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Research Article

Diagnosing Integrity of Transformer Windings by Applying Statistical Tools to Frequency Response Analysis Data Obtained at Site

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Abstract: This study presents the results of Sweep Frequency Response Analysis (SFRA) measurement work carried out on number of power transformers at various sites involving problems like shorting of winding turns, core faults and related issues, On-Load Tap Changer (OLTC) open contacts and winding displacement issues. The numerical parameters Viz., Min-Max ratio (MM), Mean Square Error (MSE), Maximum Absolute difference (MABS), Absolute Sum of Logarithmic Error (ASLE), Standard Deviation (S.D.) and Correlation Coefficient (CC) computed in three different frequency bands are presented to aid the interpretation of SFRA data. Comparison of frequency responses among different phases of the same transformer and with sister units were carried out to interpret the data. The study presents limits for various numerical parameters to diagnose the condition of the transformer and discriminate the faulty winding after accounting for manufacturing, design and asymmetry of the winding. The results presented in the study will help in interpreting the SFRA data by applying numerical techniques and assess the condition of the transformer.

Keywords: Condition assessment, deformation, displacements, numerical approach, SFRA

INTRODUCTION

Large power transformers are most expensive and the important components of any power generation and transmission system. Outages in Transformer have a considerable economic impact on the operation of an electrical network. Deformation/movements of winding assemblies are caused by electromagnetic forces caused by external short-circuit currents or by ageing for the transformers in service or by stresses originating from mechanical vibrations during transport as noted by Lapworth and McGrail (1999). Identifying winding movements/deformations is very important for the safe operation and better planning of maintenance of transformer in service and to improve its reliability. Frequency Response Analysis (FRA) method as per Lapworth and Mc Grail (1999), Al-Khayat and Haydock (1995) and Ryder (2002) using sweep frequency voltage source and Transfer Function (TF) method as per Leibfried and Feser (1999) and Christian and Feser (2004), using a low voltage impulse source are the main methods used for detecting winding deformation/displacements. Short circuit reactance measurement is described in IEC 60076-5 (2006) standard as a diagnostic method to check the mechanical integrity of the winding. However, it is observed by Feser *et al*. (2000) that, this method is not applicable to power transformers already in service due to its low sensitivity.

All the conventional FRA techniques are based on graphical analysis for diagnosis, which requires trained experts to interpret test results in order to identify both the failure and failure tendencies in the transformer. Therefore, conclusions will differ depending on the personnel experienced in interpreting the FRA data. In CIGRE SC12 (1999), it is reported that some interpretation of FRA results are not so clear and failure criteria is uncertain. FRA results are sensitive to a variety of winding faults and are said to be less dependent on previous reference measurements. However, there are no systematic guidelines for interpretation of the FRA results. Hence, studies to collect field data by conducting measurement at site and analyze them for an objective and systematic interpretation methodology using different diagnostic techniques are essential.

Many attempts have been made and are being continued to develop an evaluation method that can be applied by inexperienced personnel using numerical methods as per Bak-Jensen *et al*. (1995), Coffeen *et al*. (2003), Jong-Wook *et al*. (2005), Nigris *et al*. 2004), Nirgude *et al*. (2008), Secue and Mombello (2008a, b), Tang *et al*. (2010) and Xu *et al*. (1999). This study presents the results of SFRA measurement work carried out on number of power transformers at various sites involving problems like shorting of winding turns, core faults and related issues, OLTC open circuit and winding displacement issues. Numerical evaluation

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techniques to compare different phase windings of the same transformer or sister units for interpreting frequency response measurement data are applied to obtain the realistic numerical parameters that can be used to critically detect the faulty condition of the transformer. The results presented in the study will help in interpreting the FRA data based on the phase comparison/sister unit comparison, even in the absence of fingerprints, in order to assess the condition of the transformer.

