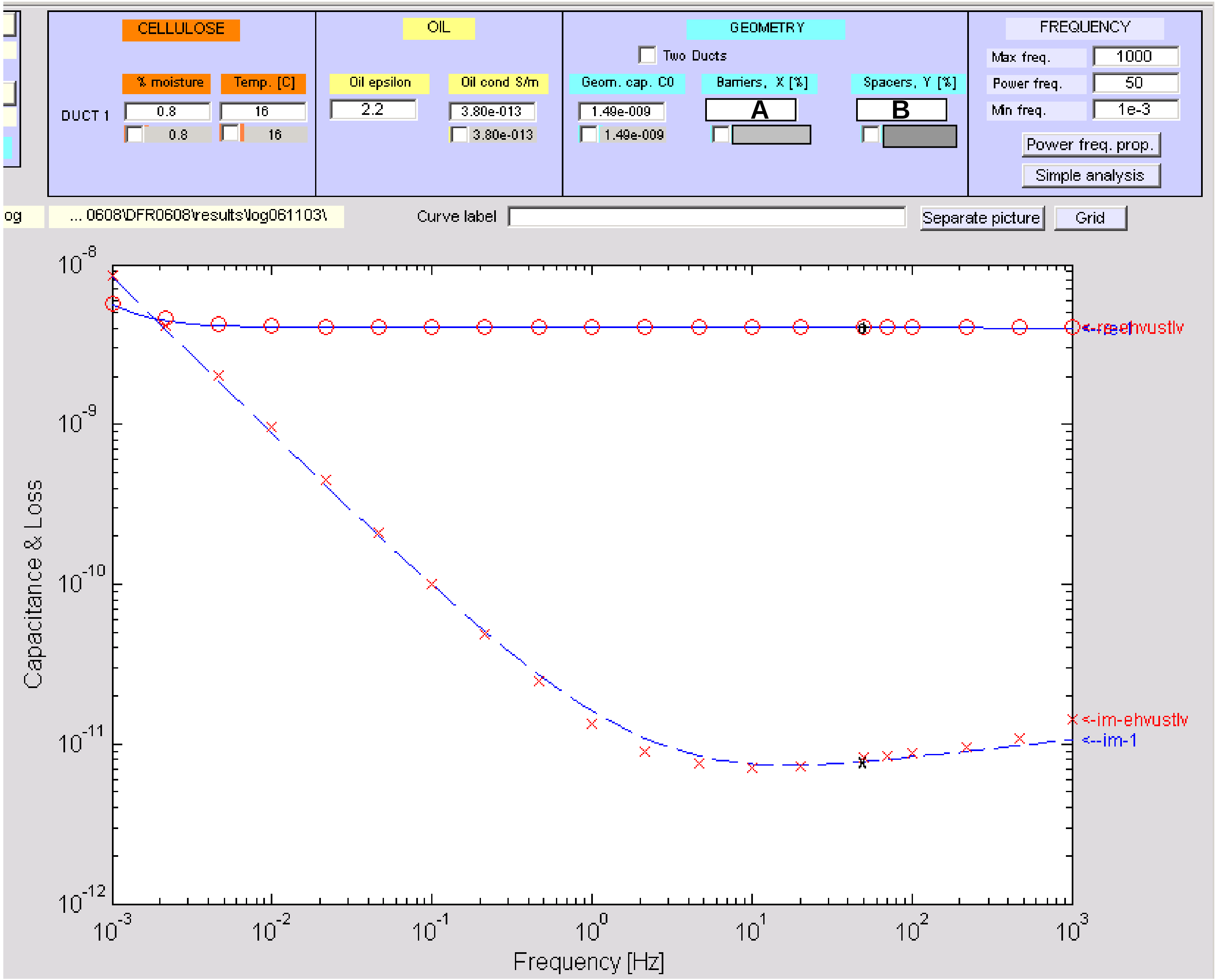
Case #3: Winding Configuration



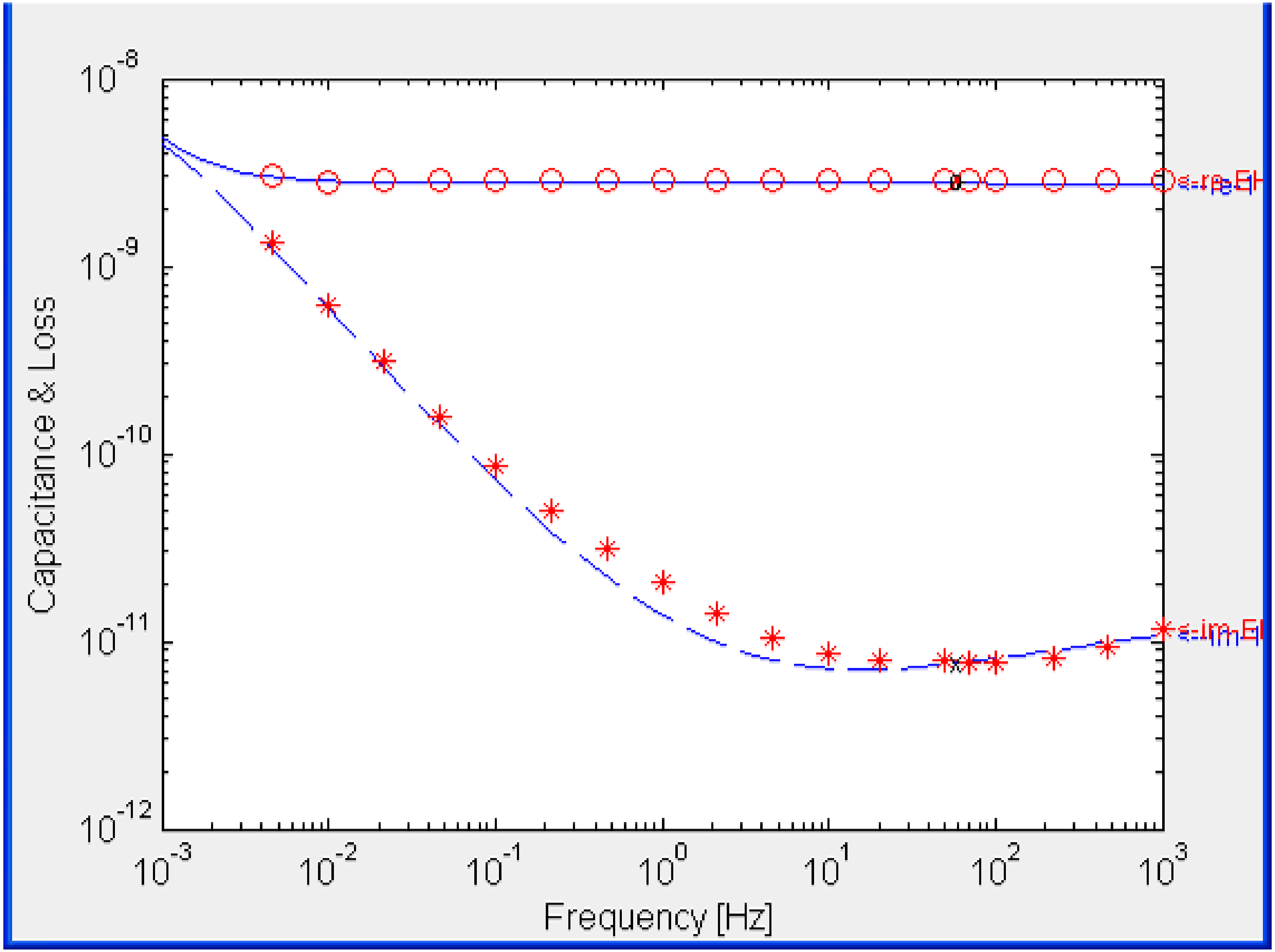
Test Set-up

-CHL
-CL
-CH

Case #3: Unit Gassing in Operation -HV to XV



Case #3: Unit Gassing in Operation -HV to Ground



Case #3: Unit Gassing in Operation

- 1. The tip up test on the HV indicated the potential of a loose connection

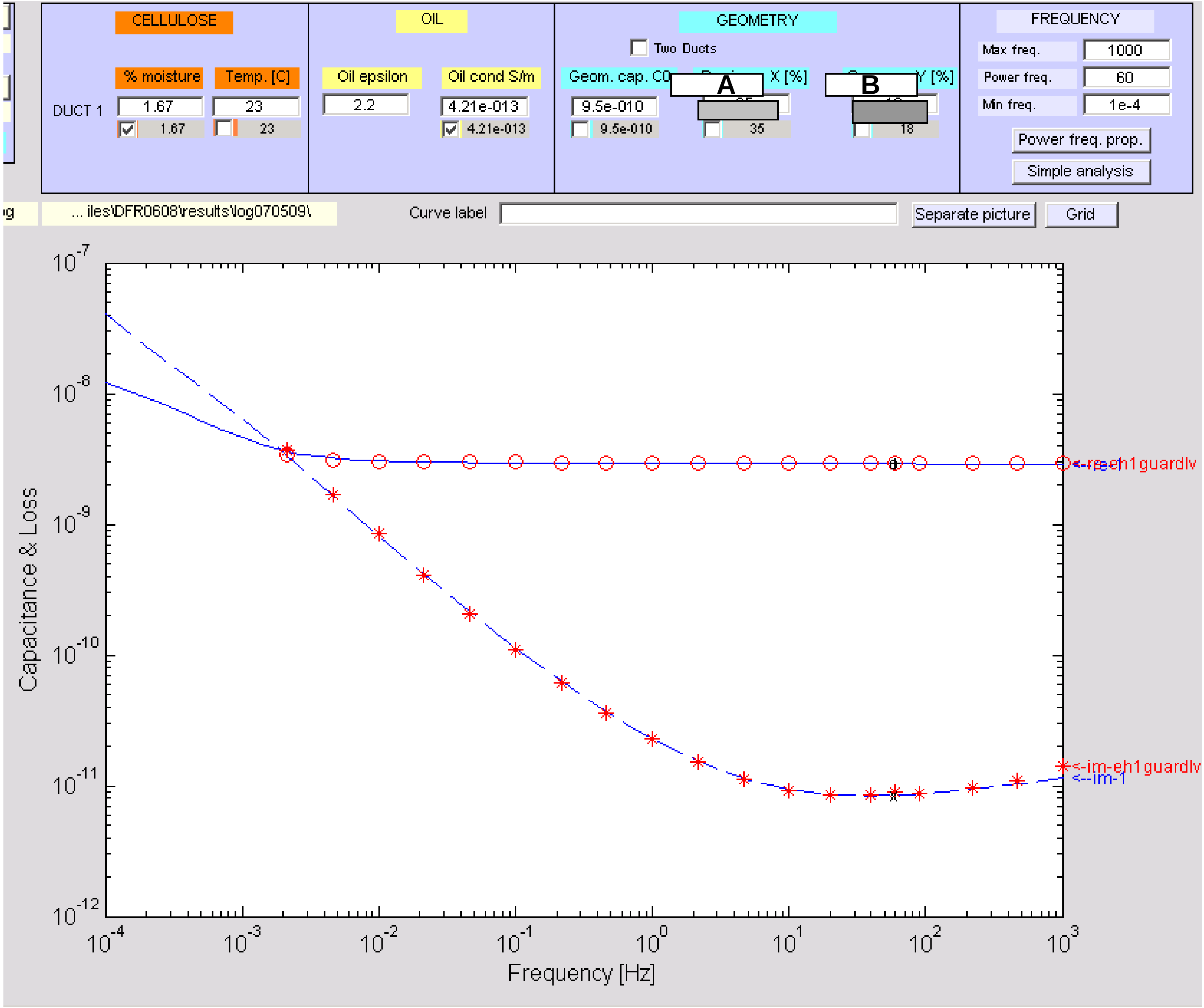
- 2. The DFR test on the HV indicated the presence of a parallel capacitance resistance circuit

Case #3: Unit Gassing in Operation

- The inspection of the shielding tube showed that the sleeve (also called union coupling) that connects the vertical tube with the horizontal Y tubes at the HV windings connection was loose and did not make proper contact.

  There had been arcing at the sleeve and also between the cable inside the shielding tube and the tube.

Case: Unit Gassing in Operation - After Repair



Summary

- Determine moisture of the insulation

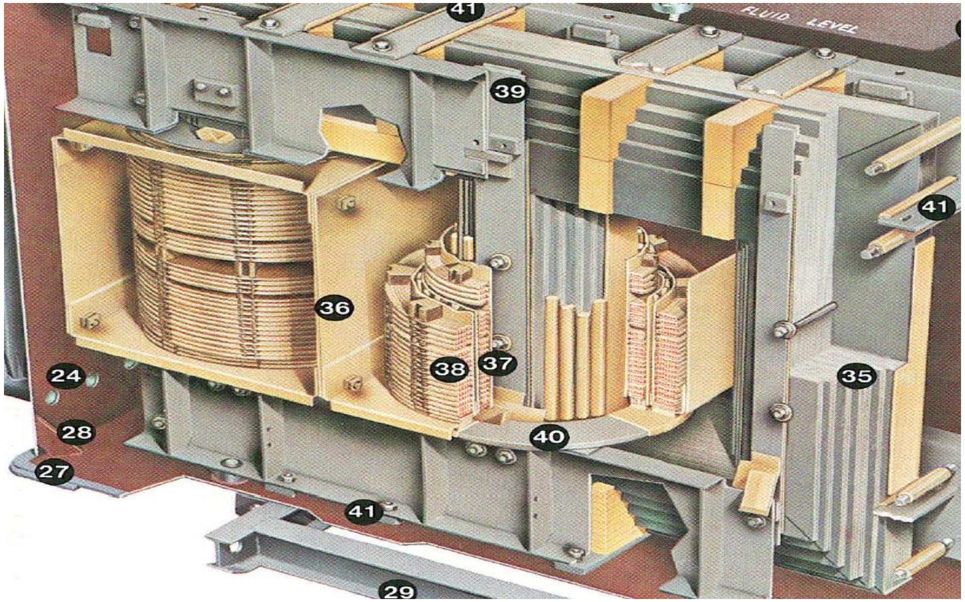
- Abnormal DGA

- Just want to know the condition of your transformer

- Suspect contamination or core issues

.DFR!

-SFRA- What is that ?



ABB

What is SFRA?

SFRA means: Sweep Frequency Response Analysis

SFRA is: "An off-line, non-destructive diagnostic technique"

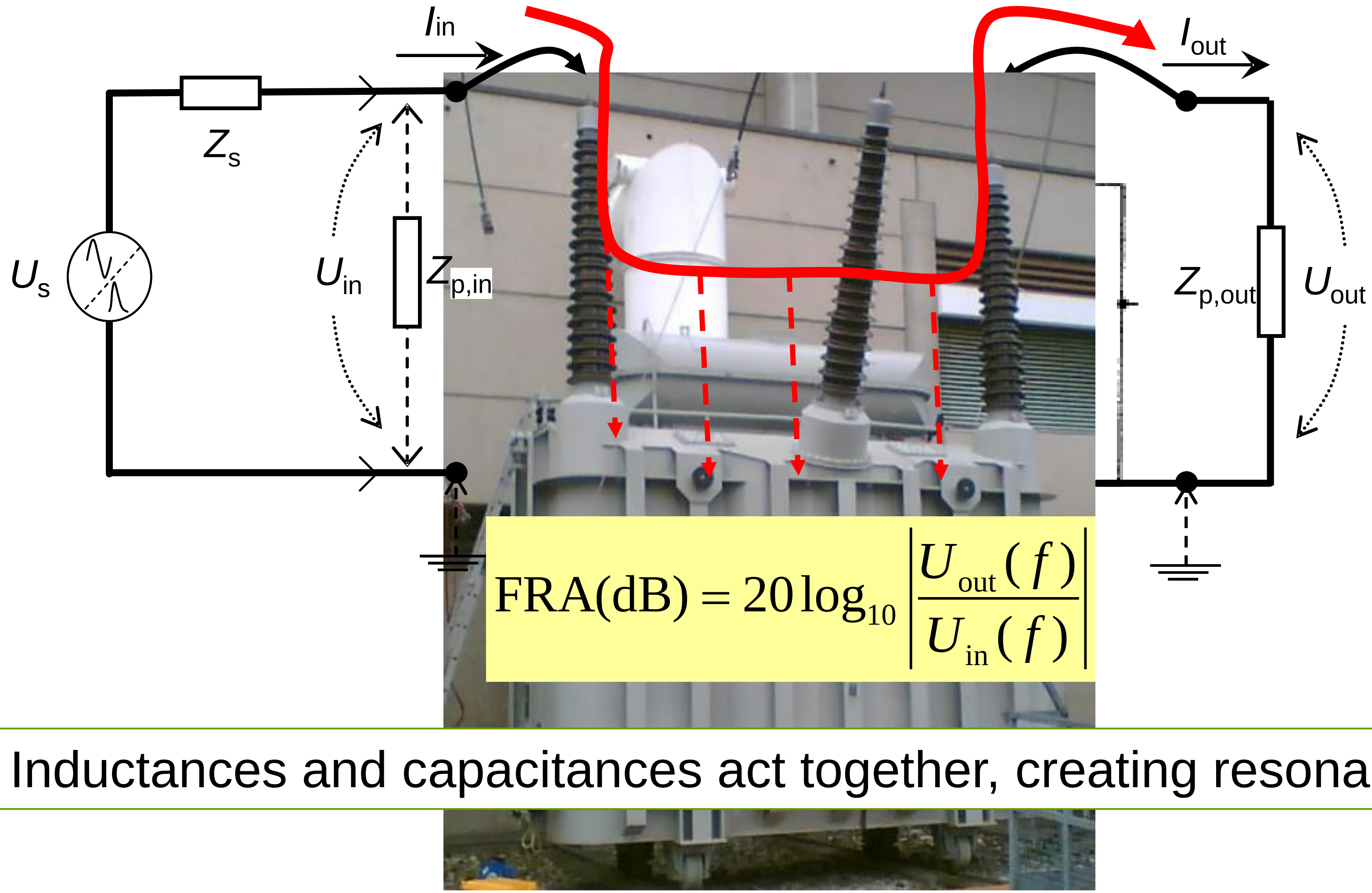
SFRA is: Measurement of electrical response
(from 10 Hz to 2 MHz or more).

