ISSN (Print) : 2320 – 3765

ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Website: www.ijareeie.com

Vol. 6, Issue 1, January 2017

Investigating Mechanical Integrity in Power Transformer Using Sweep Frequency Response Analysis (SFRA)

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ABSTRACT

Sweep Frequency Response Analysis (SFRA) is an established tool for determining the core deformations, bulk winding movement relative to each other, open circuit and short circuit turns, residual magnetism, deformation within the main transformer winding, axial shift of winding etc. This test is carried out on the transformer without opening it and is an off line test. A change in frequency response as measured by SFRA technique indicates a physical change inside the transformer, the cause of which then needs to be identified and investigated.

Keywords

SFRA method; Measurement of SFRA; Analysis and interpretation of SFRA data; Statistical method

I. INTRODUCTION

Power transformers are one of the most expensive elements in a power system and their failure is a very costly event [1]. Power transformers are mainly involved in the energy transmission and distribution. To have a reliable operation of transformer, it is necessary to identify problems at an early stage before a catastrophic occurs. In spite of corrective and predictive maintenance, the preventive maintenance of power transformer is gaining due importance in modern era and it must be taken into account to obtain the highest reliability of power apparatus like a power transformer. The well known preventive maintenance techniques such as dissolved gas analysis (DGA), thermal monitoring, oil analysis, partial discharge measurement, capacitance and tan delta measurements, sweep frequency response analysis, etc. are applied for transformer for a specific type of problem [1,2].

In the FRA technique, a low amplifier swept frequency signal is applied at the end of one of the transformer windings and the response is measured at the other end of the winding with one phase at a time as shown in Figure 1. The method is based on the fact that every transformer winding has a unique signature of its transfer function which is sensitive to change in the parameters of the winding, namely resistance, inductance and capacitance. Difference in signature of the responses may indicate damage to the transformer which can be investigated further using other techniques or by an internal examination [3].

Two methods used for the interpretation of SFRA data are: 1) graphical interpretation and 2) statistical method.

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Vol. 6, Issue 1, January 2017

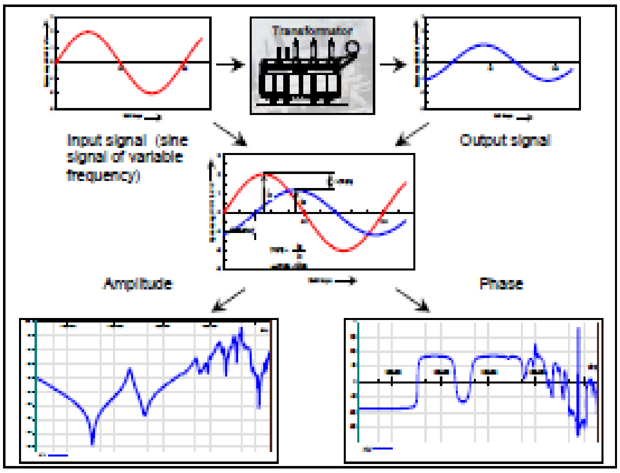

Figure 1: Principle of SFRA.

Winding deformation in transformer is difficult to establish by conventional methods of diagnostic tests like ratio, impedance/ inductance, magnetizing current etc. Deformation results in relative changes to the internal inductance and capacitance of the winding. These changes can be detected externally by low voltage impulse method or FRA method [4].

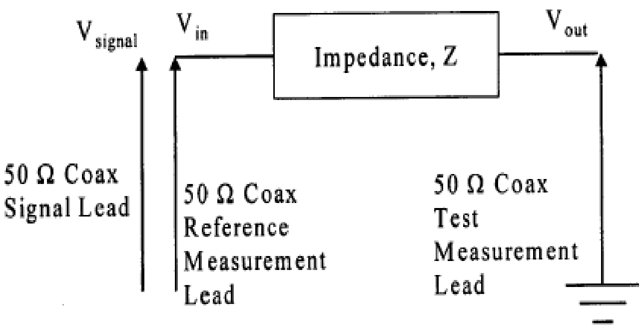

Figure 2: Measurement circuit of SFRA model.

This Paper describes SFRA measurement and practical aspects of sweep frequency response analysis. After measurement of SFRA data, how SFRA data is to interpret using a graphical interpretation technique is given in Section III. Section IV presents statistical method instead of graphical interpretation of SFRA data and section V presents experimental results showing magnitude versus frequency plots (graphical interpretation) of three phase 100 MVA autotransformer under open circuit test on series winding using M5200 SFRA analyzer.

