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TESTING AND DIAGNOSTIC OUT OF THE SERVICE POWER TRANSFORMER USING A SWEEP FREQUENCY RESPONSE ANALYSIS (SFRA) COMPARING WITH CHINA STANDARD

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Abstract

A several diagnostic methods used to evaluate and detect any potential issues or faults in the transformer before they cause significant problems. The research proposal focuses on employing the SFRA (Sweep Frequency Response Analysis) technique, renowned for its exceptional sensitivity and diagnostic capabilities. This method serves to identify the mechanical integrity of the transformer's core, winding distortion, and clamping structures by analyzing their electrical transfer functions across a broad frequency spectrum. By utilizing SFRA, the study aims to accurately predict the internal physical condition of the transformer, making it a highly effective and reliable indicator for assessing its overall health. The motivation of this present work is using all experiments of SFRA were conducted and validated on a three-phase 30kV/0.4KV voltage transformer with 50kVA at the laboratory of Msila university. The result of these experiments is presented and discussed in terms of interpretation the analyses based on different standards.

Keywords: power transformer; diagnostics; sweep frequency response analysis (SFRA)

1. INTRODUCTION

Electrical transformers are one of the most important parts of the electrical system because of their significant role in increasing the reliability of the electrical grid and the durability of the power supply. The power transformer is an essential element of an electrical power system because it regulates the voltage level to set the best possible system operation [1]. In order to ensure a long, useful service life, it is critical that a power transformer and its ancillary components are tested regularly for incipient fault modes. Sweep Frequency Response Analysis (SFRA) test is considered one of the tests that are relied upon to detect deformations that occur in transformer windings those that are difficult to detect by traditional tests such as the Turns Ratio test, Winding Resistance test, or Excitation current test. Furthermore, The SFRA methods are founded on comparing the characteristics of power transformers before and after the test [2]. Each of these tests has a set of advantages and disadvantages that distinguish it from the others[3].In some cases, any failure of these transformers will result in the system's failure as a whole [4].The SFRA test offers highly potent diagnostic capabilities.

However, to derive true value from the tests, two critical aspects must be carefully considered: first, the proper application of the test must adhere to acceptable standards, ensuring its accuracy and reliability. Second, the interpretation of the test results requires meticulous attention to detail, allowing for meaningful insights to be extracted from the gathered data. By addressing both these aspects diligently, the SFRA test can deliver valuable and insightful information[5],[6].

In case of a mechanical change in the coils or iron core, the system of resistances, inductances, and capacitances of the transformer will differ according to a specific pattern depending on the type of fault, which is reflected in the result of this test and indicates the presence of this type of faults, where the frequency response is indicative of the compounds that make up the transformer system and any difference in these compounds will affect this frequency response [7],[8]. In this test (SFRA), a low-voltage wave with a variable frequency is applied to one end of the coil, and this wave is

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measured at the other end of the same coil or another coil according to the adopted test pattern.

The interpretation of SFRA results is performed by visualization of images obtained using specialized devices [8]. In our case, the distribution transformer of rating 50 kV A, 30V/0 .4KV, three phase, 50 Hz has been specially used in laboratory of Msila university by the authors and his team for carrying out SFRA testing by practically using FRAX101 instrument of megger companyto detect winding displacements in power transformers or faults in the magnetic core.

The main work of this research is the detection of winding deformations and to extend the guideline approach for analysis and interpretation of results based by visualization of images on experiences according to China standards.

2. EXPERIMENTAL WORK

The laboratory, as depicted in Fig. 1, is dedicated to the design and development of a specialized 50 kVA power transformer. This transformer serves as the subject of study for analyzing SFRA (Sweep Frequency Response Analysis) using FRAX101 traces through practical testing. The hardware of the SFRA system is meticulously engineered to identify winding displacements and potential faults in the magnetic core of power transformers.

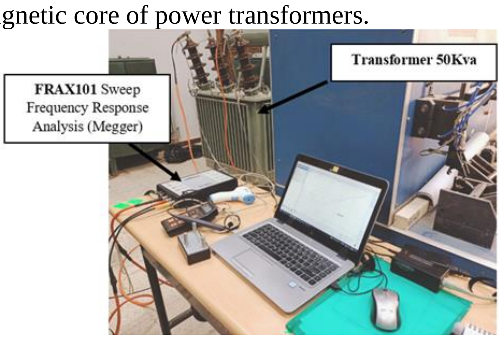

Fig. 1. Details of experiment materials using FRAX101 in the lab

In the philosophy of testing, a voltage wave is applied to one of the transformer coils, where this wave is a small amplitude sinusoidal wave (2-15V) and variable frequency (from 20 Hz to 2 MHz) [9],[10], [11], according to the standards of the International Electrotechnical Commission [12]. Then, this applied voltage is measured to serve as a reference wave, and the output voltage is measured to be the response wave as shown in Fig. 2, which illustrates a transformer testing circuit using coaxial cables.

With the help of the model's function, one can compute nearly any parameter by utilizing the measured or stored data [12].

2.1. Characteristics of power transformer

In the absence of the transformer's fingerprint (time based), the study will be based on a comparison between the three phases, which is one of the methods relied upon in the absence of the fingerprint (time based), taking into account some differences in the location of the files in the iron core. The table 1 shows the transformer's characteristics for testing.

