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Research Article

Determination of Winding Deformations in Power Transformers by Sweep Frequency Response Analysis and a Sample Field Study

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ABSTRACT

Power transformers are expensive pieces of electrical equipment that are used to connect transmission and distribution networks. Power transformers are inspected and tested on a regular basis throughout production, shipment, installation, and operation. There are several ways for determining the mechanical integrity of power transformers. Power transformers are monitored using these diagnostic procedures, and any breakdowns and issues are avoided. Sweep Frequency Response Analysis (SFRA) is an efficient method for determining the condition of the transformer core and windings. To evaluate the state of the transformer winding, SFRA, winding direct current resistance, and winding capacitance tests were done in this study. In the case study, a comprehensive case analysis was done on the SFRA test findings for a 50/62.5 MVA power transformer, and the results were analyzed. The results reveal that the SFRA test finds structural winding problems in transformers with high accuracy.

1. INTRODUCTION

Power transformers are among the most critical and costly components of power transmission infrastructure. It is extremely difficult to repair or replace a transformer promptly following a breakdown. A new transformer is expensive, and it might take a long time to arrive on site. Power transformers operate in a variety of climatic, electrical, and mechanical settings and might be subjected to significant risks. The maintenance function includes monitoring their status and diagnosing faults [1]. As a result, energy transmission firms devote considerable financial resources to transformer failure detection and repair. Correctly executed diagnostics enable for the verification of transformer electrical and mechanical properties, as well as the estimation of approximate maintenance time [2]. Sweep frequency response analysis is a popular diagnostic approach for determining the mechanical system condition of a power transformer. This approach is extremely sensitive to changes in the transformer's mechanical structure. This SFRA test is effective in identifying a wide range of flaws and malfunctions produced by short circuit currents in transformer windings [3-6].

Power transformers are subjected to various electrical and chemical tests from the time they are manufactured in the factory until they are commissioned in the field. Routine and type tests specified in the standards are applied in factory tests. After the transformers are commissioned, many additional electrical and chemical tests are carried out in order to maintain them for trouble-free operation, to determine the fault conditions in advance and to determine the fault location if it has occurred. These tests are: Capacitance, loss factor, DC insulation resistance, winding ratio, DC resistance, power factor (%PF) and puncture resistance on oil and oil dissolved gas analysis (DGA). Recently, tests such as partial discharge, sweep frequency response analysis and dielectric frequency response, which are called new generation test methods, have also started to be applied in the field. SFRA is a very sensitive method especially in the determination of problems such as short circuit and breakage in transformer windings, deformations and insulation faults in the core, axial displacement and shifts that may occur in windings and core [7].

The study by Hashemnia et al. provides valuable insights into the impact of mechanical faults on transformer frequency response analysis. Their simulation analysis demonstrates that axial and radial faults, in particular, have a noticeable influence on the SFRA signature.

Specifically, these faults manifest as shifts in the anti-resonance and resonance peaks, particularly within the medium to high frequency ranges. This information is crucial for accurately interpreting SFRA data and identifying potential mechanical faults in transformers. The comprehensive table summarizing the sensitivity of transformer SFRA to mechanical faults serves as a useful reference for engineers and technicians involved in transformer maintenance and condition monitoring [8]. Murawwi et al. stated that 2D time frequency distribution plots are superior in interpreting SFRA and are more successful in eliminating noise sources [9]. Devadiga et al., tests investigating the effect of SFRA voltage source size in a laboratory environment showed a significant effect on the SFRA test, which was evident both in the low frequency range and at high frequencies [10]. Almehdhar et al. showed that the SFRA method is more sensitive compared to measuring the short-circuit reactance of windings [11]. Secue et al. considered the optimal number of frequencies in SFRA to be 2000 spot frequencies, which they showed to be sufficient to represent the frequency response and to obtain a satisfactory approximation model [12]. Yang et al. compared two methods for diagnosing winding faults in transformers: pulse wave and sweep frequency response analysis. They designed a step-up transformer and built test platforms to record voltage responses on both the high and low voltage sides and calculate the corresponding transfer functions. They then compared the statistical indicators of the two methods and found that they were similar in their sensitivity to detect winding-ground and winding-interlayer short-circuit conditions [13]. Gahani et al. investigated the use of the SFRA method to diagnose the condition of transformer main mechanical parts such as the core and winding. They used a MV Dyn11 30 MVA transformer and found that symmetrical phase comparison of both high voltage (HV) and low voltage (LV) windings was the best way to find transformer historical SFRA measurement data and interpret SFRA measurement data. Both studies suggest that new methods are being developed to diagnose transformer faults more accurately. These methods could help to prevent transformer failures and improve the reliability of the power grid [14].

