Sweep Frequency Response Analysis
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...**
Comparative tests

Transformer A

Transformer A

Design based

Transformer B

Time based

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
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

- HV [short] identical between phases
- LV [open] as expected for a ΔY tx
- Very low deviation between phases for all tests – no winding defects
- HV [open] as expected for a ΔY tx
  "Double dip" and mid phase response lower
Transformer with serious issues...

Large deviations between phases for LV [open] at low frequencies indicates changes in the magnetic circuit/core defects.

Large deviations between phases at mid and high frequencies indicates winding faults.
FRAX
The Features And Benefits
FRAX101 – Frequency Response Analyzer
FRAX101 – Frequency Response Analyzer

- Power Input 11-16VDC, internal battery (FRAX101)
- USB Port On all models
- Bluetooth On FRAX101
- Rugged Extruded Aluminum Case
- Active Probe Connector on FRAX101
- Generator Reference Measure Connectors
- All Connectors Panel Mounted

Most feature rich and accurate SFRA unit in the world!
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

Optional Internal Battery
Over 8h effective run time

Industrial grade class 1
Bluetooth (100m)
USB for redundancy

Easy to connect shortest braid cables
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

"Obvious distortion" as by DL/T911-2004 standard (missing core ground)
Time Based Comparison – After repair

"Normal" as by DL/T911-2004 standard (core grounding fixed)
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)
Type Based Comparison – 3x HV [open]
Type Based Comparison – 3x HV [short]
Type Based Comparison – 3x LV [open]

Interpretation according to DL/T 911-2004, China 2005-06-01
Frequency response analysis on winding deformation of power transformers

<table>
<thead>
<tr>
<th>Type</th>
<th>Value</th>
<th>Severe Distortion</th>
<th>Obvious Distortion</th>
<th>Light Distortion</th>
<th>Normal</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-LF</td>
<td>2.98</td>
<td>R-LF &lt; 0.6</td>
<td>0.6 &lt; R-LF &lt; 1</td>
<td>1 &lt; R-LF &lt; 2</td>
<td>2 &lt; R-LF</td>
</tr>
<tr>
<td>R-MF</td>
<td>3.49</td>
<td>R-MF &lt; 0.6</td>
<td>0.6 &lt; R-MF &lt; 1</td>
<td>1 &lt; R-MF</td>
<td>1 &lt; R-MF</td>
</tr>
<tr>
<td>R-HF</td>
<td>1.41</td>
<td></td>
<td></td>
<td></td>
<td>0.6 &lt; R-HF</td>
</tr>
</tbody>
</table>

Conclusion: Normal
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]
Designed Based Comparison – LV [open]

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

Frequency response analysis on winding deformation of power transformers

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</tr>
</thead>
<tbody>
<tr>
<td>R-LF (1kHz - 10kHz)</td>
<td>R-LF &lt; 0.6</td>
<td>0.6 &lt;= R-LF &lt; 1</td>
<td>1 &lt;= R-LF &lt; 2</td>
<td>2 &lt;= R-LF</td>
</tr>
<tr>
<td>R-MF (10kHz - 60kHz)</td>
<td>R-MF &lt; 0.6</td>
<td></td>
<td>0.6 &lt;= R-MF &lt; 1</td>
<td>1 &lt;= R-MF</td>
</tr>
<tr>
<td>R-HF (60kHz - 1MHz)</td>
<td></td>
<td>0.6 &lt;= R-HF &lt; 1</td>
<td></td>
<td>0.6 &lt;= R-HF</td>
</tr>
</tbody>
</table>

Conclusion: Normal
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?)
Design Based Comparison – After Suspected Fault

- HV-0 (LV shorted)
- A and C phase OK, deviation on B-phase
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?
Test results – always comparisons

Repeatability is of utmost importance!
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 multiple 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
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
FRAX cable set and grounding

Always the same ground-loop inductance on a given bushing
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"

"Open"/internal noise measurements
Red = Other brand
Green = FRAX101
Example of internal noise problem

H1 – H2 (open & short) measurements
Black = Other brand
Red = FRAX101
Why you need at least -100 dB...

Westinghouse 40 MVA, Dyn1, 115/14 kV, HV [open]
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!

After demagnetization

After winding resistance test
Measurement voltage 0.1 – 10V

Grey 0.1 V
Light Blue 0.5 V
Blue 1 V
Brown 2 V
Black 5 V
Green 10 V
Effect of applied measurement voltage

- 2.8 V Omicron
- 10 V FRAX, Doble and others
FRAX has adjustable output voltage!
Field verification unit with known frequency response is recommended in CIGRE and other standards to verify instrument and cables before starting the test.
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!