Failure Analysis of Power Transformer Based on Transformer Turn Ratio Test and SFRA

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Abstract. A power transformer is one of the most key components of energy transmission and distribution in an electric power system. Inter-turn disturbances or short circuit faults may occur because of insulation degradation between one or more successive turns of the windings. If the fault is not detected early, it may spread to the nearest winding turn and causes permanent damage to the winding. Therefore, it is necessary to detect inter-turn faults to prevent catastrophic failure of the transformer. In this study, failure analysis of a transformer that approaching the catastrophic stage is conducted using sweep frequency response analysis (SFRA) and transformer turns ratio (TTR) testing methods. Correlation between SFRA & TTR tests is analyzed. TTR test before rewinding is > 0.5%, while after rewinding is < 0.5%. 400 VAC voltage is applied, and the output voltage is measured. SFRA and TTR results show that there is a linear correlation for all phases. It can be concluded in this study that the TTR test can be used to detect transformer failure.

1. Introduction

A power transformer is one of the most important components of energy transmission and distribution in a reliable electric power system. It may be subjected to enormous hazards during operation. Any faults occurred in the transformer will cause interference with the electrical power supply [1]. One of the most common causes of interference is the internal winding fault in the transformer. A short circuit of the transformer windings will cause a load of fault current in the short-circuit winding [2,3]. However, changes in the current transformer terminals will be minimal due to the high transformation ratio between the whole winding and the short-circuited turn [4].

Sweep frequency response analysis (SFRA) is a tool for determining the mechanical integrity of core, winding, and clamping frameworks within power transformers by analyzing their electrical transfer functions over a broad frequency spectrum [5,6]. SFRA can be used to detect the mechanical movements of the integrated components inside transformers, such as the coil, core, and others [7,8]. Mechanical changes of the coil may result in transformer failure due to damaged insulation, which causes a short circuit in the transformer. Transformers are designed to last for a considerable long operation time, but disturbances and mechanical changes will reduce the transformer operation life span [9].

Transformer turns ratio (TTR) is the division of the number of turns in the primary winding by the number of turns in the secondary winding of a transformer. This calculation method analyzes the condition of the primary or secondary windings of the three phases (R, S, and T). It will determine whether they are balanced or short, related to the transformer's output voltage [10]. Complexity in the measured versus nameplate ratio occurs with most of the three-phase power transformers. This is due to the requirement of multipliers, such as √3, to match the measured ratio to the nameplate ratio [11].

TTR test validates the transformer's ratio accuracy. TTR determines the right ratio of both primary and secondary turns. It may also help detect problems related to tap-changer performance, shorted turns, faulty winding connections, and open windings. Due to the significant benefits a TTR test can achieve, frequent monitoring and testing of the transformer are essential [11]. Quality verification, design specifications validation, potential damage evaluation, and the establishment of transformer condition and condition trends are some of the reasons and advantages of a transformer's ratio measurements. The accuracy of the transformer can be determined by having the TTR test conducted regularly. The inconsistent ratio results from the expected target values reflect a high likelihood of error or defect. Untargeted results may indicate a winding defect or a tap-changer.

It is crucial to determine the best type of transformer test set before beginning the process. There are various styles and test connections on the different types of TTR test sets. However, all test sets consist of at least two high leads and two low leads. TTR test set styles include single-phase and three-phase models. Single-phase models are generally applied in the testing of single-phase power with low ratios. It is designed to analyze the turn ratio and exciting current windings in power transformers. It can also be applied in a three-phased transformers test, but each phase must be tested separately. Three-phase models can test high ratios, unlike the single-phase models. The models are designed to evaluate the turn ratio of power, instrument, and distribution transformers in a manufacturing setting.

Several steps must be understood before conducting this measurement test, including the vector group and the TTR calculation formulas.

2. Transformer Turn Ratio (TTR) Test Measurement

2.1. Vector Group

On transformers' nameplate, vector combination diagrams such as Dyn-5, and YNd-5, are displayed. The vector group is related to the phase shift between the High-Voltage (HV) and Low-Voltage (LV) sides. Figure 1 shows an example of the Dyn-5 vector group.

