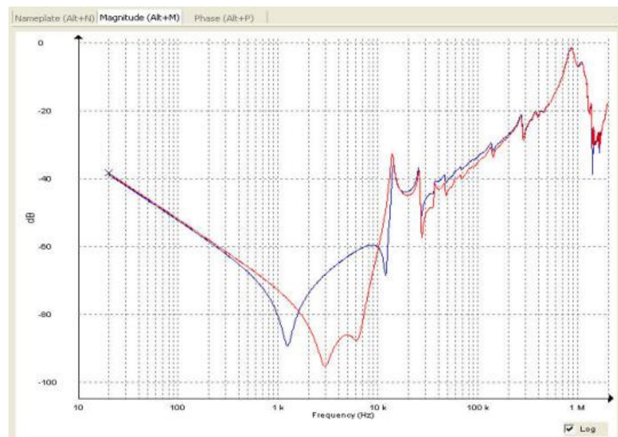
Sweep Frequency Response Analysis



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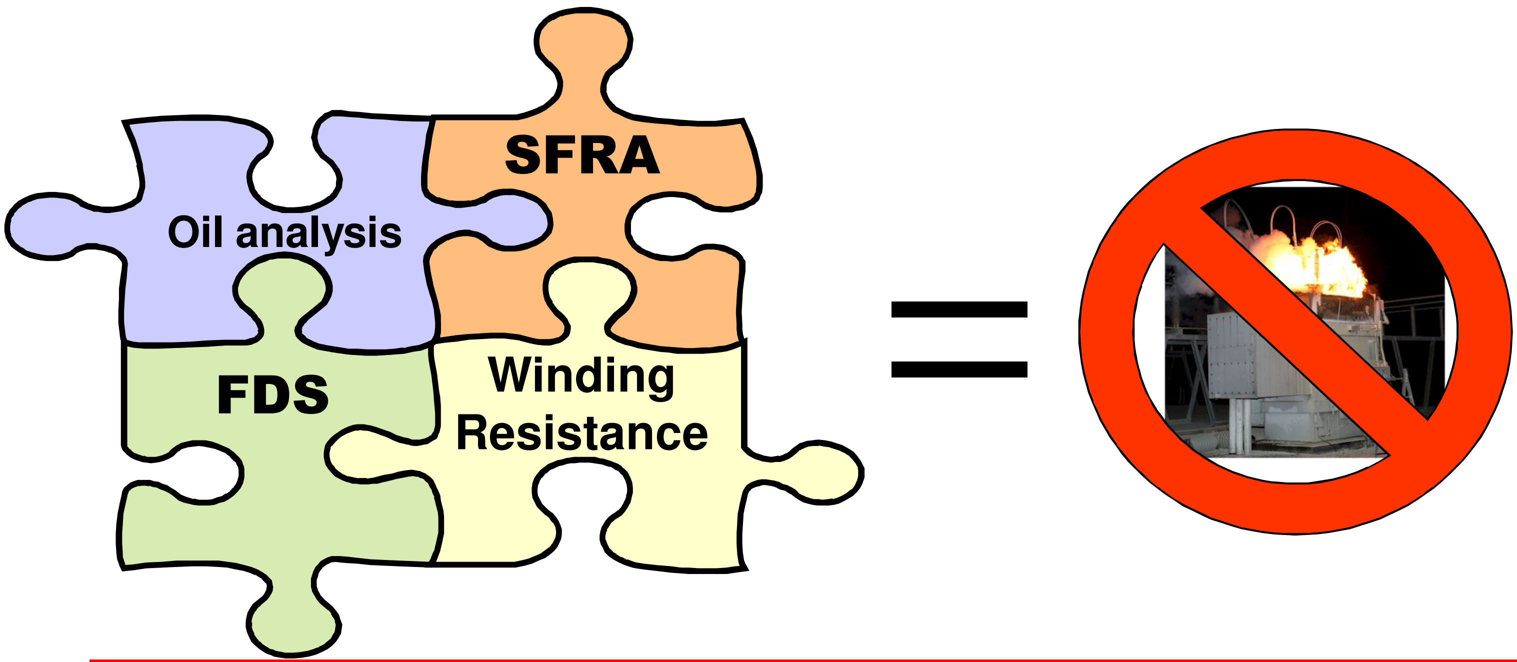
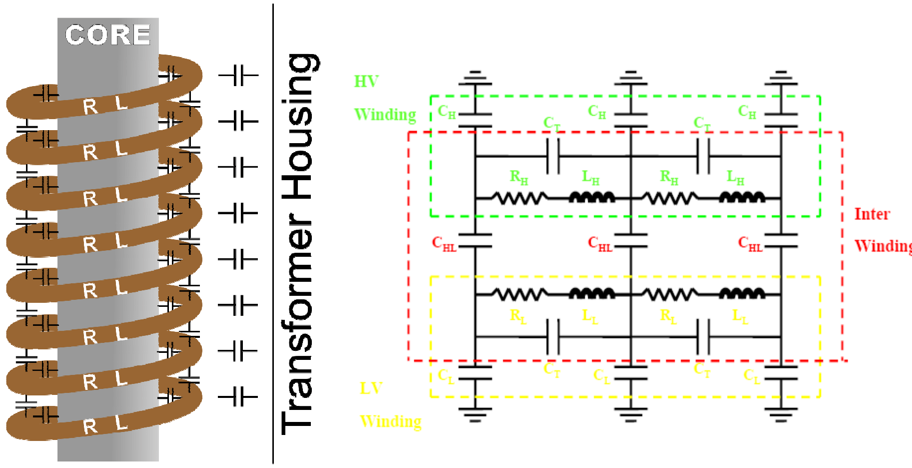
Transformer Diagnostics

- Diagnostics is about collecting reliable information to make the correct decision
- Making the correct decisions saves money



SFRA testing basics

- Off-line test
- The transformer is seen as a complex impedance circuit
- [Open] (“excitation current”) and [Short] (“short-circuit impedance”) responses are measured over a wide frequency range and the results are presented as magnitude response curves (“filter response”)
- Changes in the impedance can be detected and compared over time, between test objects or within test objects
- The method is unique in its ability to detect a variety of winding faults, core issues and other electrical faults in one test



Detecting Faults with SFRA

- **Winding faults**
  - Deformation
  - Displacement
  - Shorts
- Core related faults
  - Movements
  - Grounding
  - Screens
- Mechanical faults/changes
  - Clamping structures
  - Connections
- And more...

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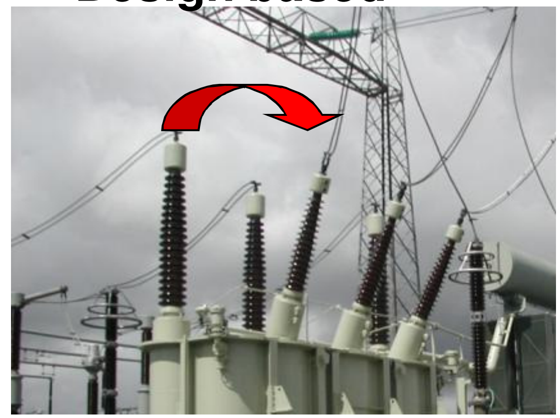
Comparative tests

Transformer A

Design based



Time based

Transformer A

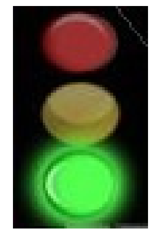
Transformer B

Type based

SFRA Measurement philosophy

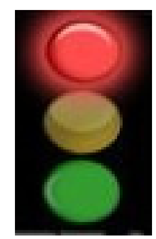
New measurement = Reference measurement

Back in Service



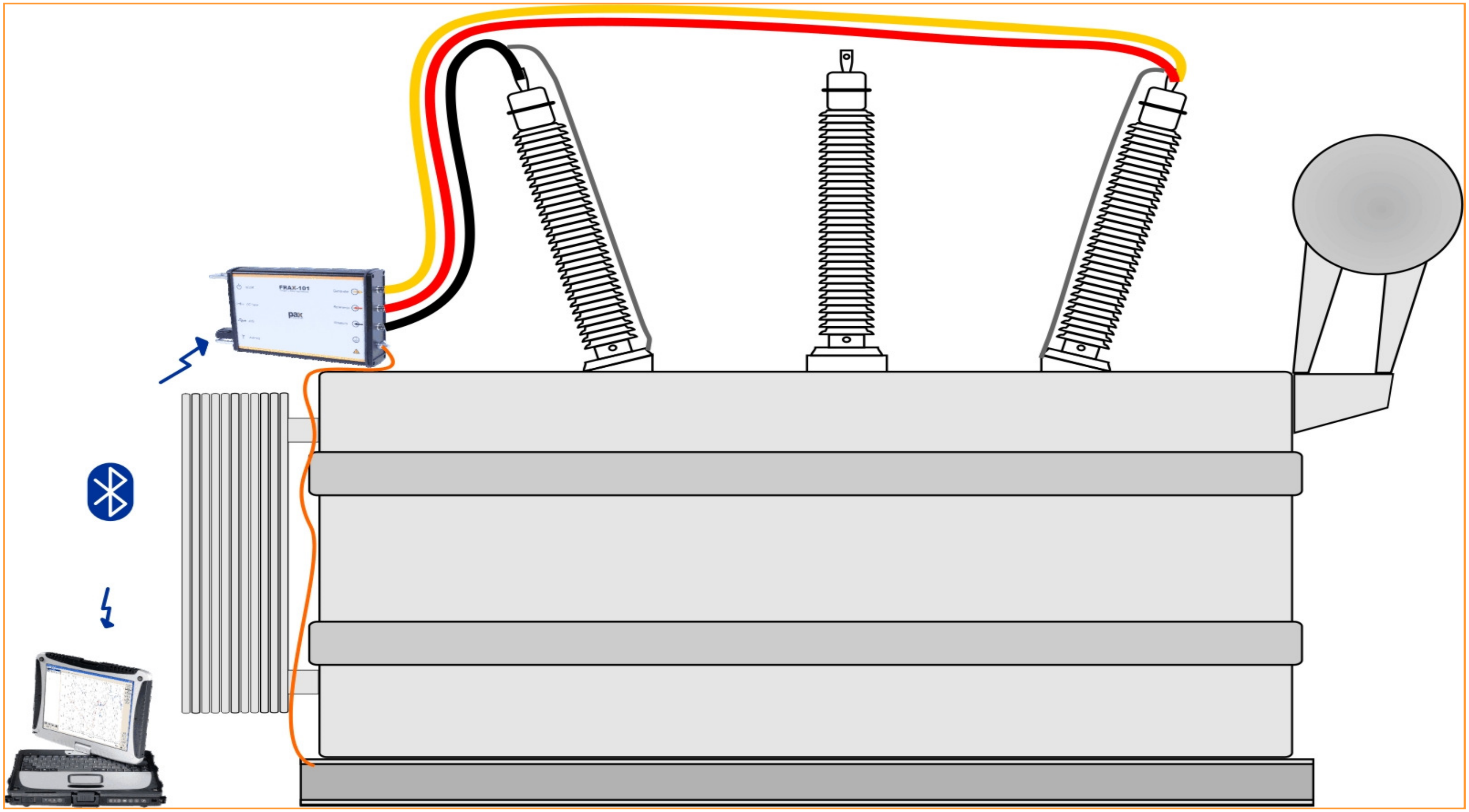
New measurement ≠ Reference measurement

Further Diagnostics Required

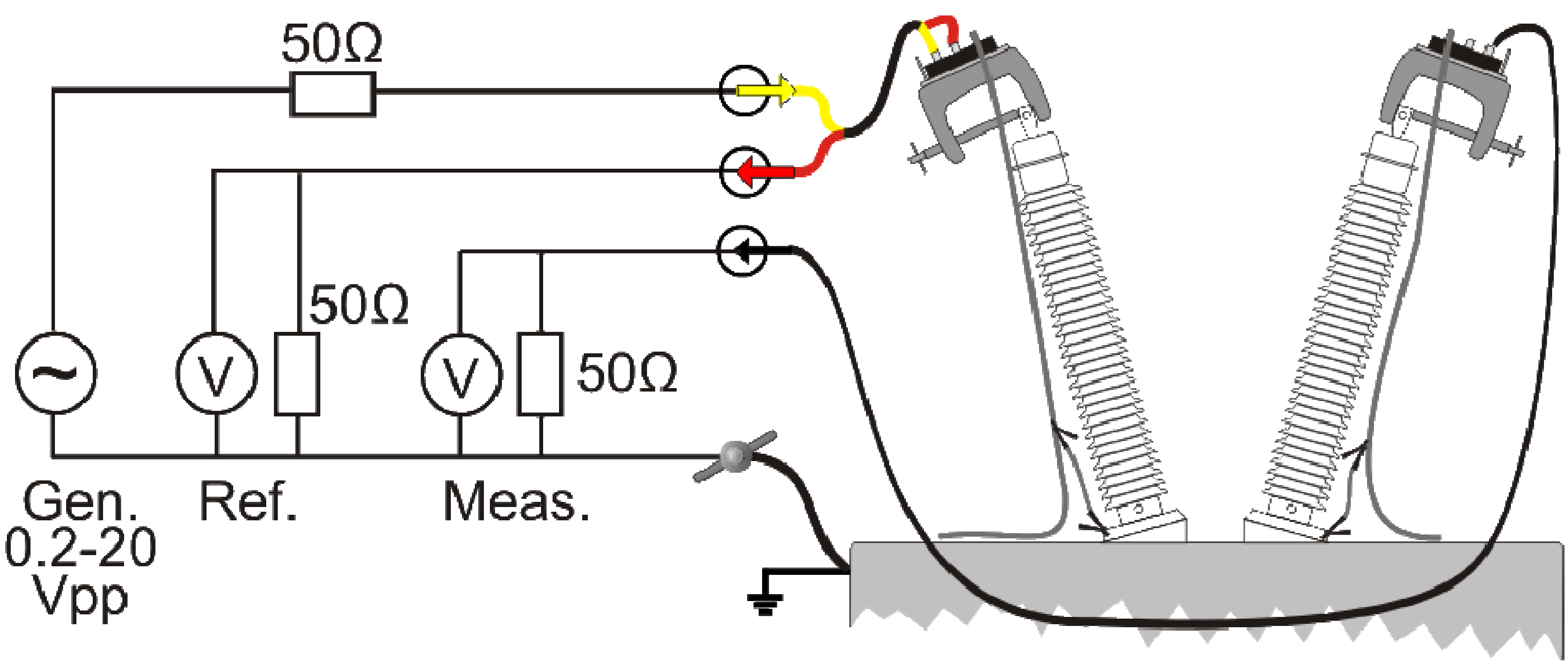


SFRA Measurements

SFRA test setup



FRAX measurement circuitry



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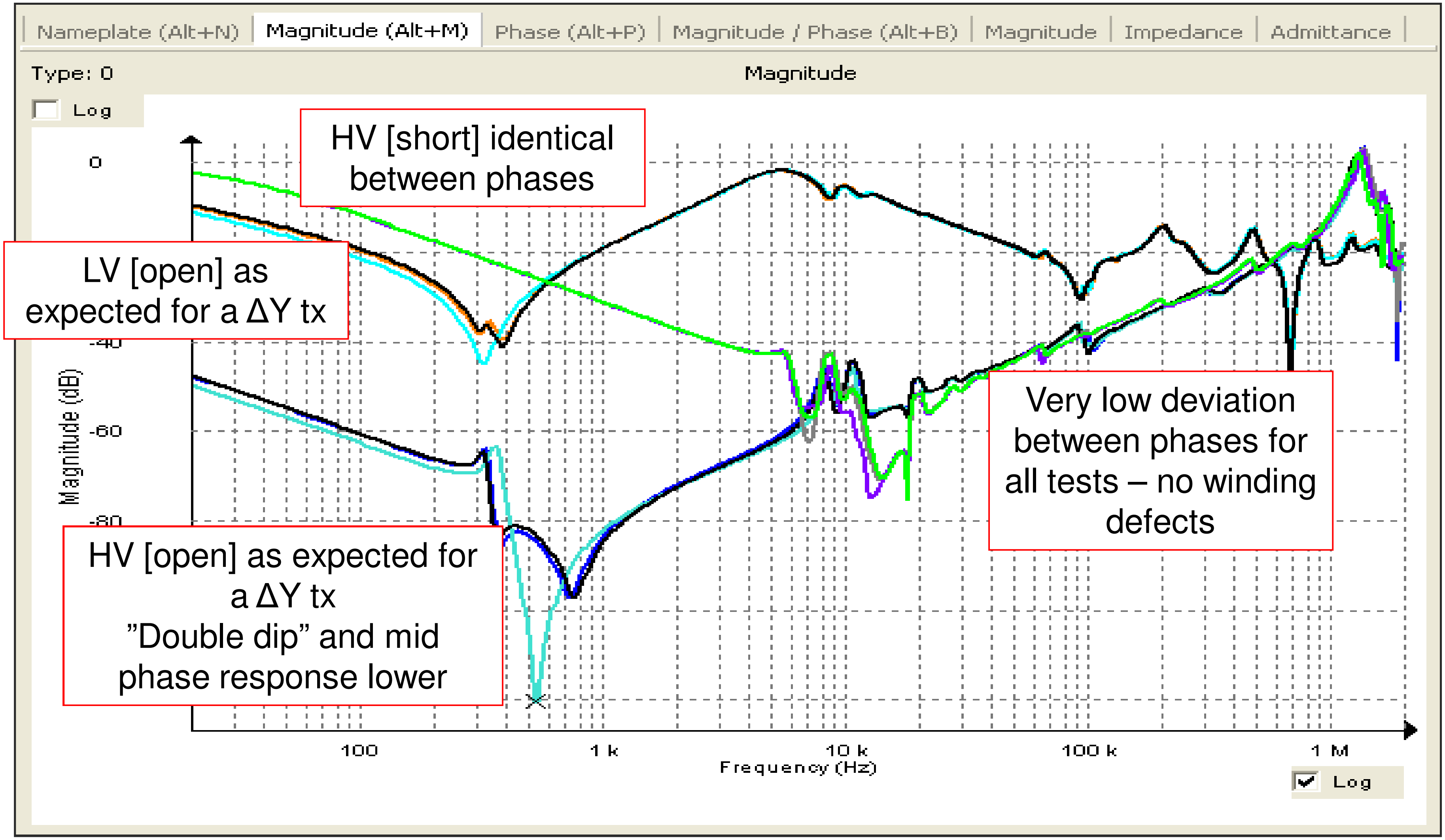
SFRA Analysis

