Applying Sweep Frequency Response Analysis and Leakage Reactance to Determine Mechanical Faults in a Power Transformer

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Abstract

Sweep Frequency Response Analysis (SFRA) and Leakage Reactance (LR) testing provides essential information needed to determine the "mechanical" condition of transformer assets. Fault events or shipping impacts are the main causes of transformer winding damage. Winding movement and/or deformation may cause changes in the leakage channels and associated passive RLC elements. Both Sweep Frequency Response Analysis (SFRA) and Leakage Reactance (LR) can be used in conjunction to identify and confirm changes in the leakage channels and associated passive RLC elements:

These changes are used to identify the following mechanical failure modes:

- Radial Deformation
- Axial Deformation
- Bulk Winding Movement

This paper focuses on how the Sweep Frequency Response Analysis (SFRA) and Leakage Reactance (LR) tests can be applied to power transformers. The audience will be provided with an understanding, application, and analysis of these tests, supported by specially selected case studies validating the value that these diagnostic tests bring to testing, and finally, assessing power transformers.

Introduction

The primary goal when performing diagnostic tests on power transformers is to ensure safe operation and accomplish life extension. Failure modes are often categorized in three common descriptions: dielectric, thermal, and mechanical failure modes. Understanding the mechanical condition of the power transformer can help predict an impending failure mode. This paper focuses on mechanical failure modes, and how Sweep Frequency Response Analysis and Leakage Reactance tests can be used for this condition. We will investigate test procedure, test preparation, and expected results for these two important tests. For the purpose of this paper, we will focus on a delta-wye power transformer (Dyn1); this will simplify our discussion.

We introduce and focus on the following "mechanical" tests:

1.) Sweep Frequency Response Analysis (SFRA)
2.) Leakage Reactance (LR)

The test plan, procedure, and analysis recommendations found in this paper are based on the contents of:

- IEEE C57.149-2012, "IEEE Guide for the Application and Interpretation of Frequency Response Analysis for Oil-Immersed Transformers".

- IEEE C57.152-2013, "IEEE Guide for Diagnostic Field Testing of Fluid-Filled Power Transformers, Regulators, and Reactors".

<u>Diagnostic Testing – Mechanical Movement</u>

1.) Sweep Frequency Response Analysis (SFRA)

Sweep Frequency Response Analysis (SFRA) is a diagnostic tool used to assess the mechanical and electrical integrity of power transformers. The SFRA test consists of measuring the transfer function (Vout/Vin) of a power transformer winding over a wide sweep of frequencies from 20 Hz to 2 MHZ. The equivalent circuit of a transformer winding includes the coil resistance and inductance as well as capacitances between the turns and the other windings, and between the winding, the tank wall, and the core. Winding movement and/or deformation will cause changes in these passive RLC elements, thus changing the frequency response of the transformer winding. Deviations in the SFRA Measurements can be used to identify the following mechanical failure modes:

- Radial Deformation (faults)
- Axial Deformation (faults)
- Bulk Winding Movement (transportation)

It can also identify electrical problems such as:

- Broken or Loose Connections
- Shorted Turns (Compromised Insulation)

<u>Test Preparation</u>:

1.) Ensure that the transformer tank and core are solidly grounded, also include both the test instrument and power source ground to this point. We will refer to this point as the “GROUND” node.
2.) Completely isolate the transformer terminals; remove external connections, such as cables, from H1, H2, H3, X1, X2, X3, and X0.
3.) Confirm that the bushing flanges are clean and acceptable. They are being used as a ground reference for the SFRA measurement.

