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Ability of SFRA to Detect Change in Transformer Oil Parameters

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Abstract

Sweep Frequency Response Analysis (SFRA) has become very popular now – a - days due to its ability to provide comprehensive information regarding mechanical integrity as well as electrical parameters of power transformer. The SFRA is a signature test, and provides better information when assessment of transformer condition with comparing actual set of SFRA results with reference results. During life cycle of a power transformer, insulating oil required to replace on deterioration of oil properties beyond permissible limits. Deterioration of oil parameters hampering insulating properties ultimately reflects change in capacitance of the winding with respect to earth and between windings. The change in capacitance also noticed in capacitance and tan delta measurement. Capacitance between windings measured in various conditions of the power transformer - with old oil, without oil, and with old and new oil. SFRA test taken in each of these conditions. Change in capacitance measured by tan delta test and change in capacitance calculated from SFRA trace both value are comparable. Capacitance measured with deteriorated oil and after oil replacement - measured with good oil, and SFRA taken in both conditions. In this paper, the author has tried to interpret effect of Insulating oil parameters on SFRA traces for a Transformer. With help of SFRA test, one can judge about quantity and quality of oil in power transformer - in a single test. It is worth mentioning here that, available tool for SFRA analysis may misguide when replacement of Transformer oil was carried out and available SFRA analytical tool may indicate minor deformation in winding, however change in SFRA is due to replacement of oil.

Keywords. Sweep Frequency Response Analysis, oil, Life cycle, Power transformer, capacitance and tan delta, electrical property.

1 INTRODUCTION

In service life of power transformers, insulating oil being replaced due to deterioration of insulating property, resultant due to thermal stress or ingress of moisture. Generally, oil replacement in power transformer carried out with drying out process. In draying out process, vacuum and nitrogen cycle applied to power transformer - to remove moisture ingress from windings. To ascertain mechanical integrity of power transformer after sustained stress of vacuum and nitrogen cycle, SFRA test needs to perform. SFRA test provides useful information about mechanical deformation of windings [1]. For analysis of SFRA - thorough skill and experience is required. Many analytical tools developed for analysis of SFRA, among most popular-ones implements cross-correlation coefficients to analyze the SFRA test results [2]. Normalization covariance factor taken in account for detection of mechanical deformation in power transformer [3]. Artificial neural network for analysis of SFRA [4]. Fuzzy logic tool for analysis of SFRA [5]. None above analysis tools gives proper insight into shift in SFRA traces due to oil change. There is no mechanical deformation-taking place in winding due to oil replacement, but overall capacitance changes due to oil replacement and it noticed in SFRA traces. On such occasions, all analytic tools available for SFRA analysis indicate, “light, obvious deformation in winding”, actually shift in SFRA traces is due to oil replacement. Author has analyzed various SFRA results of various classes of power transformers - before and after oil replacement. Over and above, author has carried out SFRA test on transformers without oil and with oil - to understand effect of oil on SFRA results. In this paper, author has tried to correlate SFRA and tan delta test results – for change in capacitance with presence / absence of oil, change in oil properties. With practical case studies, the author has tried to interpret deviation in SFRA traces due to oil replacement.

2 POWER TRANSFORMER OIL

Mineral oil most commonly used cooling cum insulating fluid for Power Transformer. Now a day, natural and synthetic ester oil also used in power transformer. Oil in Transformer serves two-fold purpose: Insulation and cooling. The service life of oil may differ from service life of the Transformer. While power transformer is in service, due to electrical stress, thermal stress, and moisture ingress, electrical property of transformer oil may deteriorate. If deterioration crosses prescribed limits, Transformer oil requires to be replace. Resistivity, tan delta, Break down voltage Known as BDV and PPM of water in oil etc. decide the overall insulation property of Oil. Replacement of oil at site in uncontrolled weather condition requires special care. At the time of oil replacement, drying out process is also adopted to dry out active parts - nitrogen and vacuum cycle applied in this process to power transformer i.e. core and winding. Thereafter oil filling done under vacuum. After oil replacement SFRA, tan delta and low voltage test carried out to ascertain healthiness and to confirm favorable outcome on transformer insulation. After replacement of oil, Oil parameters also assessed through testing oil sample in laboratory.

