OMICRON

SFRA Testing on Power Transformers: Introduction

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

SFRA Testing on Power Transformers: Introduction

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

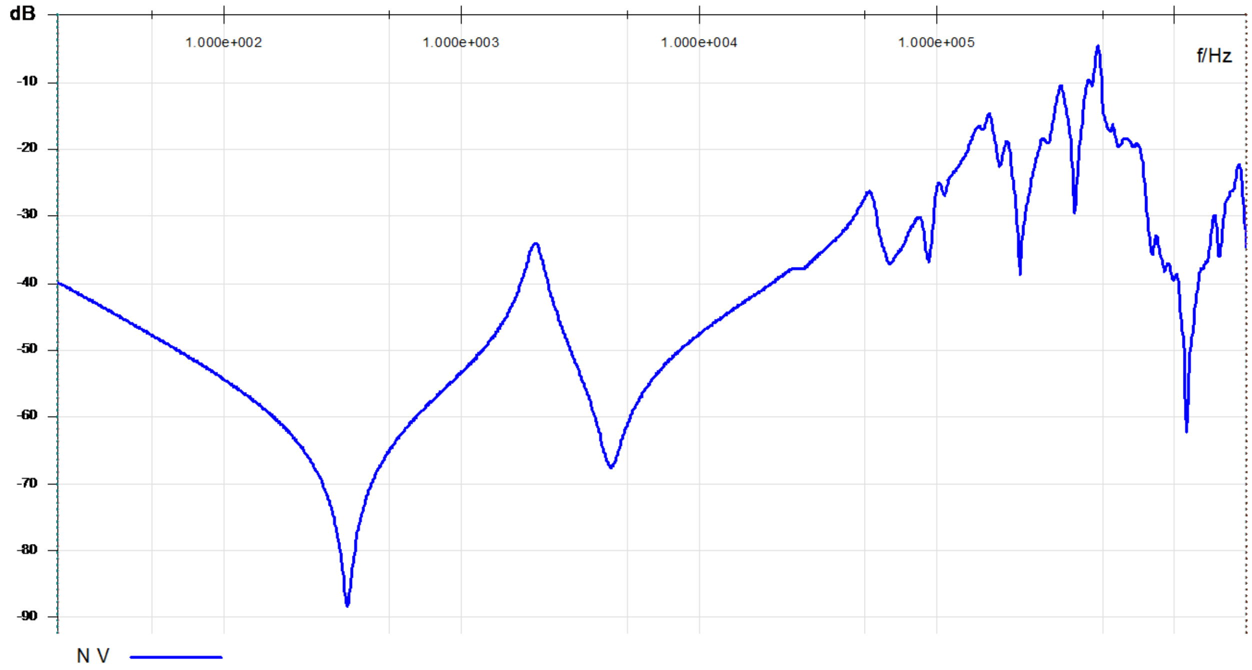
3) Core Problems (e.g. a “loss of core ground” connection)

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)

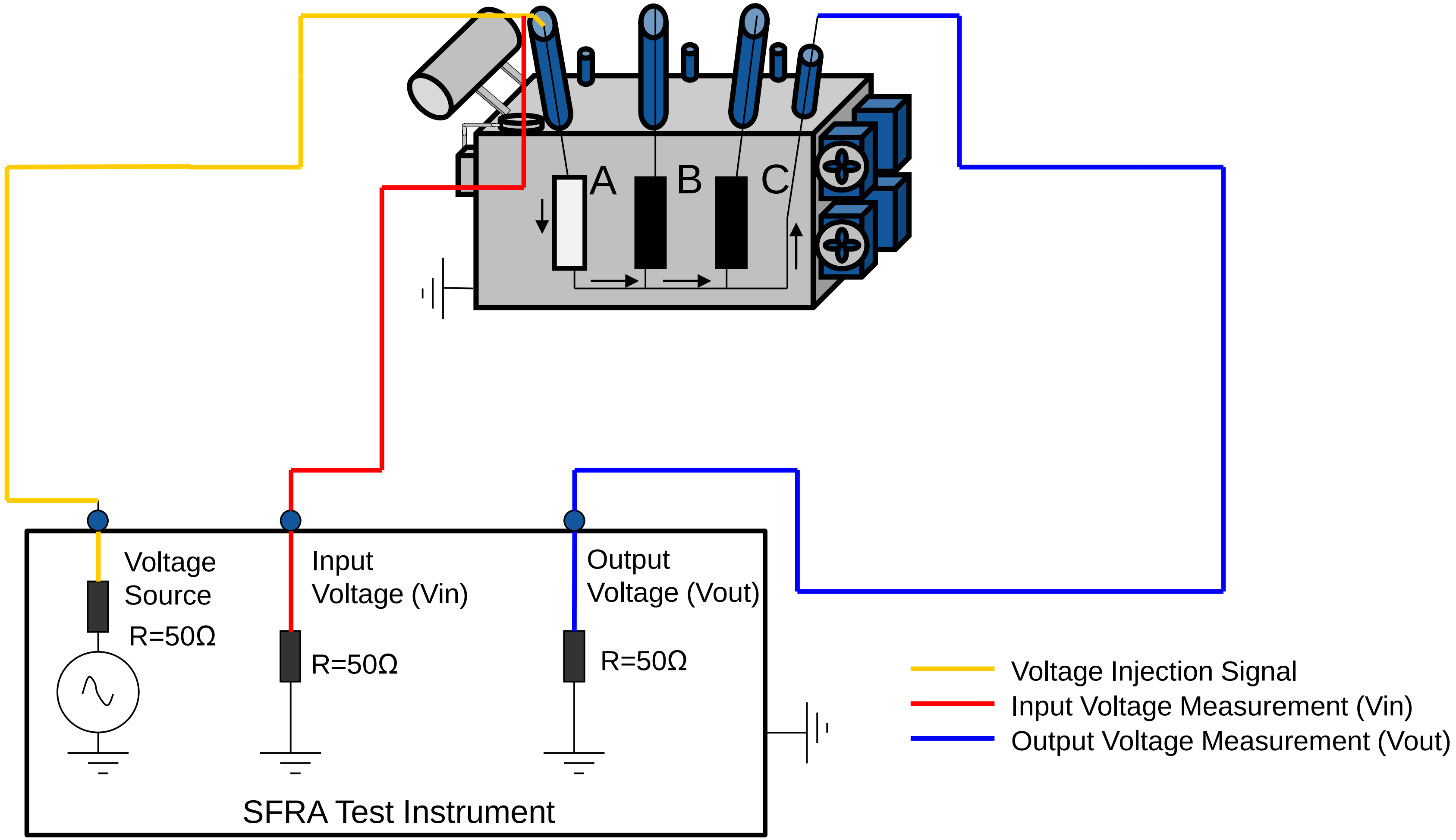
SFRA - Test Connections

- 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



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)

