Analysis of the Performance of Distribution Transformers under Short Circuit Conditions. Experiments

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Abstract - **The design of power transformers is heavily influenced by their performance during short circuit. This paper explores the experimental analysis of a power transformer with circular concentric coils, utilizing metal foil conductor in the low-voltage winding, and a rated power of 2000 kVA. To validate its behavior, the study employs Frequency Response Analysis (FRA), a widely recommended diagnostic method for identifying internal faults in power transformers. Furthermore, the paper provides insights into the design specifics of power transformers used in renewable energy power plants. By highlighting the unique aspects and criticalities examined, this study establishes itself as a niche contribution to understanding safety in transformer operation. The research also delves into experiments conducted in a high-power laboratory to investigate how transformers respond to the dynamic effects of short circuit. Particular attention is given to the thermal and mechanical impacts of short circuit currents, with an emphasis on their negative consequences. Additionally, the paper discusses a system configuration where direct current (DC) produced by photovoltaic cells is converted into alternating current (AC) using one or more inverters connected to the low-voltage windings of a step-up transformer. Finally, the study underscores the importance of assessing the short circuit behavior of power transformer, focusing on the irreversible deformations caused by axial and radial forces during short circuit events.**

Cuvinte cheie: *transformator de distribuţie, circuit de putere, scurtcircuit, plot, defect, înfăşurare de joasă tensiune, centrala electrica, resurse regenerabile.*

Keywords: *distribution transformer, power circuit, short-circuit, tap, fault, low-voltage winding, power station, renewable resources.*

I. INTRODUCTION

A transformer is a static electrical device that transfers electricity from one circuit (the transformer's primary) to another (the transformer's secondary) by the law of electromagnetic induction. A transformer consists of a ferromagnetic core with two or more windings insulated from each other and from the core.

The winding that receives energy is called the primary winding (and behaves as a receiver), and the winding that supplies energy to an external circuit is called the secondary winding (and behaves as a generator) [1], [2], [3].

The magnetic flux, which varies in time with the frequency of the primary current, induces in the transformer windings an electromotive voltage of the same frequency, with values proportional to the number of turns of the windings.

Power transformers are subject to an increased failure rate due to the occurrence of external faults, which are characterized by short circuits caused by equipment within the distribution system to which the transformer is connected, as well as the occurrence of internal faults, which can occur within the transformer and are characterized by short circuits between turns of the same phase, short circuits between windings, and the tank or at the transformer terminals, environmental factors such as temperature, humidity and corrosive substances can also cause transformer failure.

If no action is taken during the service life, the superior quality of the modern insulators may deteriorate and the insulators will age, eventually leading to transformer failure, so it is imperative to check the condition of the insulators and insulating materials on a regular basis.

When a short circuit occurs, high currents flow through the transformer, not only heating the transformer, but also creating electromagnetic forces that can damage the transformer winding [1].

The flow of power and energy through the transformer causes active and reactive power losses due to losses in the magnetic circuit, losses in the windings due to the Joule effect, eddy currents or magnetostriction.

The presence of moisture in the transformer leads to a deterioration of the insulator condition and consequently to a high risk of heat induced solid insulation failure (e.g. in the paper barrier). Failures due to short-circuit currents are inevitable in split-winding transformers with stabilizing windings and the resulting transient electromagnetic force can cause damage to equipment [4].

A power transformer plays an essential role in power distribution systems. With the increase in grid capacity and transformer capacity, the number of short circuit accidents in power transformers has increased significantly [5], [6]. Studies discussing short-circuit fault can be found in the references listed below [9-13].

Transient short-circuit current can cause a short-circuit force that induces critical mechanical stress on a transformer when the short-circuit condition occurs. [7], [8].

II. Design Details of Transformers Used in Power Plants Producing Electricity from Renewable Energy Sources

One of the most important pieces of equipment in an electrical distribution network is the power transformer. The recent energy crisis, along with the push for new forms of green energy, has driven the need for distribution transformers to adapt to harmonics produced by electrical inverters and imbalances caused by unbalanced consumers or other factors. These transformers, which can handle up to 10 MVA, are designed to operate with low losses and voltage ratios that are tailored to specific needs [14].

Depending on the time of day, they function as either step-up or step-down transformers and must meet various individual, standard, or special requirements dictated by specific regulations.

One key issue is that the presence of harmonics results in additional losses within the transformer—both in the windings and the magnetic core—leading to increased heating and a lower thermal class for transformers in substations. The growing amount of energy generated by photovoltaic systems and subsequently converted and distributed through medium-voltage networks has posed new challenges for transformer designers, particularly in addressing the specific operational conditions in inverter circuits [15].

In these systems, the direct current (DC) generated by photovoltaic cells is converted into alternating current (AC) through one or more inverters connected to the low-voltage windings of a step-up transformer.