3 SFRA

The first technical paper published on Frequency Response Analysis was by Mr. E.P. Dick and Mr. C.C. Erven in 1978 [1]. Sweep frequency response analysis has been developed to detect winding movement and deformation in power transformers. High voltage power transformer can be represented as a complex electric system consisting of inductances, capacitances and resistances.

a) **Resistances**: - resistance of windings, joints of bushing leads and OLTC.

b) **Capacitances**: - capacitance between windings to transformers tank, windings and core and turn to turn capacitance.

c) **Inductances**: - inductance due to coil formation of winding, inductance and mutual inductance of other windings.

As shown in figure 1, geometrical changes within and between the elements of the network cause deviations in the SFRA plot.

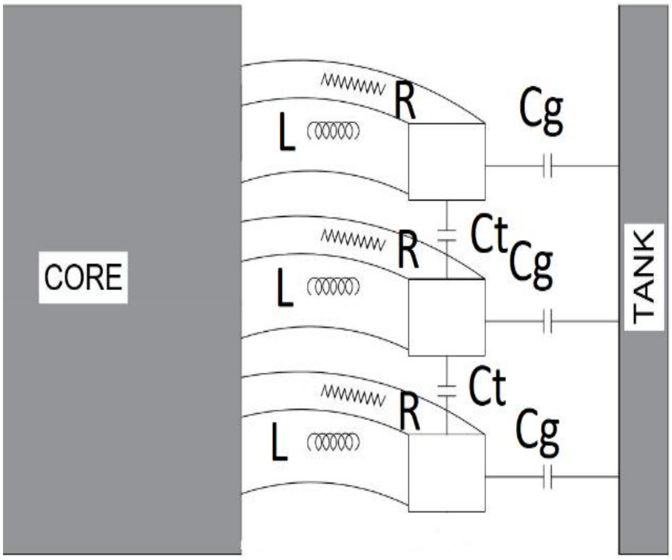

Figure 1. R, L and C of Transformer.

The complex structure of power transformers can be represented with two- port network as shown in figure 2.

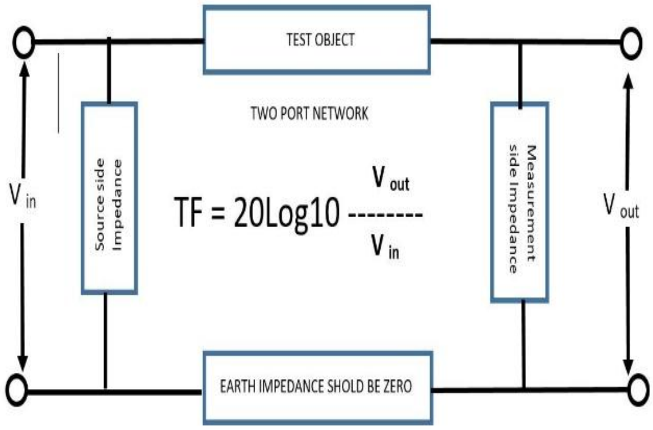

Figure 2. Power Transformer as a two-port network

The two port network, excited by the sinusoidal voltage signal, produces an electrical response which is dependent on the frequency of the input signal, and the value of output voltage depend on impedance of particular winding that have withstood test at particular frequency. Output voltage Vout and Input Voltage Vin are compared in the frequency domain, the gain in dB as under

$$dB = 20 \log10 V_{out} / V_{in} \ldots\ldots\ldots\ldots (1)$$

The values of RLC elements depend on the geometry and materials used. Oil replacement / absence of oil / reduction in oil quantity results in change in the capacitance of RLC network. As we know, capacitance formed by dielectrics depend on

$$C = \varepsilon A/d \qquad (2)$$

Where ε is permittivity constant of dielectric material used for insulation. In power transformer, paper and insulation oil are major part of dielectric material. Hence, change of oil or reduction in oil qty. ultimately changes the ε permittivity constant. SFRA test broadly divided in two part: Inductive measurement and capacitive measurement.

3.1 Inductive measurement

Low voltage sinusoidal signal with variable frequency from 20Hz to 2MHz applied at one end of winding and response measured at other of same winding as shown in below figure.