Kumar et al. showed that in the frequency region up to 2 kHz, a core magnetization effect will be observed and to get rid of the magnetization effect, it is necessary to demagnetize before starting the SFRA measurement [15]. Murawwi et al.'s research on the effect of terminal connections on SFRA test results for three-winding transformers found that different terminal connections can produce different SFRA responses, which could lead to a misdiagnosis of the transformer's condition. The authors recommend that the same terminal connections be used for a particular test type in order to ensure accurate results. This finding has important implications for the interpretation of SFRA results. SFRA is a diagnostic technique that is commonly used to assess the mechanical integrity of power transformers. By measuring the frequency response of the transformer's windings, SFRA can detect a variety of faults, such as loose connections, cracked windings, and core damage. However, as Murawwi et al. have shown, the interpretation of SFRA results can be complicated by the use of different terminal connections. Different terminal connections can produce different frequency responses, even for a healthy transformer. This can make it difficult to determine if a particular feature in the SFRA spectrum is due to a fault or simply to the terminal connections. To avoid this problem, Murawwi et al. recommend that the same terminal connections be used for all SFRA tests on a particular transformer. This will ensure that any changes in the SFRA spectrum are due to changes in the transformer's condition, not to changes in the terminal connections. This recommendation is important for all users of SFRA, but it is especially important for utilities that use SFRA to monitor the condition of their transformers in-service. By using the same terminal connections for all SFRA tests, utilities can be confident that the results they are getting are accurate and that they are not missing any potential faults. In conclusion, Murawwi et al.'s research on the effect of terminal connections on SFRA test results is important for the interpretation of SFRA results and for the diagnosis of transformer faults. Their recommendation that the same terminal connections be used for all SFRA tests on a particular transformer is an important step in ensuring the accuracy of SFRA results [16].

This revised text emphasizes the distinct optimal combinations of terminal connections and system functions for SFRA in single-phase and three-phase transformers. It also highlights the positive impact of modifying the terminal configuration on the sensitivity of SFRA measurements for three-phase transformers. Specifically, the study determined that for single-phase transformers, the optimal terminal connection involves connecting the primary and secondary windings in series, while the system function is the transfer function between the voltage across the primary winding and the current in the secondary winding. These findings have significant implications for SFRA measurement practices and the interpretation of SFRA results. SFRA is a diagnostic technique widely used to evaluate the mechanical integrity of power transformers. By analyzing the frequency response of the transformer's windings, SFRA can detect various faults, including loose connections, cracked windings, and core damage. However, as Arumugam's research highlights, the interpretation of SFRA results can be influenced by the choice of terminal connections. Different terminal connections can produce distinct frequency responses, even for a healthy transformer. This can complicate the identification of whether a specific feature in the SFRA spectrum stems from a fault or simply from the terminal connections. To address this challenge, Arumugam's study recommends employing identical terminal connections for all SFRA tests on a particular transformer. This approach ensures that any alterations in the SFRA spectrum are attributable to changes in the transformer's condition, not variations in the terminal connections. This recommendation is crucial for all SFRA users, but it holds particular importance for utilities that utilize SFRA to monitor the condition of their in-service transformers. By adopting consistent terminal connections for all SFRA tests, utilities can gain confidence in the accuracy of their results and minimize the risk of overlooking potential faults. In summary, Arumugam's research on the impact of terminal connections on SFRA test outcomes provides valuable insights for interpreting SFRA results and diagnosing transformer faults. The recommendation to use identical terminal connections for all SFRA tests on a particular transformer represents a significant step towards ensuring the accuracy and reliability of SFRA results. For three-phase transformers, the best terminal connection is to connect the primary windings in wye and the secondary windings in delta, and the system function is the transfer function between the voltage across one of the primary windings and the current in one of the secondary windings. The study also found that for three-phase transformers, using the neutral connection can improve sensitivity in some cases. However, the use of the neutral connection is not always necessary, and it can sometimes make the measurement more difficult. Overall, the study found that the best way to make SFRA measurements on transformers is to use the terminal connection and system function that is recommended for the specific type of transformer being tested [17].