SFRA measuring equipment and test connections: FRA measurements were carried out using Sweep Frequency Response Analyzer (SFRA) instrument. Different types of test conditions with tested and non tested terminals are applied to obtain various frequency responses in order to detect the faulty winding and type of fault. Some work is done to compare the relative sensitivities of different connection techniques as stated in Nirgude *et al.* (2004) and CIGRE Working Group-A2.26 (2008). It is important to note that the variation in FRA results is introduced by different types of faults which are detected by certain type of measurement with greater sensitivity. Some of the common types of test connections, which are found to be very sensitive to different types of faults in a transformer, employed in SFRA measurements are explained in CIGRE Working Group-A2.26 (2008). In this study, the frequency response data obtained from the end-to-end (open) test connection, which examines each winding separately, is used to compute the various statistical parameters for further analysis.

METHODOLOGY

Application of numerical parameters: Frequency response of transformer windings has two plots, i.e., magnitude plot and phase plot. Both these plots contain information about the status of winding. Interpretation of the frequency responses on graphical display requires experts to locate a problem in the transformer. For inexperienced personnel, numbers come in handy to detect the problem based on some criterion given to them. Recent literature survey as per Bak-Jensen *et al.* (1995), Coffeen *et al.* (2003), Jong-Wook *et al.* (2005), Nigris *et al.* (2004), Nirgude *et al.* (2008), Secue and Mombello (2008a, b) and Tang *et al.* (2010) indicates various important numerical techniques for the detection of a defect. Vardeman (1993) and Montgomery and Runger (2003) gave definitions of these statistical numerical Viz., Correlation Co-efficient (CC), Mean Square Error (MSE), Absolute Sum of Logarithmic Error (ASLE), Maximum Absolute difference (MABS), Min-Max ratio (MM) and Standard Deviation (S.D.) and they are computed using Eq. (1) to (6), respectively. These parameters have been used to statistically quantify deviations between two sets of frequency responses. Much of the research is focused on magnitude plot; although the phase plot is also important. Magnitudes from the frequency response measurements are only compared to determine the statistical parameters in this study. While defining the numerical parameters, reference data (fingerprints/sister unit/phase comparison etc.) are compared with another set of measured frequency response data using SFRA for end to end (open) test condition. In all the equations given below, X(i) and Y(i) are the ith elements of reference fingerprint and measured frequency response, respectively and 'N' is the total number of samples in the frequency response in that particular frequency band.

Correlation Coefficient (CC): The correlation coefficient is a measure of linear relationship between two sets of data variables. The correlation coefficient ideal values range between +1 and -1. Correlation coefficient is defined by Eq. (1):

$$CC_{(X,Y)} = \frac{N\sum_{i=1}^{N} X(i)Y(i) - \sum_{i=1}^{N} X(i)\sum_{i=1}^{N} y(i)}{\sqrt{\left[N\sum\left[X(i)^2\right] - \left[\sum X(i)\right]^2\right]\left[N\sum\left[Y(i)^2\right] - \left[\sum Y(i)\right]^2\right]}} \qquad (1)$$

Mean Square Error (MSE): Mean square error is defined by Eq. (2). MSE measures the average of the square of the error. MSE indicates the severity of difference in two sets of data. When the two data sets are exactly equal, its ideal value is 0:

$$MSE = \frac{\sum_{i=1}^{N}\left(X(i) - Y(i)\right)^2}{N} \qquad (2)$$

Absolute Sum of Logarithmic Error (ASLE): ASLE compares the logarithmic scale and data. When two sets of data is matching and then ASLE ideal value becomes 0. ASLE is defined by Eq. (3):

$$ASLE_{(X,Y)} = \frac{\sum_{i=1}^{N}\left|20\log_{10} Y(i) - 20\log_{10} X(i)\right|}{N} \qquad (3)$$

Maximum Absolute difference (MABS): MABS is defined by Eq. (4). MABS gives absolute variations between two data sets. MABS is sensitive to small difference between data sets. MABS is almost similar to ASLE except for logarithmic data conversion:

$$MABS = \frac{\sum_{i=1}^{N}\left|Y(i) - X(i)\right|}{N} \qquad (4)$$

Min-Max ratio (MM): MM is defined by Eq. (5). MM considers only maximum and minimum values of the data. It is sensitive to peak changes of amplitude plots and its ideal value is 1:

$$MM = \frac{\sum_{i=1}^{N} \min\left(Y(i), X(i)\right)}{\sum_{i=1}^{N} \max(Y(i), X(i))} \tag{5}$$

