Using the Frequency Response Analysis (FRA) In Transformers Internal Fault Detection

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Abstract: This paper deals with diagnostic methods of the internal faults in power transformers. The diagnostic process uses some of the current diagnosis methods (e.g. oil test, dissolved gases analysis (DGA), partial discharge (PD), etc.) to determine the condition of the transformer. In this process, the most frequent diagnostic methods were listed and applied practically to be compared.

A conventional faulty oil-immersed transformer 400 V / 10 kV, 100 kVA was diagnosed and tested with different methods. The parameters and results were compared with a normal working transformer with the same parameters and age. After that an opening of the transformer was performed to approve and to make a visual verification of the diagnostic methods and the used devices. Among the applied methods, the frequency response analysis FRA reflects the real situation of the internal faults such as short circuits, mechanical displacement and deformation of the transformer windings.

Keywords: Transformer Fault Diagnosis, Case Study, Frequency Response Analysis (FRA), Polarization and Depolarization Current (PDC).

1 Introduction:

Power transformers are important and expensive components in electric system networks. Because of the economic motivation, preventive tests and diagnosis are of benefit to predict fault conditions, optimize maintenance and increase reliability of power transformers. There is a large amount of academic and industry researches dealing with transformer diagnosis and maintenance. Advanced diagnostic techniques and recently introduced online monitoring approaches for power transformers, provide the means to enhance the classical maintenance program [1, 2].

Transformer fault diagnosis and repair is a complex task that includes many possible types of faults and demands special trained personnel. Moreover, the minimization of the time needed for transformer fault diagnosis and repair is an important task for electric utilities, especially in cases where the continuity of supply is crucial [3].

Faults on distribution circuits are normally detected by simple over current relays.

The interruptions service of transformer and the failures usually result from dielectric breakdown which may be caused by over current (or overload), short circuit or ground fault, also there is possibility of over voltage due to shifting of neutral if it is with ungrounded neutral.

The short circuit caused a winding distortion if it withstand for long time, winding and magnetic circuit hot spot, failure of accessories such as load tap changers and bushings catastrophic failures of transformers such as dielectric breakdown and short circuit [4, 5].

The full tests for a transformer is a series of: Polarity, Phase-Relation, Ratio, Applied Voltage Test of the HV, Applied Voltage Test of the LV, Induced Voltage Test, No-Load (Excitation) Loss and Excitation Current, Circuit Breaker Test (for CSP transformers only), Impedance

Voltage and Load Loss, Full Wave Impulse and Continuity Check.

When a transformer is removed from service as a result of an automatic operation of the protective devices, the transformer should be tested to be sure it does not have an internal fault.

These tests differ according to the indications of the recording and the protective devices before and after accruing the fault.

In principle, the types of the fault can be classified by analyzing the concentration of gases. But in fact, it is very difficult. The main reasons are showed as following [1, 9, 15]:

I) Accumulating Effect of Fault and Normal Aging: The dissolved gases in oil possess the effect of accumulation. For example, CO, CO_2 which are the aging products of fibrous material, can be accumulated in the condition of non-fault, while there is high concentration of CH_4, the main product of low temperature overheating, in the oil. Therefore, it is very difficult to decide whether these gases are caused by faults or by accumulation.

2) Influence due to Random Error in Measurement: Inevitably, there is dispersion for the analyzed result of the dissolved gases because of the differences of sampling method, suction method and instruments used in these measurements.

3) Possibility of Existence of Multi-Fault: Usually, there is only one main fault leading to failure, but some faults may occur simultaneously. Sometimes, one serious fault involved large area will generate the similar sorts of gases as the unimportant faults.

Fault conditions in a power transformer can be detected in several ways. One method is based on detection of the degradation products of the insulating oil – usually dissolved gases – which are produced as the result of an abnormal dissipation of energy within the transformer. However, this energy, released through fault processes such as overheating, PD and arcing, is often sufficient to generate the fault gases initially in the form of bubbles. Also, high moisture conditions and sudden overloads can cause the inception of moisture vapor bubbles released from conductor insulation.