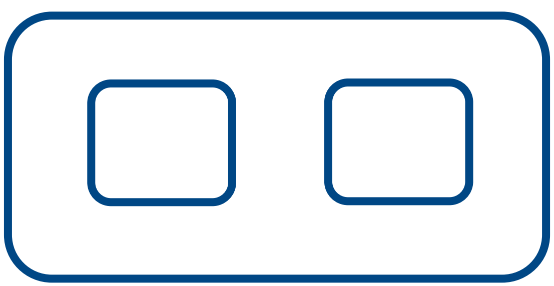
- is heavily influenced by the physical position of the transformer’s internal components, most notably the transformer’s windings
- is probably the most important frequency range of the SFRA measurement

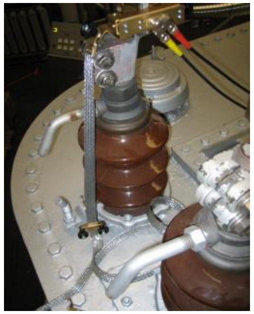
3.) The **“Very-High-Frequency Range”** (>500kHz)

- 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

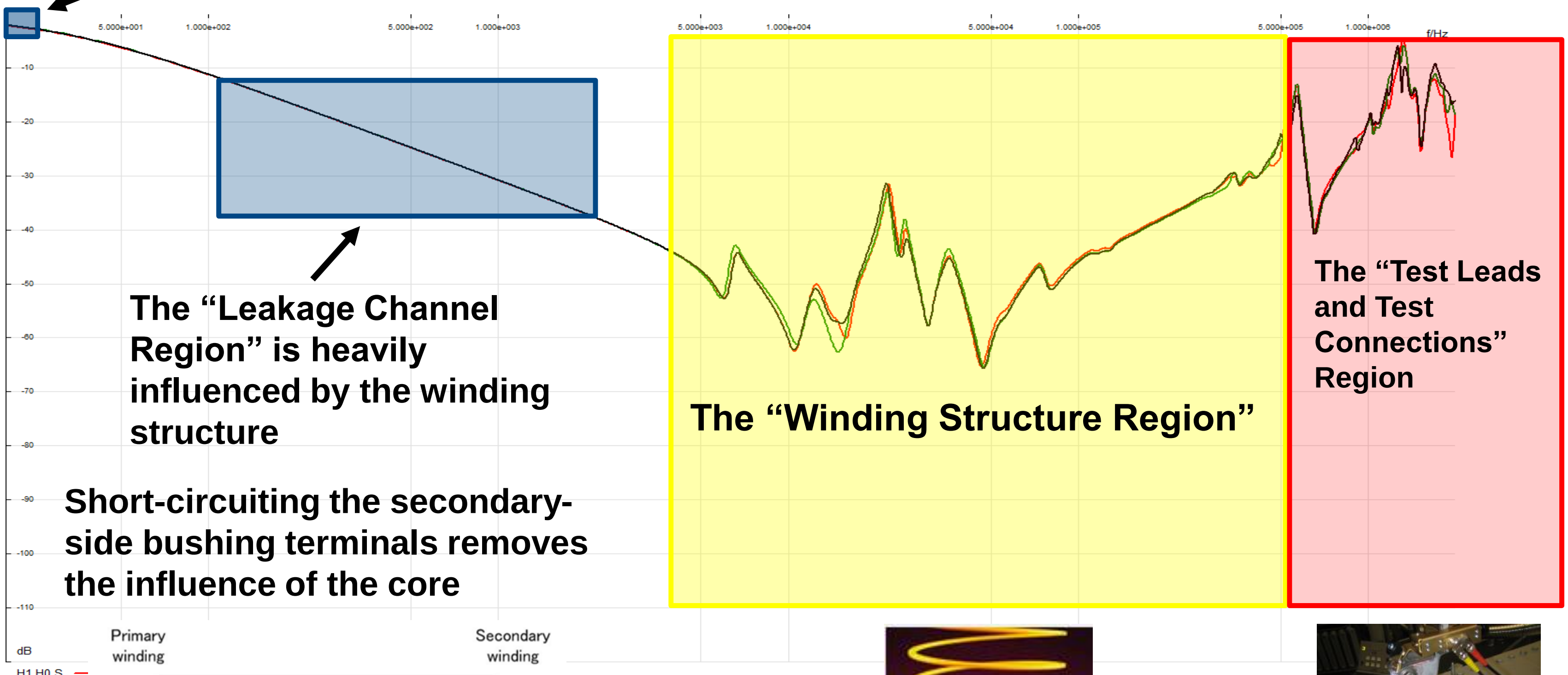
The Key “Frequency Ranges” of an Open-Circuit Test





