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Implementation of Sweep Frequency Response Analysis (SFRA) for Condition Assessment of Power and Distribution Transformers

Burak Özçelik[1], Osman Bülent Tör[1], Mahmut Erkut Cebeci[1], Kürşat Tanrıöven[2], Adela Bara[3], Simona Oprea[3]
[1]EPRA Engineering Procurement Research Analysis, Ankara, Turkey
[2]Kayseri and its Vicinity Electricity Distribution Co. (KCETAS), Kayseri, Turkey
[3]Bucharest Economic Studies, Bucharest, Romania

SUMMARY

Transformers are one of the most important equipment of electrical transmission and distribution systems. Sweep Frequency Response Analysis (SFRA) test method is predominantly characterized by the ability to detect mechanical and electrical failures of transformers, and therefore, it is implemented in many utilities particularly in transmission sector for more than 15 years. By this method, the smallest fault in the core and winding structure of the transformer can be detected graphically by the transmitted low voltage signals. This study presents consideration of the SFRA technique by a distribution company, KCETAS in Turkey, in the context of reliability based maintenance strategy. SFRA tests are performed for some pilot distribution transformers initially during factory acceptance tests. Fingerprints of the pilot transformers are recorded before transporting them to site. SFRA tests are repeated after the transportation in order to detect mechanical failures, if any, during the transportation. SFRA tests are also performed for some transformers during maintenance period. It is observed that the SFRA test gives a strong indication about the failures in the transformers and saves effort and time of staff for failure detection.

KEYWORDS

Sweep Frequency Response Analysis (SFRA), SFRA Analyzer Megger FRAX-101, Power and Distribution Transformers

1. INTRODUCTION

Transformers play significant role in path of transmitting electrical energy from generation sites to the end-users. On the other hand, transformers are among those expensive assets of power system that should be well maintained against possible failures. Transformer failures, which might happen due to mechanical or electrical reasons, lead to electricity interruptions and impose associated costs to the system operator and customers. Transformer failure diagnosis in a timely manner is crucial to avoid aforementioned issues on one hand and extend life span of the transformer on the other hand. Transformer fault diagnosis is a critical issue in maintenance planning of power systems. Several methods are proposed in the literature for fast transformer failure detection [1]. Sweep Frequency Response Analysis (SFRA) is among those approached which has been widely used by transformer

*burak.ozcelik@epra.com.tr

manufacturers, transmission and distribution companies. SFRA is a powerful tool for evaluating mechanical status of transformer windings and detecting iron core defects. The main superiority of SFRA approach in comparison with other available schemes is its precision which provides detection of trivial failures [2].

In this study, possible transformers failures are first explained in Section 2. In Section 3, the basics of SFRA technique are presented. Different types of SFRA test methods for real-world applications are described in Section 4. Section 5 addresses implementation procedure of SFRA for the selected pilot transformers in KCETAS. Test results pertaining to SFRA analysis for factory acceptance and post-shipment conditions are presented in Section 6. Section 7 concludes findings of the study.

2. COMMON TRANSFORMER FAILURES

Failures in transformers are usually originated from small internal faults such as inter-turn short-circuits within the windings. Failure might also have mechanical source, like winding deformation, which starts by a small mechanical strike and grows gradually over the time. By overlooking such small defects, they turn into transformer failures that can lead to permanent interruption [2]. Figure 1 depicts different types of defects which includes; (1) transformer windings deformation; (2) inter-turn short circuit; (3) broken conductor in windings; and (4) broken clamping elements.

