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Combination of Non-contact and Contact Measuring Methods for Analyzing Structural Conditions of Dry Transformers

Miroslav Gutten[1*], Daniel Korenciak[1], Martin Karman[1], Peter Brncal[1], Matej Kucera[1], Tomasz N. Koltunowicz[2], Maciej Sulowicz[3]

[1]*Faculty of Electrical Engineering and Information Technology, University of Zilina, 8215/1 Univerzitna, 01026 Zilina, Slovakia, miroslav.gutten@feit.uniza.sk, daniel.korenciak@feit.uniza.sk, martin.karman@feit.uniza.sk, peter.brncal@feit.uniza.sk, matej.kucera@feit.uniza.sk*
[2]*Department of Electrical Devices and High Voltage Technology, Faculty of Electrical Engineering and Computer Science, Lublin University of Technology, 38A, Nadbystrzycka Str., 20-618 Lublin, Poland, t.koltunowicz@pollub.pl*
[3]*Department of Electrical Engineering, Cracow University of Technology, 24, Warszawska Str., 31-155 Kraków, Poland, maciej.sulowicz@pk.edu.pl*

Abstract: The article describes the non-contact and contact analysis of 1-MVA dry power transformers with epoxy-resin insulation using an acoustic camera and frequency analyzer with automatic sweeping for low-middle frequency areas. Power transformers are most commonly used for construction component (core, windings, taps) analysis. The electrical, non-rotating machine generates electromagnetic and acoustic emissions that can be used to analyze dry transformers during their operation. Non-contact online diagnostic methods have many advantages over offline methods because it is not necessary to shut down the transformer, and also, the condition and behaviour of the machine are analyzed during its normal operation. The article presents the analysis and comparison of structural parts of the distribution dry transformers of the same type and power. The problem of insufficient or incorrect clamp-screw connection was identified using the SFRA (Sweep Frequency Response Analysis) method.

Keywords: Diagnostics, dry distribution transformer, acoustic emission, frequency method.

1. INTRODUCTION

Transformers are among the most important electrical devices in the transmission and distribution system. Therefore, serious breakdowns in their insulating, structural and mechanical parts must be prevented. It is necessary to perform regular diagnostic measurements and tests, both during measurement and outside of operation, in order to detect possible aging of the material and thus prevent major damage to the machine.

With the help of various experimental measuring methods, the aging of machine components or insulation during shutdown or operation can be detected without contact (diagnostics of transformer oil, solid barriers/paper, taps windings, ferromagnetic core) [1], [2], [3].

Fig. 1 shows the diagnostic options for non-contact and contact measuring methods in the analysis of insulation and structural (mechanical) parts of power transformers.

Non-contact online diagnostic methods have many advantages over offline methods because it is not necessary to shut down the transformer, and also, the condition and behavior of the machine are analyzed during its normal operation. If a change in parameters compared to normal is identified (increased temperature or noise, change in acoustic frequencies or electromagnetic radiation parameters), it is possible to shut down the electrical machine and perform offline diagnostic measurements (electrical, chemical, physical).

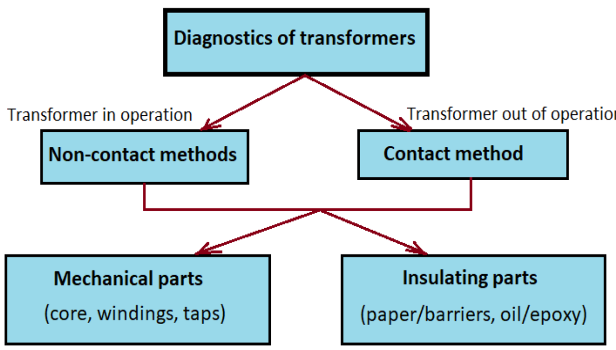

Fig. 1. Scheme of activities for online and off-line measuring methods of power transformers.

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Corresponding author: miroslav.gutten@feit.uniza.sk (M. Gutten)

A fault in a transformer may develop slowly or quickly, depending on the type and magnitude of the unwanted effect from the electrical network (short-circuit or inrush currents, overvoltages, overcurrents). Therefore, it is advisable to monitor the operation of the transformer in real-time, so that we constantly know what is happening inside. In the case of power dry transformers with a solid insulation system - epoxy resin - a non-contact method such as acoustic (AE), electromagnetic or thermal emission analysis is used at the beginning of diagnostic analysis [4], [5], [6].

