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SFRA TRANSFORMER LIFE MANAGEMENT BULLETIN:

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INTRODUCTION

Sweep frequency response analysis (SFRA) is an electrical test used to assess the mechanical integrity of a transformer. Mechanical health is one of the health indices that determines the overall condition of a transformer. Other health indices, for example, include dielectric (the ability of the transformer's insulating materials to support an electric field) and thermal (the ability of the transformer to dissipate heat safely and effectively so that transformer action can continue uninterrupted) indices.

When used as a noun, one definition of mechanical is "the working parts of a machine". Mechanical integrity, therefore, may be defined as the integrity (or soundness in construction) of the working parts of a machine, in this case, a transformer. Note that "working" does not always mean "moving". In fact, a transformer is a passive[1] electromagnetic device/machine with very few moving parts. Depending on its design, a transformer may actually have no moving parts. When present, moving components associated with a transformer are limited to tap changers, pumps and fans.

The "working" components of a transformer are often referred to as the "active part" of the transformer and include the core, (main and tap) windings, pressed parts (as well as the frame and clamping structure), tap-changer(s) and connecting cables. So an SFRA test is concerned about the soundness in construction and permanence of these active parts. The manufacturer is deliberate about the placement of active components in the design and construction of the transformer but how important is the validation that the construction is sound and that nothing has changed since initial construction? A review of the mechanical aspects of a transformer helps answer this question.

[1] A passive component cannot introduce net energy into a circuit

Sweep frequency response analysis (SFRA)

MECHANICAL ASPECTS OF A TRANSFORMER

The total energy of a circuit (transmission or distribution) is brought into and back out of a transformer tank for the benefit of controlling the voltage level of the energy present. From a mechanical perspective:

- **Current carrying components create electromagnetic fields.**
- **The presence of electromagnetic fields exerts mechanical force, described by the Lorentz force law, on (other) current carrying components.**
- **Current carrying components in a transformer tank (e.g., main winding turns times the number of windings times the number of phases; tap winding turns; leads) are in relatively close proximity to each other.**

Therefore, all leads, windings, etc. are tied down and/or clamped so they do not move when the transformer is in an energized condition. Why is this important?

The mechanical health of windings and leads relates to their ability to carry current. Any mechanical change may compromise this ability. As examples:

- **Excessive mechanical force that results in damage such as deformation of a typically rigid coil or a mechanically compromised crimp that results in localized overheating and burning may alter a winding's (or lead's) current carrying ability, particularly if these involve short-circuit or open-circuit conditions.[2]**
- **Transformer core damage may affect the ability for flux to build, subsequent magnetic induction and, ultimately, amount of current flow.**

There are also secondary effects of winding and lead displacement that ultimately invalidate guaranteed design behavior of the transformer. One can appreciate some of these less obvious problems by considering the "collateral" effects of transformer action[3] and transformer loading, such as leakage flux and load losses summarized as follows.

When current flows in a transformer's secondary (and primary[4]) windings, leakage flux results. Leakage flux is flux that does not stay confined in the transformer core for the entirety of its closed loop path. When leakage flux cuts a conductive component (such as the windings, tie plates, transformer tank, etc.), it induces voltage in that component, which then gives rise to circulating currents within the component and produces heating. For example, when leakage flux cuts through the primary or secondary windings and therefore induces voltage, it gives rise to additional[5] eddy currents within the windings. These proximity[6] effects produce an increase in eddy losses. In fact, these types of losses constitute a significant percentage of a transformer's load losses[7].

The location of all components (current carrying and non-current carrying) within the tank are deliberate because:

- **The structural layout of current carrying components (e.g., winding and leads) influence the location and intensity of electric and magnetic fields in the transformer.**
- **The placement and shape of non-current carrying components and shielding of the transformer tank walls control some of the load losses due to leakage flux. In fact, during the transformer design phase, seemingly small design adjustments in conductive components exposed to fields can notably improve load loss levels.**

Electromagnetic field plots, which map out field intensities and locations relative to the precise location and spatial relationship of all components, validate that design-related localized overheating will not occur. It is all a piece of an elaborate overall design and zero movement is the objective even though there are mechanical forces present and pushing against components when the transformer is in an energized condition. The relocation/re-positioning of an internal, current carrying component will change the resulting fields, including a change in the electric field(s)[8] and leakage flux, and invalidate guaranteed design behavior.

[2] In this example, a big concern is the potential collateral damage to the surrounding insulation and subsequent increased risk of dielectric breakdown.
[3] "Transformer action" can be summarized as 'the use of a magnetic field established by the current flow through one winding to induce voltage in another winding'
[4] Current in a transformer's primary windings, I_P, will follow the current present in the secondary windings, I_S. For example, if I_S increases, more current is drawn in the primary windings.
[5] Some levels of eddy currents are already present automatically by the act of ac current flowing in the conductor. When ac current flows, a changing magnetic field is created and extends radially in all directions; this induces voltage along the current-carrying conductor itself and results in the creation of eddy current loops within the conductor. The resulting eddy currents oppose the current flow in the center of the conductor and reinforce the current flow in the periphery so that effectively, the majority of current flows in the periphery, or skin, of the conductor. This is known as the skin effect. The "crowding" of the current towards the surface results in a higher effective ac resistance of the conductor as compared to the resistance of the conductor if measured using dc current. The skin effect produces so-called eddy losses. A characteristic of the skin effect is uniform current flow on the outer periphery of the conductor.
[6] Proximity effects occur when another conductor is brought into close proximity to the first. The resulting eddy currents induced in the first conductor result in non-uniform field intensity around the conductor surfaces, so current flow will not be uniform at conductor surfaces. [1]
[7] Load losses describe energy that is lost as heat as a result of loading the transformer or short-circuiting the transformer (i.e., action that causes current to flow in a transformer's secondary windings).
[8] Consequently, this raises concerns about the adequacy of the surrounding insulation system.

Meanwhile, the transformer's structural supports and clamping system are not trivial requirements either. Particularly during high (over) current events such as during a through fault[9], these components may prevent failure of the transformer. Although a transformer is designed to handle certain (high!) mechanical forces, design limits may be exceeded during electrical faults whereby, for example, resulting mechanical forces exerted on transformer windings in a radial direction may be upwards of tens of millions of Joules[10] while those exerted axially register near one million Joules. A somewhat infamous, decades-old, Westinghouse video shows a time altered internal view of a winding failure in progress and the quick-building pressure wave that precedes it.

Excessive mechanical impact such as during transportation of a transformer or from earthquakes may also create forces that well exceed a transformer's design limits[11]. It is important to note that mechanical strength weakens as the transformer ages. This may result in less capability to handle high stress/ forces, increased risk of mechanical problems, and increased risk for insulation problems.

With regard to transformer tap changers, it is worth noting certain design limitations there, which include the difficulty in designing tap windings for short-circuit strength. Designers cannot design against tap-to-tap faults.

Failure to detect mechanical faults may allow the fault(s) to progress to dielectric or thermal breakdown, which in turn results in the loss of the transformer. Moreover, once in a compromised condition, the next time that a force due to a surge in current comes along, this may result in mechanical failure and immediate failure of the transformer.

WHAT TYPES OF PROBLEMS DOES SFRA DETECT?

SFRA tests have the ability to reveal a number of mechanical changes in a transformer, including those associated with the core, windings (main and tap), leads, supports, and clamping structure. Specific examples include:

- Core movements
- Faulty core grounds
- Short-circuited core laminations

  In order to reduce no-load losses, a transformer core is constructed out of thin sheets of electrical steel rather than a solid mass so that the paths of eddy currents are broken up without increasing the reluctance of the magnetic circuit. This fault involves the breakdown of the thin coating of insulating material that separates each lamination to prevent undesirable short-circuits between the laminations.

- Core lamination gaps (Figure 4)
- Bent core limb (Figure 4)
- Radial winding deformations, usually of the low voltage winding

  For a core-form transformer, radial forces are directed inward on the low voltage winding (placed in the innermost position closest to the core leg) while radial forces are directed outwards on the concentric, high voltage winding. This creates repulsive forces between the two windings, as illustrated in Figure 1.

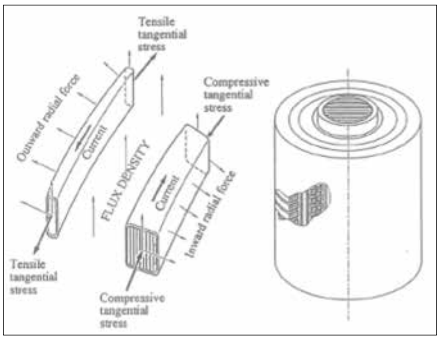


FIGURE 1: Radial forces on a two-winding transformer [2]

[9] As from close-up lightning strikes, which are a common cause of winding movement failures. Also, for example, due to faulty synchronization and tap changer faults.
[10] The unit Joule is defined as the amount of energy transferred when a force of 1 Newton is applied on an object for a length of 1 meter.
[11] Design calculations do not typically take into account the effects of twisting forces.

The tensile strength of the conductor is the crucial withstand factor for the HV windings while the winding support structure is critical for shoring up the LV winding. While the radial collapse of the inner windings is common, the outward bursting of the outer windings usually does not take place [3]. There are two categories of LV winding deformation, illustrated in Figure 2:

a. Forced buckling – failure of the LV winding due to bending between axially placed supporting spacers (i.e., sticks) all along the circumference.

b. Free buckling – the conductors bulge inward as well as outwards at one or more location along the circumference (Figure 4).

The number and severity of short-circuit events suffered are important. Any minor winding deformation usually results in the mis-alignment of the electromagnetic centres of the windings and increases stresses during subsequent faults.

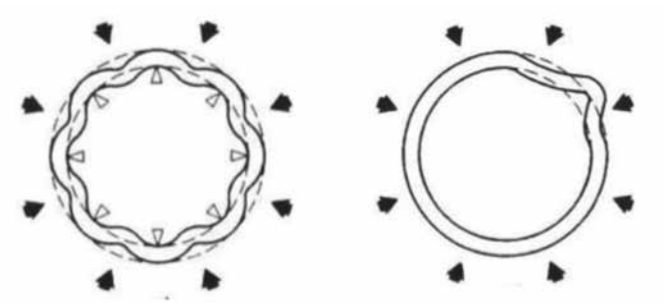


FIGURE 2: a) Forced bucking – conductors bend between the supports all along the circumference b) Free buckling [2]

- Winding displacements
- Short-circuited turns and open-circuited windings/leads
- Conductor tilting (Figure 4) – due to axial compressive forces as illustrated in Figure 3

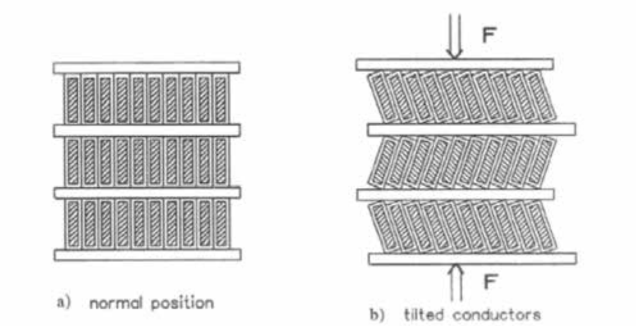


FIGURE 3: Conductor tilting [2]

- Conductor telescoping

Telescoping of conductors occurs when the support given by an inner cylinder is exceeded and the layers slip over adjacent layers. Turns or disks may also telescope over the end insulation or supports due to high axial forces in combination with inadequately dried and compressed insulation. [4]

The axial force in transformer coils occurs when the electrical centers of the primary and secondary windings are unbalanced. This unbalance causes a force to be exerted from primary to secondary windings. The force tends to make the primary and secondary windings slide past one another (i.e., telescoping of the coil). [5]

- Partial winding collapse (Figure 4)
- End insulation collapse
- Spiral tightening (Figure 4)
- Lead displacement
- Broken clamping structures (Figure 4)

Sweep frequency response analysis (SFRA)

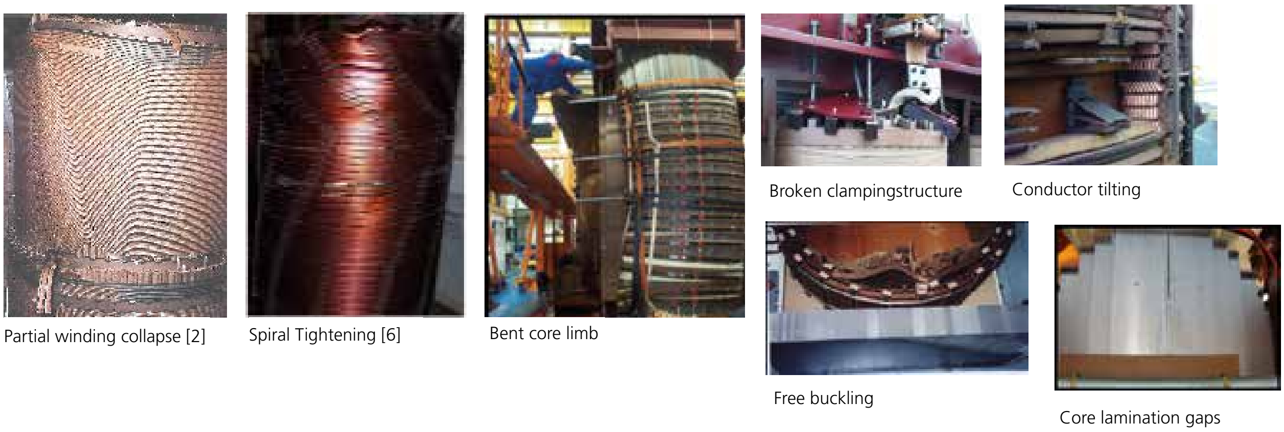


FIGURE 4: Examples of problems that may be detected with SFRA testing

SFRA – THE TEST:

The name Sweep Frequency Response Analysis (SFRA), when read backwards, suggests that we are analyzing the response of the transformer (a.k.a., its output as compared to its input; or, in other words, its behavior as a complex impedance) as the frequency of the input signal changes. So what constitutes the input and the output of a transformer?

A transformer magnetically couples two separate circuits. Through magnetic induction, energy is transferred from one circuit to the magnetically linked one such that voltage and current are present on the coupled circuit.

And indeed, in some SFRA measurements, we may be examining the sinusoidal output signal from a non-primary winding as compared to the sinusoidal signal we inject (through the transformer) on a primary winding. These are known as inter-winding measurements (i.e., inject a signal into one winding and measure the output of its winding pair). However, the central SFRA measurements examine the output signal of the transformer's primary circuit as compared to the signal injected into the primary circuit (or vice-versa, examines the output signal of the transformer's non-primary circuit as compared to the signal we inject into the non-primary circuit). In other words, the principal SFRA measurements compare the voltage at one end of the winding to the voltage input at the other end of the same winding (i.e., "end-to-end" tests).

In all scenarios (i.e., "end-to-end" tests on a primary winding, "end-to-end" tests on a non-primary winding, or inter-winding tests), the transformer presents as a complex impedance to the circuit:

- The transformer's main and tap windings introduce inductance[12];
- capacitance is present from the potential differences existing in an energized transformer (including series capacitances in the winding turns, ground capacitances, inter-phase capacitances, and inter-winding capacitances);
- and resistance (dc and ac) is encountered by: current flow through the windings and leads, leakage current, changing magnetic domains in the core and polarization processes occurring in energized insulation.

Because of this, when we apply a sinusoidal signal of constant amplitude and variable frequency, V_I (f) to one end of the primary winding under test (as an example), the response that is measured on the other end of the primary winding, V_O (f), is expected to be different. Notice, for example, the attenuation of the voltage output signal shown in green in Figure 5 as compared to the voltage input in purple, and the phase shift between the two signals.

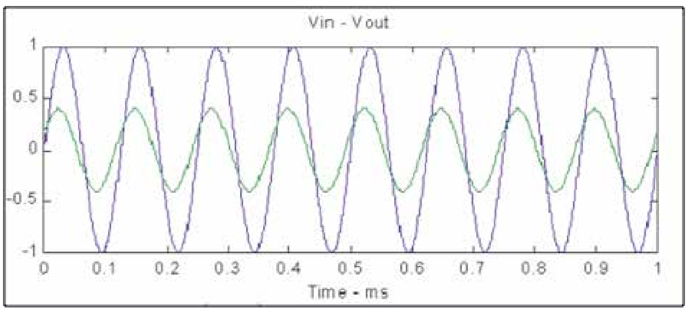


FIGURE 5: Voltage input signal (purple) and voltage output signal (green)[13]

[12] Self and mutual inductances; these are influenced by the transformer's core characteristics
[13] Figure 5 displays a single frequency measurement

The impedance of the complex RLC network (which represents the transformer) is different at different frequencies. Therefore, the output voltage, V_O (f), will vary in amplitude and phase depending on the frequency. The SFRA method involves applying a large number of low voltage signals with varying frequencies to the transformer. The applied terminal voltage V_I and the resultant voltage V_O at another terminal are measured in amplitude and phase. The ratios of the output signals to their respective applied signals give the frequency response or transfer function (H (jω))[14] of the transformer as given by:

$$H(j\omega) = \frac{V_O(j\omega)}{V_I(j\omega)} = \frac{50}{Z(j\omega)+50} \qquad \text{[EQN 1]}^{15}$$

where Z(jω) is the effective impedance of the RLC network while a look at a typical SFRA measurement circuit[16] in Figure 6 reveals that the "50" accounts for the impedance supplied by the test instrument.

The primary objective of SFRA is to determine how the impedance of a test specimen behaves over a specified range of frequencies (e.g., how well a transformer winding transmits a low voltage signal that varies in frequency) because the impedance is intimately related to the physical construction of the transformer. As seen in Equation 1, the measure of the transfer function H(jω) does not isolate the true specimen impedance Z(jω), which is positioned between the instrument leads and does not include any impedance supplied by the test instrument.

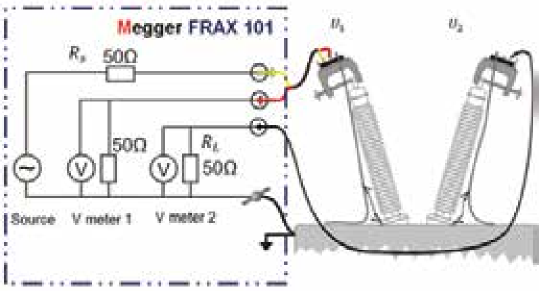


FIGURE 6: SFRA measurement circuit

A measuring resistance, R_S, is typically required to produce the input voltage drop V_I (f). The wave impedance of each measuring cable (i.e., one that measures the voltage input and the other that measures the voltage output) must be the same as the resistance of the source input.

The output voltage V_O is the voltage across a 50 Ohm resistor ("V meter 2" in Figure 6), and, hence, is proportional to the current flowing through the transformer winding. Therefore, the magnitude of the transfer function represents the admittance information (I / V_I) of the transformer. In fact, references abound wherein SFRA tests are referred to as self-admittance (rather than end-to-end), inter-winding admittance and transfer admittance tests. With the admittance information in hand, impedance can be derived.

