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Detection of Near Failure Winding due to Deformation in 33/11kV Power Transformer by using Low Voltage Impulse (LVI) Test Method and Validated through Untanking

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Abstract**—**Power transformer consists of components which are under consistent thermal and electrical stresses. The major component which degrades under these stresses is the paper insulation of the power transformer. At site, lightning impulses and cable faults may cause the winding deformation. In addition, the winding may deform due to impact during transportation. A deformed winding will excite more stress to its insulating paper thus will degrade it. Insulation degradation will shorten the life-span of the transformer. Currently there are two methods of detecting the winding deformation which are Sweep Frequency Response Analysis (SFRA) and Low Voltage Impulse Test (LVI). The latter injects current pulses to the winding and capture the admittance plot. In this paper, a transformer which experienced overheating and arcing was identified, and both SFRA and LVI were performed. Next, the transformer was brought to the factory for untanking. The untanking results revealed that the LVI is more accurate than the SFRA method for this case study.

Keywords**—**Winding Deformation, Arcing, Dissolved Gas Analysis, Sweep Frequency Response Analysis, Low Voltage Impulse Method

I. Introduction

POWER transformers are essential components of power systems and are often the most valuable asset in any substation. The reliability of the power system depends on whether the transformer used in the power electrical substations is trouble-free. At site, lightning impulses and cable faults may cause massive electromagnetic forces to the winding, which may cause it to deform. A deformed winding will cause damage on the insulation and change the turn ratios of the transformer. In addition, the winding can be damaged during the transportation of the transformer from the factory to site. This will eventually reduce the reliability of the transformer. An unattended winding problem will lead to transformer failure. The failure of transformer can cause interruption of power supply and result in loss of revenue to both the power utilities and to the society. Therefore, the reliability of power transformers is important for a safe and economic operation of transmission electrical networks. Unexpected failure is always a major disturbance in the system operation, resulting in unscheduled outages with power delivery problems. If the failure mode involves a major internal arcing, the tank may rupture with resulting fire and collateral damages. Replacement by a spare unit can usually be completed within a week but replacement with a new unit can take more than a year.

There are two ways of detecting winding deformation in the transformer which are Low Voltage Impulse Test (LVI) and Sweep Frequency Response Analysis (SFRA). Sweep Frequency Response Analysis (SFRA) is the ratio of a steady sinusoidal output from a test object subject to a steady sinusoidal input. Sweeping through the frequency range of interest gives rise to the response in SFRA to distinguish it from impulse methods where the response is estimated rather than measured. On the other hand, the low voltage impulse response and analysis (LVI) method of detecting transformer winding movement is based on taking a “signature” of the winding.

In this project, the LVI test was performed on 33/11kV, 7.5MVA transformer together with the SFRA test. This transformer was reported experiencing arcing and overheating problem. The LVI test utilized the Spectral Density Estimate (SDE) building blocks to formulate the transfer function. The test results of both measurement techniques were compared with the transformer’s history data and the transformer was untanked to validate the measurement. The decision for untanking was done due the conflicting results of both tests where the SFRA detected slight deformation, while the LVI measurement has detected high percentage of deformation.

II. Concept of Low Voltage Impulse (LVI) Test

Low Voltage Impulse (LVI) method has been used to detect the winding deformation in power transformer for several years [1, 2]. In this paper, a new technique, termed Objective Winding Asymmetry (OWA), which is an extension of the low voltage impulse method, utilizing Spectral Density Estimate (SDE) building blocks to formulate the transfer function.

1. Estimation of the Transfer Function

The basics of transfer function development is covered in [3,4,5]. The equipment used in the project was Power Transformer Frequency Response Analyser FRA-100, manufactured by Phenix. The equipment came with its software utilizing the Spectral Density Estimates using the optimum transfer function / least-squares models.