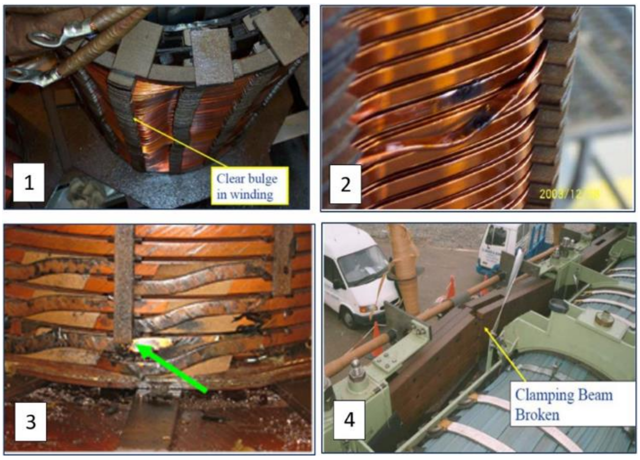

Figure 1: **Transformer common failures [2]-[4]**

3. BASICS OF THE SFRA TECHNIQUE

The SFRA method is a well-known approach among transmission and distribution companies around the world for its capability to detect failures which cannot be detected by other available methods. The main theory behind SFRA is investigation of transformer equivalent circuit alterations. To offer greater details, winding conductors are equivalent to a series resistive-inductive circuit. In addition, the voltage difference among the winding rings in conjunction with associated insulator represent capacitive performance. Accordingly, the transformers can be modeled as a RLC network. In case of any damage to the windings, the parameters of RLC equivalent circuit changes which can be good index for discriminating the faulty conditions. For instance, any damage that changes the distance between the windings affects the amount of capacitance in the equivalent model. By the SFRA approach, variations in RLC parameters of transformers are monitored and failures can be predicted by a sufficient lead time. SFRA implementation is based on the input and output signals measurement. These signals are low voltage signals at different frequencies which are applied to transformer windings.

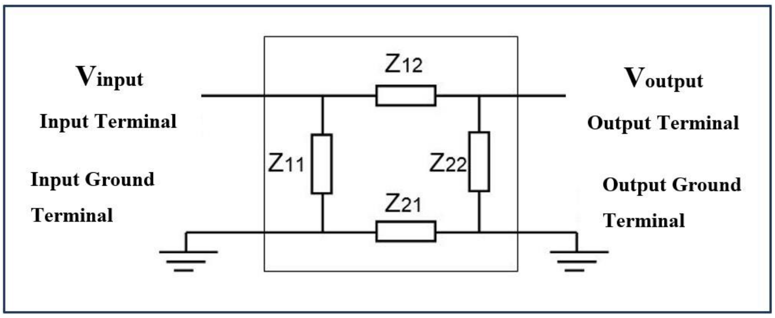

Figure 2: **Modelling of transformers** winding **[5]**

Two pole circuit representation of a transformer is depicted in Figure 2 [5].The transfer function associated with this network can be expressed as the Fourier transform function in frequency domain ($\omega = 2\pi f$):

$$H(j\omega) = \frac{V_{output}(j\omega)}{V_{input}(j\omega)} \tag{1}$$

It is advantageous to draw the *H(jω)* transfer function logarithmically over a wide frequency range on the bode diagram. The Bode amplitude diagram represents the amplitude of system frequency response which is usually measured in decibels (dB). Besides, the Bode phase diagram expresses the phase shift in the system. The diagrams are drawn versus frequency as horizontal axis. Bode diagram is preferred by engineers for SFRA test which can be calculated as [5]. It is advantageous to draw the *H (jω)* transfer function logarithmically over a wide frequency range on the bode diagram.

$$\mathrm{A}(dB) = 20log10(H(\mathrm{j\omega})) \tag{2}$$

$$\mathrm{A}(\Theta) = \tan - 1(H(\mathrm{j\omega})) \tag{3}$$

The resultant plot is called as the reference fingerprint of transformer as illustrated in Figure 3. The reference fingerprint can be used for future investigations and potential threats can be identified by comparing fingerprints at different times.