II. SFRA MEASUREMENT

The swept frequency method for making FRA measurements inject the wide range of frequencies required by making a frequency sweep using a sinusoidal signal. The sinusoidal signal is generate using a network analyzer, which is also use to make the voltage measurements and manipulate the results [5]. A large number of measurement configurations are possible. The most widely used technique is to inject a signal at one terminal of a winding and measure the voltage at both ends, with all of the other winding terminals disconnected from one another and ground. This gives rise to the measurement circuit shown in Figure 2. There are a number of possible methods of presenting the results of measurements made using the swept frequency method.

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International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

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Vol. 6, Issue 1, January 2017

The most widespread is to plot a graph of the so-called amplitude, as measured by the network analyzer, against frequency. Both linear and logarithmic scales are used, but the preferred one uses logarithmic scale. The response in dB is calculated by following equation.

Response in dB= $20\log(\frac{Vout}{Vin})$ (1)

The output voltage, Vout is referenced via a 50 Ω co-axial cable to ground. This means we have;

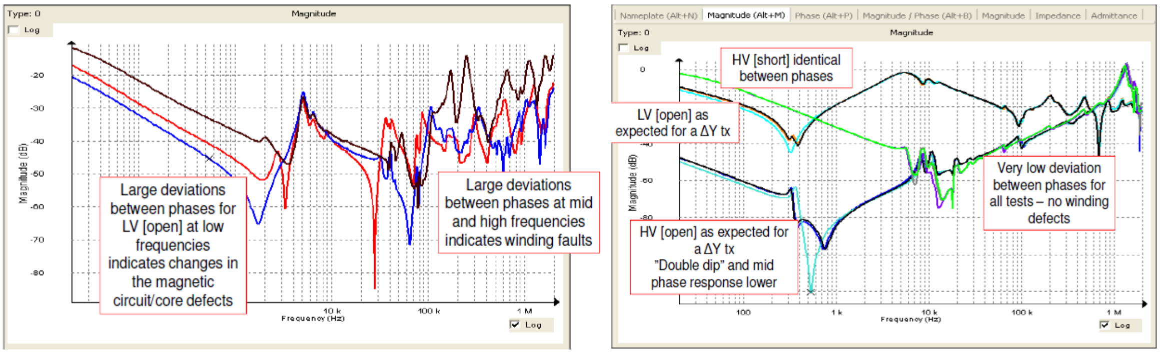
$(\frac{Vout}{Vin})=\frac{Z}{Z+50}$ (2)

SFRA is a comparative measurement method. This means results of an actual test, usually a set of curves (mainly the amplitude in dB's over the frequency) representing all windings of a transformer are compared to reference or baseline data. There is a hierarchy of analysis using SFRA [5]. The best method is to compare SFRA results to those obtained previously as a baseline data as shown in Figure 3 (a, b). If baseline results are not available, we can rely on three further types of comparison over baseline comparisons:

1. Time-based (current FRA results will be compared to previous results of the same unit)

2. Type-based (FRA of one transformer will be compared to another of the same design)

3. Phase comparison (FRA results of one phase will be compared to the results of the other phases of the sam



(a) (b)

Figure 3: Comparison of results (plot: magnitude (dB) versus frequency) of sister units: (a) Frequency response of sister units under healthy condition (b) Frequency response of sister units under abnormal condition.

A SFRA measurement is made from one terminal of the transformer (e.g. H1 or A) to another terminal (e.g. H2 or N). It is important to record all relevant information, which includes tap position, oil level and terminals grounded or shorted of transformer. One has to be sure that good electrical connections are made at bushing terminals and at the base of bushings of transformer. Table 1 and 2 illustrate all possible combinations of SFRA test for deriving meaningful analysis related to mechanical integrity of three phases and two winding power transformer.

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Test type	Test three phase	Δ-Y three phase	Y-Δ three phase	Δ-Δ three phase	Y-Y threephase
HV open circuit (OC), all other terminal floating	Test 1	H1-H3	H1-H0	H1-H3	H1-H0
	Test 2	H2-H1	H2-H0	H2-H1	H2-H0
	Test 3	H3-H2	H3-H0	H3-H2	H3-H0
LV open circuit (OC), all other terminal floating	Test 4	X1-X0	X1-X3	X1-X3	X1-X0
	Test 5	X2-X0	X2-X1	X2-X1	X2-X0
	Test 6	X3-X0	X3-X2	X3-X2	X3-X0
Short circuit (SC) High (H)to Low (L), Short [X1-X2-X3]	Test 7	H1-H3	H1-H0	H1-H3	H1-H0
	Test 8	H2-H1	H2-H0	H2-H1	H2-H0
	Test 9	H3-H2	H3-H0	H3-H2	H3-H0

Table 1: Two winding power transformer connections [6].

