SFRA Testing on Power Transformers: Introduction
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Author Biography

Brandon Dupuis received a B.S. Electrical Engineering from the University of Maine. He joined OMICRON electronics Corp, in 2013, where he presently holds the position of Regional Application Specialist for transformer testing. Brandon’s focus is currently on standard and advanced electrical diagnostics for power transformers and circuit breakers. Presently, Brandon is a well-known OMICRON instructor teaching electrical transformer diagnostic testing theory, application, and test result analysis, which includes both presentations and hands-on training. Brandon is an active member of the IEEE/PES Transformers Committee.
Transformer Testing Support Contacts

**Brandon Dupuis**
Regional Application Specialist - Transformers
OMICRON electronics Corp. USA
60 Hickory Drive
Waltham MA 02451 | USA
T +1 800 OMICRON
T +1 781 672 6230
brandon.dupuis@omicronenergy.com
www.omicronenergy.com

**Fabiana Cirino**
Application Engineer
OMICRON electronics Corp. USA
3550 Willowbend Blvd.
Houston, TX 77054 | USA
T +1 800 OMICRON
T +1 713 212 6154
fabiana.cirino@omicronenergy.com
www.omicronenergy.com

**Moritz Pikisch**
Application Engineer
OMICRON electronics Corp. USA
Sacramento, CA 95816 | USA
T +1 800 OMICRON
T +1 713 212 6150
Call me via SIP | Web
moritz.pikisch@omicronenergy.com
www.omicronenergy.com

**Charles Sweetser**
PRIM Engineering Services Manager
OMICRON electronics Corp. USA
60 Hickory Drive
Waltham MA 02451 | UNITED STATES
T +1 800 OMICRON
T +1 781 672 6214
charles.sweetser@omicronenergy.com
www.omicronusa.com
The Transformer “Mechanical Integrity Tests”

• The two transformer “mechanical integrity tests” are,
  
  1) The SFRA Test
  
  2) The Leakage Reactance Test

• These two tests are used to detect mechanical changes within the main tank of a power transformer (e.g. winding movement or winding deformation)

• The measurements provide information about the physical position of the components within the main tank of a power transformer (i.e. the position of the core, the windings, the insulation, the space, etc.)

• Both measurements are “fingerprint” measurements – In general, the measurements should not change over time
The SFRA and Leakage Reactance Tests

- The two measurements are not typically utilized as “routine tests”, but are intended to be “situational tests”, and are typically performed,

  1) Before and after transporting a transformer, to check for “shipping damage”

  2) When there is a reason to suspect that there is an issue with the transformer (e.g. after a fault event, or due to an increase in combustible gases in the main tank oil)

- At a minimum, one of the two measurements should be performed, and documented, for future reference (but of course, performing, and documenting, both measurements is the “best practice”)

- The hope is that a fault detected by one of the two measurements, can be confirmed by the other measurement - In other words, the two tests complement each other well
SFRA – Failure Mode Detection

1) Mechanical Winding Movement
   - Radial Winding Deformation (aka “Hoop Buckling”)
   - Axial Winding Deformation (aka “Telescoping”)
   - Bulk Winding Movement

2) Compromised Insulation
   - Turn-to-Turn Insulation Failure
   - Winding-to-Ground Insulation Failure

3) Core Problems (e.g. a “loss of core ground” connection)

4) Severe Discontinuities or “Bad Connections” Involving the Current Carrying Path
The Sweep Frequency Response Analysis (SFRA) Test

• The most sensitive electrical diagnostic test, to mechanical changes within a power transformer

• An SFRA trace is a “fingerprint” of a transformer’s main tank construction (i.e. the position of the core, the windings, the insulation, the space, etc.)
SFRA – Test Procedure

1. Inject an AC Voltage into one end of a transformer winding (Vin)

2. Measure the AC Voltage that comes out the other end of the transformer winding (Vout)

3. Calculate the ratio of the Output Voltage and the Input Voltage (Vout / Vin)

4. Repeat the measurement over a broad frequency range (e.g. from 20Hz to 2MHz)
SFRA - Test Connections

• Three coaxial test leads are used to perform the SFRA measurement

1. Voltage source lead (Yellow)

2. Voltage input measurement lead - Vin (Red)

3. Voltage output measurement lead - Vout (Blue)
SFRA - Test Connections

- Three coaxial test leads are used to perform the SFRA measurement

  - The Yellow and Red leads are connected in parallel, and are always connected to the same bushing terminal, for the SFRA measurement.

  - The Red lead is used to measure the “reference voltage” that is injected directly at the bushing terminal, at one end of the transformer winding.

  - The Blue lead is always connected by itself, to the bushing terminal at the “other end” of the transformer winding under test.