The Key “Frequency Ranges” of a Short-Circuit Test

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

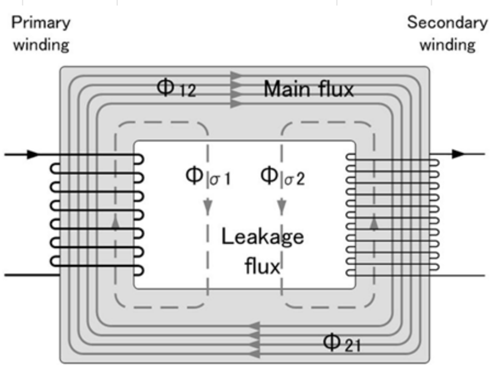


The “Leakage Channel Region” is heavily influenced by the winding structure

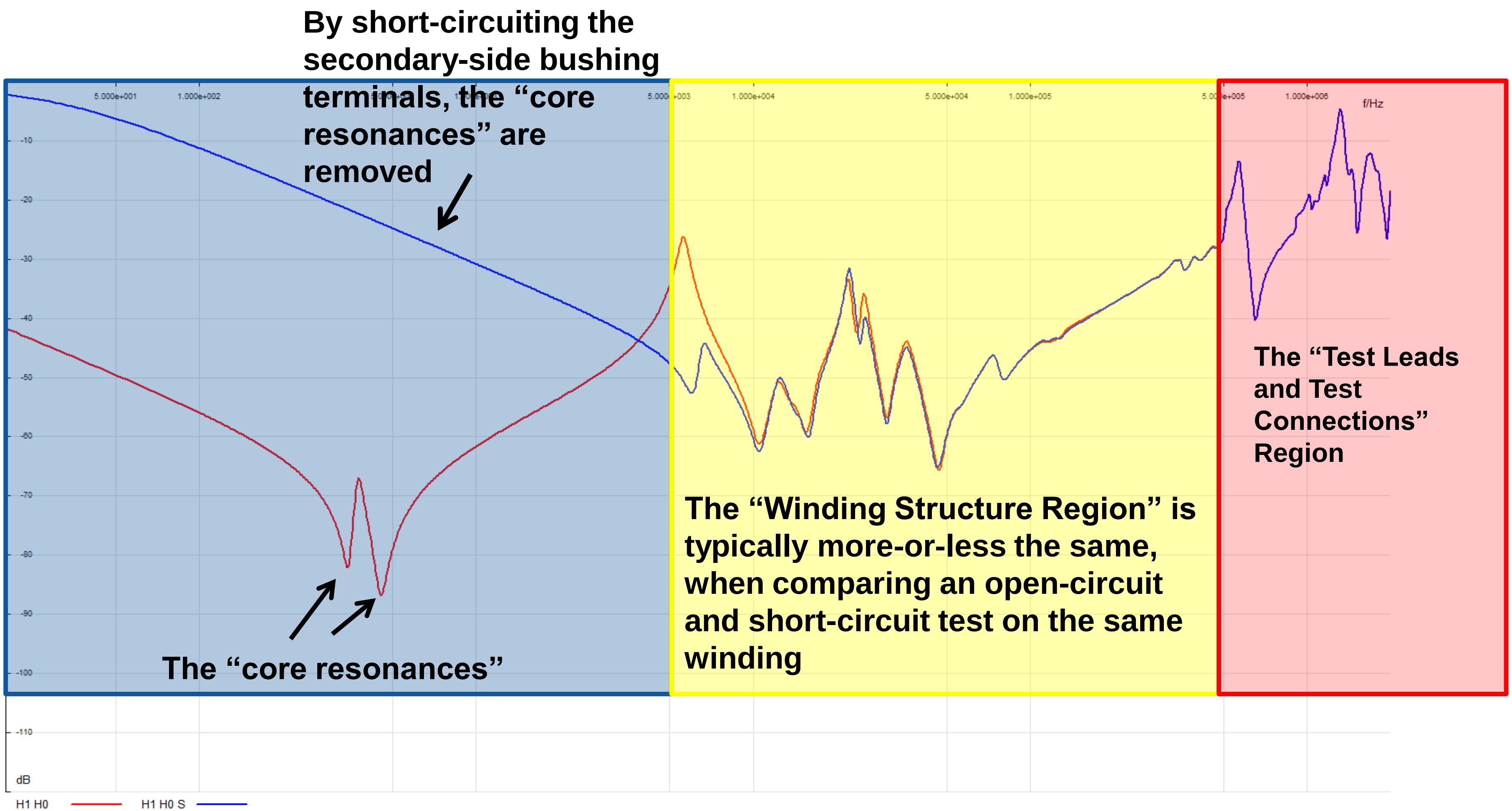
Short-circuiting the secondary-side bushing terminals removes the influence of the core

The “Winding Structure Region”

The “Test Leads and Test Connections” Region



Open Circuit Test vs. Short-Circuit Test on the Same Winding



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.?

OMICRON

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

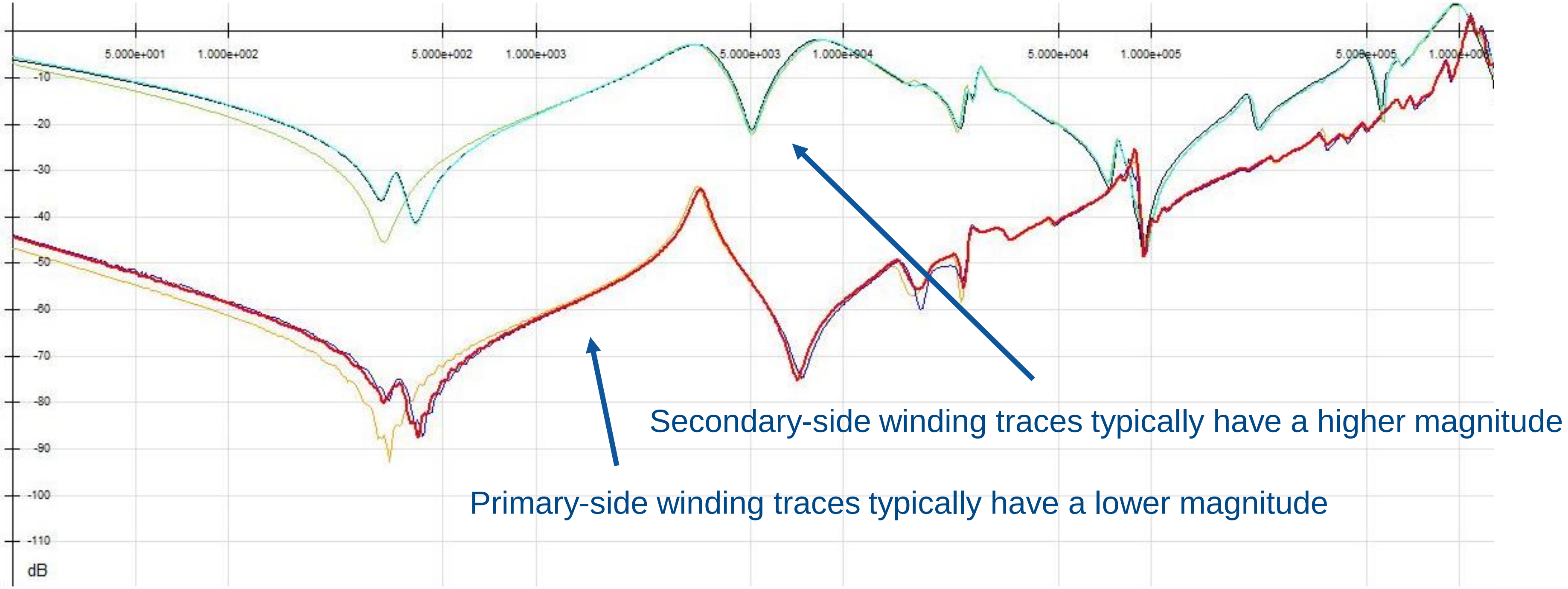
- The higher the impedance of test circuit, the more the measurement signal is attenuated, and the lower the magnitude of the output signal will be