If equipment is to meet EMC (electromagnetic compatibility) requirements, the level of its emittance must be below the maximal permissible level, which means that limit of emittance must be below the limit of resistance, so a satisfactory level of EMC is achieved. There is no defined numerical value for this EMC reserve, and the value is determined either by the manufacturer itself or by a customer specification.

Various EMC analyses demonstrate that strong non-sinusoidal regimes occur, especially for the currents in the transformer windings. Higher harmonic currents can cause new power quality or EMC problems (including related electromagnetic interference problems) that are not addressed by existing standards [3].

Using these methods, it is possible to determine and find a possible fault or the cause of a future fault at a specific location of an epoxy-insulated transformer. The use of non-contact methods is advantageous for dry transformers compared to the inappropriate use for oil transformers with a metal container [7].

2. DESCRIPTION OF MEASURING AND DIAGNOSTIC METHODS

The diagnostic sequence of transformer measurement research analysis is shown in Fig. 2. Currently, it is advisable to find a suitable non-contact measurement for detecting mechanical faults in dry transformers, which may be noisier compared to other transformers. Noise measurement in dB alone is sometimes not enough to detect a fault. It is necessary to perform acoustic emission analysis by noise visualization and frequency analysis of the individual components of the transformer noise at no load and under load.

In noise measurement by acoustic emission analysis, a camera with an acoustic modular system was used. In this way it is possible to analyze the frequency spectrum with the possibility of 3D monitoring of the transformer and identify the place with the greatest noise. In this way, the cause of the excessive noise can be found. Thanks to the continuous measurement of the acoustic signal depending on the frequency, there is no need to use an external frequency filter, as is the case with conventional sound measuring devices. The Nor848A acoustic camera with a modular hexagonal plate system with 128 microphones was used to analyze two dry transformers.

When detecting higher noise components in the frequency tone spectrum up to 1000 Hz compared to a normally noisy transformer, it is necessary to pay attention to the analysis of the mechanical condition of the transformer, which affects the increase in tonal noise. In dry transformers, the most common fault in changing the acoustic emission may also be incorrect connection of the screws on the fastening structure or when connecting the windings. As a complementary method, a number of different contact measurements can be used to more accurately detect a fault in the insulation or structural system of transformers. One of the most suitable complementary methods is the SFRA (Sweep Frequency Response Analysis) method using the Megger FRAX apparatus. The above method measures the frequency dependence of the transformer conductivity from 20 Hz to 2 MHz in the no-load and short-circuit state. With the help of these measurements it is possible to detect a fault in the iron core, in individual windings, branches or connections.

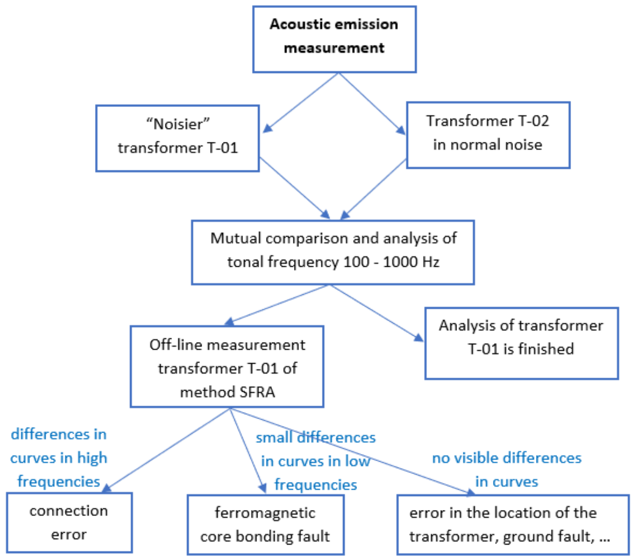

Fig. 2. Scheme of activities for diagnostic sequence of the transformer measurement research analysis.

Both described methods were used to measure two 22000/400 V, 1-MVA distribution transformers with epoxy resin insulation during standard power supply operation. One of the T-01 transformers was noisier to the human ear than the T-02 transformer. The analyzed machines were in normal insulating and mechanical condition. The measured dry-type transformers were placed in the closed cells of the distribution transformer, where the distribution of electricity for the work organization dealing with lighting technology is provided. Next to the transformer cells, the offices are separated only by a wall. The T-01 transformer was noisier than the T-02 transformer in the office, which made the working atmosphere in the office unpleasant. The noise from the T-02 transformer in the other office was barely audible.