For faulty transformer it is not real and it is a time consuming to do all the further mentioned tests and it replaced by a diagnostic tests. In this regards, different diagnostic techniques such as PD measurements, tan δ tests, thermal monitoring, oil analysis, RVM and FRA, have been developed and it should be noted that each method could be applied for diagnosing a specific type of problem within transformers.

The FRA method has been found one of the effective for detecting mechanical displacement and deformation of windings inside a transformer [6, 7]. It is particularly useful to determine if there is an inter-turn or OLTC fault following the trip off of the transformer.

However, when using FRA, unless the transformer is totally undamaged, the interpretation of measurement results remains difficult and it relies on the knowledge and experiences of experts. It is, therefore, of vital importance to study the signatures of FRA measurements associated with various winding deformations such that a generic knowledge of the relationship between FRA results and types of deformation can be formed.

Measurements have been performed and designed in laboratory at Schering- Institute, Leibniz University of Hanover, Germany. For a distribution transformer 400 V / 10 kV, 100 kVA oil filled. The decision was taken to investigate the situation of this transformer as a case study by the diagnostic devices and methods.

2 Power Transformer Condition Evaluations

Evaluating the condition of the power transformer is related to the condition of the main components that ensures the normal operation of a transformer. The main components are the windings, core, main tank, bushings, cooling system, oil, and tap changer. Failure statistics of large transformers can be beneficial in determining which component is more important in evaluating the condition of transformers. In Table1, the important failures in percent of some components are presented for power transformers with and without on load tap changer [1].

Table 1- Percentage of Failures of Transformers

Condition	With OLTC	Without OLTC
Tank	6%	17.4%
Tap changer	40%	4.6%
Winding + Core	35%	33%
Auxiliaries	5%	11%
Bushings + Terminals	14%	33.3%

The failure pattern of transformers follows a "bath-tub" curve, as shown in figure 1. The first part of the curve is failure due to infant mortality; the second part of the curve is the constant failure rate; and the last part of the curve is failure due to aging. Referring to Fig. 2, it shows that the numbers of transformer failures in the second part is greater than the last part. Although failed transformers have a higher priority for technical and financial planning but according to the large number of transformers in second the part that do not have any serious problems, planning for them is also important.

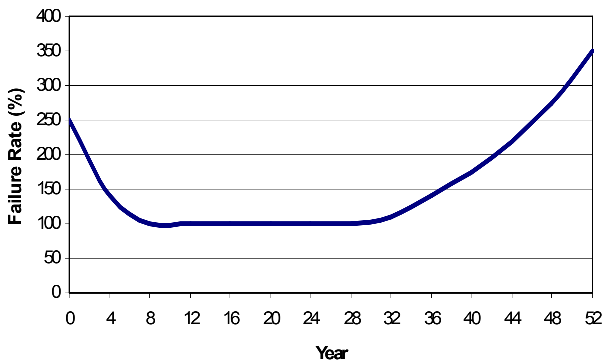

Figure 1 – Bath-tub Failure Curve for Power Transformers [2]

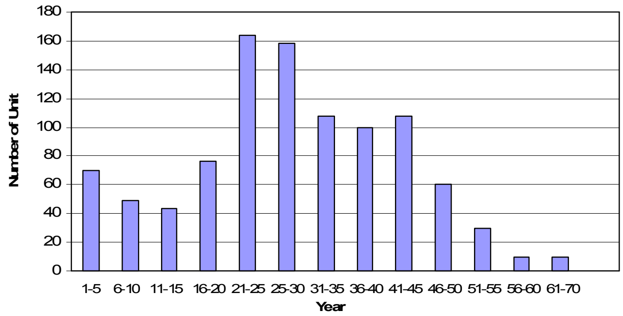

Figure 2 – Age Distribution Profile for Power Transformer [2]

According to the economic evaluation of the transformers, their age, intensity of faults, their roll in the electrical network, capacity value and loading curve, will determine with on line monitoring systems.