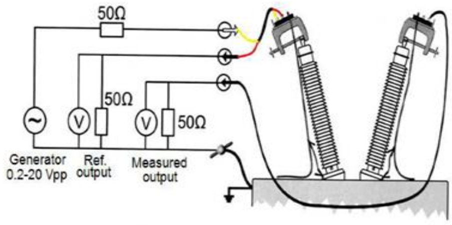

Fig. 2. SFRA test connection using FRAX 101

Table 1. Transformer characteristics

Company	ENEL Azazga-tizi-Algeria
Transformer type	4746C
Number	03525
Years of manufacture	1987
Power capacity	50 kVA
Rating power HV/LV	30 kV /400 V
Frequency	50 Hz
Vector group	Yzn11
Type of cooling	ONAN

2.2. Analysis of transformer by SFRA method

There are several connections between the test device and the transformer to be tested through which this test can be performed according to the adopted method. Referring to international standards issued by renowned organizations such as the International Council on Large Electric Power Systems (CIGRE) [13], the International Electrotechnical Commission (IEC) [14], and the Institute of Electrical and Electronics Engineers (IEEE) [15].

Before commencing the test, the FRAX101 device provides the feature of verifying the device's functionality and connection cables. The verification method as shown in Fig.3. and the result should match what is described in the device's user manual [16].

Fig. 3. The connection method of verification test

2.3 Type of measurement

In this part, various tests have been used to distribution transformer according to the four typical of the SFRA method:

1. End-to-end open circuit

In this experiment six tests have been achieved by connection method as show in Table 2 (Three in HV and three in LV).

Table 2. Connection method for end-to-end open circuit typical

Test type	Test number	Delta – Start
HV open circuit all other terminals floating	1	H_1-H_3
	2	H_2-H_1
	3	H_3-H_2
LV open circuit all other terminals floating	4	X_1-X_0
	5	X_2-X_0
	6	X_3-X_0

Note:
(H_1- H_2-H_3)**: HV phases; (**X_1- X_2- X_3-X_0)**: LV phases**

Figures 4 and 5, show how the FRAX101 device clamps are connected to the transformer stages (H3-H2; X3-X0) In the same way the other tests are according to the table.

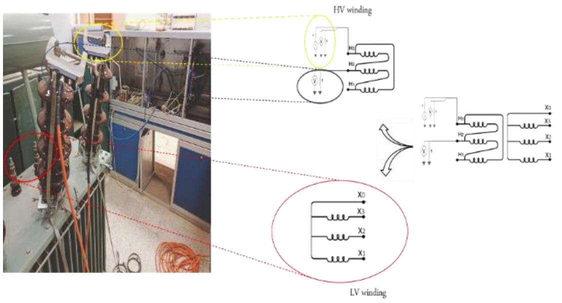

Fig. 4. HV open circuit (H3-H2) all other terminals floating

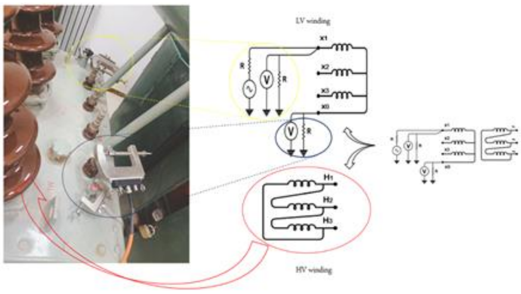

Fig. 5. LV open circuit (X3-X0) all other terminals floating

The results of the tests according the Table 2 are showing in Fig. 6 and 7.

2. End-to-end short circuit

In this test, three tests (generated and measured in HV, short[X1-X2-X3]) are implemented with a different connection as well as show in Table 3.

Table 3. Connection method for end-to-end short circuit typical

Test type	Test number	Delta – Start
End to end short circuit short[X_1-X_2-X_3-X_0]	1	H_1-H_3
	2	H_2-H_1
	3	H_3-H_2

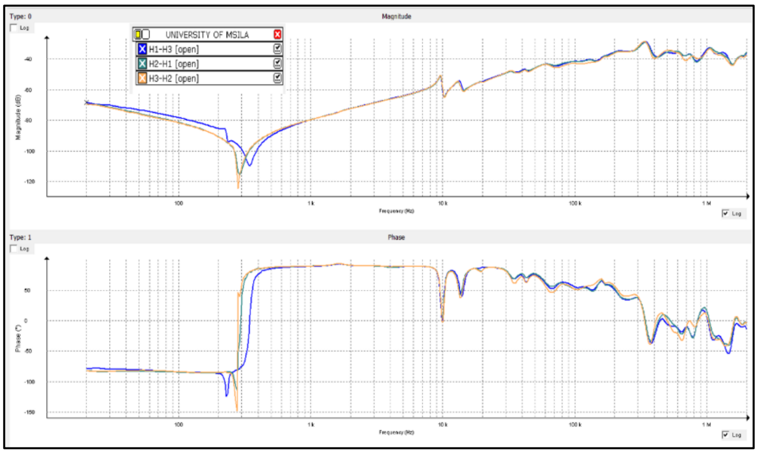

Fig. 6. Results of end-to-end open circuit typical (HV)