By proper analysis of experimental measurements, it is possible to find the source of increased acoustic activity of a noisier transformer. Since the human ear was disturbed by noise mainly up to the tonal frequencies of 1000 Hz, our task will be to analyze AE only in this frequency range.

3. RESULTS

A. Analysis of the condition of dry transformers using acoustic emission analysis and contact frequency method SFRA

Strong vibrations occur in the ferromagnetic core and windings of epoxy-insulated transformers, the measurement of which can be used to diagnose individual parts of the equipment during operation.

Any change in vibration in a certain frequency range is affected by a fault for a certain structural or insulation area of the dry transformer. A change in the level of acoustic emission at low frequencies in the range below 1000-2000 Hz may indicate an incipient fault in the structural parts of the electrical machine (fault in the winding, in the core, or the fastening system).

Magnetoacoustic emission (Barkhausen phenomenon) and magnetostriction occur in the mentioned transformer system. Acoustic emission spectra are generated in the transformer at a supply frequency of 50 Hz, which is twice the frequency of the electrical network, i.e. they are a multiple of the frequency of 100 Hz. Thus, the frequency spectrum starts at twice the frequency of the network, which is caused by vibrations in the winding, ferromagnetic core, and transformer [8], [9], [10].

Diagnostic systems for identification and localization of dangerous discharges in solid or oil insulation of dry or oil transformers are described in several scientific studies. These are mainly concerned with the identification and localization of partial discharges [11], [12], [13].

To locate partial discharges in the insulation system of transformers, microphones with a frequency range above 200 kHz and beyond with a range of several MHz are used. It can also be supplemented by measuring the radiation of the electromagnetic field of the dry transformer in the frequency range of several tens of MHz [14], [15].

Many advantages in the application of acoustic emission for diagnosis or modeling of high-voltage electrical equipment with epoxy insulation are presented in scientific articles [8], [9], [16].

The 3D acoustic emission analysis for the real measured transformer is shown in Fig. 3.

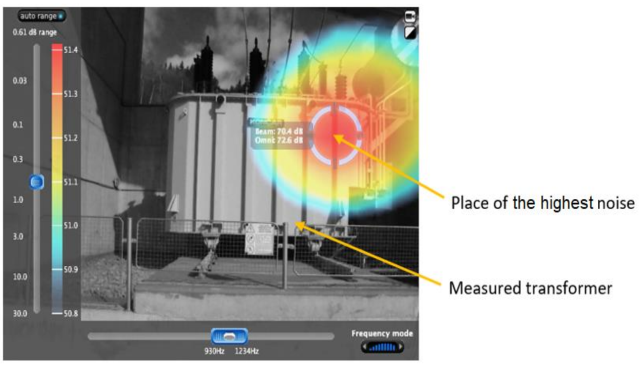

Fig. 3. 3D view of acoustic emission analysis for the real measured high-voltage transformer.

Offline diagnostic methods can be added to the non-contact methods mentioned, thanks to which a possible error on the structural, mechanical, or insulating part of the power transformers can be identified as reliably as possible. For the diagnosis of the structural system of transformers, the most reliable analysis is the SFRA method, and for the analysis of the epoxy insulation system of high-voltage machines, the analysis of partial discharges is the most advantageous [17], [18].

To analyze the mechanical condition or possible damage of the transformer (core, winding, taps, fixing screws), the offline contact method SFRA is often used, which can be used as a complementary method after the non-contact analysis of power transformers by acoustic or thermal emission analysis.

In particular, this method is used when the acoustic emission analysis also reveals an increased amplitude of the harmonic acoustic components in the frequency range up to 1 kHz and the thermal emission analysis reveals an increased rate of warming of the damaged site compared to other parts of the transformer [19], [20].

The equivalent transformer RLC circuit used for SFRA broadband frequency analysis includes electrical and magnetic bonds between individual transformer elements. Such an RLC circuit has unique frequency characteristics for a given geometry [21], [22].

The connection of the Megger FRAX apparatus to the measured transformer is shown in Fig. 4.

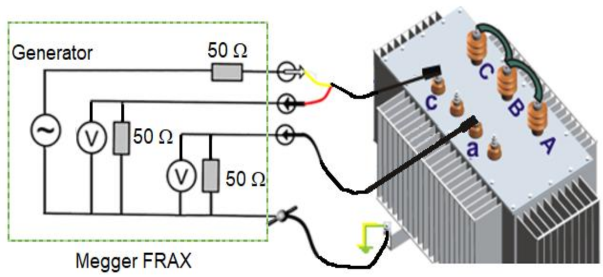

Fig. 4. The connection of the Megger FRAX apparatus to the measured transformer.