SFRA analysis tools

- Visual/graphical analysis
  - Starting dB values for
    - [Open] (excitation impedance/current)
    - [Short] (short-circuit impedance)
  - The expected shape of star and delta configurations
  - Comparison of fingerprints from;
    - The same transformer (symmetry)
    - A sister transformer
    - Symmetric phases
  - New/missing resonance frequencies
- Correlation analysis
  - DL/T 911 2004 standard
  - Customer/transformer specific

Typical response from a healthy transformer



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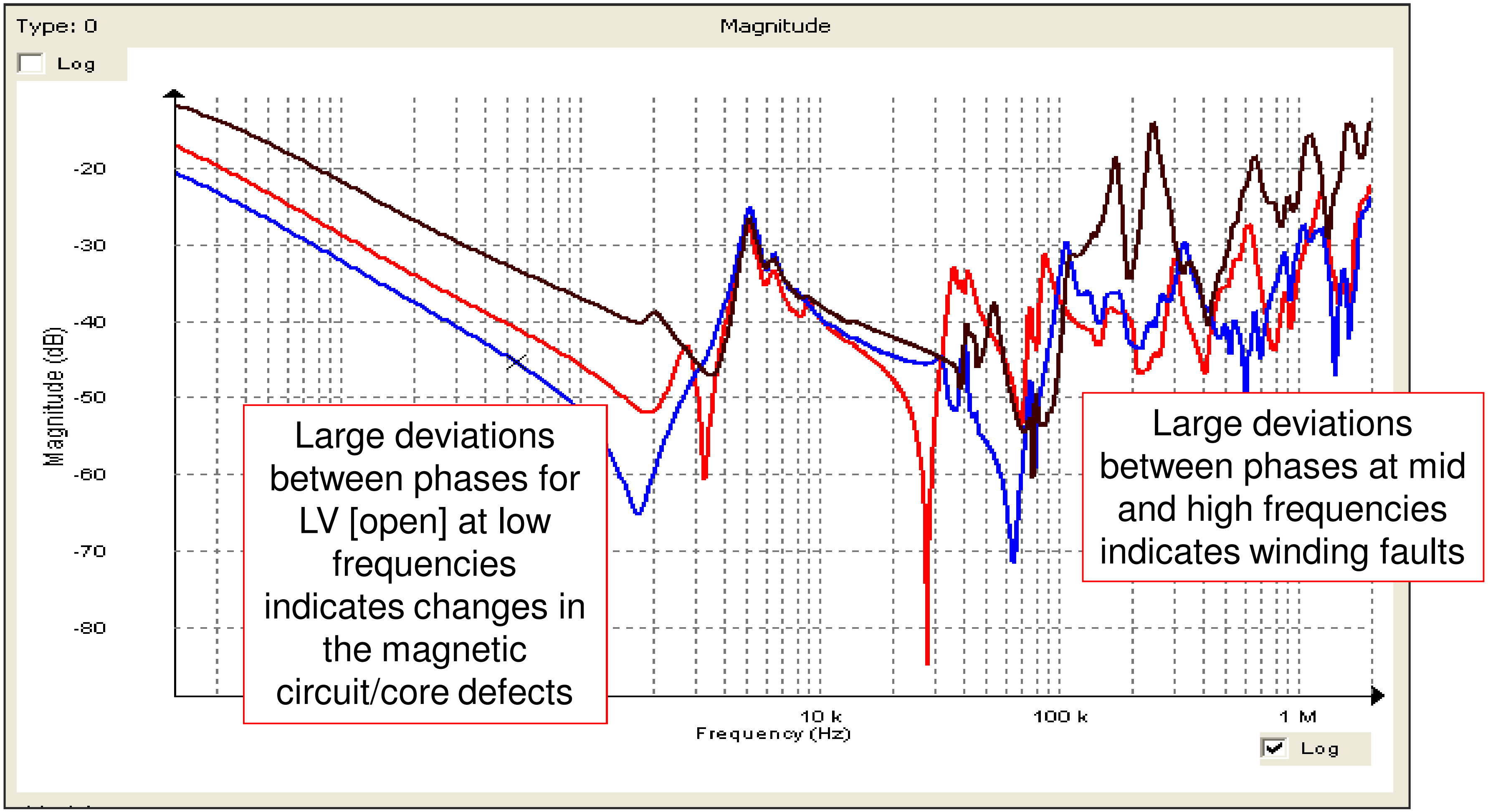
Transformer with serious issues...



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FRAX
The Features And Benefits

FRAX101 – Frequency Response Analyzer

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FRAX101 – Frequency Response Analyzer

Most feature rich and accurate SFRA unit in the world!

Power Input
11-16VDC,
internal battery
(FRAX101)

USB Port
On all models

Bluetooth
On FRAX101

Generator
Reference
Measure
Connectors

Rugged Extruded
Aluminum Case

Active Probe
Connector on FRAX101

All Connectors
Panel Mounted

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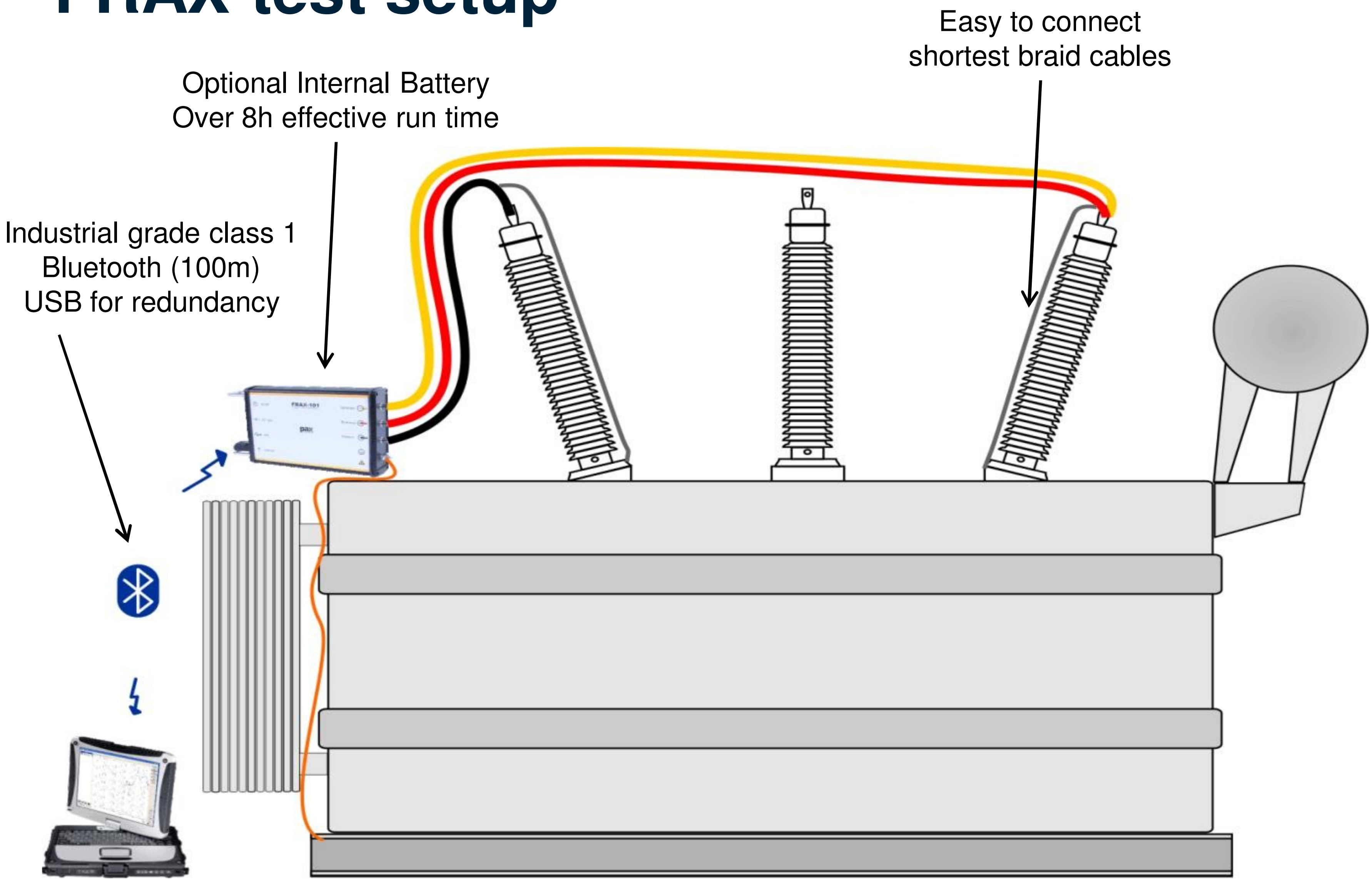
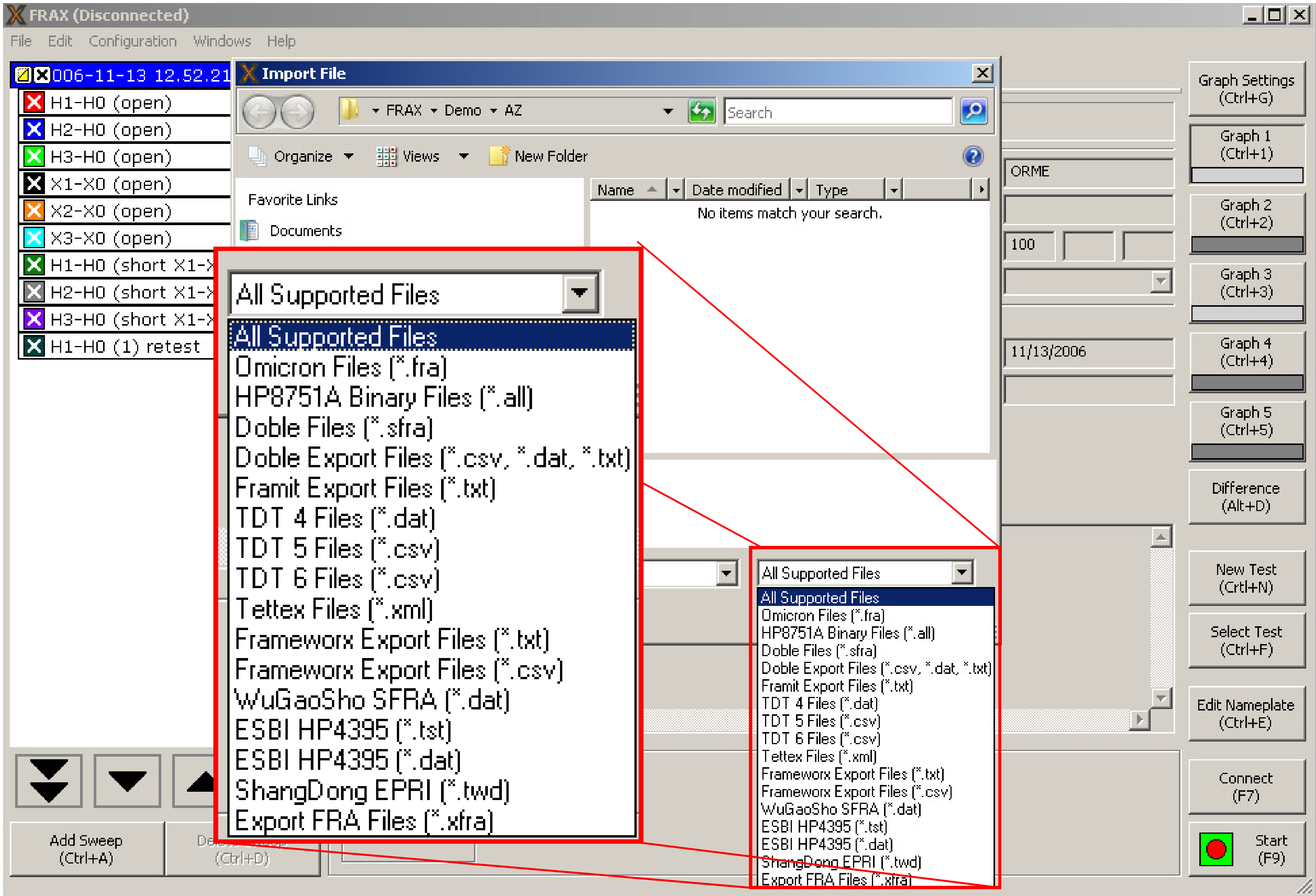
News in FRAX 2.3 SW

- System integrity test (as recommended in GIGRE and other standards) added in measurement templates and field test box FTB-101 with defined response included as standard accessory
- Adjustable output voltage (FRAX101 and FRAX150)
- Extended frequency range 0.1 Hz – 25 MHz
- Standard (low-high) or reversed (high-low) frequency sweeps
- New fast and optimized default frequency sweep and detailed description of alternative sweep settings
- IEEE, IEC and VDE standard measurement templates
- Improved Doble and Omicron import including template data
- CIGRE standard *.xfra file export and import
- Standardized CSV export
- Doble export

FRAX test setup

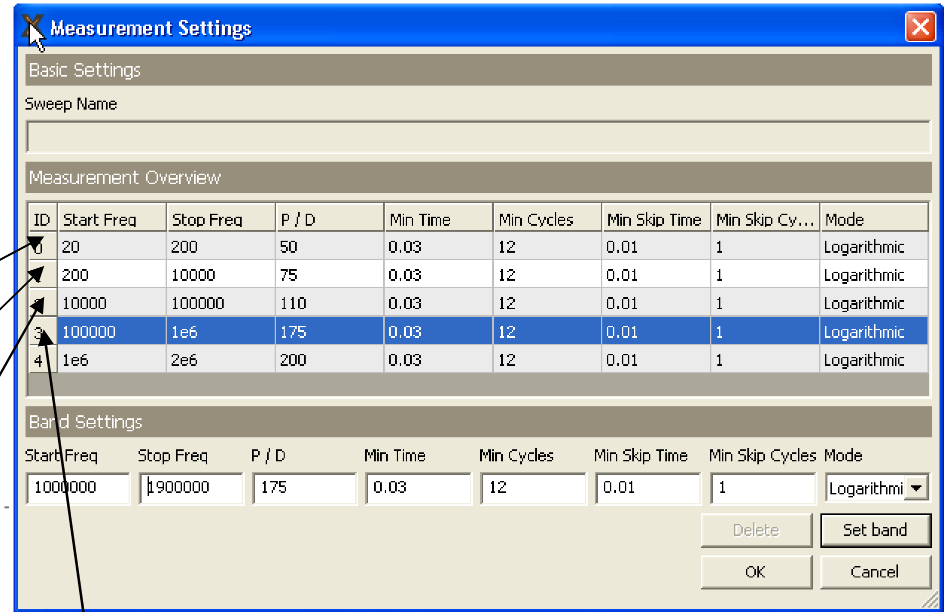


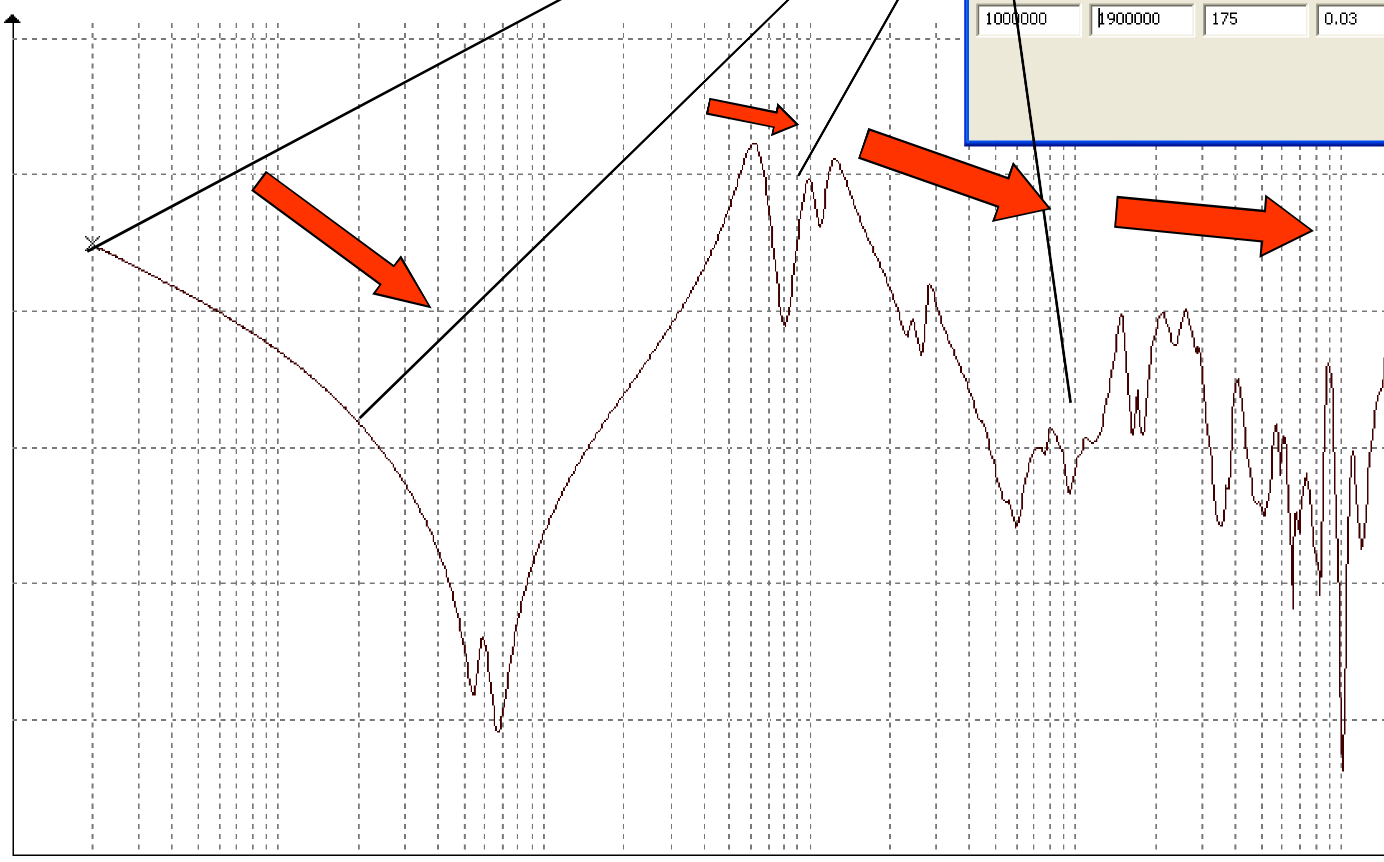
Import formats



Fast testing

Less points where it takes time to test and where high frequency resolution is not needed