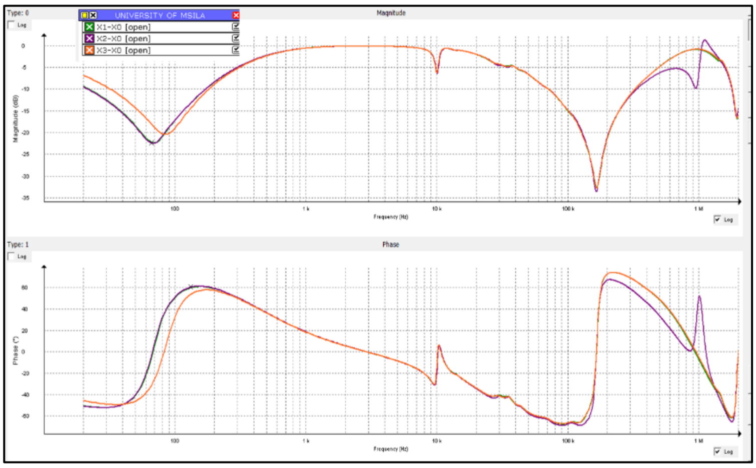

Fig. 7. Results of end-to-end open circuit typical (LV)

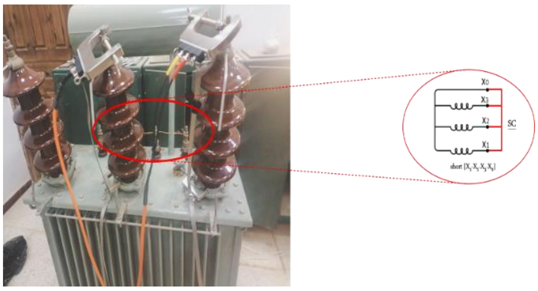

Fig. 8. Typical connection of end-to-end short circuit method (H3-H2)

The result of this test shown in Fig. 9 using Table 3.

3. Capacitive Inter Winding

Three tests (generated in HV and measured in LV), connection method as show in Table 4.

The Fig. 10 shows the experiment wiring of the capacitive inter winding test (H1-X1).

Table 4. Typical connection of capacitive inter winding method

Test type	Test number	Delta – Start
Capacitive inter winding all other terminals floating	1	H_1-X_1
	2	H_2-X_2
	3	H_3-X_3

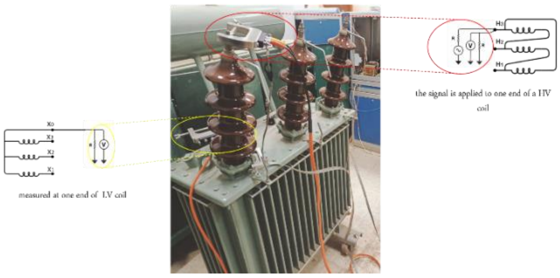

Fig. 10. One of the topicals connection of capacitive inter winding method

The result of this method is presented in Fig. 11.

4. Inductive Inter Winding

In this test, we apply three tests (generated in HV and measured in LV, with the other end of both windings being grounded), the connection method as show in Table 5.

Table 5. Typical connection of inductive inter winding method

Test type	Test number	Delta – Start
Inductive inter winding around [U-an-X]	1	H_1-X_1
	2	H_2-X_2
	3	H_3-X_3

The Fig. 12 shows an example of how perform this method.