Test Procedure:

Based on the IEEE C57.149 guide [1], 9 tests are recommended for the Dyn1 configuration. The 9 tests are shown in **Table 1**:

Table 1 - SFRA Test Plan

Test	Name	Reference	Response	Shorted	Grounded	Test Type
1	HV-A OC	H1	H3	None	None	HV Open Circuit (OC) All Other Terminals Floating
2	HV-B OC	H2	H1	None	None	
3	HV-C OC	H3	H2	None	None	
4	LV-A OC	X1	X0	None	None	LV Open Circuit (OC) All Other Terminals Floating
5	LV-B OC	X2	X0	None	None	
6	LV-C OC	X3	X0	None	None	
7	HV-A SC	H1	H3	X1,X2,X3	None	Short Circuit (SC) Short [X1,X2,X3]
8	HV-B SC	H2	H1	X1,X2,X3	None	
9	HV-C SC	H3	H2	X1,X2,X3	None	

Expected Results:

For a Dyn1 transformer, as shown in **Figure 1**, the expected results are as follows:

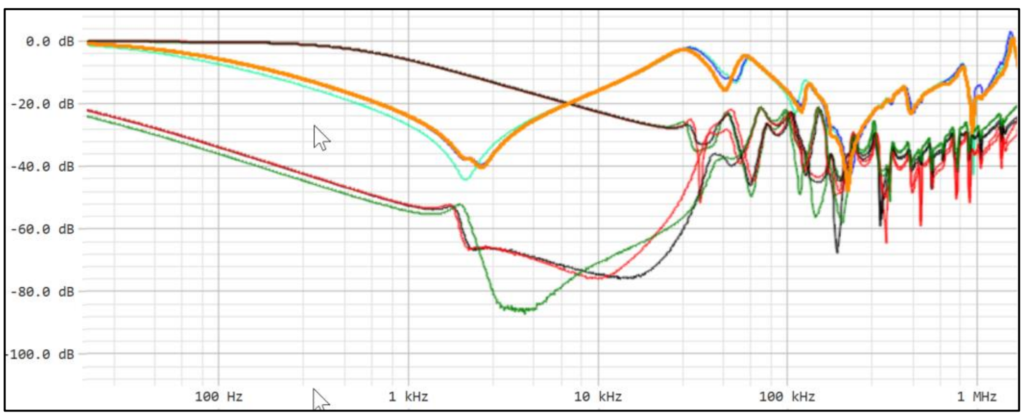


Figure 1 – Typical SFRA Results (Dyn1)

Three groups of traces emerge from a typical SFRA measurement. These three groups are known as HV Open Circuit, LV Open Circuit and HV-LV Short Circuit responses. It should be noted for reference that the HV-LV Short Circuit responses correspond with the same configuration used by the Leakage Reactance test.

Experience has shown that winding movement caused by a high current fault in a 3-phase core form transformer is generally associated with the LV winding in the form of radial deformation. So, diagnostic focus will be given to the LV Open Circuit and HV-LV Short Circuit responses. IEEE C57.149 Guide for SFRA Testing [1] documents both Open Circuit and HV-LV Short Circuit responses. **Figure 2**, shown below, illustrates what happens to the measurements during a high current radial deformation event.