Fig. 1 illustrates the general configuration of such a system.

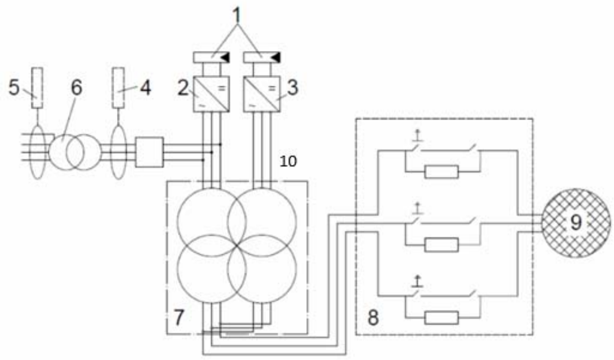

Fig. 1. Schematic system design of the MV-system (1 - photovoltaic generator; 2,3 - photovoltaic inverters; 4,5 - current transformer; 6 - auxiliary transformer; 7 - LV side of the MV transformer, 8 - regular MV switch-gear; 9 - MV grid; 10 - MV side of MV transformer).

The technical solutions used in the construction of these transformers vary from manufacturer to manufacturer, but generally the type of transformer with two secondary windings, each with half windings for both low voltage (LV) and high voltage (HV), arranged concentrically, is used.

When an inverter becomes inactive, current imbalance occurs, resulting in high loss currents and transformer heating. To avoid these effects, the solution is to use semi-winding on low voltage (LV) and high voltage (HV), arranged according to the diagram in Fig. 2.

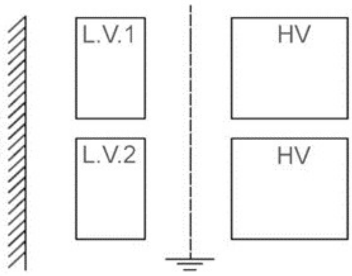

Fig. 2. Power transformer with 4 concentrated windings, two primary and two secondary.

The magnetic impedances of the LV1-HV and LV2-HV windings are almost equal, and the low voltage (LV) winding is axially split. However, this type of construction is large and LV connections are difficult to make. However, this design is preferred by most manufacturers of power transformers used in power plants producing electricity from renewable energy sources.

Since inverter-fed transformers are fed by low-voltage (LV) windings with significant harmonic content and are often subject to transient regimes, the most common type of transformer from a design point of view is the three-winding transformer: two LV windings and one HV winding [14].

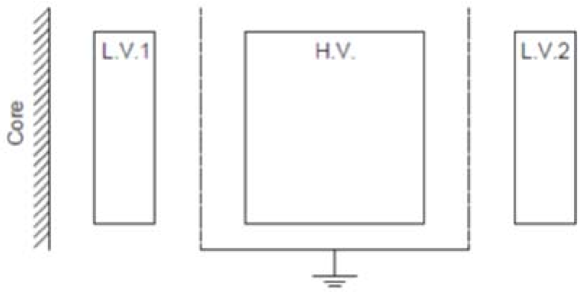

Fig. 3. Power transformer with 3 concentrated windings, two secondary and one primary.

One type of concentrated winding transformer used in renewable power plants is an 8.4 MVA power transformer with one 33 kV LV winding and two 0.66 kV HV windings with the following characteristics:

Transformer rated power, S_N = 8400 kVA; HV side voltage, U_{HV} = 33 kV ± 2 × 2.5%; LV side voltage, U_{LV} = 0.66 kV / 0.66 kV; rated current of energized winding, I_N = 147 A/3674 − 3674 A; vector group, ΔY11Y11; cooling type, Oil Natural Air Natural (ONAN); windings, aluminum conductor, non-circular (oval).

Short-circuit voltages:

- $U_{k\ 75°}$ = 7.35%-LV 2u-2v-2w;
- $U_{k\ 75°}$ = 7.49%-LV 3u-3v-3w.

Rated current short-circuit losses:

- $P_{k\ 75°}$ = 28,270 W-2u-2v-2w;
- P_k = 30,506 W-3u-3v-3w.

No-load losses according to rated conditions P_0 = 6200 W:

- 1U-1V-1W–HV winding;
- 2u-2v-2w–LV winding no. 1;
- 3u-3v-3w-LV winding no. 2.

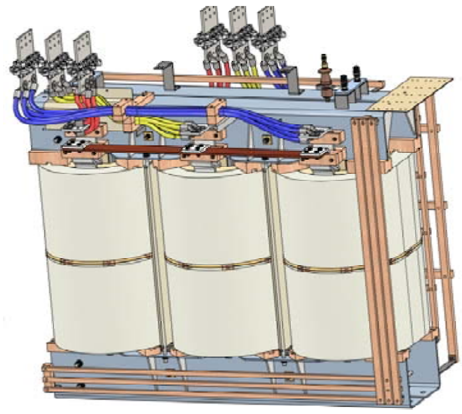

Fig. 4. Power transformer used in power plants to generate electricity from renewable energy sources.

