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FAULT DETECTION USING FRA IN ORDER TO IMPROVE THE AGING MODEL OF POWER TRANSFORMER

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Abstract. *Power transformers are constantly exposed to mechanical, thermal and electrical stresses during operation. In this paper, the authors propose an improved aging model of power transformers by adding the impact of mechanical deteriorations. In the current practice, the mechanical deformation and dislocation of the windings and core are not sufficiently distinguished as components that influence the aging of the transformer. Hence, the current aging model was expanded with a functional block that contains several typical failures in order to emphasize their impact on the lifetime of transformers and their aging as well. The authors used the Frequency Response Analysis (FRA) method for the fault detection and location of the mechanical deformations of its active parts. The correlation function is used to determine the level of the detected failure. All presented test results are obtained in real exploitation conditions.*

Key words: *Aging model, fault detection, frequency response analysis, maintenance, monitoring*

1. INTRODUCTION

Reliable, safe and continuous production flow in today's industry is of undeniable importance. Modern, automated production cycles are fully based on electricity as the cleanest and the most easily applicable energy source. Any delay in the production can cause potentially significant financial losses and must be entirely prevented or reduced to a minimum duration. Hence, plant engineers must have scheduled inspections of the equipment "health" and planned interventions in the most appropriate point in time, as production must be carried out. That is the most convenient and the cheapest way to maintain a large, valuable, important facility.

As mentioned above, there is no industry without a sustainable electrical power source. Foundations of the electricity relate to the power transformers and generators. Power transformers are irreplaceable and crucial in all areas of the industry, as they step up voltage and thus enable long-distance transmission of electricity with lower looses,

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and step-down voltage and enable its use in medium and low voltage motors, converters, lighting, AC, etc. Any major fault in power transformer causes a power outage and delay in production.

Preventing unplanned outages which can jeopardize production and financial gain became the main task for field test engineers, as they must provide information about equipment "health" and schedule needed services and interventions.

Condition monitoring, fault detection and diagnosis, prognosis and several types of management are effective means to reduce the downtime and the maintenance cost and to improve the reliability and lifetime of the power transformers and generators.

During the last two decades, the use of a large number of theories in order to improve their operations in the field of management, maintenance, monitoring and control of electrical power systems is noticeable. Entire scientific and technical areas have expanded researching these issues. In recent years, business trends in the power sector imply the need to reduce maintenance costs, operate transformers as much as possible and prevent forced outages. Today's development of measurement techniques and methods, as well as the development of software tools and hardware, encourages the rapid development of complex monitoring systems and diagnostic methods for measuring, monitoring, predicting and analyzing potential failures of capital equipment (generators, transformers, boilers, HV motors...) in the power sector. There is a number of off-line and on-line monitoring/diagnostic techniques which are currently used and developed further [1], [2], most relevant being:

- Dissolved gas analysis
- Partial discharges
- Direct hot spot measurement
- Degree of polymerization
- Furan analysis
- On-load tap changers
- Power factor of bushings
- Recovery voltage measurement
- Detection of winding displacement
- Frequency response analysis (FRA)

Three main mechanisms contribute to the insulation aging or deterioration in transformers: hydrolysis, oxidation and pyrolysis. Therefore, insulation aging or deterioration is a time function of temperature, moisture content, and oxygen content [3]. However, these mechanisms can be initiated and accelerated by mechanical deterioration of almost all parts (windings, core...) of the transformer.

This paper emphasizes the need to monitor and analyze mechanical deterioration (deformations) and potential mechanical failures in power transformers. The authors also emphasize the fact that the mechanical deformations of the power transformer further shorten its lifetime. Based on the foregoing, the paper presents an advanced model of aging of the power transformer by adding the influence of mechanical failures on the existing model. As a tool for mechanical deformations, the detection method of the windings frequency response analysis is suggested, in the form of the Frequency Response Analysis (FRA). FRA is an offline test based on the measurement of the impedance, admittance, or transfer function of a particular phase as a function of a wide frequency range which is used as a transformer fingerprint that can be compared with its previous signatures to detect any mechanical deteriorations (such as winding displacements, etc.) [4 - 7].