3 General Diagnostics Algorithms:

Utilities today are being challenged by three important questions that affect their competitiveness. How can incipient faults in strategically important units be detected at an early stage? How can service-age of transformers be extended without loss of reliability or availability? How can the utilities further reduce the cost for maintenance and refurbishment?

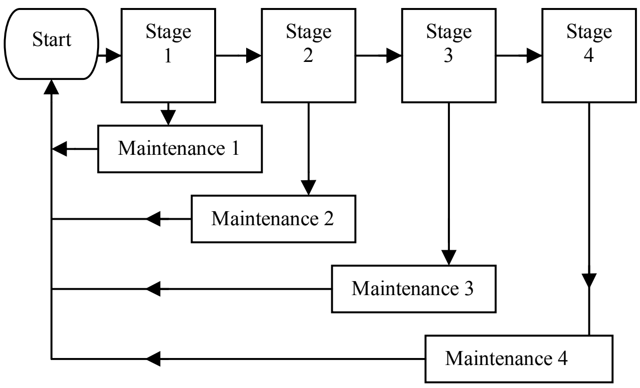

Figure 3- Condition Based Diagnosis and Maintenance Methodology.

To answering these three questions at once, condition based diagnostic and maintenance technique is proposed. With this method, a transformer is observed through its service time. This observation is done in four stages where each stage operates as individual programs (Figure3). This means that the diagnostic method in each stage can be different for each transformer.

4 Condition Based Diagnosis

In the stage 1, according to the history of the transformer e.g., factory tests, installation and commissioning tests, periodic inspections, loading curve, previous faults and oil test, the condition of the transformer will be evaluated.

If a problem is observed in the transformer in stage 1 through its condition evaluation, a Dissolved Gas in Oil Analysis (DGA) test needed to be done (stage 2). Using the DGA test results and the previous information, the problem with the transformer can be determined. The DGA test can be done according to the IEEE C 57.104 1991, Doernenberg, Roger, IEC 60599 Duval's triangle method and EC Triple-Ratio.

The most common final failures involve local or catastrophic dielectric breakdown of paper insulation, this is followed by lengthy partial discharge activity and thermal runaways. According to DGA test results, failures can be categorized in five groups as partial discharge (PD), discharge of low energy, discharge of high energy, thermal oil fault (T.O) and thermal cellulose fault (T.C) [3, 8].

In the stage 3, if a serious fault is observed by an expert in stage 2, other diagnostic tests (see Table II) are done based on the flowchart in Figure 4. For example, if the transformer is subject to discharges, the pulses can be small or large. The small pulses are PD and can be measured by an on line or off line PD detection system. The large pulses with high energy can be from the main flux or bad electrical connections. In the case of bad electrical connections, coil resistance values in all taps must be different than previous values. Each difference between recently and previous no load tests can be referred to as main flux error.

Table 2- Diagnosis Tests for Power Transformers

Components	Tests	Subject
General	Key Gases Oil Condition Partial Discharge	Thermal, Dielectric Dielectric Dielectric
Tap Changer	Key Gases Tap Resistance Current Continuity Power of Motor Drive Oil Condition	Thermal, Dielectric Electrical Electrical Thermal, Dielectric Electrical
Bushings	Tan δ & Capacitance Partial Discharge	Electrical Dielectric
Core	No Load Losses No Load Current Ground Test	Electrical Electrical Dielectric
Windings and paper	CO_2 Concentration Ratio/polarity/phase Furan Concentration Dielectric Response Frequency Response	Mechanical Electrical Mechanical Dielectric Mechanic Dielectric Mechanic
Tank and Connection	Contact Resistance Stray Fields	Electrical Thermal

If measuring or sampling a parameter such as PD or H_2 (dissolved hydrogen in oil) is needed periodically (daily or weekly), it is better to use the online detection and monitoring systems (stage 4). In recent years a number of new devices.