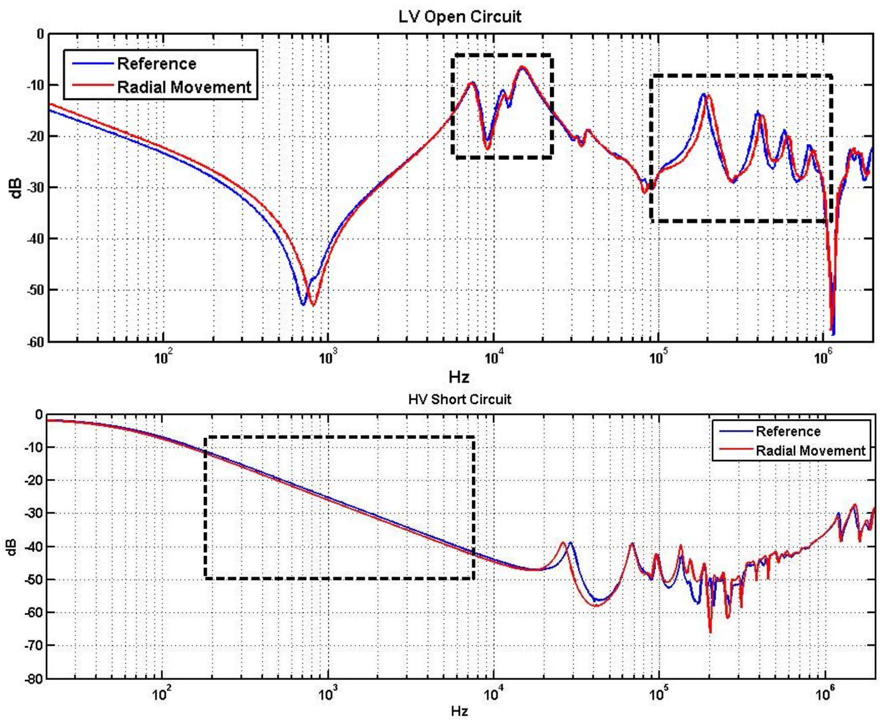


Figure 2 – IEEE C57.149 - Radial Movement

If the transformer is not a two-winding unit, then the test plan will vary. Shown below are additional test plan architectures that include three-winding and auto-transformer configurations.

- 2 Winding (H, X)

  ✓ 3-H OC
  ✓ 3-X OC
  ✓ 3-HX SC

- 3 Winding (H, X, Y)

  ✓ 3-H OC
  ✓ 3-X OC
  ✓ 3-Y OC
  ✓ 3-HX SC
  ✓ 3-HY SC

- Auto Transformer (Series, Common, Tert)

  ✓ 3-H Series OC
  ✓ 3-X Common OC
  ✓ 3-Y Tert OC
  ✓ 3-HX SC
  ✓ 3-HY SC

2.) Leakage Reactance

The field Leakage Reactance test is an AC (60Hz) short-circuit impedance test, which is performed to detect mechanical winding movement and/or deformation within a power transformer. There are two methods for performing Leakage Reactance tests, as follows:

1.) Three Phase (3-Phase) Equivalent Test
2.) Per-Phase Test

The Leakage Reactance measurement directly corresponds to the leakage flux. Leakage flux is flux that does not link all the turns of the winding. It is normal that some of the flux escapes. This leakage flux also helps create impedance that is used to limit short circuit current. Leakage flux creates reactive magnetic energy that behaves like an inductor in series in the primary and secondary circuits. This impedance can be easily measured, analyzed, and trended. This simple model is shown in **Figure 3**. Winding movement changes the reluctance of the leakage flux path, resulting in a change in the expected leakage reactance measurement.

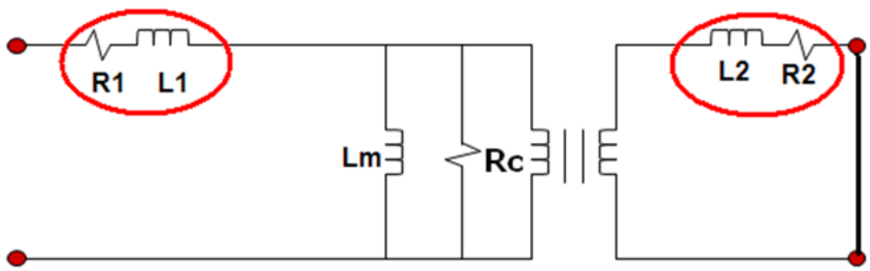


Figure 3 - Leakage Reactance Circuit Model

When performing the Three Phase (3-Phase) Equivalent Test, the secondary is short circuited and the neutral connection, if present, is not included. Please note that single phase units can also be tested. Shown below, in **Figure 4**, are the equations that are used to calculate the per unit Leakage Reactance impedance.