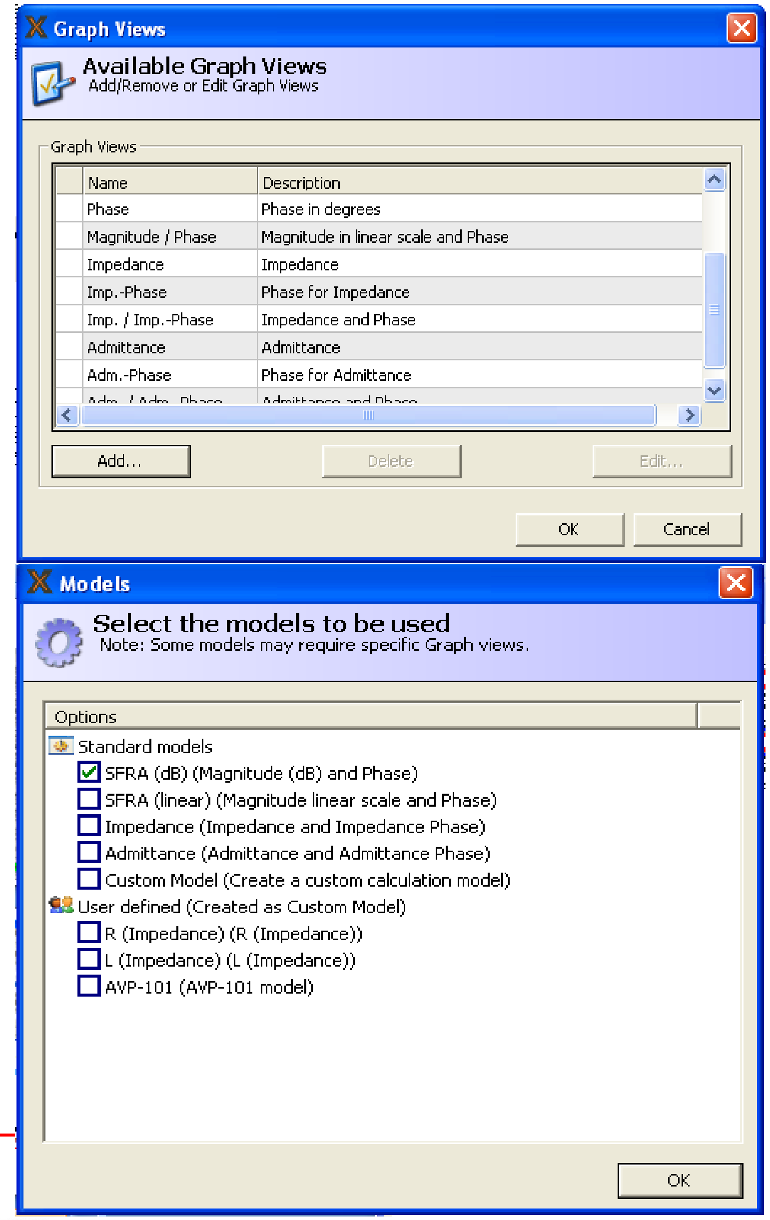


More points where higher frequency resolution is useful

Traditional test about 2 min
vs.
FRAX fast test
< 40 seconds

Unlimited analysis

- Unlimited graph control
- Lots of available models/graphs e.g. magnitude, impedance, admittance, etc
- Ability to create custom calculation models using any mathematic formula and the measured data from all channels



FRAX99

Same As FRAX101 except:

- No internal battery option
- No Bluetooth
- Dynamic range > 115 dB
- Fixed output voltage
- 9 m cable set
- No active probes

FRAX150 (Q1 2010)

Same As FRAX101 except:

- Internal PC/stand-alone
- No internal battery option
- No active probes
- No Bluetooth

FRAX product summary

- Light weight
- Rugged
- Battery operated
- Wireless communication
- Accuracy & Dynamic Range/Noise floor
- Cable practice
- Easy-to-use software
- Export & import of data
- Complies with all SFRA standards and recommend
- Only unit that is compatible with all other SFRA instruments

Sweep Frequency Response Analysis

Application Examples

Time Based Comparison - Example

- 1-phase generator transformer 400 kV
- SFRA measurements before and after scheduled maintenance
- Transformer supposed to be in good condition and ready to be put in service…

Time Based Comparison - Example

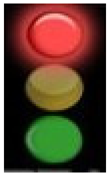
Interpretation according to DL/T 911-2004, China 2005-06-01

Frequency response analysis on winding deformation of power transformers

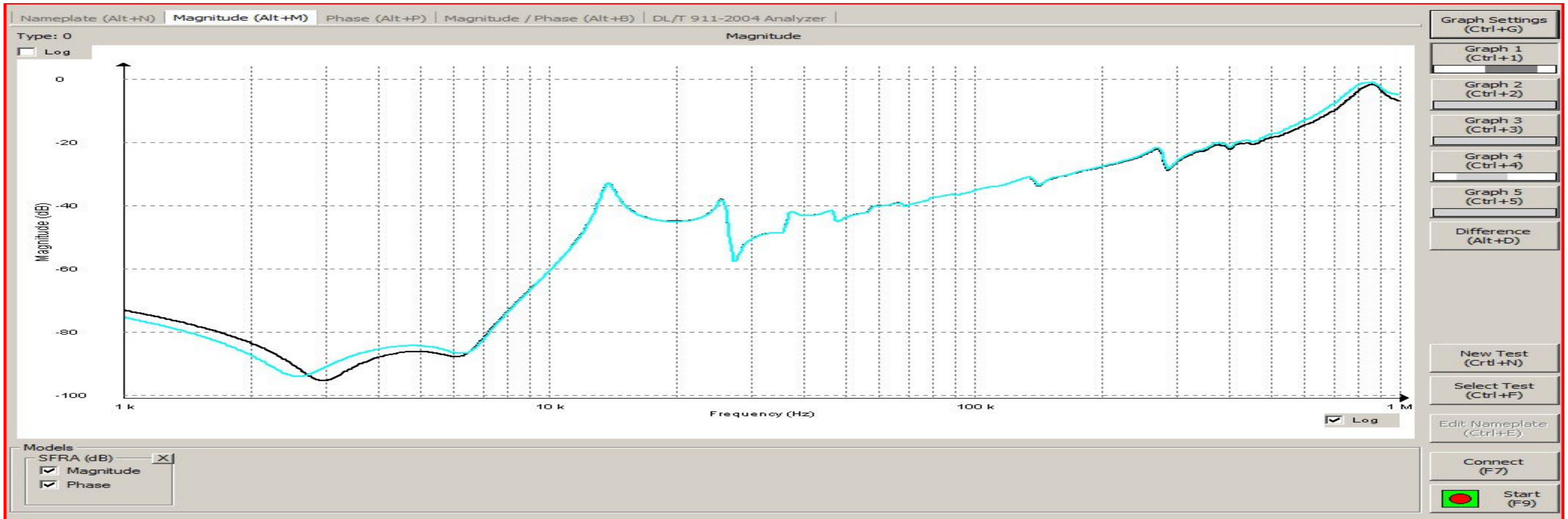
	Value	Severe Distortion	Obvious Distortion	Light Distortion	Normal
R-LF (1kHz - 100kHz)	0.83	R-LF < 0.6	0.6 <= R-LF < 1	1 <= R-LF < 2	2 <= R-LF
R-MF (100kHz - 600kHz)	3.35		R-MF < 0.6	0.6 <= R-MF < 1	1 <= R-MF
R-HF (600kHz - 1MHz)	2.23				0.6 <= R-HF

Conclusion: Obvious Distortion

”Obvious distorsion” as by DL/T911-2004 standard (missing core ground)



Time Based Comparison – After repair



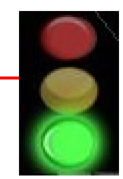
Interpretation according to DL/T 911-2004, China 2005-06-01

Frequency response analysis on winding deformation of power transformers

	Value	Severe Distortion	Obvious Distortion	Light Distortion	Normal
R-LF (1kHz - 100kHz)	2.39	R-LF < 0.6	0.6 <= R-LF < 1	1 <= R-LF < 2	2 <= R-LF
R-MF (100kHz - 600kHz)	3.4		R-MF < 0.6	0.6 <= R-MF < 1	1 <= R-MF
R-HF (600kHz - 1MHz)	2.15				0.6 <= R-HF

Conclusion: Normal

”Normal” as by DL/T911-2004 standard (core grounding fixed)



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Type Based Comparisons (twin-units)

Some parameters for identifying twin-units:

- Manufacturer
- Factory of production
- Original customer/technical specifications
- No refurbishments or repair
- Same year of production or +/-1 year for large units
- Re-order not later than 5 years after reference order
- Unit is part of a series order (follow-up of ID numbers)
- For multi-unit projects with new design: “reference” transformer should preferably not be one of the first units produced

Type Based Comparison - Example

- Three 159 MVA, 144 KV single-phase transformers manufactured 1960
- Put out of service for maintenance/repair after DGA indication of high temperatures
- “Identical” units
- SFRA testing and comparing the two transformers came out OK indicating that there are no electromechanical changes/problems in the transformers
- Short tests indicated high resistance in one unit (confirmed by WRM)

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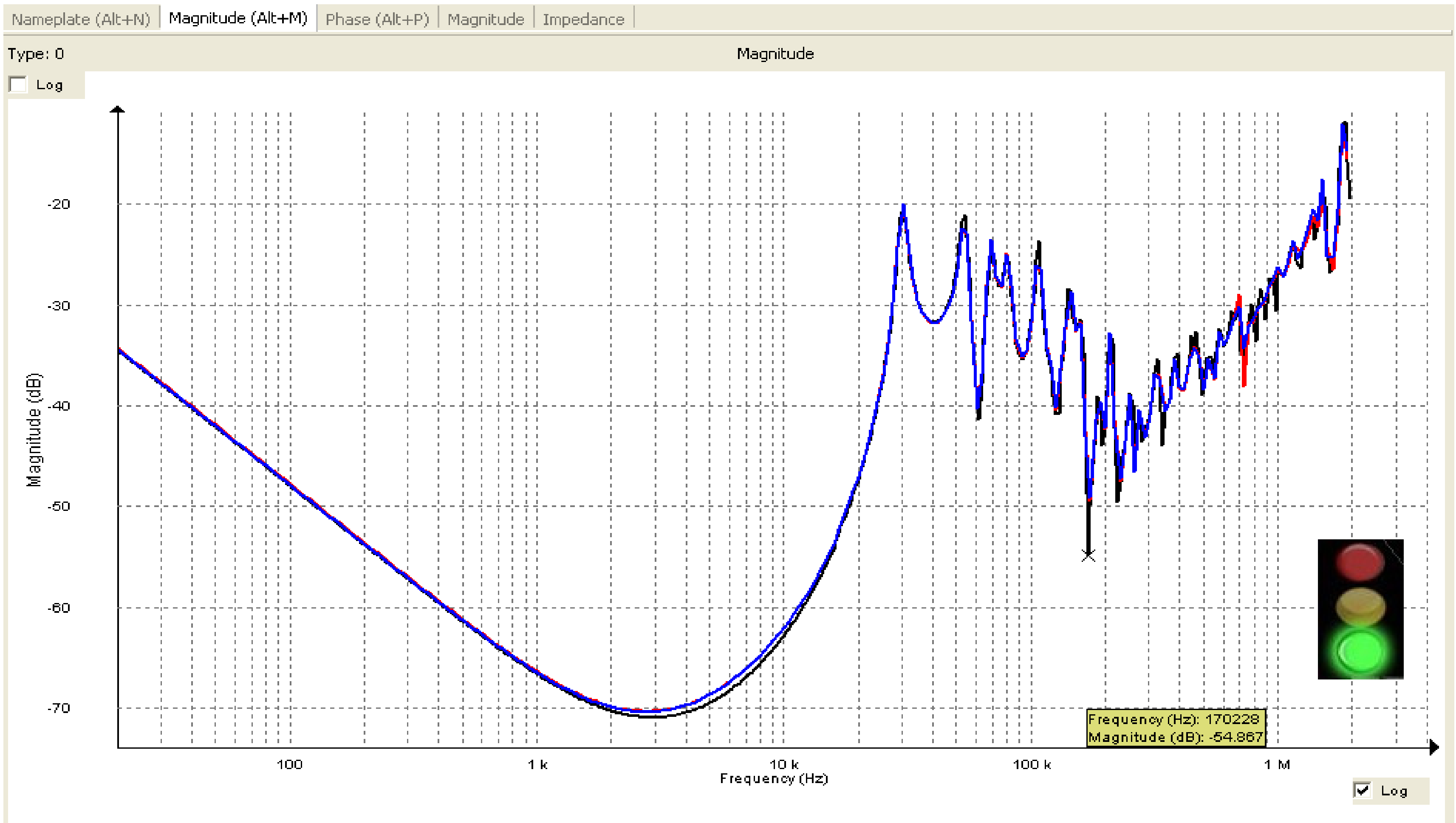
Type Based Comparison – 3x HV [open]



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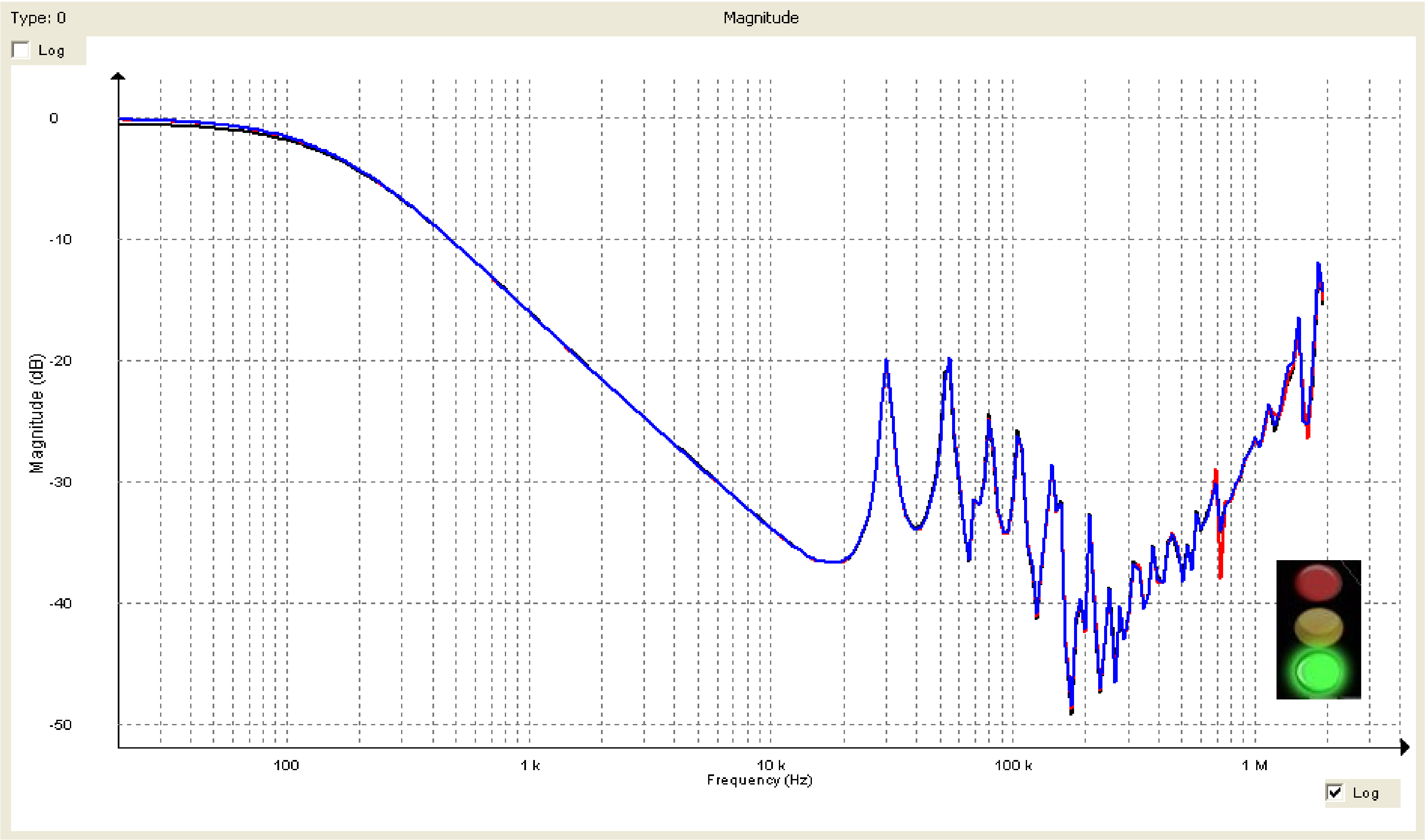
Type Based Comparison – 3x HV [short]