There are many mathematical methods, algorithms and procedures for signal processing and analysis [8]. FRA is one of the methods that were created as a result of the mentioned multi-year research effort in order to improve monitoring and fault detection in power systems. This method aims to detect and recognize mechanical deformations inside the transformer without the need for its opening and visual inspection. This is one of the main reasons why the authors decided that the results obtained with this method illustrate the importance of the proposed, improved and expanded aging model of power transformers.

2. Power Transformer Aging and Lifetime

Power transformers are constantly exposed to mechanical, thermal and electrical stresses during operation. Therefore, fault detection and monitoring are very important for condition and remaining lifetime assessment of power transformers [9], [10].

Contrary to an ideal transformer, a practical transformer has winding resistance, flux leakage, finite permeability and core losses [11], [12]. A transformer is designed to have sufficient dielectric and mechanical strength to withstand the maximum predicted and expected operating stresses. Various stresses during the service life of a transformer can exceed these expectations and degrade transformer insulation, magnetic core and the whole mechanical structure.

During an unpredicted short-circuit current, axial and radial electromagnetic forces in the windings can significantly exceed the projected values and cause permanent deformation such as tilting and buckling, or destroy the entire winding [13]. Excessive radial forces can cause buckling of a transformer, while tilting is usually caused by axial forces. These forces combined can cause axial bending, winding twisting, and other winding deformations. Certain magnitudes of forces that cross the point of elastic deformation of the conductors can permanently deform the winding, without interrupting it, destroying it, etc. If you do not notice this winding can be safely kept in operation. However, its projected mechanical integrity is compromised and at the time of the next stress, the deformed winding can no longer withstand the projected electromagnetic force of short-circuits, i.e. its mechanical strength is significantly reduced.

For example, when a transformer is taken off-line, a certain amount of residual flux remains in the core. The residual flux can be as much as 50% to 90% of the maximum operating flux, depending on the type of core steel. When voltage is reapplied to the transformer, the flux introduced by this source voltage builds upon the one already existing in the core. Then the magnitude of this inrush current can be up to 10 times the rated full-load current [14]. These operating conditions happen often. There is a special danger to the transformer if it already has some mechanical deteriorations. In this case, additional mechanical deterioration (dislocation and deformation of the windings and/or core) occurs due to additional stress forces. When the transformer returns to the nominal operating regime, these deteriorations can be reflected in the increase in losses, which inevitably leads to an increase in temperature, increased partial discharges, increased vibrations, etc.

Planning the flow and schedule of activities and selecting measurement and test methods for testing power transformers are the first steps in planning maintenance. Fig.1 presents a simplified algorithm for maintenance and testing of power transformers in order to systematize the flow of all necessary activities.