Let say, the spectral densities acquired from the input and output pulses are [3]:

$$G_{xx} = X(f)^* X(f) \quad (1)$$

$$G_{yy} = Y(f)^* Y(f) \quad (2)$$

$$G_{xy} = X(f)^* Y(f) \quad (3)$$

where
G_{xx} is the auto-spectral density of x(t)
G_{yy} is the auto-spectral density of y(t)
G_{xy} is the cross-spectral density of x(t) with y(t)

Asterisk (*) denotes complex conjugate

The transfer function *H(f)* and coherence function, $\gamma^2_{xy}(f)$, were defined by using the above-calculated functions. The frequency response function which best fits the application of the OWA FRA technique is [3]:

$$H(f) = \frac{G_{xy}(f)}{G_{xx}(f)} \quad (4)$$

$$\gamma^2{}_{xy}(f) = \frac{|G_{xy}(f)|^2}{G_{xx}(f)G_{yy}(f)} \quad (5)$$

It has been mentioned in [3] that the data in non-repetitive in nature. So it is necessary to perform 5 to 10 averages in the frequency domain of the SDEs given above. This will refine the output of *H(f).*

2. Comparison of the Transfer Function

Extensive research has been carried out to evaluate the difference of the transfer function to a single condition number or Weighted Normalized Difference (WND) [4, 5, 8]. The WND is calculated as follows:

The key points of the WND calculation are as follows:

- The difference between H1(f) & H2(f) is computed at each frequency. H1 and H2 are the winding phases.
- Each data point is normalized and weighted according to the error function at the particular frequency.
- The WND is calculated as the constant times the average of the weighted values [8].

By using the WND, each set of winding will be assigned to its unique number. This number can be used as a benchmark for that particular winding. Any future deformation can be detected if the WND number deviates.

Another alternative is by using the Objective Winding Asymmetry (OWA). In the OWA analysis, the transfer function are compared from each high voltage winding to the other two high voltage windings on the same transformer, or from each low voltage winding to the other two low voltage windings on the same transformer. In addition, the high voltage winding to low voltage winding transfer functions (coupling comparisons) can also be made. The OWA results obtained will benchmark that the coupling between the high voltage and low voltage windings.

The OWA is defined as the average of the two highest WND values divided by the lowest WND values. This number is converted to a percent difference by subtracting 1 from the result, and multiplying by 100 [8]. The formula for OWA calculation is shown in (6) [8]:

$$OWA(\%) = \left(\frac{(WND(\max_1) + WND(\max_2))/2}{WND(\min)} - 1 \right) x \;\; 100 \quad (6)$$

The conditions of the windings are drawn based on the calculated OWA. The conditions developed are Good (OWA<100%), Marginal (101 %< OWA<150%) and Bad (OWA>150%).

III. Field Tests by Using SFRA and LVI

The transformer identified in this project (Fig. 1) was reported experiencing arcing and overheating problem. The details of the transformer are shown in Table 1. The SFRA and LVI test have been done on the transformer to assess its winding integrity. In general, the LVI test is 3 times faster than the SFRA testing. Normally, the LVI test will require around 60 seconds per phase.

TABLE I
TRANSFORMER DETAILS

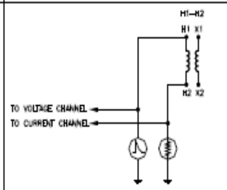
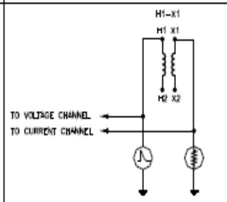
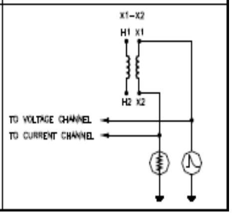
Voltage	33/11kV
Capacity	7.5MVA
Impedance	7.78%
No. of Taps	16
Cooling System	Oil Natural Air Forced
Phase	3
Vector Group	Dyn11

Fig. 1: Transformer under study

A. LVI Test [8].

The high voltage and the low voltage side are defined as H and X respectively. The connections for the test are made based on Table 2.