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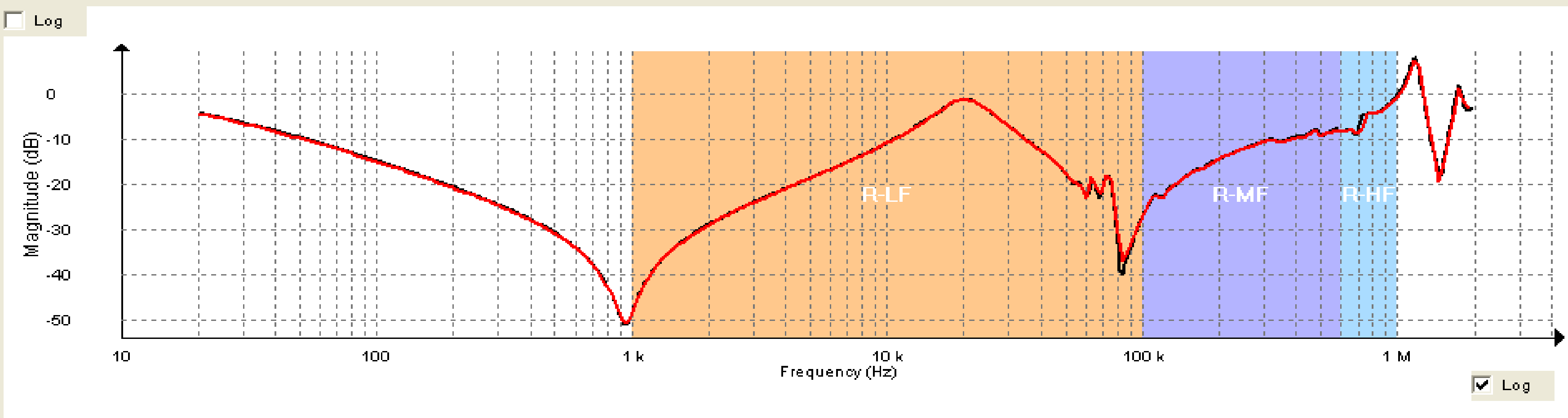
Type Based Comparison – 3x LV [open]

Nameplate (Alt+N) | Magnitude (Alt+M) | Phase (Alt+P) | Magnitude | Impedance | DL/T 911-2004 Analyzer

Model: SFRA (dB) - Magnitude   Type: 0

Id	Name	R-LF	R-MF	R-HF	Conclusion
R 1-2	[X1-X2 (open) v1v2-u1u2] - [X1-X2 (open) v1v2-u1u2]	2.98	3.49	1.41	Normal
R 1-3	[X1-X2 (open) v1v2-u1u2] - [X1-X2 (open) v1v2-u1u2]	2.93	2.40	0.82	Normal
R 2-3	[X1-X2 (open) v1v2-u1u2] - [X1-X2 (open) v1v2-u1u2]	3.61	2.43	0.94	Normal



Interpretation according to DL/T 911-2004, China 2005-06-01

Frequency response analysis on winding deformation of power transformers

	Value	Severe Distortion	Obvious Distortion	Light Distortion	Normal
R-LF (1kHz - 100kHz)	2.98	R-LF < 0.6	0.6 <= R-LF < 1	1 <= R-LF < 2	2 <= R-LF
R-MF (100kHz - 600kHz)	3.49		R-MF < 0.6	0.6 <= R-MF < 1	1 <= R-MF
R-HF (600kHz - 1MHz)	1.41				0.6 <= R-HF

Conclusion: Normal

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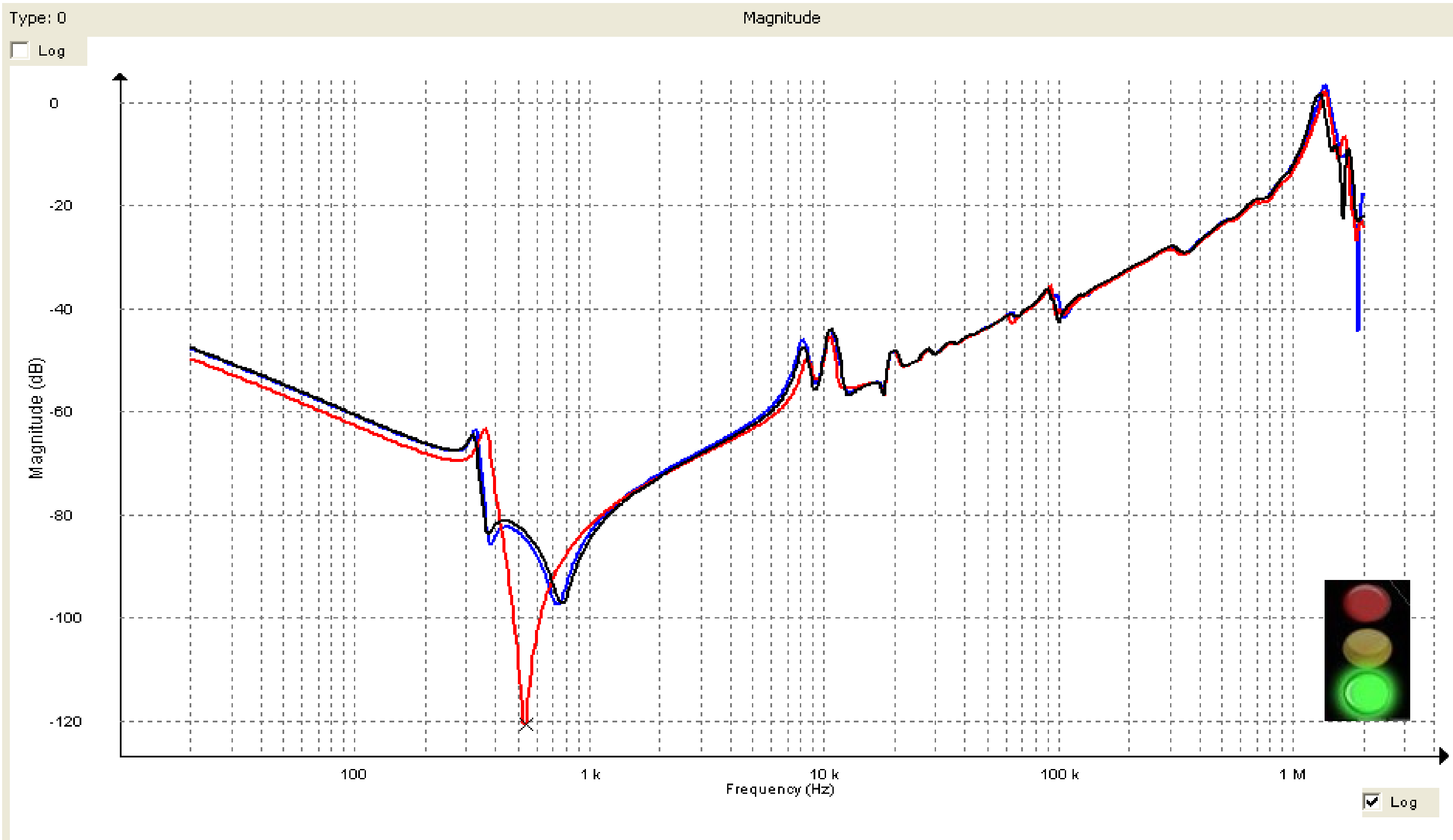
Design Based Comparisons

- Power transformers are frequently designed in multi-limb assembly. This kind of design can lead to symmetric electrical circuits
- Mechanical defects in transformer windings usually generate non-symmetric displacements
- Comparing FRA results of separately tested limbs can be an appropriate method for mechanical condition assessment
- Pending transformer type and size, the frequency range for design-based comparisons is typically limited to about 1 MHz

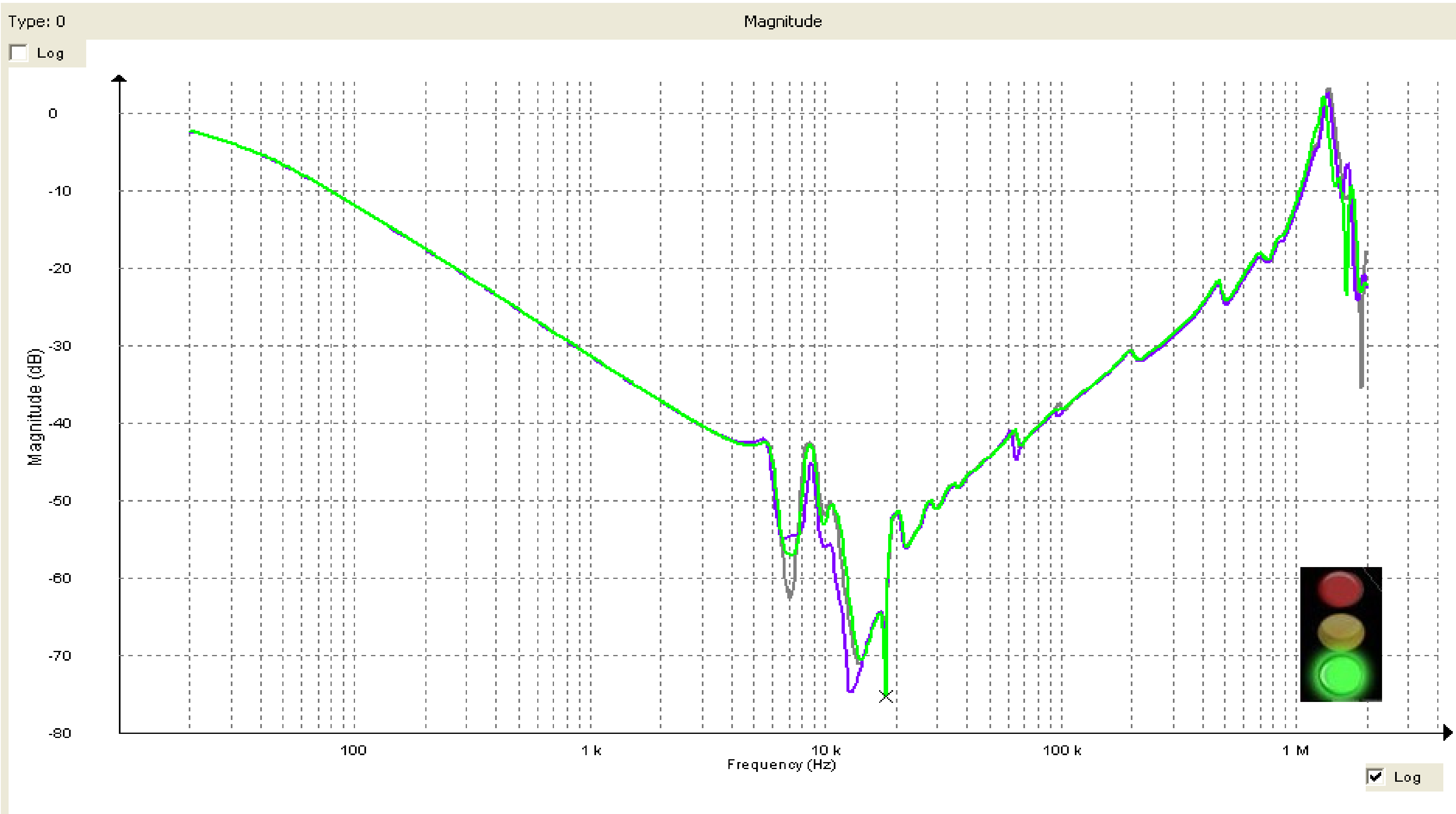
Design Based Comparison - Example

- 40 MVA, 114/15 kV, manufactured 2006
- Taken out of service to be used as spare
- No known faults
- No reference FRA measurements from factory
- SFRA testing, comparing symmetrical phases came out OK
- The results can be used as fingerprints for future diagnostic tests

Designed Based Comparison – HV [open]



Designed Based Comparison – HV [short]



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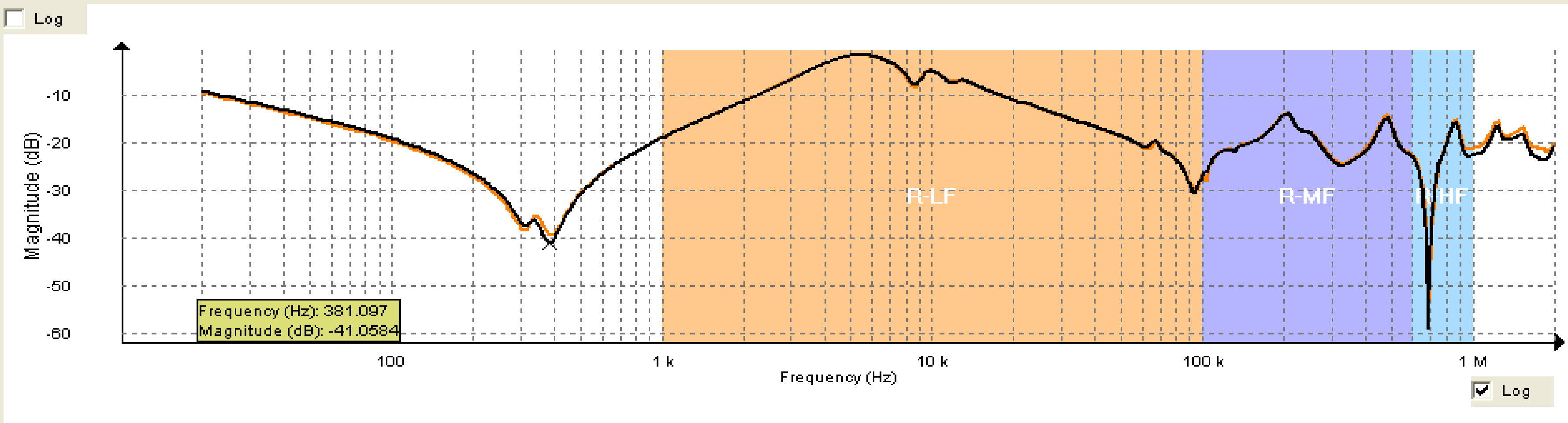
Designed Based Comparison – LV [open]

Model: SFRA (dB) - Magnitude   Type: 0

Id	Name	R-LF	R-MF	R-HF	Conclusion
R 1-2	[a1-n1 [open]] - [b1-n1 [open]]	2.69	2.62	2.68	Normal
R 1-3	[a1-n1 [open]] - [c1-n1 [open]]	3.44	2.37	1.65	Normal
R 2-3	[b1-n1 [open]] - [c1-n1 [open]]	2.94	2.31	1.48	Normal

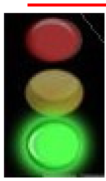


Interpretation according to DL/T 911-2004, China 2005-06-01

Frequency response analysis on winding deformation of power transformers

	Value	Severe Distortion	Obvious Distortion	Light Distortion	Normal
R-LF (1kHz - 100kHz)	3.44	R-LF < 0.6	0.6 <= R-LF < 1	1 <= R-LF < 2	2 <= R-LF
R-MF (100kHz - 600kHz)	2.37		R-MF < 0.6	0.6 <= R-MF < 1	1 <= R-MF
R-HF (600kHz - 1MHz)	1.65				0.6 <= R-HF