Kumar et al. identified four fault levels by finding the amplitude differences in specified frequency regions and made predictions about winding and core condition [18]. In a study by Yoon et al., RLC circuit was designed in Matlab ™, compared with real SFRA tests and found to be compatible [19]. Brandt et al. considered the condition assessment of a 40 MVA power transformer. This revised text provides a more concise and clear explanation of the diagnostic methods used to identify faults in the study. It also highlights the successful application of inter-winding SFRA measurements to detect axial distortion in the tertiary winding [20]. Statistical indices are preferred for the comparison of SFRA test results on transformers due to their simple and easy application [21, 22]. Recently, statistical indices have been used in the evaluation and interpretation of SFRA results and many studies have been carried out in this regard [23-26, 27, 28]. Comparative studies have been carried out to reveal the characteristics of statistical methods in fault diagnosis and accordingly their performance has been evaluated [22, 29, 30].

In this study, conventional tests and SFRA test, which are among the tests for diagnosing power transformer faults, are discussed and the relationship between the two methods is tried to be explained. The easy detection of winding deformation by SFRA test is evaluated. A case analysis is performed on a power transformer and the results are interpreted.

2. SFRA TEST

For many years, short-circuit impedance (SCI) measurement has been used as a simple technique to detect transformer winding deformation and core displacement. It is still applied in many countries for transformer diagnostics. As a more sensitive method, frequency response analysis for transformers was first introduced by Dick and Erven in 1978 [31]. Frequency domain measurement involves injecting a sinusoidal waveform that sweeps within a predetermined frequency band. The voltage measured at this input terminal is used as a reference signal, and a second voltage signal (response signal) is measured at a second terminal. The frequency response amplitude is the scalar ratio between the response signal (Vout) and the reference voltage (Vinput) (presented in dB) as a function of frequency. The phase of the frequency response is the phase difference between Vinput and Vout (presented in degrees). The response voltage measurement is made across a 50 Ω impedance. Any coaxial cable connected between the test object terminal and the voltage meter will have a matching impedance. Frequency domain measurement is also a relatively fast and inexpensive technique. As a result, it is becoming increasingly popular for transformer diagnosis.

SFRA has several advantages over traditional methods like SCI measurement, including:

- Higher sensitivity to defects
- Faster measurement times
- Lower cost

As a result, SFRA has become the preferred method for transformer diagnosis in many industries. The SFRA measurement scheme is shown in Figure 1. The reference voltage Vinput is injected into the test object at terminal 1, and the response voltage Vout is measured at terminal 2. The voltage meter measures the amplitude and phase of Vout and calculates the frequency response amplitude and phase. The frequency response is then compared to a reference frequency response to identify any changes in the transformer.

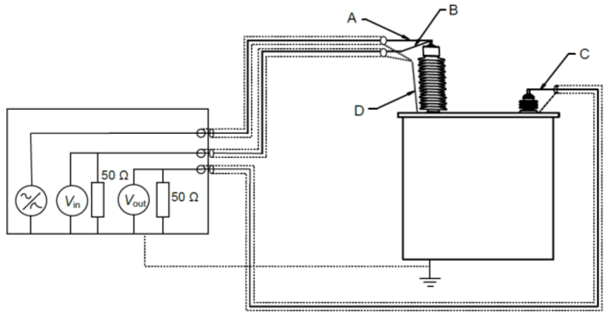

Figure 1. SFRA measurement scheme [32] (A: source, B: reference, C: response, D: earth connection

The transfer function is the ratio of the measured output voltage V to the reference input voltage V. The amplitude response of the system is calculated from Equation 1 and the phase angle response of the signal is calculated from Equation 2.

$$A_{amplituderesponse}[dB] = 20log_{10}\left(\frac{V_{out}(jw)}{V_{input}(jw)}\right) \quad (1)$$

$$\varphi_{phaseresponse}[°] = tan^{-1}\left(\frac{V_{out}(jw)}{V_{input}(jw)}\right) \quad (2)$$

To ensure all resonance frequencies are detected in the SFRA spectrum, measurements can be taken in the 20 Hz-2 MHz range for all transformers, regardless of their voltage ratings. However, for exceptional transformers or reactors, the upper frequency limit may be increased further. In the case of air core reactors, this limit can be extended up to 20 MHz. SFRA measurements can be used to identify undesirable oscillations or supplementary fluctuations at frequencies above 2 MHz. SFRA measurements conducted during factory testing provide a winding fingerprint [33].