TABLE II
LVI TEST EQUIPMENT CONNECTIONS

Test Connection Number See Note (1)	Frequency Response Measured	Voltage Lead Bushing Designation	Current Shunt Bushing Designation	Connection Diagram
1	H Winding Response	H1	H2	
2	H to X Coupling Response	H1	X1	
3	X Winding Response	X1	X2	

B. SFRA Test.

The SFRA testing is done by injecting a sinusoidal 5V voltage with a frequency sweep across each winding. The frequency ranges from 0-5MHz. The test setup is shown in Fig. 2. The response of V_{out}/V_{in} is calculated and plotted. The transfer functions are compared with the other phases or SFRA response from sister unit. The deviation of the winding is quantified by Cross Correlation Index (CCI).

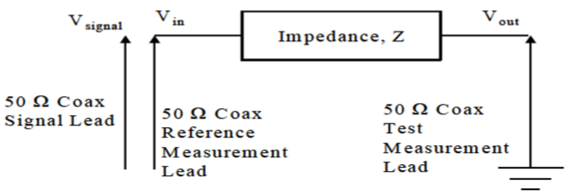


Fig. 2 Test setup for SFRA testing

IV. RESULTS AND DISCUSSION

The LVI test was done on the H and X phases. The transfer functions for the H phases shown in Fig. 3 and Fig. 4.

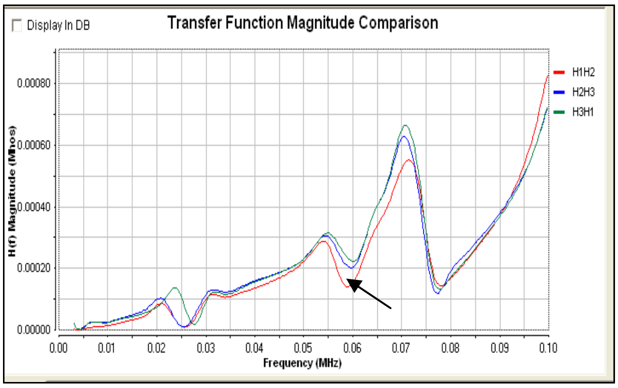


Fig. 3 Transfer function magnitude comparison (0.1 MHz range)

Fig. 4 shows the transfer function up to 0.1MHz range. It can be observed that the R-Y (H1-H2) winding's transfer function is slightly deviated from the other windings. The WND values are given in Table 3 with the asymmetry percentages. The asymmetry percentages were calculated based on (6). The asymmetry percentage is assigned to the winding which has the highest WND [8].

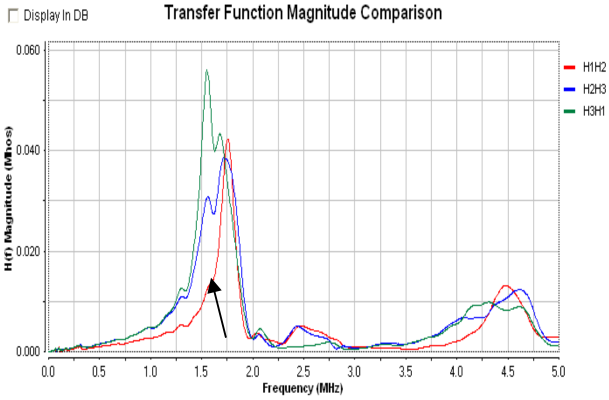


Fig. 4 Transfer function magnitude comparison (5MHz range)

TABLE III
WND VALUES AND ASYMMETRY CALCULATION

Winding	WND	Asymmetry(%)
H1-H2	216.9	**138.7**
H2-H3	187.5	-
H3-H1	84.7	-
H1-X0	158.7	-
H2-X0	272.9	47
H3-X0	193.7	-
X1-X0	315.3	103.4
X2-X0	183.7	-
X3-X0	432	-

It can be observed that the R-Y (H1-H2) winding has the highest asymmetry compared to the other windings. This can be an indication that the winding has deformed seriously [9]. However, the asymmetry percentages on the X phases and H-X coupling are comparatively low.