III. RESEARCH METHODOLOGY

The method used for Frequency Response Analysis (FRA) is made with central conductor of the coaxial measurement should be connected directly to the transformer terminal using the shortest possible length of unshielded conductor. The shortest possible connection between the screen of the measuring lead and the flange at the base of the bushing was made using braid. A specific clamp arrangement or similar was used to make the earth connection as short as possible. This method was expected to give repeatable measurements up to 2 MHz.

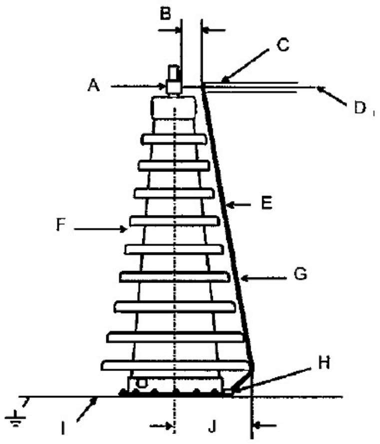

Fig. 5. Frequency Response Analysis connection method (A - connection clamp; B – unshielded length to be made as short as possible; C – measurement cable shield; D – central conductor; E – shortest braid; F – bushing; G – earth connection; H – earth clamp; I – tank; J – smallest loop).

Transformers up to 2500 kVA, 20/0.4 kV are essential components in distribution networks, playing a critical role in transforming voltage for distribution to consumers. Primarily used in substations and transformer stations, they are designed for efficient operation under normal and light overload conditions.

But sometimes, due to damage on the low-voltage side (0.4 kV), they have to withstand a short-circuit regime without damage. In general, well-designed and well-built older generation transformers can withstand the stresses (thermal and dynamic) produced by a short circuit.

In recent years, EU regulations on minimizing active losses, increasing material prices and reducing size have led to the emergence of a new generation of hermetically sealed transformers with new active part and tank manufacturing technology that makes them slightly vulnerable to electrodynamic stresses. From a thermal standpoint, they are also at the maximum temperature limit of oil and seals to make them more cost effective [15].

It is well known that the dynamic forces generated by a transformer short-circuit depend on its internal short-circuit impedance, but also on the external impedance of the circuit or network in which it operates, i.e.:

$$F = f(I^2) \ \text{[N]} \tag{1}$$

$$F = \frac{U}{\sqrt{3} \times (Z_t + Z_r)} \tag{2}$$

where: F = electrodynamic force; I = peak short-circuit current.

$$Z_t = \frac{u_k \times u_2}{100 \times S_N} \tag{3}$$

[Ω/phase] – phase impedance

$$Z_r = \frac{u^2}{Sr} [\Omega] \tag{4}$$

u_k = short-circuit voltage [%]

u = rated transformer voltage [kV]

S_N = transformer power [MVA]

S_r = apparent grid power [MVA]

Thus, the electrodynamic forces are proportional to the square of the peak current:

$$I = I \times k \times \sqrt{2} \ \ [\text{kA}_{\text{max}}] \tag{5}$$

$$k \times \sqrt{2} = f(X / R) \tag{6}$$

According to [3], Table 4:

$$1.51 \le k \times \sqrt{2} \le 2.55 \tag{7}$$

The ability of a transformer to successfully withstand a short-circuit regime shall be determined by special tests to withstand the dynamic effects of the short-circuit, preceded by routine tests.

In general, power transformers of the 2nd and 3rd categories (power over 100 MVA) cannot be tested under short-circuit conditions because of the limited power of the test stations, so the forces generated in this regime and the ability of the transformers to withstand them are checked by calculation.

Category I transformers hermetically sealed or with conservator, oil-immersed transformers, and dry-type transformers, fully equipped as in service, are first subjected to all individual tests:

- determination of the transformation ratio;
- determination of the switching system and the vector group;
- measurement of ohmic resistance of connections;

- dielectric tests (applied voltage, induced voltage, tg δ, partial discharges);
- dry-running tests including measurement of current and losses;
- measurement of short-circuit voltage, short-circuit impedance and active losses.

IV. Two-Winding Transformer Short-Circuit Test

The two-winding transformer short-circuit test consists of applying rated voltage to one winding of the transformer while the other winding is short-circuited to three phases.

In order to avoid magnetic saturation, it is preferable to supply the high-voltage winding, which is further away from the magnetic core, and there are two known methods of short-circuiting: pre-short-circuiting, where the low-voltage winding is short-circuited beforehand, and post-short-circuiting, where the low-voltage winding is short-circuited by means of a precision short-circuiting switch which closes after the high-voltage winding has been supplied.