5 Transformer Detection Procedure: Case Study

A simple algorithm was performed to investigate the internal faults and condition of the transformer. After test an opening ceremony were performed to make clear verifications.

1- The inner fault of oil-immersed power equipment can be monitored by using the dissolved gas analysis technique. An oil samples were taken from the transformer bank and the routine techniques, such as EC Triple-Ratio Methods were performed, which are based on calculating the ratios of the characteristic gases

(C_2H_2/C_2H_4, CH_2/H_2, C_2H_4/C_2H_6, etc.). These methods are static technique essentially. The results are come from the measured data in present and only can reflect if here is overheating or discharge.
The ratio of the

$$d(H_2)/d(CH_4) \rangle 10 \qquad (1)$$

which indicate PD in oil [4, 11]. As the PD is related to solid insulation, a certain quantity of CO, CO_2 was observed. Therefore, according to the analysis of relative increment of H_2 and CO, CO_2, the different sorts of the hydrogen-dominant-fault is a distinguished. But in this case the results shows that the $d(H_2)/d(CH_4)$ was about 131.2 which is a real prove of discharges related to solid insulation failure and damaging.

2- The second test on the transformer was the measurements of the resistance between phases to have the basic information about the internal transformer condition with ohmmeter.

The measurements were compared with the same type of transformer without failure. The results are shown in table 3.
From the results it is easily to realize that the faulty transformer has a problem in the high voltage side and the windings resistances are different and very high in compare with normal one which indicates that high voltage windings may be has a partial disconnection.

Table 3: The between phases resistant of Transformer

Winding Resistance	Normal Transformer	Faulty Transformer
U-V	18.1 Ω	4.76 k Ω
U-W	18.1 Ω	294.2 k Ω
V-W	18.0 Ω	288.9k Ω
u-v	0.1 Ω	0.7 Ω
u-w	0.1 Ω	0.7 Ω
v-w	0.1 Ω	0.7 Ω
u-N	0.2 Ω	0.5 Ω
v -N	0.2 Ω	0.5 Ω
w-N	0.2 Ω	0.5 Ω

3- The insulation resistance was measured with the "UNILAP ISO 5kV" device at different voltages such. These measurements were compared with other measurements of an undamaged normal working transformer with the same time of service.
The measurements were compared with the same type of transformer without failure. The results are shown in table 4.

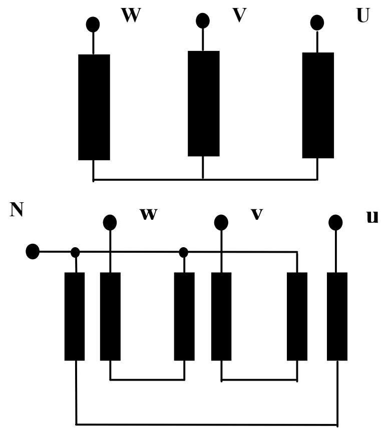

Fig. 4: Transformer schematic diagram, (YZ-5).
Table 4: Insulation Measurements

	First value MΩ		After 1min MΩ		After 3 min MΩ	
	normal	faulty	normal	faulty	normal	faulty
0.5 kV	172	373	338	474	386	491
1 kV	183.3	373	358	442	397	449
2.5 kV	189	313	353	370	386	373

These measurements are different from the normal but they don't show a clear difference or indication between the normal and the faulty transformer that can be considered.

4- Oil characteristics influenced by presence of oxygen, catalysts, and temperature to which the oil is exposed, determines the rate of the aging process. Aging processes are equilibrium reactions, and therefore the decay rate of oil is a function of activity of water rather than absolute

water content. High temperatures and mechanical stresses accelerate the process.
The “Vaisala” sensor in the faulty transformer measured the water content in oil of about 45,61 ppm and using the Oommen’s equilibrium curves for moisture equilibrium for paper-oil system[10], gives a moisture in paper of about 9-10 present which is a very high and indicate a serious problem internal the transformer. The water content for the undamaged transformer was about 24,61 ppm at the same temperature.