Standard Deviation (S.D.): S.D. is defined by Eq. (6). S.D. gives measure of the dispersion of a set of data from its mean. The more spread apart the data, the higher the deviation. Standard deviation is calculated as the square root of variance. Ideally, S.D. value is 0 for a complete match between the two sets of data:

$$SD = \sqrt{\frac{\sum_{i=1}^{N} \left[\left(X(i) - X\right) - \left(Y(i) - Y\right)\right]^2}{N - 1}} \tag{6}$$

Comparison of frequency responses of different phases of the same transformer and/or comparison of frequency responses of sister units are carried out and the numerical parameters are computed considering one of the response as base frequency response in the absence of the fingerprints. However, because of the asymmetry of the core, manufacturing differences, winding length due to tap connections, measurement differences etc., different numerical parameters have to be assigned as realistic values, close to ideal, for using them for comparison purposes to diagnose the integrity of the transformer windings. It is clear that, there is no possibility of obtaining the ideal parameters even for the new transformer with measurements at two different times or by two different people using the same equipment because of measurement issues or test layout issues etc. Hence, the realistic numerical parameters in the three frequency bands are arrived from the SFRA data obtained on the healthy transformers using frequency responses of the comparison of sister units, outer winding and identical design etc. The realistic numerical parameters thus account for the winding geometry, design and measurement differences. These parameters in three frequency bands are then analyzed to identify the faulty winding, type of fault and the severity of fault in the transformer.

RESULTS AND DISCUSSION

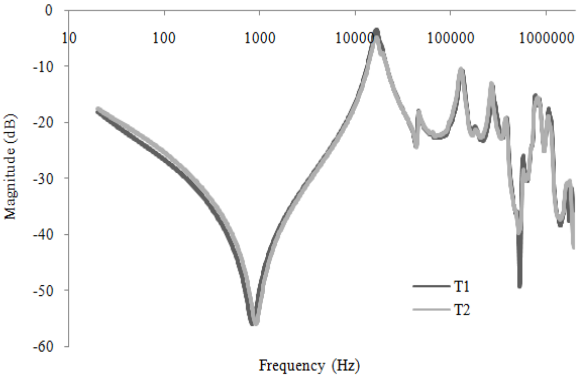

Fig. 1: Magnitude response plots for series windings of two sister units

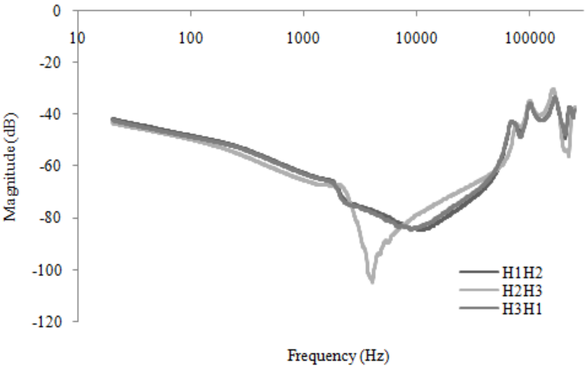

Fig. 2: Frequency responses of a three phase delta connected winding of a core type transformer

Results given in the following sub sections are based on the comparison of frequency responses of different phases of the same transformer and/or comparison of frequency responses of sister units and computation of numerical parameters between the two SFRA data sets. Numerical parameters are computed in three frequency bands-Band 1 (20Hz–10 kHz), Band 2 (10-100 kHz) and Band 3(100 kHz-1 MHz) for the two SFRA data based on the comparison sets.