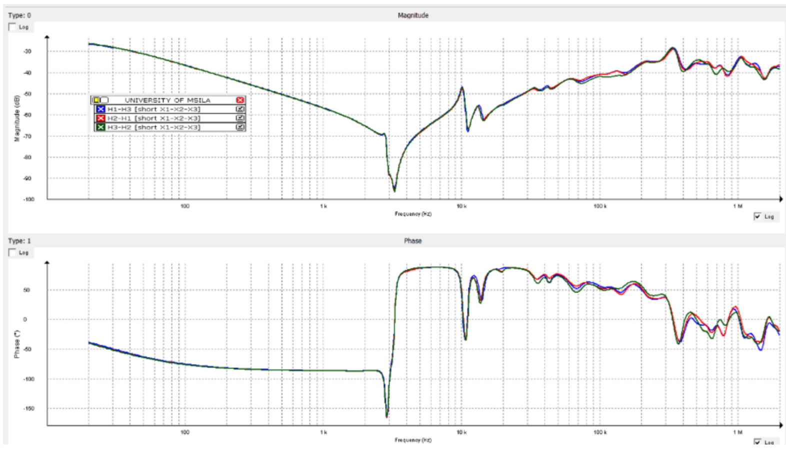

Fig. 9. Results of end-to-end short circuit typical

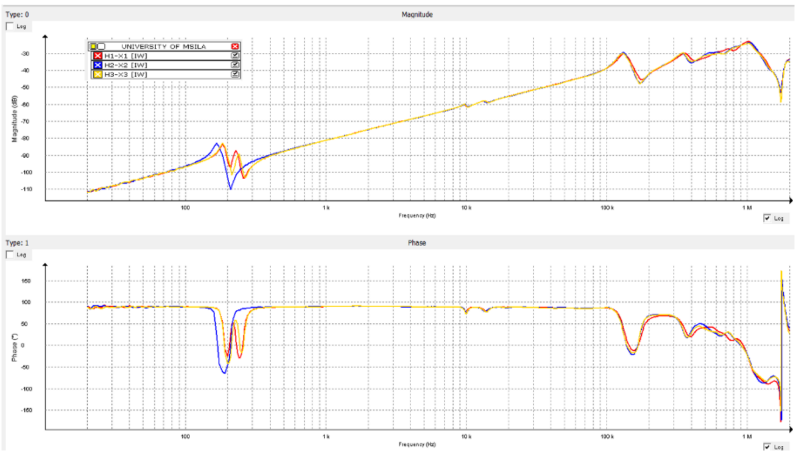

Fig. 11. Results of Capacitive inter winding typical

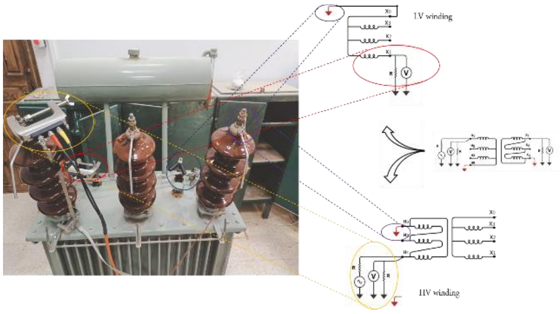

Fig. 12. One of the typical connections of inductive inter winding method (H1-X1)

The result of this typical method is showing in Fig. 13 using Table 5.

3. RESULTS AND DISCUSSION

The Chinese standard DL/T911-2004 technique, a pioneering standard globally, was created in China under the management of the Technology Commission for Electric Power Industry & High Voltage Test Technology Standardization. This standard emerged as a result of collaboration among six national power engineering institutes, with its exclusive focus on SFRA measurements. The standard encompasses the test principle, requirements for testing instruments, testing methods, and the analysis of results [17].

The frequency range evaluated by this standard is between 1 kHz and 1 MHz. This standard is unique in that it provides a rule for judging test results based on a calculation of covariances [18].

Table 6 provides a clear classification of winding deformation degrees based on specific relative factors in different frequency bands, facilitating understanding and analysis.

Table 6. Relation between relative Factors and degree of transformer winding deformation

Winding Deformation degree	Relative Factors R
Severe Deformation	$R_{LF} < 0.6$
Obvious Deformation	$1.0 > R_{LF} \geq 0.6$ or $R_{MF} < 0.6$
Slight Deformation	$2.0 > R_{LF} \geq 1.0$ or $0.6 \leq R_{MF} < 1.0$
Normal Deformation	$R_{LF} \geq 2.0$, $R_{MF} \geq 1.0$ and $R_{HF} \geq 0.6$

Note:
R_{LF} represents the relative factor when the curve is in low frequency band (1kHz~100kHz).
R_{MF} represents the relative factor when the curve is in medium frequency band (100kHz~600kHz).
R_{HF} represents the relative factor when the curve is in high frequency band (600kHz~1000kHz).

The terms "normal, Severe, Obvious, Slight " indicates of degree of transformer winding deformation based on relative Factors R

According the Chinese standard DL/T911-2004 technique, this work has been compered all results of curves between the results obtained in previous section and the limits curves of this standard for every typical wiring method, The results and interpretations as a recap in a Table is presented for every method of SFRA application as follow:

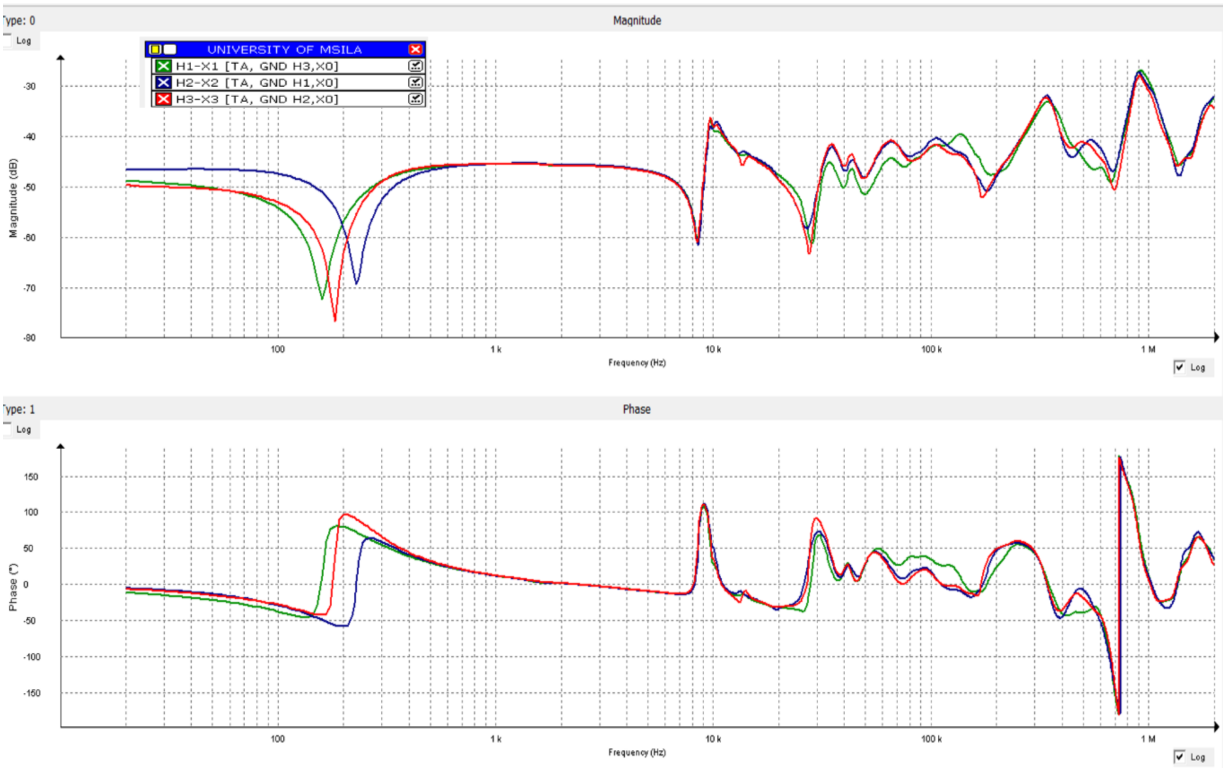

Fig. 13. Results of Inductive inter winding typical

1. End-to-end open circuit

The figures (14,15,16) represent the comparison of each pair of curves, where it has three curves related to high-voltage phases as illustrated in Table 2. In general, the comparisons indicate the normal state of the windings and iron core, because End-to-end open circuit method focuses on looking at the winding and core characteristics).

The comparison all of curves, three curves related to low-voltage phases shown in figures (17, 18, 19) and indicate the normal state of the windings and iron core.

Table 7 summarizes the results of curves comparison for end-to-end open circuits, highlighting the interpretation based on the relevant standards and concluding whether conditions are normal.

2. End-to-end short circuit

The End-to-end short circuit method focuses on the winding's characteristics, the figures (20, 21, 22) represent the comparison of each pair of curves related to high-voltage phases as illustrated in Table **3. However, the comparisons indicate the normal state of the windings**

In the table 8, the comparison of curves [H1-H3[short X1-X2-X3]] to [H2-H1[short X1-X2-X3]] indicates normal operation. The curves [H2-H1[short X1-X2-X3]] to [H3-H2[short X1-X2-X3]] show high-frequency resistance (R-HF) above the limit, while low-frequency (R-LF) and medium-

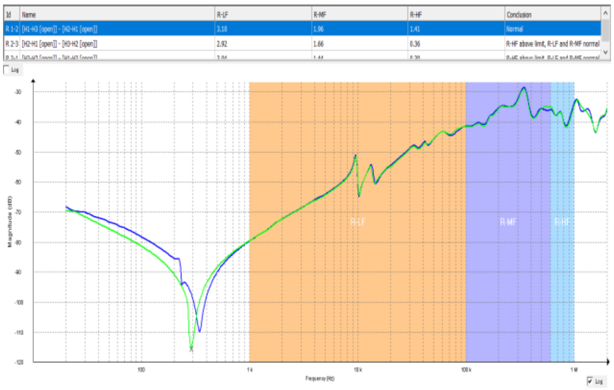

Fig. 14. Result of curves comparison [H1-H3[open]]- [H2-H1[open]]

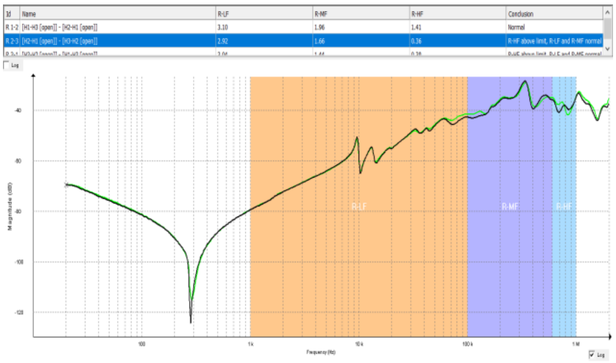

Fig. 15. Result of curves comparison [H2-H1[open]]- [H3-H2[open]]

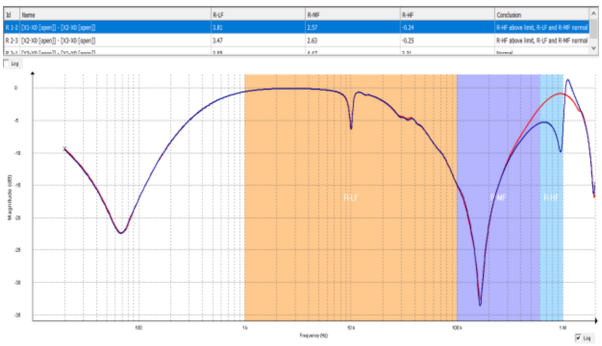

Fig.16. Result of curves comparison [H3-H2[open]]- [H1-H3[open]]