5- A reliable and effective method for diagnosing the insulation of the HV equipments in the transformers for condition monitoring of the oil paper insulation is the polarization and depolarization current (PDC) measurement. The measuring system “Dirana” from Omicron, (see in fig.5 the schematic diagram of the PDC measurements connections), acquires data in frequency domain from 1 kHz to 0,1 Hz and in time domain from 0,1 Hz to 100 μHz. For further evaluation the time domain data are transformed to frequency domain. The data for 1 kHz down to 0,1 mHz required about 3 hours to record data from 1 s to 10000s which corresponds in frequencies from 1 Hz to 0,1 mHz.
The insulation between transformer windings is charged by a dc voltage step of 200 V. A long charging time is required (10,000 s) in order to assess the interfacial polarization and paper condition. The initial time dependence of the polarization and depolarization currents (<100 s) is very sensitive to the conductivity of the oil while the moisture content of pressboard influences mainly the shape of the current at longer times [7, 12].

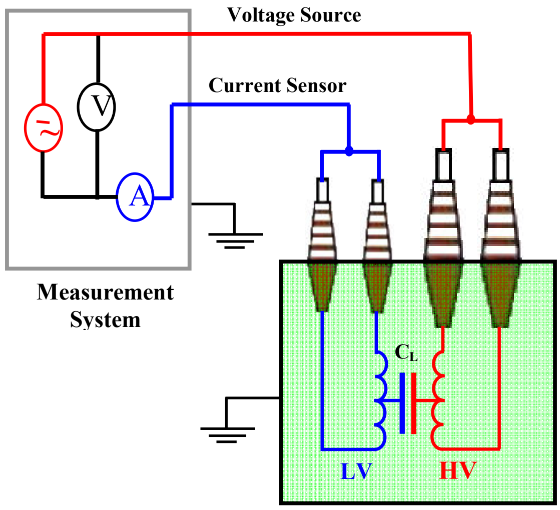

Fig.5: Schematic diagram of the PDC measurements connections.

Oil conductivity has the major influence on the tan δ at the frequency range [13, 16]. The dielectric response was measured and the results of the measurements are illustrated in fig 3 in graphic form.

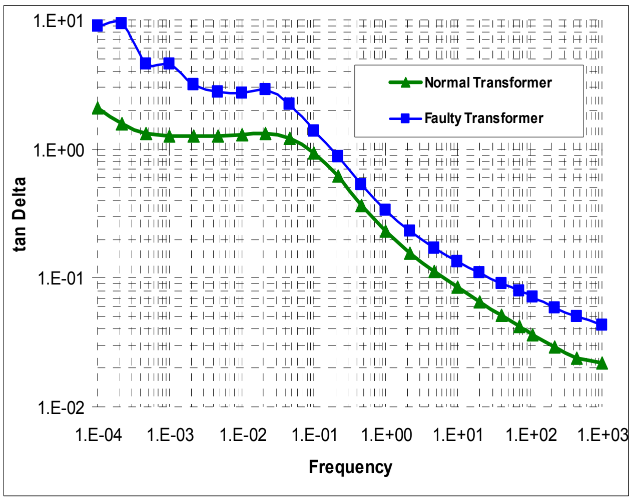

Fig. 6: PDC measurements for the faulty and normal transformer

Analyze the results of the of the PDC measurements shows that tan δ is higher than the normal one, in all frequencies ranges which indicates that water content in the faulty transformer is higher than the normal. But it doesn’t show or reflect the fault place specifically so it cannot be an efficient indicator in this case.

6-The FRA measurements can be considered as finger print of the transformer dielectric conditions. If any changes in the internal transformer dielectric caused for any reason the curves will be changed correspondingly. For that comparison measurements between the faulty transformer and the normal one were performed.