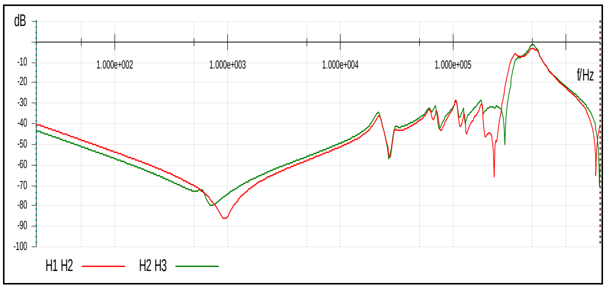


Fig. 5 SFRA results for R-Y and Y-B windings (HV)

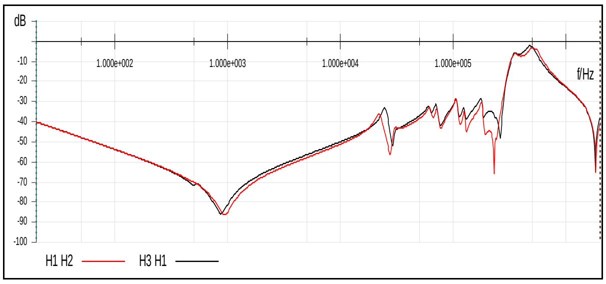


Fig. 6 SFRA results for R-Yand B-Y windings (HV)

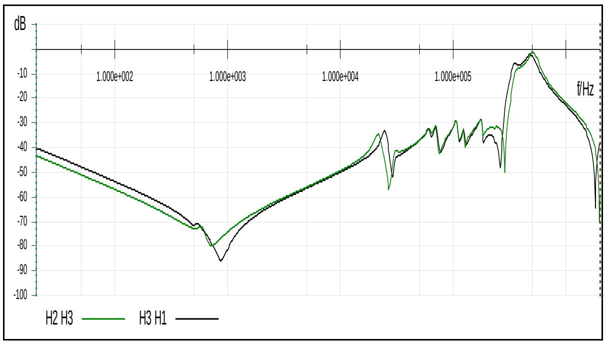


Fig. 7 SFRA results for Y-B and B-R windings (HV)

In order to compare with the LVI findings, SFRA test was done. Fig. 5, Fig. 6 and Fig. 7 show the SFRA results for R-Y, R-B and Y-B windings respectively. The Cross Correlation Index (CCI) was calculated for low, medium and high frequency (Table 4). It can be observed that the R-Y winding has the highest CCI at the low frequency range. The results were compared with its limits is Table 5. The limits and the calculation algorithm were obtained from The Electric Power Industry Standard of China (DL/T 911-2004) and utility best practices. From the comparison, it has been diagnosed the R-Y winding had deformed slightly.

TABLE IV
CROSS CORRELATION INDEX

	Cross Correlation Index, measured		
Comparison between	**Low Freq**	**Med Freq**	**High Freq**
R - Y	**1.75**	**0.92**	4.46
Y - B	1.1	1.11	3.41
R - B	1.3	1.39	3.67

TABLE V
LIMITS FOR SFRA CROSS CORRELATION INDEX.

Diagnosis	Limits
No deviation	*CCI at low freq zone > 2.0* *CCI at mid freq zone > 1.0* *CCI at high freq zone > 0.6*
Minor deviation	*1.0<CCI at low freq zone <2.0* *0.6<CCI at mid freq zone < 1.0*
Moderate deviation	*0.6<CCI at low freq zone <1.0* *CCI at mid freq zone < 0.6*
Significant deviation	*CCI at low freq zone <0.6*

Next, the transformer was untanked in the factory. The internal inspection revealed that the R-Y winding on the HV side has some deformations. The pressboard looked wavy (Fig. 8(a)) and damaged due to the coaxial force (Fig. 8(b)).