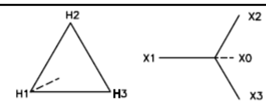
1ϕ UNIT ➡ $$\%Z = \frac{1}{10}\left[(Z)\left(\frac{BasekVA_1}{kV^2}\right)\right]$$

3ϕ UNIT ➡ $$\%Z = \frac{1}{60}\left[(Z_{AC} + Z_{BA} + Z_{CB})\left(\frac{BasekVA_3}{kV_{ll}^2}\right)\right]$$

Figure 4 - Leakage Reactance Equations

Figure 5, as an example, puts the 3-Phase equivalent equation to use. The base power, base voltage, and individual phase impedance measurements are applied.

Nameplate: 6.85% 69 kV 12.5 MVA



Phase	V	I	Z	R	X	L
H1-H3	55.22	1.05	51.59	4.38	51.41	136.4
H2-H1	54.68	1.05	51.15	4.37	50.96	135.2
H3-H2	54.46	1.05	50.96	4.46	50.76	134.2

$$\%Z = \frac{1}{60}[(Z_{AC} + Z_{BA} + Z_{CB})(\frac{BasekVA_3}{kV_{ll}^2})]$$

$$\%Z = \frac{1}{60}[(51.59 + 51.15 + 50.96)(\frac{12{,}500}{69^2})]$$

$$\%Z = 6.73$$

$$\Delta Z = \frac{6.85 - 6.73}{6.85}(100) \qquad \Delta Z = 2.04\%$$

Figure 5 - Leakage Reactance Typical Results

<u>Test Preparation</u>:

1.) Ensure that the transformer tank and core are solidly grounded, also include both the test instrument and power source ground to this point. We will refer to this point as the "GROUND" node.
2.) Completely isolate the transformer terminals; remove external connections and buswork from H1, H2, H3, X1, X2, X3, and X0.
3.) Isolate H1, H2, and H3, making sure that they are not connected together.
4.) Document temperatures and humidity.
5.) Supply #4 solid bare copper conductor and C Clamps/Vice Grips/Channel Nuts.
6.) Solidly short X1, X2, and X3, do NOT include X0; ground X0.
7.) Identify impedance, base power, and base voltage from nameplate.
8.) Verify that the DETC and OLTC are in the nominal rated tap position. If not, the 3-phase equivalent measurement will not be comparable to nameplate.

Test Procedure:

Six tests are to be performed; 3 (3-Phase Equivalent) and 3 (Per-Phase). A four-wire Kelvin connection will be applied. An AC test current should be injected to establish a 30 -100 VAC drop across the primary winding. It is recommended to start with 1.0 A of current injection. With 1.0 A of current injection, the voltage developed across the primary winding should be verified that the voltage is in the 30 -100 VAC range at 60 Hz. If not, adjust the current injection proportionately to obtain a voltage drop within 30 -100 VAC range at 60 Hz. For some sources in combination with some transformers, it may not be possible to achieve a voltage drop of 30 -100 VAC. Always optimize the source and meters if possible.

Table 2 and **Table 3**, shown below, provide the connections for both the 3-Phase Equivalent tests and Per-Phase tests, respectively.

Table 2 - Connections for the 3 Phase Equivalent Test

Test	Phase	Terminals	Ground	Short	Measure
1	LL-A	$H1_{RED}$-$H3_{BLACK}$	X0	X1,X2,X3	H1-H3
2	LL-B	$H2_{RED}$-$H1_{BLACK}$	X0	X1,X2,X3	H2-H1
3	LL-C	$H3_{RED}$-$H2_{BLACK}$	X0	X1,X2,X3	H3-H2

Table 3 - Connections for the Per Phase Test

Test	Phase	Terminals	Float	Short	Measure
4	LL-A	$H1_{RED}$-$H3_{BLACK}$	X2,X3	X1 & X0	H1-H3
5	LL-B	$H2_{RED}$-$H1_{BLACK}$	X1,X3	X2 & X0	H2-H1
6	LL-C	$H3_{RED}$-$H2_{BLACK}$	X2,X1	X3 & X0	H3-H2

Expected Results:

The purpose of the 3-Phase equivalent test is to produce a test result to compare to the factory short-circuit impedance percentage value (Z% nameplate), which can be found on the transformer nameplate. A deviation greater than ±3% of the reported value should be investigated [2].