- 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



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

Name	Tap position	Ref.	Resp.	Shorted	Grounded
Zero Check					
1: H1 H3	max	H1	H3	None	None
2: H2 H1	max	H2	H1	None	None
3: H3 H2	max	H3	H2	None	None
4: X1 X0	max	X1	X0	None	None
5: X2 X0	max	X2	X0	None	None
6: X3 X0	max	X3	X0	None	None
7: H1 H3	max	H1	H3	X1-X2-X3	None
8: H2 H1	max	H2	H1	X1-X2-X3	None
9: H3 H2	max	H3	H2	X1-X2-X3	None

Three-Winding YNyn0d1 Transformer - SFRA Test Plan

Name	Tap position		Ref.	Resp.	Shorted	Grounded
Zero Check						
1: H1 H0	max		H1	H0	None	None
2: H2 H0	max		H2	H0	None	None
3: H3 H0	max		H3	H0	None	None
4: X1 X0	max		X1	X0	None	None
5: X2 X0	max		X2	X0	None	None
6: X3 X0	max		X3	X0	None	None
7: Y1 Y3	max		Y1	Y3	None	None
8: Y2 Y1	max		Y2	Y1	None	None
9: Y3 Y2	max		Y3	Y2	None	None
10: H1 H0	max		H1	H0	X1-X2-X3	None
11: H2 H0	max		H2	H0	X1-X2-X3	None
12: H3 H0	max		H3	H0	X1-X2-X3	None
13: H1 H0	max		H1	H0	Y1-Y2-Y3	None
14: H2 H0	max		H2	H0	Y1-Y2-Y3	None
15: H3 H0	max		H3	H0	Y1-Y2-Y3	None
16: X1 X0	max		X1	X0	Y1-Y2-Y3	None
17: X2 X0	max		X2	X0	Y1-Y2-Y3	None
18: X3 X0	max		X3	X0	Y1-Y2-Y3	None

Autotransformer without Tertiary - SFRA Test Plan

Name	Tap position		Ref.	Resp.	Shorted	Grounded
Zero Check						
1: H1 X1	max		H1	X1	None	None
2: H2 X2	max		H2	X2	None	None
3: H3 X3	max		H3	X3	None	None
4: X1 H0X0	max		X1	H0X0	None	None
5: X2 H0X0	max		X2	H0X0	None	None
6: X3 H0X0	max		X3	H0X0	None	None
7: H1 H0X0	max		H1	H0X0	X1-X2-X3	None
8: H2 H0X0	max		H2	H0X0	X1-X2-X3	None
9: H3 H0X0	max		H3	H0X0	X1-X2-X3	None

Autotransformer with Accessible Tertiary - SFRA Test Plan

Name	Tap position		Ref.	Resp.	Shorted	Grounded
Zero Check						
1: H1 X1	max		H1	X1	None	None
2: H2 X2	max		H2	X2	None	None
3: H3 X3	max		H3	X3	None	None
4: X1 H0X0	max		X1	H0X0	None	None
5: X2 H0X0	max		X2	H0X0	None	None
6: X3 H0X0	max		X3	H0X0	None	None
7: Y1 Y3	max		Y1	Y3	None	None
8: Y2 Y1	max		Y2	Y1	None	None
9: Y3 Y2	max		Y3	Y2	None	None
10: H1 H0X0	max		H1	H0X0	X1-X2-X3	None
11: H2 H0X0	max		H2	H0X0	X1-X2-X3	None
12: H3 H0X0	max		H3	H0X0	X1-X2-X3	None
13: H1 H0X0	max		H1	H0X0	Y1-Y2-Y3	None
14: H2 H0X0	max		H2	H0X0	Y1-Y2-Y3	None
15: H3 H0X0	max		H3	H0X0	Y1-Y2-Y3	None
16: X1 H0X0	max		X1	H0X0	Y1-Y2-Y3	None
17: X2 H0X0	max		X2	H0X0	Y1-Y2-Y3	None
18: X3 H0X0	max		X3	H0X0	Y1-Y2-Y3	None