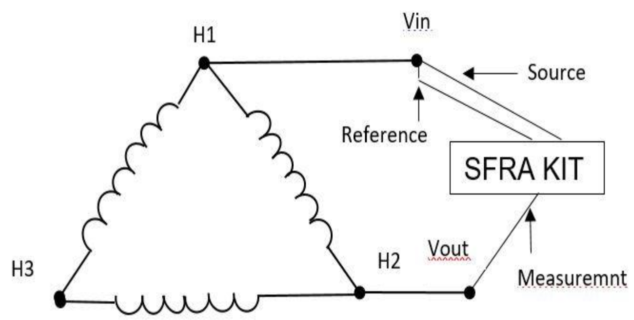

Figure 3. SFRA Inductive measurement

3.2 Capacitive measurement

Low voltage sinusoidal signal with variable frequency from 20Hz to 2MHz applied at one winding and response measured at other end of winding as shown in figure 4

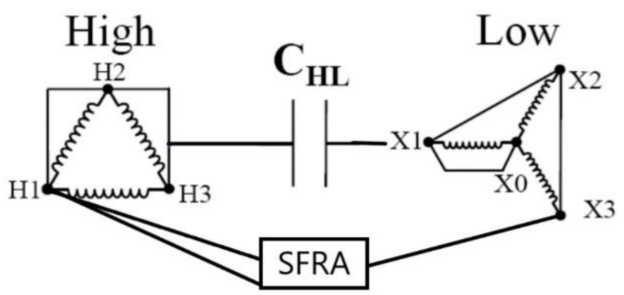

Figure 4. SFRA Capacitive measurement

In most of the cases inductive measurement adopted, capacitive measurement done in special case.

4 TAN DELTA MEASUREMENT

Capacitance and tan delta measurement generally carried out on power transformer to assess transformer insulation. In this test 10kV, A.C. Voltage is applied and capacitance and tan delta measurement carried out. In this test, prime focus is on Transformer Insulation. Capacitance and tan delta measurement done at regular intervals to ascertain condition of insulating material used in power transformer. If rise in tan delta value if noticed, should be treated as matter of concern. Change in capacitance value also treated seriously. However, if is because of oil replacement, oil filtration, bushing replacement etc. – should not be regarded as any problem / defect. Any dielectric material can be represented as below figure.

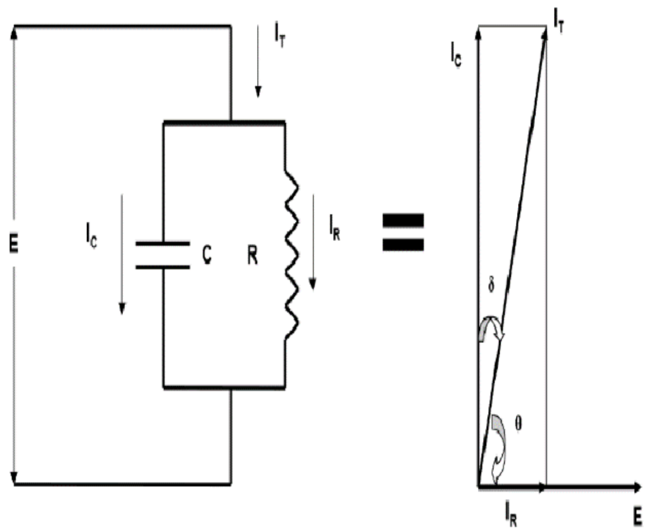

Figure 4. Tan Delta test principle

Tan delta measurement done in various modes and in various conditions. For two winding transformer tan delta be measured for winding as under

a) High voltage winding to Earth CH
b) Low voltage winding to Earth CL
c) Between HV and LV winding CHL

In our case study, to analyze effect of transformer oil in SFRA traces and to correlate capacitance measured during tan delta test - only CHL considered important, as we cannot measure SFRA with HV winding to earth directly. Tan delta test between HV and LV winding performed in UST mode as shown in below figure.