SFRA is: Comparative method (two spectra are compared)

SFRA shows: Spectrum changes ⇔ mechanical
defo

SFRA can detect mechanical problems **without** opening the transformer.

What is FRA? **(principle of FRA)**



$$\mathrm{FRA(dB)} = 20\log_{10}\left|\frac{U_{out}(f)}{U_{in}(f)}\right|$$

Inductances and capacitances act together, creating resonances

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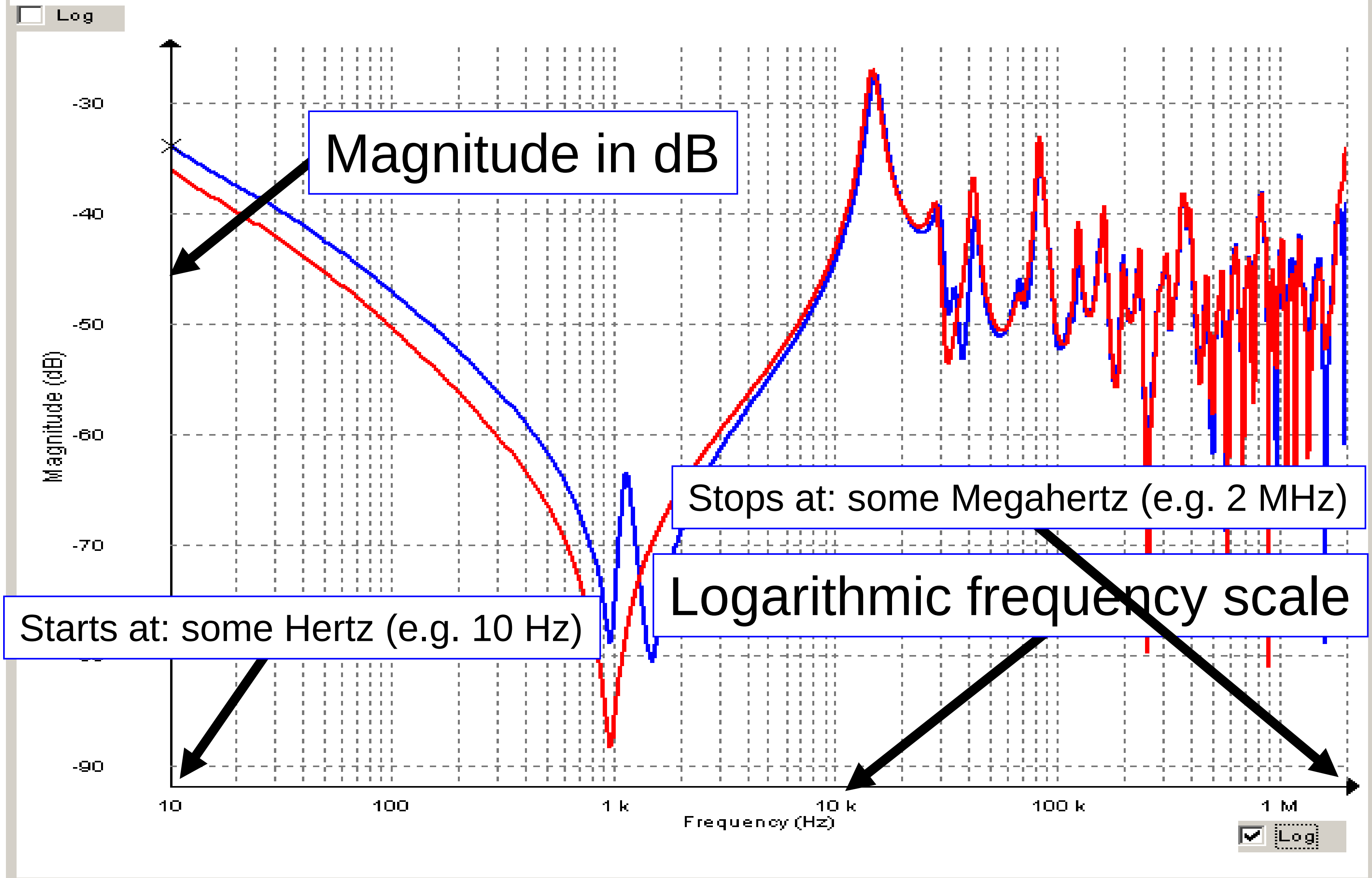
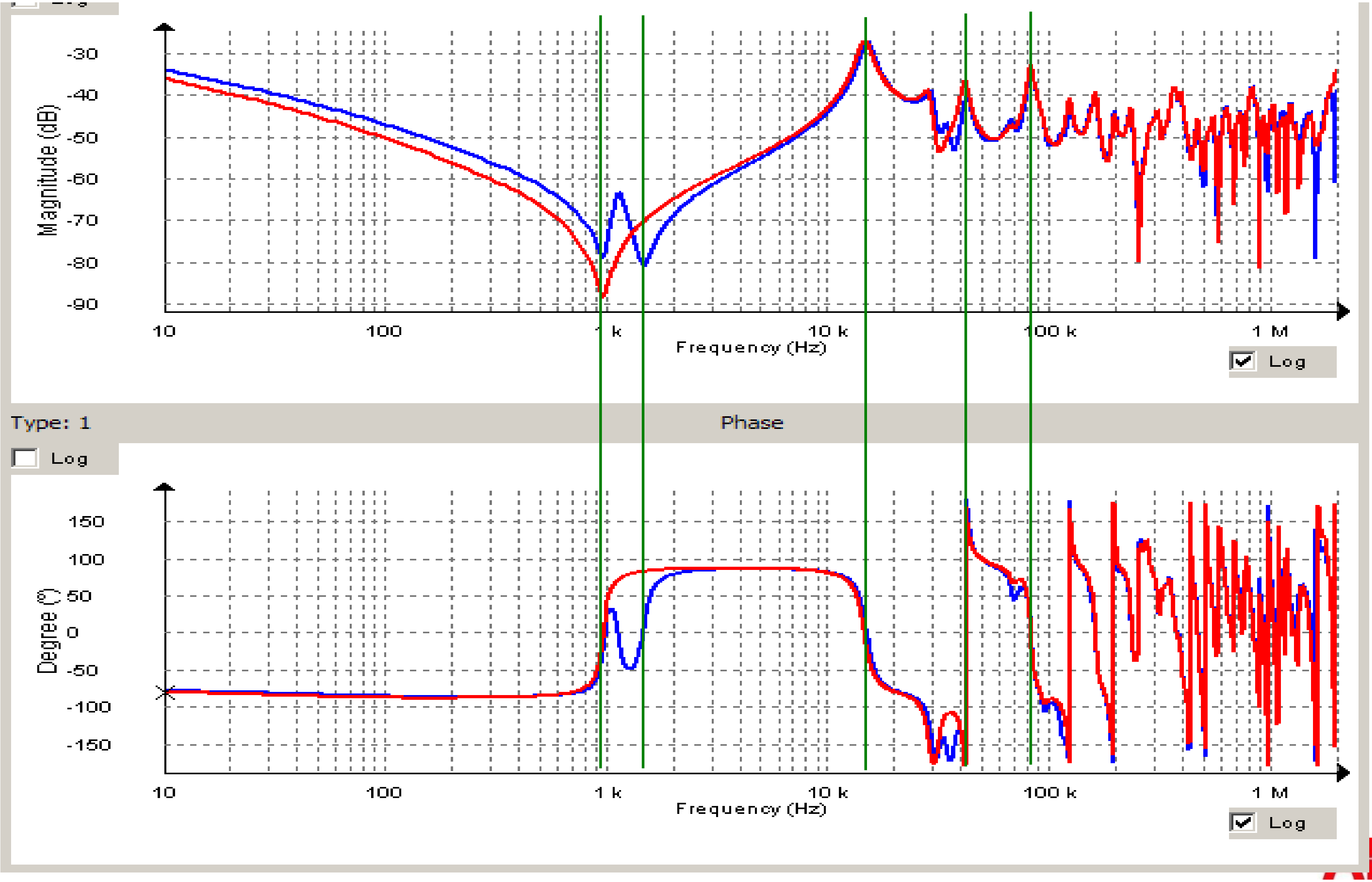
What is FRA ? **What the responses look like?**

Typical FRA spectrum (logarithmic scales):



What do we see in an FRA spectrum?

Typical FRA spectrum, larger transformer (HV self-winding, open circuit)



What is FRA ?

What we can detect today using FRA?

Changes in FRA response reveal a wide range of fault types:

- axial winding collapse
- clamping failure
- hoop buckling
- shorted turns
- bad core grounding
- open, broken, grounded, … tertiary winding
- bad contact (?)
- …

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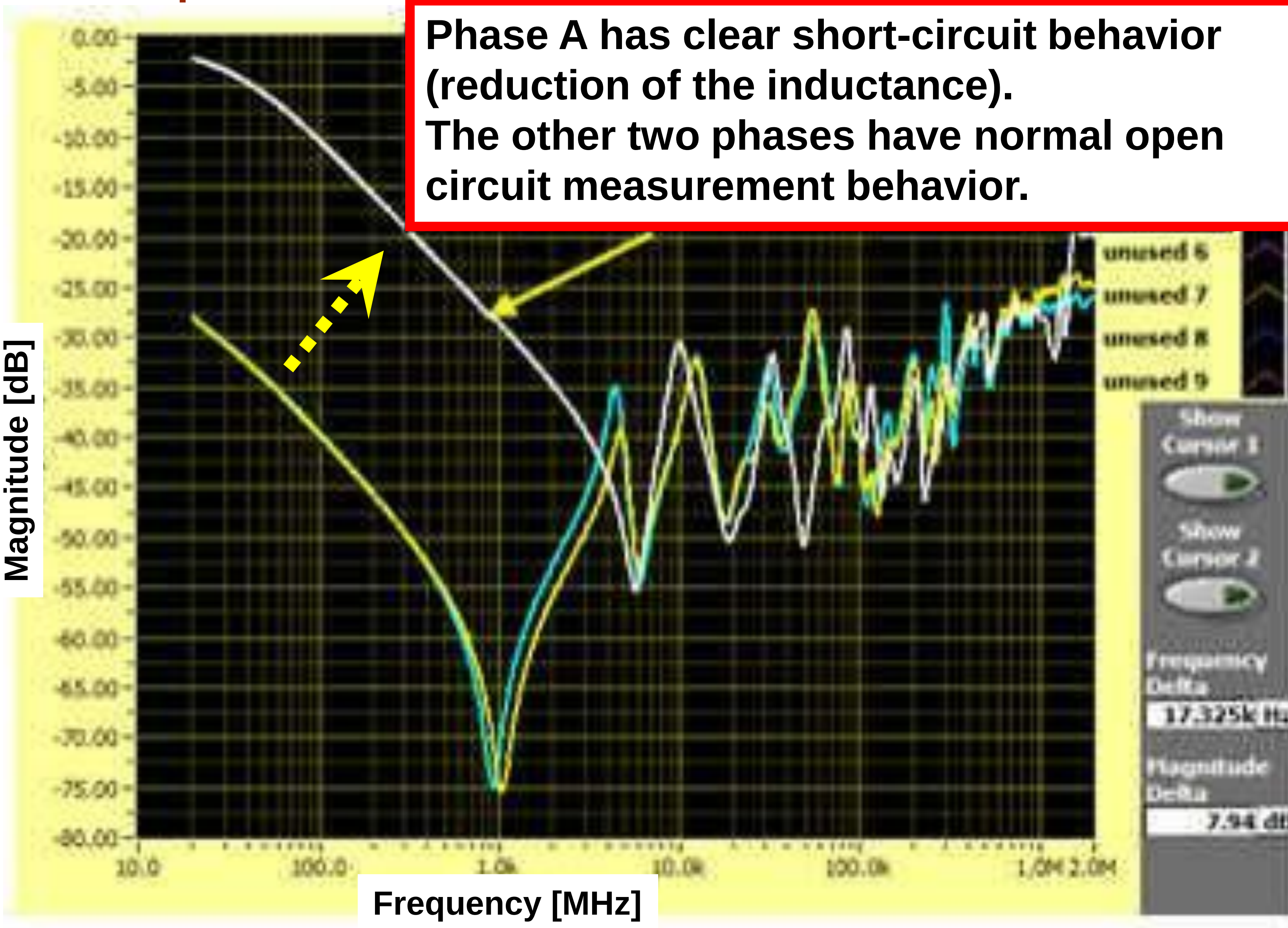
Two Examples

1) Short-circuited turns

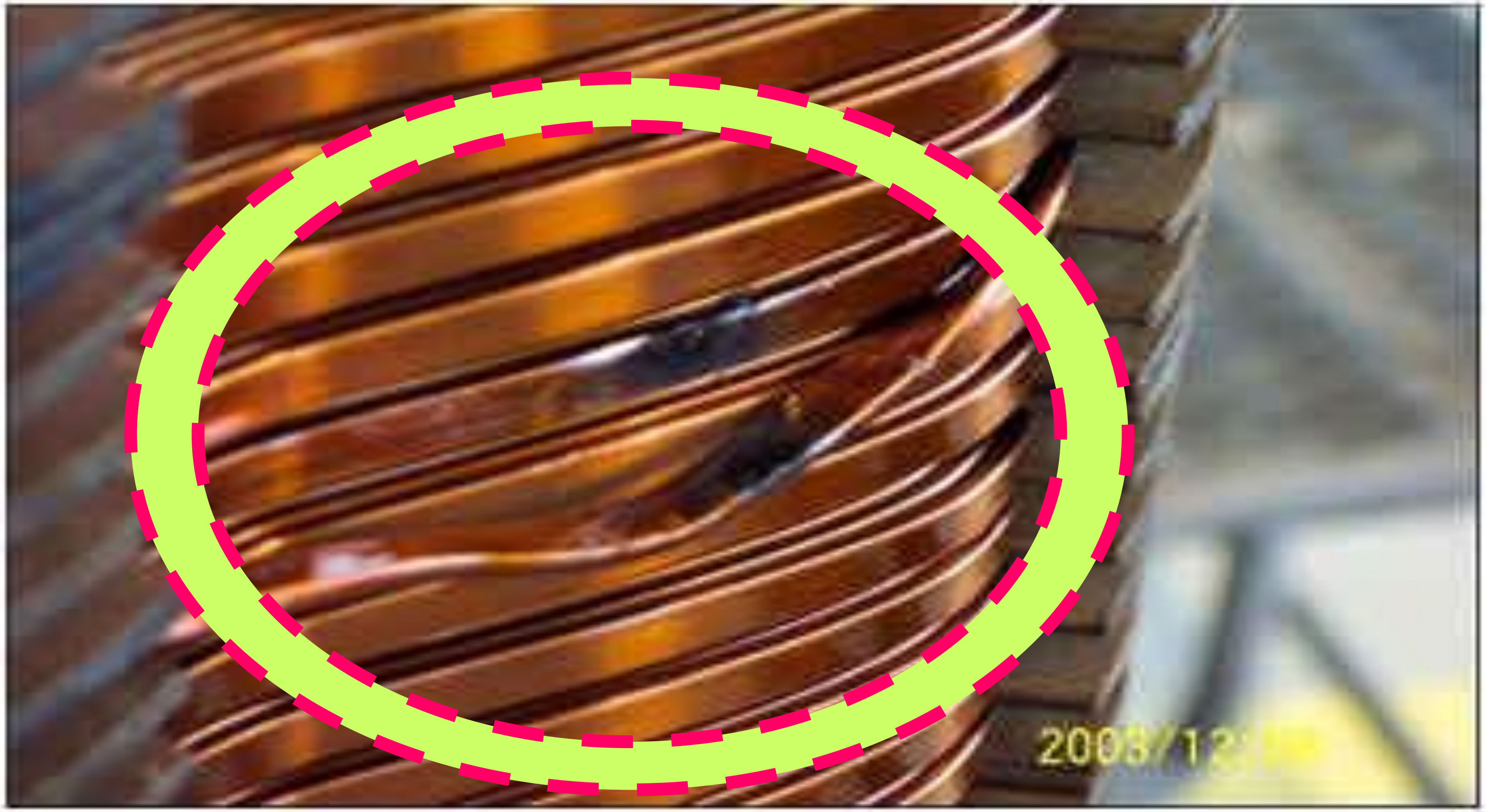
2) Hoop Buckling

Example: Short-circuited turns

Phase A has clear short-circuit behavior (reduction of the inductance).
The other two phases have normal open circuit measurement behavior.



Example: Short-circuited turns



Example: Hoop Buckling

Hoop buckling means:

- Internal winding (usually LV) collapses

- Reason:
  - large (compressive) radial forces on the winding during a short-circuit fault.