The values of the short-circuit currents at the extreme and nominal taps [1, 3 and 5] corresponding to the minimum, nominal and maximum voltages of the tested transformer are calculated in [1-7].

The tests were carried out on a 2000 kVA, 33/0.4 kV, oil-immersed, hermetically sealed transformer and consisted of applying nine short circuits, three on each of the three taps (minimum, nominal and maximum) with the corresponding peak current value.

The transformer has the following characteristics:
$S_N = 2000$ kVA; $U_N = 33$ kV/0.4 kV;
$U_1 = 28.5$ kV; $u_{k75°} = 5.72\%$;
$U_4 = 33$ kV; $u_{k75°} = 6.1\%$;
$U_6 = 36$ kV; $u_{k75°} = 6.26\%$; $P_{k75°} = 16.361$ kW.

Applying (3) to the extreme and nominal taps, we obtain:

$$Z_1 = \frac{5.72 \times 28.5^2}{100 \times 2} = 23.23 \quad (\Omega/\text{phase}) \qquad (8)$$

$$Z_4 = \frac{6.1 \times 33^2}{100 \times 2} = 33.21 \quad (\Omega/\text{phase}) \qquad (9)$$

$$Z_6 = \frac{6.26 \times 36^2}{100 \times 2} = 40.56 \quad (\Omega/\text{phase}) \qquad (10)$$

$$Z_r = \frac{u^2}{s} = \frac{6.26 \times 36^2}{100 \times 2} = 1.29 \quad (\Omega/\text{phase}) \qquad (11)$$

The peak factor is chosen according to [3] and the expression:

$$k \times \sqrt{2} = (1 + (e^{-\left(\theta + \frac{\pi}{2}\right)\frac{R}{X}} \sin\theta) \times \sqrt{2} \qquad (12)$$

where e is the base of the common logarithm and θ is the phase angle, which is equal to arctan X/R in radians.

X is the sum of the reactances of the transformer and the system (X_t+X_s), in ohms and R is the sum of resistances of the transformer and the system (R_t+R_s), in ohms, were R_t is at reference temperature.

The result is: $k \times \sqrt{2} = 2.3$- tap 1; $k \times \sqrt{2} = 2.35$-tap 4; $k \times \sqrt{2} = 2.37$ - tap 6.

Next, the currents are calculated and the peak current for each tap is determined:

$$I_1 = U_1 / \sqrt{3}Z = 0.6709kA; \quad I_{peak1} = 1543\ A_{max} \qquad (13)$$

$$I_4 = U_4 / \sqrt{3}Z = 0.5736kA; \quad I_{peak4} = 1348\ A_{max} \qquad (14)$$

$$I_6 = U_6 / \sqrt{3}Z = 0.51238kA; \quad I_{peak6} = 1214\ A_{max} \qquad (15)$$

where: $Z=(Z_t+Z_r)$.

In order to assess the condition of the transformer after the short-circuit, in addition to the repetition of individual tests, the short-circuit inductance shall be measured with precision measuring equipment with an accuracy of at least 0.2 % and the permissible variation of the reactance after each short-circuit may be 2 %, 3 %, 4 % or 7.5 %, depending on the power of the transformer and the type of construction.

The nine short-circuits of 0.5 s duration were applied to the transformer in question, the oscillogram of the short-circuit currents and voltages was recorded, and the current variation during the short-circuit was followed.

The oscillograms shown in Fig. 6, Fig. 7 and Fig. 8 were obtained, and after each test, the short-circuit reactance was measured and compared to that measured before the tests.

After removing the tank and inspecting the active part, the faulty behavior of the transformer is confirmed. The following was observed: displacement of the high voltage coils, deformation of the low voltage terminal, confirmed by the displacement of the wedges on the front side of the windings [15].

Values obtained in the first experimental test on tap 6 and shown in Fig. 6. with terminals u2v2w2 short-circuited: voltage U_{U1V1}=32,8 kV; U_{V1W1}=33,3 kV; U_{W1U1}=33,2 kV; peak current I_{U1}=1238 A; equivalent effective current I_{U1}=478 A; I_{V1}=479 A; I_{W1}= 472 A; duration of the test t= 500 ms.