However, SFRA test results are usually shown as the magnitude plotted against frequency, each on a logarithmic scale; for the magnitude, this means that it is expressed in decibels (dB) as calculated by equation 2. The phase angle (°) is typically displayed as well (Equations 3 and 4).

$$|H(j\omega)|_{dB} = 20\log_{10}\left|\frac{V_O(j\omega)}{V_I(j\omega)}\right| \qquad \text{[EQN 2]}$$

$$\varphi = \tan^{-1}(H(j\omega)) \qquad \text{[EQN 3]}$$

$$\text{Or, Phase (°)} = \text{Phase}(V_O) - \text{Phase}(V_I) \qquad \text{[EQN 4]}$$

The decibel (dB) is a logarithmic way of describing a ratio. A bode plot provides a simple and convenient visualization of the frequency response of a system, graphing (negative) gains (in the case of the transformer's transfer function) and phase-shift plots. For example, if the output voltage of the transformer winding is one-tenth of its input voltage, the magnitude of the response in dB equals 20 log10 (0.1), or -20 dB. If V_O is one-hundredth of V_I, the response in dB equals -40 dB. If V_O is one-thousandth of V_I, the response in dB is -60 dB, and so on. For every factor of 10 smaller V_O becomes as compared to V_I, the magnitude changes by an additional -20 dB. In fact, one advantage of plotting the response using a decibel scale is that very big ratios can be represented using numbers of modest size.

[14]The Frequency Response is the relationship between the system output and input in the complex Fourier Domain while the Transfer function is the relationship between the system output and input in the Laplace domain. Under certain conditions, as those present during SFRA testing, the frequency response and the transfer function are equal. The frequency response is obtained from the transfer function by using the following change of variables: s = jω, where (jω) denotes the presence of a frequency dependent function, and ω=2πf

[15]The transfer function is recognizable as the impedance of a voltage divider

[16]Since SFRA uses a 50 ohm impedance match measuring system, the 50 ohm impedance must be incorporated into H(jω).

Sweep frequency response analysis (SFRA)

HOW DOES SFRA WORK TO DETECT A PROBLEM?

Changes in the transformer's active parts (windings, leads, core, etc.) due to mechanical stress result in a change in the RLC parameters of the transformer's equivalent circuit. In turn, the transfer function measured in an SFRA test changes (from its baseline) at different frequencies, revealing that the mechanical health of the transformer is different. The nature of the change in the transfer function as compared to its baseline and the frequency range over which the response deviation occurs provide useful information to the evaluator as to the likely transformer component affected and, in some cases, the problem with the transformer. Before discussing typical transformer (frequency) response features and showing examples of how problems manifest in the test results, it is helpful to start small and consider the frequency response of:

- open- and short-circuits
- individual electrical components (R, C, and L) that constitute the equivalent circuit of passive devices (e.g., a transformer)
- simple combinations of RCL parameters.

A sound understanding of these fundamental response behaviours underpins success in comprehending SFRA test results of a transformer.

THE FUNDAMENTALS OF RESPONSE BEHAVIOUR

Open Circuit

Voltage drops completely across an open circuit (Figure 7), i.e., V_O goes to zero. Therefore, the transfer function (V_O/V_I) is essentially zero. Expressed in decibels (i.e., 20 log to the base 10 of a value near zero, e.g. 10^{-8}), this transfer function equals, for example, -160 dB.

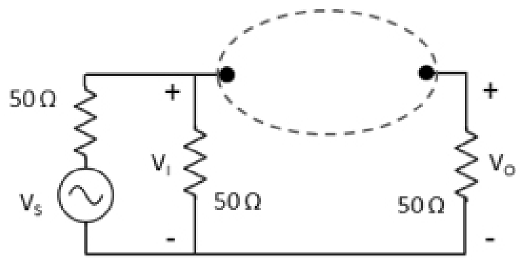


FIGURE 7: Open circuit

In these cases (i.e., open circuits), the "measured" transfer function becomes a measure of the noise floor[17] of the network analyzer[18] instead. It is important to verify the noise floor of an instrument; this is unique to each manufacturer's instrument. Ideally, the noise floor should be -120 dB or better[19] (e.g., -140 dB); otherwise important first resonance information may be lost, as explained later. As an example, the frequency response of an open circuit measured by the Megger FRAX is given by the green trace in Figure 8.

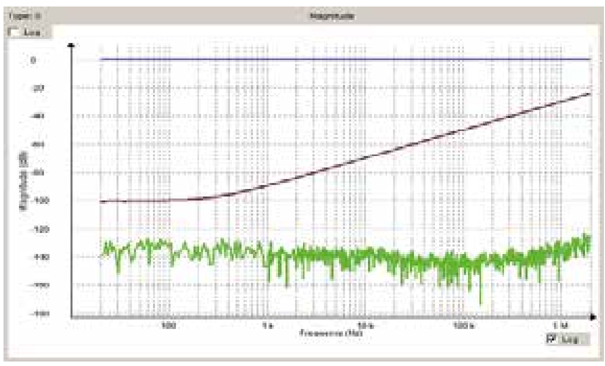


FIGURE 8: Open circuit frequency response (green); short circuit frequency response (blue); frequency response of a Megger field verification test box (black)[20]

[17] The noise floor of an instrument is revealed when trying to measure extremely small output signals, i.e., at some threshold, the output signal is too small for the test instrument to differentiate signal from (inescapable though low) "noise" present.
[18] SFRA test instrument
[19] A network analyzer with a very low noise floor is also referred to as a test instrument with good range.
[20] A field verification test box comes standard with the Megger FRAX to verify that the test instrument is working

Sweep frequency response analysis (SFRA)

Short Circuit

There is essentially no voltage drop across a short circuit (Figure 9). Therefore, the transfer function (V_O/V_I) approaches unity, i.e., 0 dB[21].

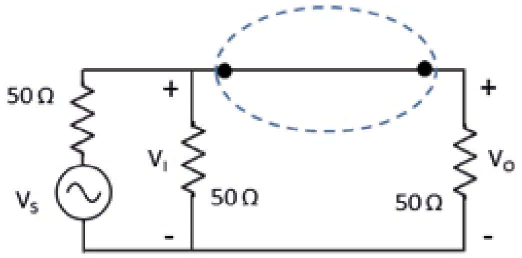


FIGURE 9: Short circuit

A typical SFRA test setup protocol recommends first measuring the test cables themselves, e.g., by connecting the test cables together. The expected response is a flat line (Figure 8). Sometimes, "rolling off" may be observed at higher frequencies, particularly if the test leads are not laid out completely straight during the test, whereby some inductive and capacitive effects may be introduced.

Resistor (R)

Voltage drops across a resistor when current flows through the resistor (Figure 10). Therefore, the transfer function (V_O divided by V_I) will be a number less than unity.

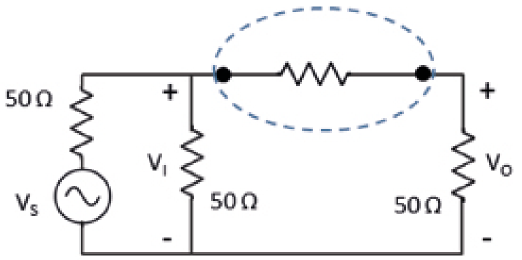


FIGURE 10: Resistive circuit

The transfer function/ response of a resistor does not change with frequency. Therefore, a resistor's (frequency) response amplitude is a flat line at a dB level matching the impedance that the resistor represents (Figure 11). The larger the resistance, the greater the voltage drop across it. Therefore, the ratio of the output voltage (which becomes increasingly small as resistance becomes larger) to the input voltage (which is held constant), is an increasingly smaller number. The log to the base 10 of this number is an increasingly negative decibel reading.

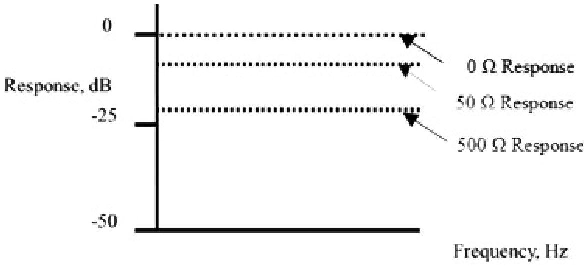


FIGURE 11: Frequency response of a 50 Ω and 500 Ω resistor

However, and this is a BIG POINT of CONFUSION – resistors effectively model the losses that occur when materials in the transformer are subjected to fields at one frequency. The physical behavior that results in losses may be frequency dependent. For example, hysteresis losses in the core vary linearly with frequency. Even the resistance in a conductor changes with frequency; this is evidenced by the fact that apparent resistance (ac) is larger than dc resistance (Figure 12).

[21] $20 \log_{10} (1) = 0$ dB

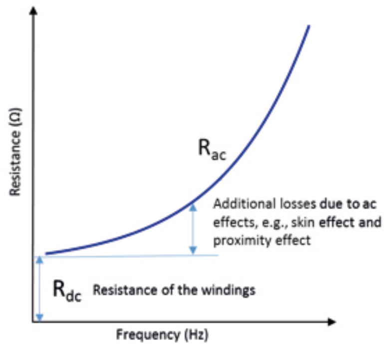


FIGURE 12: Resistance in a conductor as a function of frequency

Therefore, while the "resistance" of a pure resistor does not vary with frequency, the losses in a transformer (which resistance is used to model) often vary with the frequency of the source signal.

When impedance increases linearly with test frequency, it forms a straight line on a logarithmic scale (Figure 13).

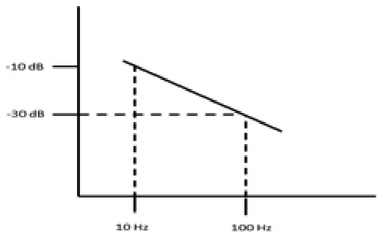


FIGURE 13: Frequency response of a frequency dependent loss component such as hysteresis losses

For simplicity, the responses of applicable circuits discussed below (e.g., Figure 16, 18, 22, etc.) were generated using pure resistors (i.e., no change in resistance characteristics as frequency changes).

Capacitor (C)

When current flows through an impedance (such as a capacitor), the voltage across the impedance will drop but in the case of a capacitor (Figure 14), the amount by which the voltage will decrease is highly dependent upon the frequency of the current signal.

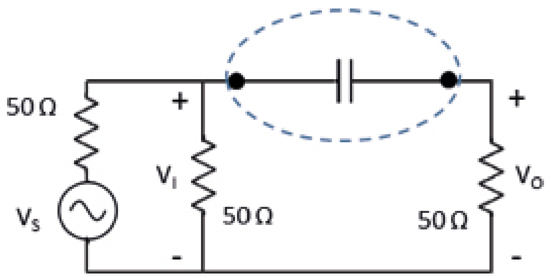


FIGURE 14: Capacitive circuit

At 0 Hz (i.e., DC), a capacitor presents as an open circuit[22] to the flow of current (e.g., as an infinite impedance). Consequently no DC current passes, as given in equation 5:

$$I_C = C\ (dV/dt) \qquad \text{[EQN 5]}$$

, where IC is capacitive current, C is capacitance and dV/dt describes how voltage varies with respect to time. With DC voltage (i.e., voltage is constant), dV/dt nears zero, and therefore, DC capacitive current nears zero. The voltage drop is extremely large across the capacitor at 0 HZ, so the ratio of V_O (with voltage dropping to near 0) to V_I nears zero. Expressed in decibels (i.e., 20 log to the base 10 of a value near zero, e.g. 10^{-5}), this transfer function equals, for example, -100 dB.

[22] After the capacitor has charged

Sweep frequency response analysis (SFRA)

Conversely, at very high frequencies, capacitive reactance as given by $X_C = 1/(2\pi f)C$, approaches zero and a capacitor begins to look like a short circuit. Therefore, there is little voltage drop across the capacitor and its transfer function (i.e., V_O/V_I) approaches unity or 1. The log to the base 10 of 1 equals 0 dB.

Figure 15 shows the frequency responses (amplitude and phase) of different sized capacitors. The responses exhibit a characteristic "climb" as frequency increases. As capacitance values get larger, the so-called capacitive "climb (i.e., to 0 dB)" begins at lower and lower frequencies. This concept becomes important when considering the sweep frequency response of a transformer. Bulk-winding capacitances are large (e.g., typically on the order of a few nanoFarads) while turn-to-turn capacitances are small (e.g., picoFarads). In Figure 15, it is noted for example that the effect of a 1μF capacitor is observable below approximately 20 kHz only.

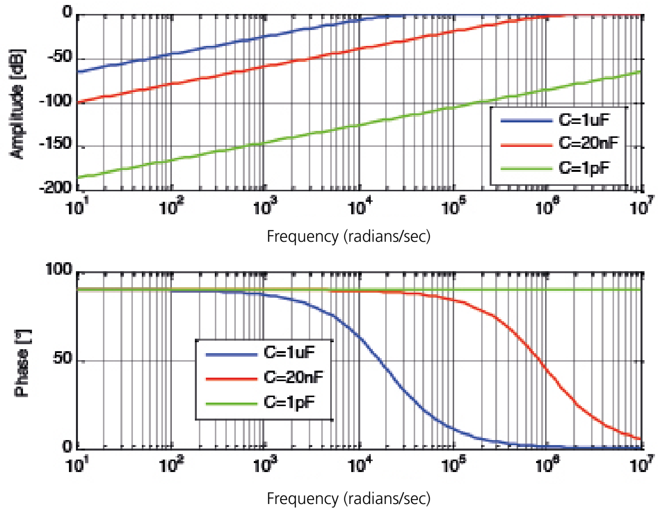


FIGURE 15: Frequency response of a single capacitor circuit (examples for 3 different sized capacitors are shown)

Capacitors model the electric fields that are established within a transformer when the transformer is in an energized condition. A capacitor's dielectric stores electrical energy that is placed across it just like the insulation materials used in a transformer do. Most dielectric materials have associated losses in the presence of an electric field. Resistors model these losses so it is instructive to examine the frequency response of a capacitor when combined with a resistor. However, it should be noted that dielectric losses (conductive and polarization) are frequency dependent so the following responses are not directly relatable but are good practice towards understanding the influence of combining two passive components.

Series RC circuit

At low frequencies, the capacitor in a series RC circuit (Figure 16) resembles an open-circuit and causes the voltage drop across the series RC impedance to be very large (i.e., the output voltage nears zero). Therefore, the amplitude of the transfer function in decibels is a very large negative number.

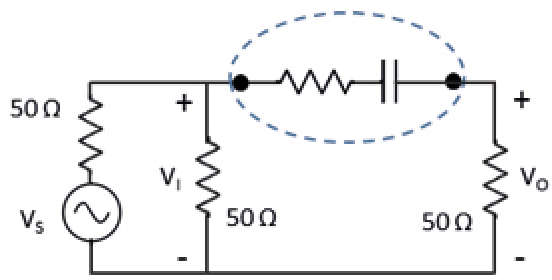


FIGURE 16: Series RC circuit

At higher frequencies, a capacitor behaves like a short circuit so the impedance of the circuit is reduced to the value of the resistance only. The response becomes a flat line [since the impedance (i.e., resistance) of a resistor does not change with frequency]. The larger the resistance is, the greater the voltage across it drops, and the closer to zero the transfer function (V_O/V_I) nears. Therefore, the amplitude of the transfer function in decibels becomes increasingly negative (with an increasingly large resistor). Up until that frequency where the reactance of the capacitor becomes effectively less than the resistance, the transfer function exhibits the characteristic "climb", which trends with the capacitor's transition from an open circuit to a smaller and smaller impedance (i.e., reactance) value. Once the reactance of the capacitor is less than the resistance, the resistance determines the response.

Sweep frequency response analysis (SFRA)

As expected, when the value of the resistance in the circuit is made larger (e.g., 1 MΩ), the response (in green in Figure 17) becomes dominated by the resistive influence almost immediately as frequency starts to increase.

At frequencies where the resistance dominates the impedance, the "phase" of the frequency response (also shown in Figure 17) is zero since there is negligible phase shift between V_O and V_I. Conversely, at frequencies where the capacitive reactance dominates the impedance, the phase of the response is 90º.

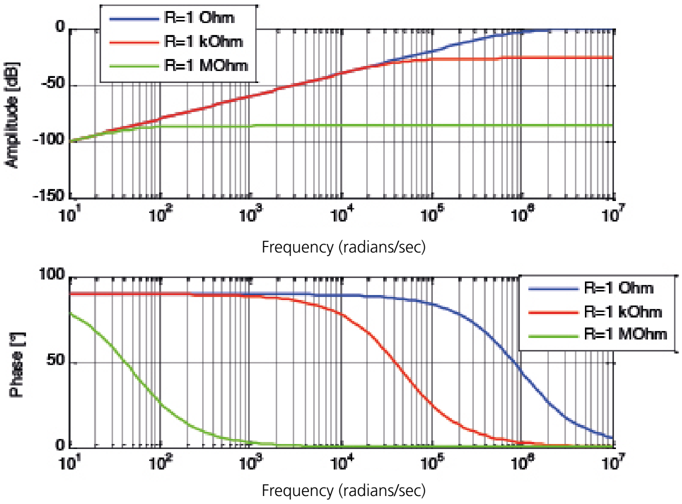


FIGURE 17: Influence of resistance on the frequency response of a series RC circuit with 20 nF capacitance

Series RC Circuit

At near zero frequencies, since the capacitor (Figure 18) presents as an infinite impedance to the circuit, all current flow (and therefore voltage drop) will be across the parallel resistor. Therefore, the transfer function begins as a flat line.

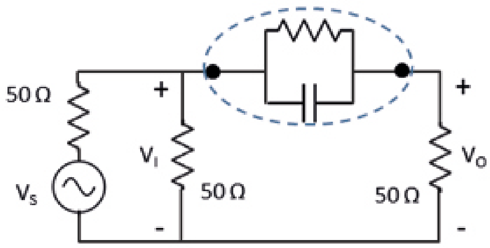


FIGURE 18: Parallel RC circuit

As expected and shown in Figure 19, the transfer function has a more negative dB value at these low frequencies for larger resistance values. Resistance does not change but as the frequency increases, the capacitor becomes a smaller and smaller impedance. As this happens, the frequency response exhibits the influence of the capacitor in the parallel RC impedance; that is, it begins to "climb" to 0 dB.

At very high frequencies, where the capacitor behaves as a short circuit, the resistor is shorted and there is virtually no voltage drop across the parallel RC combination. Therefore, the transfer function (i.e., V_O/ V_I) goes to 1, which equals 0 dB.

As expected, considering that this is a parallel combination, when the value of the resistance is made smaller (e.g., 1 kΩ instead of 1 MΩ), the frequency at which the capacitive reactance diminishes enough to influence the response, increases. Therefore, the capacitive "climb" (to 0 dB) is not observed until higher frequencies (Figure 19).

Sweep frequency response analysis (SFRA)

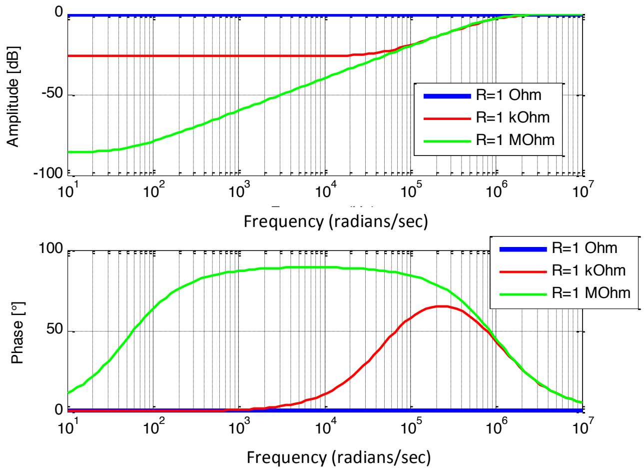


FIGURE 19: Influence of resistance on the frequency response of a parallel RC circuit with 20 nF capacitance

Inductor (L)

The transfer function of an inductor (Figure 20) is opposite that of a capacitor. At low frequencies, inductive reactance is very small ($X_L = 2\pi fL$) so the response is nearly unity (voltage output = voltage signal input), or 0 dB. At very high frequencies, inductive reactance is a very large impedance (i.e., voltage output is nearly 0) such that the inductor's response (i.e., V_O/V_I) approaches zero, or, expressed in decibels, is a very large negative number (e.g., – 120 dB).