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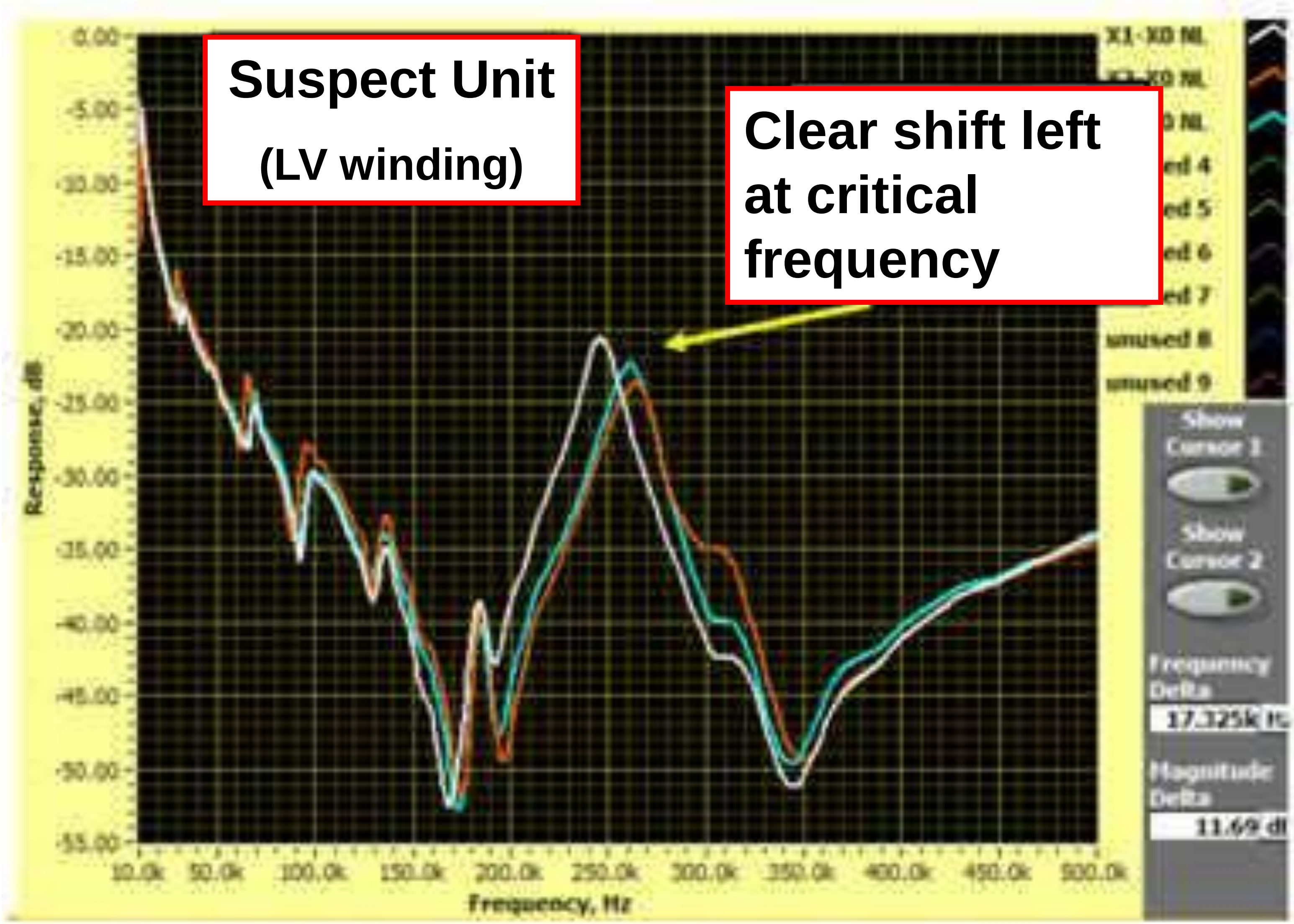
Example: Hoop Buckling



Example: Hoop Buckling

Clear deformation in winding

When should we perform FRA?

When should we perform FRA?

- After manufacturing
  - Fingerprint measurement
  - Create first reference

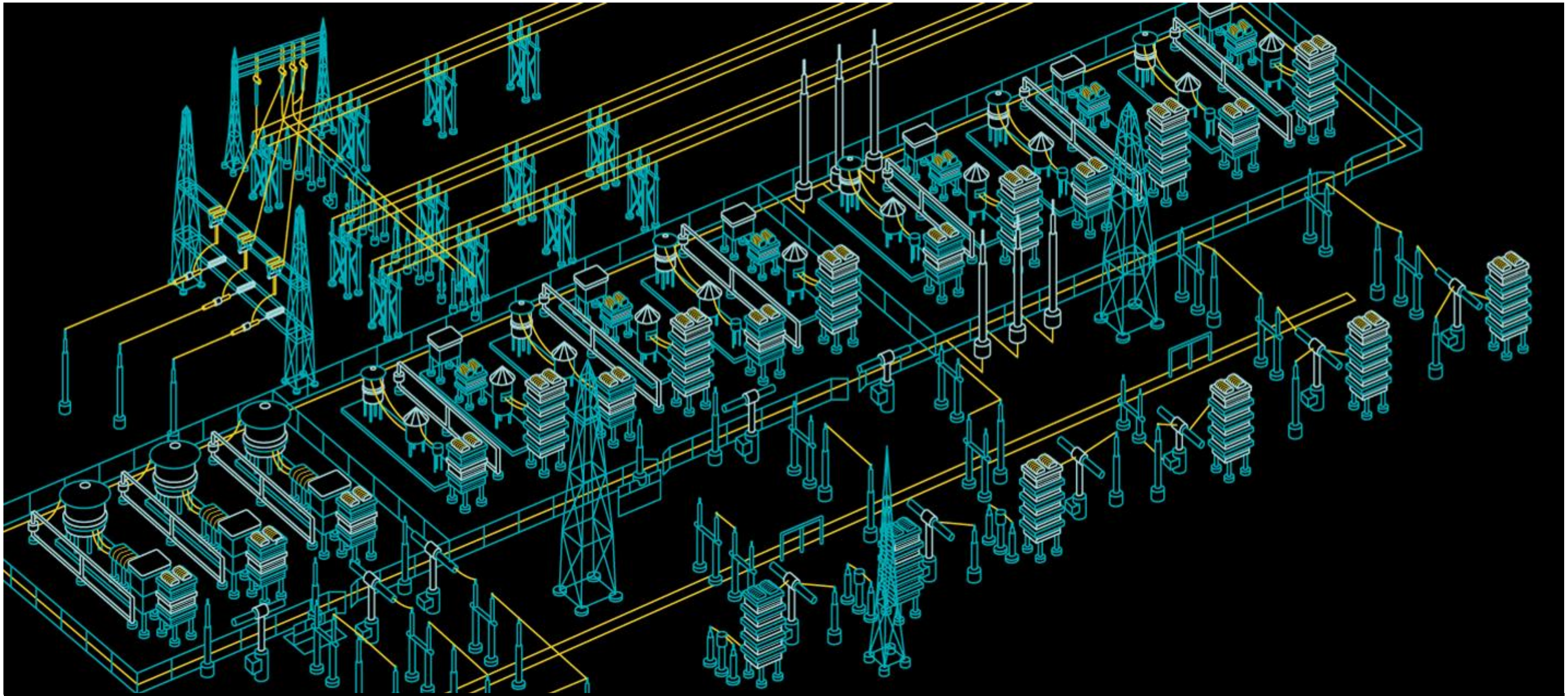
- As part of a routine diagnostic protocol
  - To check for changes during service time

- After installation or relocation
  - To check for transformer integrity

When should we perform FRA?

In case of troubles:

- After a major change in on-line diagnostic condition
  - After a transformer alarm
  - After a significant through-fault event
- After external failures compromising the transformer condition (short circuits, close lightning impact, ...)
- To compare with a sister unit in troubles



SFRA-Measurements

ABB

What is FRA ? **What the devices look like?**

FRAX-101 produced by Megger Group

ABB-Switzerland is working with this device

M5300 produced by Doble

ABB-USA is working with this device

FRAnalyzer produced by Omicron

ABB-Germany is working with this device

Agilent (HP) – Network analyzer

General device – Not dedicated to FRA

Traftek produced by B&C Diagnostics

FRA-100 produced by Phenix

FRAmit produced by Utility & Industrial Products, Inc

FRA 5310 produced by Haefely

SoFT produced by ABB

Complete transformer fingerprinting

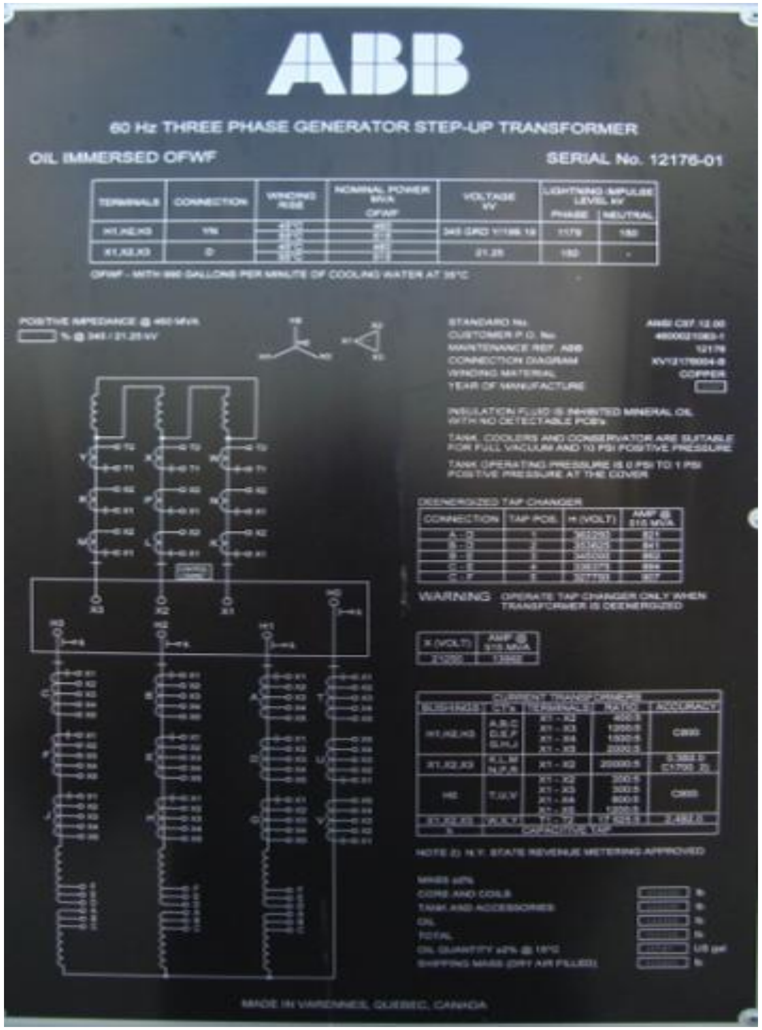
Measurement procedure (do not forget!!!)

Take Pictures:

-Name plate

-Transformer

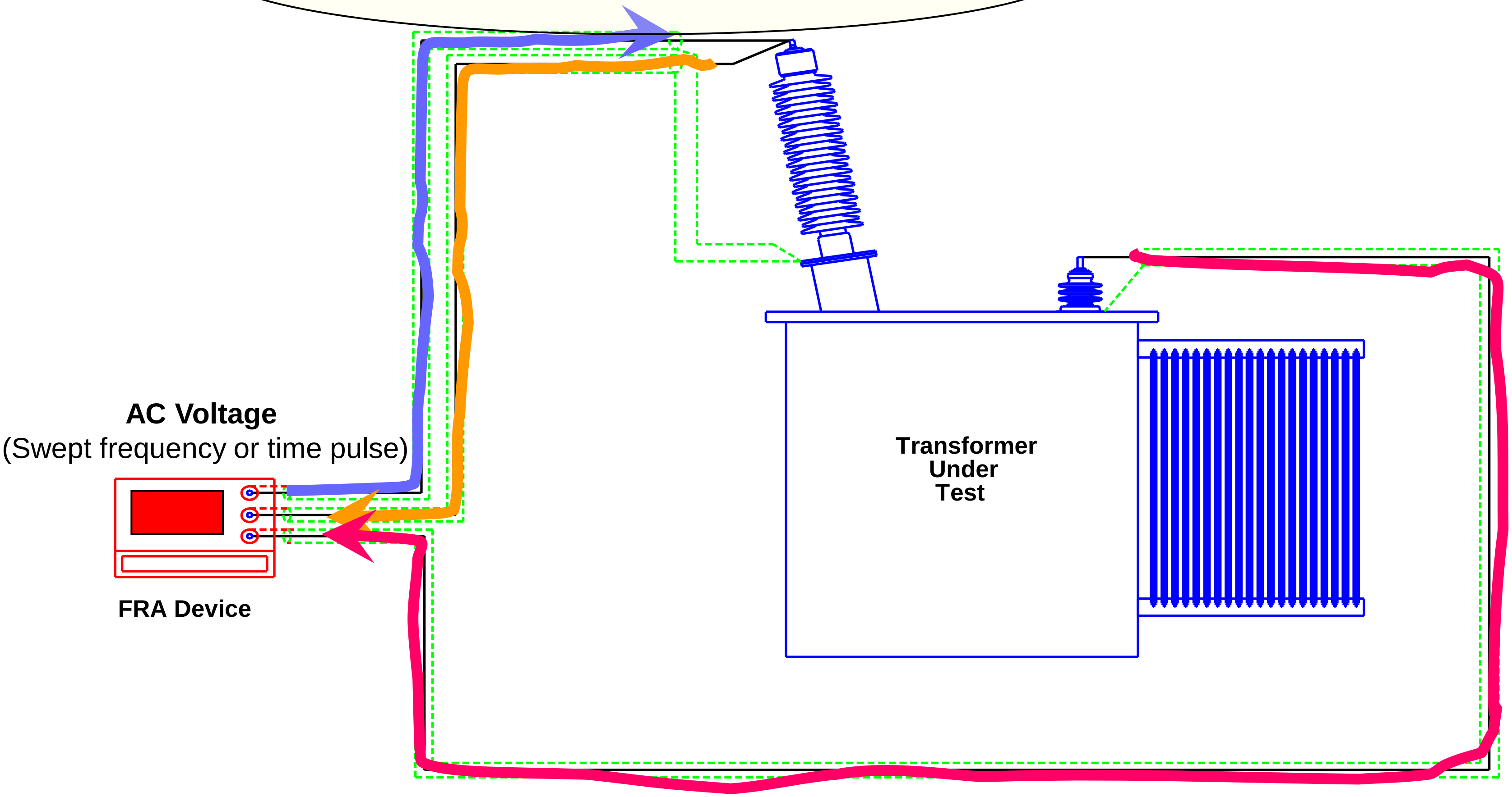
-Connections



Measurement procedure (setup installation)

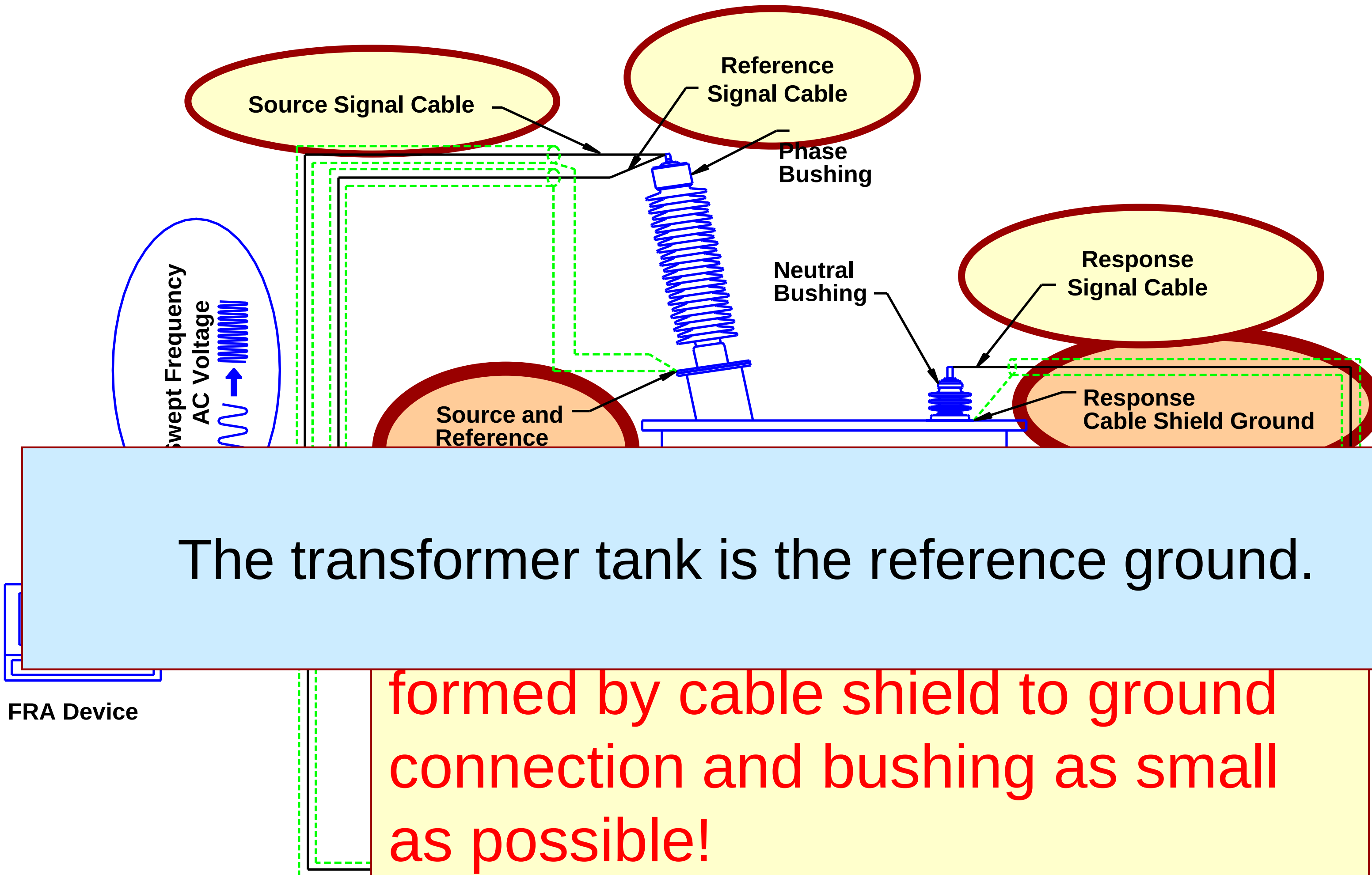
Typical test connection (three key elements):

- The unit under test (Transformer)
- The FRA device (Many possibilities)
- The cabling (three coaxial cables)



Measurement procedure (setup installation)

Typical test connection (Avoid loops in GND connections)