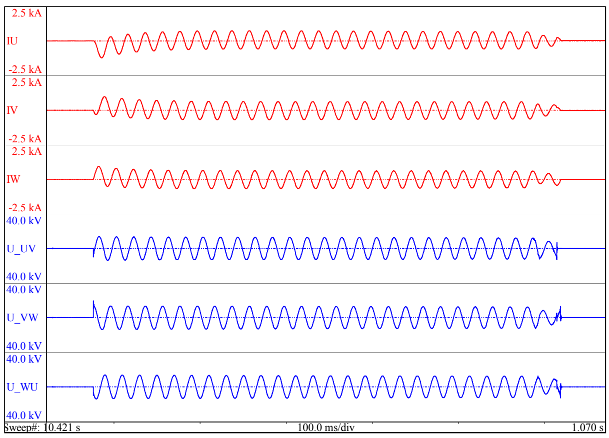

Fig. 6. Oscillogram recorded from the first experiment on tap 6 with short circuit terminals u2v2w2.

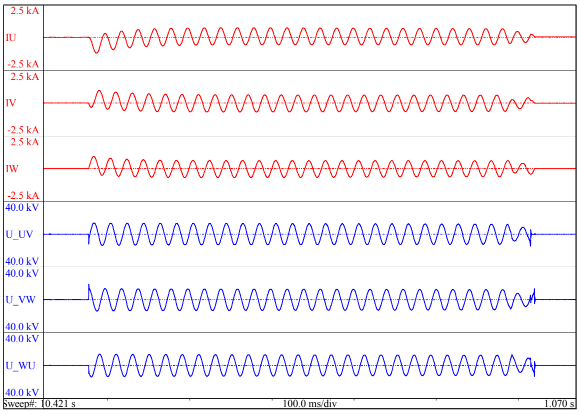

Fig. 7. Oscillogram recorded from the second experiment on tap 6 with short circuit terminals u2v2w2.

Values obtained in the second experimental test on tap 6 and shown in Fig. 7. with terminals u2v2w2 short-circuited: voltage U_{U1V1}=32.9 kV; U_{V1W1}=33.3 kV; U_{W1U1}=33.2 kV; peak current I_{U1}=1223 A; equivalent effective current I_{U1}=474 A; I_{V1}=474 A; I_{W1}= 471 A; duration of the test t= 500 ms.

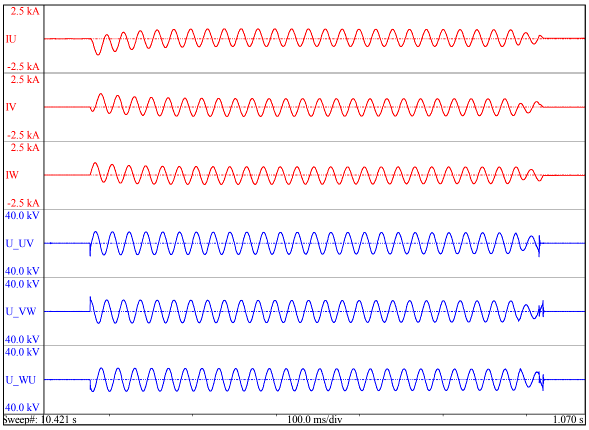

Fig. 8. Oscillogram recorded from the third experiment on tap 6 with short circuit terminals u2v2w2 .

Values obtained in the third experimental test on tap 6 and shown in Fig. 8. with terminals u2v2w2 short-circuited: voltage U_{U1V1}=32.9 kV; U_{V1W1}=33.3 kV; U_{W1U1}=33.2 kV; peak current I_{U1}=1213 A; equivalent effective current I_{U1}=472 A; I_{V1}=476 A; I_{W1}= 476 A; duration of the test t= 500 ms.

V. Verification Methods Using Frequency Response Analysis

Transformer behavior is also confirmed by Frequency Response Analysis (FRA), a recommended method for detecting internal transformer faults.

One of the most common fault modes in the power system is the short-circuit mode, in which power transformers (along with other equipment) are subjected to short-circuit currents and the mechanical stresses generated by these overcurrents during the fault.

Transformers can be damaged by mechanical stress caused by a short circuit. Problems are more common with high power transformers because their short circuit performance is rarely proven by experimental testing.

Frequency Response Analysis (FRA) is a method that provides information about various types of faults occurring in the transformer, such as winding insulation faults, tap changer faults, or winding displacement faults. However, this method does not provide quantitative data to assess the severity of defects.

Therefore, this method is recommended, but not required, to evaluate the condition of the transformer after a short circuit.

In this experiment, a low voltage signal was applied between one terminal of the test object and the tank.

The amplitude of the frequency response is the scalar ratio between the response signal (Vout) and the reference voltage (Vin) and is shown in Fig. 9 - Fig. 17 in dB as a function of frequency [14].