If one or more of the Per-Phase measurements is dissimilar from the others, a mechanical failure may exist within the transformer, which should then trigger further investigation. We recommend that the measured impedance (Ω) values of the three Per-Phase measurements compare to within ±3% of the average of the three (Ω) values.

Case Studies

Leakage Reactance and SFRA I:

This case study is an example of winding deformation identified by both the Leakage Reactance and SFRA tests. The transformer experienced a fault and acetylene gas was produced. After confirming the gas, Leakage Reactance and SFRA tests were performed. **Figure 6, Figure 7**, and **Figure 8** present the DGA, Leakage Reactance and SFRA tests, respectively.

Report #		Sample # 1				Received	06/01/2011	Date	June 01, 2011

Serial Number:		Equipment Number:		Container Id:	LAB ASSIGNED #	LAB ASSIGNED #	Phase:
Substation Name:		Preservation System:	Gas Blanketed	Miscellaneous Id:			Ambient Temp °C:
Design Type:		Transformer Name:		Second Name:	Kent		Humidity:
Manufacturer:	W	Transformer Type:	Transformer	Sample Point:	Main Tank Bottom		Top Oil Temp °C:
MFR. Year:	1969	Maximum kV:	115	Sequence #:			Peak Temp °C:
Cooling System:		Maximum MVA:	50	Sample Date/By:			Fluid Level:
Fluid Type:		XFMR Oil Capacity:	6416 Gallons	Appr Type:	XFMR		Pressure PSI:
LTC MFR./Model:		LTC Type:		LTC Tank Type :		LTC Capacity:	Filter LTC:

Dissolved Gas Analysis The dissolved gas analysis is run in accordance with ASTM D 3612 and IEC 60567. Values are reported in ppm vol/vol at STP and calibrated with gas-in-oil standards. Values before August 15, 2002 are reported at NTP and calibrated with gas standards.

Report #	Sample Date	Top Oil Temp °C	Hydrogen (H2)	Oxygen (O2)	Nitrogen (N2)	Methane (CH4)	Carbon Monox. (CO)	Ethane (C2H6)	Carbon Dioxide (CO2)	Ethylene (C2H4)	Acetylene (C2H2)	Total Gas	COMB GAS	EST TCG %	C2H4/ C2H2	Comb Gas Rate ppm/day
104489	**06/01/2011**		**64**	**816**	**83400**	**38**	**291**	**11**	**5130**	**31**	**21**	**89802**	**456**	**0.41**	**1.48**	**0.21**
86641	12/03/2008	40	7.1	503	71400	18	226	8.4	4670	6.9	0	76839	266	0.26	0.00	-0.14
83315	07/02/2008	54	8.7	193	70086	20	239	11	5583	8.5	0	76149	287	0.28	0.00	0.28
79981	01/04/2008	34	7.7	401	77000	16	196	10	4950	7.7	0	82588	237	0.21	0.00	-0.24
76464	07/09/2007	58	8.3	1780	86600	17	237	9.2	6040	8.5	0	94700	280	0.22	0.00	0.35
73096	01/22/2007	24	6.7	1280	84500	16	181	10	4630	7.7	0	90631	221	0.18	0.00	0.05
33900	03/16/1998	38	0	750	79300	6.0	33	4.0	1930	1.0	0	82024	44	0.03		0.02
30709	01/13/1997	30	0	763	74100	5.0	23	5.0	1810	3.0	0	76709	36	0.03		0.06
27942	01/22/1996	35	0	2430	74300	5.0	0	5.0	1760	5.0	0	78505	15	0.00		-0.03
23435	05/20/1994	45	0	1230	105000	7.0	21	4.0	1820	3.0	0	108085	35	0.02		

INVESTIGATE Arcing in oil. Overheating of cellulose. Condition is severe.