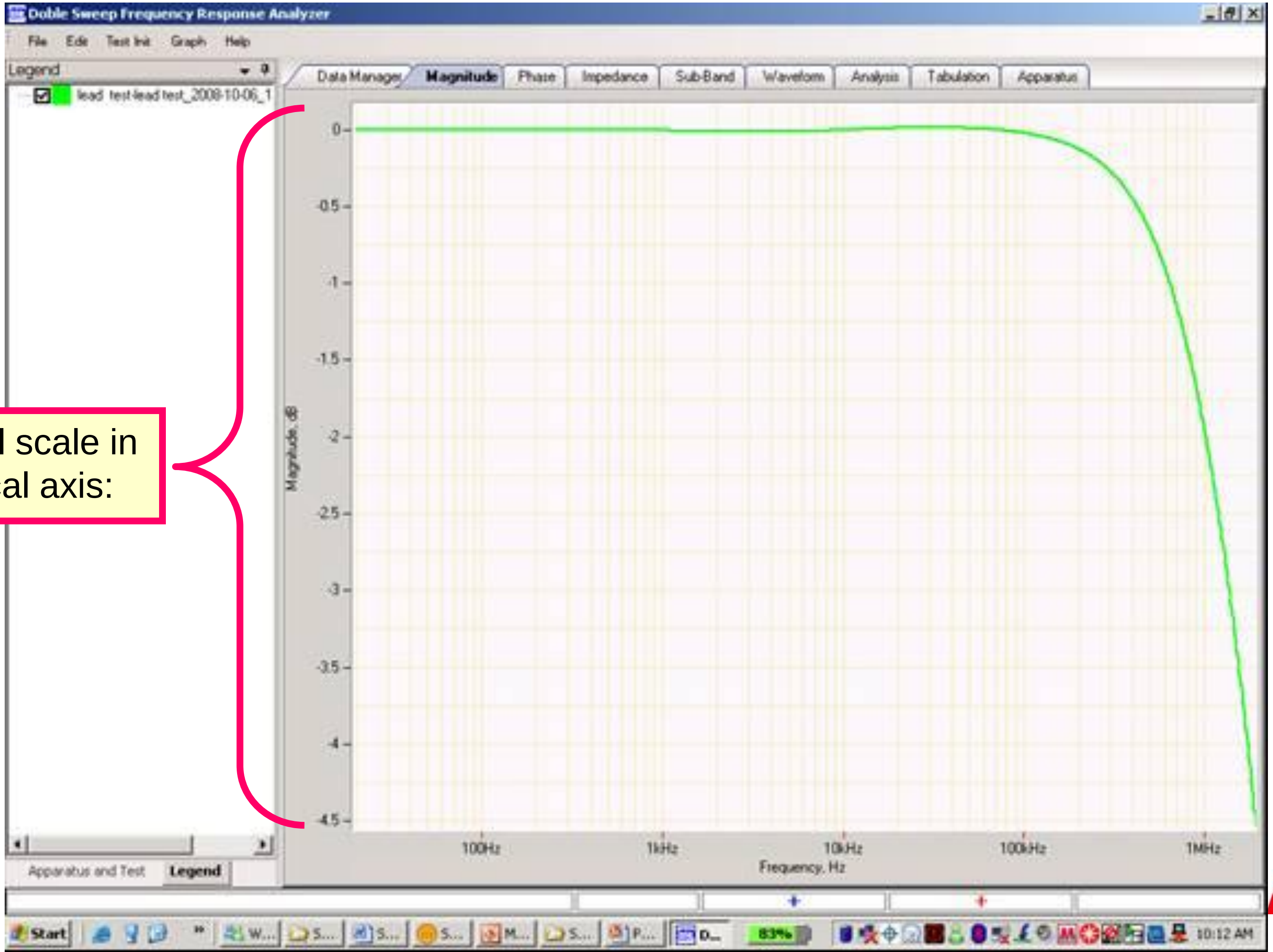
The transformer tank is the reference ground.

formed by cable shield to ground connection and bushing as small as possible!

Measurement procedure (before to start)

Check your leads

$$\mathrm{FRA(dB)} = 20\log_{10}\left|\frac{U_{out}(f)}{U_{in}(f)}\right|$$



Small scale in vertical axis:

Measurement procedure (list of test)

Which measurements do we want to do?

Test type	Test N°	3-phases Delta-Wye	3-phases Wye-Delta	3-phases Delta-Delta	3-phases Wye-Wye
HV self-winding (open circuit) Terminals floating	1	H1-H2	H1-H0	H1-H2	H1-H0
	2	H2-H3	H2-H0	H2-H3	H2-H0
	3	[illegible]	[illegible]	[illegible]	[illegible]
LV self-winding (open circuit) Terminals floating	4	[illegible]	[illegible]	[illegible]	[illegible]
	5	X2-X0	X2-X3	X2-X3	X2-X0
	6	X3-X0	X3-X1	X3-X1	X3-X0
HV self-winding (short circuit) Short [X1, X2, X3]*	7	H1-H2	H1-H0	H1-H2	H1-H0
	8	[illegible]	[illegible]	[illegible]	[illegible]
	9	[illegible]	[illegible]	[illegible]	[illegible]
LV self-winding (short circuit) Short [H1, H2, H3]*	10	[illegible]	[illegible]	[illegible]	[illegible]
	11	X2-X0	X2-X3	X2-X3	X2-X0
	12	X3-X0	X3-X1	X3-X1	X3-X0
Capacitive Inter-Winding Terminals floating	[illegible]	[illegible]			
Inductive Inter-winding Ground [H-, X-]	16	H1-X1, ground [H2, H3, X2, X3]			

(A) Open circuit: (HV and LV windings)

(B) Short circuit: (HV and LV windings)

(C) Capacitive inter-winding: (Between HV and LV windings)

(D) Inductive inter-winding : (Between HV and LV windings)

ABB

Measurement procedure

Why open circuit measurements?

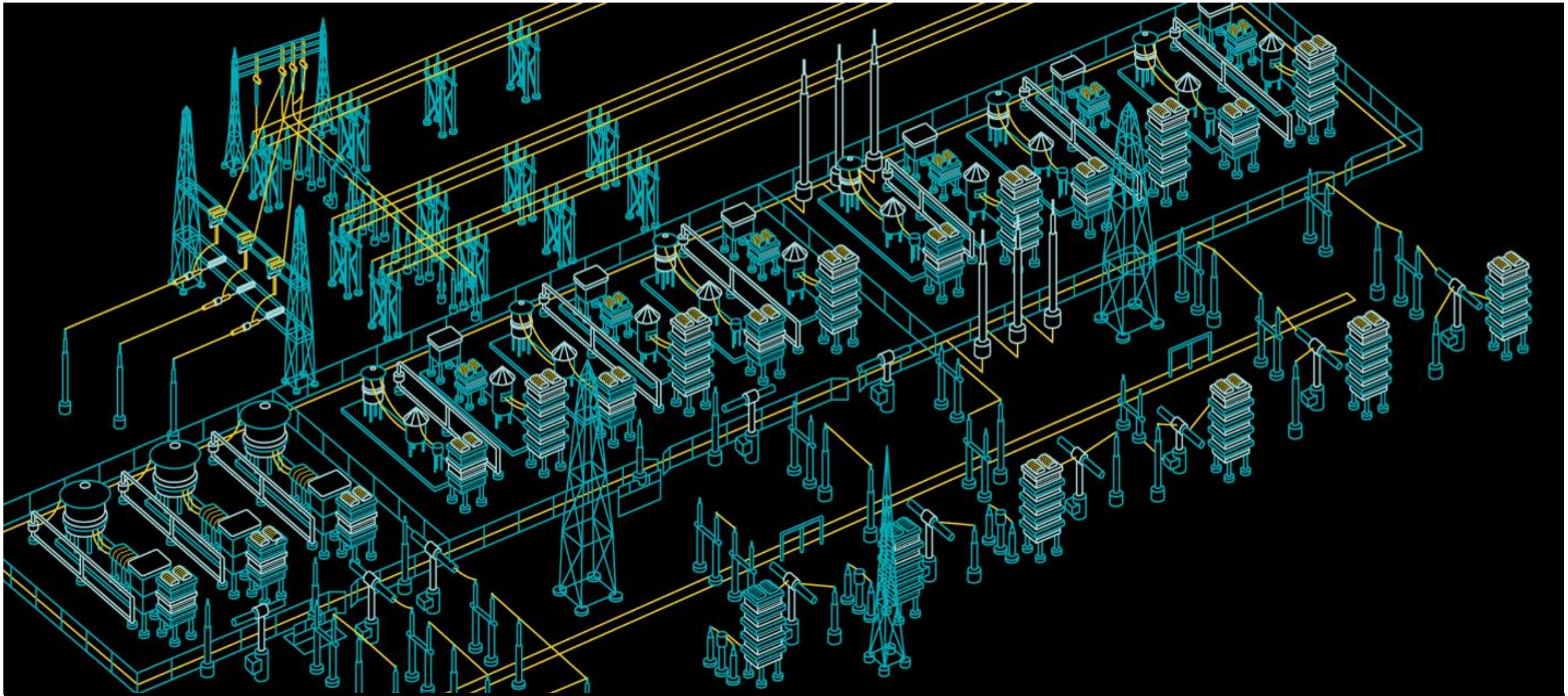
We can see:

- Winding short-circuits
- Broken delta winding
- Core related problems (circulating currents, bad joints, …)

Why short circuit measurements?

- Precise short-circuit reactance measurement
  $\rightarrow$ close agreement between phases (0.1 dB rule)
- Very good reproducibility within the whole frequency range
- Not affected by core magnetization

ABB



SFRA-
Analysis

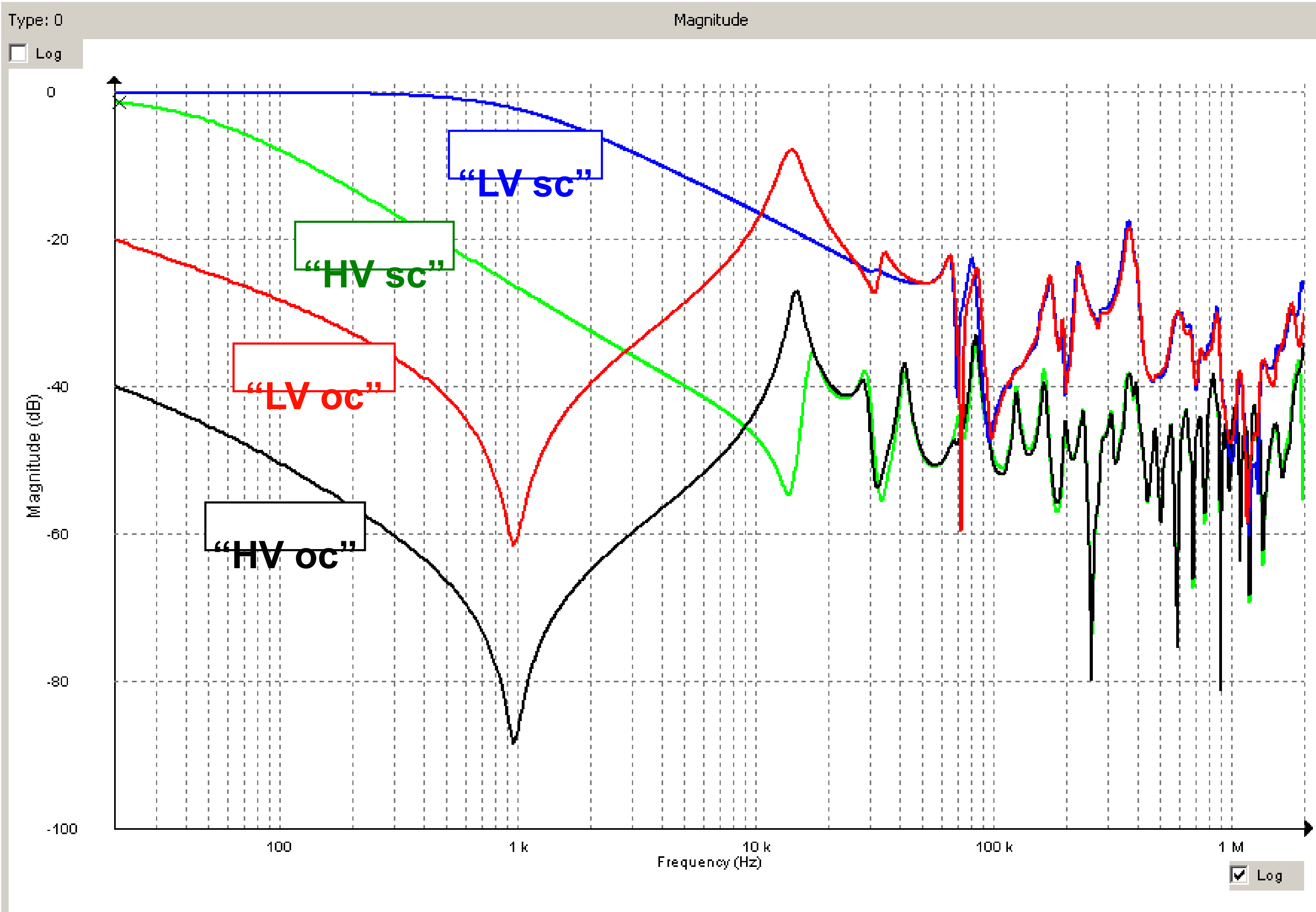
Analysis:

-Baseline Measurements

-Sister units

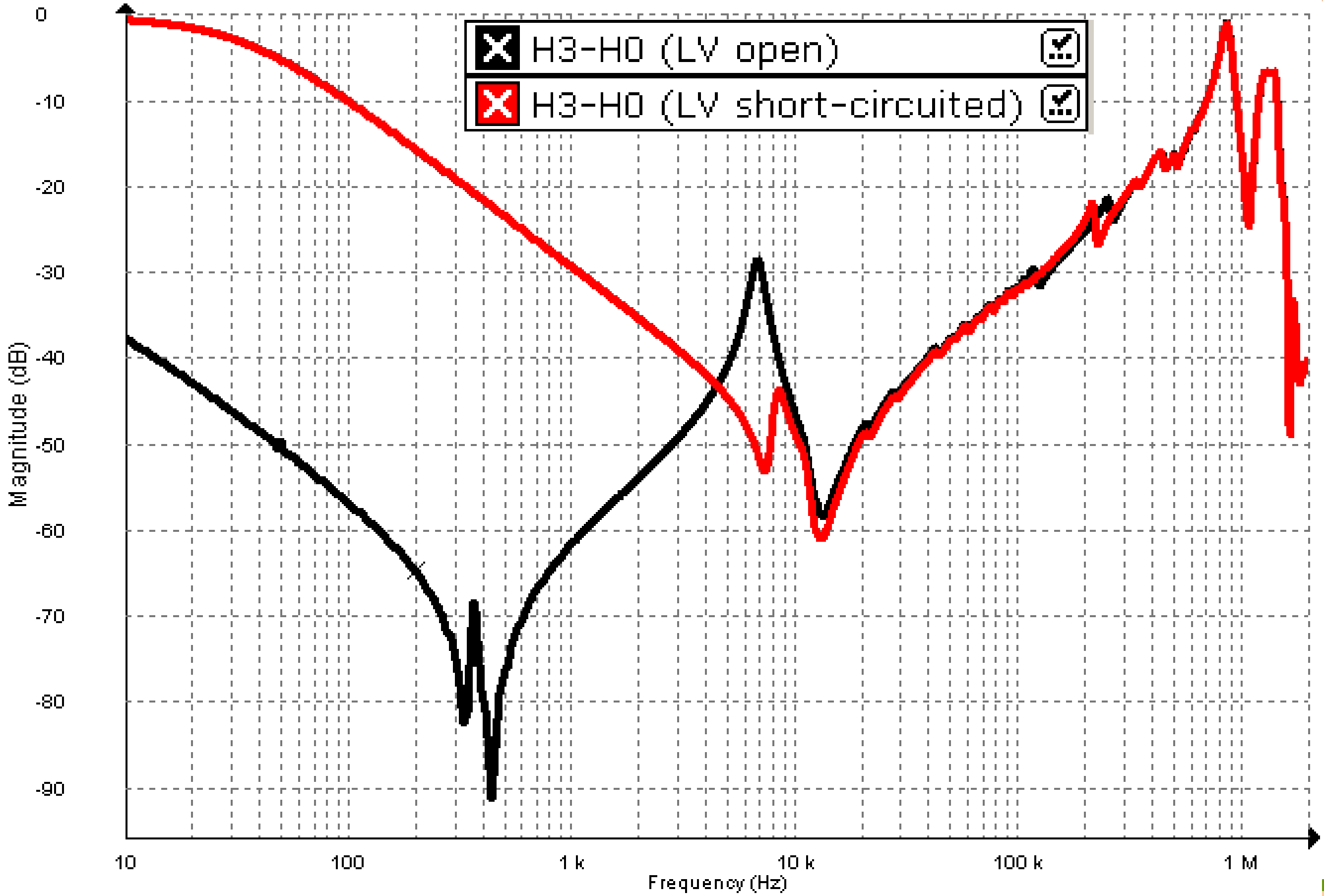
-Phase to Phase

Typical results: Large transformer



Typical results: **Open- vs. short circuit**

Configuration – Self-Winding (Short circuit)



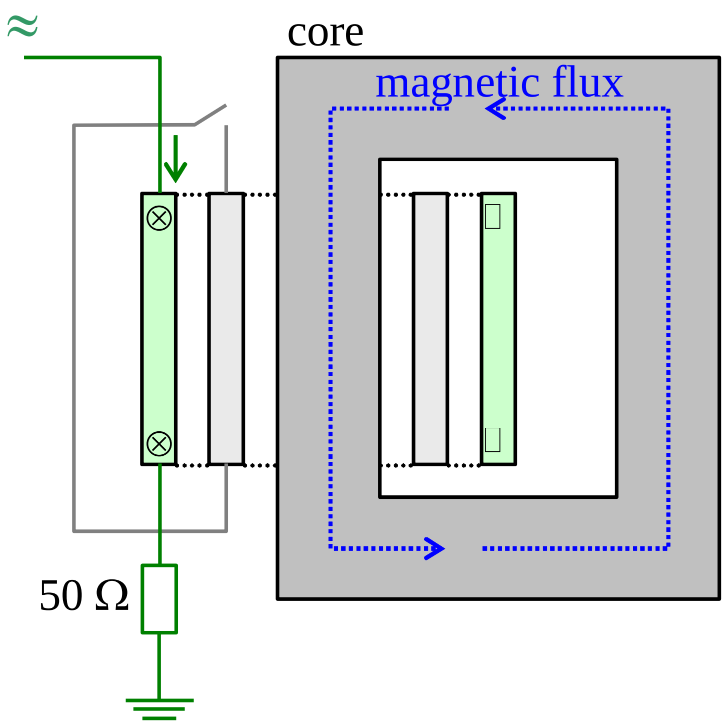
The Low Voltage terminals are short-circuited