Conclusion: Normal



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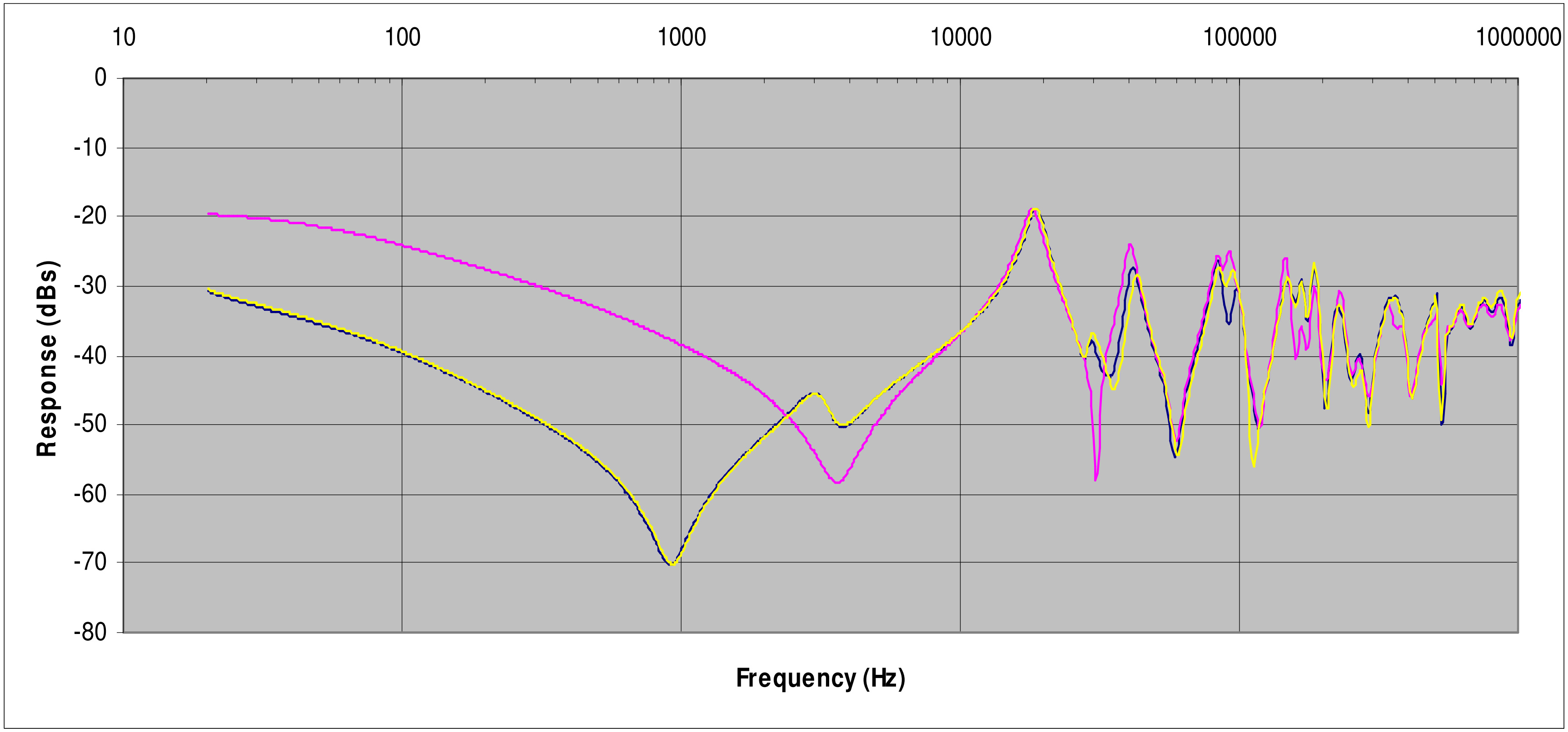
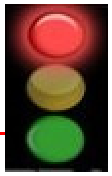
Design Based Comparison – After Suspected Fault

- Power transformer, 25MVA, 55/23kV, manufactured 1985
- By mistake, the transformer was energized with grounded low voltage side
- After this the transformer was energized again resulting in tripped CB (Transformer protection worked!)
- Decision was taken to do diagnostic test

Design Based Comparison – After Suspected Fault



- HV-0, LV open
- A and C phase OK, large deviation on B-phase (shorted turn?)



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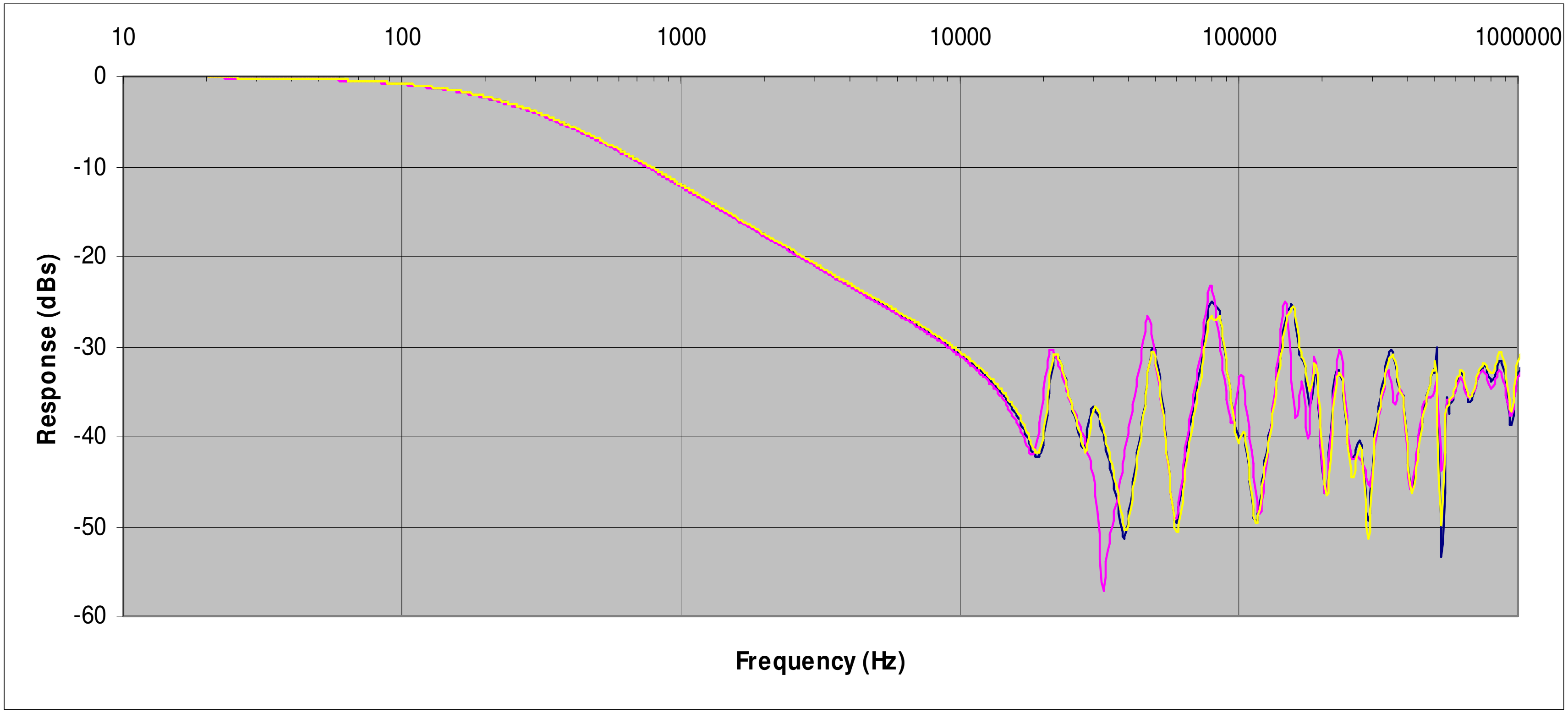
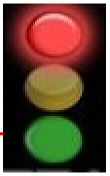
Design Based Comparison – After Suspected Fault



- HV-0 (LV shorted)
- A and C phase OK, deviation on B-phase



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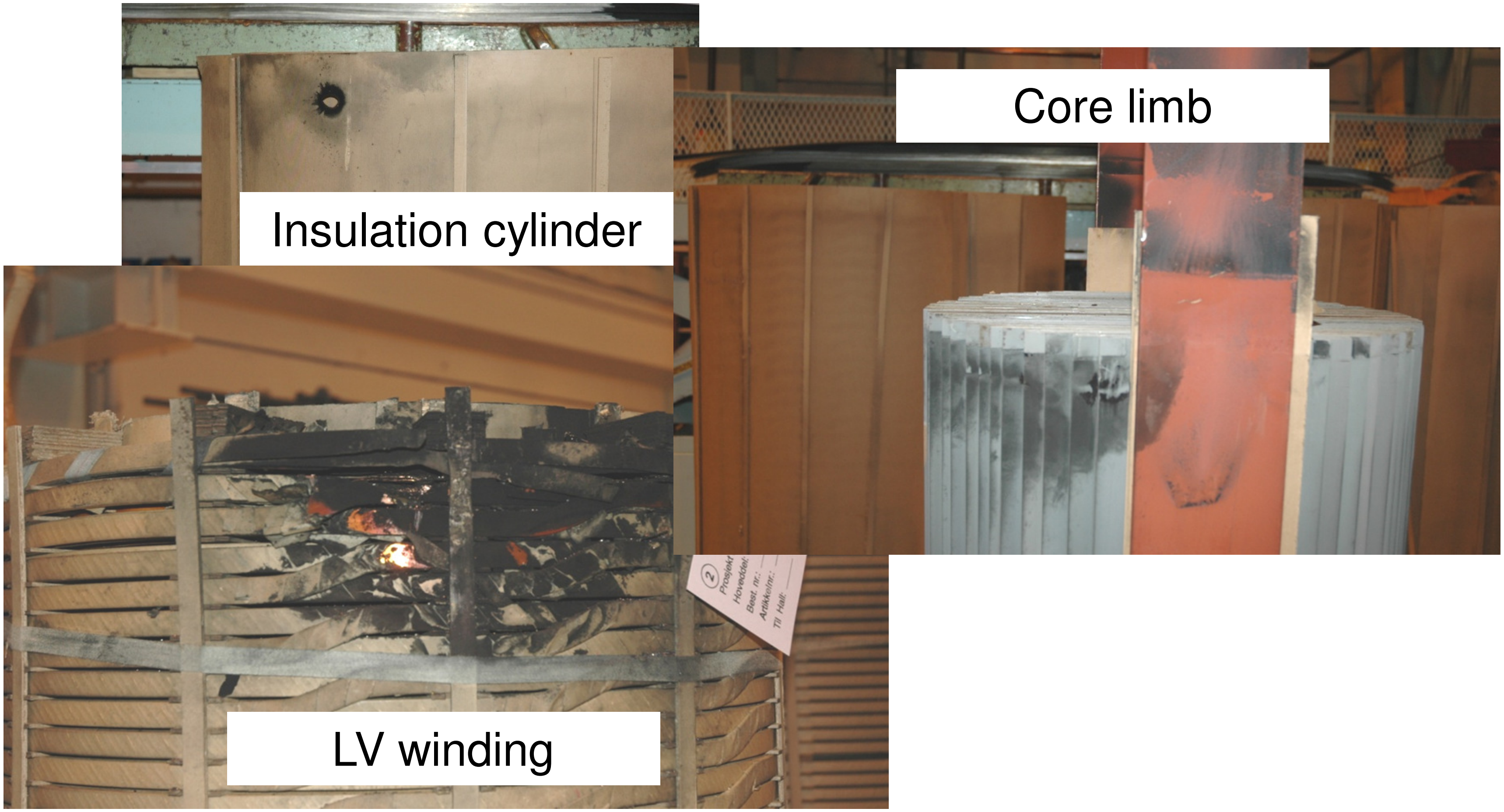
And how did the mid-leg look like…?



Considerations when performing SFRA Tests

or

How do I maximize my investment in time and money when performing SFRA measurements?

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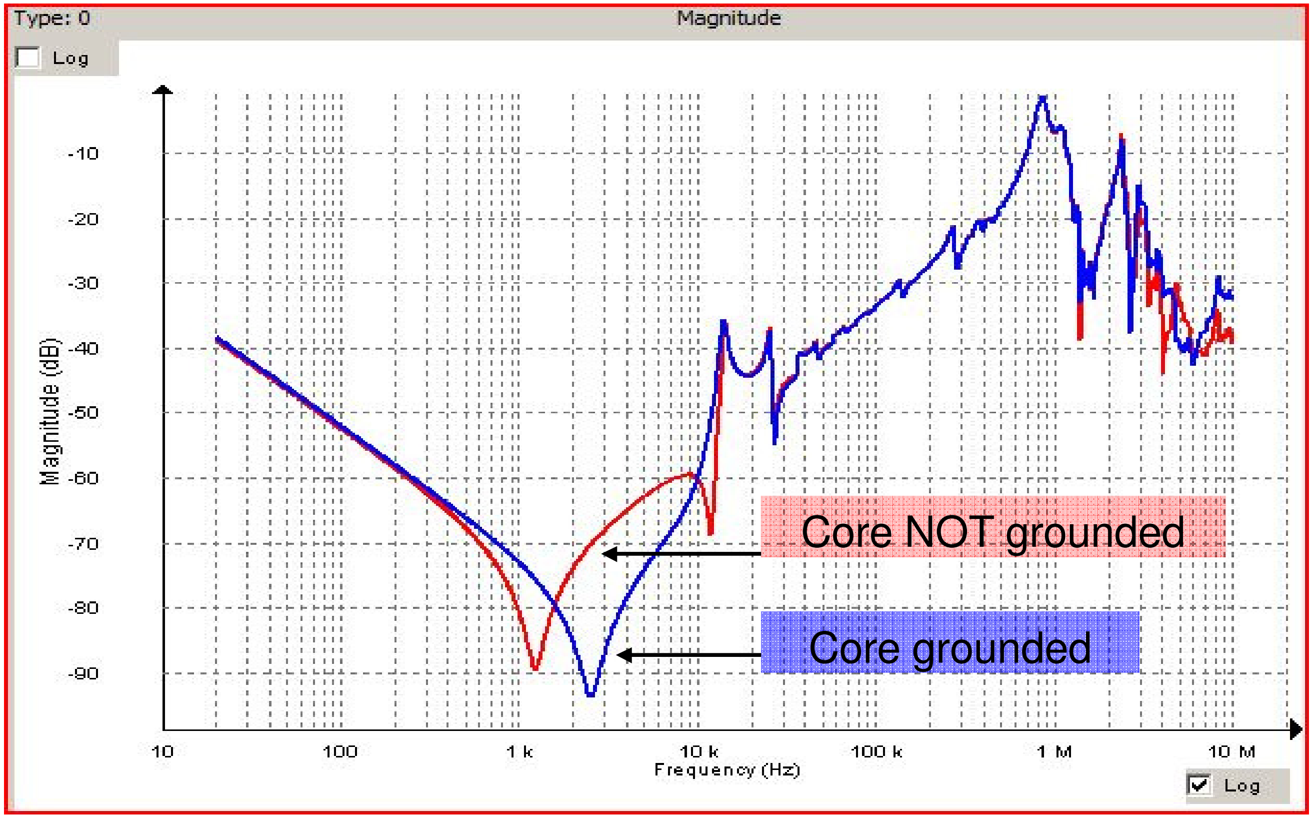
Test results – always comparisons



Repeatability is of utmost importance!