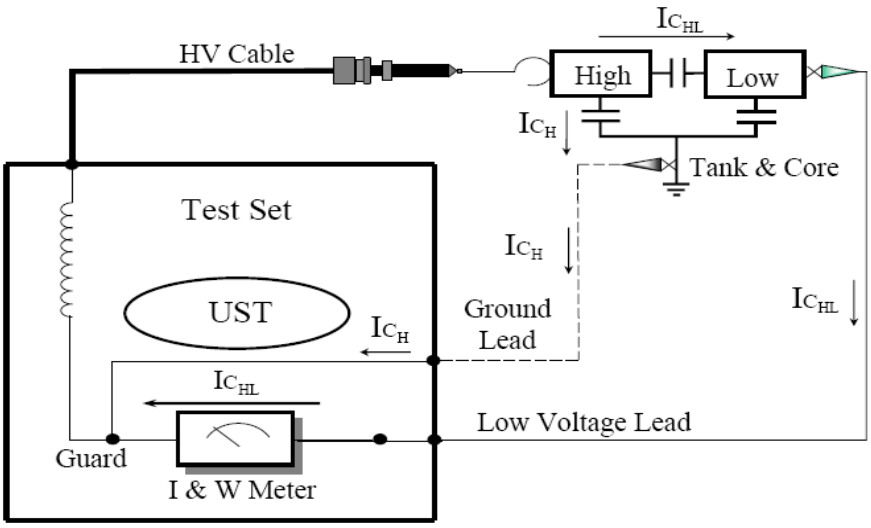

Figure 5. Tan Delta test for CHL

To correlate SFRA test results and tan delta test measurement results - SFRA carried out in capacitive mode, and capacitance measured during tan delta test for CHL (HV Winding to LV Winding) to facilitate comparison.

5 CASE STUDY

In case study to study the effect of transformer oil on SFRA traces, various practical case studies carried out on various class of power transformers.

In of the 66kv Sub-Station, 66/11.5Kv, 15MVA Power Transformer selected to conduct capacitance and tan delta measurement along with SFRA.

SFRA test carried out for the Power Transformer - with oil and without oil. To check the effect on SFRA two types of SFRA test carried out on 66/11.5kV 15MVA power transformer filled with oil. Inductive as well as capacitive test carried out on the power transformer with and without oil successively. In capacitive measurement of SFRA, the capacitance between high voltage and low voltage winding known as CHL is more significant. To verify the change in capacitance value with and without oil capacitance and tan delta test also carried out and value of capacitance between high voltage and low voltage winding observed as shown in table 1.

Table 1. CHL capacitance without and with oil

Tan Delta and capacitance test			
Test configuration	**Cap. with oil (in pf)**	**Cap without oil (in pf)**	**Change in Capacitance (in pf)**
CHL	5833.5	3543.7	2289.8

In SFRA test, response of transformer winding is measured. As we know that transformer is a bunch of series and parallel combinations of number of RLC networks. Any change in value of R, L and C element leads to change in SFRA trace. Here in our case study, only change in C due to presence and absence of oil in power transformer - is considered prevalent.

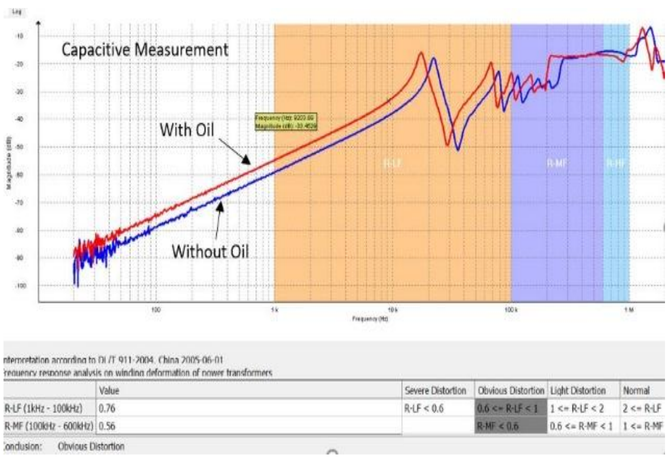

Figure 5. SFRA capacitive measurement comparison

SFRA traces with and without oil are shown in figure 5. Trace marked in blue shows SFRA for the Transformer without oil and red color marked trace denotes SFRA for the Transformer with oil. As can be seen form the figure, red trace shifted left side in low frequency area.