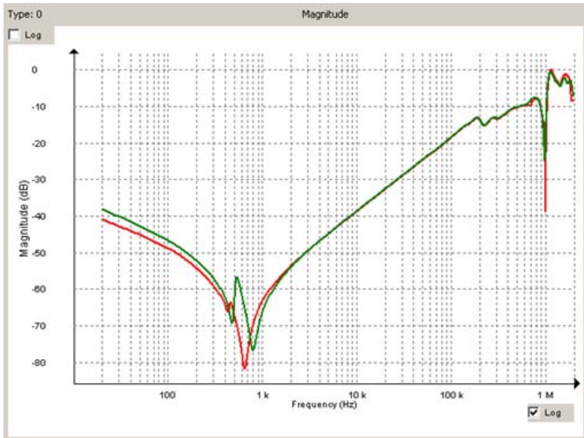

Fig. 9. FRA before and after short circuit on windings 1u-1v.

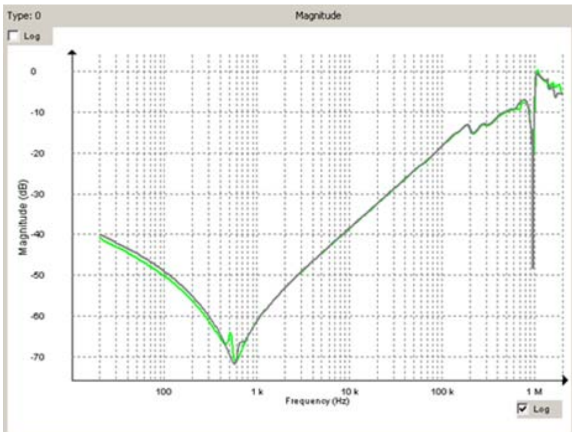

Fig. 10. FRA before and after short circuit on windings 1v-1w.

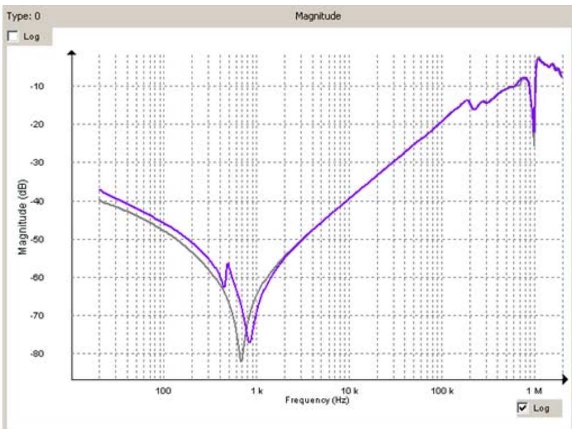

Fig. 11. FRA before and after short circuit on windings 1w-1u.

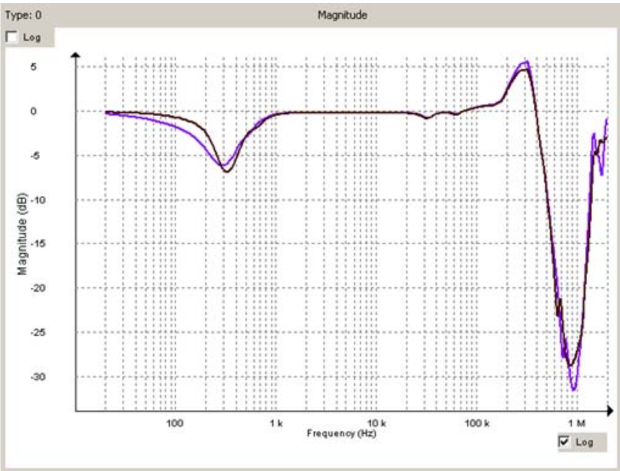

Fig. 12. FRA before and after short circuit on windings 2u-2w.

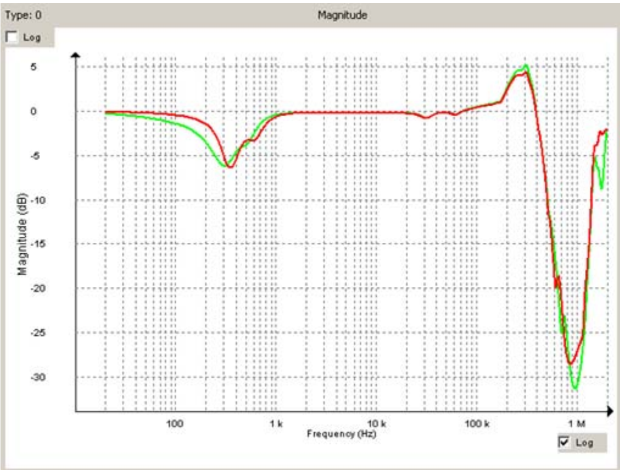

Fig. 13. FRA before and after short circuit on windings 2v-2w.

The phase of the frequency response is the phase difference between the input voltage (Vin) and the output voltage (Vout), expressed in degrees.

The 1 kHz to 1 MHz portion of the frequencies, corresponding to the windings, shows an identical variation before and after the test, indicating that no winding change occurred on the UVW phases, either high or low voltage. This is also confirmed by the variation of the short-circuit reactance.