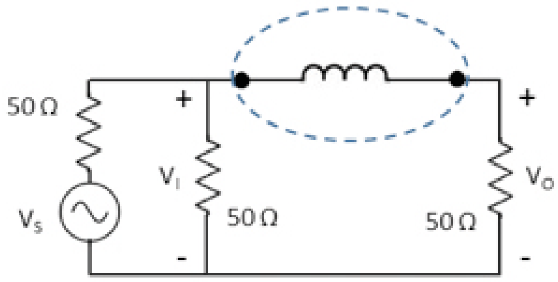


FIGURE 20: Inductive Circuit

Figure 21 shows the frequency responses (amplitude and phase) of different sized inductors. The responses exhibit a characteristic (inductive) "roll off" as frequency increases. As inductance values get larger, the "roll off" starts at lower and lower frequencies.

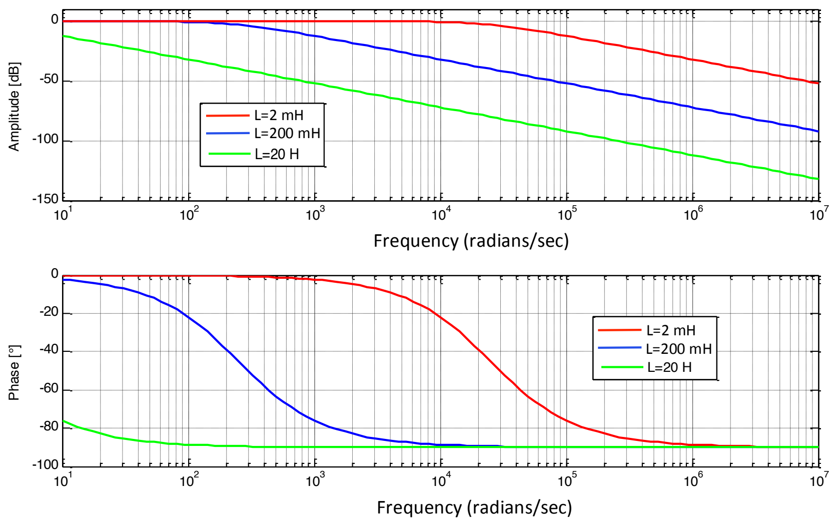


FIGURE 21: Frequency response of a single inductor circuit (examples for 3 different sized inductors are shown)

Sweep frequency response analysis (SFRA)

Inductors model magnetic energy in windings (main and tap) in a transformer. This magnetic energy (created by energizing a transformer's primary winding) induces voltage in 'coupled', non-energized secondary windings (i.e., mutual inductance) and also induces voltage in the energized winding itself (i.e., self-inductance). Transformer action, as this is known, consumes some energy, which is lost as heat. Resistors model these losses, which include transformer core losses, such as hysteresis and eddy losses. Therefore, it is instructive to examine the frequency response of an inductor when combined with a resistor. It is noted, however, that core losses (hysteresis and eddy) are frequency dependent so the following responses are not directly relatable to those of a transformer since the resistors used in these circuits do not model frequency dependent behavior. If the response of a frequency dependent loss component is added to an inductive response, the slope of the response becomes steeper.

Series RL Circuit

At very low frequencies where the inductor (Figure 22) behaves as a short circuit, the impedance of the series RL circuit is reduced to that of the resistance only.

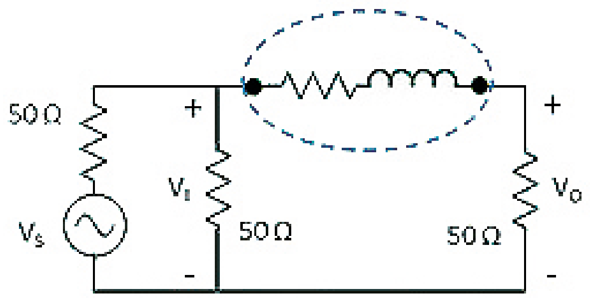


FIGURE 22: Series RL circuit

Therefore, as shown in Figure 23, the frequency response of this circuit begins as a flat line. The influence of resistance size on the frequency response is visible here at the lowest frequencies. As the resistance increases, the voltage drop across the circuit increases and the transfer function (V_O/V_I) decreases (i.e., magnitude in decibels becomes increasingly negative).

At highest frequencies, the inductor resembles an open-circuit and causes the voltage drop across the series RL impedance to be very large (i.e., the output voltage to be near zero). Therefore, the magnitude of the transfer function in decibels is a very large negative number.

At frequencies where the reactance of the inductor becomes effectively greater than the resistance, the frequency response exhibits the characteristic inductive "roll-off", which trends with the inductor's transition from a relatively small impedance (i.e., reactance) value to an open circuit.

At frequencies where the resistance dominates the impedance, the "phase" of the frequency response (also shown in Figure 23) is zero since there is negligible phase shift between V_O and V_I. Conversely, at frequencies where the inductive reactance dominates the impedance, the phase of the response is -90º.

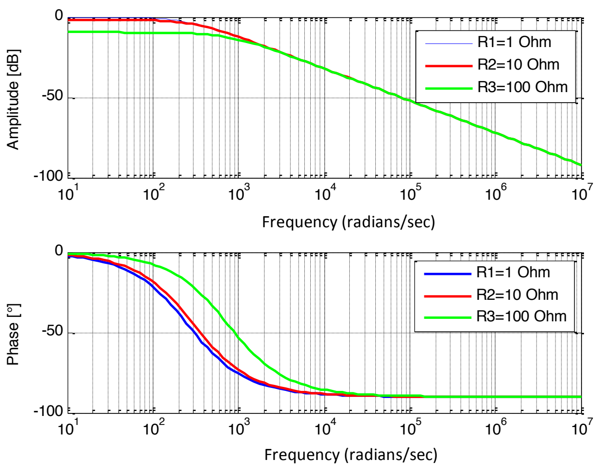


FIGURE 23: Influence of resistance on the frequency response of a series RL circuit

Parallel RL Circuit

At very low frequencies, since the inductor (Figure 24) behaves as a short circuit, the resistor is shorted and there is virtually no voltage drop across the parallel RC combination. Therefore, the transfer function (i.e., V_O/V_I) goes to 1, which equals 0 dB.

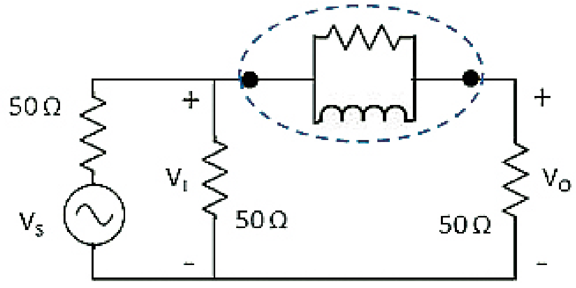


FIGURE 24: Parallel RL circuit

As frequency increases and the reactance of the inductor begins to increase, the influence of the inductor in the parallel RL impedance is seen as the frequency response (in dB) exhibits the characteristic inductive "roll-off". At very high frequencies, where the inductor presents as an infinite impedance to the circuit, all current flow (and therefore voltage drop) will be across the parallel resistor.

LC Circuit

Next we look at circuits that represent simple combinations of an inductor (L) and capacitor (C) and introduce the important concept of resonance. These circuits are known as second order circuits because they contain two energy storage elements, L and C. As explained above, a capacitor's influence is 'in play' when the frequency response "climbs" and an inductor's influence is 'steering' when the response "rolls". The configuration in which the inductor and capacitor are combined (e.g., parallel or series) will determine whether the response will roll-off or climb at the "start" (i.e., as the frequency increases from dc).

Parallel LC Circuit

In a parallel LC circuit (Figure 25), at very low frequencies and at very high frequencies, one of the two components will always present as a short-circuit to the current in the circuit and will "short" out the other component. Therefore, the transfer function of a parallel LC network is 0 dB at low frequencies and 0 dB at high frequencies.

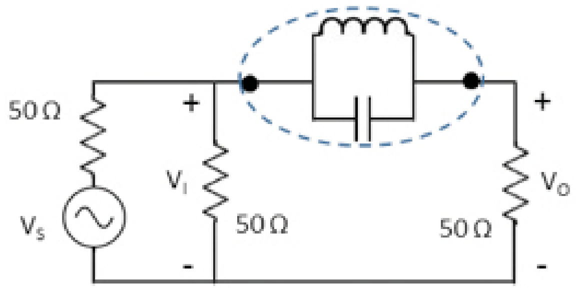


FIGURE 25: Parallel LC Circuit

Between these extreme frequency limits, either the inductor or the capacitor will present with a lower impedance[23] to the circuit (depending on frequency). Accordingly, the transfer function will "climb" (if the capacitor presents a lower impedance) or "roll" (if the inductor does). Up to a certain frequency, the inductor presents as a lower impedance to the circuit so the response rolls. At some frequency, the capacitor (which presents as a smaller and smaller impedance as the frequency increases) becomes a smaller impedance than the inductor so the response takes on the characteristic of a capacitor and starts climbing back to 0 dB.

The frequency at which the impedance of the capacitor matches the impedance of the inductor in magnitude (i.e., $X_C = X_L$) is a "resonance". A resonance signifies the frequency at which the inductive influence is controlling the response on one side and the capacitive influence determines the response on the immediate other (side).

[23] Or more specifically, reactance

Sweep frequency response analysis (SFRA)

The resonance frequency depends on the relative size of capacitance versus inductance and can be calculated as given in equations 6 – 9.

$$X_L = X_C \quad \text{[EQN 6]}$$

$$\omega L = 1 / \omega C \quad \text{[EQN 7]}$$

$$\omega^2 = 1 / LC \quad \text{[EQN 8]}$$

$$\omega = 1 / \sqrt{LC} \quad \text{[EQN 9]}$$

As an example, Figure 26 shows that with an inductance held at 100 mH, as the capacitance becomes progressively larger, the resonance frequency shifts to the left. In other words, with a larger capacitance, the characteristic behavior of climbing will happen quicker than with a smaller capacitance. Since the inductance in Figure 26 is constant, the roll-off is the same for each of the three LC combinations. It is often helpful to envision the separate inductive response and the separate capacitive response and then the combination of the two components by superposition. While the effect of the 100 nF capacitor is observable up to approximately 300 kHz, when combined in parallel with an inductor, its influence isn't visible in the response until 10 kHz (at approximately -63 dB).

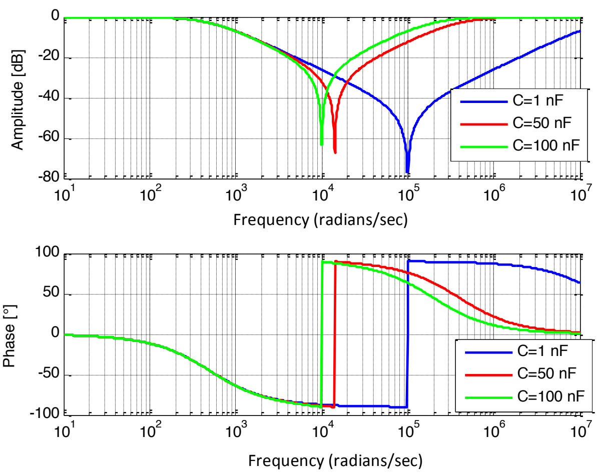


FIGURE 26: Influence of capacitance on the frequency response of a parallel LC circuit (L = 100 mH)

The impedance of an LC circuit is calculated by the standard "product-over-sum", which applies for any two impedances in parallel, and is given in equation 10. At the resonance frequency[24], the denominator nears zero (Equation 11), which implies an infinite impedance[25]. Consequently, the voltage drop is most significant at this frequency, and the transfer function (V_O/V_I) reaches a minimum point in dB. These resonance points are known as parallel resonances.

$$Z = \frac{(jX_L)(-jX_C)}{(jX_L) + (-jX_C)} \quad \text{[EQN 10]}^{26}$$

$$Z = \frac{-j(X_L)(X_C)}{(X_L - X_C)} \quad \text{[EQN 11]}$$

Series LC Circuit

In a series LC network (Figure 27), at very low frequencies and at very high frequencies, one of the two components will always present as an infinite impedance to the current in the circuit. Therefore, the transfer function of a series LC network is very negative dB at low frequencies and at high frequencies.

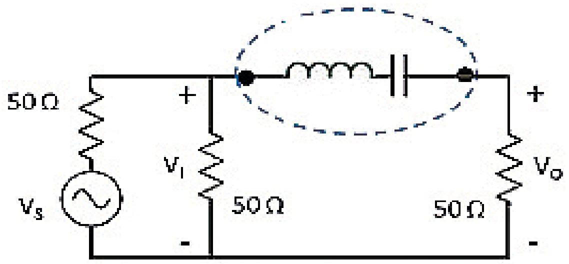


FIGURE 27: Series LC circuit

[24] Where $X_C = X_L$
[25] With equal reactance values, current is exchanged, or circulates, between the capacitor and inductor in parallel; none is drawn from the source
[26] The "j" factor is included to account for the phase shifts in both components

Sweep frequency response analysis (SFRA)

When the inductor and capacitor are combined in series, at the resonance frequency, the matching inductive and capacitive impedances nullify (as given in Equation 12) and result in no net voltage drop across the circuit (i.e., $V_O = V_I$). Therefore, the amplitude of the transfer function at resonance is 0 dB. These resonance points are known as series resonances.

$$Z = \sqrt{(X_L - X_C)^2} \qquad \text{[EQN 12]}$$

The resonance frequency will depend on the relative size of capacitance versus inductance. For example, Figure 28 shows that, with an inductance held at 100 mH, as the capacitance becomes progressively larger, the resonance frequency shifts to the left. In other words, with a larger capacitance, the characteristic behavior of climbing will happen "sooner" (e.g., at relatively lower frequencies than for the same circuit with a smaller capacitance).

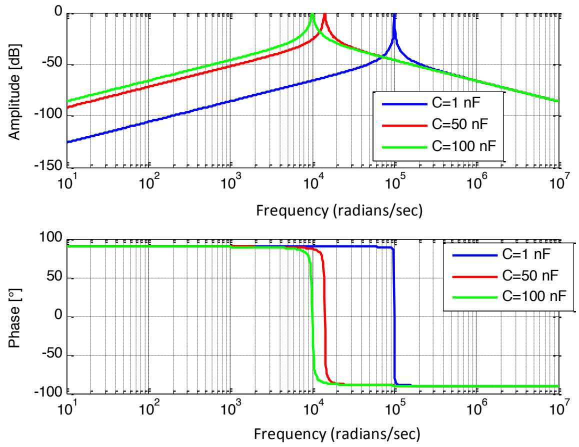


FIGURE 28: Influence of capacitance on the frequency response of a series LC circuit (L = 100 mH)

RLC Circuit

Finally, consideration is given to the influence of combining all three passive elements.

Parallel RLC Circuit

As explained earlier for a parallel LC circuit, and applicable here, at very low frequencies and at very high frequencies, the inductor or capacitor, respectively, will present as a short-circuit to the current in the circuit and will "short" out the other components. Therefore, the transfer function of a parallel RLC network (Figure 29) is 0 dB at low frequencies and 0 dB at high frequencies.

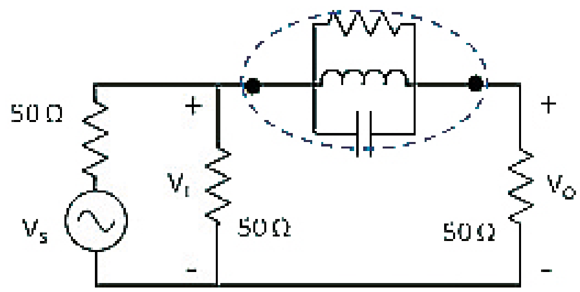


FIGURE 29: Parallel RLC circuit

Since there will be cancellation between the inductive and capacitive impedance in the parallel RLC circuit, the total impedance of the circuit is mostly resistive. The phase plot in Figures 30 and 31 confirms this. The response phase never reaches a full 90 or – 90 degrees.

At resonance in a parallel RLC circuit, current circulates through L and C without leaving these two components, and the source only needs to supply enough current to make up for losses. In this case, R represents the energy losses within the circuit, and is the only component that draws current from the source. The effective impedance of the circuit is nothing more than R at resonance, and the current drawn from the source is in phase with the voltage.

Figure 30 shows the influence of inductor size on the frequency response. In addition to the resonance point shifting to the left as the inductor progressively grows larger, another feature is worthy of note. The capacitance is held constant for each of the three responses in this example so the "knee point" of the capacitive influenced section of the response is "anchored" and does not move. The progressive increase in inductance predictably causes the "roll-off" to occur at lower and lower frequencies in each response. However, because of the resistor in the parallel RLC circuit, the amplitude of the resonance point cannot "deepen" as was the case with the parallel LC circuit responses given in Figure 26. The resistor solely determines the amplitude of the resonance point in a parallel RLC arrangement and that does not change irrespective of the inductor and capacitor. Therefore, the net effect is a flattening of the response (i.e., the bandwidth increases) as the inductor increases in size relative to the capacitor.

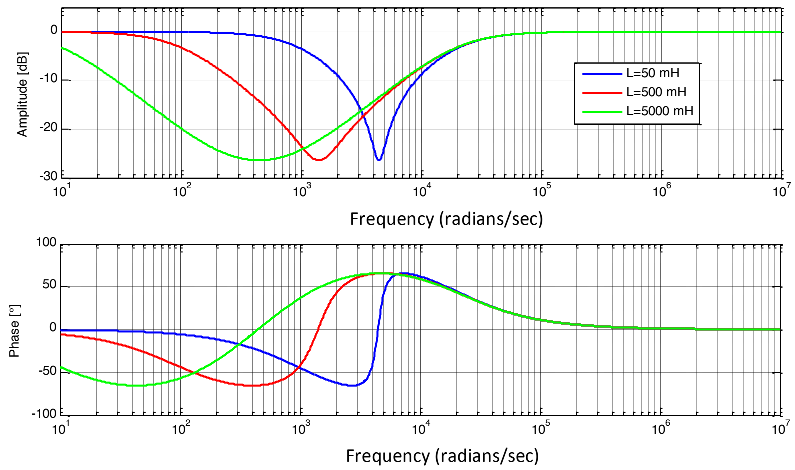


FIGURE 30: Influence of inductance on the frequency response of a parallel RLC circuit (C = 1µF; R = 1kΩ)

In contrast, Figure 31 shows the influence of capacitor size on the frequency response of a parallel RLC circuit. Holding the inductor size constant, the inductive roll-off stays anchored. The progressive increase in capacitance predictably causes the "climb" to occur "sooner", at lower and lower frequencies in each response. Once again, because of the resistor in the RLC parallel circuit, the amplitude of the resonance point cannot "deepen" as was the case with the parallel LC circuit response given in Figure 26 (i.e., the resistor solely determines the amplitude of the resonance point in this arrangement). Therefore, the net effect is a flattening of the response (i.e., the bandwidth increases) as capacitance decreases in size relative to the inductor. In other words, changing the size of the capacitor relative to the inductor, or vice versa, changes the size of the resonance.