The FRA measurement between the high voltages windings V-U and V-Win fig 4, theoretically should be similar referring to their position in the transformer (see fig.4) but the results shows a clear difference in the characteristics. Normally, the transfer function for the W-w and U-u should be identical as they have the same position and characteristics in the transformer (see fig.7).

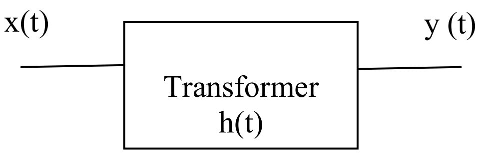

Fig. 7: the transfer faunction applied on the transformer.

The FRA source device applied an input signal x(t) and detected output signal y(t) are measured. From these simultaneously recorded time signals the transfer functions:

$$H(jw) = Y(jw) / X(jw) \qquad (2)$$

are calculated with the aid of the Fast Fourier Transforms (FFT). The transfer function is the Fourier Transform of the impulse response h(t) and is (for a linear system) independent of the applied input signal x(t).

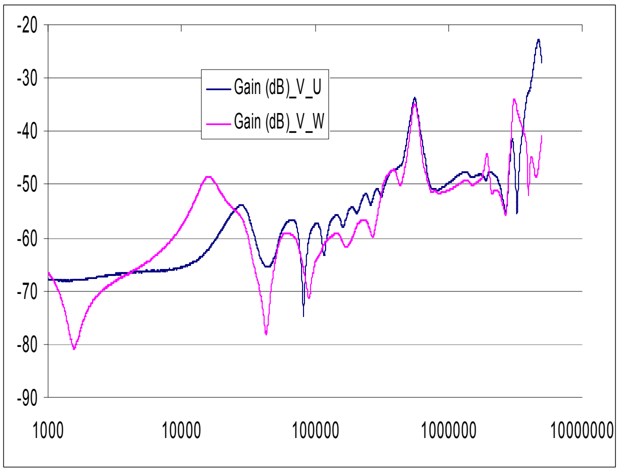

Fig. 8: FRA measurements between the high voltage windings for faulty transformer.

For the faulty transformer, the FRA measurement between the high voltage windings and high – low voltage windings results are shown in figures 8 and 9. The overall characteristics of the FRA responses do not change significantly for the U-u and V-v windings and they are almost similar. For the W-w it has a clear different shape, which can be an evidence for a possible fault in this side of the transformer.

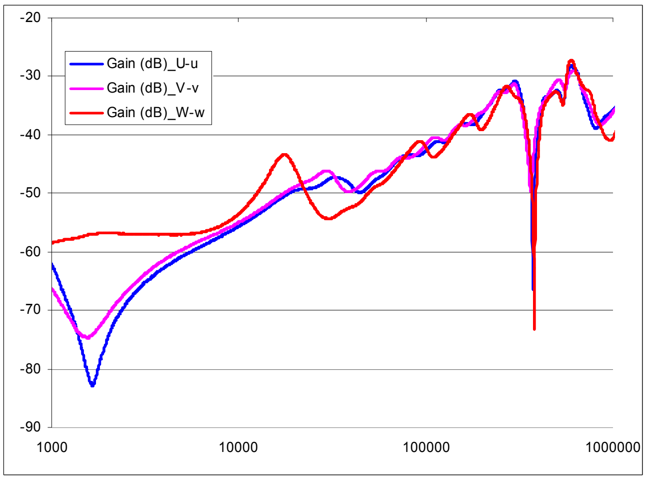

Fig. 9: FRA measurements between the high – low voltage windings for faulty transformer.

The results of the FRA measurements between: the high windings normal transformer and the high voltage windings the faulty transformer is shown in figures 8, 9 , 10 and 11.