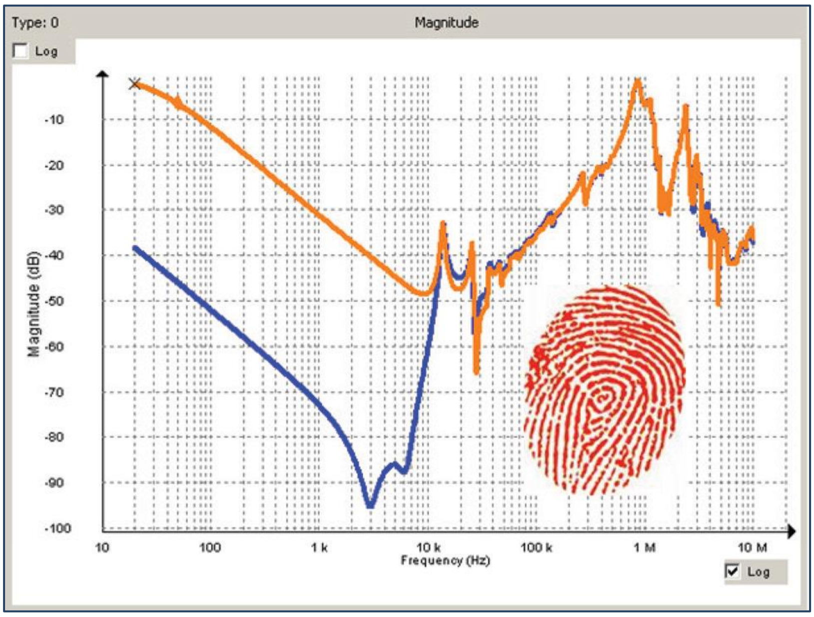

Figure 3: Reference Fingerprint (Blue: End to end open circuit; Orange: End to end short circuit)

4. SFRA METHODS

The SFRA test technique is a comparative measurement method which requires availability of reference data. The common practices for evaluating the measured traces are:

- **Time-based Analysis:** A comparison study is performed among the obtained SFRA results and previously recorded ones.
- **Type-based Analysis:** SFRA results associated with a transformer are compared with those of other transformer which have the same type and design.
- **Phase Comparison Analysis:** SFRA results of a phase are compared with those of the other phases of the same transformer under study.

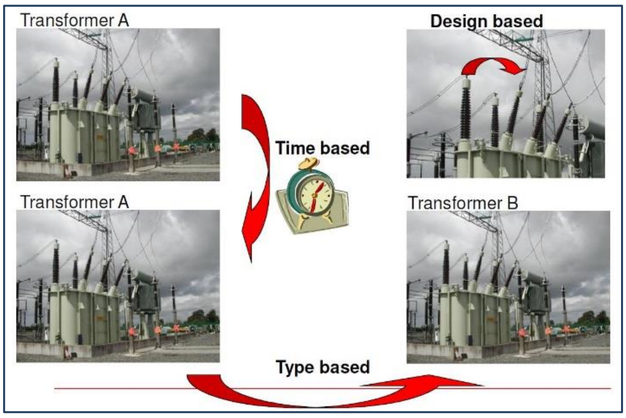

Figure 4: Comparative tests

5. SFRA TESTS AND RESULTS

SFRA test can be performed via several devices procured by different manufacturers. Despite differences in manufacturer and model, their backbone theory and functions are almost the same. SFRA tests are usually performed on all coils and the transfer function of each test are compared with the reference data. Figure 5 shows the results of SFRA test on a 630 kVA distribution transformer in KCETAS where the signals are applied on both low voltage (LV) and medium voltage (MV) sides. The tests are carried out using the Megger FRAX-101 SFRA tester and associated software. During the tests, open-circuit and short-circuit conditions are considered which are the most common type of SFRA measurement. The obtained results can be considered as the fingerprint curves of the tested transformer besides the fingerprint attained at factory tests.

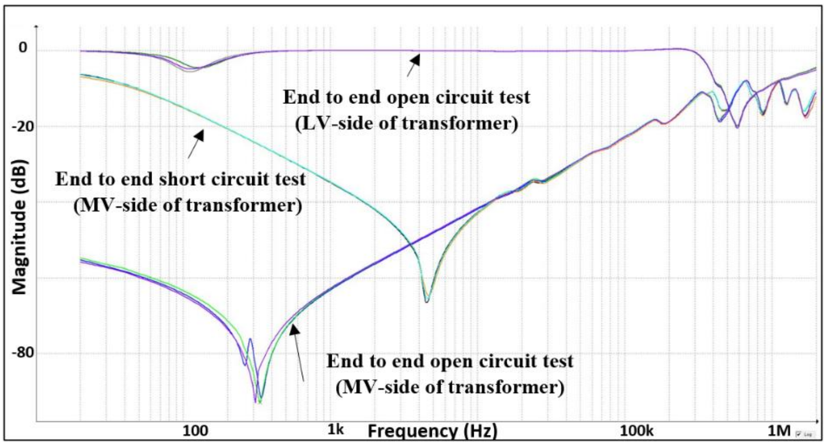

Figure 5: 630 kVA distribution transformer fingerprint test

During the SFRA tests, special attention should be dedicated to accuracy and suitability of the connections. The main reason is that the connections have direct impact on the results and play a significant role from device safety point of view. Figure 6 depicts the result of open circuit test at MV "A" (H1-H2) phase in case of incorrect and correct connections. Due to the inappropriate connection, significant deviations are observed in low-frequency and medium-frequency ranges. After amending the connection structure, the same test is repeated and accurate results are obtained (see Figure 6).