Realistic numerical parameters for diagnosis:

Numerical parameters comparison for sister units: The end to end (open) LV winding frequency responses of three numbers of 13.33 MVA, 11/132 kV, Single Phase, Generator Transformers by two different manufacturers of identical design is shown in Fig. 1. It can be observed from Fig. 1 that all the frequency responses of three units closely match up to 1 MHz indicating no core or winding abnormalities. Numerical parameters obtained for the two sister units are given in Table 1. It can be seen that the numerical parameters closely match with defined ideal values. The small deviation in these parameters in all the three bands from its ideal values could be attributed to manufacturing, measurement etc., differences and these are to be accounted for while assigning tolerance limit values to identify as fault using the numerical parameters.

Numerical parameters comparison of outer windings: Figure 2 gives the frequency response of the high voltage windings of a healthy 1000

Table 1: Numerical parameters comparison for two sister units

Frequency range	20 Hz-10 kHz	10-100 kHz	100 kHz-1 MHz
Numerical parameter	T2-T1	T2-T1	T2-T1
CC	0.99910	0.9985	0.9920
MSE	0.01010	0.0200	0.0230
ASLE	0.05680	0.0003	0.0989
MABS	0.00346	0.0012	0.1008
MM	0.99950	0.9981	0.9987
S.D.	0.69870	0.9991	0.9988

Table 2: Numerical parameters comparison of a delta connected outer windings of a transformer

	Numerical parameters		
Numerical technique	Band 1	Band 2	Band 3
CC	0.999	0.993	0.980
MSE	0.700	0.800	2.600
ASLE	0.150	0.400	0.800
MABS	0.700	0.800	1.800
MM	1.010	1.020	1.080
S.D.	8	10	12

Table 3: Critical realistic numerical parameters to diagnose integrity of transformer

	Critical realistic parameters		
Numerical techniques	Band 1	Band 2	Band 3
CC	0.998	0.991	0.975
MSE	0.800	0.900	3
ASLE	0.150	0.400	0.800
MABS	0.700	0.800	1.800
MM	1.010	1.020	1.080
S.D.	8	10	12

11kV/433V, Delta/Star, core type, three phase transformer. It can be observed from the Fig. 2 that the frequency responses of all the three windings have identical peaks and valleys beyond 40 kHz. For frequencies below 40 kHz, the outer winding responses match closely and the middle limb response deviates with respect to the outer limb responses because of the magnetic paths/structure of outer limbs being identical as compared to the middle limb. In order to obtain the realistic values, for the comparison of numerical parameters that can be used in diagnosing transformer faults, numerical parameters by comparison of the two outer limbs as given in Table 2 are obtained for all the three frequency bands. It can be observed that the deviation of the various parameters is much larger when compared with the case of sister units. MSE and MABS parameters in band 1 show considerably large deviation when compared to ideal values where as MM and S.D. show marginal deviation. However, ASLE and CC parameters do not indicate significant deviations when compared with sister unit comparison of parameters. Similarly in Band 2, all parameters are marginally high and band 3 parameters have higher deviation from the ideal values. The realistic values for comparison of numerical parameters computed based on the outer winding responses show much wider tolerance with respect to the ideal values.

Realistic numerical parameters for diagnosing transformer faults: The case studies presented in the above sections and analysis of many more transformers gives the spread in realistic values of the different numerical parameters based on the comparison of parameters for sister units, outer windings and similar design windings in the three frequency bands. The spread in the values of the various numerical parameters obtained from the analysis of the results of the study, for the transformer to be in a healthy state, is given in Table 3. Any numerical parametric values obtained exceeding the critical values given in this Table can be considered as an indication of the fault in the transformer winding structure. The severity of the winding fault and type of fault can also be analyzed by interpreting the various parameters in different frequency bands.