  - The impedance of the Red and Blue leads must be equal, so that the voltage drop across the two leads is approximately equal, when comparing the Input Voltage (Red) and the Output Voltage (Blue).
SFRA - Test Connections

• All three test leads are coaxial cables (Yellow, Red, and Blue)

• The “inner conductor” of each test lead is used to pass the measurement signals to-and-from the transformer

• The “outer shield conductor” of each test lead is used to “protect” the relatively small measurement signal, from interference

• It is critical that the “outer shield conductor” of each test lead is grounded, to obtain the correct measurement

• The “outer shield conductor” of each test lead is typically grounded near, or at the end of, each test lead (i.e. at the end of the cable closest to the bushing terminal connection)
SFRA - Test Connection Example

SFRA Test Instrument

Voltage Source
R=50Ω

Input Voltage (Vin)
R=50Ω

Output Voltage (Vout)
R=50Ω

Yellow: Voltage Injection Signal
Red: Input Voltage Measurement (Vin)
Blue: Output Voltage Measurement (Vout)
The Key “Frequency Ranges” of an SFRA Trace

1.) The “Low-Frequency Range” (<10kHz)
   • when performing an open-circuit test, is heavily influenced by the transformer’s core and “magnetizing impedance”
   • when performing a short-circuit test, is heavily influenced by the physical position of the transformer’s internal components, most notably the transformer’s windings

2.) The “Mid-to-High Frequency Range” (10kHz-500kHz)
   • is heavily influenced by the physical position of the transformer’s internal components, most notably the transformer’s windings
   • is probably the most important frequency range of the SFRA measurement

3.) The “Very-High-Frequency Range” (>500kHz)
   • is heavily influenced by the test leads and the test connections (most notably, the shield conductor ground connection, made near the end of each test lead)
   • In most cases, this “frequency range” is not assessed

• Note, the actual “frequency range” of a trace will vary slightly from transformer-to-transformer, so keep in mind, that the frequency range magnitudes provided above are not hard and fast rules
The Key “Frequency Ranges” of an Open-Circuit Test

- **The “Core Region”**
- **The “Winding Structure Region”**
- **The “Test Leads and Test Connections” Region**
The Key “Frequency Ranges” of a Short-Circuit Test

Continuity Check – A “DC Winding Resistance Cross-Check”

The “Leakage Channel Region” is heavily influenced by the winding structure.

Short-circuiting the secondary-side bushing terminals removes the influence of the core.

The “Winding Structure Region”

The “Test Leads and Test Connections” Region
Open Circuit Test vs. Short-Circuit Test on the Same Winding

By short-circuiting the secondary-side bushing terminals, the “core resonances” are removed.

The “Winding Structure Region” is typically more-or-less the same, when comparing an open-circuit and short-circuit test on the same winding.
SFRA – Time-Based Comparison Analysis

• The most effective way to assess a set of SFRA test results

• In short, you document the “fingerprint” measurement, when the transformer is known to be in “good condition”, and then compare the “fingerprint” to future field measurements

• In general, the SFRA trace should not change over time (but note, there are a few exceptions)
SFRA – Phase-Comparison Analysis

• SFRA test results can be assessed reasonably well by comparing the similar traces amongst the three phases

• Analyzing SFRA test results by comparing similar traces amongst the three phases takes practice and experience

• In general, when comparing the similar traces amongst the three phases, we are just looking for something obvious (i.e. some “abnormal” discrepancy when comparing the three phases amongst each other)
SFRA – Sister Unit Comparison Analysis

• Two transformers must be true sister units, and must have a near-identical construction, to compare the SFRA test results amongst them

• A good way to determine whether two power transformers are true sister units, is to compare their serial numbers

• This analysis strategy is particularly useful when comparing single-phase transformers, that are part of a 3-Phase system
Factors That Can Influence an SFRA Measurement

• A physical change within the main tank of the transformer

• User error (e.g. a “bad” test connection)

• A poor ground connection - Ensure that the transformer ground, the test equipment ground, and the test lead shield connection, are solidly bonded to earth-ground potential

• Test instrument failure - Perform the “zero check” test, to verify that the test equipment is functioning properly

• The tap-changer position of both the DETC and the LTC – The transformer must be tested on the same tap-position(s) each time the SFRA measurement is performed, to “overlay” and compare similar SFRA traces
Factors That Can Influence an SFRA Measurement

- Residual magnetism – The SFRA trace may change, depending on how the core is magnetized at the time of the test

  - Residual magnetism typically only influences the open-circuit tests, but not the short-circuit tests

  - Residual magnetism typically only influences the “core region” of the SFRA trace (i.e. frequencies <10kHz)

- The “bus connection” – Was the SFRA measurement performed with the bushing terminals completely isolated, or was the bus connected during the time of the test?