B. Measuring system for acoustic emission analysis

A dish with multiple microphones can be the best alternative for the analysis of the acoustic spatial spectrum with the possibility of visualizing the measured electrical equipment, making it possible to determine the source of the largest or most intense noise [23], [24], [25].

By using an acoustic camera with a modular system, it is possible to identify the maximum point of noise and acoustic emission with the possibility of tracking the frequency spectrum and tracking the measured object in a 3D sound field. Thanks to the displayed 3D acoustic field of the sound camera, it is possible to spatially identify a potential fault on the measured device during its operation.

In diagnostics, the acoustic camera can be used wherever incipient transformer failure can cause a change in vibrations and, consequently, a change in the amplitudes of the frequency spectrum of the acoustic emission of the measured object [26], [27], [28], [29].

The advantage of these systems is that, thanks to the displayed frequency spectrum, it is not necessary to use an external frequency filter, which is used by some measuring devices for noise measurement.

The application of non-contact analysis using acoustic emission for the diagnosis of distribution transformers has significant advantages over offline contact methods [30], [31]:

- it is possible to identify the area of the source of the increased noise intensity and thus a possible defect in the equipment,
- when using a modular camera system, it is possible to direct the microphone plate to the location of the increased acoustic emission or noise,
- the possibility to analyze a wide range of the frequency spectrum.

The principle of acoustic field analysis is the formation of feedback within the frequency spectrum from the noise source [32].

The Nor848A acoustic camera used in our research represents a modular approach to a measurement camera that provides the user with portability and high resolution for a wide variety of measurement situations. The plate array is based on a hexagonal shape, thanks to which it can combine multiple acoustic tiles into larger measurement systems. The microphone array contains up to 128 microphones arranged in concentric circles on a circular disk with a diameter of 0.4 m. With the microphone array system, it is possible to identify acoustic sources and visualize the noise map in the frequency range of 0.316 - 15 kHz (Fig. 5) [33].

The live display of the measurements in combination with an intuitive software interface allows users without previous experience to perform measurements within the first five minutes after switching on the device [33], [34].

The disadvantage of this system is the impossibility to measure the acoustic emission above 100-200 kHz, where it would be possible to analyze the insulation system of the transformers by identifying the number of partial discharges [35], [36], [37], [38], [39].

The advantage of high-frequency acoustic measurement is the detection of faults in the insulation system of transformers [40], [41], [42], [43], [44].

The acoustic emission analysis method for transformer diagnosis may have some advantages compared to electrical and optical and chemical methods [45], [46], [47], [48].

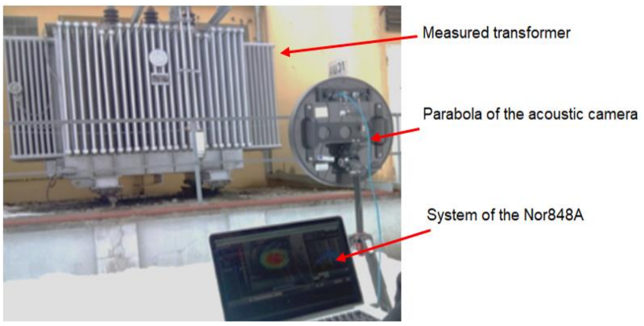

Fig. 5. Pointing the Nor848A acoustic camera at the measured transformer.

C. Experimental online measurement of acoustic emission

Experimental diagnosis with AE analysis was carried out on 22000/400 V, 1-MVA power transformers with epoxy resin insulation at standard power supply operation. One of the T-01 transformers was noisier to the human ear than the T-02 transformer. The analyzed machines were in normal insulating and mechanical condition.

Diagnostic dry-type transformers are placed in the closed cells of the distribution transformer, where the distribution of electricity for the work organization dealing with lighting technology is provided. Next to the transformer cells, the offices are separated only by a wall. The T-01 transformer was noisier than the T-02 transformer in the office, which made the working atmosphere in the office unpleasant. The noise from the T-02 transformer in the other office was barely audible.

For the analysis of the acoustic emission from the two distribution dry transformers T-01 and T-02, a Nor848A camera was used, installed at the same distance of 1.8 meters from the measured object and rotated at the same angle. The measurement was performed in an open object - a transformer room with humidity of 70% and ambient temperature of 6 °C.