Diagnosing transformer winding faults using realistic numerical parameters:

Case A: winding deformation and shorting of turns: Figure 3 shows the FRA response of the HV series windings of a 220/132/33 kV, 160 MVA, 3 phase, Ynya0d11, Shell type, Auto Transformer. It can be observed from Fig. 3 that ‘C’ (H3X3) phase winding responses of series winding deviate largely at low frequencies up to about 40 kHz from the other two phase responses clearly indicating the faulty ‘C’ phase. The lowering of inductance due to shorting of turns resulted in variation in frequency response at low frequencies. Table 4 gives different numerical parameters computed in three different frequency bands. It can be observed that SD, ASLE, MABS and MM parameters between H2X2-H1X1 are much lower than H2X2-H3X3 in band 1 and band 2 and less than realistic values given in Table 3 indicating healthiness of H2X2 and H1X1. It can also be observed that ASLE and S.D. parameters between H2X2-H3X3 are much higher in band 1 and 2 and correspondingly CC is much lower when compared with realistic values given in Table 3 indicating H3X3 as faulty phase winding. It can be concluded that for winding deformation and shorted turns, band 1 parameters except MM show considerably large deviation i.e., more than ten times when compared to critical values. Similarly in Band 2, all parameters are marginally high and band 3 parameters are not affected. Thus, for these type of faults, significant changes in all the parameters are observed in band 1and extended in to band 2.

Case B: OLTC open circuit problem: A 100 MVA, 220/132/33 kV, Yy0Yd11, 50 Hz, 3 phase, Auto Transformer is investigated with frequency response measurements. Figure 4 shows end to end (open) frequency response measurements of H3X0-‘B’ phase winding at different tap positions. Table 5 gives the numerical parameters corresponding to Fig. 4 considering minimum tap position as reference. It can

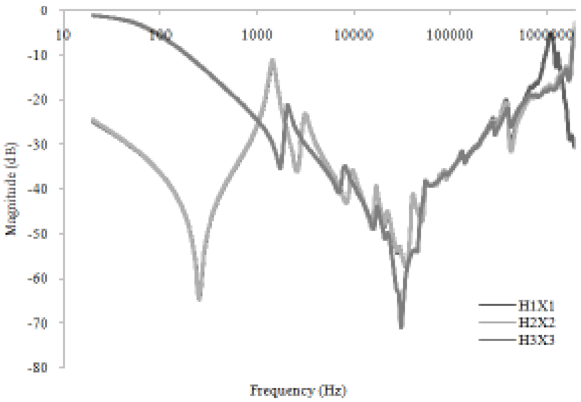

Fig. 3: Magnitude response plots for HV series windings

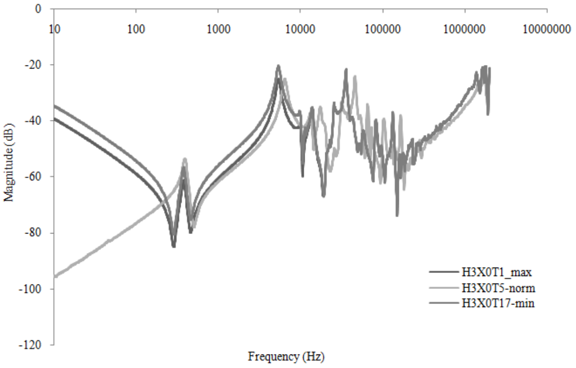

Fig. 4: Frequency response measurements of 'B' phase winding at different tap position

Table 4: Numerical parameters that corresponding to Fig. 3

	Frequency range					
	20 Hz-10 kHz		10-100 kHz		100 kHz-1 MHz	
Numerical parameter	H2X2-H1X1	H2X2-H3X3	H2X2-H1X1	H2X2-H3X3	H2X2-H1X1	H2X2-H3X3
CC	0.9997	0.1612	0.9930	0.8999	0.9838	0.9579
MSE	0.0538	548.2314	0.0505	28.0610	4.6294	2.6652
ASLE	0.0494	9.8598	0.0270	0.6216	0.6192	0.3382
MABS	0.1720	19.2433	0.1395	3.5933	1.2641	0.9503
MM	1.0051	2.1762	1.0032	1.0816	1.0505	1.0371
S.D.	2.4751	188.3200	0.7022	162.9000	17.8620	12.0830

Table 5: Parameters corresponding to frequency response measurements of 'B' phase winding at different tap position