Figure 6 - DGA Results

Leakage Reactance HV (H) - LV (X)

Measurement Results

OLTC Position	DETC Position	Test Type	I AC sel. [A]	V1 AC sel. [kV]	Phase [°]	Watt Loss [W]	R [Ω]	X [Ω]	Z [Ω]	L [mH]
		3P-Equiv.	1.100	0.07	-87.82	2.808	2.321	60.97	61.04	161.74
		3P-Equiv.	1.097	0.07	-87.81	2.792	2.321	60.68	60.75	160.97
		3P-Equiv.	1.115	0.06	-87.62	2.979	2.398	57.70	57.77	153.05
		Per Phase	1.038	0.03	-87.40	1.422	1.320	29.07	29.11	77.12
		Per Phase	1.045	0.03	-87.64	1.432	1.313	31.86	31.89	84.50
		Per Phase	1.034	0.03	-87.41	1.393	1.301	28.77	28.81	76.31

Test Type	X % PU Measured	X % PU Nameplate	Z % PU Measured	Z % PU Nameplate	Z % Diff.	Rating
3P-Equiv.	6.78		6.79	6.60	-2.85	NONE

Test Type	X % PU Measured	X % PU Nameplate	Z % PU Measured	Z % PU Nameplate	Z % Diff. Average	Dominance Order	Rating
Per Phase	6.60		6.60	6.60	-0.06	2	NONE
Per Phase	7.23		7.24	6.60	-9.62	3	FAIL
Per Phase	6.53		6.54	6.60	0.99	1	NONE

Comment:

Figure 7 - Leakage Reactance Results

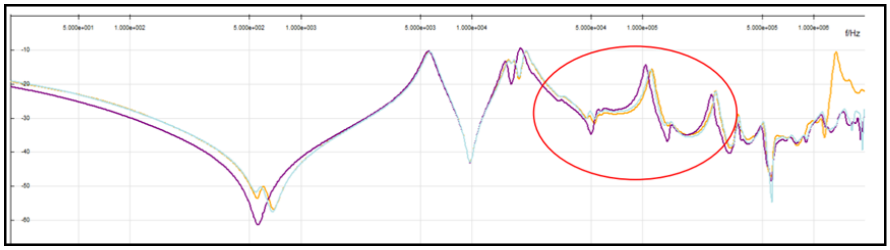


Figure 8 - SFRA Results LV Open Circuit Tests

The DGA clearly indicated a substantial event, while both the SFRA and Leakage Reactance results exhibit an anomaly on Phase B. Winding deformation is expected. Upon internally inspecting the unit, it was clear that there was obvious winding deformation on the Phase B LV winding. This is shown in **Figure 9**.

Figure 9 - Observed Winding Movement LV Winding Phase B

<u>Leakage Reactance and SFRA II</u>:

The transformer in this case study is rated at 50 MVA 90.2kV/34.5kV. The unit is configured as a Dyn1. It tripped from service and oil appeared to be leaking from the LV DETC.

The standard test protocol was applied, which included SFRA and Leakage Reactance.

The Power Factor tests would not run on the low side at 10 kV, so the voltage was lowered to 7 kV. A Power Factor of almost 50% was obtained for the CL insulation; this is clearly unacceptable. The Power Factor results are show in **Figure 10**.