This allows for the analysis of diagnostic data on the physical structure of the transformer viewed as a complex RLC circuit. Changes to the transformer's internal structure impact the passive components in the RLC circuit, thus affecting the transfer function. Modifications to the winding configuration will result in changes to the frequency response analysis. Additionally, it would be beneficial to compare the initial readings of the distributed resistance and capacitance of a coil with the respective readings taken after carrying out maintenance, repairs, or transportation of the transformer. Three types of comparison should be considered: (1) comparing the current SFRA spectrum with the previous baseline, (2) comparing the current SFRA spectrum with that of a sister (twin) transformer, and (3) comparing the SFRA spectrum between separate phases (utilising winding symmetry) [32, 32-36]. Technical term abbreviations will be defined when first used, and language will remain clear, objective, and value-neutral. Consistent use of technical terminology and simple sentence structures will ensure grammatical accuracy. Adherence to academic conventions and impartial language will also be prioritised.

2.1. SFRA connection types

Four different measurement methods are applied in SFRA measurements. The measurement connections to be made according to star, delta and winding number are specified in both standards [32, 37]. Circuit connections are open-circuit, short-circuit, capacitive inter-winding and inductive inter-winding which are described below and shown in Figure 2. The reference voltage (Vr) and response voltage (Vm) is just showing the point that the measurement should be done in each of the connections.

2.1.1. End to end

In Figure 2(a), the end-to-end measurement is conducted from one end of the transformer winding to the other. Simultaneously, all other transformer terminals remain open. The measuring signal is applied to one end of each winding, and the signal transmitted across the winding is measured at the opposite end. Due to its simplicity and ease of use, this test is more widely employed. Each winding can be tested individually.

2.1.2. End-to-end short circuit

Figure 2(b) illustrates end-to-end short-circuit measurements, which are performed from one end of the high-voltage winding to the other end while the low-voltage winding is short-circuited. However, the neutral connection should not be included in the measurement.

2.1.3. Between capacitive windings

Figure 2(c) demonstrates capacitive inter-winding measurements, which involve applying the voltage (signal/signal) to one end of the winding and measuring the response signal from one end of the other winding of the same phase. Meanwhile, the other terminals are disconnected. Measurements between windings are inherently capacitive.

2.1.4. Inductive inter-winding

Inductive inter-winding measurements are depicted in Figure 2(d). In an inter-winding inductive measurement, the signal is applied to the HV terminal. The response signal is measured at the LV terminal of the same phase. Meanwhile, the other ends of both windings are grounded.

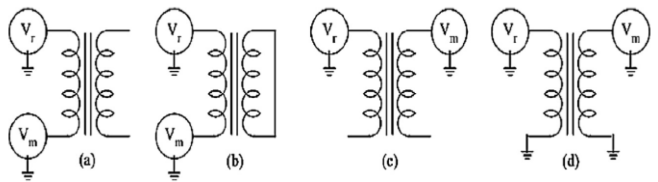

Figure 2. SFRA standard test setups

2.2. SFRA evaluation

2.2.1. Visual assessment

Visual assessment of the SFRA spectrum is a common practice, relying on physical principles and expert knowledge. To interpret SFRA signatures and evaluate transformer condition, the transformer's frequency response spectrum needs to be categorized. For easier classification, the frequency response data can be divided into frequency bands. The European and American standards [32, 33] divide it into four frequency bands, while the Chinese Standard divides it into three frequency bands (low, medium, and high frequency). Transformer characteristics differ across frequency bands, resulting in variations in the SFRA spectrum across each frequency region. Consequently, interpretation depends on the frequency band in which the winding will operate.

The frequency regions in Figure 3, the part indicated by A is up to 2 kHz. This region gives information about the core. The part indicated with B is the 2 kHz-20 kHz frequency region. This region shows the interaction states between the windings. The part indicated by C is the 20 kHz-1 MHz region. This region is mostly affected by inter-winding coupling. D is the frequency region above 1 MHz. This region gives information about winding end connections and earth connections.

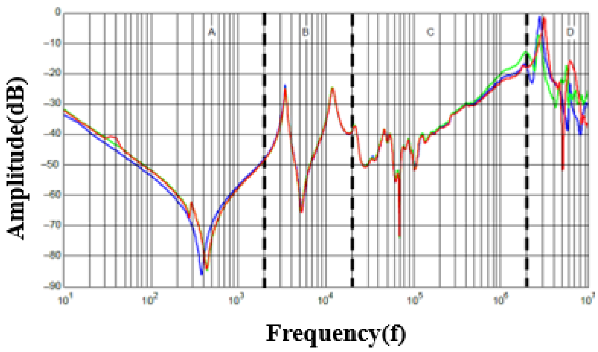

Figure 3. SFRA frequency regions [29]

The condition of the transformer is determined by the comparison between two SFRA measurements, before and after. If there is no deviation between these two results, it is understood that the transformer is sound. In order to detect a malfunction that may occur later in the transformer, it is important for a healthy evaluation that the previous measurement and the next measurement connections, step, measurement types are the same.