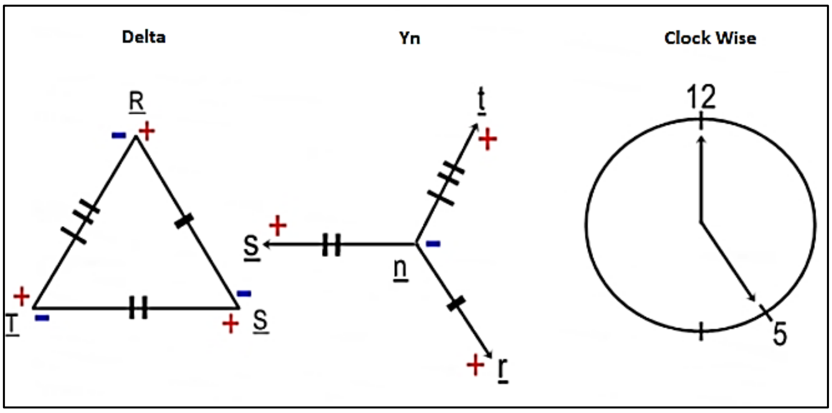


Figure 1. Dyn-5 vector group.

For the Dyn-5 vector group, the letter D (Delta) indicates the primary winding and the transformer connected to Delta. The letter Yn (Wye) shows the secondary winding and the transformer connecting Wye with a star point (N), issued or can be called a 3 phase 4 wire. The number 5 shows the first phase or phase (r) in the secondary winding, which is pointed at the 5 o'clock direction. There is a 120-degree shift between the first phase of the primary winding (R) and the second phase of the secondary winding (r). To simplify, in the vector group, the upper case is identical to the primary winding, the lowercase to the secondary winding, and the last digit to the clock position. Figure 2 shows an example of a transformer connection with the Dyn-5 group vector.

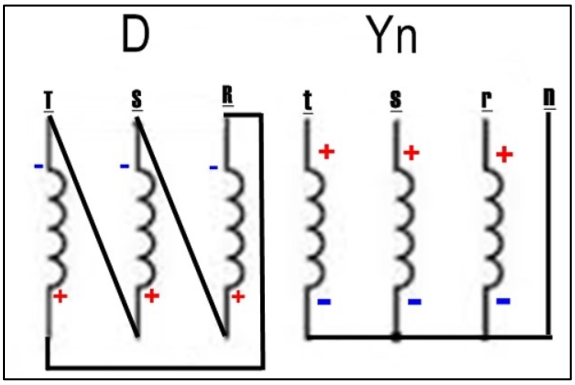


Figure 2. Transformer connection with the Dyn-5 group vector.

2.2. TTR Calculation Formula Based on Vector Group

Table 1. Transformer Nameplate

Data	Value
Rated Power	1250/1600 kVA
Frequency	50 Hz
Phases	3 Phase
Volt HV	6300 V
Volt LV	400 V
Ampere HV	114.55/146.63 A
Ampere LV	1804.22/2309.40 A

Table 1 shows the details from the nameplate of the transformer investigated in this study. It is stated that the transformer has a primary voltage (Vp) of 6,300 V and a secondary voltage (Vs) of 400 V. TTR calculation (1) using the Dyn formula for normal operation (6,300 V / 400 V) is:

$$A = \frac{Vp}{\left(\frac{Vs}{\sqrt{3}}\right)} = \frac{6{,}300}{\left(\frac{400}{\sqrt{3}}\right)} = 27.27 \quad (1)$$

The use of a voltage of 400V is highly recommended to analyze the TTR test method and for safety purposes during testing. To analyze the turn ratio test method and pay attention to safety during testing, the use of a voltage of 400V is highly recommended. A 400V rated supply is easy to obtain. Equation (2) shows the calculation of Vs when Vp is 400 V, and A is 27.27, where A is the transformation rate, Vp is the primary voltage, and Vs is the secondary voltage.

$$Vs = \frac{Vp}{A}\sqrt{3} = \frac{400}{27.27}\sqrt{3} = 25.4\,V \tag{2}$$

The TTR measurement results are then compared with the results of tolerance calculations, as shown in Table 2 and Table 3.