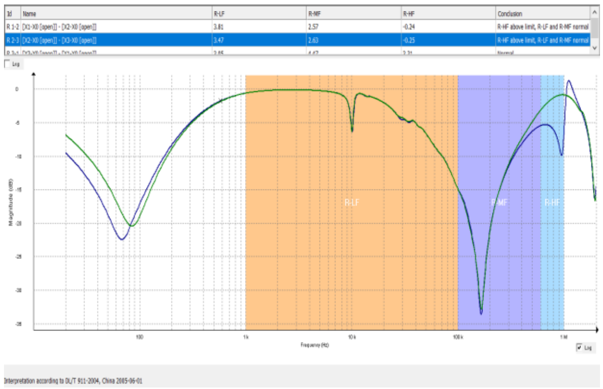

Fig. 17. Result of curves comparison [X1-X0[open]]- [X2-X0[open]]

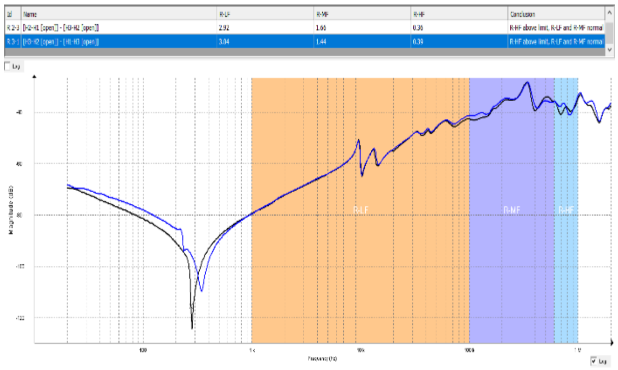

Fig. 18. Result of curves comparison [X2-X0[open]]- [X3-X0[open]]

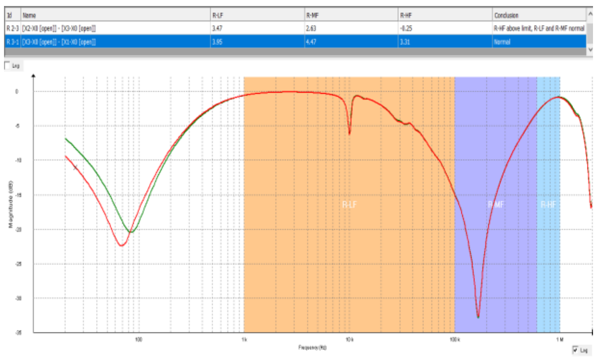

Fig. 19. Result of curves comparison [X3-X0[open]]- [X1-X0[open]]

Table 7. Result of curves comparison end-to-end open circuit typical (HV)

Interpretation according to DL/T 911-2004, China 2005-06-01	
Curves comparison	Conclusion
[H1-H3[open]]- [H2-H1[open]]	Normal
[H2-H1[open]]- [H3-H2[open]]	**R-HF above limit, R-LF and R-MF normal**
[H3-H2[open]]- [H1-H3[open]]	**R-HF above limit, R-LF and R-MF normal**
[X1-X0[open]]- [X2-X0[open]]	**R-HF above limit, R-LF and R-MF normal**
[X2-X0[open]]- [X3-X0[open]]	**R-HF above limit, R-LF and R-MF normal**
[X3-X0[open]]- [X1-X0[open]]	Normal

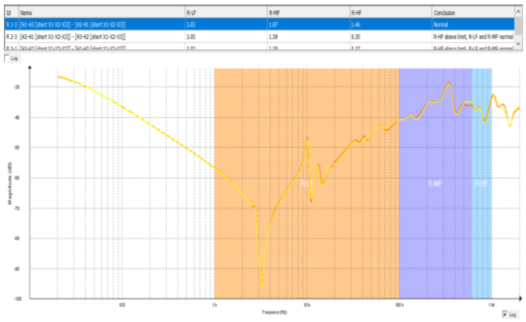

Fig. 20. Result of curves comparison [X3-X0[open]]- [X1-X0[open]]

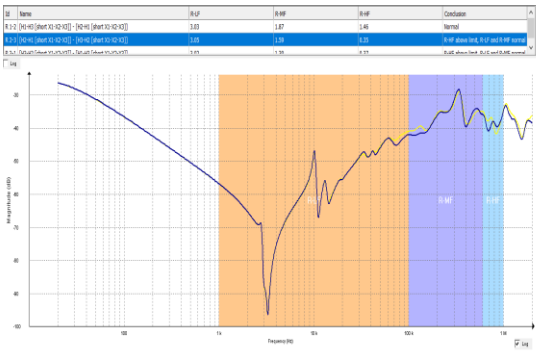

Fig. 21. Result of curves comparison [X3-X0[open]]- [X1-X0[open]]

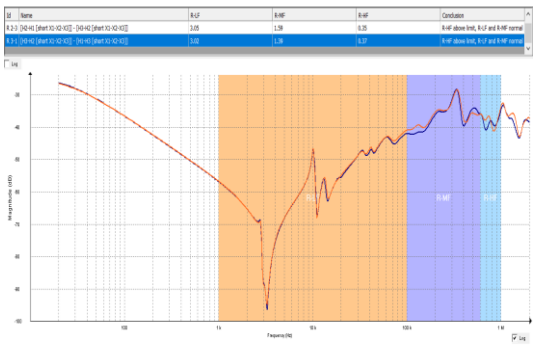

Fig. 22. Result of curves comparison [X3-X0[open]]- [X1-X0[open]]

frequency (R-MF) resistances are within normal limits. In addition, the curves [H3-H2[short X1-X2-X3]] to [H1-H3[short X1-X2-X3]] indicates high-frequency resistance (R-HF) above the limit, but low-frequency (R-LF) and medium-frequency (R-MF) resistances are within normal limits.