If there is no displacement or structural change in the windings inside the transformer, the previous and subsequent test curves overlap exactly. Shifting resonance points or deviations in SFRA magnitude indicate the presence of a fault.

Several factors influence the outcomes of SFRA measurements. The IEC standard recommends conducting the SFRA test solely at the tap position with the highest effective winding count and at the tap position with the tap winding disabled [32]. This ensures consistent and reliable results by minimizing the impact of tap changer positions and tap winding connections. The measurement direction affects the SFRA measurement, especially at high frequencies [32, 38]. SFRA measurement voltage is affected by temperature, connection group, core short circuits, screen between high winding and low winding, oil, residual magnetization of the core, resistance of test cables [36, 39], humidity [40].

2.2.2. Statistical evaluation

An alternative method for interpreting SFRA data [41] involves employing statistical indicators, such as the correlation coefficient (CC), standard deviation (SD) [42, 21], and the relative factor [43]. These statistical measures provide a quantitative assessment of the similarity between two SFRA spectra, enabling the detection of anomalies and potential transformer faults. The mathematical statistical indicators frequently employed when performing SFRA spectrum analysis can be categorised into two distinct groups. The first group is directly calculated from the SFRA amplitude vector, while the second group is derived from resonance and anti-resonance points [44]. Jianqiang and colleagues assessed the SFRA findings by gauging the extent of transformer winding deformation errors through mathematical measures [44].

Bagheri et al. conducted offline short-circuit impedance and SFRA tests on a transformer that malfunctioned owing to the deformation of the B-phase of its HV winding. The short-circuit impedance values, according to IEEE Standard 62-1995, revealed no winding deformations; however, as per IEC Standard 60076-5, each of the three windings experienced deformations. The statistical indicators CC and SD, derived from comparing fingerprint and measured SFRA data, showed that the phase B winding was deformed, and a third index - the relative factor - indicated its slight deformation. Furthermore, visual inspection of the faulty transformer confirmed that the phase B winding suffered from deformation [41].

CC is defined in equation 3:

$$CC_{(X,Y)} = \frac{\sum_{i=1}^{N_s} X_i Y_i}{\sqrt{\sum_{i=1}^{N_s}[X_i]^2 \sum_{i=1}^{N_s}[Y_i]^2}} \tag{3}$$

The correlation coefficient (CC) is a numerical value ranging from 0 to 1 that quantifies the similarity between two SFRA spectra. It is a useful tool for identifying anomalies and potential transformer faults. A higher correlation coefficient indicates a greater similarity between the two spectra, while a lower correlation coefficient suggests significant differences. X_i and Y_i represent the i-th elements of the fingerprint and the measured SFRA traces, respectively N_s denotes the number of elements (or samples) In the context of SFRA analysis, the CC is used to compare a measured SFRA spectrum to a reference spectrum. The reference spectrum is typically obtained from a healthy transformer or from a previous measurement of the same transformer. A low CC value indicates that the measured spectrum is significantly different from the reference spectrum, which could be a sign of a transformer fault. The CC is a relatively simple and easy-to-understand metric, but it is important to note that it is not a foolproof indicator of transformer health. Other factors, such as the specific type of transformer and the operating conditions, can also affect the CC value. Therefore, it is important to use the CC in conjunction with other diagnostic techniques, such as visual inspection and analysis of individual resonances, to make a definitive diagnosis of transformer health.
SD is defined by equation 4.

$$SD_{(X,Y)} = \sqrt{\frac{\sum_{i=1}^{N_s}[Y_i - X_i]^2}{N-1}} \tag{4}$$

CC and SD values have been assessed across different sub-bands in the SFRA spectrum [4], although the frequency range used varies amongst authors. In Nirgude et al.'s investigation, transformer windings were intentionally deformed both radially and axially, achieving physical deformation up to 1%. Subsequently, CC and SD values were computed at each stage. It was established that in any frequency band between 10 Hz and 3 MHz, single CC and SD values are appropriate as indicators of winding deformation. In the context of winding deformation, $|CC| < 0.9998$ and $SD > 1$ are reliable indicators [45].