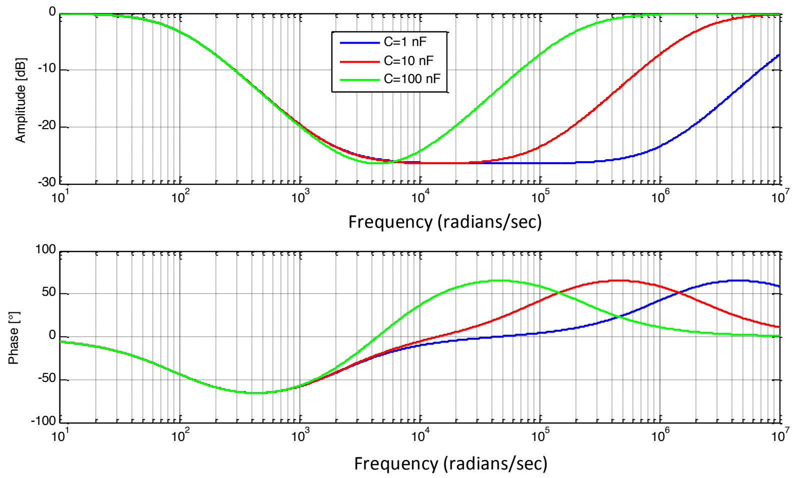


FIGURE 31: Influence of capacitance on the frequency response of a parallel RLC circuit (L = 500 mH; R = 1kΩ)

Sweep frequency response analysis (SFRA)

Series RLC circuit

As explained earlier for a series LC circuit, and applicable here, at very low frequencies, the capacitor (Figure 32) behaves like an open circuit and virtually no current will flow through the circuit. The output voltage goes to zero and the transfer function (V_O/V_I) nears zero (e.g., a very negative magnitude in dB). At very high frequencies, the inductor behaves like an open circuit so, similarly, the response amplitude will be a very negative dB.

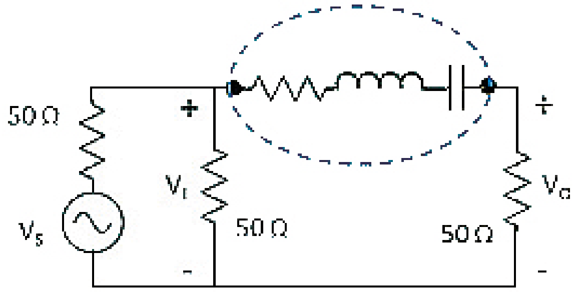


FIGURE 32: Series RLC circuit

At intermediate frequencies, the difference between capacitive reactance (X_C) and inductive reactance (X_L) is small. At resonance, the difference is zero and only the resistance will limit current flow in the circuit. If the value of resistance is small, there will be very little voltage drop so the transfer function (V_O/V_I) at resonance will near unity (i.e., close to 0 dB). However, the impedance increases quickly as the frequency changes. If the value of resistance is relatively large, the amplitude 'bandwidth' of the frequency response is much broader, however, the amount of current through the circuit never reaches the same peak as that achieved for a small resistance value. Changing the size of the resistor changes the size of the resonance (Figure 33).

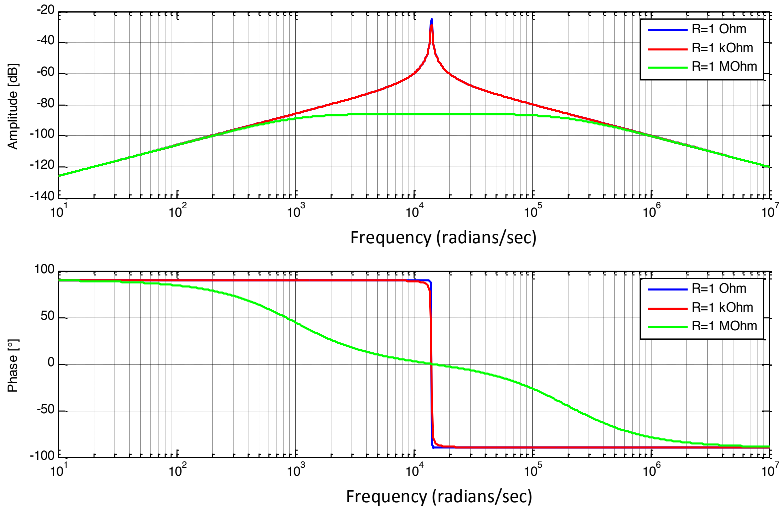


FIGURE 33: Influence of resistance on the frequency response of a series RLC circuit (C = 1 nF; L = 5000 mH)

Figures 34 and 35 illustrate the influence of increasing the size of the capacitor and the inductor, respectively, in a series RLC circuit. An increase in capacitance results in the series resonance shifting to the left as the characteristic "capacitive climb" occurs at progressively lower frequencies. The inductance is held constant for each of the three responses in Figure 34 so the "roll-off" section of the response is "anchored" and does not move. Because the resistance is held constant too, the bandwidth of the three responses stay the same.

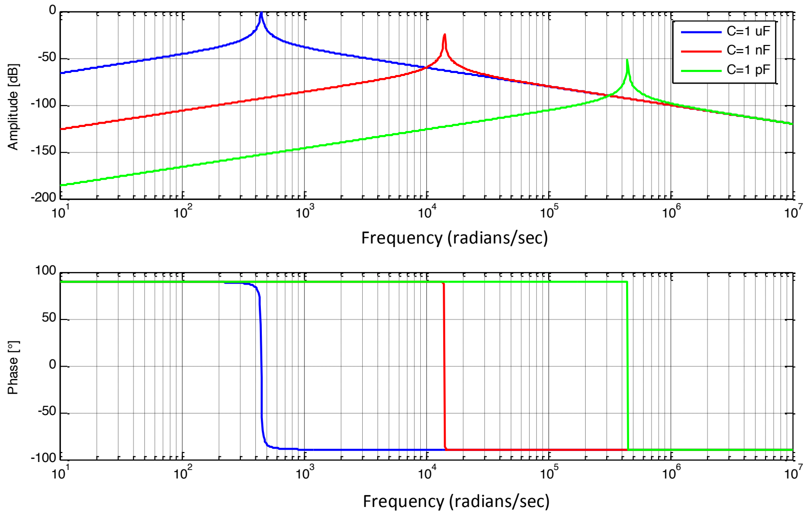


FIGURE 34: Influence of capacitance on the frequency response of a series RLC circuit (L = 5000 mH; R = 1 Ω)

An increase in inductance results in the series resonance shifting to the left as well since the characteristic "roll-off" occurs at progressively lower frequencies as an inductor becomes larger. The capacitance is held constant for each of the three responses in Figure 35 so the "capacitive climb" portion of the response is "anchored" and does not move. Because the resistance is held constant too, the bandwidth of the three responses stay the same.

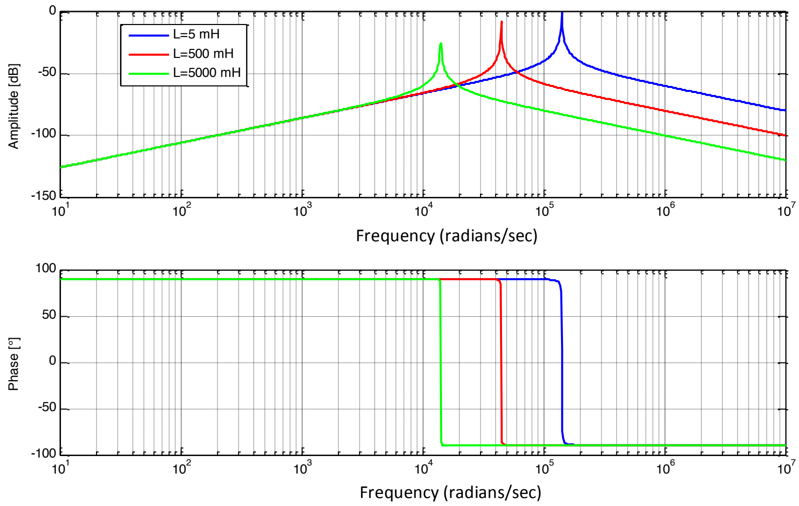


FIGURE 35: Influence of inductance on the frequency response of a series RLC circuit (C = 1 nF; R = 1 Ω)

COMPLEX RLC CIRCUIT – THE TRANSFORMER

After reviewing the frequency responses for single electrical parameters and simple RLC combinations, one can appreciate that the response of a complex RLC circuit, which represents a transformer's effective impedance, will be more complicated. As stated previously, the collective losses in a transformer vary with frequency, which contributes to the complexity.

A real transformer has many inductances and capacitances (all of varying sizes) and each LC pair gives a resonance. For example, Figure 36 shows an open circuit SFRA trace for a low voltage winding, which exhibits both parallel (i.e., valleys) and series (i.e., peaks) RLC resonances. This trace is provided for illustrative purposes only as there is a lot of variation between the responses of different manufacturer and make transformers, winding configurations, etc.

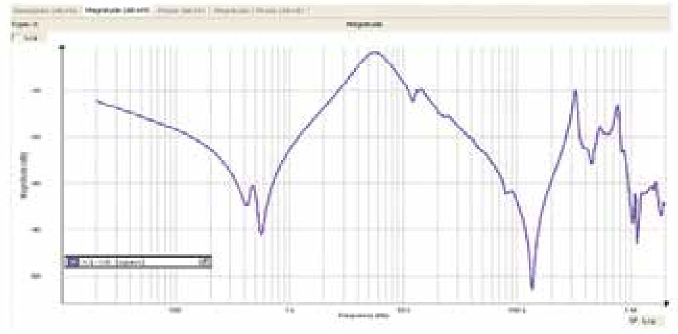


FIGURE 36: Example of a low voltage open circuit SFRA trace

In order to understand the general appearance of a transformer's open-circuit SFRA frequency response, it is helpful to consider the equivalent circuit model of a transformer. Bear in mind that a transformer is designed to operate at a given operating frequency because its characteristics change when frequency changes.

FEATURES OF A TRANSFORMER'S SFRA RESPONSE (WHY DOES IT LOOK THE WAY IT DOES):

Open circuit SFRA measurements

Low Frequencies

The equivalent circuit of a transformer, given in Figure 37, models transformer behavior well at low frequencies (e.g., from 20 Hz to 1 or 2 kHz). It consists of an ideal transformer, plus the excitation impedance and leakage impedances of the HV and LV windings. When the SFRA signal is injected into the HV winding with the LV winding open (or into the LV winding with the HV winding open), the measurement is dominated by the excitation impedance. In fact, at low frequencies, an open circuit SFRA test is similar to an excitation current measurement.

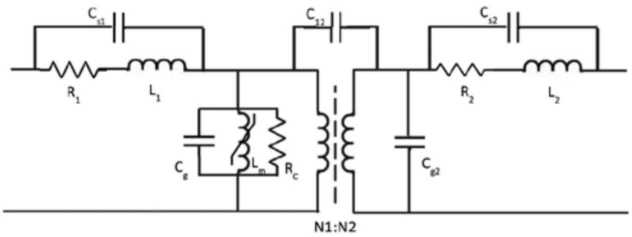


FIGURE 37: Equivalent Circuit of a Transformer

The excitation impedance[27], Z_m, of a transformer is both resistive and reactive (modeled using a non-linear inductance and a capacitance component) as given in Figure 38 and represents the total opposition to the flow of excitation current (i.e., the energy required to force transformer action).

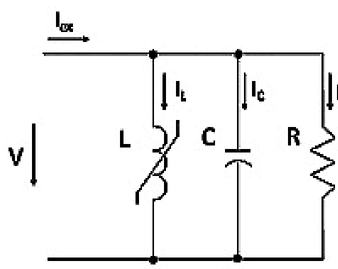


FIGURE 38: Excitation Impedance, Z_m

[27] also referred to as the open-circuit or magnetizing impedance

Sweep frequency response analysis (SFRA)

Specifically:

- L (a non-linear inductance) represents the impedance encountered by magnetizing current in building a magnetic field in the transformer core. The energy required to "overcome" this impedance is stored in the magnetic field on every other half-cycle (and returned on the others). This typically constitutes the predominant part of an excitation current measurement and is influenced by the energized winding and the core.
- R (resistance) represents the collective losses produced as heat (i.e., unrecoverable energy) in the process of establishing transformer action. This includes "magnetic field losses" (i.e., core losses, such as hysteresis and eddy losses) and, to a relatively smaller degree, "electrical field losses" (i.e., dielectric loss in insulation[28] that is charged during excitation of the transformer) and copper loss[29].
- Finally, C (capacitance) represents the impedance encountered by the capacitive current drawn (from the source) to build the electrical field in the insulation. Energy stored in the electric field is created by the charging currents through the inter-winding (i.e., high to low voltage windings), interphase, winding-to-ground and turn-to-turn insulation[30].

Because the inductive reactance of the core dominates the measurement at low frequencies, the SFRA open circuit sweep for a winding begins with a characteristic inductive roll-off.

> As an aside: The behavior exemplified in an open circuit SFRA trace at these low frequencies highlights the very reason why a transformer designed for 60 Hz cannot be used at the same voltage on a 50 Hz system. Since core impedance becomes smaller as the frequency goes lower, (assuming that the voltage is held the same) a 60 Hz designed transformer would experience core saturation if operated at 50 Hz.

The magnetizing inductance that builds due to the magnetism of the core is also affected by: the number of turns of the winding under test, the core material and core geometry (a.k.a., coil area and length)[31].

The influence of the number of winding turns and coil area on inductance is seen when comparing a transformer's high voltage (HV) open circuit SFRA response to a transformer's low voltage (LV) open circuit SFRA response (e.g., given in the green and blue traces, respectively, in Figure 39). Inductance is larger when more turns are added to a winding and when the coil area is greater. Therefore, when a transformer is energized from an HV winding with many turns (as opposed to an LV winding with fewer turns) and with a greater coil area than the LV winding (e.g., in a core form configuration, the HV winding is the outer wound winding), this will result in a higher excitation impedance from the HV side[32]. In fact, most open circuit HV traces start between –30 dB and –50 dB whereas most open circuit LV traces start between –5 dB and –15 dB.

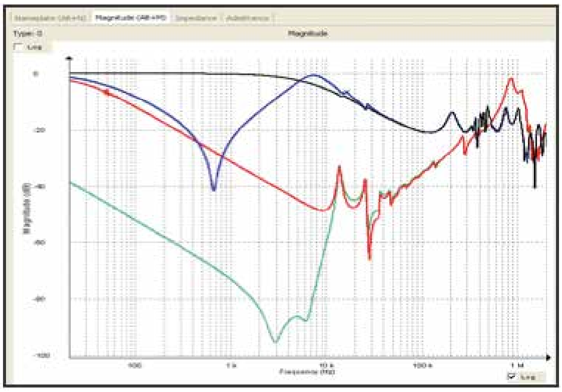


FIGURE 39: HV open circuit SFRA response (green); LV open circuit response (blue); HV short circuit SFRA response (red); LV short circuit response (black)

[28] An excitation current measurement includes losses in the turn-to-turn insulation only (see next footnote)

[29] Copper loss is comparatively negligible here (i.e., in an open-circuited condition) and is attributed to heat produced by the relatively small excitation current flowing through the transformer winding conductors.

[30] In an excitation current field test, the inter-winding, interphase and winding-to-ground components are excluded due to the test circuit configuration, i.e., the UST circuit; therefore, only the turn-to-turn capacitance influences the single-phase excitation current measurement.

[31] The magnetizing inductance is also frequency dependent.

[32] Therefore, a test instrument is burdened less when trying to excite the transformer from the HV winding (than from the LV winding); hence, excitation tests are typically performed on the HV side of a transformer.

Sweep frequency response analysis (SFRA)

Typical characteristics of open circuit SFRA responses of high voltage (HV) windings as compared to low voltage (LV) windings are summarized in Table 1.

TABLE 1: Typical characteristics of open circuit SFRA traces

HV windings	LV windings
• Start between –30 dB and –50 dB	• Start between –5 dB and –15 dB
• Greatest attenuation (as compared to LV and TV windings)	• Least attenuation (as compared to HV and TV windings)
• Greater complexity in its distributive network	• Generally smoother response
• Greater number of resonances	• First peak after the core resonance approaches – 5 dB to 0 dB
• Steeper resonances	

When a short-circuit develops across turns of the winding under test (Figure 40), the magnetizing inductance notably decreases and the inductive dominated beginning part of the open circuit SFRA response shifts predictably up and to the right consistent with a smaller inductance (reference Figure 21). The response assumes a similar behavior as that of a short circuit SFRA measurement. The compromised winding's response is affected most but this failure mode will also be noticeable in the open circuit SFRA measurements of the other, undamaged windings. Short-circuited turns in the HV winding specifically, result in an impedance decrease at low frequencies in the HV short circuit SFRA test as well. This is one of the easiest types of faults to recognize with SFRA testing.

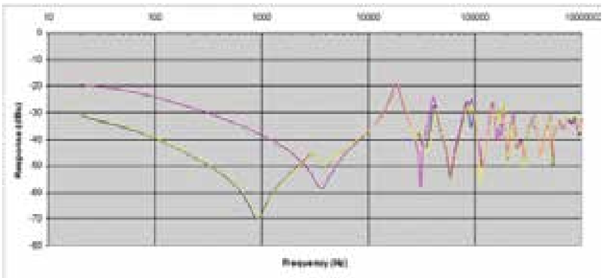


FIGURE 40: HV open circuit SFRA tests with shorted turns in B-phase winding (red trace)[33]

An additional point of note in this low frequency range is the influence of voltage. The magnetizing impedance of a transformer is non-linear and depends on the level of excitation. For this reason, SFRA tests made on a transformer at different voltages may not overlay at lowest frequencies, as evidenced in Figure 41, and therefore should not be compared. Rather, it is advised to use the same measurement voltage in an SFRA test as was applied in previous SFRA tests. Typically, a 10 V p-p signal is used[34].

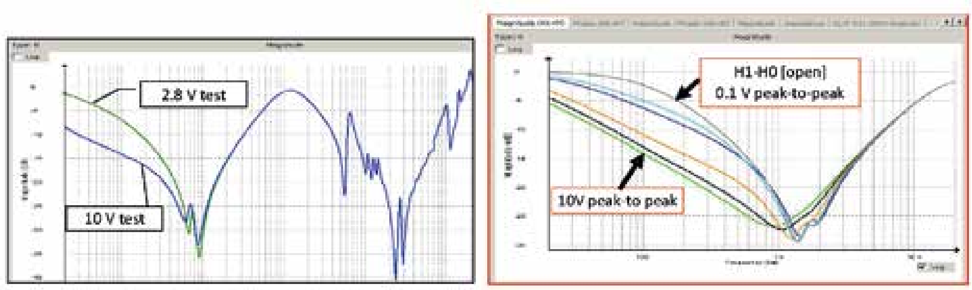


FIGURE 41: Influence of test voltage on open circuit SFRA test response

The inductive reactance of the excitation impedance increases with frequency while the capacitive reactance decreases. The inductive roll-off continues down to that point where the capacitive reactance is equal to the inductive reactance. The first resonance is a minimum that occurs at the resonance between the parasitic capacitances[35] of the transformer and the magnetizing inductance of the given winding.