	Frequency range					
	20 Hz-10 kHz		10-100 kHz		100 kHz-1 MHz	
Numerical parameter	Min.-normal	Min.-max.	Min.-normal	Min.-max.	Min.-normal	Min.-max.
CC	0.6956	0.9890	0.6483	0.5597	0.9440	0.9527
MSE	21.0224	9.9144	76.5560	106.6080	4.7728	3.9553
ASLE	2.2559	2.6886	1.1531	1.3136	0.2657	0.2065
MABS	4.1243	3.0131	6.4168	6.9117	1.4968	1.0868
MM	1.2368	1.2075	1.1508	1.1719	1.0307	1.0222
S.D.	38.1020	25.0670	31.6010	30.4985	17.6860	19.7200

Min.: Minimum; Max.: Maximum

Table 6: Parameters corresponding to end to end (open) responses of two sister units highlighting core related issue

Frequency range	20 Hz-10 kHz	10-100 kHz	100 kHz-1 MHz
Statistical parameter	H1H0-UNIT1H2H0-UNIT2	H1H0-UNIT1H2H0-UNIT2	H1H0-UNIT1H2H0-UNIT2
CC	0.8758	0.9382	0.94490
MSE	35.5241	1.5388	1.42600
ASLE	1.8032	0.5462	0.58380
MABS	6.8951	1.6788	1.48090
MM	1.9690	1.0616	1.12910
S.D.	48.5217	5.1036	3.36205

Table 7: Parameters corresponding to magnitude response curves of LV windings of 240 MVA, 236/15.75 kV generator transformer

	Frequency range					
	20 Hz-10 kHz		10-100 kHz		100 kHz-1 MHz	
Numerical parameter	X2X0-X1X0	X2X0-X3X0	X2X0-X1X0	X2X0-X3X0	X2X0-X1X0	X2X0-X3X0
CC	0.9523	0.9628	0.9962	0.9991	0.9670	0.9249
MSE	1.0282	0.4767	0.5820	0.2231	3.5103	1.7609
ASLE	0.4910	0.4210	0.0170	0.0300	0.5650	1.2180
MABS	0.7761	0.5910	0.5315	0.2910	1.2869	1.7797
MM	1.0110	1.0320	1.0546	1.0360	1.0324	1.0560
S.D.	9.3900	9.3200	3.7900	3.7900	12.2000	13.3900

be observed from Fig. 4 that in a particular tap position the frequency response begins with very high attenuation (more than 90 dB) indicating open circuit.

The frequency response with minimum winding included appeared to have normal FRA curve. This can also be correlated with abnormal values in band 1 and 2

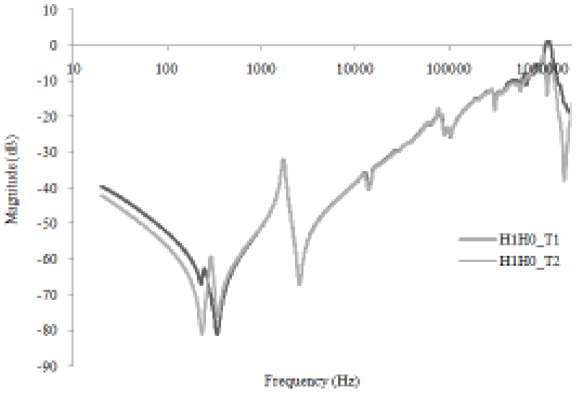

Fig. 5: Frequency responses of two sister units highlighting core related issue

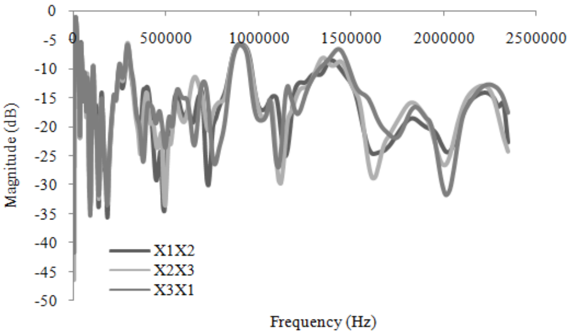

Fig. 6: Magnitude response curves of LV windings of 240 MVA, 236/15.75 kV generator transformer

parameters, when compared with the realistic values given in Table 3, as against the normal deviation expected due to position of the tap switch and thus can be confirmed to be faulty and similar to the fault with open circuit of the winding.