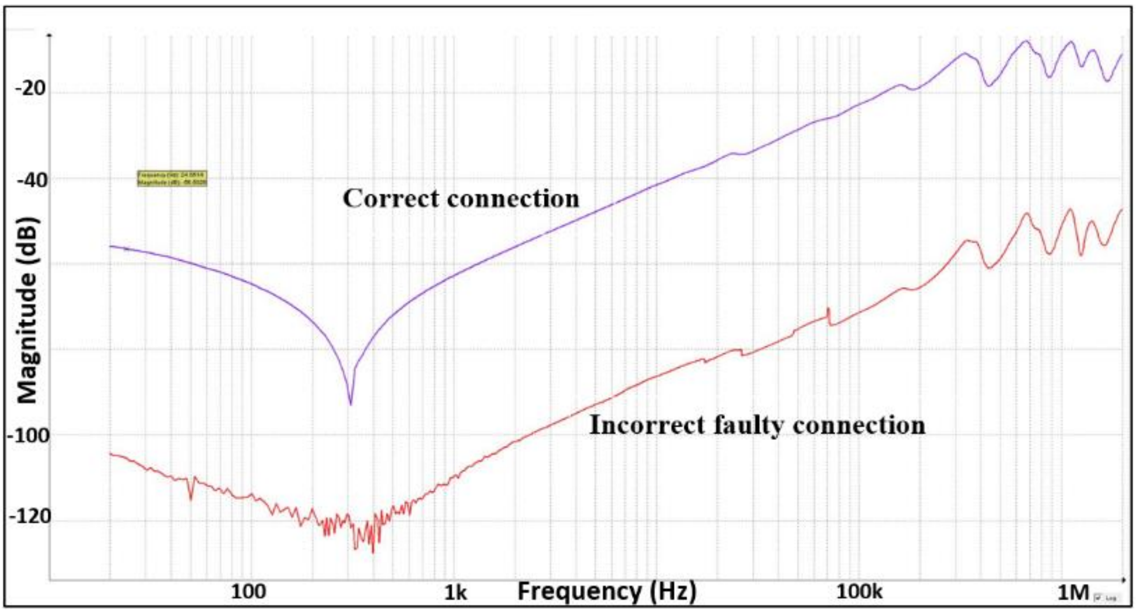

Figure 6: Correct and faulty connection in SFRA tests

6. ASSESSMENT OF THE SFRA TEST RESULTS

Performing regular factory and field SFRA tests for transformers is of great importance for maintaining electricity provision and preventing undesired interruptions SFRA is a comparative measurement method that analyzes test results with respect to the reference data. In this framework, logarithmic scale on the bode diagram is used for the frequency which covers wide frequency range and leads to stable solution. The Megger FRAX-101 SFRA tester software offers easy comparison facilities through user-friend analyzing features. Through the analyzing features, correlations and DL/T 911-2004 analyzes can also be performed. The DL/T 911 analyzer is based on the standards of the People's Republic of China Electricity Energy Industry. It evaluates the electrical and mechanical integrity of the transformer and specifies the basic requirements for SFRA analysis. Correlation analysis is a copy of DL/T 911 analyzer as structure and analysis feature. The only difference between correlation analysis and the DL/T 911 analyzer is that the former provides creation of a special analyzer by changing and limiting the frequency ranges [6].

Figure 7 and Figure 8 show the result of comparison study for short circuit SFRA test associated with "A" (H1-H2) phases on the MV side of the 630 kVA distribution transformer. The results are for after factory acceptance and post-shipment conditions which are attained by DL/T 911 standards analysis. At the bottom of the screen, the results screen evaluates the low, medium and high frequency ranges separately and represents transformer status on this screen.