The winding construction (i.e., middle or outer phase leg) will determine whether this first resonance is a "single" parallel resonance or "double" parallel resonance at these lower frequencies. A single parallel resonance occurs when testing a middle phase winding because there are symmetrical return paths for flux through the outer phase legs. On the other hand, there are two parallel resonances when testing an outer phase winding as the return paths for flux are two different lengths.

[33] Note the large impedance decrease in B phase (red). In healthy condition, as compared to A and C-phase, the B-phase should exhibit a very large, negative dB response (i.e., should be the lowest of the three traces on the graph).

[34] The Megger FRAX SFRA test instrument defaults to a 10 V p-p test voltage but provides the user with the ability to change the test voltage if needed in order to produce test results that may be compared to previous results obtained at a different test voltage.

[35] The series lumped capacitance is nearly impossible to calculate but includes inter-winding (i.e., high to low voltage windings), interphase, winding-to-ground and turn-to-turn insulation.

Sweep frequency response analysis (SFRA)

Figure 42 shows a typical result where A phase and C phase responses have two parallel resonances at low frequencies and nearly overlay each other while the B phase response has a single parallel resonance. The middle phase (B) response, as shown here, has a higher impedance through the core region as compared to the two outer phase windings of this core-form transformer. This correlates well with the behavior of exciting current test measurements, whereby less excitation current is required to excite a transformer when energizing the middle-wound phase winding[36]. In comparison, more (excitation) current will be drawn from the source to excite a transformer when energizing either of the outer two phase windings, which have relatively lower impedance.

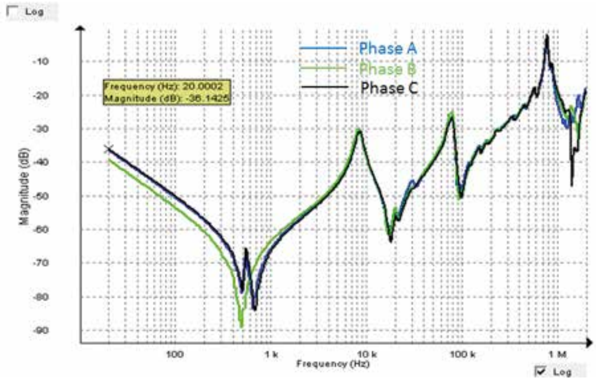


FIGURE 42: Open circuit HV SFRA traces – different magnetic paths lead to different responses between middle phase and outer wound phases

The winding configuration (e.g., wye or delta) also impacts the look of the SFRA sweep in this low frequency range. While wye windings have a distinct first resonance (or two), high voltage delta windings exhibit a "flattened valley" response at low frequencies [7], as seen in Figure 43 (dark blue bottom-most traces). Low voltage delta windings, however, tend to resemble wye windings.

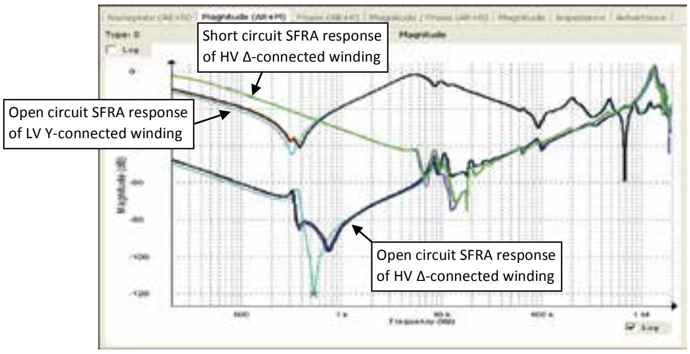


FIGURE 43: SFRA responses of a Δ- Y transformer

Mid Frequencies

In the mid frequency ranges (e.g., typically around 2 kHz to 20 kHz), mutual inductance chiefly influences the response. Mutual inductance refers to the phenomenon whereby voltage is induced in the 'coupled', non-energized secondary windings. It is interesting to note that because the coupled winding(s) becomes energized through induction, capacitive current will be drawn to electrically charge the insulation surrounding this winding. The bushings[37], for example, on the coupled secondary winding will have current through their capacitive body, which must flow through the secondary winding and is therefore reflected by mutual coupling into the exciting current measured in the energized winding. Current (albeit small) in the secondary winding will result in mutual inductance in the primary winding.

The amount of mutual inductance that links one winding to another depends very much on the relative positioning of the two windings. If a winding is positioned next to another winding such that the physical distance separating them is small, then nearly all of the magnetic flux generated by the first winding will interact with the winding turns of the second winding, inducing a relatively large emf and producing a large mutual inductance.

[36] When a winding has a higher open-circuit impedance, a test instrument is burdened less when trying to excite the transformer; in contrast, a lower open circuit impedance draws more current.

[37] A capacitive graded bushing is constructed with a system of capacitive layers with a ground reference on the last (or nearly last) capacitive layer

Sweep frequency response analysis (SFRA)

Coupling between windings is also enhanced by the magnetic permeability of the material around which the windings are wrapped. The coupling between windings is improved in a transformer with an iron core as opposed to an air core as supported by Equation 13 for mutual inductance[38]:

$$M = \frac{\mu_0 \mu_r N_1 N_2}{\ell} \qquad \text{[EQN 13]}$$

,whereby μ_0 is the permeability of free space (4π10-7), μ_r is the relative permeability of the core, N is the number of winding turns in the first and second windings, respectively, A is the cross-sectional area in m^2, and ℓ is winding length.

The shape and resonances in this area will vary depending on the type of connection and arrangement of the windings.

High Frequencies

The core's excitation impedance does not dominate an open-circuit SFRA trace for the entirety of the response. The excitation impedance decreases with the increase of frequency due to the frequency dependent core permeability. An example of this behavior is given in Figure 44, which shows the relative permeability of a sample core material as a function of frequency. It can be seen that as frequencies go up, the core permeability will finally drop to the permeability of air. This is caused by the fact that the skin effect phenomenon also occurs for the magnetic core. At sufficiently high frequency, the magnetic field is no longer able to penetrate the laminations and as a result, the permeability reduces significantly.

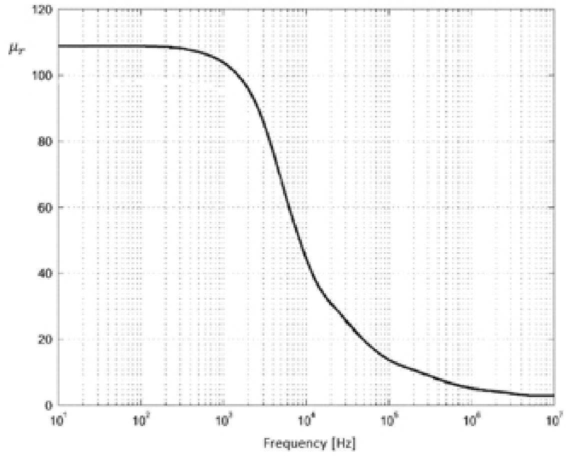


FIGURE 44: Relative permeability of a transformer core[39] as a function of frequency [8]

The frequency dependent core permeability manifests as the convergence of the open circuit response and the winding's short circuit response. For example, it can be observed in Figure 43 that from 40 kHz and above, the "short" and "open" give identical responses. The core permeability is equivalent to that of the non-magnetic medium surrounding the magnetic core from that frequency point onwards.

Therefore, in the high frequency range, typically from 10 kHz or 20 kHz to 1 MHz, the core no longer influences the open circuit response. Resonances here are due to the self-inductance of conductors[40] and the capacitance of winding discs/turns. The high frequency equivalent circuit is shown in Figure 45, where node "n" represents the number of winding turns. Each turn consists of self-inductance, mutual inductance and resistance. In addition to that, there are turn-to-turn capacitors and turn-to-ground capacitors.

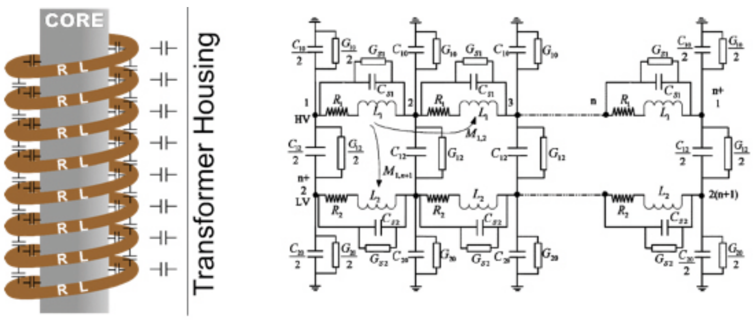


FIGURE 45: Lumped circuit model for a single phase transformer [8]

[38] This equation for the mutual inductance between two windings assumes a perfect flux linkage between the two windings
[39] For illustration only. The initial magnetic permeability of grain-oriented steel will likely be much higher than the 110 H/m shown in Fig. 43.
[40] Typically nH/m

Sweep frequency response analysis (SFRA)

As the sweep progresses into this high frequency range, the leakage inductances, along with the series (i.e., turn-to-turn) and ground capacitances of the winding (all of which are quite small in magnitude) determine the overall shape of the response curve. In both mid and high frequency ranges, the responses of all three phases are nearly the same (i.e., practically overlay) since the response depends on the winding and, generally, all three windings should be nearly identical.

Any mechanical change within the winding structure affects this frequency range. Towards the higher frequencies within this range, deviations due to phase asymmetry of the lead structure and the tap changer becomes visible. If a transformer has a tertiary winding, deviations may occur here as well.

Highest Frequencies

At frequencies above 1 MHz for transformers greater than 72.5 kV, or above 2 MHz for transformers 72.5 kV and below, the response depends more on the test setup and connections than on the transformer itself although the internal tap leads will have some influence [9]. Therefore, it is not standard practice to analyse SFRA traces at these highest frequencies. At this point or a little before, the response for each phase will start to diverge when compared to each other. This can be seen for example in the data above 1 MHz shown in Figure 42.

Short circuit SFRA measurements

Short circuit SFRA measurements remove the effect of the core at low frequencies and are essentially the same as a (3-phase equivalent) leakage reactance test[41]. When a transformer carries load or is short-circuited, leakage flux occurs. This flux travels outside the core material for at least some or most of its path in contrast to flux that builds in the core during transformer excitation, which stays contained within the core. The path outside the core that the leakage flux follows is primarily comprised of the windings and the space between the windings (i.e., the leakage channel). The impedance measured under short-circuited conditions is primarily attributed to leakage flux.

The leakage impedance is much less than the excitation impedance so the excitation impedance is essentially "shorted out" during this measurement (Figure 46). The leakage inductance component (e.g., L_1 or L_2 in Figure 46) accounts for the additional voltage component that builds in a winding due to at least some of its turns being "cut" by the leakage flux[42]. The problem with leakage flux is that it does not uniformly occupy all space with the leakage channel. Therefore, since the number of high voltage (HV) winding turns "cut" by the leakage flux is not proportional to the number of low voltage (LV) winding turns "cut" by the leakage flux, each winding has a different leakage reactance assigned.

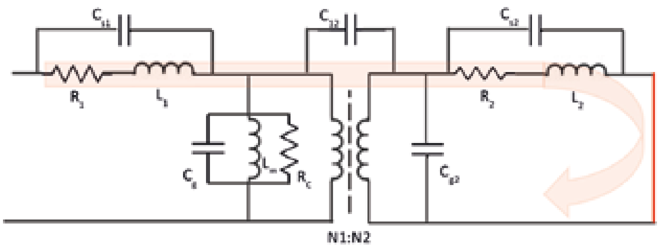


FIGURE 46: Short circuit equivalent circuit

The short circuit SFRA response begins with an inductive roll off. If the geometry of either winding changes, the number of winding turns being cut by leakage flux will change and result in a different leakage inductance. Therefore, the curve will move either to the left (if leakage inductance increases) or to the right (if leakage inductance decreases).

All three short circuit responses should be nearly identical. A magnified view of the linear part of the roll off should reveal no more than a 0.1 dB difference between the three traces and the roll-off should be close to -20 dB/ decade. Poor connections (i.e., increased resistance) will affect the short circuit SFRA responses at the lowest frequencies (e.g., ≤ 20 Hz).

As frequency increases, the open circuit SFRA traces and the short circuit SFRA traces come together (Figure 47) as the lumped circuit model (e.g., the winding structure) represents higher frequency behavior in either case.

[41] Although leakage reactance or short circuit impedance measurements are performed at line frequency only.
[42] When flux "cuts" a winding, voltage is induced across any involved winding turn(s)

Sweep frequency response analysis (SFRA)

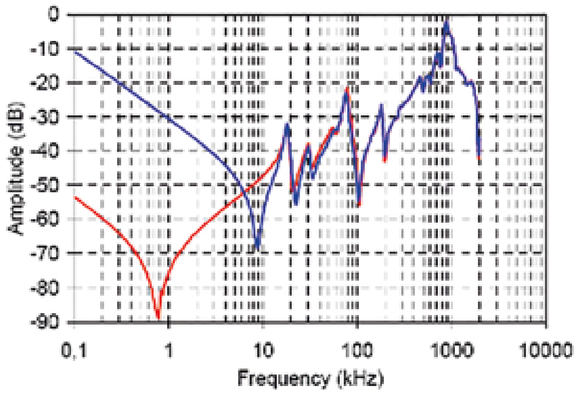
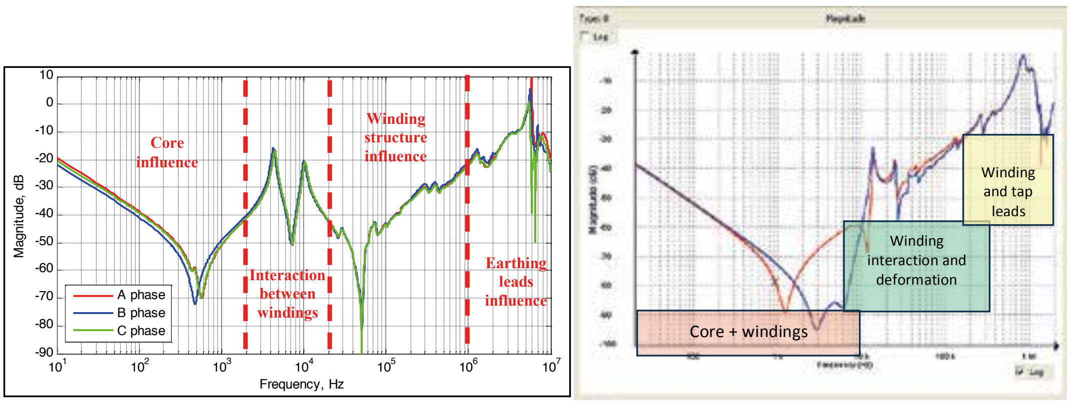


FIGURE 47: Comparison of HV open circuit SFRA test to HV short circuit SFRA test

Summary – Open circuit and Short circuit SFRA responses

In summary, frequency ranges (or bands) of the open circuit (and short circuit) SFRA response are dominated by different components of the transformer. As a helpful reference, standards organizations provide visual aids that define these frequency ranges for the typical transformer, for example as given in Figure 48a.



(a) (b)

FIGURE 48: Frequency ranges over which different transformer components wield most influence:
(a) IEEE C57.149TM-2012 guidelines
(b) Guidelines in use to interpret measurement differences on a (403/√3)/ 16/ 16 kV single phase GSU [ungrounded core (red) and properly grounded core (blue)]

If an SFRA response has changed as compared to a reference trace (as in Figure 48b), the failure mode(s) implicated depends, in part, on the frequency "band" in which the response has changed. A summary of these is given in Table 2. Note that the frequency band boundaries are approximate and may change due to transformer design.

TABLE 2: Influence of transformer failure modes on SFRA responses

Frequency band	Component	Possible failure
< 2 kHz	Core[43] Magnetizing inductance	Core problems, core ground problem, shorted turns, open circuits
	Leakage channel[44] Winding Leakage Inductance	Poor connections/ high resistance, short-circuit impedance changes
2 kHz to 20 kHz	Bulk Component	Bulk winding movement, winding displacement
20 kHz to 400 kHz	Main winding	Deformation within the main or tap windings
400 kHz to 2 MHz	Main winding, tap winding and internal leads	Movement of the main and tap windings, winding looseness, ground impedance variations

[43]This row pertains to open circuit SFRA responses, specifically
[44]This row pertains to short circuit SFRA responses

Sweep frequency response analysis (SFRA)

It is worth noting here that the frequency ranges defined in Table 2 are the primary areas where the respective failure modes manifest. A failure mode may have additional (though lesser) effects in other frequency bands and further, may wield marginal influence on the responses of other, directly unaffected windings.

Capacitive Inter-winding Measurements – CHL capacitance

Inter-winding SFRA measurements are different than the open circuit and short circuit SFRA measurements discussed thus far in that a low voltage signal is injected into the primary (e.g., HV) winding and the induced voltage signal on a non-primary (e.g., LV) winding is measured. There are two types of inter-winding tests, capacitive and inductive, which are realized by either leaving the opposite ends of the two windings under test floating (for a capacitive measurement) or by grounding them (for an inductive measurement). Figure 49 provides a test circuit for a capacitive inter-winding SFRA test on a Y-Δ configured transformer.

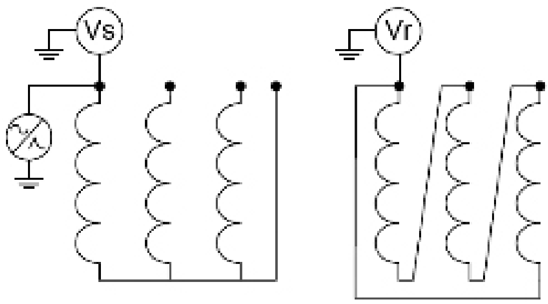


FIGURE 49: Capacitive Inter-winding SFRA Test Setup

Capacitive inter-winding measurements always start with high attenuation, typically between –60 dB and –90 dB [7]. Capacitive inter-winding measurements are valued for their long purported "high sensitivity" in the detection of radial deformations. Depending on the severity, the diagnosis of radial deformations using open circuit and short circuit SFRA measurements are not always straightforward so having an additional source of confirmation becomes invaluable.

The inter-winding capacitance measured in a power factor/dissipation factor (PF/DF) and capacitance test (e.g., CHL) can be determined from the capacitive inter-winding SFRA test. For example, at 60 Hz in Figure 50, the magnitude of all three inter-winding tests are approximately -83.19 dB.