Case C: core related problem: Two numbers of 83.3 MVA, 220/92.94 kV, YNyn0, 50 Hz, 3 Phase, Regulating Transformers considered to be sister units exhibited very different frequency responses below 1 kHz. Comparison of frequency responses of HV and LV among different phases of unit 1 indicated large deviations at frequencies below 1 kHz whereas it was perfect match for unit-2. It was observed that there could be a core residual magnetism problem with unit 1. Figure 5 shows the frequency response comparison of unit-1 with unit-2 for 'A' (H1H0) phase, which also indicates large deviations in low frequency. Otherwise, the two windings identical and are sister units with frequency responses perfectly matching even up to 2 MHz. Table 6 gives the numerical parameters corresponding to Fig. 5. It can be observed that band 2 and band 3 parameters are well within the realistic critical parameters given in Table 3. It can also be observed that ASLE and CC parameters in band 1 are very much away from the normal values seen in earlier cases indicating core related problem. Similarly, MSE and MABS parameters are also predominantly high in band 1 compared to band 2 and 3 up to 1 MHz suggesting core related issue with transformer.

Case D: transformer winding movements/ displacements: Figure 6 shows frequency response end to end (open) measurement curves of the three LV windings of a 240 MVA, 236/15.75 kV, Yd1, 50 Hz, 3 phase, Generator Transformer. Table 7 gives the numerical parameters corresponding to Fig. 6. Comparison of the three responses with each other show that they deviate largely from 300 kHz to 1 MHz. It can be observed that all the numerical parameters in band 3 are considerably higher as compared to earlier cases. Band 3 parameters in end to end (open) measurements considerably deviate from the critical values as given in Table 3 suggesting severe winding displacements.

CONCLUSION

Number of case studies involving comparison of frequency responses among different phases of the same transformer and with sister units were carried out to obtain the SFRA data. Various numerical parameters were computed and the spread in the values were analyzed to obtain the realistic numerical parameters as given in Table 3 to assess the condition of the transformer. SFRA data obtained on the number of transformers were analyzed using the numerical parameters computed in the three frequency bands for different types of problems. It was observed that for winding deformation and shorted turns, band 1 parameters show considerably large deviation when compared to critical values given in Table 3. For the open circuit/ OLTC contact open case, abnormal change in band 1 and 2 parameters, when compared with the realistic values given in Table 3, as against the normal deviation due to position of the tap switch were observed. It can also be observed that ASLE and CC parameters in band 1 are very much away from the normal values given in Table 3 for core related problem. It was also observed that, for winding movement/displacements, band 3 numerical parameters are considerably higher than the numerical parameters given in Table 3. It is thus observed that, exceeding the numerical parameters given by Table 3 is an indication of deformation/displacement in the transformer by considerable degree and necessary action has to be taken. The numerical parameters given in Table 3 can thus be used to set the tolerance limits after accounting for manufacturing differences and asymmetry of the winding to diagnose the condition of the transformer. It can also be used to discriminate the faulty winding and type of fault based on the interpretation guidelines presented on the variation of these numerical parameters in different frequency bands. However, it is felt that interpretation done using a single parameter may be lead to an underestimation or exaggeration of isolation deviations present in the data. Therefore, it is preferred to use a set of numerical parameters in a complementary way to get diagnostic conclusion.

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REFERENCES

Al-Khayat, N. and L. Haydock, 1995. Swept frequency response tests for condition monitoring of power transformers. Proceeding of the Electrical/ Electronics Insulation Conference, Rosemount, IL, pp: 45-47.