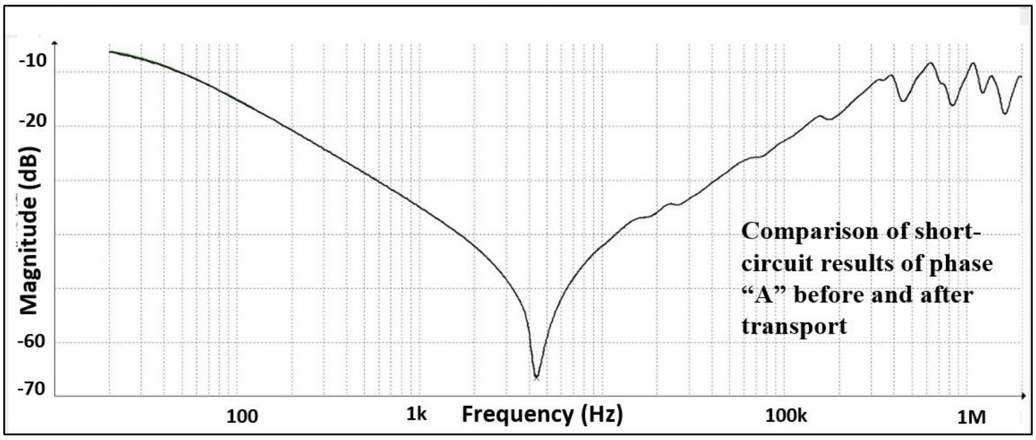

Figure 7: Comparison of SFRA test before and after transport with correlation analysis

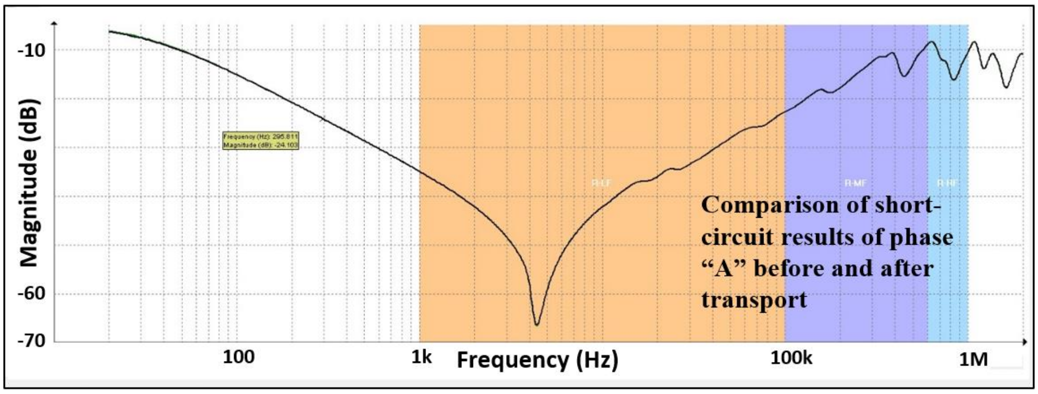

Figure 8: **Comparison of SFRA test before and after transport with DL/T 911 analyzer**

Figure 9 presents the SFRA test results for a faulty 630 kVA distribution transformer. Factory SFRA test has been performed and transformer fingerprint is recorded. Based on the test results, a typical degradation is observed at the windings of the phases "C" (H3-H1) and "c" (X3-X0), which are the third phases of the MV and LV sides of the transformer, respectively. It has been found that these phase curves are significantly degraded between 1-10 kHz which is attained by comparing with the SFRA curves of other phases (phase-based comparison).