Table 2. TTR before rewinding

Rated Voltage		Calculated Ratio	Measured Ratio & Deviation (%)					
HV (L-L) Delta	LV (L-N) Star		R-phase	Dev. (%)	S-phase	Dev. (%)	T-phase	Dev. (%)
6300	400	27.28	6.009	77.97	27.273	0.02	2.432	91.08

Table 3. TTR after rewinding

Tap	Test Point			Ratio Np.	Error (%)			Std. IEEE	Remarks
	R	S	T						
	H1H2 - X1X0	H2H3 - X2X0	H3H1 - X3X0		R	S	T		
1	28.622	28.625	28.626	28.64	0.06	0.05	0.05		Good
2	27.939	27.937	27.941	27.96	0.07	0.08	0.06		Good
3	27.256	27.258	27.262	27.27	0.08	0.07	0.06	< 0.5%	Good
4	26.576	26.571	26.573	26.59	0.06	0.08	0.07		Good
5	25.892	25.891	25.890	25.91	0.08	0.09	0.09		Good

Table 2 and Table 3 show the real measurement results value using the TTR test instrument, before and after rewinding. The results for the three phases of R, S, and T are displayed. In good condition, the results should be within the range of the maximum and minimum limit (Standard Tolerance) (3).

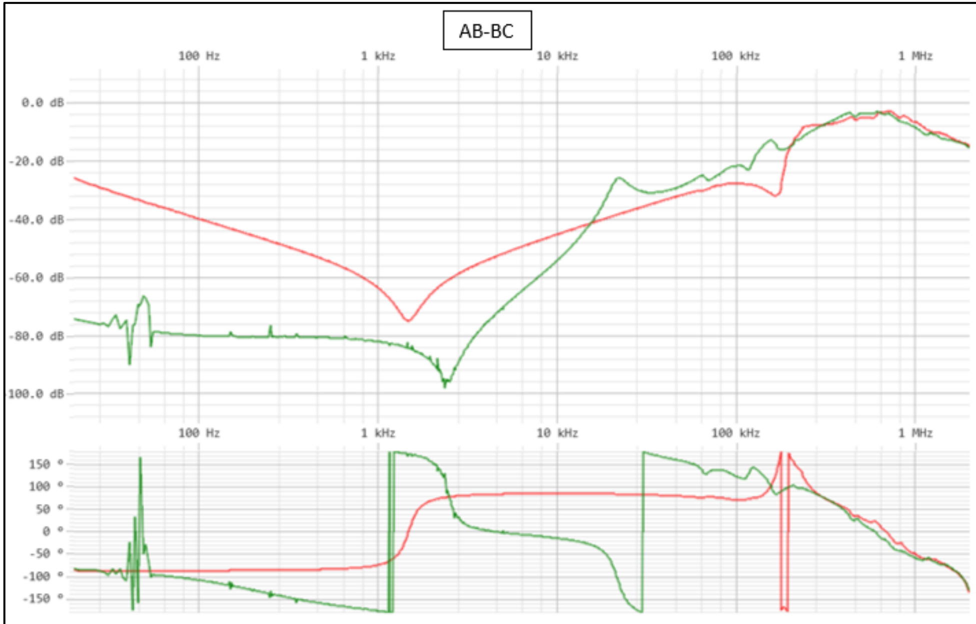
$$Maximum\ Limit = A\ (1.005) \tag{3}$$

$$Minimum\ Limit = A\ (0.995)$$

TTR results (before rewinding) that exceed the tolerance value could indicate a defect in winding or a tap-changer.

3. Results and Analysis

SFRA and TTR test method are conducted before rewinding to ensure the condition of the transformer. A sweep frequency response analyzer tool with an applied voltage of 10 V is used.