Measurement	Test mode	Sweep	V test	Freq.	V out	I out	Watt losses	PF meas	PF corr	Cap. meas	Assessment
ICL+ICLH	GST	None	7.00 kV	60.00 Hz	6.99 kV	43.28 mA	70982.28 mW	23.4631 %	23.4631 %	15953.1 pF	Fail
ICL (V)	GSTg-A	Voltage	7.00 kV	60.00 Hz	6.99 kV	26.32 mA	87252.42 mW	47.4258 %	47.4258 %	8788.0 pF	Fail
ICL (f)	GSTg-A	Frequency	2.00 kV	60.00 Hz	1.99 kV	7.77 mA	8222.91 mW	53.1804 %	53.1804 %	8787.5 pF	Fail
ICLH (V)	UST-A	Voltage	7.00 kV	60.00 Hz	7.01 kV	18.93 mA	510.54 mW	0.3847 %	0.3847 %	7167.2 pF	Pass
ICLH (f)	UST-A	Frequency	2.00 kV	60.00 Hz	2.00 kV	5.39 mA	39.58 mW	0.3671 %	0.3671 %	7166.9 pF	Pass

Figure 10 - LV Power Factor Results

The Leakage Reactance results indicated an unexpected high impedance on Phase B. This is typical of an open circuit. The DC Winding Resistance test also confirmed an open circuit. However, the other phases, A and C, produced the expected 40 mΩ. The Leakage Reactance Results are shown in **Figure 11**.

Phase	I AC	V1 AC	V1 AC phase	Watt losses	Zk	Rk	Xk	Lk
A	1.08 A	68.80 V	87.47 °	3.270 W	63.888 Ω	2.820 Ω	63.825 Ω	169.302 mH
B	6.53 mA	163.54 V	25.13 °	0.967 W	25.045 kΩ	22.674 kΩ	10.636 kΩ	28212.627 mH
C	1.08 A	70.35 V	87.51 °	3.308 W	64.988 Ω	2.823 Ω	64.927 Ω	172.223 mH

Figure 11 - Leakage Reactance Results

The SFRA results indicate a high impedance fault on Phase B of the LV Winding. Both the LV Open Circuit and HV-LV Short test provide evidence. **Figure 12** and **Figure 13** illustrate this failure mode on Phase B.