Table 8. Result of curves comparison (end-to-end short circuit typical)

Interpretation according to DL/T 911-2004, China 2005-06-01	
Curves comparison	conclusion
[H1-H3[short X1-X2-X3]]- [H2-H1[short X1-X2-X3]]	Normal
[H2-H1[short X1-X2-X3]]- [H3-H2[short X1-X2-X3]]	**R-HF above limit, R-LF and R-MF normal**
[H3-H2[short X1-X2-X3]]- [H1-H3[short X1-X2-X3]]	**R-HF above limit, R-LF and R-MF normal**

3. Capacitive inter winding

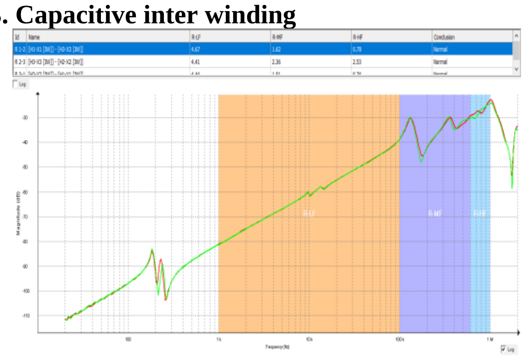

Fig. 23. Result of curves comparison [H1-X1[IW]]- [H3-X3[IW]]

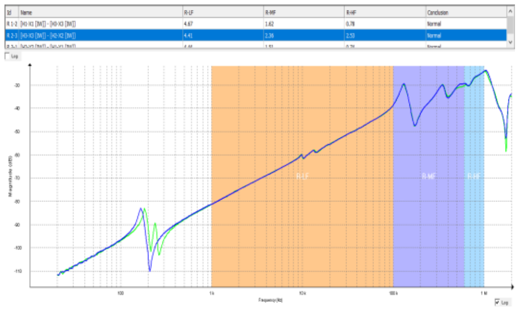

Fig. 24. Result of curves comparison [H3-X3[IW]]- [H2-X2[IW]]

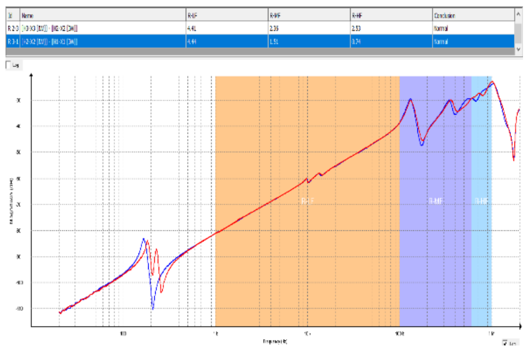

Fig. 25. Result of curves comparison [H2-X2[IW]]- [H1-X1[IW]]

The high-voltage phases as illustrated in Table 4 presented in figures (23, 24, 25). The comparisons test as shown in Table 9 indicate the normal state of the windings because the capacitive inter-winding method has high sensitivity in detecting radial/diameter deformations in the windings).

Table 9. Result of curves comparison (Capacitive inter winding)

Interpretation according to DL/T 911-2004, China 2005-06-01	
Curves comparison	**Conclusion**
[H1-X1[IW]]- [H3-X3[IW]]	Normal
[H3-X3[IW]]- [H2-X2[IW]]	Normal
[H2-X2[IW]]- [H1-X1[IW]]	Normal

4. Inductive inter winding

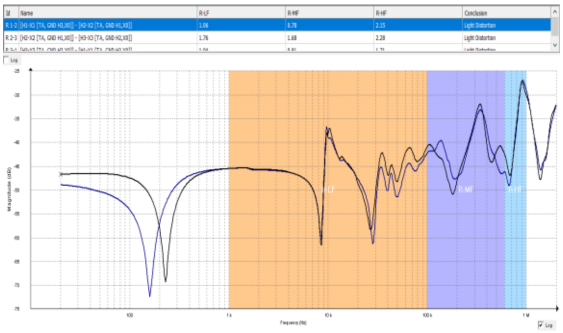

Fig. 26. Result of curves comparison [H1-X1[TA, GND H3, H0]]- [H2-X2[TA, GND H1, H0]]

The low-voltage phases test appears in figures (26,27,28) as illustrated in Table 5. It is clear a light distortion in all curves comparison as well as presented in Table 10. To ensure an optimal analysis of test results, it is necessary to consider certain factors when comparing current results with those of the same or similar transformers, or when comparing different phases, as outlined in the standard.