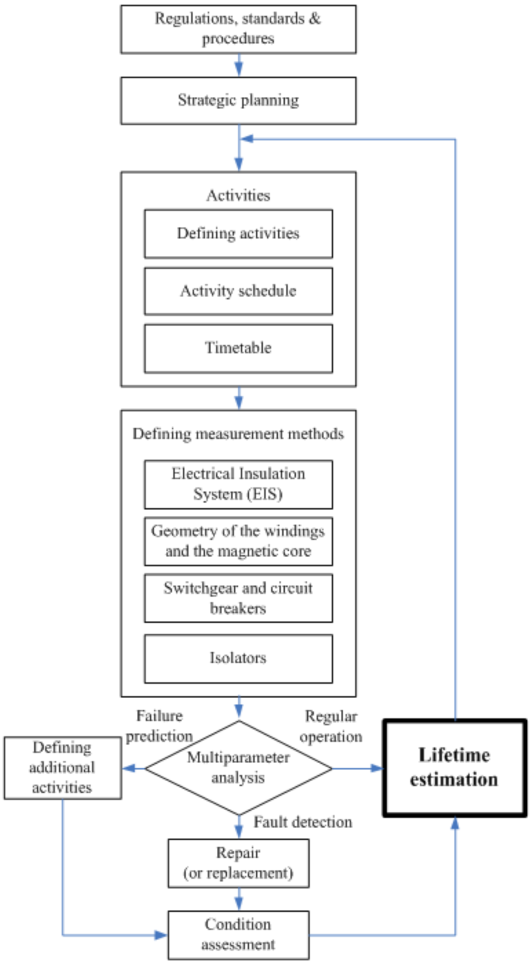


Fig. 1 Maintenance and testing algorithm

Since it is practically impossible to determine the exact size of the damage within the windings and/or core (without opening a transformer) the authors recommend that the detection of mechanical deteriorations is done by measurements using some of the previously mentioned non-invasive measurement methods.

The results of these measurements should be used as a reliable indicator of the weakening of mechanical stiffness and the occurrence of deformations, and consequently reducing the operational readiness and lifetime of the transformer. Since mechanical deteriorations are a consequence of stochastic undesirable effects, it is difficult to estimate their impact on the transformer's lifetime.

Transformer age is an important factor to consider when identifying candidates for replacement or rehabilitation. Although actual service life varies widely depending on the manufacturer, design, quality of assembly, materials used, maintenance and operating conditions, the expected life of a transformer is usually about 40 years. Some of the most important issues in the power system are closely related to the assessment of the remaining lifetime of capital equipment such as power transformers.

2.1. The temperature influence on the lifetime of power transformer

"Bathtub curve" (Fig. 2) represents a traditional approach to the graphic representation of the lifetime of the power transformer and describes its hypothetical failure rate versus time. However, the accelerated development and widespread implementation of on-line and real-time monitoring systems, as well as implementation of modern maintenance strategies (condition-based maintenance, reliability centred maintenance, risk-based maintenance, etc.) have raised numerous criticisms of this approach. There are also some papers [15], [16] that point to significant shortcomings in this approach.

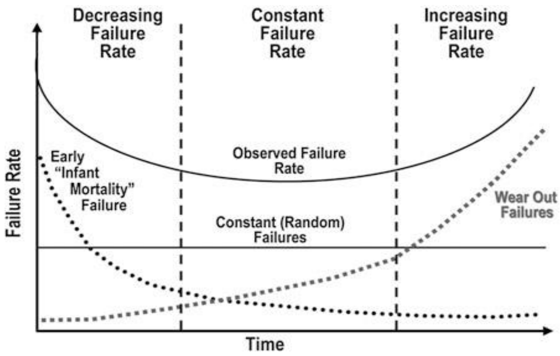


Fig. 2 Bathtub Curve [15]

The traditional approach to aging of the transformer is directly related to aging of transformer insulation that is a time-dependent function of temperature, moisture content, and oxygen content. The authors of this paper are trying to emphasize that a prior statement should be extended with the impact of mechanical failures in the lifetime and aging of the power transformer.

2.2. Mechanical failures and improved aging model

Overview of typical causes of transformer failures is given in Table 1 [17].

Tab. 1 Typical causes of transformer failures

Internal	External
Insulation deterioration	Lightning strikes
Loss of winding clamping	System switching operations
Overheating	System overload
Oxygen	System faults (short circuit)
Moisture	Mechanical deformations & damages
Solid contamination in the insulating oil	
Partial discharge	
Design & manufacture defects	
Winding resonance	
Mechanical deformations & damages	

The authors of this paper enhance the mentioned table that is complemented with mechanical failures whose causes can be both inside and outside of the transformers. This is done because of two reasons. The first reason is the need to extend the existing aging model with mechanical movements and deformations that can accelerate the rate of aging. The second reason is the need to timely recognize the type of failure in terms of selecting the most appropriate measuring methods that can detect, locate, monitor, and/or analyze its impact on the condition of the power transformer.