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

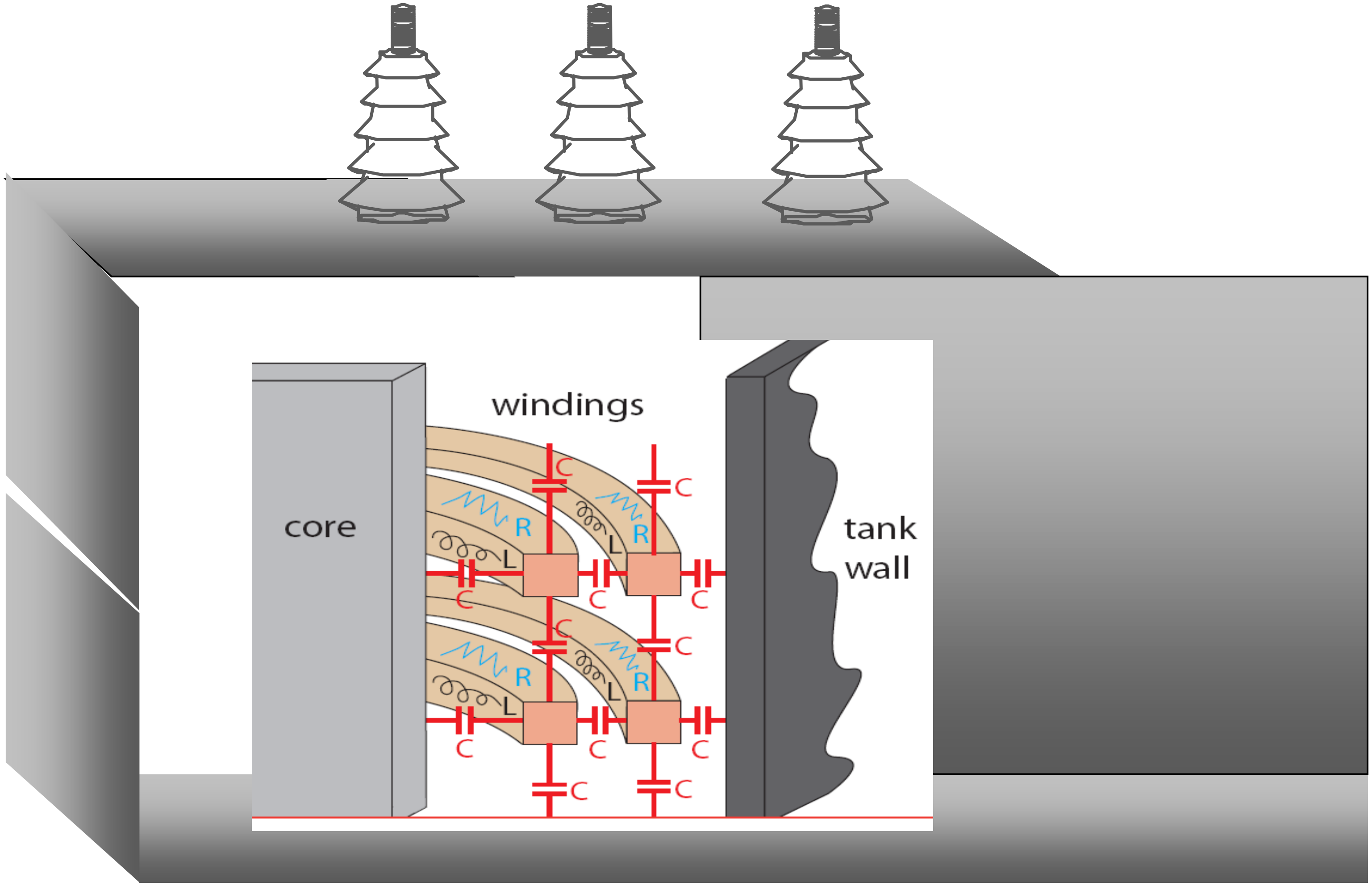
- **Capacitance** (frequency dependent)

  - ❑ 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

$$X_L = j\omega L$$

$$\omega = 0 \rightarrow X_L = 0 \rightarrow Short - Circuit!$$
$$\omega = \infty \rightarrow X_L = \infty \rightarrow Open - Circuit!$$

Capacitor

$$X_C = \frac{1}{j\omega C}$$

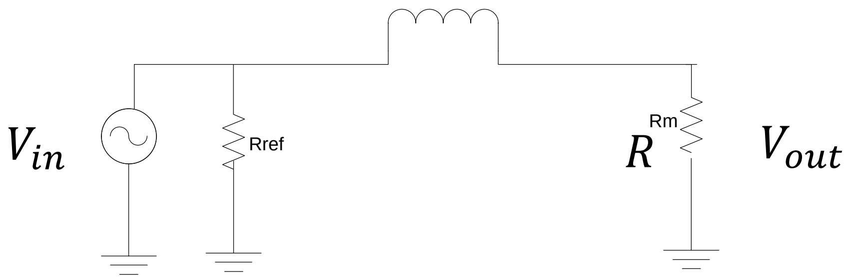
$$\omega = 0 \rightarrow X_C = \infty \rightarrow Open - Circuit!$$
$$\omega = \infty \rightarrow X_C = 0 \rightarrow Short - Circuit!$$

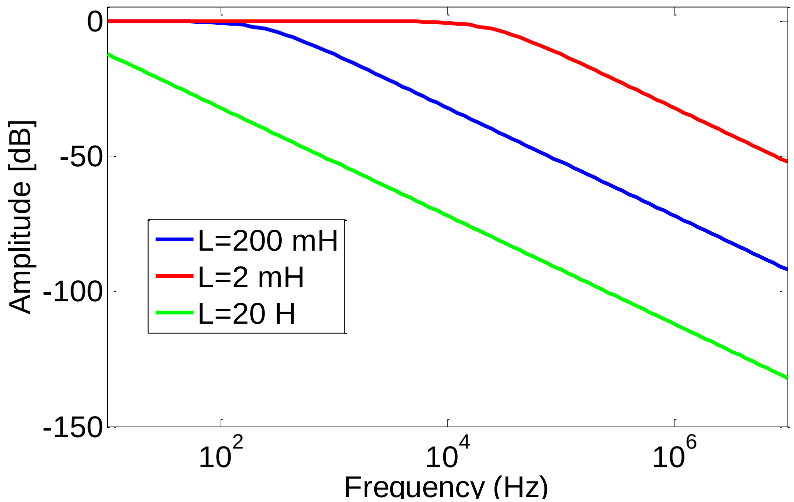
Understanding the Four Main Filter Types