- The bushing(s) state – Was the SFRA test performed with the bushings installed, with the bushings not installed, or were temporary bushings used during the time of the test?
Factors That Can Influence an SFRA Measurement

- The direction of the input voltage injection (e.g. X1-X0 vs. X0-X1) – We recommend using the “head-to-tail” method, when performing the SFRA test

- The insulating fluid state – Was the transformer tank filled with oil or not, when the SFRA measurement was performed?

- The test voltage – The magnitude of the test voltage typically only influences the “core region” of the SFRA trace (i.e. frequencies <10kHz)
Factors That Can Influence an SFRA Measurement

• The tertiary winding state (if applicable) – Is there a “broken delta” tertiary, and was it open or closed, and/or grounded when the SFRA measurement was performed?

• Core ground connection – Is there an external core ground connection, and was it connected or disconnected when the SFRA measurement was performed?

• Current transformer state – Are there any bushing Current Transformers associated with the power transformer, and was the secondary-side of the CTs shorted, open, grounded, etc.?
Understanding the Magnitude of the SFRA Trace, relative to the Impedance of the Test Circuit
SFRA – Impedance vs. Magnitude

• To gain a better understanding of the SFRA test, when an SFRA measurement is performed, consider the question, will the Output Voltage be larger or smaller than the Input Voltage?

  ☐ Consider a scenario where the transformer winding is completely short-circuited – The Output Voltage would be equal to the Input Voltage, and the SFRA trace would “shift up” in magnitude

  ☐ Consider a scenario where the transformer winding is completely open-circuited – None of the Input Voltage would reach the other end of the transformer winding, and therefore, the Output Voltage would, theoretically, be zero, and the SFRA trace would “shift down” in magnitude

  ☐ Consider what happens to the Output Voltage as the impedance of the transformer winding increases – The Output Voltage decreases, and the SFRA trace “shifts down” in magnitude

  ☐ Consider what happens to the Output Voltage as the impedance of the transformer winding decreases – The Output Voltage increases, and the SFRA trace “shifts up” in magnitude
SFRA – Impedance vs. Magnitude

• The higher the impedance of test circuit, the more the measurement signal is attenuated, and the lower the magnitude of the output signal will be

• The lower the impedance of test circuit, the less the measurement signal is attenuated, and the higher the magnitude of the output signal will be

• Consider the primary winding of a step-down power transformer,
  - More winding turns = higher impedance = lower SFRA trace magnitude
  - Lower current = higher winding resistance = lower SFRA trace magnitude

• Consider the secondary winding of a step-down power transformer
  - Fewer winding turns = lower impedance = higher SFRA trace magnitude
  - Higher current = lower winding resistance = higher SFRA trace magnitude
SFRA – Impedance vs. Magnitude

Secondary-side winding traces typically have a higher magnitude

Primary-side winding traces typically have a lower magnitude
SFRA – Impedance vs. Magnitude

• What happens to an SFRA trace, if the transformer winding becomes short-circuited? The magnitude of the trace will increase (i.e. the trace “shifts-up”)

• What happens to an SFRA trace, if the transformer winding becomes open-circuited? The magnitude of the trace will decrease (i.e. the trace “shifts-down”)
Typical SFRA Test Plans
SFRA Measurement Types

1) Open-circuit test (recommended test)

2) Short-circuit test (recommended test)

3) Capacitive inter-winding test (optional test – not typically performed in North America)

4) Inductive inter-winding test (optional test – not typically performed in North America)

- In most cases, the capacitive and inductive tests do not provide information that the open-circuit and short-circuit tests do not provide
## Two-Winding Dyn1 Transformer - SFRA Test Plan

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<th>Tap position</th>
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<th>Resp.</th>
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## Autotransformer without Tertiary - SFRA Test Plan

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## Autotransformer with Accessible Tertiary - SFRA Test Plan

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<tr>
<td>16: X1 H0X0</td>
<td>max</td>
<td>▼</td>
<td>X1</td>
<td>H0X0</td>
<td>Y1-Y2-Y3</td>
</tr>
<tr>
<td>17: X2 H0X0</td>
<td>max</td>
<td>▼</td>
<td>X2</td>
<td>H0X0</td>
<td>Y1-Y2-Y3</td>
</tr>
<tr>
<td>18: X3 H0X0</td>
<td>max</td>
<td>▼</td>
<td>X3</td>
<td>H0X0</td>
<td>Y1-Y2-Y3</td>
</tr>
</tbody>
</table>
Frequency Response Theory
Transformer RLC Network (Resistor–Inductor–Capacitor)

- **Resistance** of the windings, joints, contacts, tap-selectors, switches, etc...