The condition assessment of power transformers is always preceded by their lifetime assessment. The remaining lifetime assessment is closely linked to aging. These relationships indicate the need for a more accurate aging model of transformers. The existing aging model [10] has a significant drawback because it does not take into account the impact of mechanical failures in the lifetime and aging of the power transformer. Fig. 3 shows the improved aging model that takes into account six major causes of mechanical failures. According to the aging model shown in Fig. 3, it is possible to determine the place and role of standard (traditional and new) measurement and diagnostic methods for monitoring and assessing the condition of the transformer [17–20].

To detect any mechanical change on power transformers, the best available method is by performing frequency response analysis (FRA) measurement on the transformer winding [21]. As a comparative, leakage reactance and excitation current and power measurements are usually applied. Not all of them can produce enough force to cause deformation of the winding or core, but can cause winding and core insulation breakdown and turn-to-turn faults. Recent studies tend to estimate the remaining life of the transformer by means of deep analysis of the results obtained by electrical and chemical tests. Usually, the expected power transformer life can be presented as a curve (Fig 4).

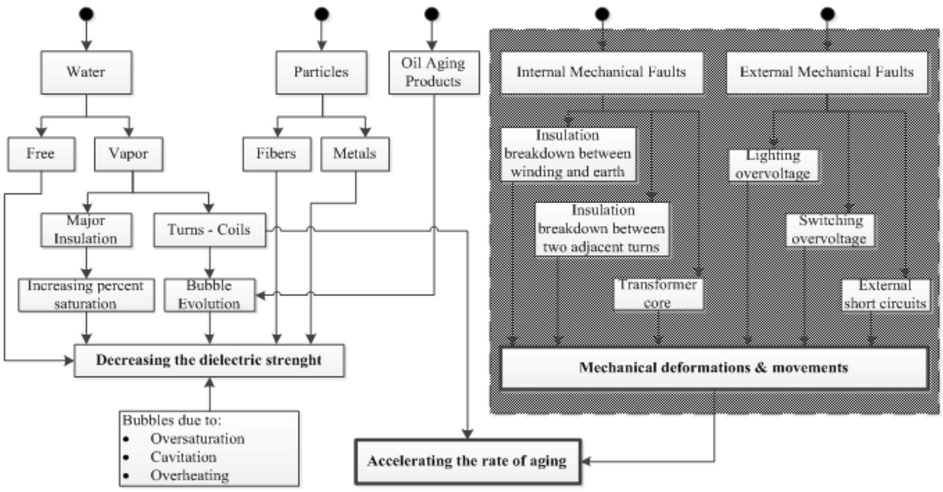


Fig. 3 Improved power transformer aging model

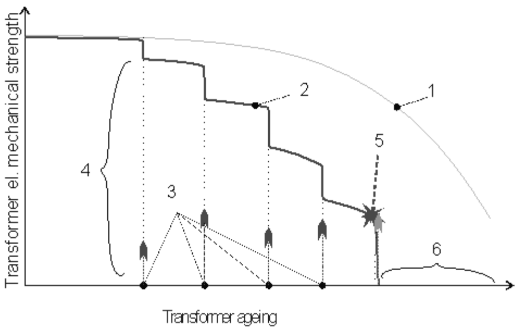


Fig. 4 Transformer aging curve: 1 – normal aging curve, 2 – accelerated aging curve, 3 – electromechanical stresses, 4 – insulation strength reserve, 5 – insulation breakdown, 6 – shortened transformer life

Each time when a transformer experiences a short circuit fault, or overvoltage, it loses some of the factory designed mechanical and electrical strength. After a long time in service, cellulose insulation becomes brittle, and cannot maintain designed mechanical specs, although dielectric strength cannot be threatened.