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
2. **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

$$X_L = j\omega L$$



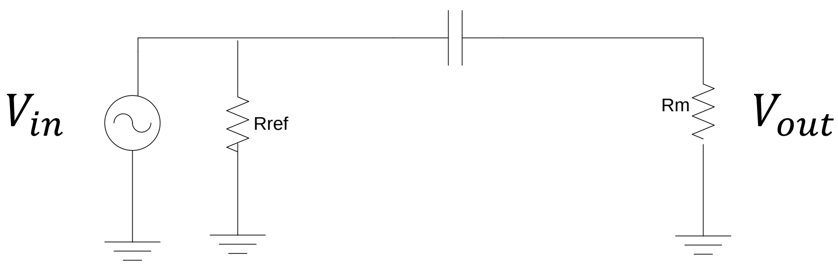


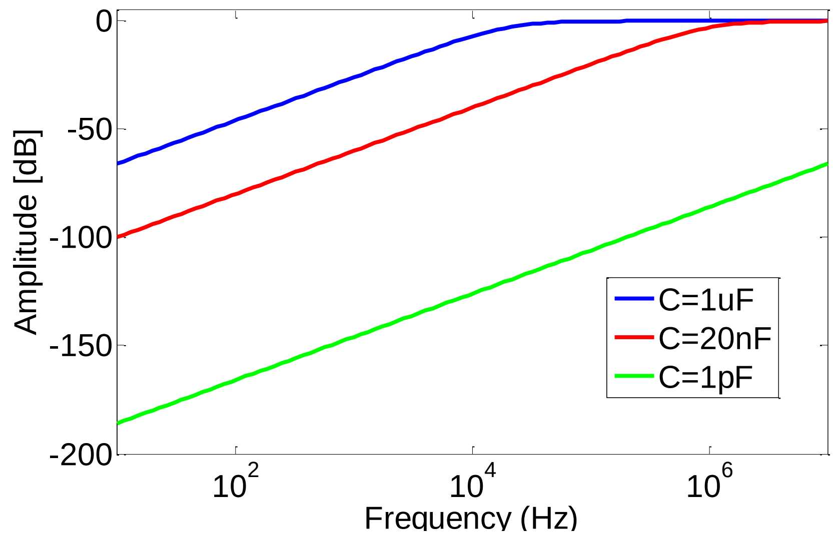
$$\omega = 0\,, \quad X_L = 0\,, \quad V_{out} = V_{in}\,, \qquad Transfer\ Function = \frac{V_{out}}{V_{in}} = 1 = 0dB$$

$$\omega = \infty\,, \quad X_L = \infty\,, \quad V_{out} = 0\,, \qquad Transfer\ Function = \frac{V_{out}}{V_{in}} = 0$$

High-Pass Filter Characteristics

$$X_C = \frac{1}{j\omega C}$$



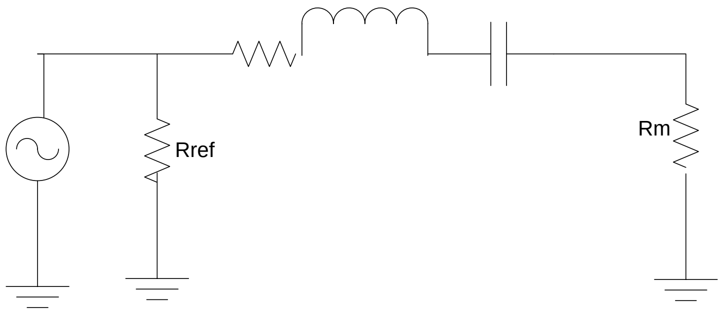


$$\omega = 0\,,\quad X_C = \infty\,,\quad V_{out} = 0\,,\qquad Transfer\ Function = \frac{V_{out}}{V_{in}} = 0$$

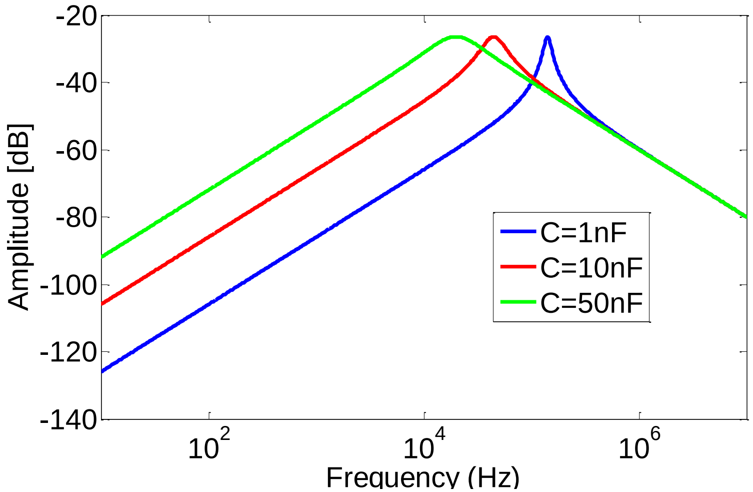
$$\omega = \infty\,,\quad X_C = 0\,,\quad V_{out} = V_{in} = 1,\qquad Transfer\ Function = \frac{V_{out}}{V_{in}} = 1 = 0dB$$