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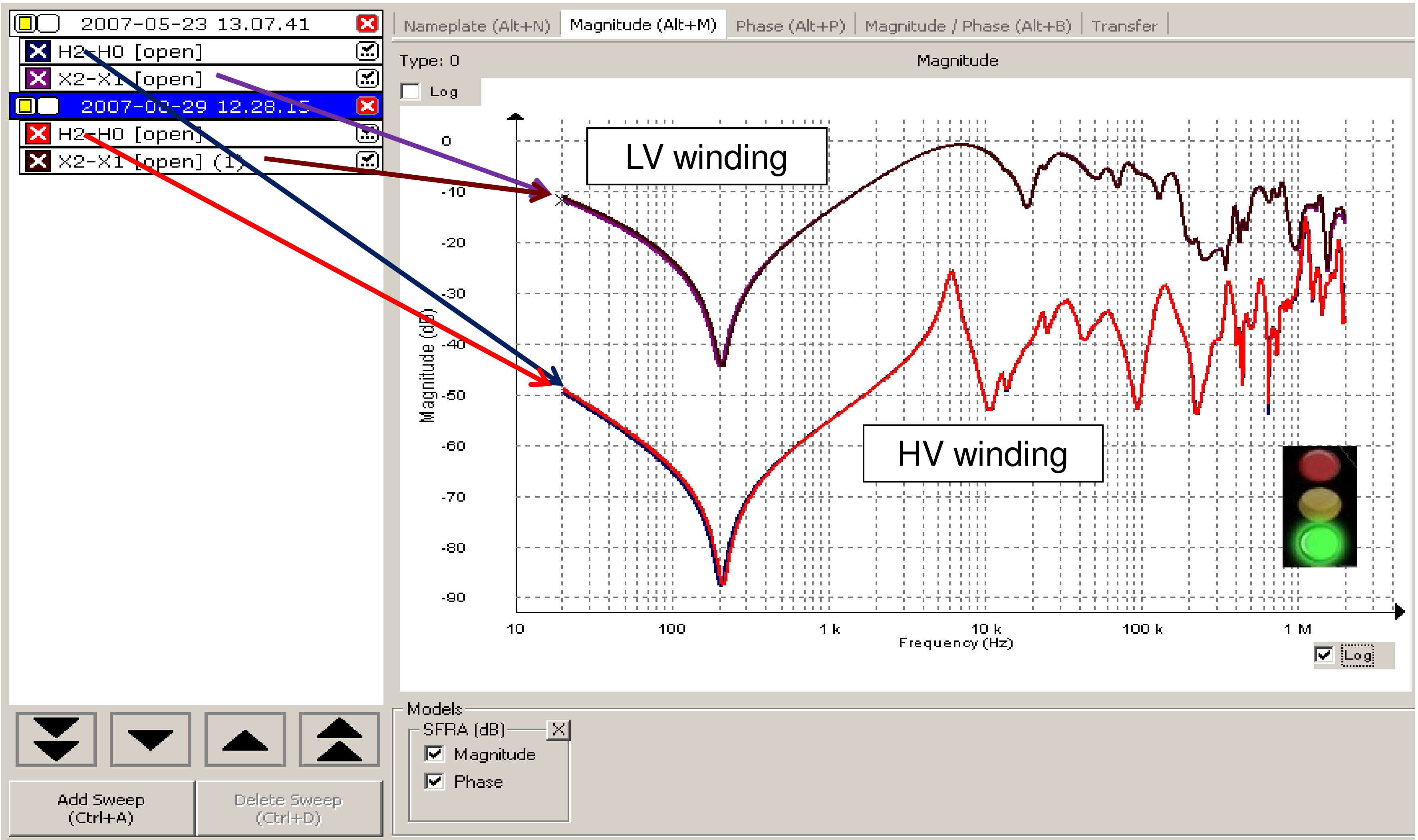
Example of repeatability

- 105 MVA, Single phase Generator Step-up (GSU) transformer
- SFRA measurements with FRAX101 before and after a severe short-circuit in the generator
  - Two different test units
  - Tests performed by two different persons
  - Test performed at different dates

Before (2007-05-23) and after fault (2007-08-29)

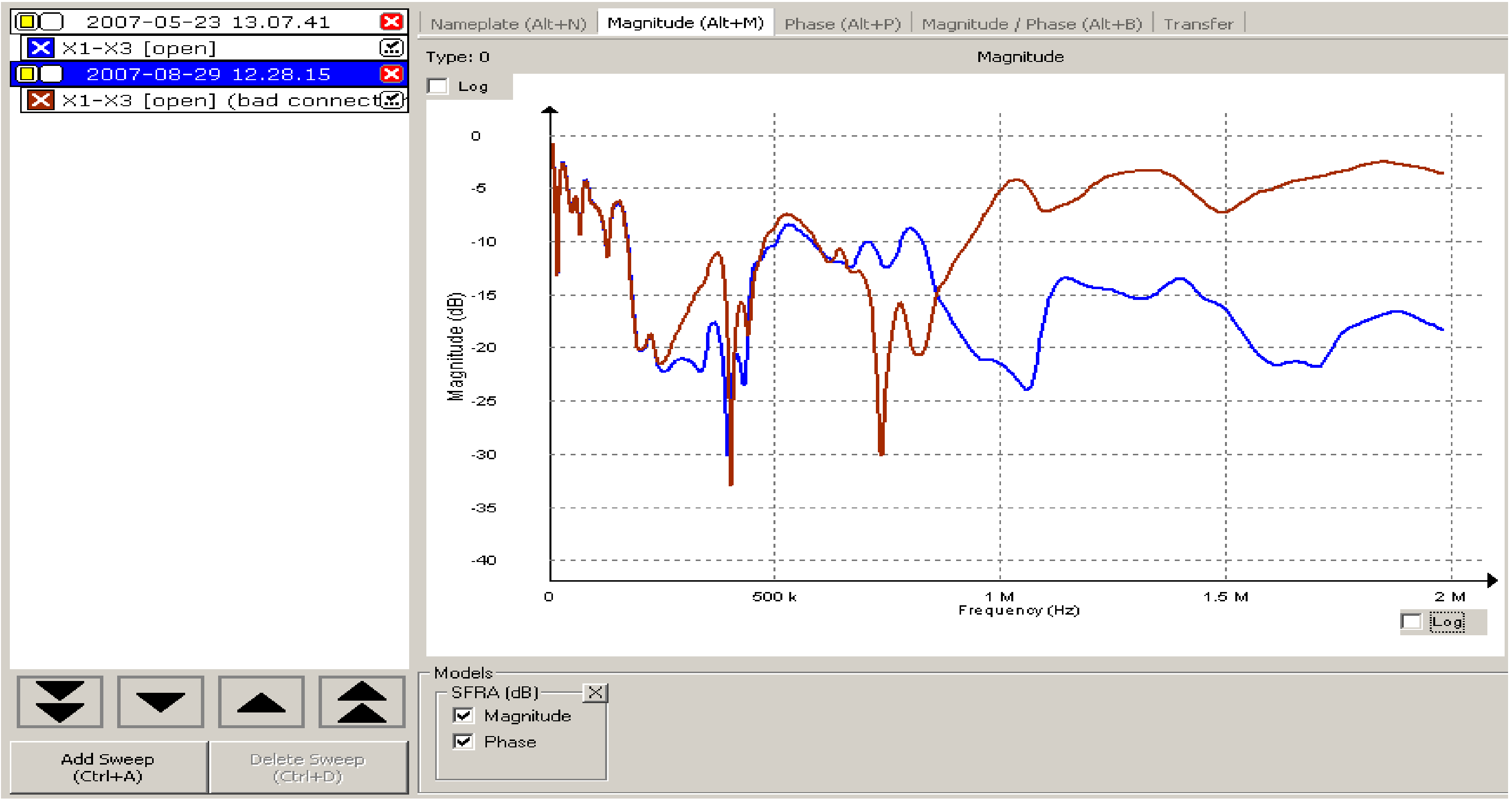


Potential compromising factors

- Connection quality
- Shield grounding practice
- Instrument dynamic range/internal noise floor
- Understanding core property influence in lower frequencies in “open” - circuit SFRA measurements

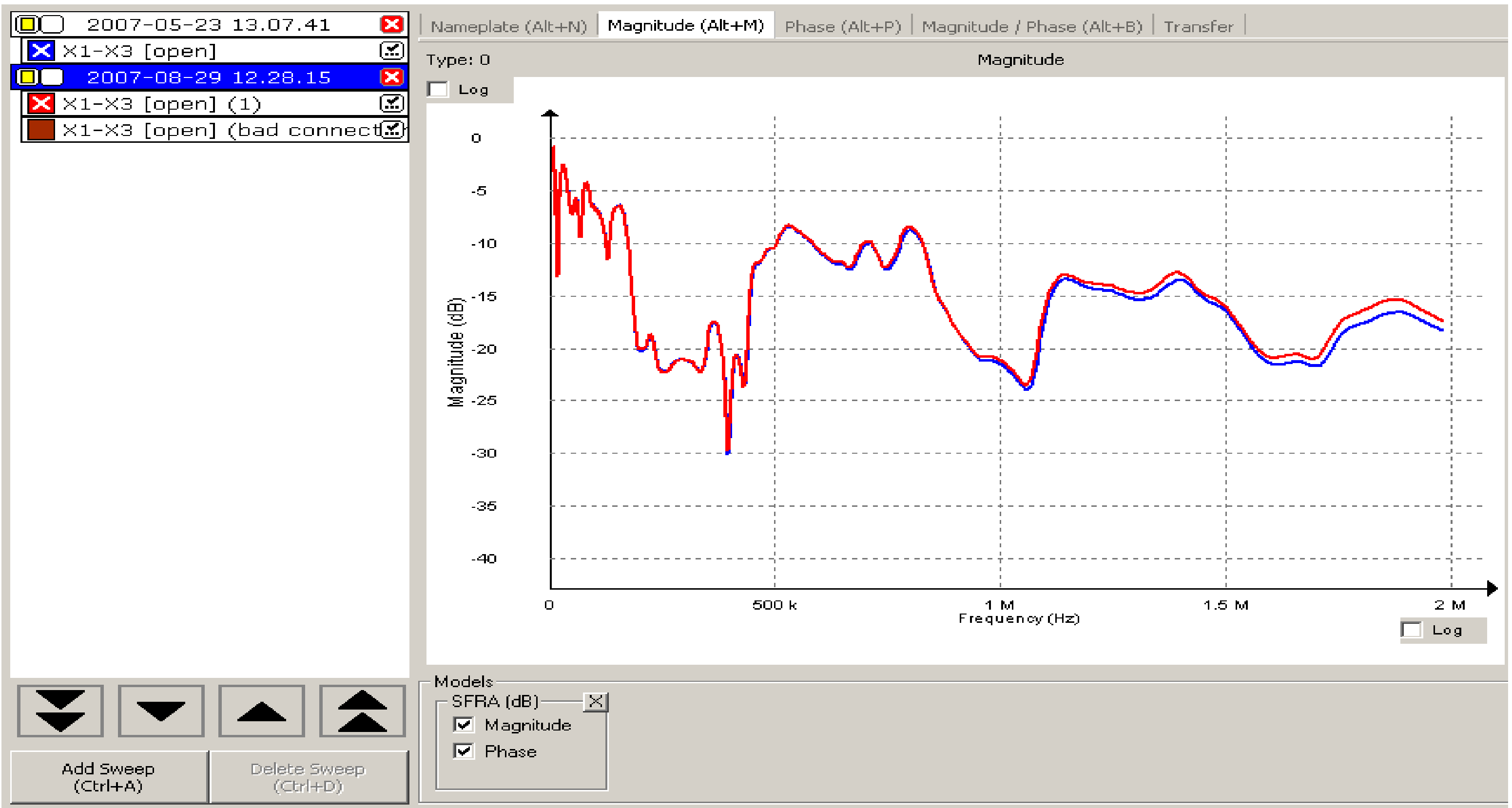
Bad connection

- Bad connection can affect the curve at higher frequencies



Good connection

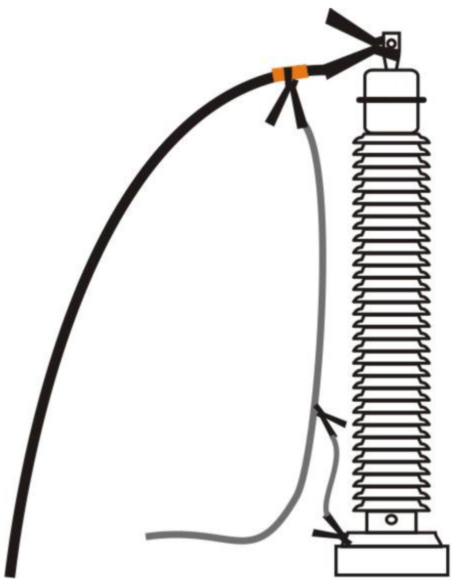
- After proper connections were made



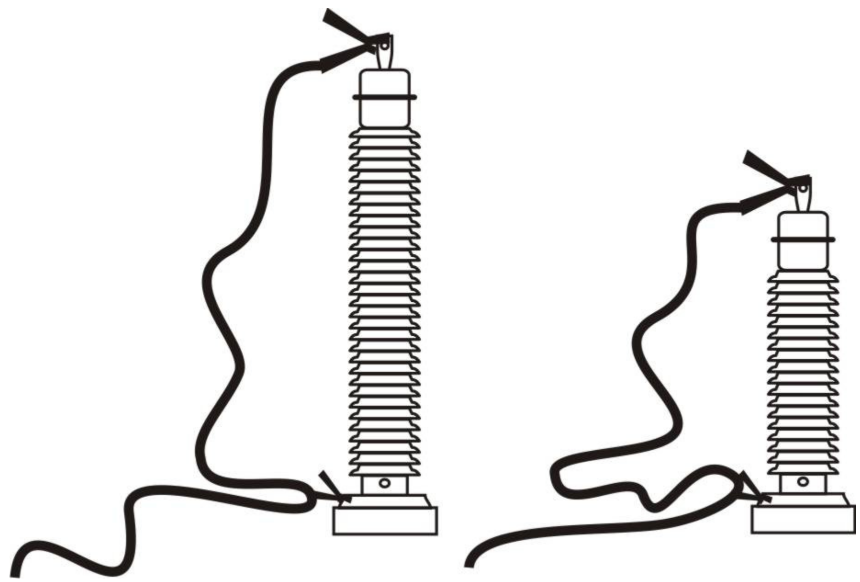
FRAX C-Clamp

- C-Clamp ensures good contact quality
- Penetrates non conductive layers
- Solid connection to round or flat busbars
- Provides strain relief for cable
- Separate connector for single or multible ground braids

Proper ground connection ensures repeatability at high frequencies



CIGRE grounding practice; use shortest braid from cable shield to bushing flange.



Poor grounding practice

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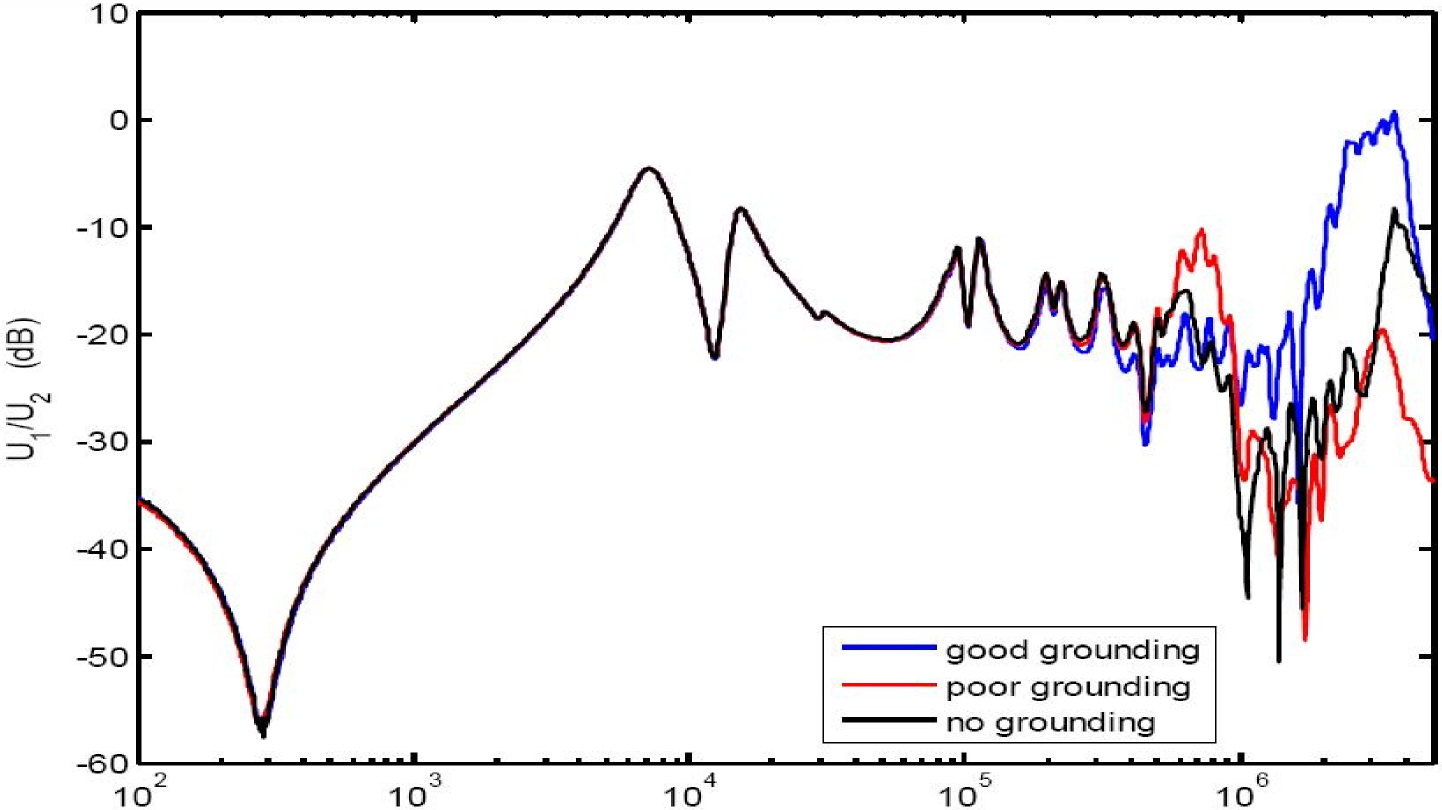
Shield grounding influence



C. Homagk et al, "Circuit design for reproducible on-site measurements of transfer function on large power transformers using the SFRA method", ISH2007