The most powerful units, 10 MVA, 20 MVA and more, are usually carefully monitored as they provide electricity for major production sectors. Those less powerful and usually cheaper, are subjected to scheduled visual inspections and perhaps scheduled insulation resistance test before being put to operation. Sometimes, even the most monitored and maintained transformer insulation can breakdown suddenly, causing unwanted outages and rising economic pressure on facility management.

Transformer failure must be estimated in a timely manner to enable top management to make the right decision (repair or replace). There are several non-invasive measurement methods (some of them are mentioned above) that may indicate some of the potential mechanical failures. The practice has shown that the FRA measurement method is the most applicable because it can detect and diagnose the greatest number of mechanical failures.

3. Power Transformer Mechanical Condition Assessment Using Frequency Response Analysis

Frequency response analysis (FRA) is a measurement method that is used to detect and identify the mechanical failure of power transformer such as movements and deformations of its windings and core [21–32]. The FRA is based on measuring the impedance of the transformer (R, L and C) that is related to the geometry of the core and windings. Actually, FRA sees the transformer windings as a distributed network of the RLC parameters, or frequency-dependent impedance. Those parameters are mainly geometry dependent, since any change in geometry alters parameters values, for example, capacitance. That change will reflect as a deviation in the frequency response of the winding. In general, any system represented as a ‘black box’, with its input and output, will react to the input signal (Fig. 5). Output signal depends on system parameters, attenuation, and input signal amplitude and frequency. The behavior of the system on the input signal is defined by the transfer function [23], [24].

FRA (SFRA - Sweep Frequency Response Analysis) is a modern, simple and reliable method for recording winding frequency responses. Responses are gathered for every winding, regarding transformer vector group, by injecting sinusoidal voltage at the one winding end. The frequency response is derived by varying frequency of the input signal from f_{start} to f_{stop} of, while amplitude is kept stable. The voltage amplitudes and phases at both ends are measuring simultaneously. Frequency range is usually predefined, and it is common to start frequency response recording in a few MHz area and tuning frequency down to a 10 Hz or 20 Hz. For oil-filled power transformers, range from 20Hz up to a 2 MHz is enough, regarding test duration and optimal, useful responses spectrum. Responses in the frequency domain are considered as a fingerprint of the winding geometry. Any change in response could indicate deformation in winding geometry. Recorded frequency responses are compared to a fingerprint response which was recorded when the transformer was considered "healthy". It is desirable to have recorded fingerprint responses recorded during the handover tests. That is common for a new powerful GSU and distribution transformers, but not for small units. If there are no recorded fingerprint responses, the comparison could be made to transformers of the same type, "sister units", or between the two phases of the same winding. Comparison is made visually, or by the means of statistical and mathematical operations. In engineering practice, the responses are divided into a few frequency sub-bands, in which SFRA traces showed sensitivity for failures specified in Table 2.

Tab.2 Frequency sub-bands sensitivity

Frequency sub-band	Failure sensitivity
<2kHz	Core deformations, open circuits, shorted turns, residual magnetism
2kHz – 20kHz	Bulk deformation, winding deformation, clamping structure deformation
20kHz – 600kHz	Windings, main or tap winding
600kHz – 2 MHz	Windings, loose connection, bad grounding influence

Comparison between two frequency responses is performed using a statistical indicator for investigating the transformer's mechanical condition. Cross correlation (CC) coefficients are widely used mathematical relation for response deviation assessment. Simplified, cross correlation of traces X and Y is (1) [33 - 38]:

$$CC = \frac{\sum_{i=1}^{n}(x_i - \bar{x})\cdot(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \cdot \sum_{i=1}^{n}(y_i - \bar{y})^2}} \qquad (1)$$

Where x_i and y_i are two traces being compared, and $\bar{x}$ and $\bar{y}$ are the means values. If two sets of numbers are perfectly matched, the value of CC is 1, whereas if there is no resemblance between these two sets, the value is 0. A rough estimation of the CC factors meaning is provided in Table 3.