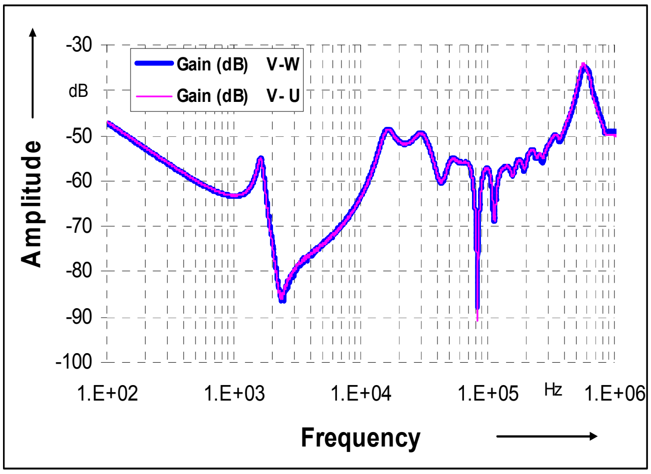

Fig.10: FRA measurements between the high voltage windings for normal transformer

Comparing the FRA measurements between: the high– low voltage windings normal transformer and the high – low voltage windings the faulty transformer. The results show that a high material degradation of insulation properties with a big deformation and disconnection of the W- winding.

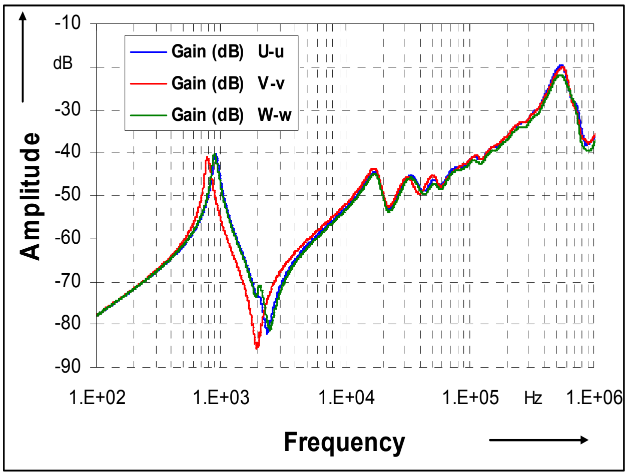

Fig.11: FRA measurements between the high – low voltage windings for normal transformer

Note that the measurements of frequency response spectra for the normal transformer were carried out after it was disconnected for more than 24 hours and it was de-energized to avoid any effect of different states of core magnetization on the transformer windings. Despite that, it was shown that there is an effect of core magnetization prevails mainly in the frequency range up to 100 kHz and when the measurements were provide after disconnecting [17].

6 Transformer Opening:

The main objective of opening the transformer is to make a visual verification of the diagnostic methods and devices. The transformer was opened and the next pictures (Figure 8) show the opening process and the defected winding was the high voltage winding W was hardly defected, deformed and mechanically displaced, as it can be clearly realized in the down pictures. This confirms the measuring and diagnostics results.
Investigations on this transformer as case study using diagnostic devices and methods has shown, that diagnostic tool are available. A variety of electrical test equipment from various manufacturers has been demonstrated and discussed with the institute professors and members [18].

Fig. 12: A picture group of the transformer opening process.

7 Conclusions:

Transformers, one of the most important components of the power systems, play a significant role in facilitating transfer of power to end users.

To evaluate the diagnosis methods of failures in transformers a test procedures are performed and discussed such as: the dissolved gas analysis technique, the resistance between phases, the insulation resistance, water content in oil, the polarization and depolarization current (PDC) measurement and frequency response analysis (FRA).

Investigations on a transformer as case study using diagnostic devices and methods have been shown for a conventional oil-immersed transformer 400 V / 10 kV, 100 kVA which was diagnosed and tested with different methods. The parameters and results were compared with a normal working transformer with the same age. The diagnostic tools are available and the most specific and reasonable was the FRA method. The results show a high material degradation of insulation properties with a big deformation and disconnection of the W- winding.

A visual verification of the results has been performed, (see pictures 12). The experimental results were identical and results emphasized the FRA diagnosis methods. The FRA technique is an effective diagnostic tool for identifying short circuits, mechanical displacement and deformation of transformer windings.

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