The first resonance in low frequency area is effect of series resonance - as peak resonance point formed by series circuit and valley resonance point created by parallel circuit (resonance?). Due to change in capacitance. Resonance Point moved from resonance frequency RF_1 22298.7Hz (SFRA for Transformer with oil) to frequency RF_2 17299.9 Hz (SFRA for Transformer without oil) as shown in below figure 6.

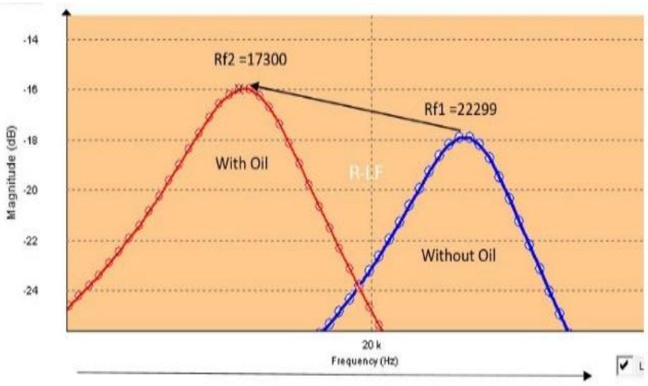

Figure 6. Shift in resonance due to absence of oil

At Resonance Point, frequency is RF_1 22298.7Hz (with oil) and capacitance measured with tan delta test is 5833.5 pf. As we know, at resonance frequency X_L=X_C. Value of C (5833.5 pf) and resonance frequency (22298.7 Hz) are known. To find out L parameter at Rf1 with use of equation of resonance frequency.

Now, at resonance frequency

$$fo = \sqrt{L}/C \quad \text{..........................} (3)$$

From above equation L= 1.438 Henry. Now oil drained completely from the transformer. Therefore, capacitance between two windings changed and same value measured with tan delta and capacitance measurement test as shown in table1. Here with assumption that there is no change in L, as there is no any change in winding and its value is 1.438 Henry. Now, the value of resonance frequency Rf2 is 17299.9Hz. From equation (3), value of Capacitance derived is 5886 pf. However, Capacitance measured with tan delta kit is 5833.5 pf. both values are more or less same. Minor difference is due to measurement error of instrument, and effect of capacitance between turn. In SFRA traces, oil effect observed same throughout - in capacitive measurement.

In inductive measurement of SFRA - low voltage sinusoidal with variable frequency applied to one end of transformer winding and response measured at other end of winding. In our case, practical testing done on 66/11.5kV 15MVA power transformer with oil and without oil and comparison of both SFRA traces shown in figure 7.

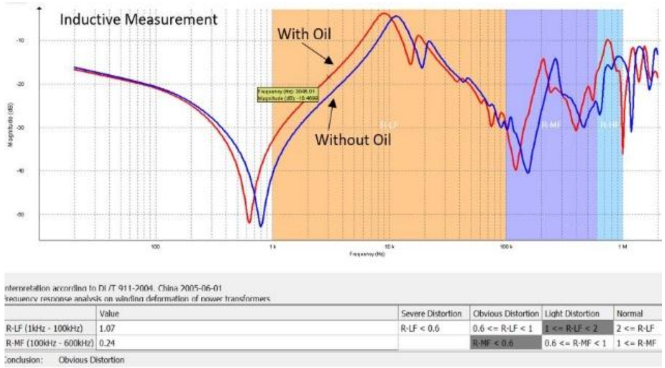

Figure 7. SFRA Inductive measurement

In both cases of SFRA test i.e. Inductive and Capacitive measurement - effect of oil is to shift SFRA traces towards left. In short circuit test i.e. Low Voltage winding of power transformer shorted SFRA traces in low frequency reflects no effect of oil - as in Inductive domain effect of capacitance is not predominant Both traces of SFRA superimpose (In low frequency region) as shown in figure8.