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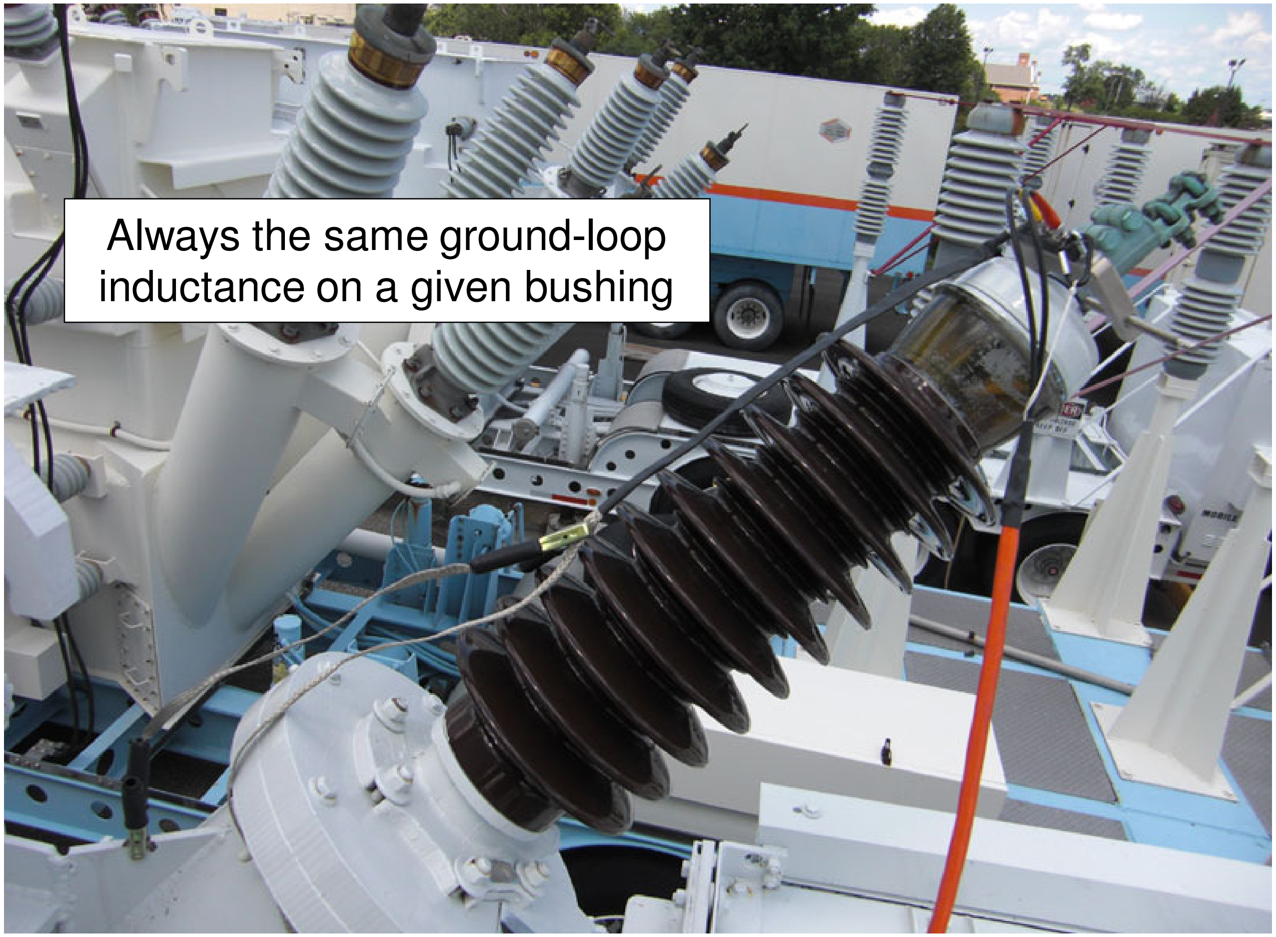
FRAX cable set and grounding



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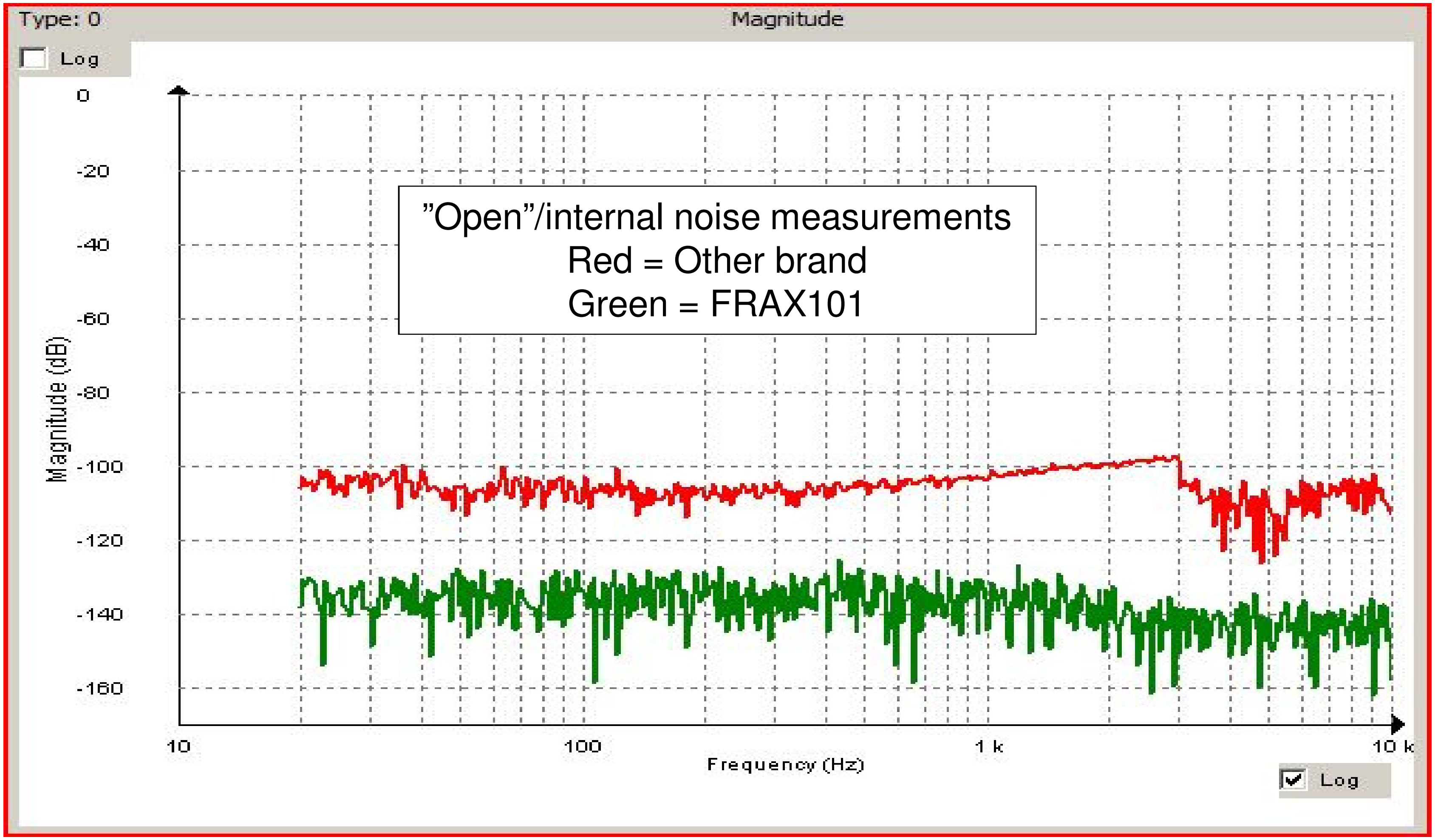
Instrument performance

- Transformers have high impedance/large attenuation at first resonance
- Internal instrument noise is often the main limiting source, not substation noise
- Test your instruments internal noise by running a sweep with “open cables” (Clamps not connected to transformer)

Internal noise level – ”Noise floor”



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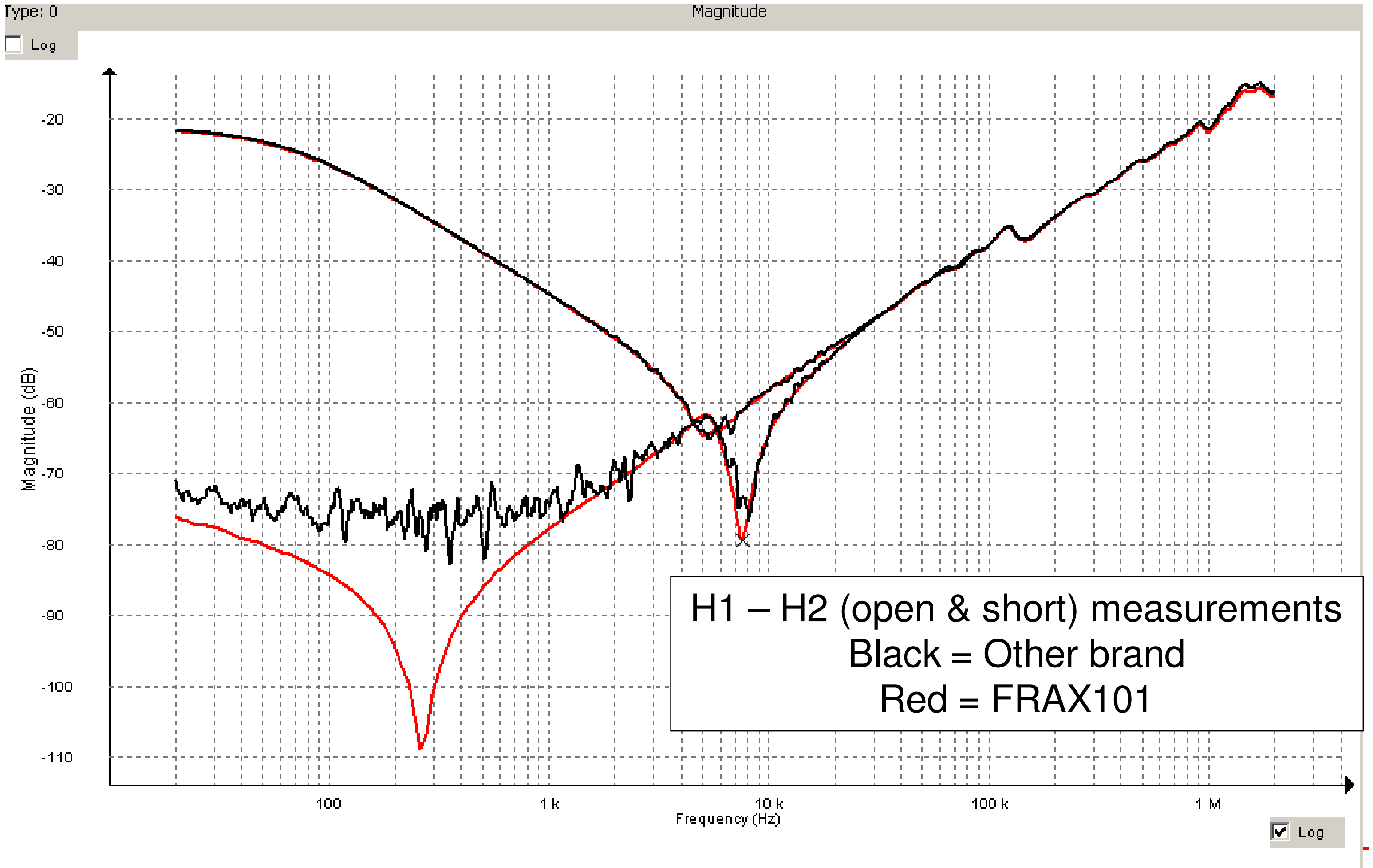
Example of internal noise problem



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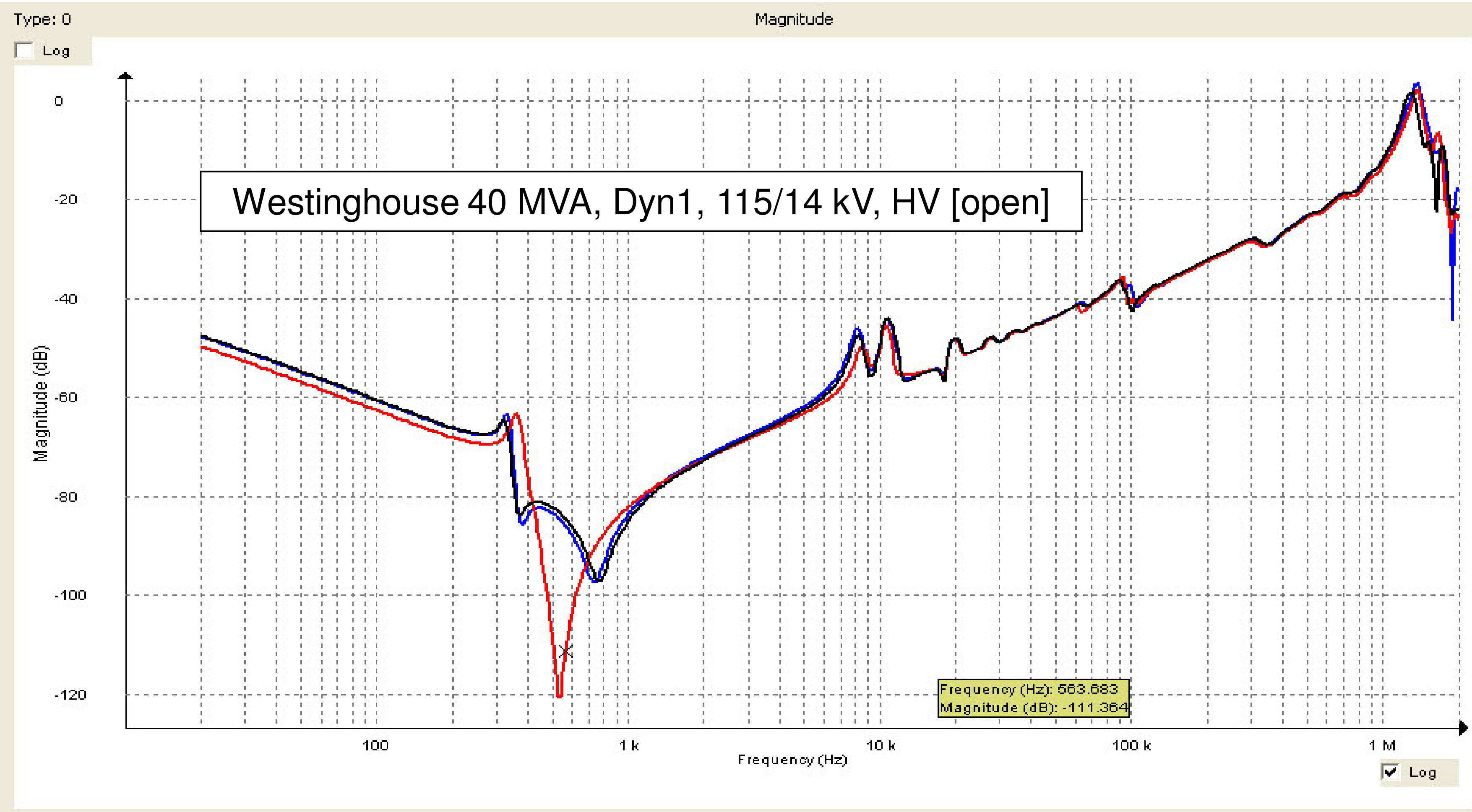
Why you need at least -100 dB...



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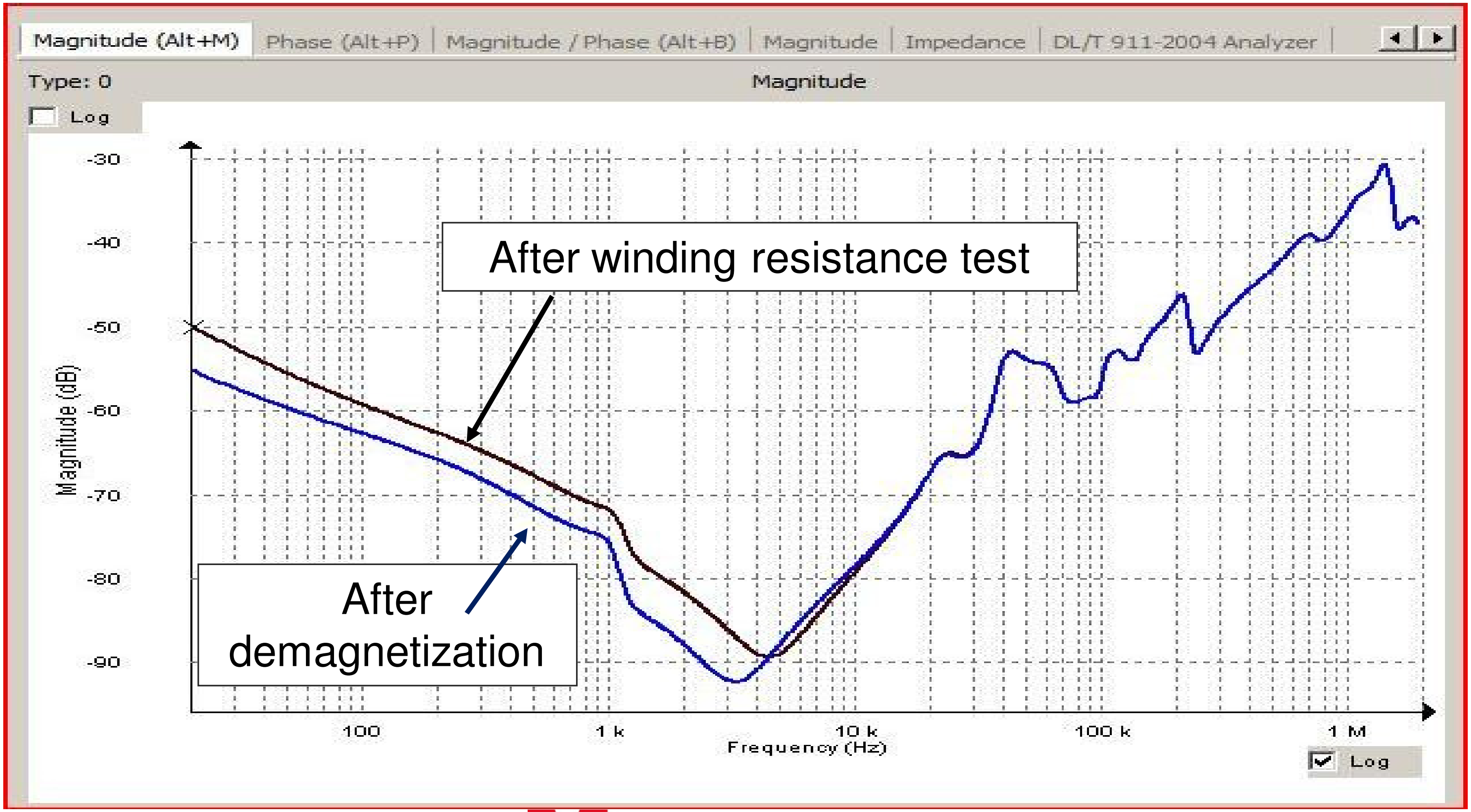
Influence of core

- Try to minimize the effect, however, some differences are still to be expected and must be accepted.
- Preferably:
  - perform SFRA measurements prior to winding resistance measurements (or demagnetize the core prior to SFRA measurements)
  - Use the same measurement voltage in all SFRA measurements

Run winding resistance test after SFRA!