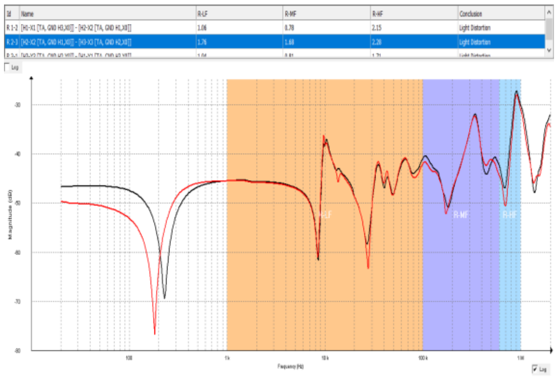

Fig. 27. Result of curves comparison [H2-X2[TA, GND H1, H0]]- [H3-X3[TA, GND H2, H0]]

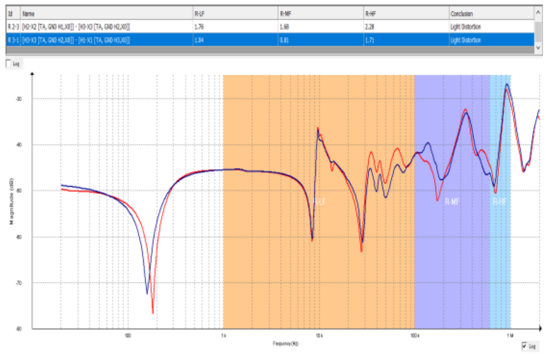

Fig. 28. Result of curves comparison [H3-X3[TA, GND H2, H0]]- [H1-X1[TA, GND H3, H0]]

Table 10. Result of curves comparison (Inductive inter winding)

Interpretation according to DL/T 911-2004, China 2005-06-01	
Curves comparison	**conclusion**
[H1-X1[TA, GND H3, H0]]- [H2-X2[TA, GND H1, H0]]	Light Distorsion
[H2-X2[TA, GND H1, H0]]- [H3-X3[TA, GND H2, H0]]	Light Distorsion
[H3-X3[TA, GND H2, H0]]- [H1-X1[TA, GND H3, H0]]	Light Distorsion

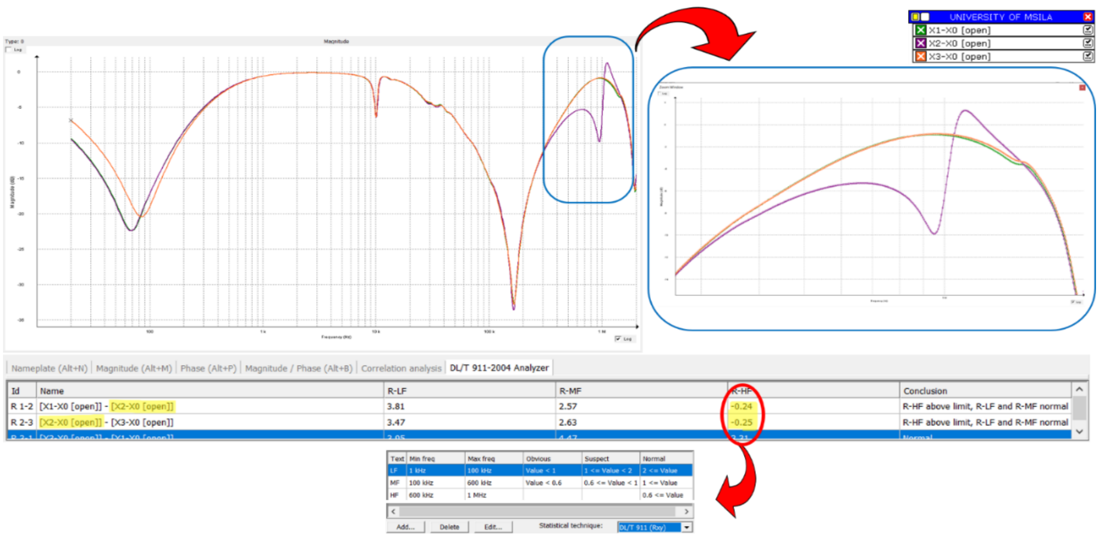

Fig. 29. Analysis of results

5. Occurrence of displacement of the waveform

The Fig. 29 indicates the difference in the fingerprint of phase X2-X0 compared to the rest of the phases X1-X0 and X3-X0 in the high-frequency range (end to end open circuit injection in LV)

4. CONCLUSION

Experimental testing of the transformer which has been out of the service more than to 7 years, allowed us to conclude that the internal mechanical condition not changed and has a perfect analysis. Upon comparing the frequency responses with the Chinese standard, it has been observed that the open and short circuit responses of the three phases of HV (H) and LV (X) windings exhibit similarities and possess identical shapes in the low and medium frequency ranges, resembling the behavior of two phases. However, further analysis is needed to explore additional aspects, it has abnormal status for last(H) and (X)phase, as analysis, it is greatly affected by the connection of the test, especially the connection of coaxial cables used in the test to the ground and it is greatly affected by the structure of the windings, which take the form of sequential leakages and capacitances in series and in parallel. On the other hand, the capacitive and inductive inter winding are similar with respect to detecting both winding-ground and winding-interlayer short circuits.

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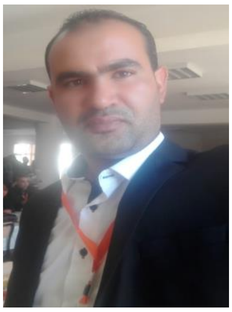

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