- **Inductance** (frequency dependent)
  - Magnetizing inductance, which is relevant when performing an open-circuit test
  - Leakage inductance, which is relevant when performing a short-circuit test

- **Capacitance** (frequency dependent)
  - Turn-to-turn insulation
  - Winding-to-ground insulation
  - Winding-to-winding insulation (aka inter-winding insulation)
Transformer RLC Network (Resistor–Inductor–Capacitor)
How do the RLC Components Vary Versus Frequency?

Resistor
\[ R \]
\[ \omega = 0 \rightarrow R \]
\[ \omega = \infty \rightarrow R \]

Inductor
\[ X_L = j\omega L \]
\[ \omega = 0 \rightarrow X_L = 0 \rightarrow \text{Short - Circuit!} \]
\[ \omega = \infty \rightarrow X_L = \infty \rightarrow \text{Open - Circuit!} \]

Capacitor
\[ X_C = \frac{1}{j\omega C} \]
\[ \omega = 0 \rightarrow X_C = \infty \rightarrow \text{Open - Circuit!} \]
\[ \omega = \infty \rightarrow X_C = 0 \rightarrow \text{Short - Circuit!} \]
Understanding the Four Main Filter Types

1. **Low-Pass Filter**
   - Allows low-frequency signals to pass
   - Blocks high-frequency signals

2. **High-Pass Filter**
   - Blocks low-frequency signals
   - Allows high-frequency signals to pass

3. **Band-Pass Filter**
   - Blocks all signal frequencies except the resonance frequency

4. **Band-Stop Filter**
   - Allows all signal frequencies except the resonance frequency
Low-Pass Filter Characteristics

\[ X_L = j\omega L \]

\[ X_L = j\omega L \]

\[ V_{in} \]

\[ V_{out} \]

\[ R_{ref} \]

\[ R_m \]

\[ \omega = 0, \ X_L = 0, \ V_{out} = V_{in}, \quad \text{Transfer Function} = \frac{V_{out}}{V_{in}} = 1 = 0dB \]

\[ \omega = \infty, \ X_L = \infty, \ V_{out} = 0, \quad \text{Transfer Function} = \frac{V_{out}}{V_{in}} = 0 \]
High-Pass Filter Characteristics

\[ X_C = \frac{1}{j\omega C} \]

\[ V_{in} \quad \text{RC} \quad V_{out} \]

\[ \omega = 0, \quad X_C = \infty, \quad V_{out} = 0, \quad \text{Transfer Function} = \frac{V_{out}}{V_{in}} = 0 \]

\[ \omega = \infty, \quad X_C = 0, \quad V_{out} = V_{in} = 1, \quad \text{Transfer Function} = \frac{V_{out}}{V_{in}} = 1 = 0\text{dB} \]
Band-Pass Filter Characteristics

\[ X_L = j\omega L \quad X_C = \frac{1}{j\omega C} \]

\[
\begin{align*}
\omega &= 0, \quad X_L = 0, \quad X_C = \infty, \quad V_{out} = 0, \\
\omega &= \infty, \quad X_L = \infty, \quad X_C = 0, \quad V_{out} = 0,
\end{align*}
\]

Transfer Function: \[ \frac{V_{out}}{V_{in}} = 0 \]
Band-Pass Filter Characteristics

\[ X_L = j\omega L \quad X_C = \frac{1}{j\omega C} \]

\[ \omega = \omega_{\text{res}}, \quad X_L = X_C \text{, The Inductor and Capacitor Create a Short – Circuit at the Resonance Frequency!} \]
Band-Stop Filter Characteristics

\[ X_L = j\omega L \quad X_C = \frac{1}{j\omega C} \]

\[ \omega = 0, \quad X_L = 0, \quad X_C = \infty, \quad V_{out} = V_{in}, \quad TF = \frac{V_{out}}{V_{in}} = 1 \]

\[ \omega = \infty, \quad X_L = \infty, \quad X_C = 0, \quad V_{out} = V_{in}, \quad TF = \frac{V_{out}}{V_{in}} = 1 \]
Band-Stop Filter Characteristics

\[ X_L = j\omega L \quad X_C = \frac{1}{j\omega C} \]

\[ \omega = \omega_{res}, \quad X_L = X_C, \quad \text{The Inductor and Capacitor Create an Open – Circuit at the Resonance Frequency!} \]
An SFRA Trace Has all Four Filter Types

- Low-Pass!
- Band-Pass!
- Band-Stop!
- High-Pass!
Thank you!