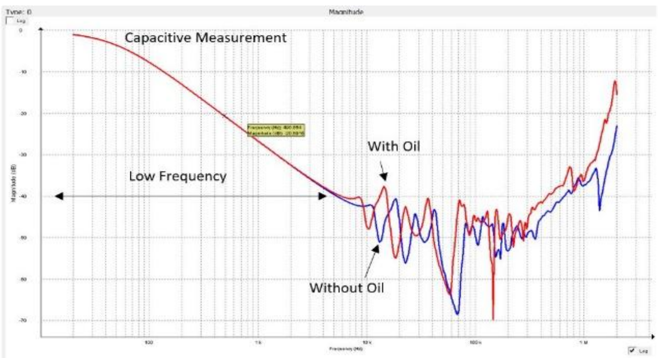

Figure 8. SFRA HVR-B SC Capacitive measurement

In our next case study of 220/66 KV, 100MVA power transformer, SFRA inductive test carried out for Transformer with contaminated oil, i.e. old oil and then Oil replacement carried out with new oil. SFRA test performed again with new oil, and effect of oil change in SFRA observed with compare both traces. Mineral oil filled in 220/66 KV, 100MVA power transformer replaced with new oil. Important parameters of Old and new oil shown in table 2.

Table 2. Comparison of oil parameter

OIL	Electric strength (BDV)	Water content (PPM)	Dielectric Dissipation factor	Resistivity
OLD OIL	54.00	29.00	0.1420	$0.13x10^{12}$
NEW OIL	89.00	4.00	0.0082	$14 x10^{12}$

Capacitance measured with capacitance and tan delta measurement kit in both condition, transformer filled with old oil, and the filled with new oil and due to auto transformer only one value of CH can possible and same is narrated in table 3. In new oil compare with old oil, capacitance value found lower.

Table 3. Comparison of oil parameter

Tan Delta and capacitance test			
winding	Cap with old oil in pf	Cap with new oil in pf	Change in Capacitance
CH	9791.1	9422.3	-368.8

SFRA test carried out for transformer with old and new oil, and traces compared. In oil replacement case study - SFRA traces of new oil just slightly shifted towards i.e. higher frequency side, however shifting observed in SFRA traces with and without oil condition in low frequency area. The shifting observed is due to change in value of capacitance due to change in electrical parameters of oil. From both case study and comparing tan delta value of both case, observation is that when capacitance increase SFRA traces move towards low frequency and when capacitance decrease SFRA trace move towards high frequency area. In SFRA horizontal movement due to change in Inductance and capacitance and in our case inductance there is no any change as there is no any change in winding. Hence shifting is due to capacitance only. 1U-n open circuit SFRA comparison as shown in figure 9 for High voltage winding.

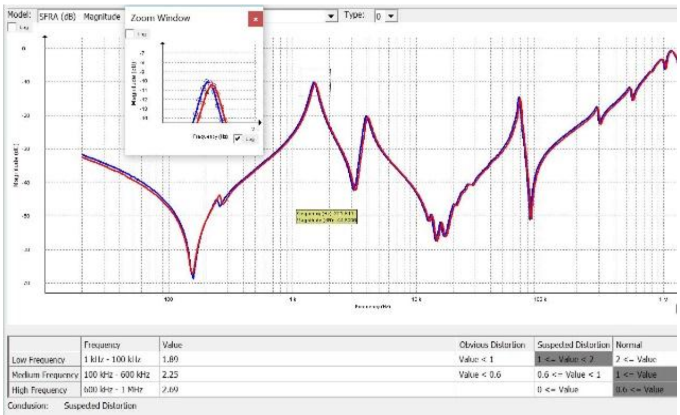

Figure 9. SFRA HVU-N OC Inductive Measurement

In SFRA traces of figure 9, first series resonance area zoomed to check clear effect of oil change. In zoomed portion, one can easily notice that new oil SFRA trace moved towards high frequency side, and same type effect observed in SFRA traces of low voltage winding as shown in figure 10.