(H): High voltage winding, (X): Low voltage winding, (0): Ground or neutral, (1): Red phase, (2): Yellow phase, (3): Blue phase

An open circuit measurement is made from one end of a winding to another with all other terminals floating. For a delta winding, connections would be H1 to H3 and for star winding measurements are taken from HV terminals to neutral, such as H1 to H0. A short circuit measurement is made with the same SFRA test lead connections as an open circuit measurement but with the difference that another winding is short-circuited, for example shorting X1 to X2, X2 to X3 and X3 to X1. This ensures all three phases are similarly shorted to give consistent impedance. Any neutral connections available for the shorted winding should not be included in the shorting process [6].

Test type	Test	Three Phase
SeriesWinding(OC), all other terminal floating	Test 1	H1-X1
	Test 2	H2-X2
	Test 3	H3-X3
Common Winding (OC), all other terminal floating	Test 4	X1-H0X0
	Test 5	X2-H0X0
	Test 6	X3-H0X0
Short Circuit (SC), high (H) to low (L) short [X1-X2-X3]	Test 7	H1-H0X0
	Test 8	H2-H0X0
	Test 9	H3-H0X0

Table 2: Two winding autotransformer connections [6].

There are several ways to analyze the SFRA results. One of them, used in this paper is to divide the graph into four frequency bands and analyze them separately. The main reason for examining the sectioned spectrums is the dependence of

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ISSN (Online): 2278 – 8875

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occurrence of deviation (i.e. their specific frequency) with physical location of the fault in the transformer. Table 3 summarizes the frequency bands of concern and their corresponding effects on the different parts of the transformer.

Band	Likely Causes of Variation
<2kHz	Core deformation, open circuits, Shorted turns and residual magnetism
2kHz to 20kHz	Bulk winding movement relative to each other and clamping structure
20kHz to 400kHz	Deformation within the main and tap windings
400kHz to 2MHz	Movement of main and tap winding leads, axial shift

Table 3: Frequency bands and possible sources of variations [7].

III. INTERPRETATION OF SFRA DATA

There are a number of possible methods of presenting the SFRA results of measurements made using the swept frequency method. The most widespread is to plot a graph of the so-called amplitude, as measured by the network analyzer, against frequency (graphical interpretation). Both linear and logarithmic scales are used, but the preferred one is to use logarithmic scale. The network obtained by SFRA provides good condition insight of the transformer winding orientation [8,9]. A good interpretation method can give the exact location of fault inside the transformer. An effort to extend this technique to a level as to see the effect of fault on each turn can prove to be a milestone. An advantage is that reference responses are not required to make an accurate decision as a comparison of response to the different phase of the same transformer and a comparison of response from sister transformer are used successfully to diagnose the mechanical integrity of the transformer [9]. Two analyzing techniques are used for the purpose of graphical interpretation. These methods are signature and comparison. This paper explains comparison technique to interpret the SFRA data.

3.1. Comparison Technique

This technique compares a reading from one phase of a transformer to a reference set of data. The differences between the two readings represent the condition of the transformer winding as compared to the reference.

Key equation: $Di = Ri – REFi$ (3)

where,

Ri= Phase measurement at the respective frequency.

$REFi$= Reference measurement at the respective frequency.

Di= Difference at the respective frequency.

The reference spectrum can be obtained from the healthy phase of either the same transformer or the sister transformer. The signature of the healthy reference phase must be obtained from the same winding that is either high voltage (HV) or low voltage (LV) as the phase under study [10].