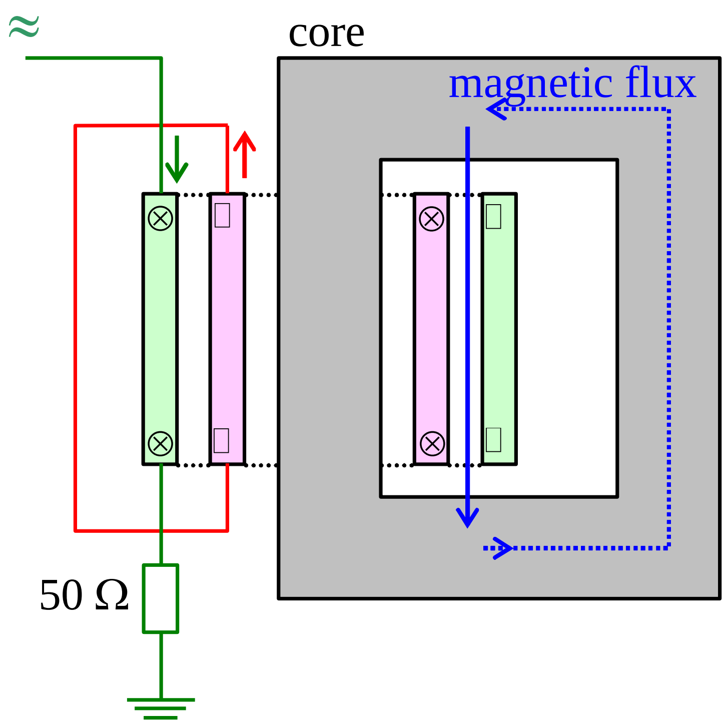
Background: **Open- vs. short-circuit**

Magnetic flux paths for low-frequency measurements

open-circuit: $L_{oc} \approx 10$ **H**

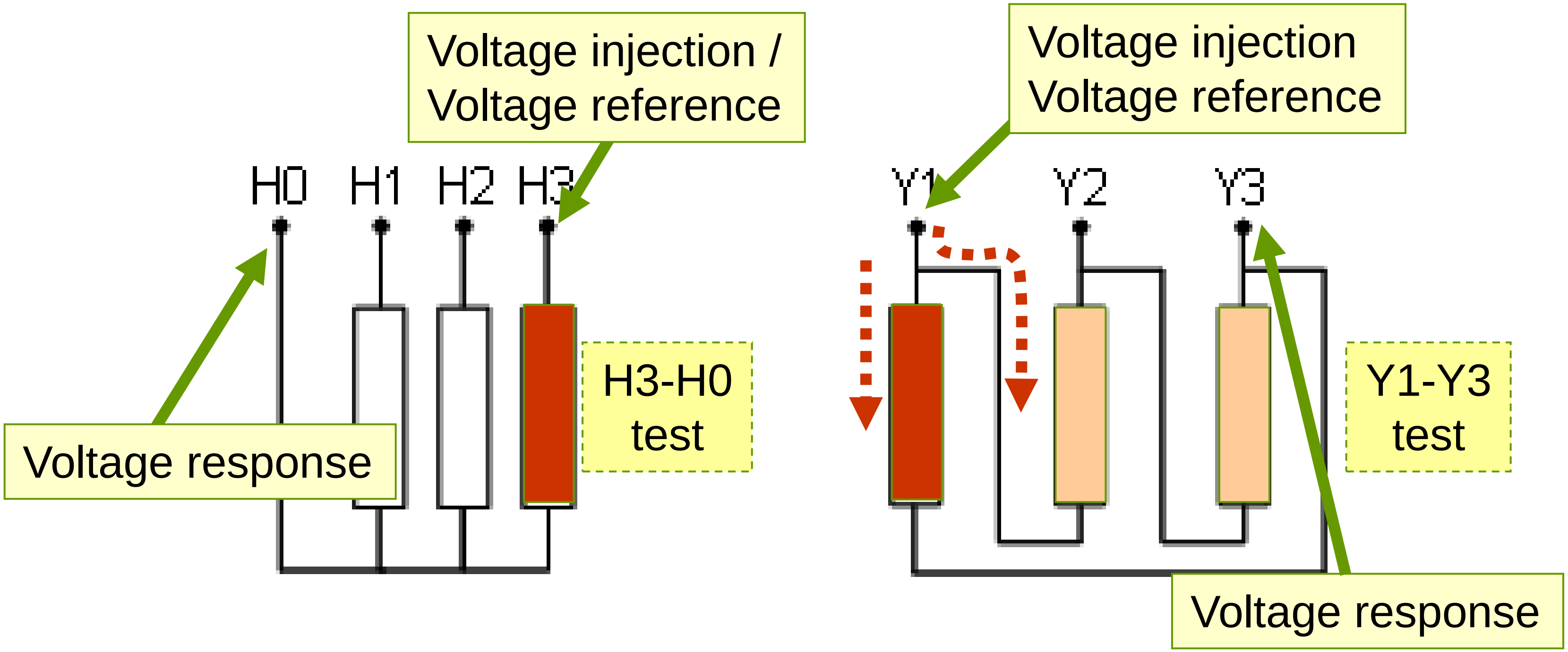
short-circuit: $L_{sc} \approx 100$ **mH**





Open-circuit test: Y vs. Delta

Configuration – Self-Winding (Open circuit)

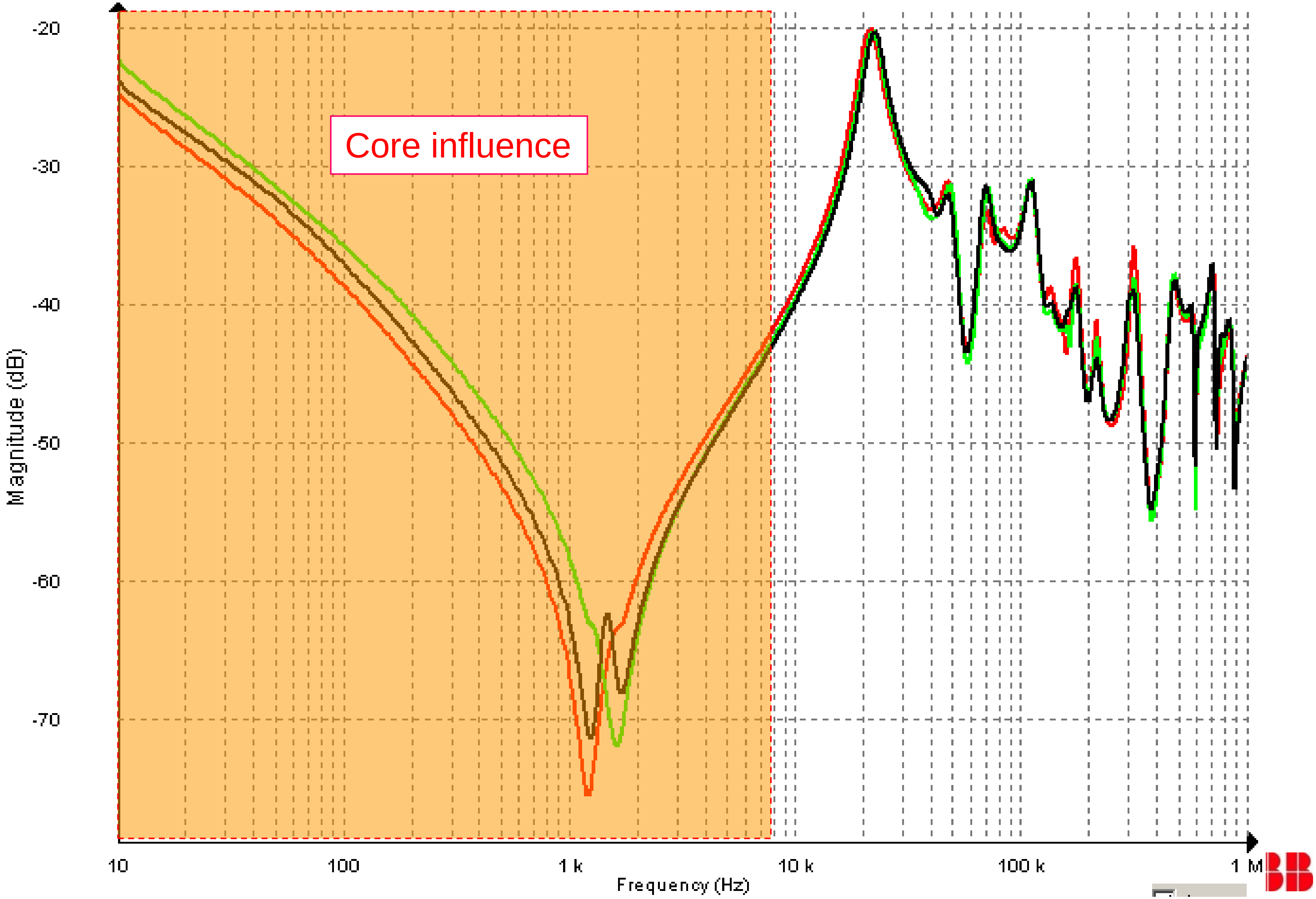


Star configuration

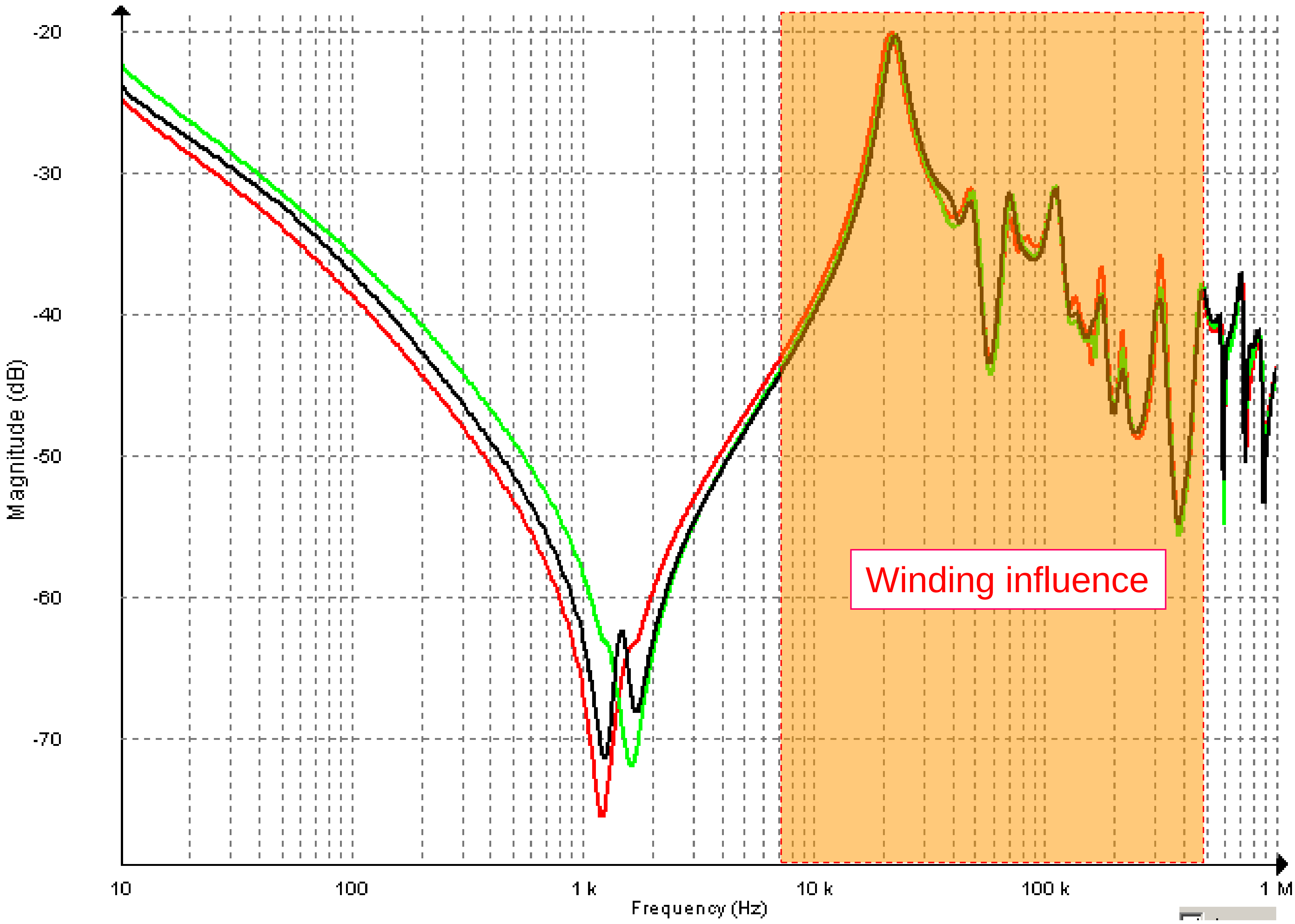
Delta configuration

The Low Voltage terminals are open (floating)

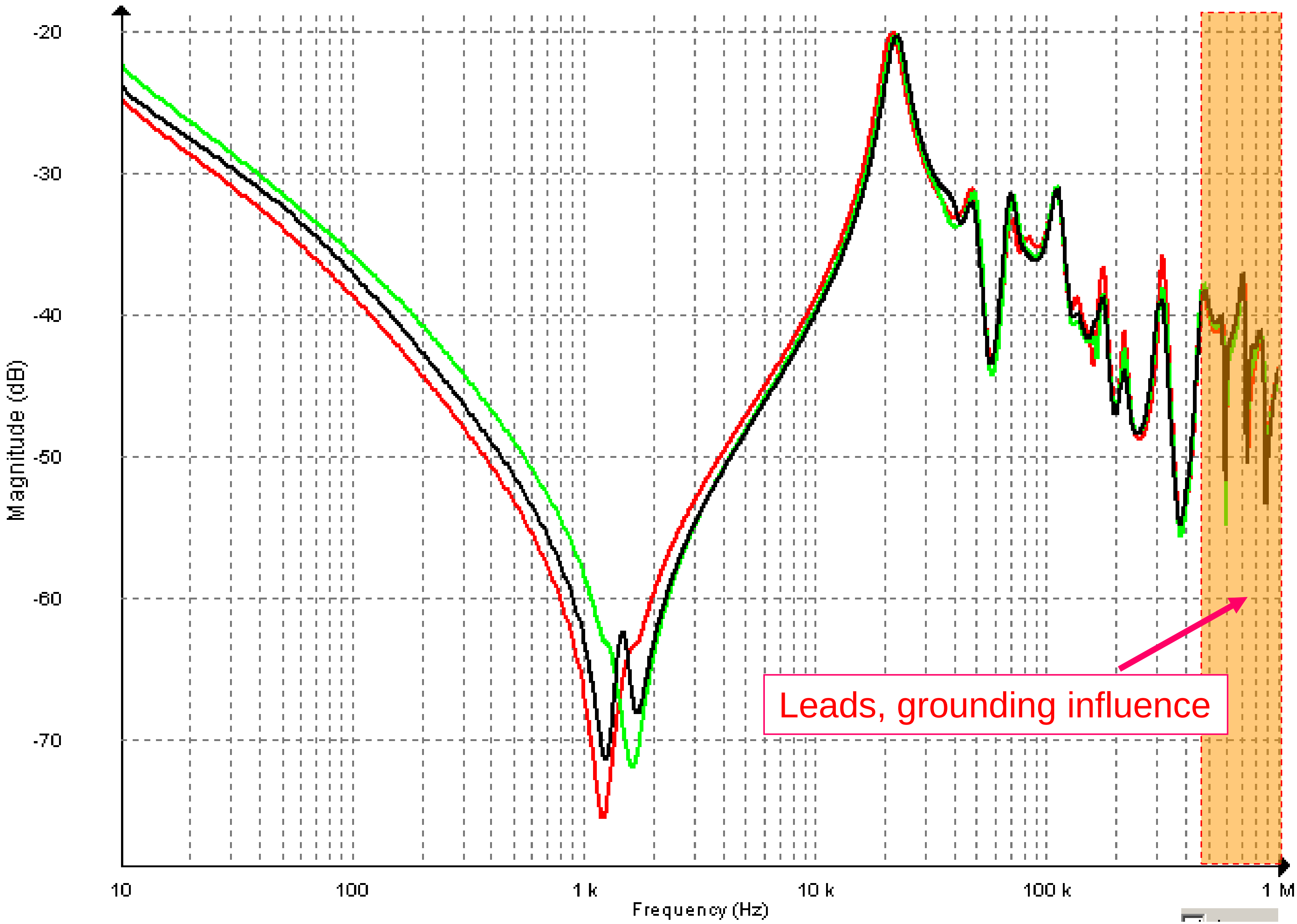
Typical results: **Areas of influences (Approx.)**