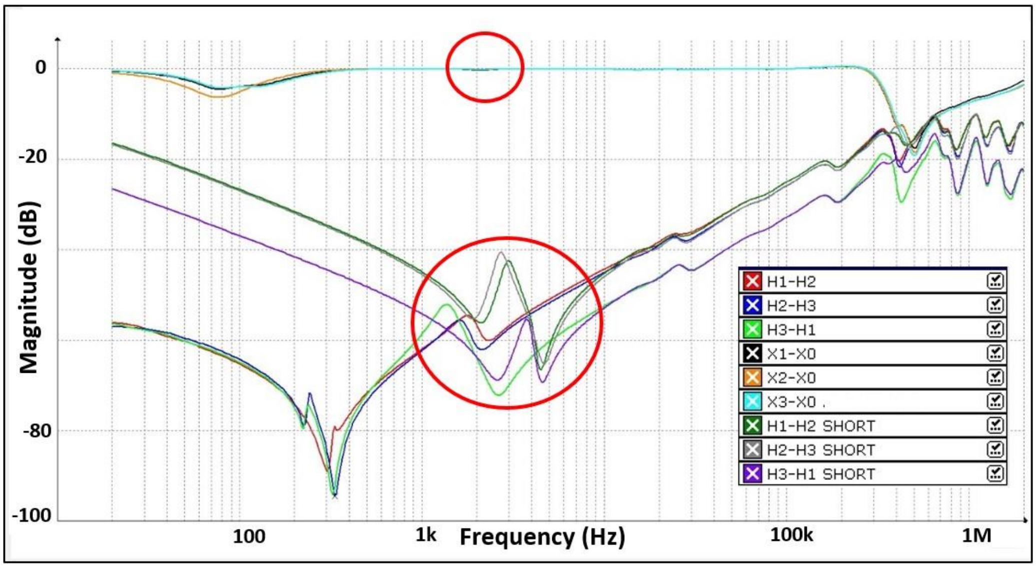

Figure 9: **Test results in SFRA-faulty transformer (Short circuit and Open circuit tests)**

Since the faulty transformer reference data is not included in the factory acceptance tests, it is decided to compare fingerprint curve of this transformer with another healthy transformer of the same type (type based). The SFRA test results of the defective transformer are compared in detail with the fingerprint curves of a healthy transformer of the same type as the power, voltage, vector group and other features. Figure 10 and Figure 11 show the results of the comparison with the correlation analysis of the phases "C" and "c" on the LV and MV sides of the faulty distribution transformer and the same type of healthy transformer. Based on the conducted studies, serious deviation and deterioration is observed between the defective transformer and the sound transformer curves in the low frequency region (1-100 kHz). The severity of the deterioration was determined and entitled as the obvious failure and the suspicious failure (see Figure 10 and Figure 11).