IV. STATISTICAL METHOD USED

SFRA diagnosis is made based on the comparison between two SFRA responses and any significant difference in low, middle and high frequency sub-bands region would potentially indicate mechanical or electrical problem due to core and

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Vol. 6, Issue 1, January 2017

winding of transformer. Instead of using graphical comparison, statistical techniques such as Cross-correlation Coefficient Function (CCF), Standard Deviation (SD) and Absolute Sum of Logarithmic Error (ASLE) can be used to interpret the SFRA results in a proper way [11,12].

$$CCF = \frac{\sum_{i=1}^{N}(Xi-\bar{X})(Yi-\bar{Y})}{[(Xi-\bar{X})(Xi-\bar{X})(Yi-\bar{Y})(Yi-\bar{Y})]^{1/2}} \quad (4)$$

X(i) and *Y(i)* are *i*th elements of the reference fingerprints and measured frequency response, respectively, using SFRA. *N* is the total number of samples in the frequency response. The magnitude value is already in logarithmic scale and therefore it is not necessary to take logarithms when calculating parameter of absolute sum of logarithmic error (ASLE) using magnitude response. In the analyzing part, CCF, SD and ASLE are designed to approach 1, 0 and 0, respectively which is done by using M5200 SFRA analyzer [13].

V. CASE STUDY AND RESULT

In this paper, a case study of three phase 100 MVA autotransformer is discussed for the detection of mechanical movement based on SFRA measurement. Graphical interpretation and statistical technique (CCF) are used to interpret the SFRA results using M5200 SFRA analyzer. In this case study, the comparison of the SFRA measurement results are done by using **time-**based comparison method (current FRA results compared to previous results of the same unit) of three phase 100 MVA autotransformer. The current SFRA result has been measured on 28/09/2016 and previous SFRA results (reference fingerprints) on 14/08/2012.

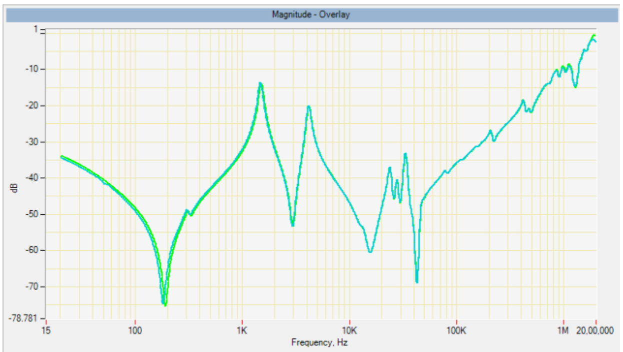

Figure 4: M5200 SFRA analyzer measurement circuit.

Doble make M5200 SFRA model is capable of doing all needed SFRA test which can be analyzed with SFRA software [14]. Cables are connected to the test set following the colour coded bayonet neill concelman (BNC), for example H1-H0, attach the red lead and yellow lead to the H1 bushing and the black lead to the H0 bushing of transformer, as shown in Figure 4.

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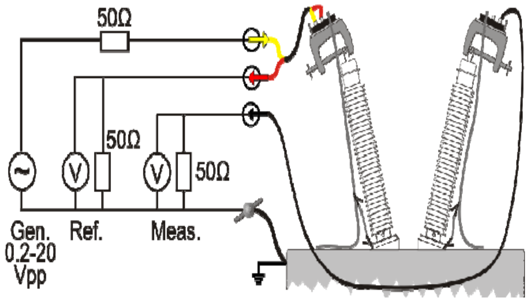

Figure 5: Time based comparison- test 1 of red phase (H1-X1) between 14/08/2012(green) and 28/09/2016(blue).

5.1. Case Study: 220 kV JEUR substation, Pune, three phase autotransformer 100 MVA, 220/132 kV

In this case, three phase autotransformer has been in-service for almost 30 years and do not indicates any major problem or defect during operation period. The SFRA measurement was done on the autotransformer of specification as shown in table 4. SFRA measurement carried out on both series and common winding of autotransformer using graphical interpretation based on time based comparison method [15,16]. Figures 5-7, illustrates the SFRA response of current FRA measurement (28/09/2016) and previous FRA measurement (14/08/2016 referred as fingerprint) of three phase 100MVA autotransformer, which is carried on series winding (H1-X1, H2-X2 and H3-X3 phase) under open circuit condition. Statistical technique such as Cross-correlation Coefficient Function (CCF) is also use to interpret SFRA result.

Manufacturer	MVA rating	HV/LV rating	Phase	Sub-statio n
BHEL	100 MVA	220/132 kV	Three	JEUR, Pune

Table 4: Detail of auto-transformer.

5.2. Open circuit test of series winding

An open circuit measurement is made from one end of red (H1), yellow (H2) and blue (H3) phase to another phases (X1, X2, X3). Where, H1-X1 means attach the red lead and yellow lead of M5200 SFRA analyzer to the H1 bushing (input response) of autotransformer and the black lead to the X1 bushing (measured response) of same autotransformer, similarly for H2-X2, H3-X3 with all other terminals floating. The response of these phases is shown in Figures 5- 7 respectively.