Typical results: **Areas of influences (Approx.)**

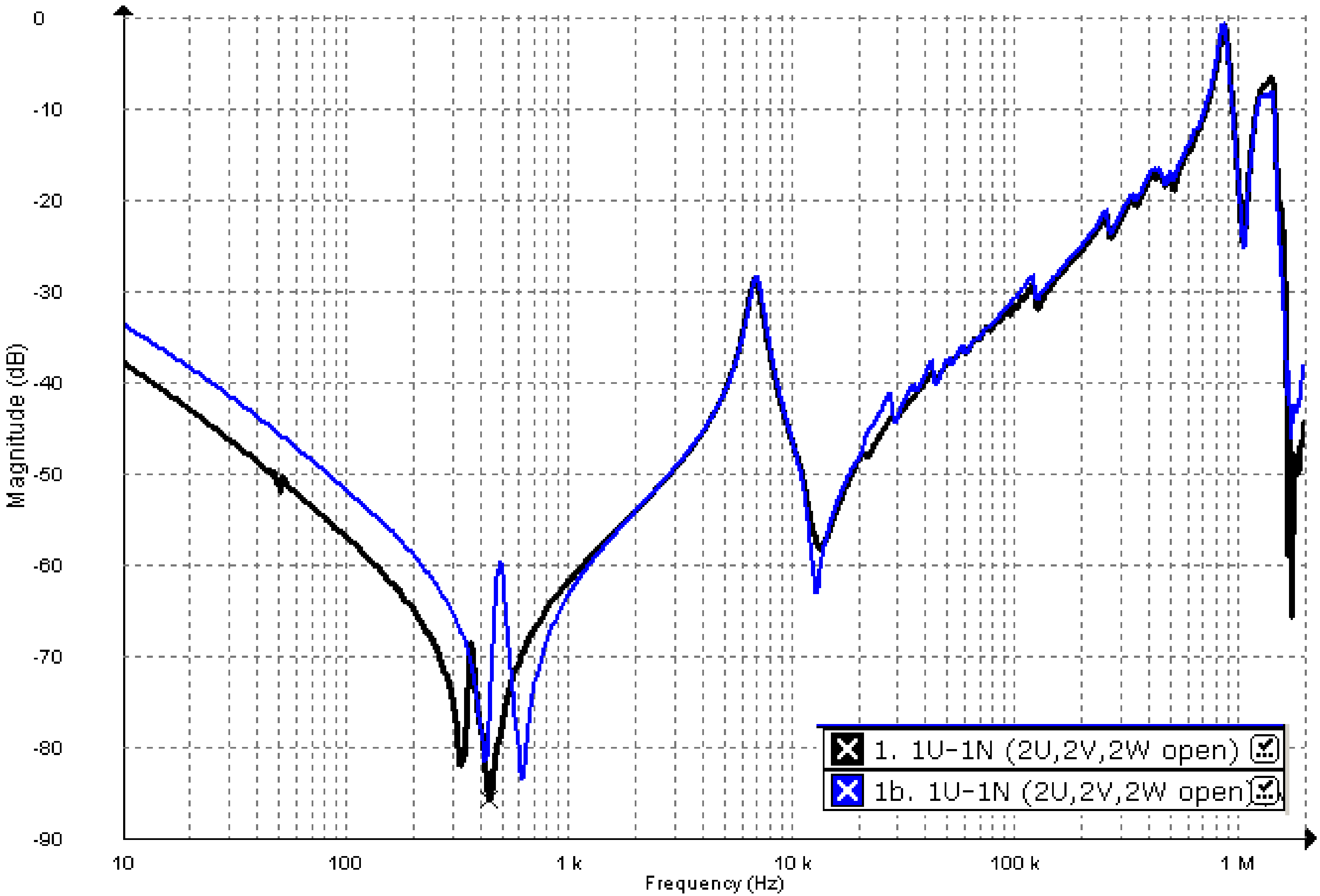


Typical results: **Areas of influences (Approx.)**

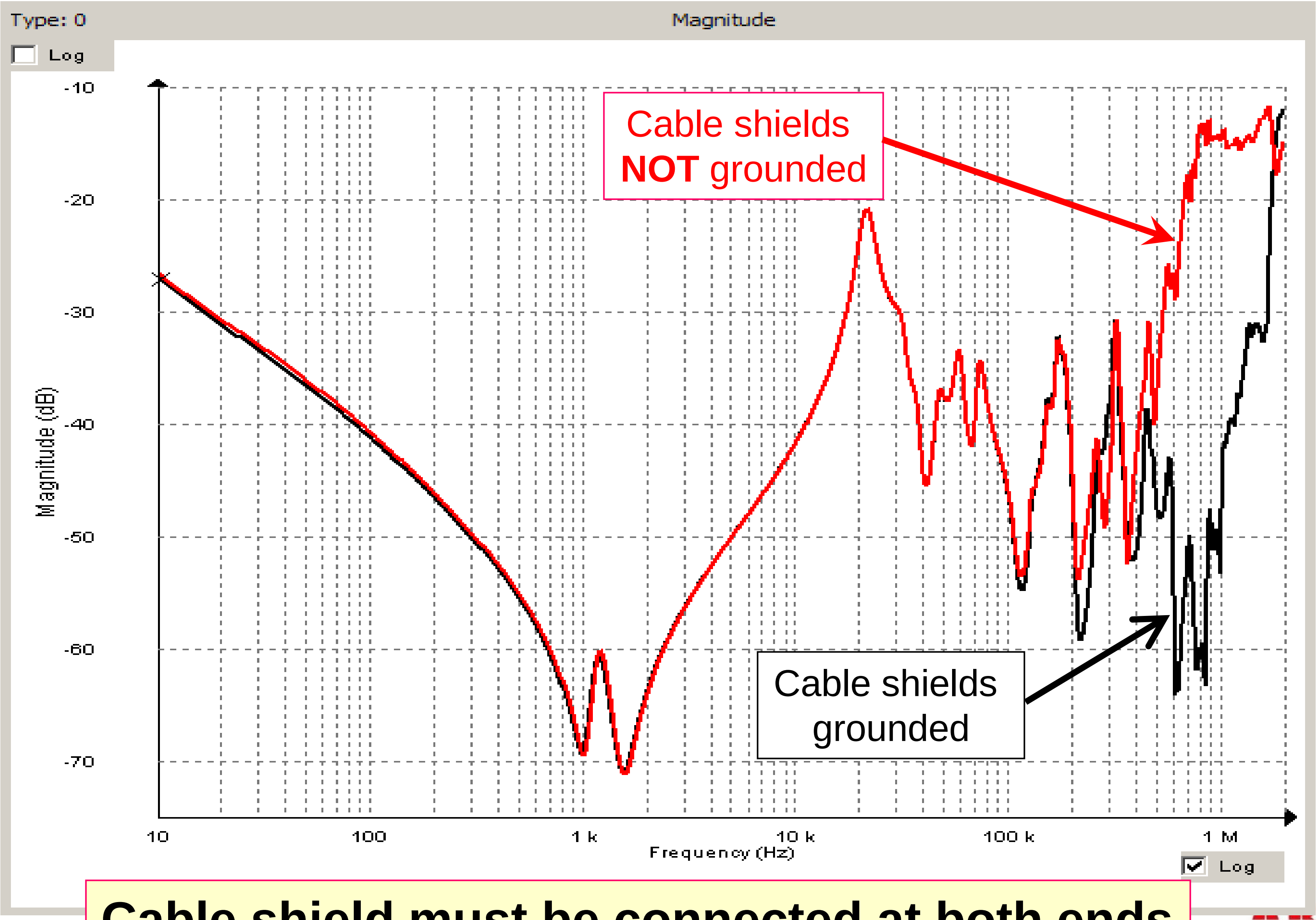


Typical results: **Influence of winding resistance test**

Measurements before and after winding resistance test

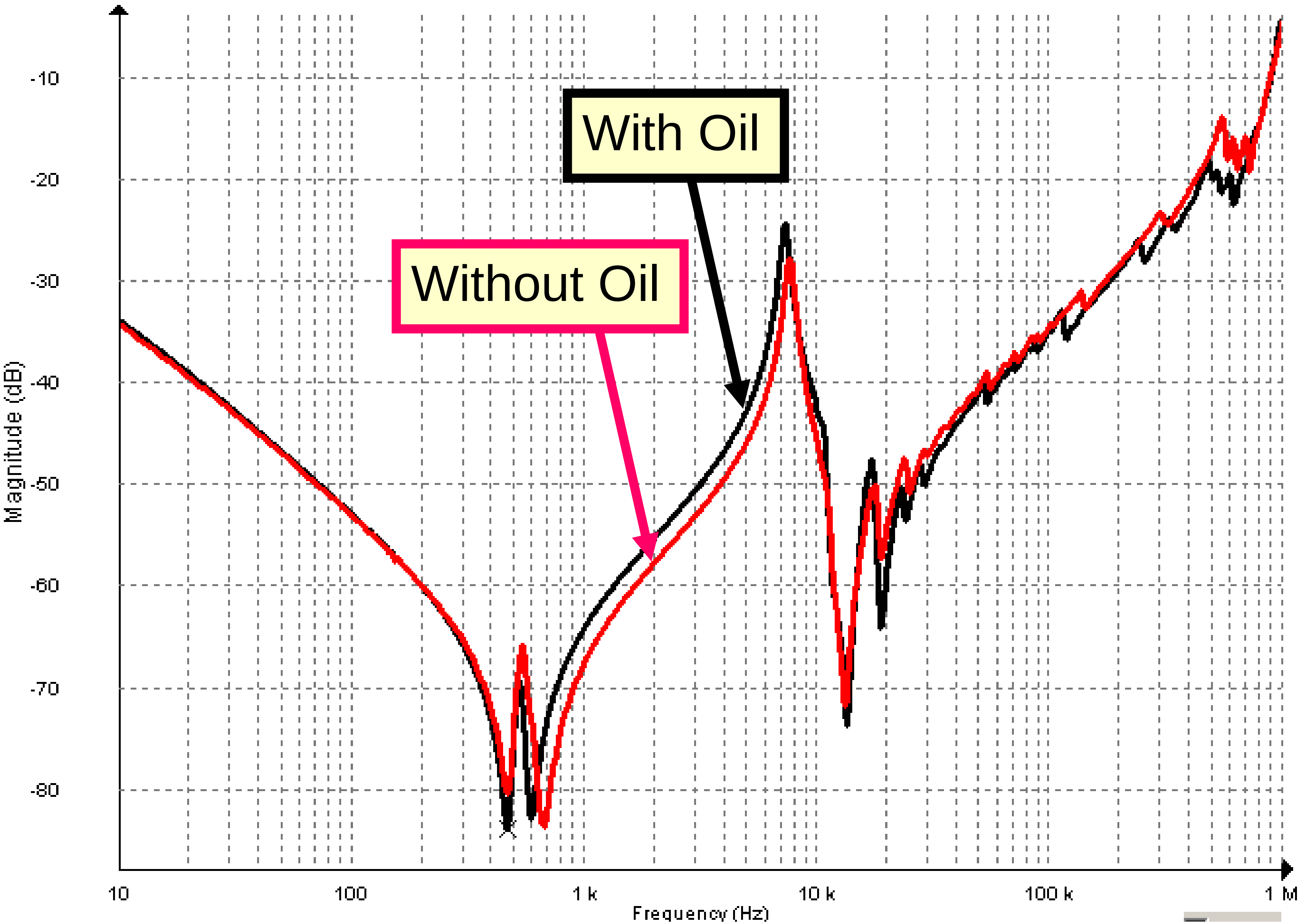


Typical results: **Cable shield grounding at bushing**

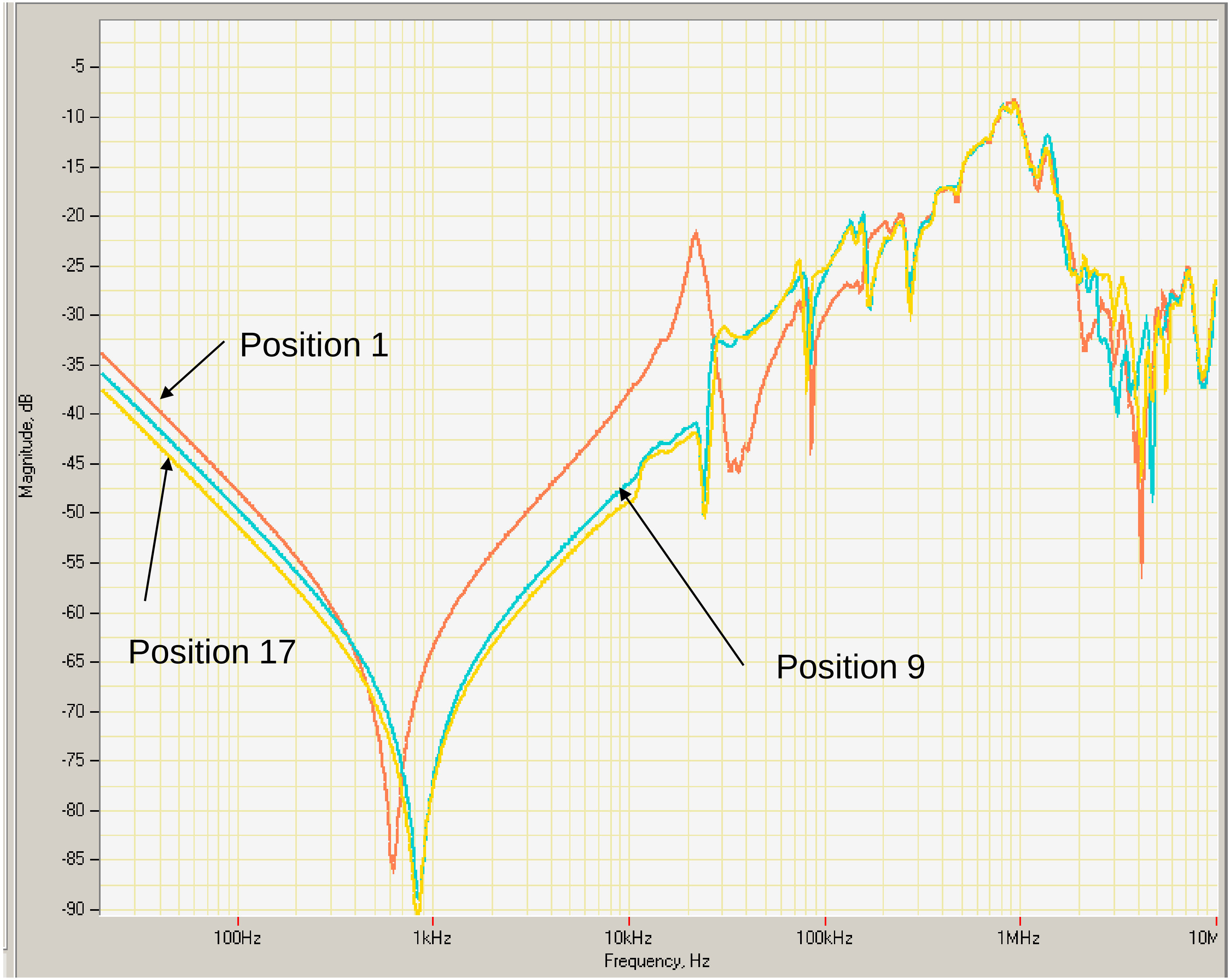


Cable shield must be connected at both ends

Oil influence in FRA signatures (HV Winding):

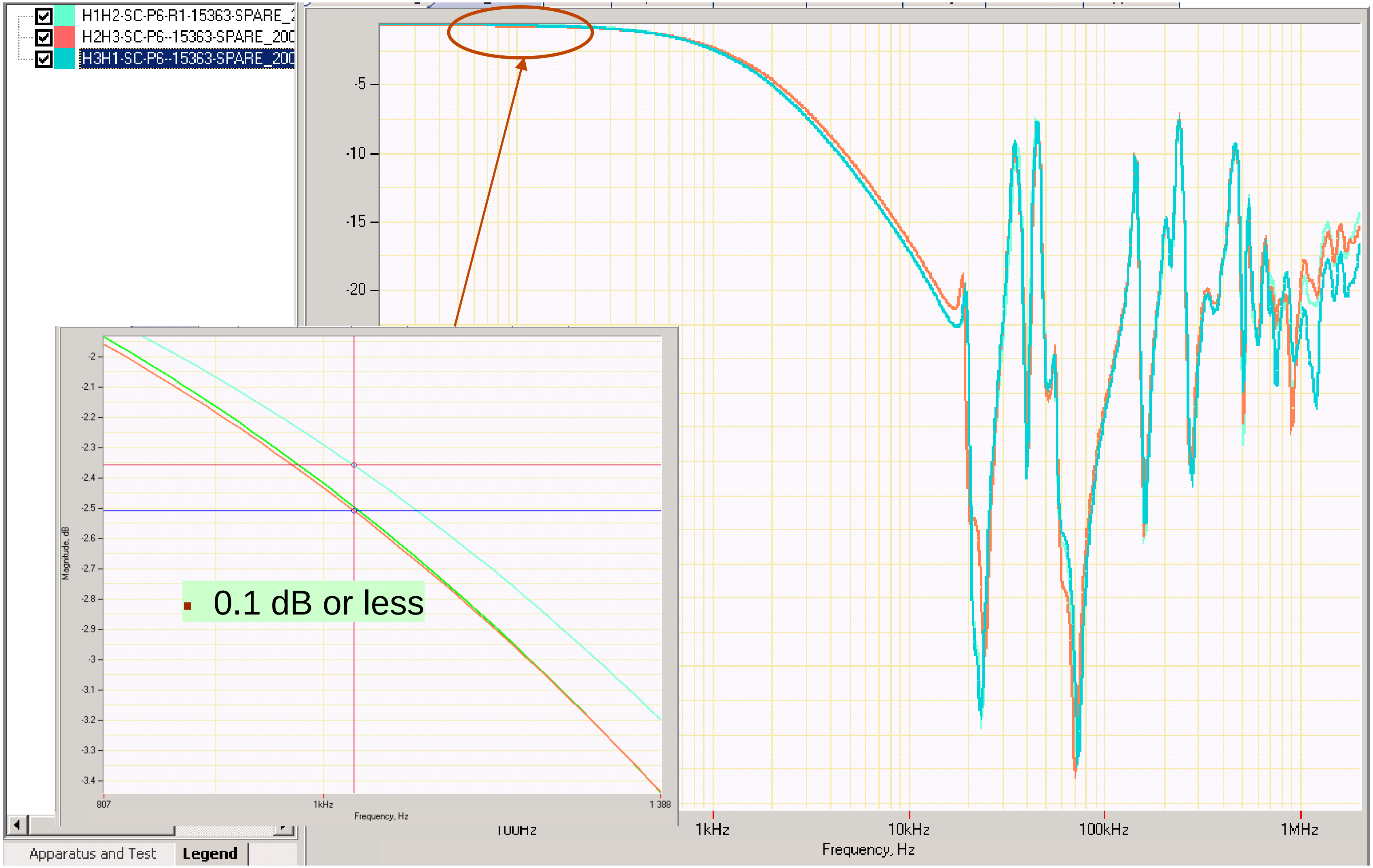


Tap Position influence in FRA signatures



Noise from Instrumentation!