Bak-Jensen, J., B. Bak and S.D. Mikkelsen, 1995. Detection of age aging phenomenon in transformers by transfer functions. IEEE T. Power Deliver., 10(1): 308-314.

Christian, J. and K. Feser, 2004.Procedures for detecting winding displacements in power transformers by transfer function method. IEEE T. Power Deliver., 19(1): 214-220.

CIGRE SC12, 1999. Transformer Colloquium. Summary on Behalf of Study Committee 12, Budapest, June 14-16.

CIGRE Working Group-A2.26, 2008. Document on Mechanical-Condition Assessment of Transformer Windings Using Frequency Response Analysis (FRA). Retrieved from: http://www.ijitee.org/attachments/File/v1i5/E0299091512.pdf.

Coffeen, L., J. Britton and J. Rickmann, 2003. A new technique to detect winding displacements in power transformers using frequency response analysis. Proceeding of the Power Tech Conference, Paper BPT03-294, Bologna, Italy.

Feser, K., J. Christian, C. Neumann, T. Leiberfried, A. Kachler, U. Sundermann and M. Loppaacher, 2000. The transfer function method for detection of winding movements on power transformers after transport, short circuit or 30 years of service.CIGRE, Paris, 12/33-04.

IEC 60076-5, 2006. Power Transformers-Part-5-Ability to withstand short circuit. PKN, Warszawa.

Jong-Wook, K., P. Byung Koo, J. Seung, K. Sang Woo and G. Poo, 2005. Fault diagnosis of a power transformer using an improved frequency-response analysis. IEEE T. Power Deliver., 20(1): 169-178.

Lapworth, J. and T. McGrail, 1999. Transformer winding movement detection by frequency response analysis. Proceeding of the 66th Annual International Conference of Doble Clients. Boston, USA.

Leibfried, T. and K. Feser, 1999. Monitoring of power transformers using the transfer function method. IEEE T. Power Deliver., 14(4): 1333-1341.

Montgomery, D.C. and G.C. Runger, 2003. Applied Statistics and Probability for Engineers. 3rd Edn., John Wiley and Sons Inc., NY.

Nigris, M. De, R. Passaglia, R. Berti, L. Bergonzi and R. Maggi, 2004. Applications of Modern Techniques for the Condition Assessment of Power Transformers. Cigré Session 2004, Paper No. A2-207.

Nirgude, P.M., B. Gunasekaran, A.D. Rajkumar and B.P. Singh, 2004. Sensitivity of frequency responses for detection of winding deformations in transformers. Proceeding of the 13th National Power System Conference (NPSC). IIT Chennai, India.

Nirgude, P.M., D. Ashokraju, A.D. Rajkumar and B.P. Singh, 2008. Application of numerical evaluation techniques for interpreting frequency response measurements in power transformers. IET Sci. Meas. Technol., 2(5): 275-285.

Ryder, S.A., 2002. Methods for comparing frequency response analysis measurements. Proceeding of the of IEEE International Symposium on Electrical Insulation, pp: 187-190.

Secue, J. and E. Mombello, 2008a. New methodology for diagnostics faults in power transformer windings through the sweep frequency analysis. Proceeding of the IEEE/PES Conference and Exposition: Transmission and Distribution. Latin America.

Secue, J. and E. Mombello, 2008b. Sweep Frequency Response Analysis (SFRA) for the assessment of winding displacement and deformation in power transformer. Electr. Pow. Syst. Res., 78: 1119-1128.

Tang, W.H., A. Shintemirov and Q.H. Wu, 2010. Detection of minor winding deformation fault in high frequency range for power transformer. Proceeding of the IEEE PES General Meeting. Minneapolis, U.S.A.

Vardeman, V.B., 1993. Statistics for Engineering Problem Solving. PWS Pub. Co., Boston.

Xu, D.K., C.Z. Fu and Y.M. Li, 1999. Application of artificial neural network to the detection of the transformer winding deformation. Proceeding of the 11th International Symposium on High Voltage Engineering (Conf. Publ. No. 467). London, U.K., 5: 220-223.