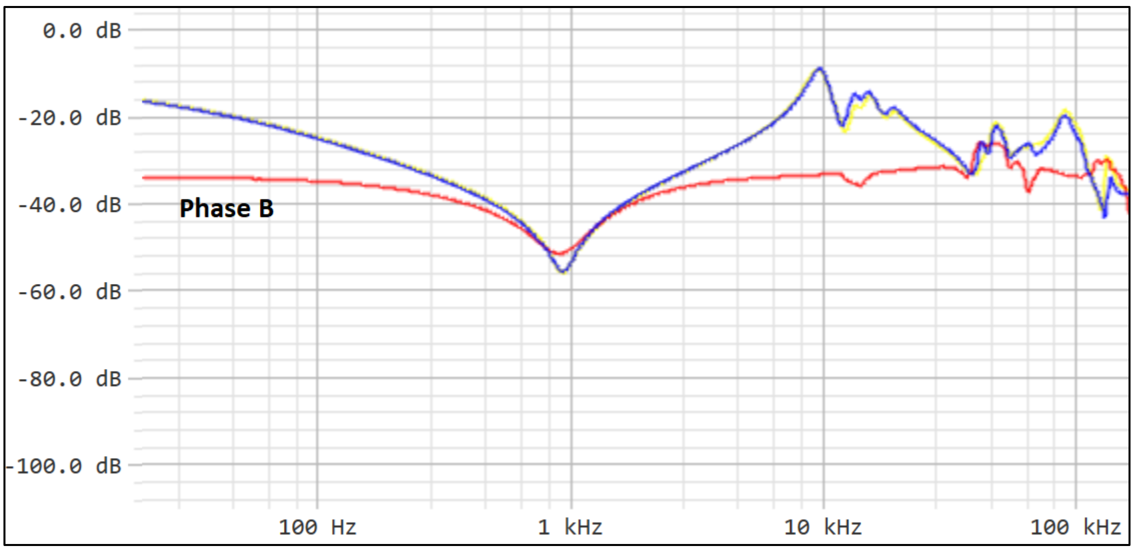


Figure 12 - SFRA LV Open Circuit Results

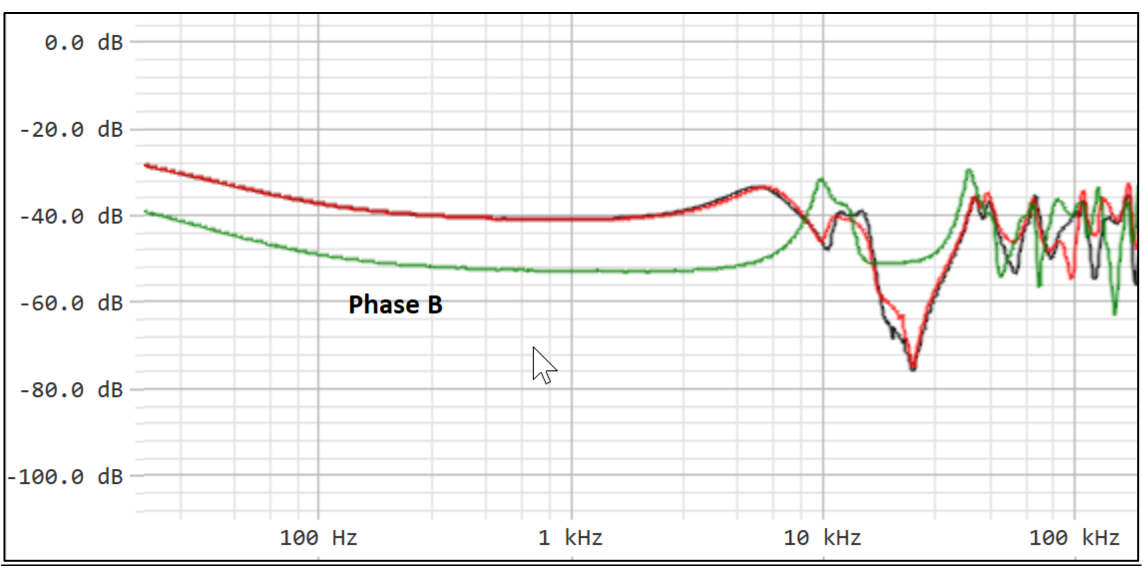


Figure 13 - SFRA HV-LV Short Circuit Results

Conclusion

- SFRA and Leakage Reactance testing can provide useful and in depth information regarding the condition of the power transformer. Mechanical incipient failure modes cannot only be identified, but also located. The problem winding and phase are often identified.

- Proper procedures should be followed to ensure useful results. The test data is only as good as the technician performing the tests. Other information (test data) such as power factor, TTR, DC Winding Resistance, Exciting Currents and DGA should be used in conjunction with SFRA and Leakage Reactance in making diagnostic decisions.

References

[1] IEEE C57.149-2012, “IEEE Guide for the Application and Interpretation of Frequency Response Analysis for Oil-Immersed Transformers”.

[2] IEEE C57.152-2013, "IEEE Guide for Diagnostic Field Testing of Fluid-Filled Power Transformers, Regulators, and Reactors".

Charles Sweetser received a B.S. Electrical Engineering in 1992 and a M.S. Electrical Engineering in 1996 from the University of Maine. He joined OMICRON electronics Corp USA, in 2009, where he presently holds the position of PRIM Engineering Services Manager for North America. Prior to joining OMICRON, he worked 13 years in the electrical apparatus diagnostic and consulting business. He has published several technical papers for IEEE and other industry forums. As a member of IEEE Power & Energy Society (PES) for 17 years, he actively participates in the IEEE Transformers Committee, where he held the position of Chair of the FRA Working Group PC57.149 until publication in March 2013. He is also a member of several other working groups and subcommittees. Additional interests include condition assessment of power apparatus and partial discharge.