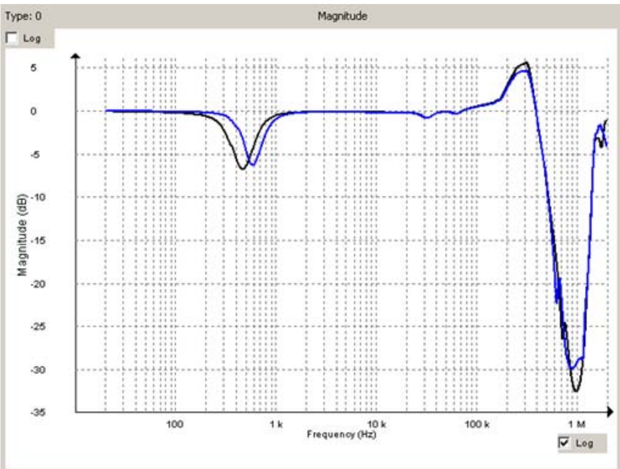

Fig. 14. FRA before and after short circuit on windings 2w–2u.

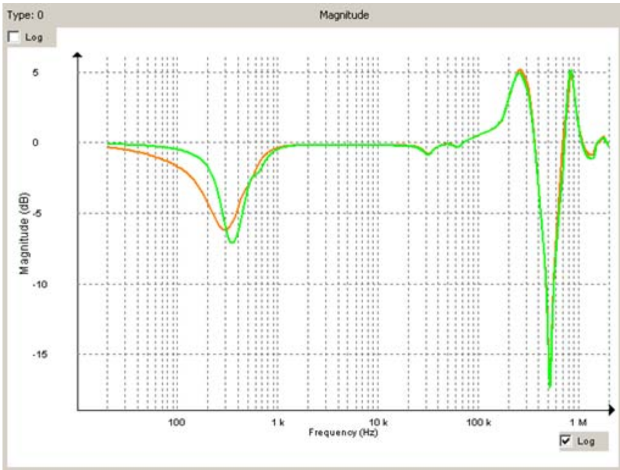

Fig. 15. FRA before and after short circuit on windings 3u-3v.

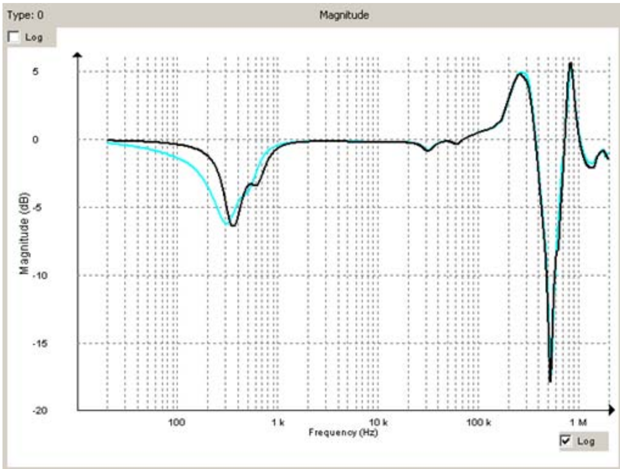

Fig. 16. FRA before and after short circuit on windings 3v-3w.

Since the frequency response of the transformer is closely related to the structure of the core and windings, various frequency response characteristics have been obtained. In Fig. 5 - Fig. 14, the frequency response can be divided into three regions: the low-frequency region, which is determined by the core; the medium-frequency region, which is determined by the interaction between the windings; and the high-frequency region, which is determined by the individual winding structure and internal connections [15].

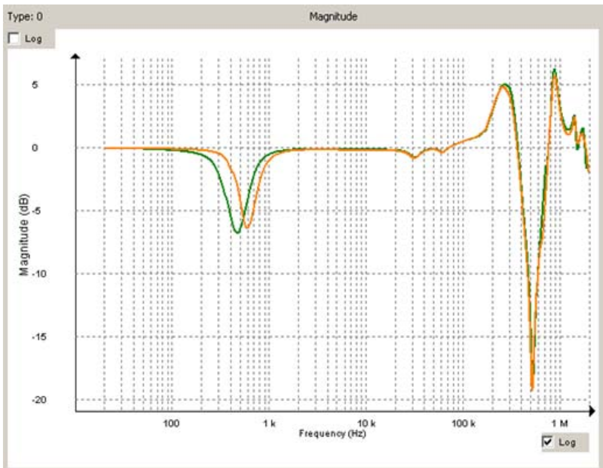

Fig. 17. FRA before and after short circuit on windings 3w-3u.