Winding deformation refers to R_{XY}, a relative factor that is defined in [39].

$$R_{XY} = \begin{cases} 10 & 1 - P_{XY} < 10^{-10} \\ -log_{10}(1 - P_{XY}) & Other \end{cases} \tag{5}$$

Here, Pxy is given by

$$P_{XY} = \frac{\left(\frac{1}{N_s}\right)\sum_{i=1}^{N_s}\left(X_i - \left(\frac{1}{N_s}\right)\sum_{i=1}^{N_s} X_i\right)^2 \left(Y_i - \left(\frac{1}{N_s}\right)\sum_{i=1}^{N_s} Y_i\right)^2}{\sqrt{D_X D_Y}} \tag{6}$$

D_X and D_Y are obtained;

$$D_X = \frac{1}{N_s}\sum_{i=1}^{N_s}\left(X_i - \frac{1}{N_s}\sum_{i=1}^{N_s} X_i\right)^2 \tag{7}$$

$$D_Y = \frac{1}{N_s}\sum_{i=1}^{N_s}\left(Y_i - \frac{1}{N_s}\sum_{i=1}^{N_s} Y_i\right)^2 \tag{8}$$

D_X and D_Y are the standard variances of the fingerprint measured values (X_i) and the last measured (Y_i) data, respectively [37]. Frequency bands for R_{XY} and deformation levels related to R_{XY} values are defined in the Chinese standard [42] and by some other workers [35] (Table 1). These definitions are widely used for SFRA monitoring assessment using the R_{XY} method.

This revised text provides a more concise and clear explanation of the definitions and applications of D_X, D_Y, R_{XY}, and their associated frequency bands in SFRA monitoring assessment. It also highlights the widespread adoption of these definitions in the field.

TABLE I
DEFORMATION LEVELS AND THE CORRESPONDING R_{XY} VALUES [33]

Level	R_{XY} Values
Severe	RDF < 0.6
Lightweight	1.0> RDF ≥ 0.6 or ROF < 0.6
Less	2.0> RDF ≥ 1.0 or 0.6 ≤ ROF < 1.0
Normal winding	RDF ≥ 2.0, ROF ≥ 1.0 and RYF ≥ 0.6

DF:1-100 kHz, OF:100-600 kHz, YF: 600 kHz-1MHz.

3. SAMPLE FIELDWORK

This field study concerns a 154/31.5 kV, 62.5 MVA power transformer with connection group YNyn0. The transformer was manufactured and commissioned in 1993. The power transformer was out of service in 2022 as a result of the operation of the bucholz and thermal protection relay. After the failure, it was determined that the pressure valve was working, the 154 kV bushings were damaged at the mounting flange and porcelain connection points due to the dynamic effect inside the boiler at the time of failure and oil leakage occurred from these points. Flammable gas accumulation occurred in the shutter valve. Since the fault from the medium voltage feeder was very close to the transformer, the fault current flowing on the 154 kV side of the transformer was 1.5 kA in A and C phase and 8.58 kA in B phase.

3.1. Traditional electrical tests

After the transformer was taken out of circuit after the fault, chemical tests of %PF and capacity, DC resistance, excitation current, SFRA and insulating oil were performed on the transformer. As shown in table 2, the %PF and capacity test values of the transformer after the fault, compared to the previous ones, CH capacity value increased by 1.2%, CHL capacity value increased by 16.7% and CL capacity value increased by 6.2%. %PF values CH, CL and CHL increased excessively. Due to the HV/Tank insulation fault, the DC insulation resistor device could not raise the voltage and no measurement could be taken.

TABLE II
TRANSFORMER %PF AND CAPACITY VALUES

Measured	Routine Test		After Failure	
	%PF (20 ^{0}C)	capacitance (pF)	%PF (20 ^{0}C)	capacitance (pF)
CH+CHL	0.07	10051	345.59	11120.6
CH	0.09	3506.3	0.65	3551.7
CHL	0.07	6544.7	316.62	7639.2
CL+CHL	0.08	19342.1	106.95	21456.3
CL	0.08	12797.2	0,39	13595

The magnetizing current values are shown in Table 3. Magnetizing current measurement could not be made at high voltage B phase.

TABLE III
TRANSFORMER INRUSH CURRENT

Meaurement	Routine Test	After Failure
	Inrush (mA)	Inrush (mA)
A-N	35.78	66.53
B-N	26.56	No measurement could be made.
C-N	35.90	66.66

DC resistance measurement results of the transformer at tap 1 are shown in Table 4. After the fault, HV B-N winding DC resistances show a decrease of approximately 5% compared to phases A and C.