Tab. 3 Frequency sub-bands sensitivity

Corellation	CC factor
Good	0.95 – 1.00
Fair	0.90 – 0.94
Poor	0 – 0.89
No correlation	< 0

There is a new FRA interpretation [35] that propose improved CC that include the phase response in the interpretation. This approach implies that instead of Euclidean distance, it introduces a complex distance which includes phase information. The phase information increases the sensitivity of the cross-correlation coefficients.

Sweep FRA (SFRA) measurement is accurate, repeatable, non-destructive since injecting voltage whose amplitude is only 10 Vpp. Since the instrument “knows” the precise signal frequency, while sweeping, narrowband filters can be applied in order to eliminate noises.

3.1. Example 1 – Faulty transformer

Three phase, two winding transformer geometry can be inspected within an hour, and since instruments plot responses during the test, an experienced engineer can make a suggestion instantly as to what might be a problem with the transformer. An example of the similar situation will be presented. Three phases, a two winding transformer which powers few pumps in a power plant had been turned off by Buchholz relay tripping a switch. It was very important to do fast fault recognition, and SFRA method seemed appropriate. Immediately after a dismantling HV and LV transformer cables, SFRA test is done. Since it is a very small unit, there are no factory recorded fingerprints. High voltage winding open-circuit SFRA traces are presented in Fig. 5 and short-circuit SFRA traces are presented in Fig. 6.

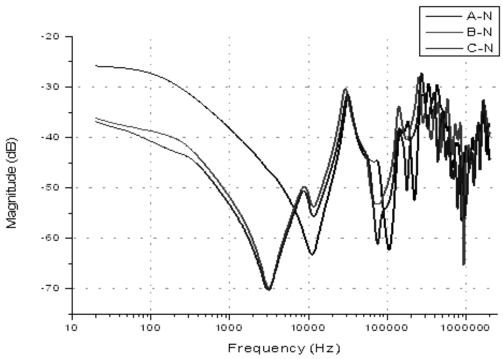


Fig. 5 Open-circuit primary winding SFRA traces

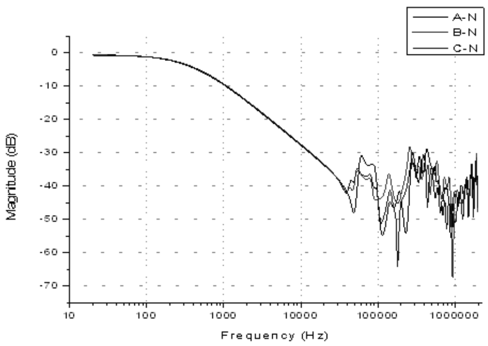


Fig. 6 Short-circuit primary winding SFRA traces

In general, traces do not match perfectly, but it was clear that the one from phase A deviate from the other two responses significantly. It was obvious in the middle and low-frequency range. Winding frequency responses gave an indication that phase "A" winding had shorted turns and that transformer would need a time-consuming repair (Table 1). Calculated CC factor in frequency sub-band 20 Hz – 5 kHz, CC=0.9785, and for sub-band 5 kHz-15 kHz, CC= - 0.4821, confirmed an already obvious problem. It is confirmed later, with no load loss measurement (Table 4). Even during a no-load test, Buchholz relay was filled with combustible gasses within a minute. It was a sign of a stable, firm turn-to-turn connection, followed by great local temperature rise. The transformer was sent to the factory for dismantling and visual inspection. After dismantling a transformer, and taking the core and windings out of the transformer tank, visual inspection gave no indication of the fault in the windings and core of the transformer. So, windings were energised again, so it was possible to visually check and confirm turn to turn insulation problem. After unwinding has been done, it was obvious that inter-turn insulation was degraded and that a few turns had actually weld themselves (Fig. 7).