Fig. 8(a): Wavy pressboard due to coaxial force

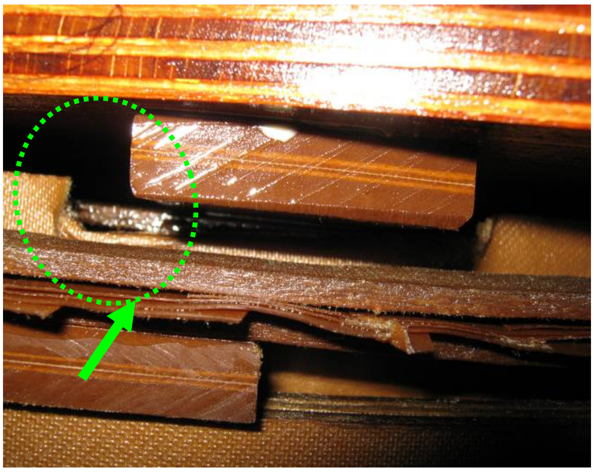


Fig. 8(b): Damaged pressboard due to coaxial force

The top support of the winding structure was removed and it has been observes that the whole pressboard was uneven (Fig. 9). In addition, the transformer had also experienced axial forces where the turn's alignments become uneven too (Fig. 10).

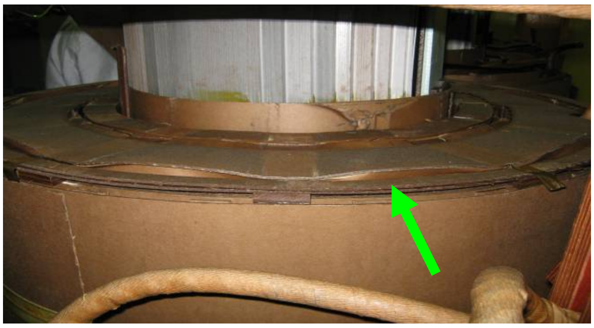


Fig. 9: Wavy pressboard

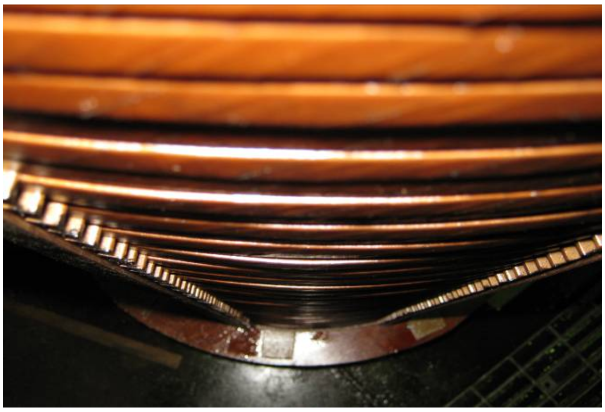


Fig. 10: Uneven turn's alignment

Next, the bottom part of the winding was inspected. It has been found that some traces of overheating and arcing activities. Some copper chips were found on the bottom supporting wood (Fig. 11). The cooper chips were former because of arcing activity inside the winding.

Fig. 11: Eroded copper chips

The regulating winding was removed and an arcing spot was detected (Fig. 12). It can be concluded that the winding has deformed first and excited additional force to the insulation. Later, the insulation failed and caused overheating and arcing.

Fig. 12: Arrow shows the arcing spot

Based on the untanking findings, the winding deformations are serious in this transformer. The seriousness of the deformation has been detected accurately by the LVI test methods whereas this was not shown as such by the SFA test. In addition, the new OWA methods using SDE's is able to overcome the shortcomings of using higher frequency in detecting winding movement and has a better sensitivity [4]. Therefore, it can be concluded that LVI test is more accurate for this transformer.A percentage asymmetry more than 130% is quite reasonable to be set as the threshold for serious deformation. This is because the transformer was operating at site before it was untanked in the factory.

V. Conclusion

The findings obtained from LVI and SFRA test has been validated through untanking. The seriousness of the winding deformation has been revealed by the LVI methods. The untanking results revealed that the LVI is more accurate than the SFRA method**.** In addition, the LVI test can be used to complement the SFRA test.

It can be concluded based on the untanking results that a percentage asymmetry of more than 130% can be considered as serious winding deformation for the in-service transformers of the same type.

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