TABLE IV
TRANSFORMER DC RESISTANCE VALUES

Level	Measurement	Routine Test	After Fault
		DC (mΩ)	DC (mΩ)
1	A-N	596.05	617.694
1	B-N	596.77	584.742
1	C-N	595.55	616.918

Oil sample was taken from the transformer after the failure. The results of dissolved gas analysis in oil are shown in Table 5. Combustible gas change rates of combustible gases according to the sampling date were calculated according to the IEC-60599 standard and the result values were found to be above the flammable gas range specified in the standard. In addition, the combustible gas amounts exceeded the typical limit values for power transformers specified in the IEC-60599 standard.

TABLE V
DISSOLVED GASES IN TRANSFORMER OIL

GASES	Routine Test (ppm) 28.04.2022	After fault (ppm) 02.09.2022	Combustible Gas Change Rate (ppm/year)
H2 (Hydrogen)	2	334	522
CH_4 (Metan)	2	225	351
C_2H_6 (Etan)	0	31	49
C_2H_4 (Ethylene)	0	287	452
C_2H_2 (Acetylene)	0	232	365
CO (Carbon monoxide)	128	186	91
CO_2 (Carbon dioxide)	876	820	-88

Different techniques, including the Doernenborg ratio method, Rogers ratio method, and Duval triangle method, are utilised for interpreting oil-dissolved gas data in faulty or suspected transformers [46]. It has been noted that any small deviations between the different methods' assessments do not yield highly conflicting findings. Duval triangle1 is applied as a fault interpretation method in power transformers [47]. Figure 4 depicts the flammable gases CH_4, C_2H_4 and C_2H_2 placed inside Duval triangle1. As stated by Duval Triangle 1, the D2 area indicates the presence of high-energy discharges within the transformer. D2 fault can arise from high local energy arcing, jumping, or magnetic flux around closed circuits between two adjacent conductors, metal rings holding the core legs and insulated bolts in the core, between windings, at the junction and tank, between windings and core or due to short circuits in oil [47].

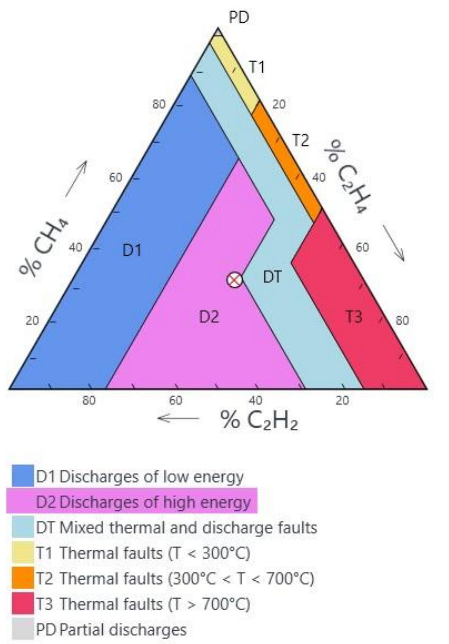

Figure 4. Representation of flammable gases in duval triangle 1

3.2. SFRA measurements

SFRA test was performed by applying 10 V to each winding and measuring the amplitude at 1000 different frequencies. The test was performed with Omicron brand Freneo 800 device. Figure 5 shows high voltage (HV) A-N winding end to end measurement, Figure 6 shows B-N winding HV end to end measurement and Figure 7 shows C-N winding HV end to end measurement.

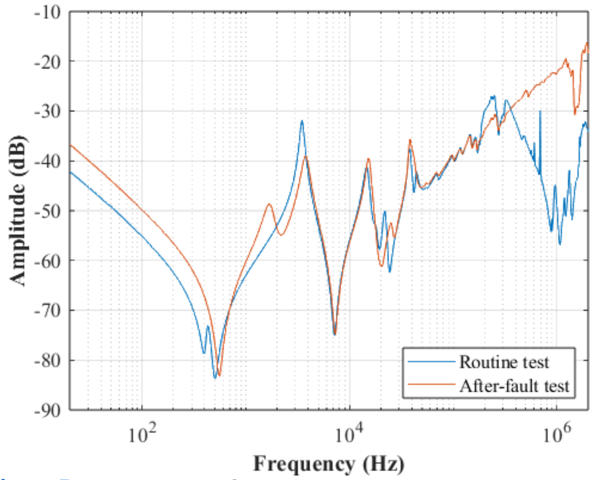

Figure 5. HV A-N SFRA plot

Figure 5 shows deviations at all frequencies in all frequency regions compared to the previous SFRA measurement. In the region up to 2 kHz, it is seen that the core may be damaged. In the region between 2 kHz-20 MHz, it is seen that the windings are deformed. The difference in the last frequency region indicates that the transformer's bushings are cracked and deformed and there is a problem in the conductor connections.