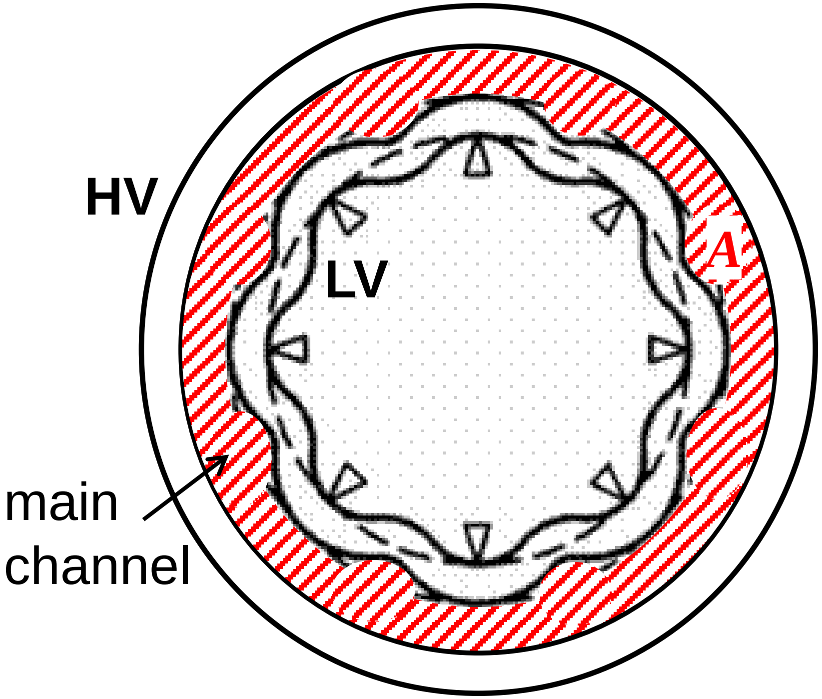
Short circuit test



- 0.1 dB or less

Short-circuit test: 0.1dB criterion

The short-circuit inductance is proportional to the cross-section area $\boldsymbol{A}$ of the main channel:



$$L_{sc} \approx \frac{\mu_0 N^2 \boldsymbol{A}}{h}$$

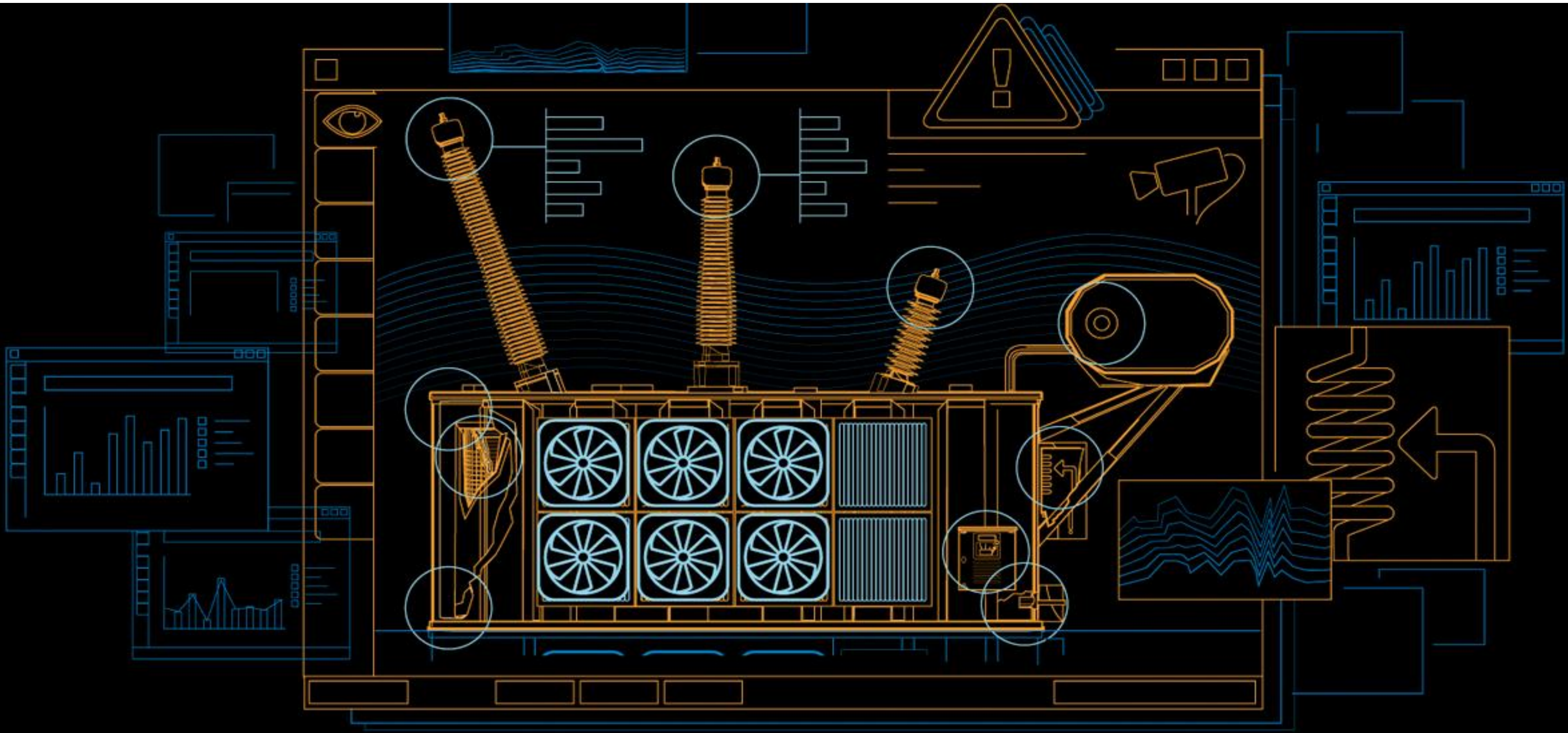
< 0.1dB means that $\boldsymbol{A}$ changes by < 1%

Good practices: **Short circuit Connection**

Very good

Good

Reduce short circuit cable resistance and inductance by using several conductors in parallel.



SFRA- Cases

Case # 1

Residual magnetization

Case # 1 Residual magnetization

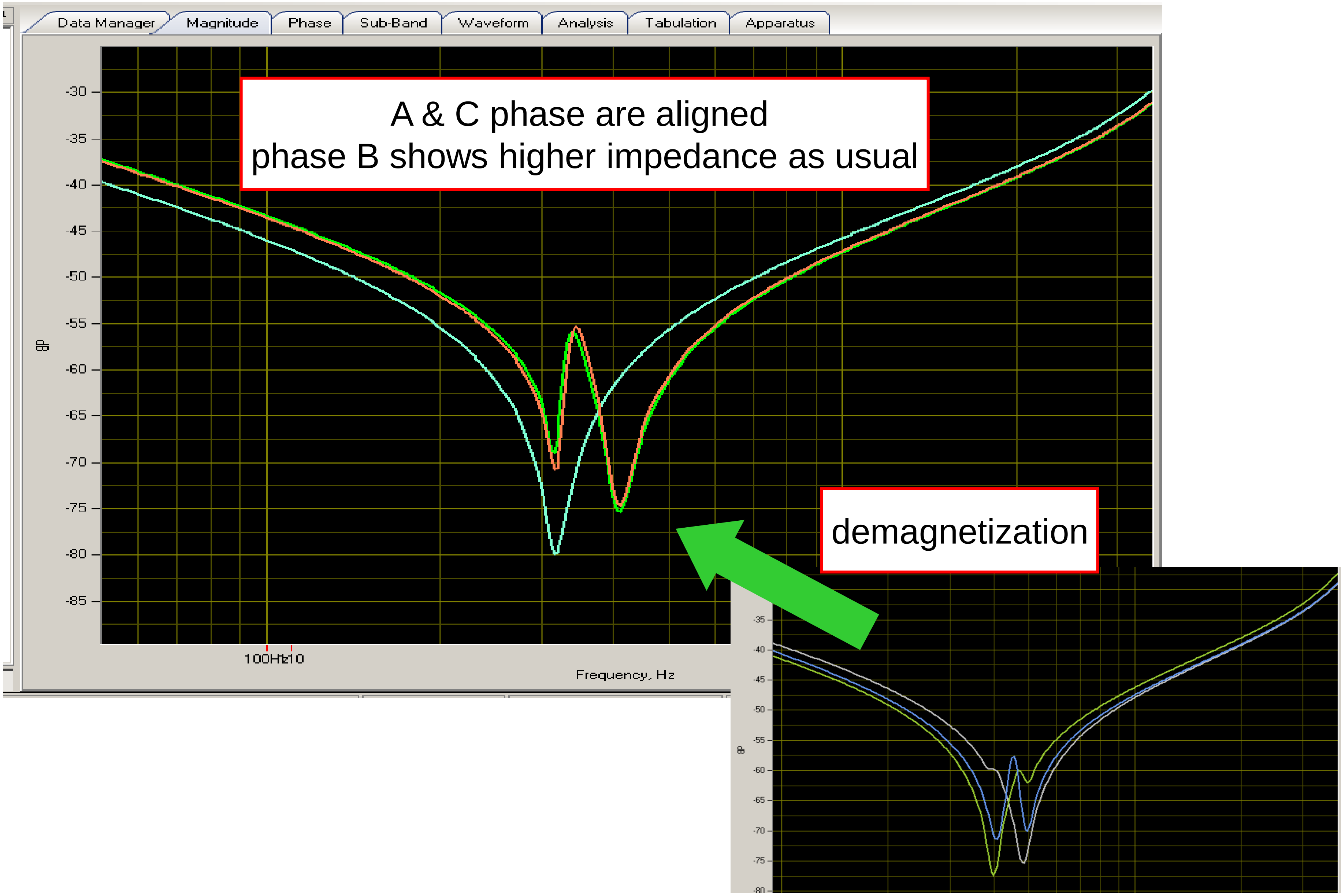
- FRA measurement identified residual magnetization
- The outer phases (A & B) did not align well with one another at the low frequency region.
- All Short circuit tests showed symmetry between windings.
- It was discovered that the field test specialist performed a DC resistance test one day earlier.

Case # 1 Residual magnetization

100 Hz – 4 kHz

All three phases show separation due to the core being magnetized

Case # 1 FRA results after Demagnetizing



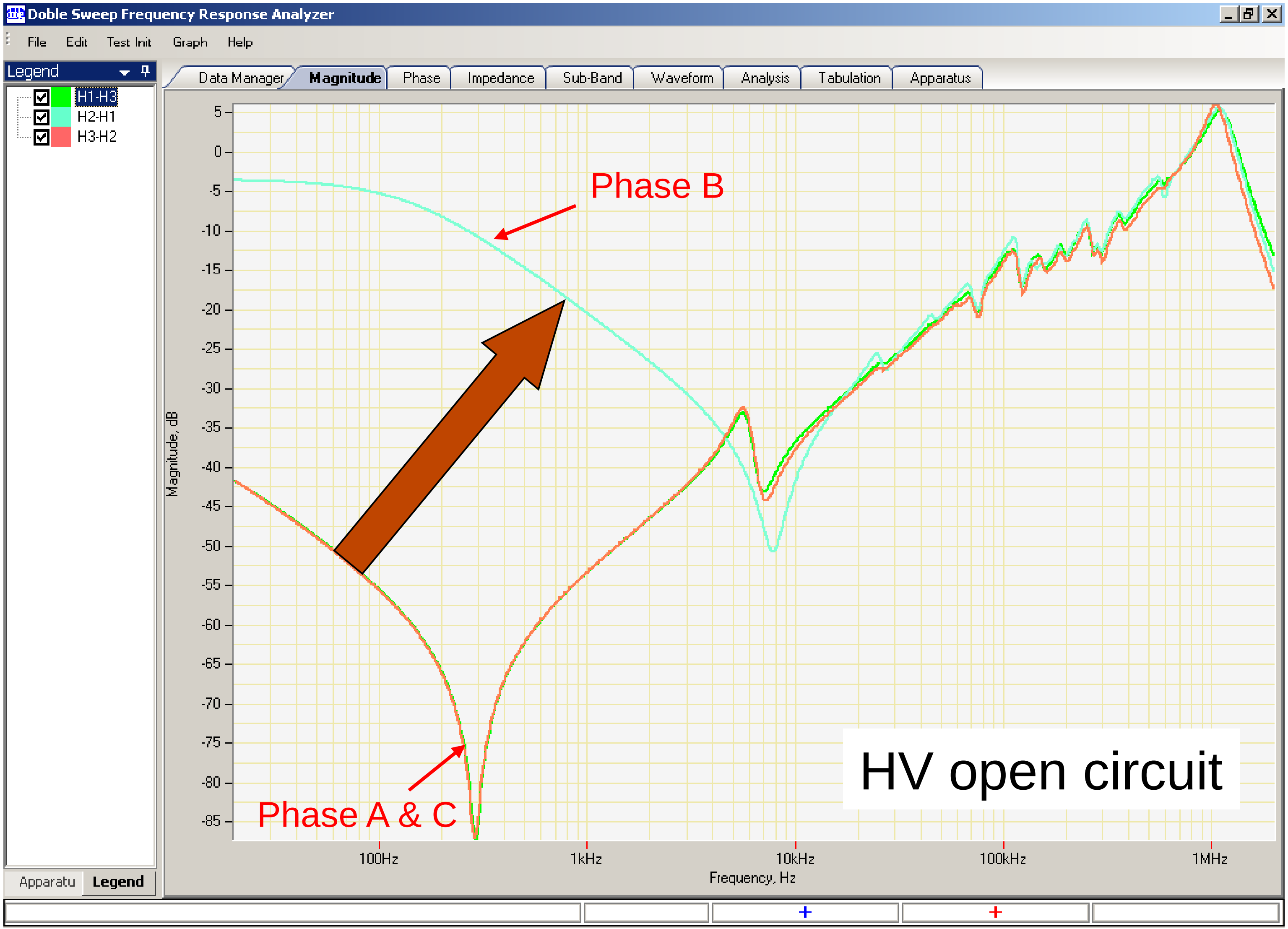
Case # 2

Shorted turns

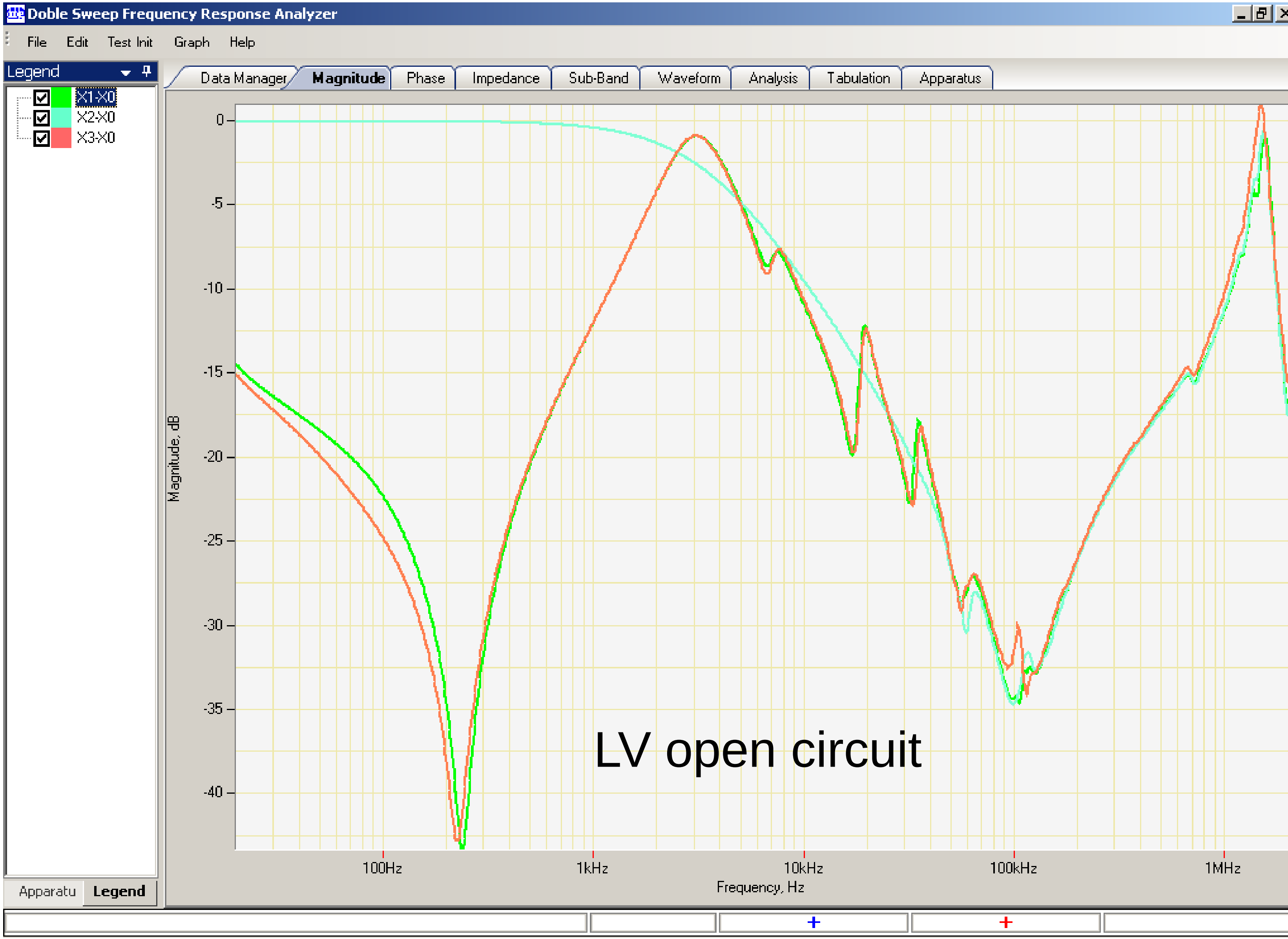
Case # 2 Shorted turns

- Ratio test indicated shorted winding turn on phase B
- FRA was made to decide whether HV or LV winding had failed