The magnitude of a capacitive SFRA response is equal to 20 log [50/(50 + X_c)]. Therefore:

$$20 \log [50/(50 + X_c)] = -83.19$$
$$[50/(50 + X_c)] = 10\wedge(-83.19/20)$$
$$50/[10\wedge(-83.19/20)] = 50+X_c = 721{,}888.3$$
$$X_c = (721{,}888.3 - 50) = 1/\omega C$$
$$\omega C = 1/721{,}838.3$$
$$C = 1.385e\text{-}6/2\pi(60) = 3{,}674.76 \text{ pF} = \text{CHL}$$

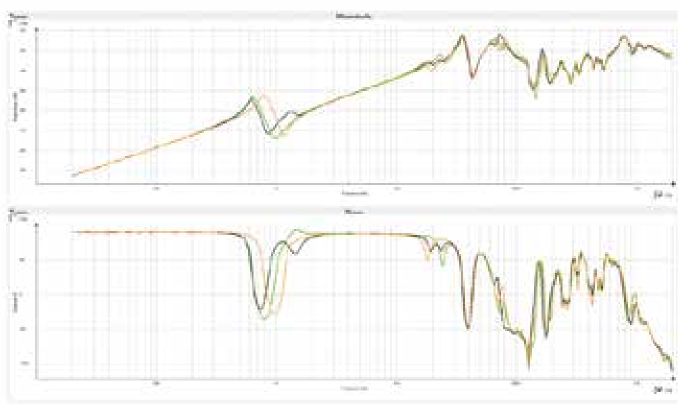


FIGURE 50: Capacitive Inter-winding SFRA Tests

Sweep frequency response analysis (SFRA)

Inductive Inter-winding Measurements – TTR

When one end of each winding involved in the inter-winding SFRA test is grounded during the test (Figure 51), the inter-winding test becomes an inductive measure of both windings. This is sometimes referred to as the transfer admittance.

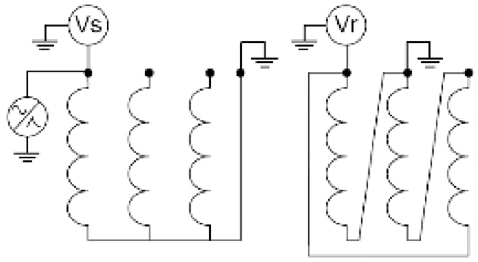


FIGURE 51: Inductive Inter-winding SFRA Test Setup

The transformer turns ratio (TTR) can be calculated from the inductive inter-winding SFRA response. As an example, the inductive inter-winding responses of a 27.36/4.16 kV three-phase transformer are provided in Figure 52. The TTR calculated from the nameplate is 0.08778. From any of the inductive inter-winding traces, at 60 Hz the magnitude is approximately -21.158 dB, which equals 20 log (V_O/V_I). Therefore, the ratio (V_O/V_I), or TTR, equals 10^(-21.158/20) or 0.0875. This is a difference of 0.32% from nameplate and within the 0.5% limit typically held as a passing criterion.

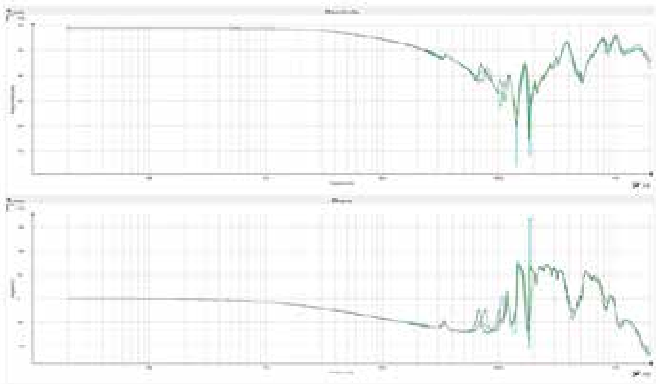


FIGURE 52: Inductive Inter-winding SFRA Tests

A helpful summary of the open circuit, short circuit and inter-winding SFRA tests and the traditional, line frequency, electrical tests with which each of these SFRA tests correlate is provided in Figure 53.

Type of Test	Transformer Characteristic	@ 60 Hz
1.) **OPEN** Circuit Self Admittance (V_R, V_M, OPEN)	Looks at Winding **AND** Core characteristics	Similar to Excitation Test
2.) **SHORT** Circuit Self Admittance (V_R, V_M, SHORT)	Looks at Winding	Similar to Leakage Reactance
3.) **CAPACITVE** Inter-Winding (V_R, V_M)	Looks at Capacitance between Windings	Similar to Capacitance
4.) **INDUCTIVE** Inter-Winding (V_R, V_M)	Looks at Inductance of BOTH Windings	Similar to TTR

FIGURE 53: SFRA tests and traditional line frequency tests to which they correlate

Sweep frequency response analysis (SFRA)

Use (Advantages) of Impedance and Admittance versus Magnitude

Typically, SFRA test results are provided as a magnitude response in dB[45]. Standards and general interpretation guidelines for SFRA tests are fairly well developed around this visualization of the transformer response. However, it is also instructive and at times, advantageous, to look at a transformer's admittance (S) and impedance (Ω) response measurements as well. For example, for low voltage (LV) windings on distribution transformers, which are typically low impedance circuits (less than 100 Ω), admittance (S) and impedance (Ω) representations provide notably improved resolution.

Figure 54 illustrates the difference between a magnitude plot and an admittance representation; the reader may refer back to page 6 for a description of how these differ. Visually, the admittance traces are essentially the same general "shape" as the magnitude traces but of particular note is the improved resolution of the LV winding's second resonance (i.e., a series resonance (peak)) in blue. It is much easier to identify the resonant frequency in the admittance representation, on the right, than by the magnitude given on the left.

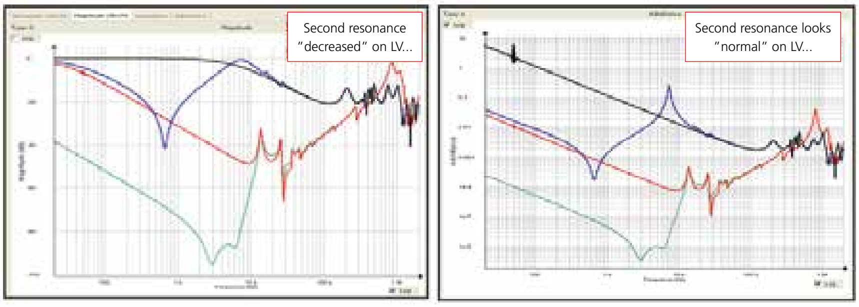


FIGURE 54: Magnitude (dB) left vs. Admittance (S) right

Admittance is a measure of how easily a circuit will allow a current to flow while impedance is a measure of the opposition to current flow. Therefore, impedance, which is the inverse of admittance, manifests as an inverted representation of admittance as shown in Figure 55.

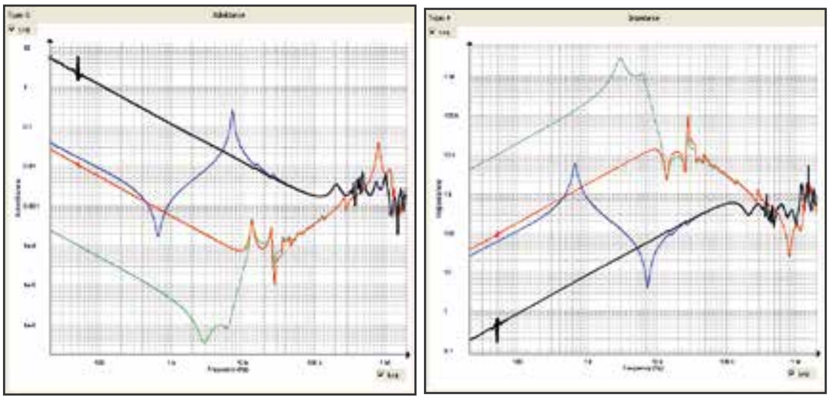


FIGURE 55: Admittance (S) left vs. Impedance (Ω) right

Figure 56 compares an impedance representation (right) to a magnitude plot (left). The open circuit response of the LV winding is shown in blue in each. As was the case with an admittance representation, the improved resolution of the LV winding response in the impedance representation is obvious, which provides much greater visual detail than is accessible on the traditional magnitude plot.

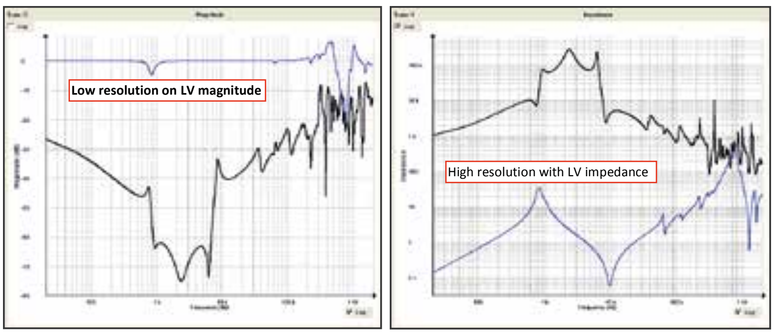


FIGURE 56: Magnitude (dB) left vs. Impedance (Ω) right

[45] A common SFRA test file format (e.g., *.xfra) supports a magnitude plot representation.

Sweep frequency response analysis (SFRA)

Power engineers, who are familiar with transformer impedance in Ohms, generally prefer the ability to view all response representations (magnitude, admittance and impedance). An additional advantage of an impedance response measurement is that it becomes possible to derive resistive and inductive influences. For example, Figure 57a shows the impedance response of open-circuit SFRA tests on HV windings. The software used here[46] provides an option to display the resistance and inductance as well, as given in both Figures 57a and 57b, the latter of which provides the impedance response of short-circuit SFRA tests on HV windings.

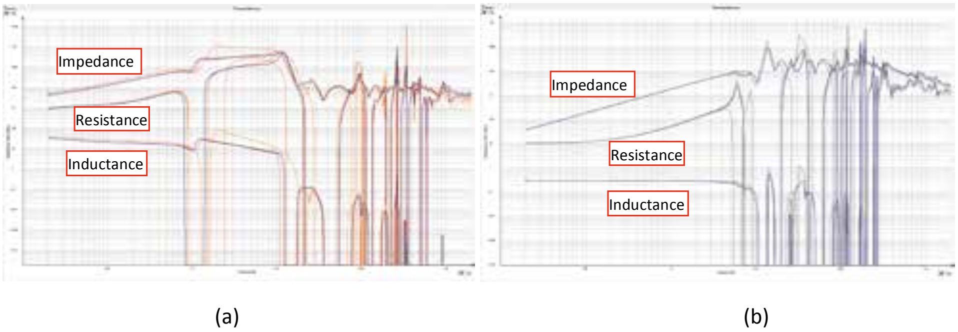


FIGURE 57: Impedance (Ω), resistance (Ω) and inductance (H) response[47] of (a) open-circuit SFRA measurements and (b) short-circuit SFRA measurements on HV windings

One can observe in Figure 57a that, as discussed previously, the inductance begins to decrease with frequency[48], driven by frequency dependent core permeability changes depicted in Figure 44. However, the value of resistance increases, indicating that the core losses reduce because of the decreasing amplitude of magnetizing current at higher frequencies. For additional clarity, magnetizing current decreases since the applied test voltage is held constant at all frequencies in an SFRA test. When the amplitude of voltage is held constant, as the frequency increases, the flux density decreases proportionally as given by Faraday's Law, $\phi = \frac{v}{f}$, and as illustrated by Figure 58 that gives a schematic drawing of a B-H loop family for changing amplitudes of flux density.

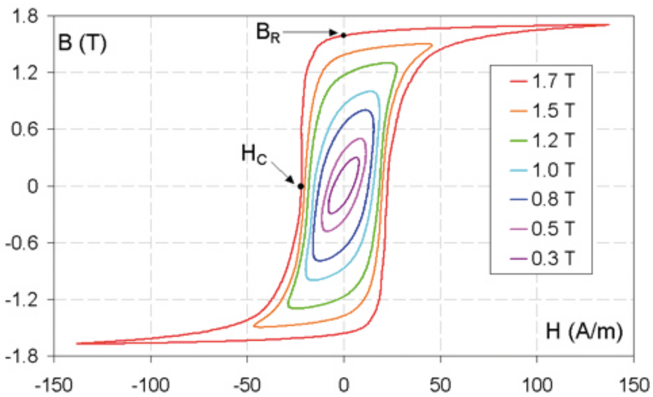


FIGURE 58: B-H loop family for changing amplitudes of flux density [10]

As an aside, if the amplitude of flux density is held constant, the voltage increases proportionally with frequency. Hence, magnetizing current and core losses increase as given in Figure 59, which illustrates a B-H loop family where the amplitude of flux density does not change.

[46] Megger FRAX software
[47] Formulas used to plot resistance (Ohms) and inductance (H) are valid for low frequencies only
[48] Note that while inductance starts to decrease, inductive reactance (ωL) still increases with frequency

Sweep frequency response analysis (SFRA)

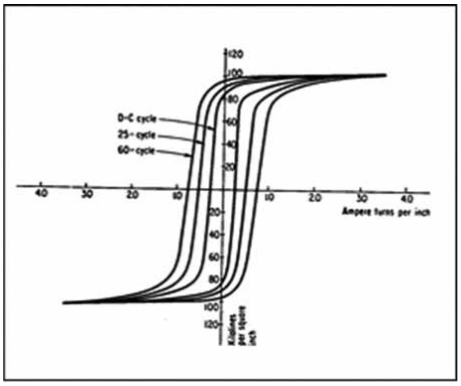


FIGURE 59: B-H loop family where the amplitude of flux density does not change [11]

Figure 57b provides the impedance response of short circuit SFRA tests on the HV windings. In these short circuit SFRA measurements, the core effects are removed and the winding response is isolated. Therefore, the inductance is constant. The resistance results are essentially the results that one would obtain when performing a "frequency response of stray losses" (FRSL) test. An FRSL test is particularly valuable in its ability to reveal a strand-to-strand short circuit at any place along a winding. The expectation is that the three individual phase resistance responses will overlay beginning at the lowest frequency through the exponentially rising portion of the trace. A strand-to-strand short circuit in a winding (in addition to other problems) are indicated in the results when the traces diverge from one another (e.g., "fan out" towards higher frequencies) or, similarly, don't overlay with previous test results in the exponentially rising portion of the resistance responses. At lowest frequencies (i.e., near DC and related to a winding resistance test), the resistance responses will reveal bad contact problems when the three resistance traces separate (e.g., "fan out" towards DC).

STANDARDS:

SFRA test standards are published in several countries, including:

- Asia
  - Std. DL/T 911-2004: Frequency Response Analysis on Winding Deformation of Power Transformers
- Europe
  - CIGRE SC A2 WG A2.26 – Technical Brochure No. 342 (2008): Mechanical Condition Assessment of Transformer Windings using FRA
  - IEC 60076-18 Ed. 1 - 2012: Power Transformers – Part 18: Measurement of Frequency Response
- Americas
  - IEEE C57.149 (March 2013): IEEE Guide for the Application and Interpretation of Frequency Response Analysis for Oil-Immersed Transformers
  - IEEE C57.152 (March 2013): Annex F – Frequency Response Testing (Informative)

These are invaluable aids in SFRA testing. The defined objectives of each of these standards, provided in Table 3, hint at the scope of each technical reference.

TABLE 3: Defined objectives of SFRA technical references provided by several standards organizations

DL/T 911-2004	CIGRE 342	IEC 60076-18	IEEE C57.149
To specify the basic requirements for testing transformer winding deformation by using FRA method.	To provide a guide for assessing the mechanical condition of transformer windings using (FRA)	To describe measurement technique and measuring equipment for FRA on-site or in the factory. Interpretation of results is not part of the normative text. Guidance is in Annex B (included).	To provide information that will assist in making frequency response measurements and interpreting the results from these measurements.

PERFORMING THE TEST:

SFRA Measurements and Test Setup

SFRA winding measurements fall into several categories, including open circuit (e.g., HV and LV), short circuit, inter-winding, series and common[49]. An open circuit SFRA measurement is typically performed on each accessible winding. Short circuit SFRA measurements, made on each winding phase (typically the high voltage winding) while short-circuiting another winding are additional mainstay SFRA tests. A short circuit SFRA measurement is arguably a variation of an inter-winding measurement [7]. An inter-winding measurement is not a true winding measurement but is rather a measure of the transfer admittance between two windings.

Capacitive and inductive inter-winding SFRA tests are considered optional measurements. For example, Table 4, which provides the IEEE C57.149 guide's recommendations for SFRA testing of two-winding transformers with differing winding configurations, highlights 9 recommended SFRA tests. These include six open circuit SFRA tests and three short circuit SFRA tests.

Test type	Test #	3φ Δ-Y Group 2 θ ⇒ 30° LAG	3φ Y-Δ Group 2 θ ⇒ 30° LAG	3φ Δ-Δ Group 1 θ ⇒ 0°	3φ Y-Y Group 1 θ ⇒ 0°	1ϕ
HV Open Circuit (OC) All Other Terminals Floating	1	H1-H3	H1-H0	H1-H3	H1-H0	H1-H2 (H1-H0)
	2	H2-H1	H2-H0	H2-H1	H2-H0	
	3	H3-H2	H3-H0	H3-H2	H3-H0	
LV Open Circuit (OC) All Other Terminals Floating	4	X1-X0	X1-X2	X1-X3	X1-X0	X1-X2 (X1-X0)
	5	X2-X0	X2-X3	X2-X1	X2-X0	
	6	X3-X0	X3-X1	X3-X2	X3-X0	
Short Circuit (SC) Short [X1-X2-X3][a]	7	H1-H3	H1-H0	H1-H3	H1-H0	H1-H2 Short [X1-X2][a]
	8	H2-H1	H2-H0	H2-H1	H2-H0	
	9	H3-H2	H3-H0	H3-H2	H3-H0	
Capacitive Inter-Winding All Other Terminals Floating	10	H1-X1	H1-X1	H1-X1	H1-X1	H1-X1
	11	H2-X2	H2-X2	H2-X2	H2-X2	
	12	H3-X3	H3-X3	H3-X3	H3-X3	
Inductive Inter-Winding High (H) to Low (L) Ground (H- and X-)[b]	13	H1-X1	H1-X1	H1-X1	H1-X1	H1-X1 Ground [H2, X2]
	14	H2-X2	H2-X2	H2-X2	H2-X2	
	15	H3-X3	H3-X3	H3-X3	H3-X3	

[a]Indicates short circuit tests terminals are shorted together, but not grounded. The neutral is not included for 3ϕ Wye connections, but may be included for 1ϕ connections.
[b]Denotes other end of winding; opposite of the reference and measure connections.

TABLE 4: IEEE C57.149 SFRA test recommendations for two-winding transformers [12]

As illustrated previously in Figure 6, it is recommended to perform SFRA testing using a three-lead system rather than two test leads as the test connections given in Table 4 might seem to infer. Notably, separate leads should be used for applying and measuring the signal at the "input" terminal (i.e., the first terminal of each pair listed in Table 4). This way the voltage drop of the test lead that is applying the signal does not become part of the SFRA measurement.

A third lead is used to measure the signal at the "output" terminal (i.e., the second terminal of each pair listed in Table 4). The test connection polarity[50] is important for repeatability as arbitrarily reversing the polarity of test connections will produce different results. It is left for the user to establish a polarity convention, such as those recommended in Table 4, and then more importantly stick to it invariably.

The transformer winding configuration determines which test protocol to use. With exception of the short circuit SFRA measurements, terminals of the phases and windings not under test are usually left floating. Neutral terminals should be ungrounded. In the case where two connections to one corner of a delta winding are brought out (of the tank), the transformer should be measured with the delta closed but not with the earth connected.

During short circuit SFRA measurements, the shorting leads used should be kept as short as possible. It is common practice not to include the LV neutral in the short circuit connection, with the exception of some single-phase transformers.

For open circuit and short circuit tests, there is no particular order that needs to be followed. However, for efficiency it is advised to run the test in an order that helps minimize lead changes.

[49] Series and common winding measurements describe the SFRA application as it is applied to autotransformers.
[50] As an example, test connection polarity H1 – H0 (for the HV A-phase winding) implies that source and reference/measure test leads are connected to bushing terminal H1 and a measure test lead is connected to H0.