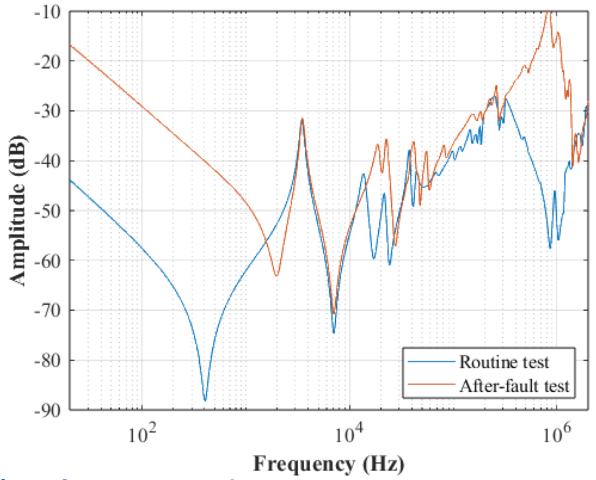

Figure 6. HV B-N SFRA plot

Figure 6 shows deviations at all frequencies in all frequency regions compared to the previous SFRA measurement. In the region up to 2 kHz, it is seen that the core may be damaged and the winding is short-circuited. The difference in the last frequency region indicates that the transformer's bushings are cracked and deformed and there is a problem in the conductor connections.

Figure 7 shows deviations at all frequencies in all frequency regions compared to the previous SFRA measurement. In the region up to 2 kHz, it is seen that the core may be damaged. In the region between 2 kHz-20 MHz, it is seen that the windings are deformed. The difference in the last frequency region indicates that the transformer's bushings are cracked and deformed and there is a problem in the conductor connections.

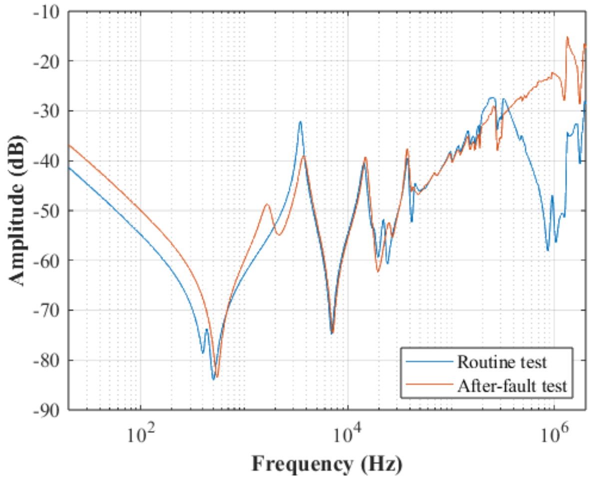

Figure 7. HV C-N SFRA plot

3.3. Statistical results

In this study, CC, SD and relative factor were used as the most common and effective methods for evaluating SFRA test results. The statistical factors calculated according to frequency regions are shown in Table 6.

TABLE VI
CC AND SD VALUES OF SFRA AFTER FAILURE

Frequency Region	CC			SD		
	A phase	B phase	C phase	A phase	B phase	C phase
f_1	0.9986	0.9625	0.9988	5.5847	27.8710	5.1530
f_2	0.9982	0.9924	0.9983	3.3418	6.6439	3.2865
f_3	0.9768	0.9475	0.9733	9.2056	14.2053	9.9284
f_4	0.9779	0.9093	0.9856	23.6437	18.8954	20.7449
f	0.9829	0.9480	0.9843	10.1749	19.2628	9.6348

TABLE VII
SFRA, R_{XY} VALUES AFTER FAILURE

Frequency Region	R_{xy}		
	A phase	B phase	C phase
Low	1.25	0.49	1.35
Medium	-0.04	-0.11	-0.05
High	-0.25	-0.26	-0.20

4. CONCLUSION

In order to evaluate the SFRA test results of the transformer in terms of fault condition, the measurement results were analyzed in the range of IEC four different frequency zones determined in relation to the possible fault type. For all frequency regions, a difference between the

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SFRA measurement results was observed in all frequency regions, especially in the f1, f3 and f4 region in the B phase, also A and C phases showed similar SFRA measurement results. The calculation results of the statistical methods (CC and SD) obtained for the transformer are given in Table 6. The calculated values of the relative factor are shown in table 7. All values in Tables 6 and 7 show that the evaluation indices are above the threshold values. When the results are analyzed; for almost all frequency regions, all available methods (CC, SD and relative factor) indicate the presence of winding deformation.

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