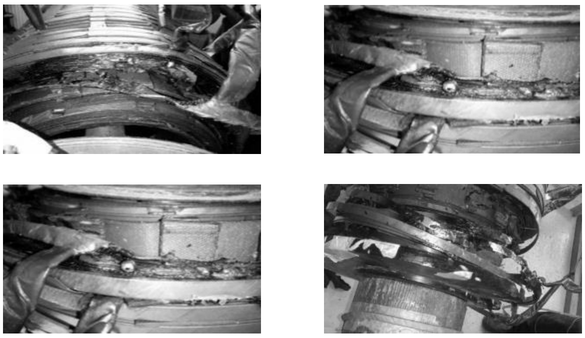


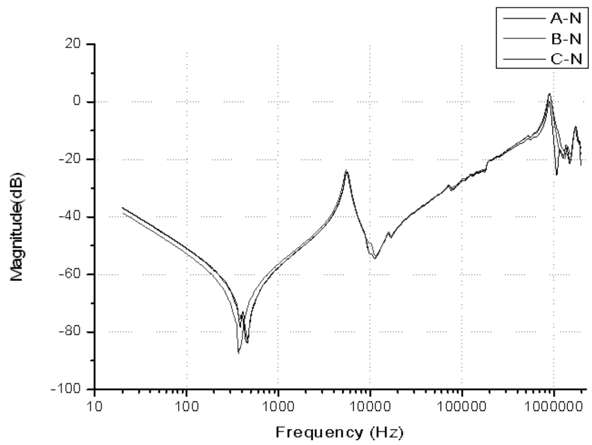
Fig. 7 Phase A winding visual inspection

3.2. Example 2 – Probably Deformed Winding

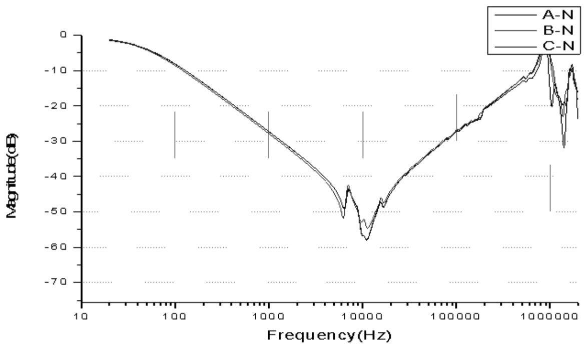
In the other example, generator's step-up transformer has a frequency response deviation which indicates possible problem with a transformer windings (Fig. 8).

Deviation is present in short-circuit measuring scheme when the effects of the core are practically eliminated and inter-winding geometry is tested. Usually, in short-circuit scheme, because the core effect is eliminated, there are no differences in the shape of the winding response between the phases.

Phase "A" and "C" responses were the same. Calculation of the CC factor between phase "C" (or "A") and "B" in the frequency sub-band 5kHz – 15kHz gave the number CC=0.9352. Referring to Table 3, it is clear that is not a perfect match, and that deeper investigation is needed. As a complementary method, measurement of the low voltage leakage reactance is done, and results showed a deviation between phases up to a 7%, which is enough for concern (Table 4). Again, phase "B" leakage inductance is about 194.5 mH, while the other two phases had similar values, around 181 mH.



a)



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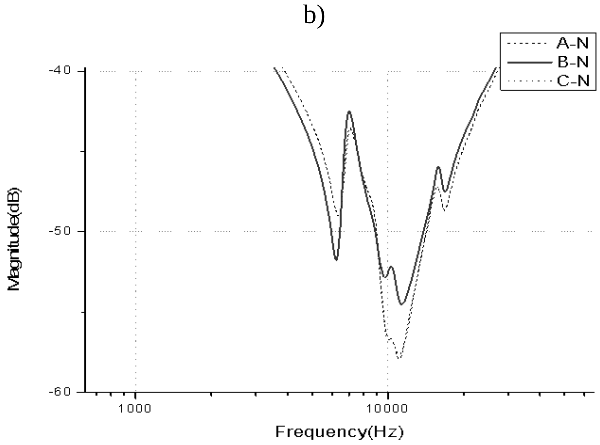

c)