Sweep frequency response analysis (SFRA)

From a safety perspective, it is recommended to touch the bushing terminals with a grounding stick before contacting and moving test leads between tests[51]. Failure to do so carries the possibility of a shock. Only qualified persons are permitted to perform tasks such as testing. This is for the very good reason that, in becoming qualified, they will have undergone extensive safety training.

Test Preparation

Recommendations for SFRA test preparations, which are documented in the standards[52], require a tester to:

- Completely isolate the transformer (electrically and physically) from the system; e.g., all external bushing connections should be disconnected; remove bus bars if possible. Lines left connected to the terminals will impact the measured SFRA test results. Note, however, that the transformer ground, internal auxiliary equipment and internal current transformer connections should be left in place.
- Verify that the transformer tank is grounded.
- Ground the SFRA test instrument.
- Place the transformer in as close to an "in service" condition as possible. Note any difference, such as lack of oil, transportation bushings, etc. Sometimes special connections are specified and provided on the transformer to enable SFRA test measurements to be performed immediately prior to its transport. In these cases, measurements must be made in both the fully assembled (e.g., fluid-filled) and transport configurations (e.g., drained, if required for transport) before transport and subsequently after as specified by the purchaser. If oil has been drained during both tests, beware of the variations in the states of oil draining. For example, SFRA testing performed shortly after draining the oil may be impacted by residual oil present while a retest on site some days later, whereby residual oil may have dropped out, may produce different results as a consequence [13].
- If applicable, record the tap position for both the deenergized tap changer (DETC) and on-load tap changer (OLTC).
    - The DETC shall be in the "in service" or "as found" condition.
    - Place the OLTC in the extreme raised position. If the sweep is measured with the OLTC set to neutral position, it should reach this position from the raised 1 position. Both tap and previous tap positions should be noted.
- Use shielded coaxial test cables, which have good high frequency characteristics, and ensure that the test leads are terminated in their characteristic impedance, usually 50 ohms, to avoid reflections. The shields must be given a ground reference to control, otherwise, unpredictable capacitive coupling with each lead's unique surroundings. The test leads should all be of the same length.
- The grounding leads (typically provided with an SFRA test instrument) should be of the flat braid type[53] and should be as short and straight as possible without coiling leads (Figure 60). To minimize ground lead length, connect a test lead's braided ground connection to the grounded flange of that bushing where the test lead is connected. Reference [14][54] shows the influence of a long ground lead length as opposed to the shortest (ground lead) length. Make sure that the braid does not touch any conducting part at the top of a bushing. It is very important to ensure reliable contact between the ground extension and the transformer tank to assure that no external impedance is measured and to reduce the effect of noise. Many measurement mistakes are related to this point.
- Make solid connections when attaching test leads to the terminals of the transformer. It is generally preferred to use connection clamps tightened firmly. Clean the point of connection on the bushing terminals, for example with a wire brush, if necessary.
- If performing other electrical tests, be mindful of the ordering of tests. If it is not possible to demagnetize the transformer before performing SFRA tests (which is ideal), perform SFRA tests before winding resistance tests. Winding resistance measurements require saturation of the transformer core. If these are performed before SFRA tests, it will be necessary to demagnetize the transformer before performing SFRA tests. Some modern winding resistance test instruments perform demagnetization of the core at the end of testing[55]. SFRA test results are actually more reliable if obtained after demagnetization is done by a winding resistance test instrument than if acquired as a first test on a non-demagnetized transformer (wherein the transformer's state of magnetization is unknown).

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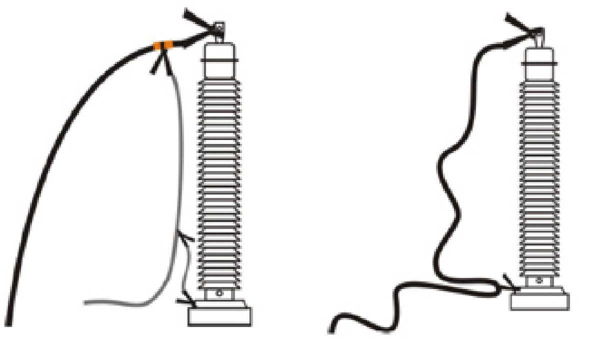
[51] Local safety regulations may already prescribe that all bushing connections be earthed/grounded when working on the transformer e.g. connecting/removing SFRA test leads.

[52] IEEE C57.149, CIGRE Brochure 342, and IEC 60076-1853

[53] A flat braided grounding lead has a lower inductivity than a single round wire grounding lead of the same cross-section and reduces impact of the skin effect on the test results at very high frequencies.

[54] See Figures 10 and 11 in Reference [14]

[55] Megger's TRAX, MTO series and MWA test instruments have demagnetization capabilities. Demagnetization is different than "discharging" which all winding resistance test instruments must do at the end of a winding resistance test before a test connection may be safely moved.



(a) Good practic (b) Poor practice

FIGURE 60: Grounding practices for FRA testing

THE THREE R'S – RANGE, RESOLUTION AND REPEATABILITY

Range, resolution and repeatability are important aspects of SFRA testing.

Range (dynamic and frequency)

Dynamic range, in particular, is one of the key specifications to consider when choosing an SFRA instrument. Dynamic range is the ratio between the largest and smallest values that a certain quantity can assume; in the case of SFRA testing of a transformer, the output voltage may equal the input voltage or may attenuate to a near zero value. So the dynamic range relates to how small of an output voltage can be measured. For an instrument to measure low values, its noise floor must be even lower. A wide dynamic range (e.g., up to -140 dB) complemented by good accuracy is desirable.

Figure 61 shows an HV open circuit and an HV short circuit SFRA response of a transformer tested using an instrument with unacceptable dynamic range (black) and one with acceptable range (red[56]). Since most of the analysis criteria center around identification of resonances, losing the ability to define any of the resonances clearly will notably limit the value of the test results.

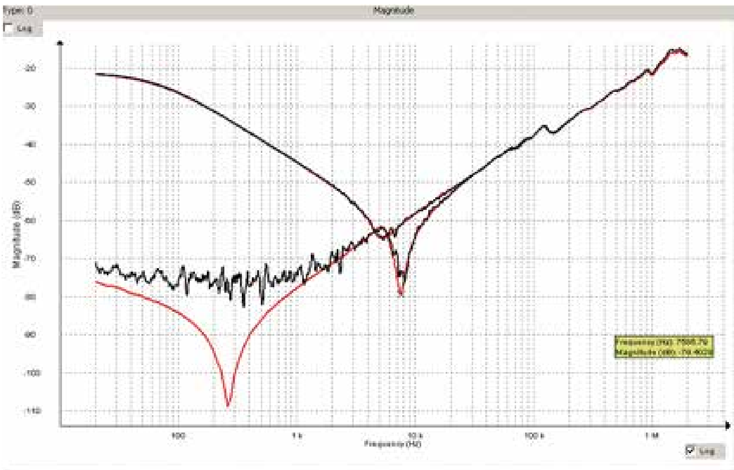


FIGURE 61: Example of a noise floor problem – HV open circuit and HV short circuit SFR traces acquired with 2 different instruments

The frequency range over which meaningful diagnostic information may be extracted is 20 Hz – 2 MHz. While frequency ranges may differ between test instruments (e.g., 10 Hz – 25 MHz), typically, all SFRA instruments provide this most critical range.

[56] The Megger FRAX measurement is displayed in red.

Sweep frequency response analysis (SFRA)

Resolution

Resolution in SFRA testing refers to an instrument's ability to show a winding's response clearly and with a lot of detail. This is paramount for a test such as SFRA where analysis requires determination of: resonant frequencies, whether resonant frequencies have changed between tests, if new resonances are present, or if they have disappeared. Resolution is dependent on sampling rate (MS/s) and the length of the test. For testing efficiency, it is desirable to minimize the time for each test, if this can be done without compromising resolution, since quite a number of tests will be performed (e.g., a minimum of nine tests on a two-winding, three-phase transformer). Herein lies the value of a solution such as "smart sampling", which achieves a reasonable balance between the required time to complete a measurement and the measurement's resolution. Smart sampling means acquiring less points where it takes a relatively longer time to test and where high frequency resolution is not needed (e.g., lower frequencies) and more points where higher frequency resolution is useful.

Repeatability

Repeatability is defined as the variation in measurements taken by a single person or instrument on the same item, under the same conditions, and in a short period. Repeatability is paramount in SFRA testing since problems with a transformer are detected by a change in its winding's response. Lack of repeatability means that there is variability between tests due to causes other than a transformer problem and, therefore, it may become difficult to identify if a change is a repeatability problem or a transformer concern.

Several factors affect repeatability and warrant further description, which follows, including:

- Grounding
- Core magnetization*
- Sweep Direction
- Test voltage amplitude (see Figure 41)**
- Test connections and test connection polarity (see "SFRA Measurements and Test Setup")**
- Tap changer position*
- Oil level*
- FRA method – time domain (i.e., low voltage impulse method, LV_I) versus frequency domain (i.e., SFRA) measurements

*Theoretically, core magnetization, tap changer position and oil level are not repeatability factors in the strictest sense of the definition because a change in these means that the transformer is not in the same condition as it was in the reference test. However, these are included here because these factors cause a change in the SFRA response that is not due to a transformer problem.

** Repeatability problems introduced by choice of test voltage, test connections and test connection polarity have been discussed previously, as noted.

Grounding

Effectively grounding the shields of the coaxial test cables is of primary importance to achieve good repeatability, particularly in the high frequency range of the SFRA winding response. From IEEE C57.149, "Grounding techniques will have a significant effect on test results. Grounding techniques, including selection of ground conductors as well as their routings, should therefore be precise, repeatable, and documented."[12] The use of digital photos to record test leads and grounding configuration are particularly helpful for future test reference.

Figure 62 illustrates the variability that poor grounding (red trace) or no grounding (black) introduces in the high frequency part of the response as compared to good grounding (blue). While failure to provide a ground reference to the signal leads is a visually recognizable mistake, it is often more challenging to qualify when proper grounding is simply not executed well. For example, perhaps the transformer tank lid (including the bushing flanges) has been painted between test dates and the ground connection is frankly ineffective.

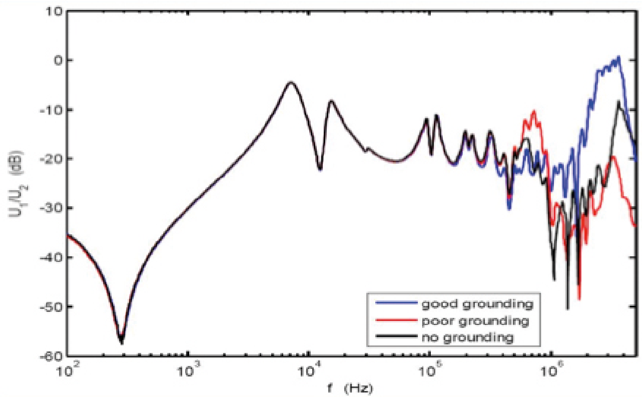


FIGURE 62: Influence of grounding on the high frequency SFRA response [15]

Sweep frequency response analysis (SFRA)

As a helpful aid to eliminate doubt and determine whether the grounding lead connections and transformer ground are "common" (i.e., zero impedance) and acceptable, a SFRA test instrument may provide a GLD (ground loop detection) feature as illustrated in Figure 63. When the check is activated, a light provides visual indication whether all is well (green light) or not (red light) with the grounding system connections.

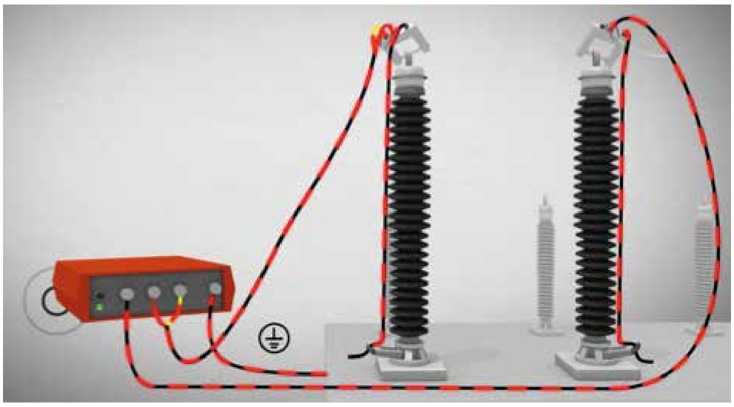


FIGURE 63: Ground Loop Detection (GLD) circuit[57]

Core Magnetization

Residual magnetization may also impact the repeatability of SFRA test measurements. This is a physical phenomenon caused by steel in the magnetic core holding on to magnetic polarity due to the tendency of any magnetic material to store energy [16]. This leads to a change in the magnetizing inductance of the core. A lower magnetizing inductance due to a magnetized core, as illustrated by the black trace in Figure 64, causes the inductive dominated beginning part of the open circuit SFRA response to shift predictably up and to the right (reference Figure 21) and, consequently, a right shift of the first main resonance.

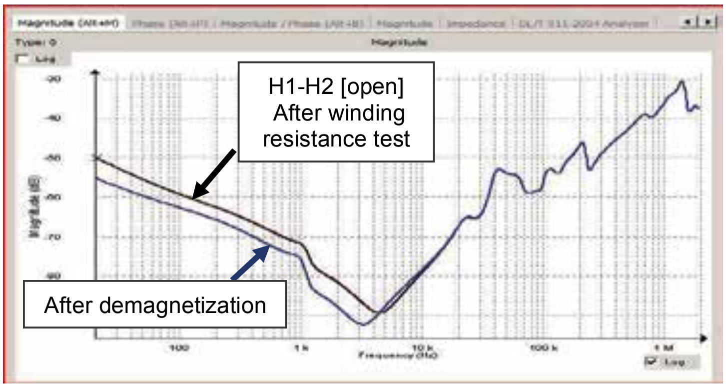


FIGURE 64: Influence of core magnetization on open circuit SFRA test results

It is recommended to demagnetize the core before performing any SFRA measurements to minimize the effect of residual magnetism or at least perform SFRA testing prior to winding resistance tests.

It is important to keep in mind, however, that once demagnetized, the transformer core may not indefinitely remain in that precise neutral state. Residual magnetization may vary over time due to so-called *magnetic viscosity*. It has been observed that any sudden change of excitation field (applying or removing magnetization current) yields a slowly varying magnetic relaxation, which causes the impedance to change with time due to magnetic viscosity [17]. Therefore, even when no DC excitation takes place, an SFRA response may shift between tests at low frequencies[58].

Sweep Direction

The sweep direction of the test [i.e., "reverse" direction where testing begins at high frequencies and ends at low (e.g., high-low) or conversely starts at low frequencies and concludes at high (e.g., low-high or "forward" direction)] is related to the foregoing discussion about the influence of core magnetization. Figure 65 illustrates six each consecutive tests performed on a 10 kV distribution transformer in a "forward" direction (blue traces) and a "reversed" direction (red traces) and the impact that the direction had on repeatability.

[57] The GLD feature of the Megger FRAX test instrument
[58] Magnetic viscosity effects are not considered uncommon.

Sweep frequency response analysis (SFRA)

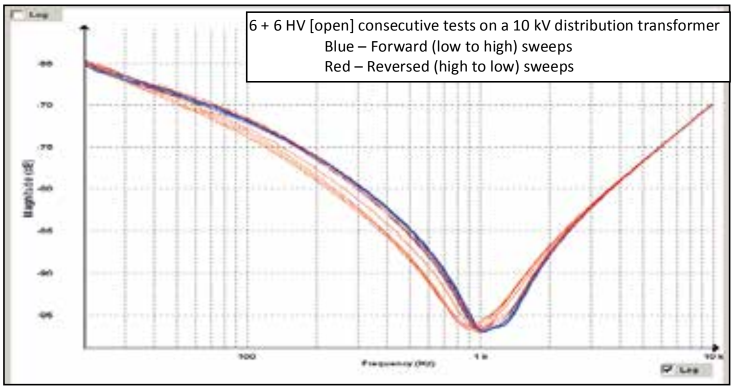


FIGURE 65: Influence of the direction in which an SFRA test is performed

In a "reverse" direction, the SFRA trace will start to appear relatively quickly and as testing continues at lower and lower frequencies, each successive test point will require a longer measurement time. In a "forward" direction, the appearance of first measurement points and the reassurance that the test is running will appear slowly so some users may prematurely abort the test if they believe that the test did not successfully begin.

From a purely magnetic view:

- In the "forward" direction as the frequency increases, the impedance of the windings also increases and the magnetising current reduces. Hence, as the frequency increases, every successive SFRA measurement effectively demagnetises the core in an inherent way (only from its own effects; not from some other magnetisation).
- In the "reverse" direction, the current keeps increasing as the frequency reduces and then the final magnetisation is dictated by the instant at which the test is stopped. This effect to such final increased current may add up to increase the shift in the remaining magnetisation.

Therefore, the reversed direction may or may not result in a visible shift of the first resonance (depending on the size and construction of the transformer, as well as the instantaneous value of current at which the test is terminated). However, the forward direction automatically takes care of this problem, regardless of the transformer type or driving conditions. So magnetically, the forward method is preferred.

Tap Changer Position

It is important for comparison purposes to test a transformer on the same DETC and OLTC tap positions. Figure 66 provides an example of the influence that changing the OLTC tap position has on the winding response. Lowering the OLTC tap position from 12L to 16L, for example, uses additional turns of the tap winding in a polarity such that the tap windings subtract from the main winding. Therefore, in the low frequency range, the magnetizing inductance decreases (via a lower net number of winding turns) and the response shifts to the right as lower inductance curves do. In the high frequency range, where tap windings influence the response, the additional turns of the tap winding in the circuit (that will subtract from the main winding) contribute to higher capacitance. Therefore, the response shifts to the left as higher capacitive windings do. In practice, SFRA tests should be performed at lowest and highest tap position respectively if any winding problem is detected.

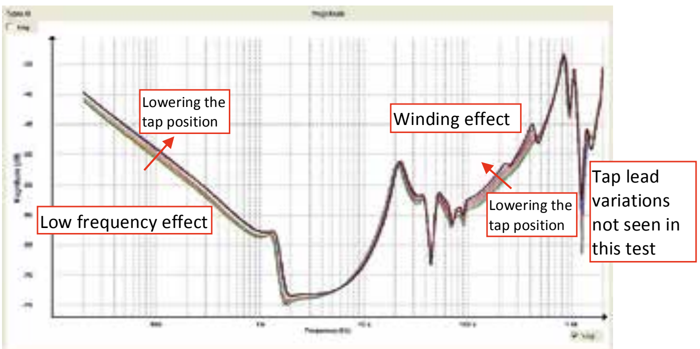


FIGURE 66: Influence of on-load tap changer (OLTC) position, positions 12L to 16L shown

Sweep frequency response analysis (SFRA)

Oil Level

When SFRA tests are performed on an oil-filled transformer in the absence of its oil, the entire response exhibits a shift to the right as illustrated in Figure 67. This is due to the change in all capacitance systems within the transformer. Capacitance is directly dependent on the dielectric constant, ε, of the material separating its electrodes. When oil (ε ≈ 2.1) is replaced by air (ε ≈ 1.0), capacitance decreases.