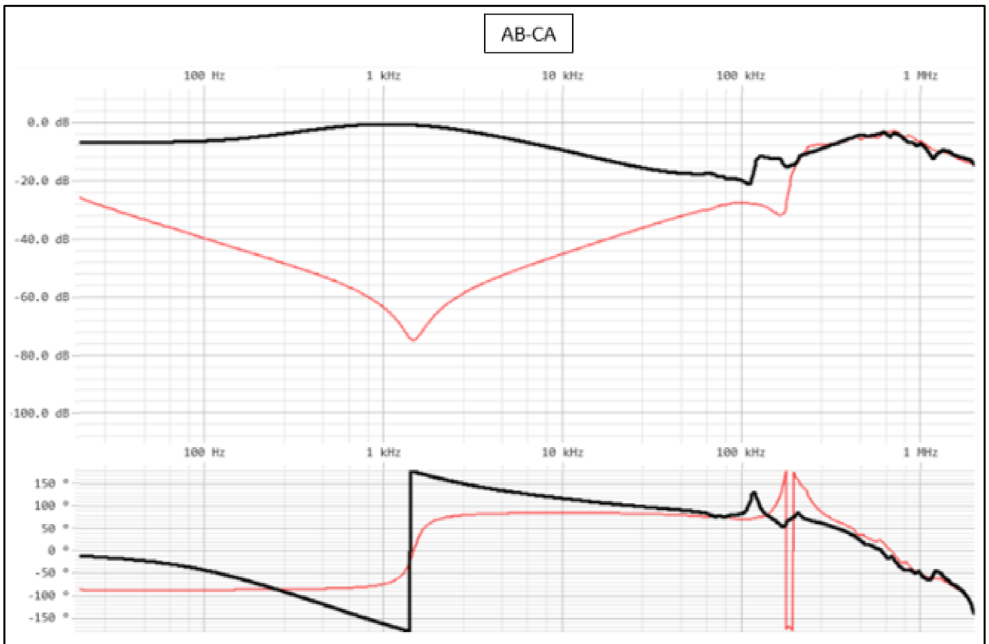
DL/T911-2004

RLF	1,33
RMF	0,87
RHF	1,12
Assessment	Slight deformation

NCEPRI

E	5,9
Assessment	Slight deformation

Figure 3. HV curve connected to LV short-circuited with interference (AB–BC).



DL/T911-2004

RLF	-0,3
RMF	0,76
RHF	1,01
Assessment	Severe deformation

NCEPRI

E	9,59
Assessment	Severe deformation

Figure 4. HV curve connected to LV short-circuited with interference (AB–CA).

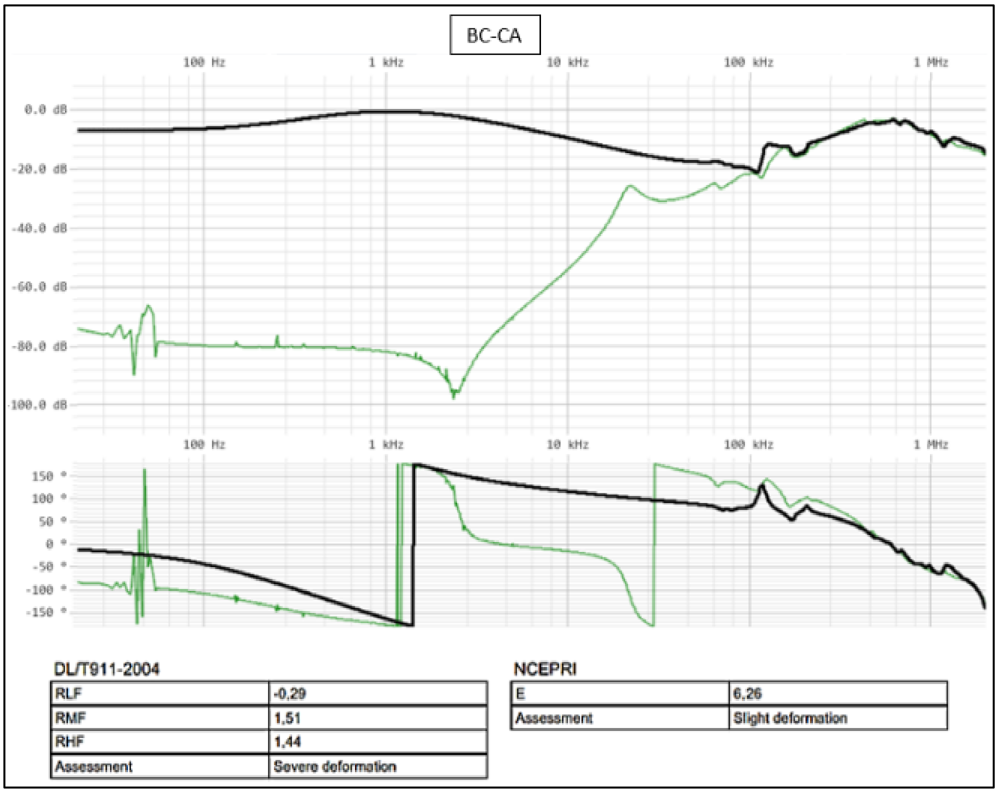
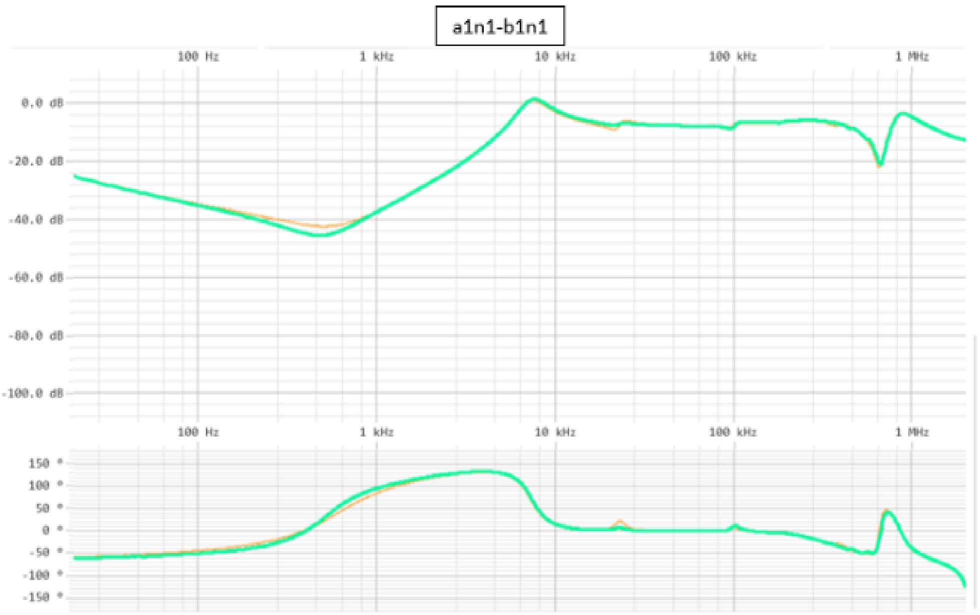