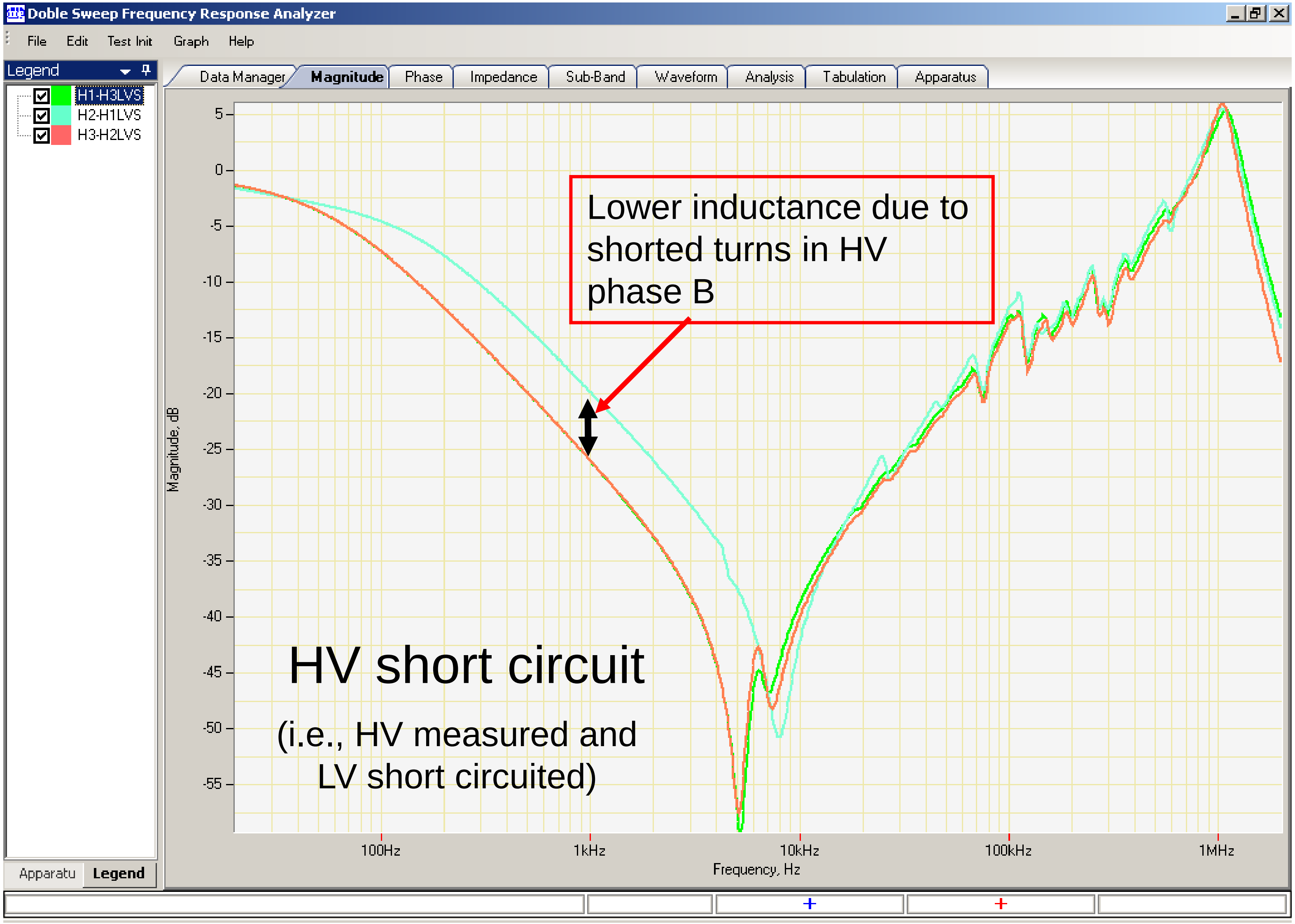
Case # 2 Shorted turns – Which winding (HV or LV)..??



Case # 2 Shorted turns – Which winding (HV or LV)..??



Case # 2 Shorted turns – Which winding (HV or LV)..??



Case # 2 Shorted turns - lesson learned

- Both HV and XV open circuit tests indicate that phase B has shorted turns
- HV short circuit test indicates that HV winding has shorted turn
- HV short deviation at low frequency also indicates that HV B-phase has extra losses

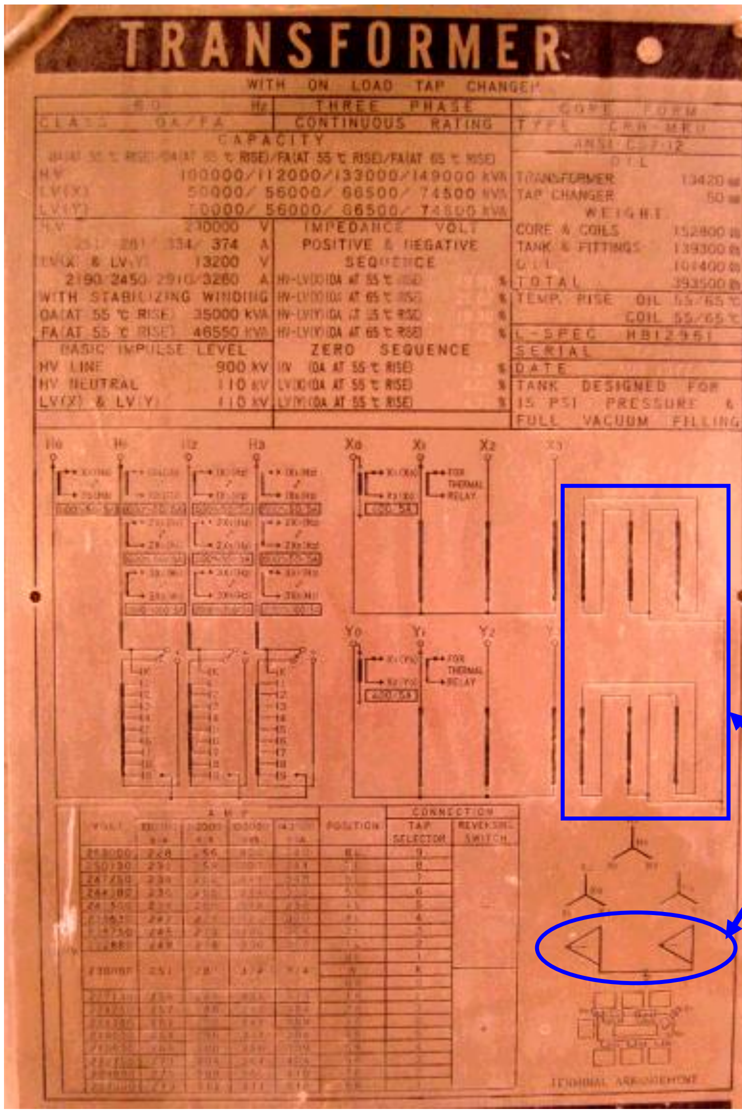
.HV - winding

Case # 3

Earthed tertiary

Case # 4 Earthed tertiary

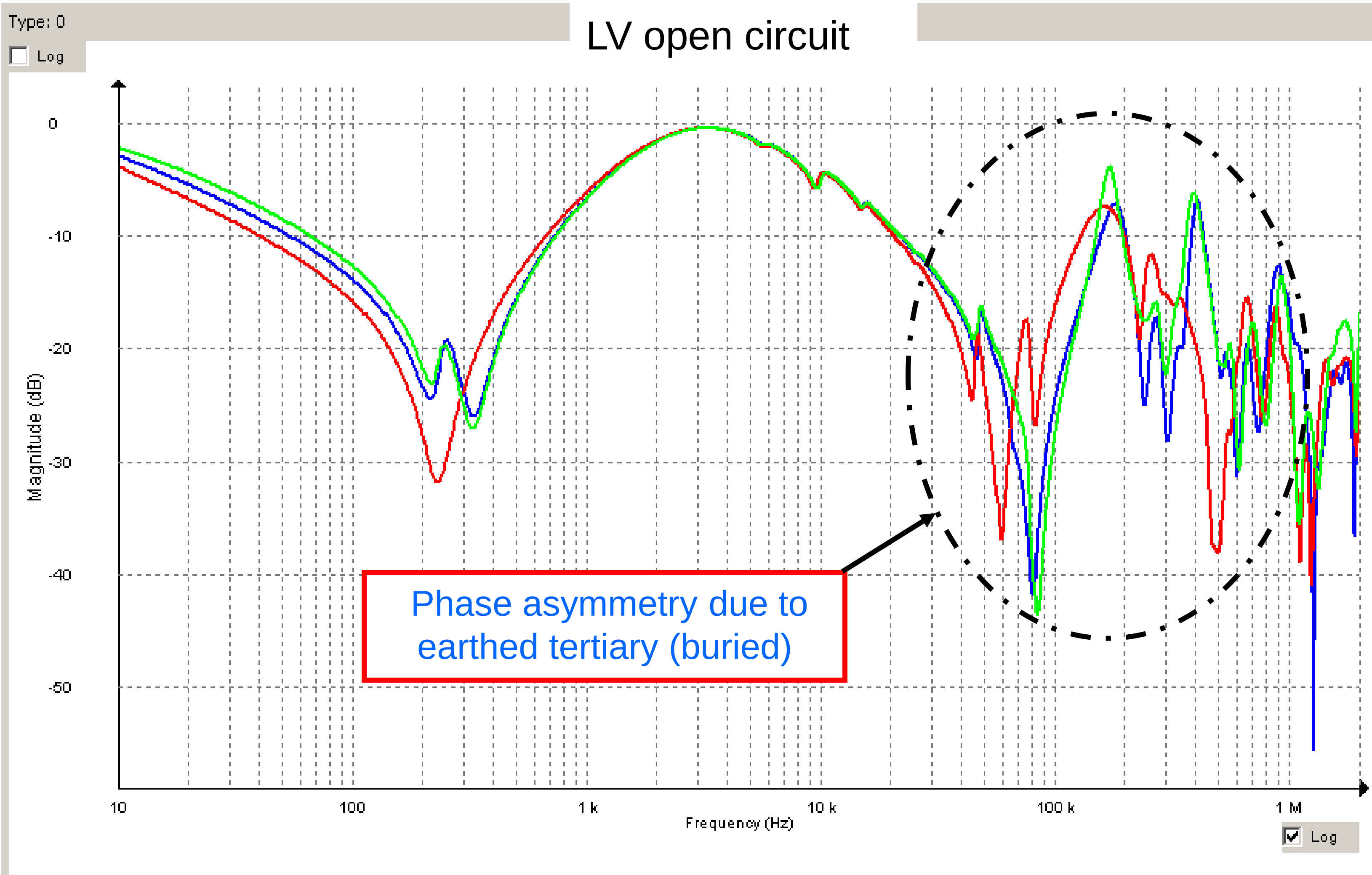
- 253/13.2 kV, 100 MVA (YNyn0yn0+dd)



Buried tertiary (with internal earth, no external access)

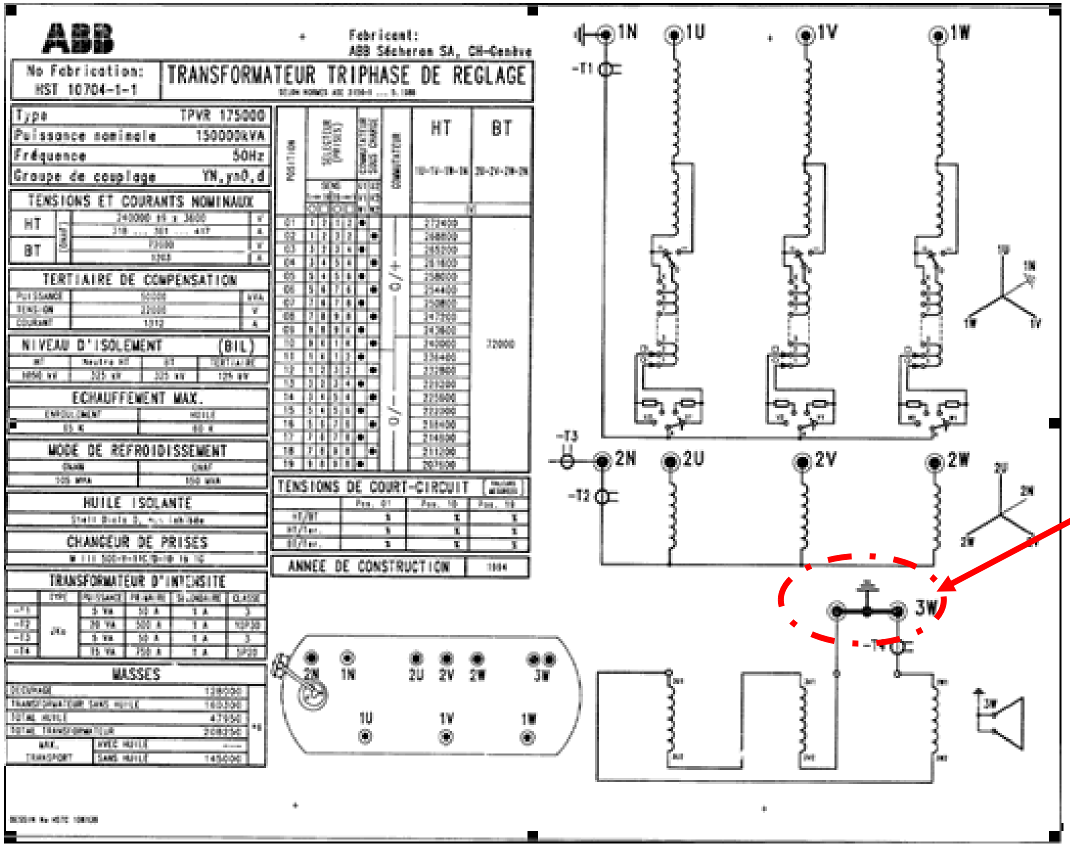
Case # 4 Earthed tertiary

- 253/13.2 kV, 100 MVA (YNyn0yn0+dd)



Case # 4 Earthed tertiary

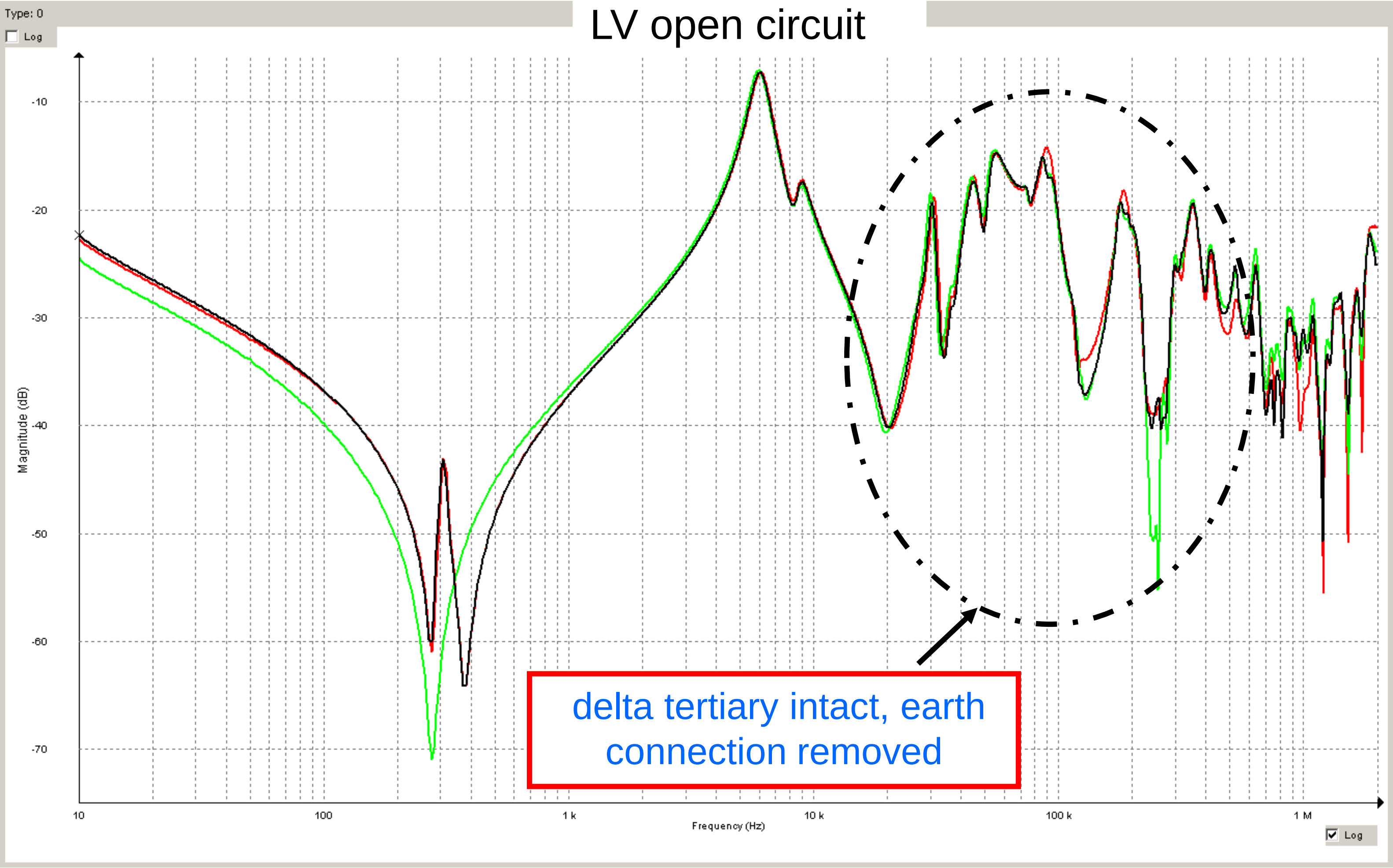
- 240/72 kV, 150MVA (YNyn0+d)
- Tertiary brought out and earthed externally
- Possible to remove tertiary earth keeping delta intact



Tertiary brought out and earthed

Case # 4 Earthed tertiary

- Tertiary earth removed and delta intact
- Symmetry between phases is preserved



Reminders
Automation & Power World 2011

- Please be sure to complete the workshop evaluation
- Professional Development Hours (PDHs) and Continuing Education Credits (CEUs):
  - You will receive a link via e-mail to print certificates for all the workshops you have attended during Automation & Power World 2011.
  - BE SURE YOU HAVE YOUR BADGE SCANNED for each workshop you attend. If you do not have your badge scanned you will not be able to obtain PDHs or CEUs.

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