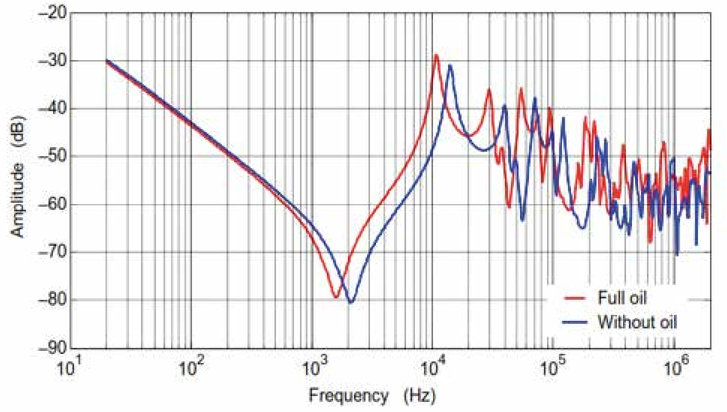


FIGURE 67: Influence of Oil Level on SFRA response

SFRA versus a low voltage impulse (LVI) method

Generally because of better repeatability, the frequency domain test method of performing frequency response analysis (or SFRA, as described throughout this bulletin) has been favored over an alternate, time domain approach known as the impulse method (or LVI). With LVI, the frequency response is measured indirectly by injecting an impulse signal of a particular shape at one terminal and measuring the response at another, and then transforming the time domain measurements into frequency domain results.

> As a final note with regard to repeatability, in spite of best efforts to eliminate all variables that may result in a change in an SFRA response as compared to a previous test, on occasion some differences are still to be expected. This is largely due to magnetic viscosity (whereby magnetic properties of the core are changing over time, as described previously) but may also be because some transformers are simply less repeatable than others are…

ANALYSIS

SFRA test results are evaluated using comparative analysis. Irrespective of a reference, however, it is helpful to have an idea of how each SFRA response should generally look in advance of performing these measurements. This way obvious mistakes can be spotted quickly (e.g., poor grounding, improper connections, etc.) and the test can be repeated after double checking test connections/preparation.

The reference to which test results may be compared include any or all of the following (listed in order of most value to the analysis):

- Previous tests performed on the same transformer. This is known as the time-based method and is the most reliable approach with which to interpret SFRA test results. Deviations between curves are easy to detect and often indicate a problem. For this reason, it is desirable to obtain benchmark SFRA test results on a transformer when it is in known good condition to have a reliable future reference with which to compare. This may happen during commissioning of the transformer or during routine scheduled testing if the transformer has checked out well. The test conditions (position of tap changer, type of FRA test, etc.) should be the same for the reference and repeated measurements for correct interpretation. [18]
- Tests performed on a transformer of the same design, i.e., the type-based method. Care is required with this approach, as small deviations between traces do not necessarily indicate a problem. This approach also requires knowledge about the transformer under test. Just because two transformers are built by the same manufacturer, have the same ratings, and even are just one serial number apart, does not guarantee that their construction is the same.
- Tests performed on winding legs and bushings of identical design, for example, the two outer phase SFRA responses of a transformer. This is known as the design-based method, or a phase comparison approach. This is the most challenging approach as small deviations between traces may be completely normal. The middle (center) phase response typically differs from the outer phase responses and there may not be symmetry between outer phases.

Sweep frequency response analysis (SFRA)

When comparing to a reference trace, any of the following can indicate a potential mechanical change:

- Resonance Shifts
- Additional Resonance
- Loss of Resonance
- Overall Magnitude Difference

Despite its aforementioned challenges, the phase comparison approach is a particularly insightful diagnostic for short circuit SFRA tests. For these tests, all three short circuit responses should be nearly identical. As noted previously, a magnified view of the linear part of the inductive roll off should reveal no more than a 0.1 dB difference between the three traces and the roll-off should be close to -20 dB/ decade. Poor connections (i.e., increased resistance) will affect the short circuit SFRA responses at the lowest frequencies (e.g., 20 Hz). This may indicate a need to check the transformer with DC winding resistance tests.

Automatic Assessment

As an aid to analyzing test results, SFRA test software may provide basic decision support tools that automatically assess how well a response compares to a reference. Generally, these include one or both of two approaches: difference plotting and correlation coefficients.

With difference plotting, one curve is simply subtracted from the other. The result is the magnitude difference between the curves. While such a visualization may be helpful, it is not considered a very reliable means for assessment.

Cross-correlation coefficients (CCF), which are used in a variety of industries to monitor signal integrity, give an indication of similarity between traces. Correlation factors are computed for each of a minimum of three frequency ranges (i.e., low, medium and high) using a covariance algorithm (Equation 14); the lower the value, the more the two traces diverge.

$$\sigma_{xy} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \left(X - \bar{X}\right)\left(Y - \bar{Y}\right) f(x, y)\, dx dy \quad \text{[EQN 14]}$$

This type of decision support is helpful to validate that a trace compares well to its reference. When a trace is flagged for poor correlation, this is generally not to be taken as an immediate fail but rather as an “investigate further”. Some SFRA tests are expected to have better correlation than others do. For example, when using, a phase-based comparative approach, short circuit SFRA responses should compare more closely than open circuit SFRA responses. Winding configuration (e.g., delta or wye-connected) also affects the importance of correlation between curves.

EXAMPLES:

The following examples take a closer look at how radial winding deformation, axial winding deformation, and core problems may influence SFRA test results.

Radial Deformation IEEE

Radial winding deformation is most obvious in the 50 kHz – 1 MHz range. This failure mode can cause a shift in, or produce new, resonance peaks and valleys depending on the severity of the deformation. In the example given in Figure 68, the most pronounced shifts are observed in the right-most dashed window, approximately 100 kHz – 1 MHz. The changes will be greater on the affected winding (typically the LV winding as in this example) but it is still possible to have the effects transferred to the opposing winding [12]. Note that in this example there is shifting at the low frequencies but this is due to a difference in core magnetization. When core magnetization differs between tests, the traces (e.g., test under evaluation and reference test) should come back together tightly once the frequency exits the core region (e.g., 20 Hz – 1 or 2 kHz). This (core) region of an open circuit SFRA test is generally unaffected during radial winding deformation.

In the short circuit SFRA response, radial deformation results in an increase in impedance for the affected phase. As shown in Figure 68, the affected phase generally exhibits slight attenuation within the inductive roll-off portion of the response (i.e., within the dashed window). This shift may not seem pronounced but if you can detect two traces in this region of the response without otherwise having to resort to a zoom feature in the software, problems are at hand.

Sweep frequency response analysis (SFRA)

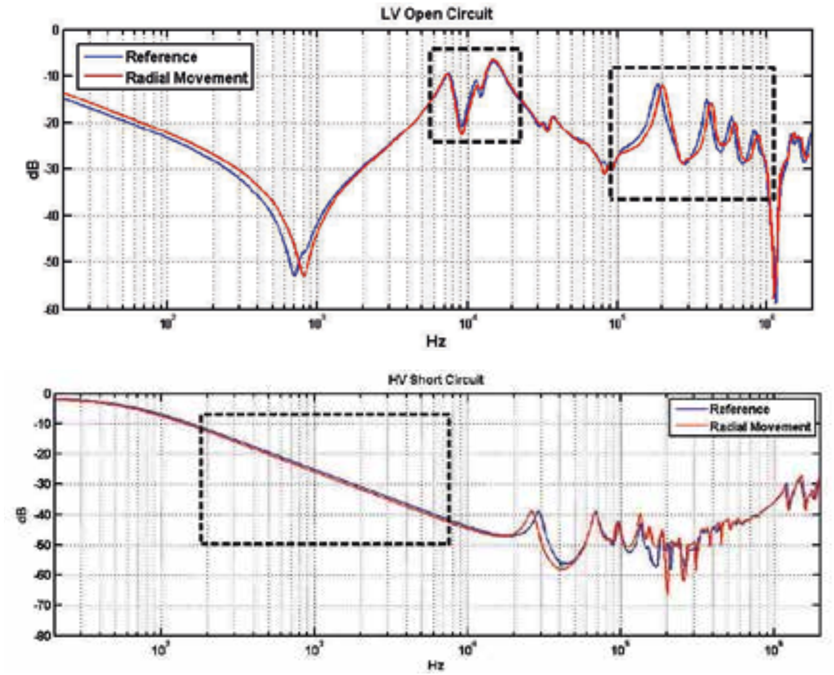


FIGURE 68: SFRA test results for a transformer with hoop buckling [12]

Axial Deformation IEEE

Axial winding deformation is most obvious in the 5 kHz – 100 kHz range. This "bulk winding" range can shift or produce new resonance peaks and valleys depending of the severity of the deformation. The changes will be greater on the affected winding but it is still possible to have the effects transferred to the opposing winding. Axial winding deformation can shift or produce new resonance peaks and valleys at frequencies beyond this (e.g., 50 kHz – 1 MHz) depending of the severity of the deformation [12]. An example where this is the case is given in Figure 69.

In the short circuit SFRA response, axial winding deformation results in a change in impedance of the affected winding that is noticeable (and causes a difference between phases or previous results) in the inductive roll-off portion.

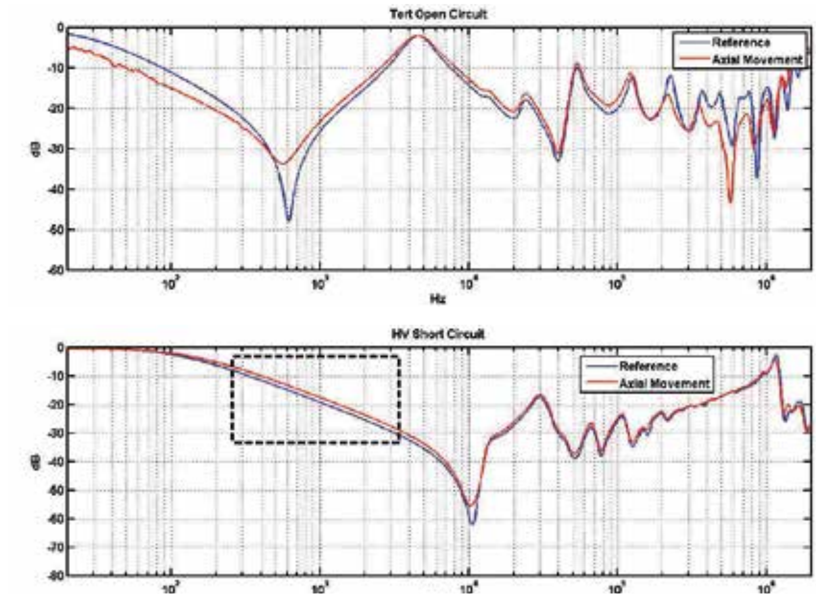


FIGURE 69: SFRA test results for a transformer with axial winding deformation ("telescoping") [12]

Sweep frequency response analysis (SFRA)

Core Defects IEEE

Core defect failures, such as burnt core laminations, short-circuited core laminations, multiple/unintentional core grounds, joint dislocations and lost core grounds, cause changes to the core's magnetic circuit.

These types of failures will affect the lower frequency region, generally below 10 kHz. Core defects often change the primary core resonance shape (Figure 70). Less weight should be placed on shifting because the effects of residual magnetization may sometimes mask the identification of core defects [12]. If the open circuit core resembles one that is carrying load (i.e., looking closer to a short circuit response as Phase C does in Figure 70), this could indicate a core defect.

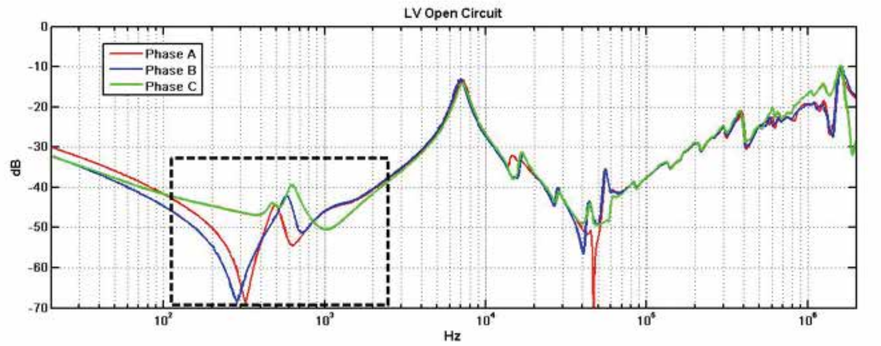


FIGURE 70: Influence of a core problem on LV open circuit SFRA measurements [12]

If the fault is due to a core ground issue, such as the loss of the core ground, changes to the CL capacitance can cause shifts in the 100 kHz – 1 MHz range of the LV open circuit SFRA response. Figure 71, from IEEE, illustrates the effect. It is instructive to take a closer look at why a missing core ground both results in CL changes and why this frequency range, in particular, may be impacted.

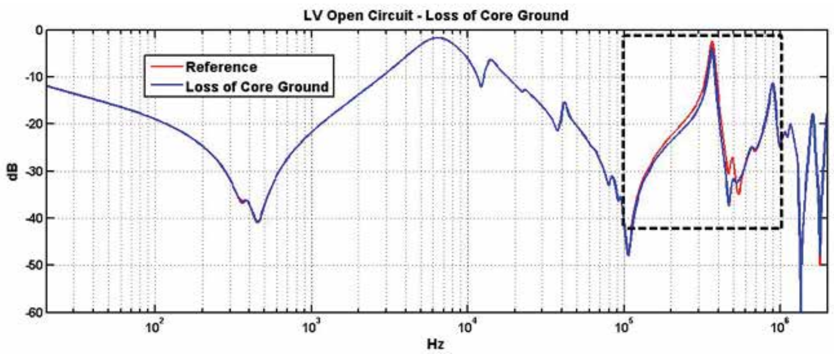


FIGURE 71: Loss of core ground influence on LV open circuit SFRA response [12]

A transformer's core is insulated from ground to control undesirable effects but still requires a ground reference or the core itself will take on a voltage potential. The core's insulation system, C_{core}, is effectively short-circuited by an intentional core ground that the manufacturer installs in at least one location of the core. If the core ground is lost or seriously compromised (e.g., nearly burns open), the measured CL capacitance on a core-form transformer will notably decrease [e.g., CL (normally) = 15,000 pF[59] versus CL' (in the absence of a core ground) = 4,500 pF]. It is helpful to look at the dielectric circuit of a two-winding transformer to understand why the measured CL capacitance decreases when the core ground is missing (Figure 72).

The low-voltage winding of a core-form transformer is typically the innermost concentric winding, nearest the core leg. A test of CL includes the insulation between the low-voltage winding and components held at ground potential, such as the transformer core. If the core ground is removed, then CL is now in series with the C_{core} insulation in the dielectric test circuit and cannot be isolated for measurement.

[59] These values are given as an example only. Capacitance values vary widely depending on the size and construction of a transformer.

Sweep frequency response analysis (SFRA)

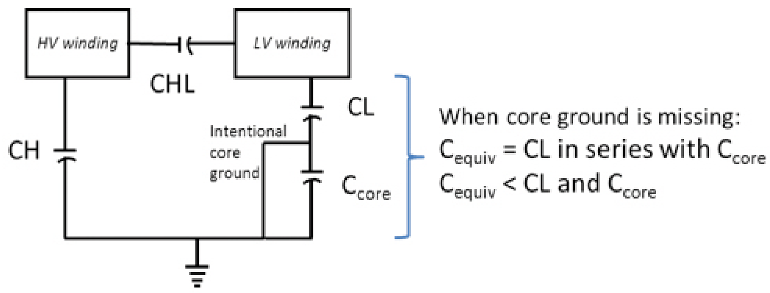


FIGURE 72: Dielectric test circuit of a two-winding transformer

It is well known that the equivalent capacitance of two capacitors in series is less than either of the two individual capacitance values (e.g., CL or C_{Core}). Therefore, if CL capacitance is known from a previous/reference test, even though the capacitance of C_{Core} is presumably unknown, it is recognized that the capacitance of CL apparent (CL') will nonetheless be less than CL.

With this in mind, it is helpful to revisit the frequency response curves of varying size capacitors given in Figure 15 but provided again in Figure 73 for convenience. In addition to the capacitance response curves given in Figure 15 (which are 1pF; 20,000 pF and 1,000,000 pF as ordered smallest to largest, or right-most response to left-most), a 15,000 pF capacitor is superimposed[60] in black (CL) and a 4,500 pF capacitor in purple (CL'). The dielectric characteristics of the transformer used to produce the IEEE example are unknown. However, if we conjecture that the CL capacitive reactance diminishes enough to influence the response at around – 25 dB as in Figure 71, one can see from Figure 73 that a change from CL (black) to CL' (purple) will shift the response from, e.g. 140,000 Hz to 190,000 Hz at – 25 dB.

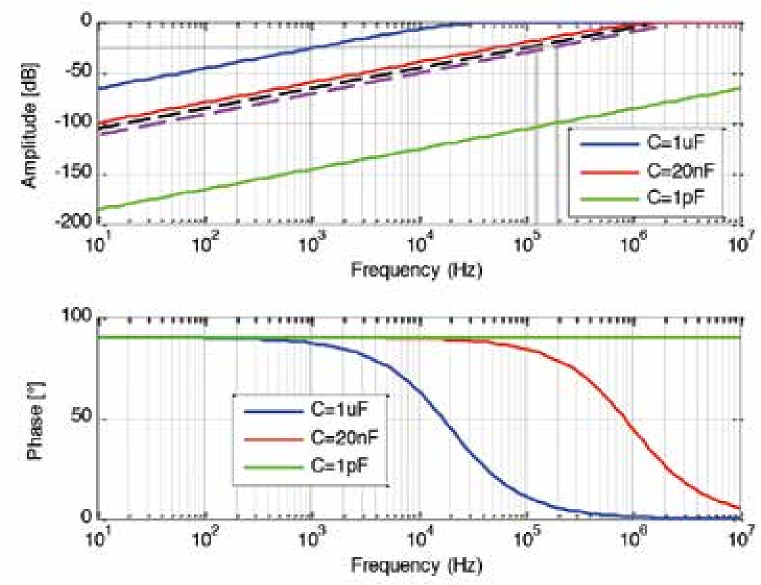


FIGURE 73: Revisit of Figure 15

[60] With no precision (example only)

WHEN TO USE SFRA:

SFRA is a very insightful test but to unleash its full diagnostic capability, one is best served to obtain reference measurements as soon as possible (e.g., at the manufacturing site or short of this, during a routine maintenance period when the transformer is known to have checked out well). Thereafter, a number of events may precipitate the need to repeat SFRA tests. If time permits, SFRA testing may be performed as part of a routine diagnostic measurement, particularly if a more thorough view of a transformer's health is desired. However, it has not been historically regarded as a recommended routine screening test. The following is a fairly comprehensive list of when SFRA tests are appropriate for use.

1. Manufacturing tests:
    - Quality check during manufacturing
    - Proof the transformer after short circuit testing
    - Before shipping
2. Check the integrity of transformers after transport (from the manufacturer or system relocation)
3. Installation/commissioning
4. As part of routine diagnostic measurement
5. Condition assessment after the occurrence of high transient fault currents (a significant through-fault event)
6. Trigger based test/ transformer alarms
    - Diagnosis after transformer alarm or protection tripping, e.g., Buchholz or high temperature
    - Testing after significant changes of monitored values (e.g. combustible gases)
    - Further inspection after the observation of unusual routine test results
7. After a catastrophic event (earthquakes, hurricanes, tornadoes)
8. Before and after maintenance

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