Band-Pass Filter Characteristics

$$X_L = j\omega L \qquad X_C = \frac{1}{j\omega C}$$



V_{in} V_{out}

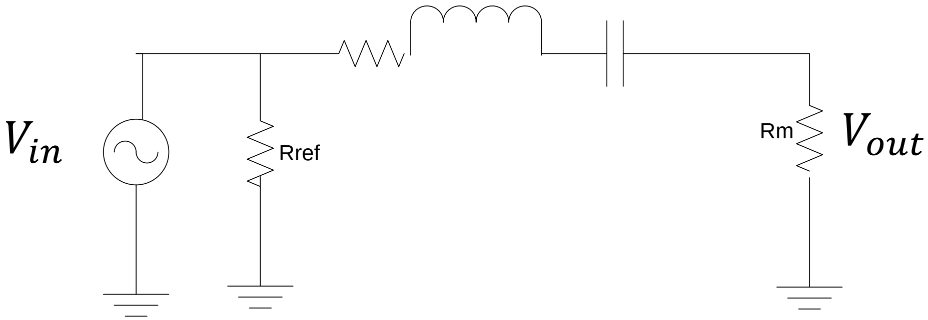


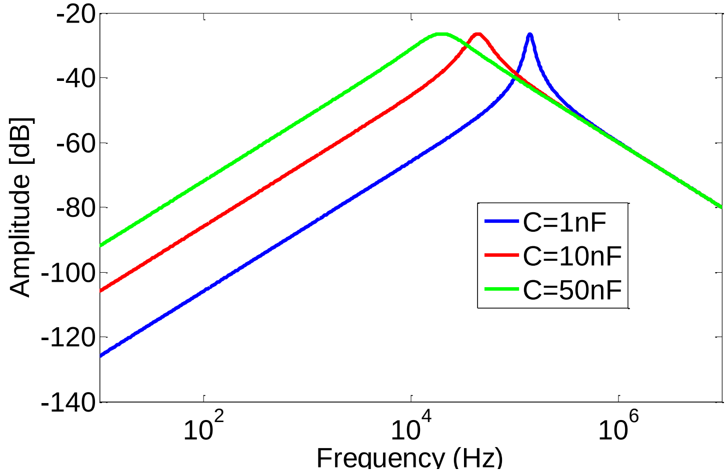
$$\omega = 0\,,\ \ X_L = 0,\ \ X_C = \infty\,,\ \ V_{out} = 0\,, \qquad Transfer\ Function = \frac{V_{out}}{V_{in}} = 0$$

$$\omega = \infty\,,\ \ X_L = \infty,\ \ X_C = 0\,,\ \ V_{out} = 0, \qquad Transfer\ Function = \frac{V_{out}}{V_{in}} = 0$$

Band-Pass Filter Characteristics

$$X_L = j\omega L \qquad X_C = \frac{1}{j\omega C}$$

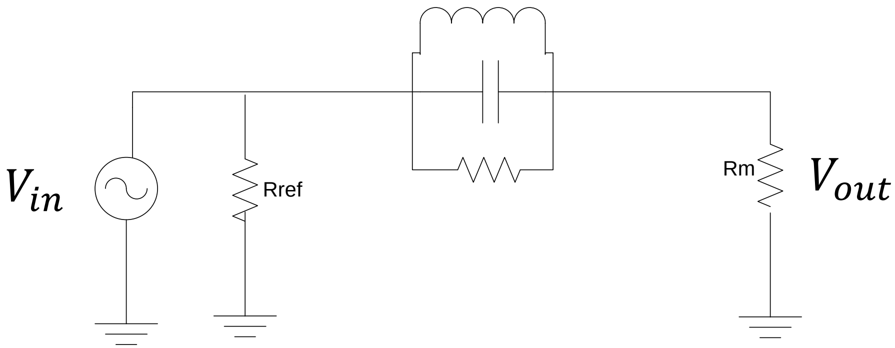


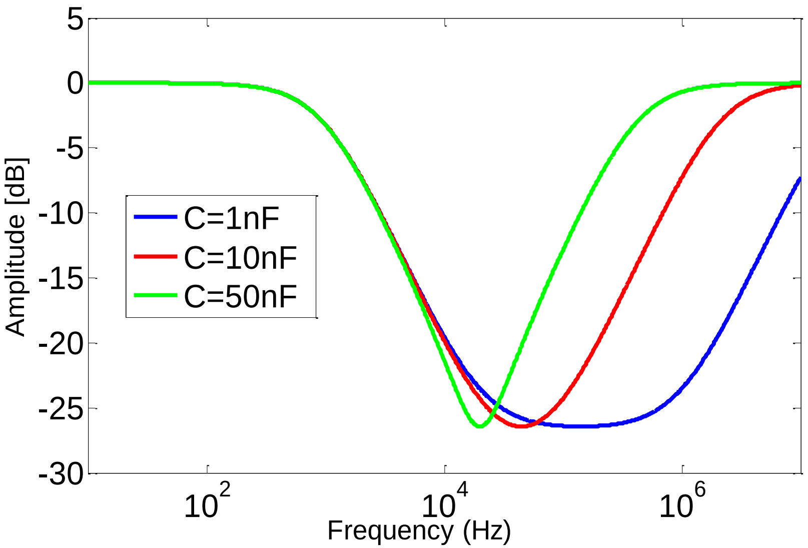


$$\omega = \omega_{res}\,,\quad X_L = X_C\,, \textit{The Inductor and Capacitor Create a Short} - \textit{Circuit at the Resonance Frequency}!$$