Fig. 8 Short circuit HV winding SFRA traces: a) HV winding, b) HV winding, LV winding shorted, c) Magnified deviation of phase "B"

Tab. 4 Results Leakage reactance measurements

Connection	Voltage (V)	Current (A)	Z (Ω)	L (mH)	ΔL/L (%)
a-n	172,40	3	57,47	181,98	
b-n	184,20	3	61,19	194,49	7,11
c-n	172,70	3	57,16	181,58	

3.3. Routine inspection and repair based on CC factor

A power transformer maintenance and testing guide with recommended frequency is given in the literature [36]. Almost all maintenance recommendations are written for the average conditions under which the transformer is required to perform and operate. Most of these recommendations are applied during preventive maintenance, which basically involves scheduled maintenance and testing. Predictive maintenance involves additional monitoring and testing. The main goals of this maintenance should predict potential failure and reduce the costs of unscheduled maintenance and ordinary maintenance.

As already mentioned, the deviation of the transformer aging curve from the normal (Fig. 4) is practically impossible to quantify and precisely mathematically calculate. Therefore, the authors recommend the alternatives in the form of detection of mechanical deteriorations and monitoring of their trends.

CC factor with its suggested values (Tab. 3) can describe the mechanical condition of the transformer taking into account for example it's coupling. Thus, from the perspective of the projected geometry of windings and/or magnetic core, it can be concluded:

- If CC is in the range of 0.95-1 it is considered that no significant mechanical deteriorations have occurred and that the curve of aging is the one that has been declared in the factory (Fig.4).
- If CC is in the range of 0.90-0.94, it is considered that there are some mechanical deteriorations, so that the factory curve is shifted downward, resulting in a shortening of the lifetime. In this case, it is recommended that measurements and tests are performed more often with the aim of monitoring the failure tendency. The optimum moment for applying additional remote (online and real-time) monitoring systems is when the CC factor is in this interval.
- If CC is in the range of 0.89-0, it is considered that there is a risk of fatal failure that may be a result of the next mechanical stress.

4. Concluding Remarks

Power transformers are irreplaceable in modern developed electricity production and distribution. The demand for reliable and safe power supply caused power transformer life management techniques to be established. Hence, aging of the transformer, or power transformer remaining service life, became one of the main topics in the asset management sector. Different aging factors are taken into account, in order to define the expected remaining lifetime of the transformer.

The problem of temperature rising and the appearance of hot-spots have been identified as the result of increased losses due to, inter alia, the occurrence of mechanical deteriorations.

Mechanical deformation and dislocation of the windings and core are not sufficiently distinguished as components that influence the aging of the transformer, so authors proposed upgrading of the current power transformer aging model by introducing a new, detached set of parameters which will introduce mechanical strength of the winding-core structure into the existing model. Focusing on the problem of disturbed geometry of the windings and core, demanded we find suitable measurement methods that would discover mentioned defects and enable their analysis and monitoring. The method of analysis of the frequency response of transformer windings was selected as the most appropriate since it is simple, fast, easy, non invasive way to detect geometry deformations of the power transformer. We analyzed its possibilities through two examples in real operating conditions. For numerical interpreting of the test results, the authors used cross correlation (CC) factors, which are calculated for mentioned examples and frequency band that indicated major response deviation. Further research will be concentrated on the quantifying and recognising mechanical deformations in their infancy, in order to make planned interventions and monitor "power transformer health". Approaching the transformer condition monitoring in this manner can prevent excessive financial losses and major equipment failures because of long, expensive repairs and also expensive, prolonged intervals without power delivery.

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