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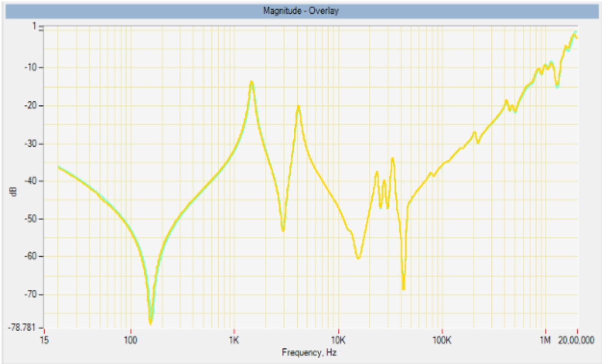

Figure 6: Time based comparison- test 1 of yellow phase (H2-X2) between 14/08/2012(blue) and 28/09/2016(yellow).

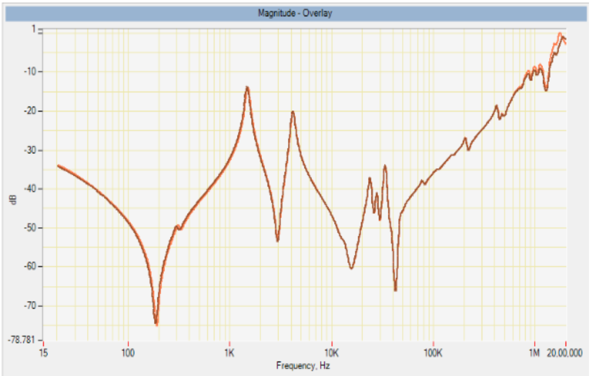

Figure 7: Time based comparison- test 1 of blue phase (H3-X3) between 14/08/2012(orange) and 28/09/2016(red).

When comparing graphically two SFRA measurements (i.e. previous SFRA measurement on 14/08/2012 and current SFRA measurement on 28/09/2016) of red phase, yellow phase and blue phase of series winding in frequency range of 1 kHz to 1 MHz, the test1, test2 and test 3 shows good congruity. This is an indication of an unchanged geometry inside the autotransformer i.e. the healthy status of the red phase, yellow phase and blue phase of tested series winding. Average value of statistical indicator (CCF) of red phase, yellow phase and blue phase (of series winding) are 0.99436, 0.99742 and 0.99784 respectively**.** These indicators show a good agreement between phases. For the purpose of simplicity, SFRA results are interpreted in tabular form as shown in tables 4-6.

Test type	**Test**	**Three phase**	**Colour of graph**
Series winding (OC), all other terminal floating	Test 1	H1-X1(14/08/2012)	Green
		H1-X1(28/09/2016)	Blue
	Test 2	H2-X2(14/08/2012)	Blue
		H2-X2(28/09/2016)	Yellow
	Test 3	H3-X3(14/08/2012)	Orange
		H3-X3(28/09/2016)	Red

Table 4: SFRA data using graphical interpretation technique.

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International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

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Test type	Test	Deformation occurs (Sub band A)	Deformation occurs (Sub band B)	Deformation occurs (Sub band C)
Series winding (OC), all other terminal floating	Test 1	Slightly differ	No	No
	Test 2	No	No	No
	Test 3	No	No	No

Table 5: SFRA data using graphical interpretation technique.

Test type	Test	Three phase	Average value of statistical indicator (CCF)	Condition of phases
Common winding (OC), all other terminal floating	Test 1	H1-X1	0.99436	Healthy
	Test 2	H2-X2	0.99742	Healthy
	Test 3	H3-X3	0.99784	Healthy

Table 6: SFRA data using statistical technique.

VI. CONCLUSION

In this paper, various concepts related to Sweep frequency response analysis (SFRA) consisting of SFRA measurement, physical aspects, analysis and interpretation of SFRA data etc. are presented .The SFRA is a powerful method for the detection and diagnosis of defects in the active part of power transformers. It can deliver valuable information about the mechanical as well as the electrical condition of core, windings, internal connections and contacts. The graphical interpretation method and statistical technique (CCF) are presented and evaluated for interpreting the results of SFRA measurements. This SFRA method can be applied to number of healthy and faulty transformers. No other method can deliver such a diversity of information; hence, the SFRA is an increasingly popular test.

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ISSN (Print) : 2320 – 3765

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Vol. 6, Issue 1, January 2017

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