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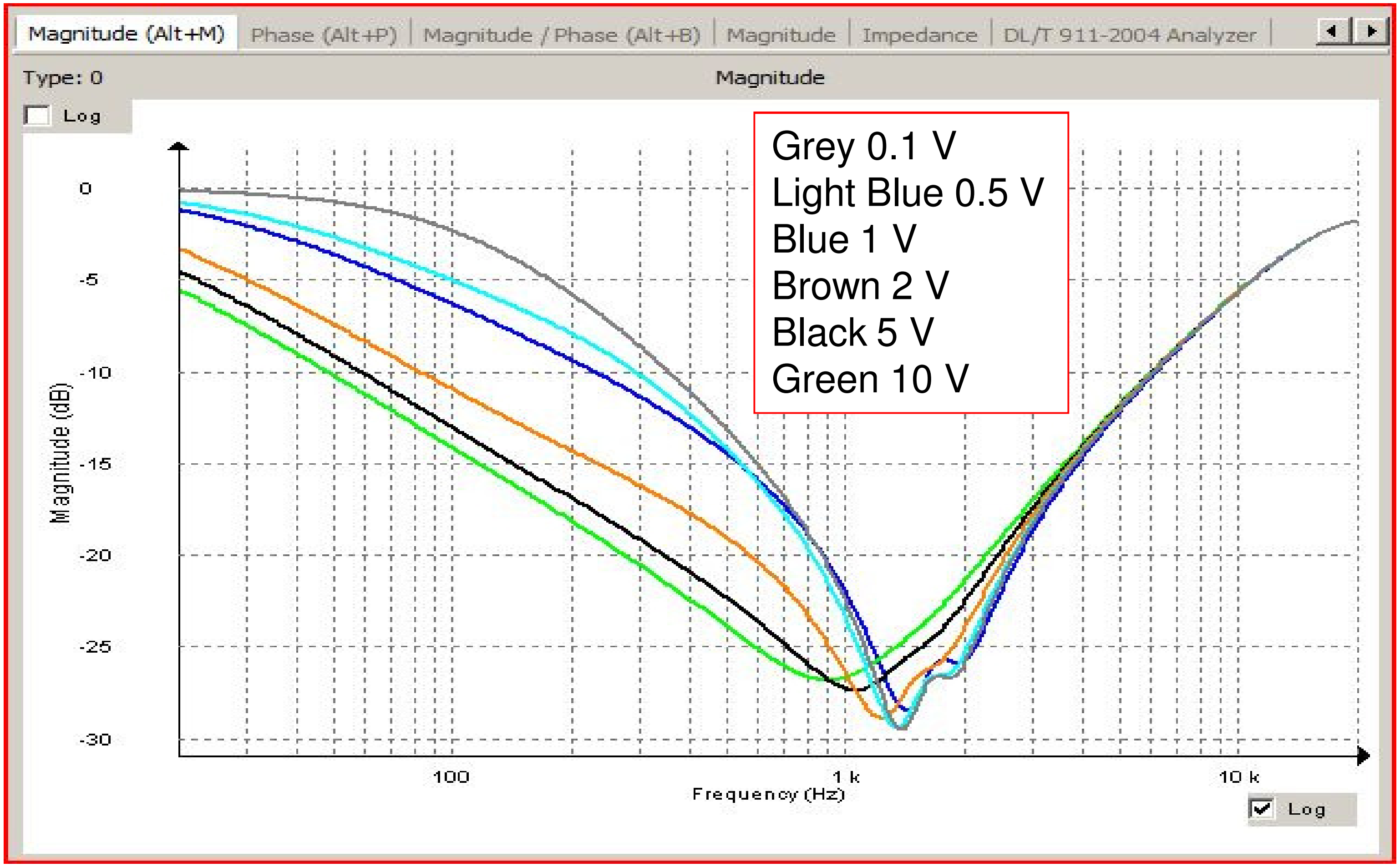
Measurement voltage 0.1 – 10V



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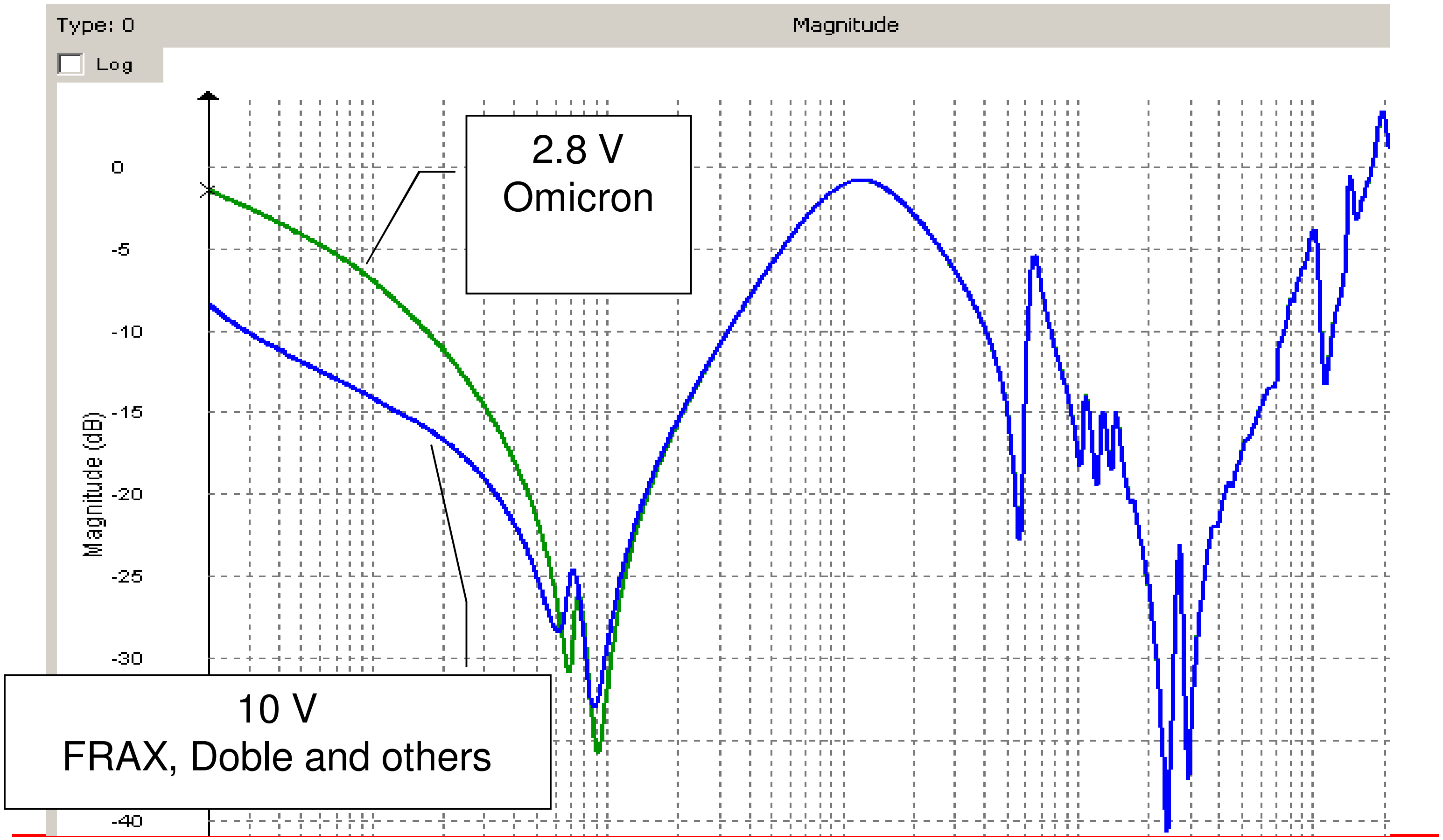
Effect of applied measurement voltage



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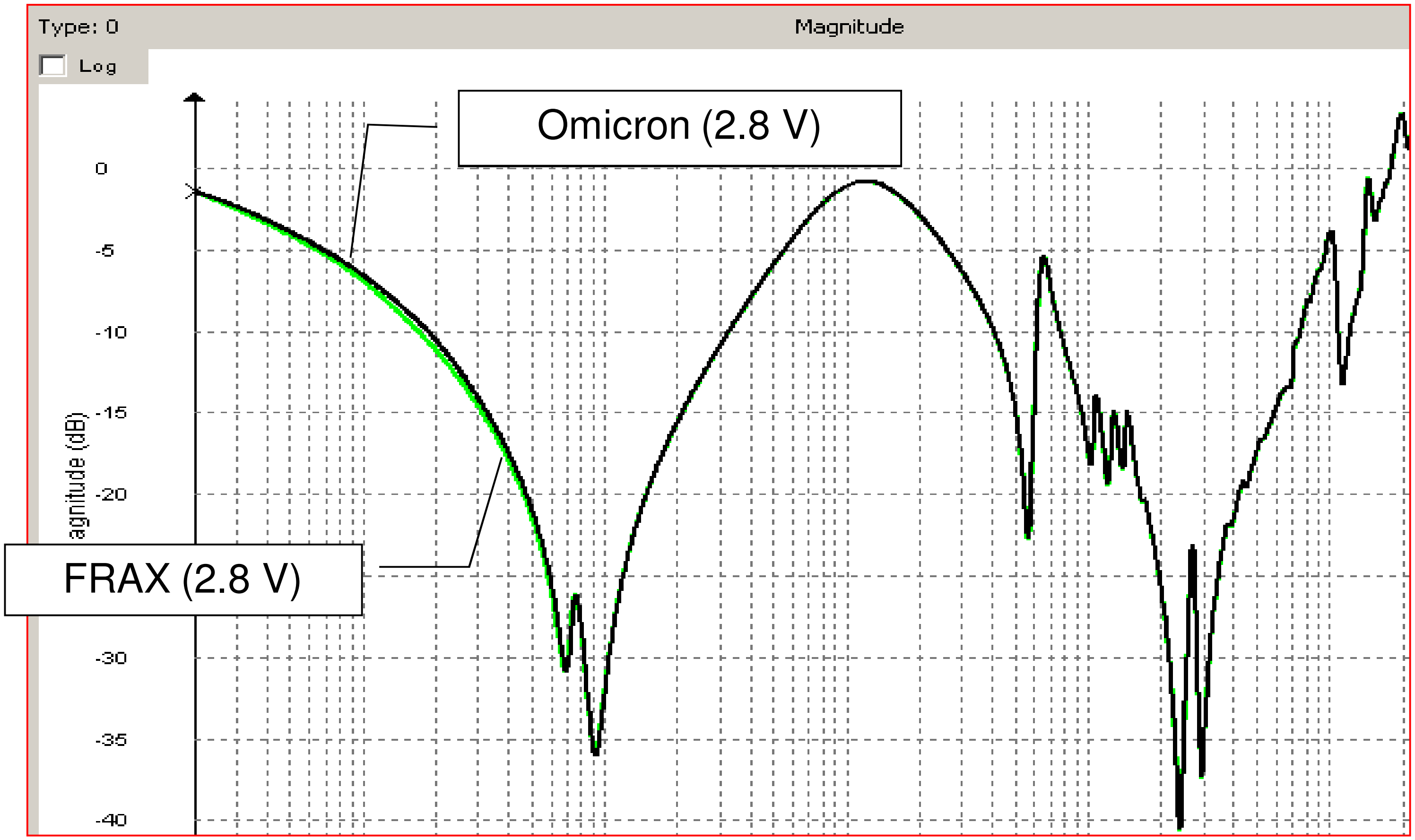
FRAX has adjustable output voltage!



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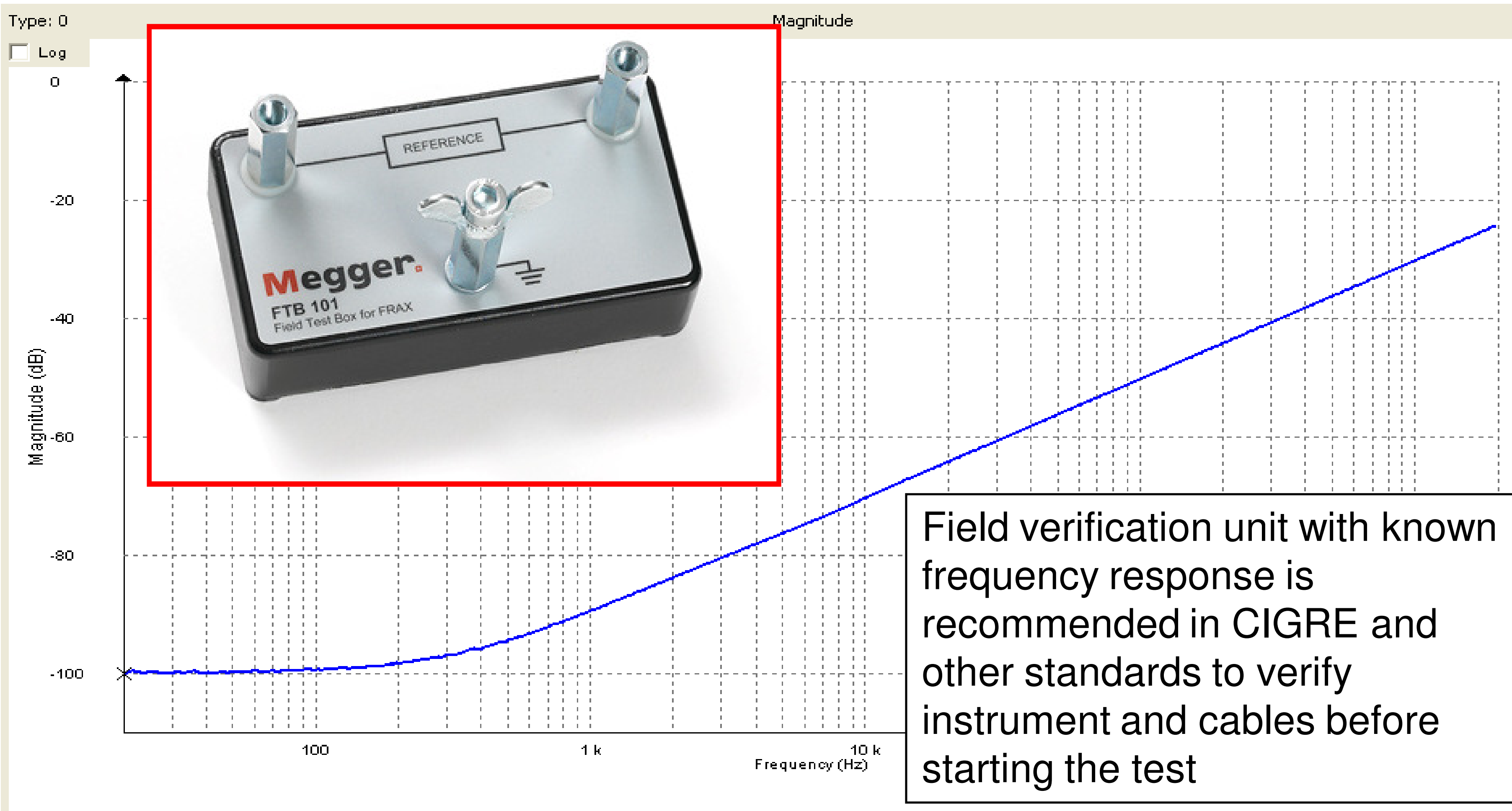
Field Verification Unit



Field verification unit with known frequency response is recommended in CIGRE and other standards to verify instrument and cables before starting the test

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Summary – Measurement accuracy and repeatability

- The basis of SFRA measurements is comparison and repeatability is mandatory
- To ensure high repeatability the following is important
  - Use of a high quality, high accuracy instrument with inputs and output impedance matched to the coaxial cables (e.g. 50 Ohm)
  - Use same applied voltage in all SFRA measurements
  - Make sure to get good connection and connect the shields of coaxial cables to flange of bushing using shortest braid technique.
  - Make good documentation, e.g. make photographs of connections.
- Follow the standard recommended in CIGRE report 342 2008!

SFRA – Summary and conclusions

- SFRA is an established methodology for detecting electromechanical changes in power transformers
- Collecting reference curves on all mission critical transformers is an investment!
- Ensure repeatability by selecting good instruments and using standardized measurement practices
- Select FRAX from Megger, the ultimate Frequency Response Analyzer!

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