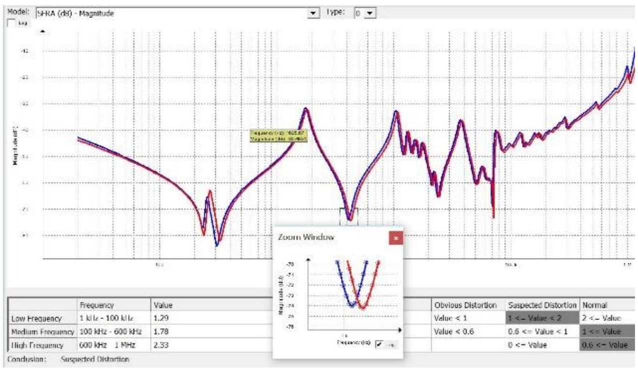

Figure 10. SFRA LVU-N OC Inductive measurement

In figure 9 and 10 both High voltage and Low voltage winding shifted towards high frequency side due to change of oil. However when both traces analyzed with available tool of SFRA analyzer, indicate suspected distortion. Actually, change in SFRA due to change of oil, not due to any winding distortion. For new beginner of SFRA tester it is quite difficult to giver conformation about SFRA test results are ok or not.

SFRA test with low voltage winding shorted and SFRA of HV winding taken known as a Short circuit test of SFRA. Short circuit test taken successively with poor quality oil and good quality oil. In this case, at low frequency area, i.e. up to 1200Hz there is no any change in both traces as shown in figure 11.

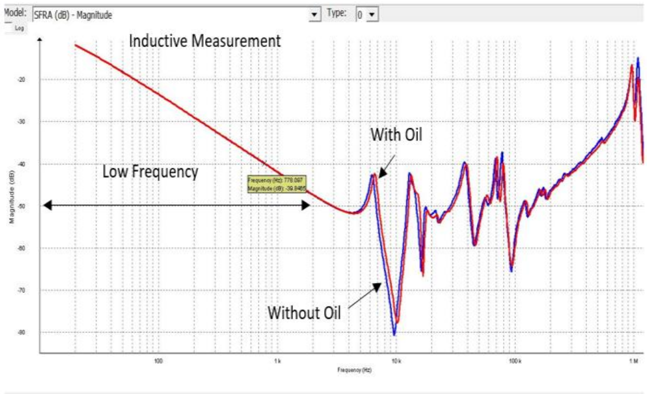

Figure 11. SFRA HVU-N SC Inductive comparison

Low frequency area known, as core area and this are core play vital role due to higher inductive value. However, change start after 1300Hz and that due to change effect of capacitance. In low frequency area, no any shifting observed due to change of oil - as change in capacitance in low frequency domain is not predominant.

6 CONCLUSION

In this article, study effect of presence, absence of insulating oil inside the power transformer on SFRA trace, carried out by conduction SFRA test on power transformer with oil and without oil condition. Effect of change in oil properties inside the power transformer on SFRA traces, also carried out by conducting SFRA test on number of power transformers. Shift in SFRA traces recorded, accountable to change in insulating oil properties, also validated by change in capacitance value reflected through tan delta and capacitance measurement test. The shift in SFRA traces because of absence of oil, change in oil properties is inferred by most of the present SFRA tool as suspected deformation in winding. It may mislead to SFRA testing personnel, especially, which are new to this area. Therefore, this necessitates need for accommodating a factor regarding change of oil properties in SFRA tools, so that shift in SFRA traces on this account is not inferred as an abnormality.

7 ACKNLOWGMENT

Authors are thankful to Gujarat Energy transmission corporation Ltd. to grant permission to publish test results, details etc. of Power Transformers. Author Ashok J. Chavda works as Superintending Engineer Testing, and author has been entrusted with carrying out SFRA analysis and take decision regarding transformer. To develop skills of beginners for SFRA analysis and to enhance knowledge of SFRA testers, author has published with permission of GETCO. we are very much grateful to the GETCO management for kind support, guidance and granting permission to publish this article.

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Mr. Ashok has attended many faulty transformers at site and save lots of money and time for utility.

Dr. Vivek Pandya received his Bachelor in Electrical Engineering from Sardar Patel University Valabh Vidyanagar Gujarat in 1995. He has completed Master Degree from same university in 2003. He has completed Ph.D. from M.S. University Baroda in 2009. At present Dr. Vivek Pandya work with Pandit Dindayal Petroleum University formally known as PDPU, Gandhinagar, as professor and HOD. Interested and research area of Dr. Vivek Pandya are protection of power system.

He had published many article in research journals and numbers of conference papers. At present Dr. Pandya, provide guidance to 7nos of Ph.D. students. Under the guidance of Dr. Pandya 5 no's of researchers have completed their research work.