Figure 5. HV curve connected to LV short-circuited with interference (BC - CA).

Table 4. SFRA results based on DT/L 911-2004 [12]

Frequency	Severe Deformation	Obvious Deformation	Slight Deformation	Normal Winding
R-LF = 0.79	R-LF < 0.6	0.6 ≤ R-LF < 1	1 ≤ R-LF < 2	2 ≤ R-LF
R-MF = 0.61		R-MF < 0.6	0.6 ≤ R-MF < 1	1 ≤ R-MF
R-HF = 1.03				0.6 ≤ R-HF

Figure 3, 4, and 5 show the HV curves connected to LV short-circuited with three different interferences. The curve in Figure 6 indicates the changes in the mechanical structure of the transformer. From the curve relationship in Figure 6, there is an inconsistency in shape between the two curves. The intersection of the two curves indicates the existence of interference of the transformer located at low frequency and middle frequency. The data is comparable to the results of the TTR Test in Table 2, which shows that the test result value exceeds 5%.



DL/T911-2004

RLF	2,25
RMF	1,81
RHF	2
Assessment	Normal winding

NCEPRI

E	0,54
Assessment	Normal winding

Figure 6. High Voltage to Low Voltage Curves short-circuited.

As shown in Fig. 6, the association result of the HV curve (H1-H3; H1-H2; H2-H3) and the short-circuited LV (x1-x2-x3) indicates that the condition of the transformer is still in a normal state and without interference. This is after referring to the responses on R-LF, R-MF, and R-HF, according to DL/T 911-2004 standard, the 'Frequency Response Analysis on Winding Deformation of Power Transformers' [12].

4. Conclusion

In this study, the correlation between SFRA and TTR test results are obtained. From the SFRA method results, both normal and fault conditions of the transformer are discovered. Relative factor values of R-LF = 2.25 > 2, R-MF = 1.81 > 1, and R-HF = 2> 0.6, according to the DL/T 911-2004 standard, show the normal conditions. While relative factor values of R-LF = -0.3 < 1, RMF = 0.6 < 0.76 < 1, and R-HF = 1.01 > 0.6, as compared to the DL/T 911-2004 standard, show the disturbances of the transformer. R-LF and R-MF values illustrate a severe fault level, which is located in the transformer core and transformer coil winding.

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