Band-Stop Filter Characteristics

$X_L = j\omega L \qquad X_C = \frac{1}{j\omega C}$



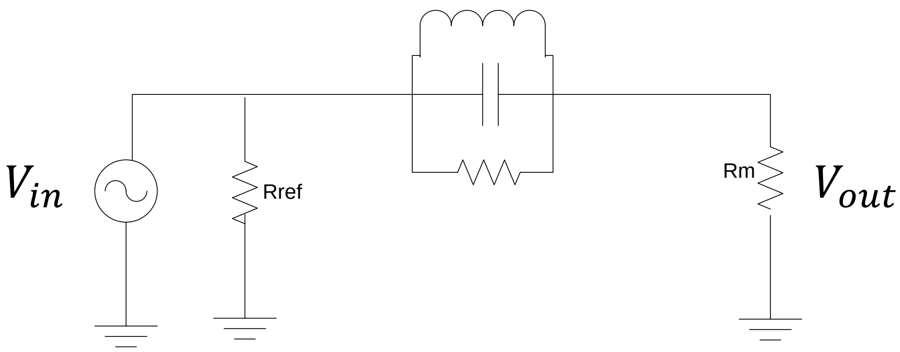


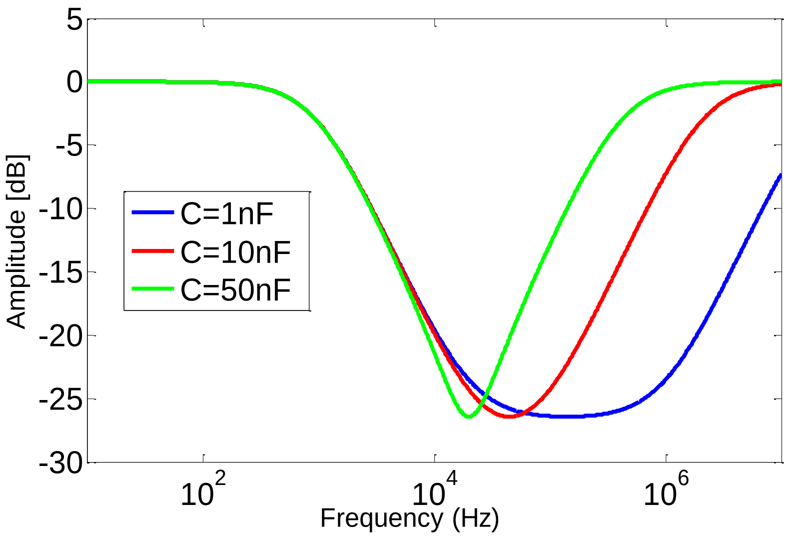
$$\omega = 0\,, \quad X_L = 0, \quad X_C = \infty\,, \quad V_{out} = V_{in}\,, \qquad TF = \frac{V_{out}}{V_{in}} = 1$$

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

Band-Stop Filter Characteristics

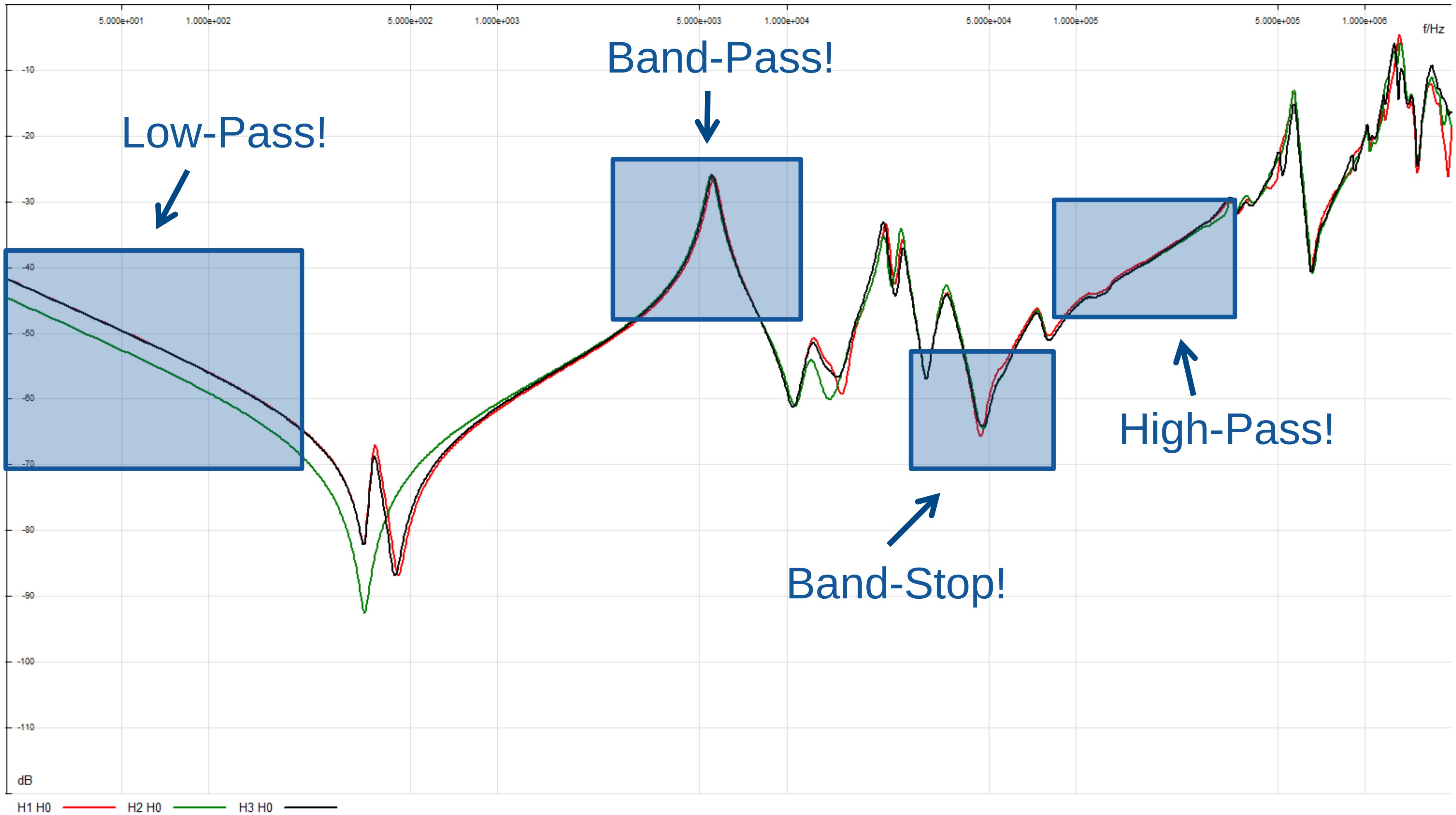
$X_L = j\omega L \qquad X_C = \frac{1}{j\omega C}$





$$\omega = \omega_{res}\,, \quad X_L = X_C \;\; ,\mathit{The\ Inductor\ and\ Capacitor\ Create\ an\ Open-Circuit\ at\ the\ Resonance\ Frequency}!$$

An SFRA Trace Has all Four Filter Types



Thank you!