The frequency response was measured at 50 ohms impedance. Any coaxial cable connected between the terminal and the instrument had the appropriate impedance. The voltage measured at this input terminal was used as the reference signal, and the second voltage signal (the response signal) was measured at the second terminal to the tank.

VI. Results And Conclusions

The experiments were carried out on a 2000 kVA, 33/0.4 kV two-winding transformer as shown in Fig. 18.

In order to assess the condition of the transformer after the short-circuit, in addition to the repetition of individual tests, the short-circuit inductance shall be measured with precision measuring equipment with an accuracy of at least 0.2 % and the permissible variation of the reactance after each short-circuit may be 2 %, 3 %, 4 % or 7.5 %, depending on the power of the transformer and the type of construction.

If this variation exceeds the permissible limits, it is a sign that the windings have shifted during the short-circuit tests, and it is decided whether the transformer behaves correctly or not, according to [3], on the basis of the individual tests and the removal of the tank and inspection of the active part [15].

Fig. 18. Photo of the transformer used for experiments with short-circuited terminals.

The nine short-circuits of 0.5 s duration were applied to the transformer in question, the oscillations of the short-circuit currents and voltages were recorded, and the current variation during the short-circuit was monitored. The oscillograms shown in Fig. 6. – Fig. 8. were obtained and after each test the short-circuit reactance was measured and compared with that measured before the tests.

When measuring the reactance values after each of the 9 tests, a constant increase of the values up to max. 4.4%, slightly above the 4% limit was observed.

The transformer has circular concentric windings, the low voltage winding is made of aluminium foil, so the allowable reactance deviation is 4%. After removing the tank and inspecting the active part, the faulty behavior of the transformer is confirmed. The following was observed: displacement of the high voltage winding coils, deformation of the low voltage terminal, confirmed by displacement of the blades at the front of the winding as shown in Fig. 19, Fig. 20 and Fig. 21.

Tap 1 inductance values before and after experiments: UV: 141.97 and 147.81 mH with a variation of 4.11% VW: 137.83 and 143.97 mH with a variation of 4.45% and WU: 141.24 and 147.69 % with a variation of 4.56%.

Tap 4 inductance values before and after experiments: UV: 206,05 and 213,98 mH with a variation of 3.84% VW: 200.63 and 209.22 mH with a variation of 4.28% and WU: 204.9 and 213.65 % with a variation of 4.27%.

Tap 6 inductance values before and after experiments: UV: 254.72 and 264.02 mH with a variation of 3.65% VW: 248.06 and 258,01 mH with a variation of 4.01% and WU: 252.83 and 263.19 % with a variation of 4.09%.

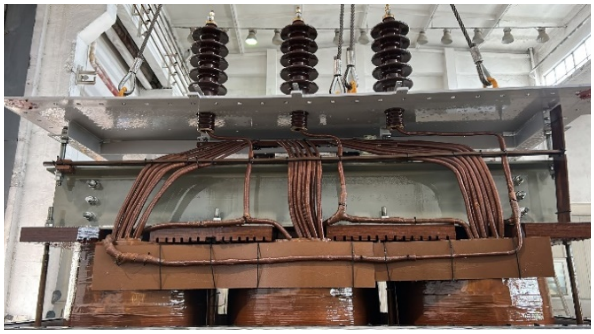

Fig. 19. Photo of the transformer after removal from the tank.

Fig. 20. Photo of the transformer after removal from the tank.

Fig. 21. Photo of the transformer after removal from the tank.

This article introduces the importance of analyzing the short-circuit behavior of power transformers and highlights the irreversible deformations due to axial and radial forces that occur in the windings of the transformer during a short-circuit.

Experiments show the importance of calculating short-circuit currents as a threat to transformer integrity.

In this article is presented experiments using SFRA method, which is an additional method of fault detection, visual inspection. This method makes it possible to detect the effects of short-circuit currents and thus evaluate the effect of mechanical forces on the transformer windings.

The increase in the percentage value of the impedance will be investigated in future research, as this data is critical not only in short circuit experiments, but also in thermal and dynamic stability experiments. Increasing the impedance value will decrease voltage stability and affect other operating parameters [14].

The main conclusions drawn from the experiments are

• No-load transformer operation requires low iron losses (PFe);

• Unbalanced and unsymmetrical behaviors also require careful design attention;

• Surges during thyristor switching (max 500V/µs) require shielding of LV windings and additional insulation;

• Low-voltage windings with 2, 3 or more identical windings present terminal connection problems;

• Separation of the LV and HV windings by columns is necessary to eliminate the disadvantages caused by unbalanced and unsymmetrical conditions;

• Attempting to demonstrate compliance with international standards is a difficult challenge [13].

Future work will focus on analyzing the thermal design and load curve of this type of transformer in relation to specific environmental conditions at the installation site. Particular attention will be given to the increased loads when operating with an auxiliary power supply.

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