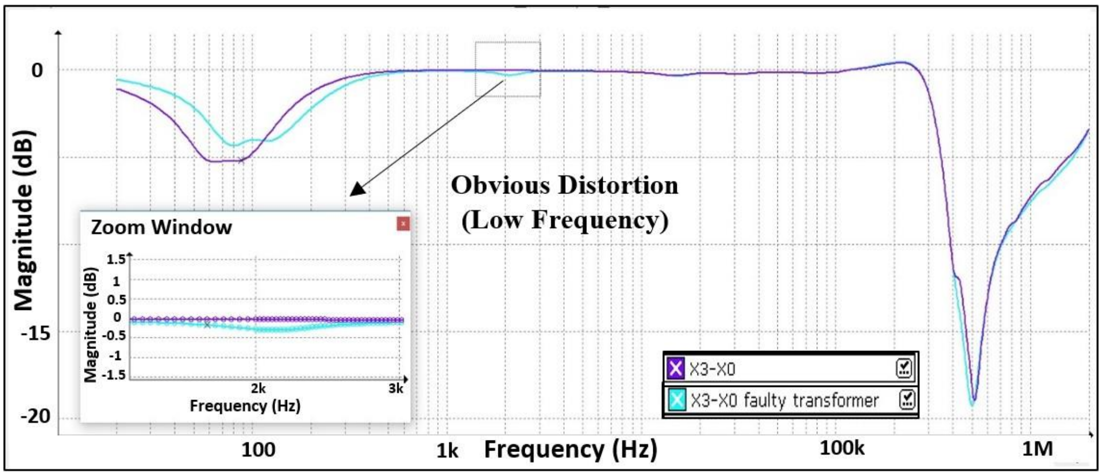

Figure 10: Comparison of LV "c" phases with correlation analysis

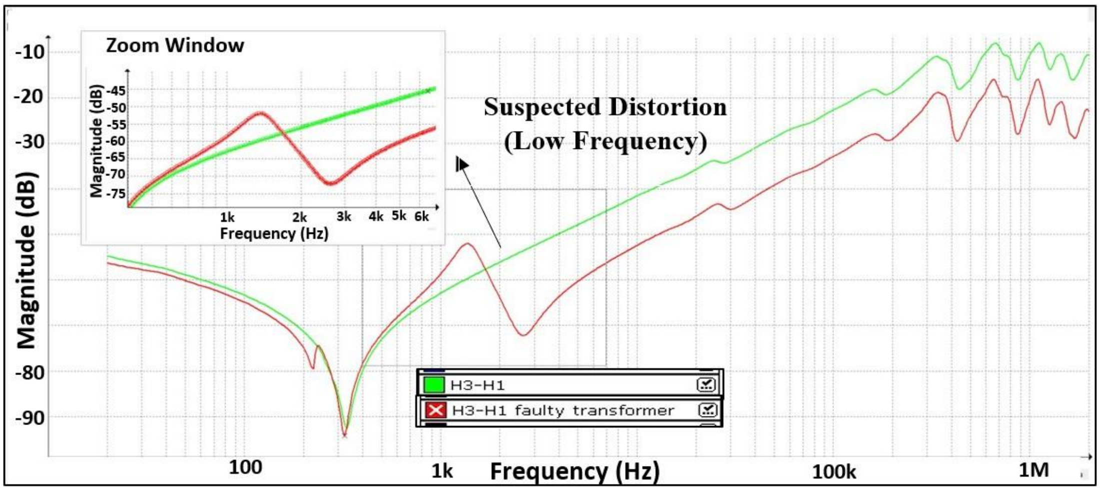

Figure 11: **Comparison of MV "C" phases with correlation analysis**

Figure 12 and Figure 13 show the results of the comparing LV and MV phases (X3-X0 and H3-H1) with DL/T 911 analyzer. As shown in the correlation analysis, the results of the DL/T 911 analyzer represent distortions in the low frequency region. Fingerprint of the healthy transformer is compared with the faulty one in Figure 13. Deviations in the low frequency range correspond to short circuit faults in the open circuit in transformer windings or core. In addition, such a frequency range can be achieved in case of transformer ground faults. Based on the obtained results, the probability of existing a short circuit phase "C" of the transformer is high.

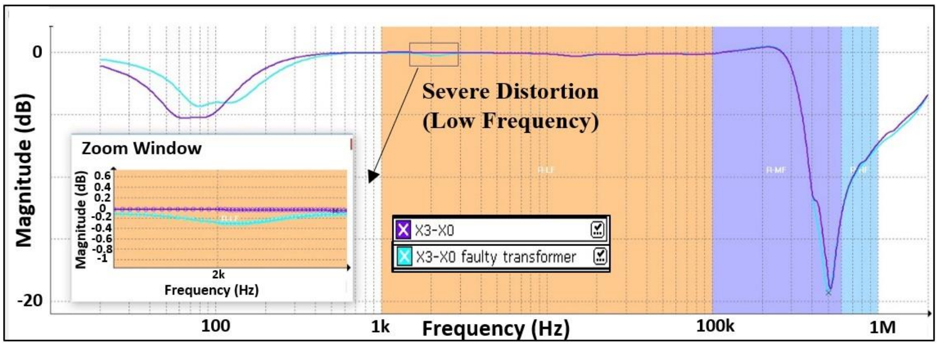

Figure 12: **Comparison of LV "c" phases with DL/T 911 analyzer**

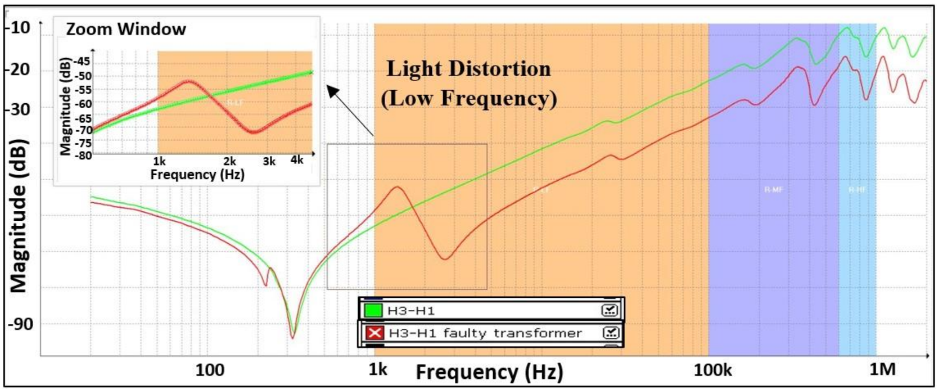

Figure 13: **Comparison of MV "C" phases with DL/T 911 analyzer**

7. CONCLUSIONS

Practical implementation of SFRA technique on distribution transformers is presented. MEGGER FRAX-101 SFRA tester was used for realization of SFRA tests and MEGGER FRAX-101 SFRA tester software was used for evaluating the results. It is illustrated that the SFRA method is a powerful method for detecting and diagnosing failures in the active parts of distribution transformers as well as in the core, windings, internal connections and grounding. This method provides precise results in case of failures which cannot be detected by other available methods.

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