Fig. 6 and Fig. 7 are images of the AE analysis of the "noisy" transformer T-01 at no-load and at 10% load in normal operation.

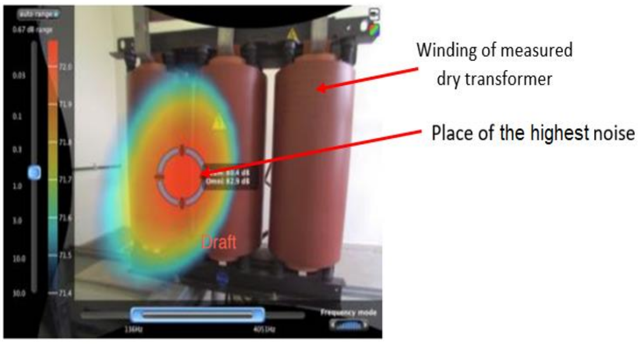

Fig. 6. Image of the found spatial noise maximum on the transformer T-01 at no-load.

Fig. 6 and Fig. 7 show a significant shift in the increased activity of the acoustic spectrum toward the winding of the middle phase. By increasing the load, the influence of the Lorentz force begins to activate in the windings.

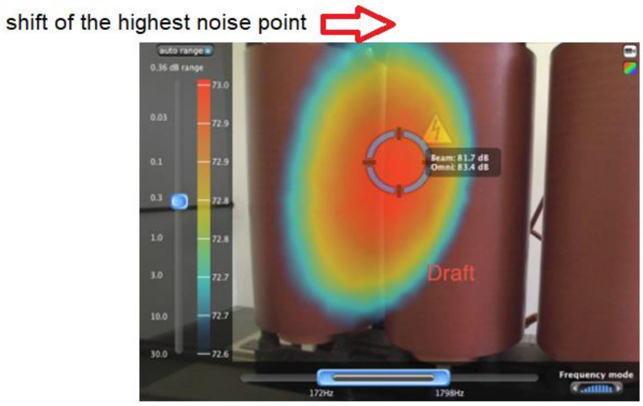

Fig. 7. Image of the found spatial noise maximum on the transformer T-01 at 10% load.

Fig. 8 and Fig. 9 are spectral analyses of the noise field of the T-01 dry transformer at no-load and at 10% load. Within the spectral analysis it is possible to see the frequency spectrum up to 1000 Hz with multiples of 100 Hz.

The graph in Fig. 10 is the spectrum of the acoustic signal at a given point of the AE field of the dry transformer T-02 at 10% load. The image clearly shows a lower acoustic emission than the tonally "noisier" transformer T-01. The graphic representation of the frequency spectrum of the loaded dry transformer T-02 is shown in Fig. 7. In the graph, comparatively smaller acoustic signals can be seen in the frequency spectrum than in the case of the dry transformer T-01 at the same load.

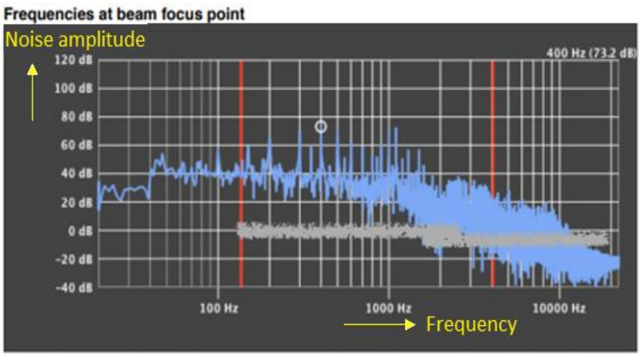

Fig. 8. Acoustic emission of transformer T-01 at no-load.

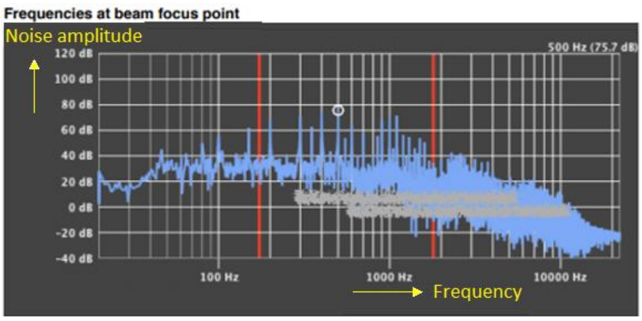

Fig. 9. Acoustic emission of transformer T-01 at 10% load.

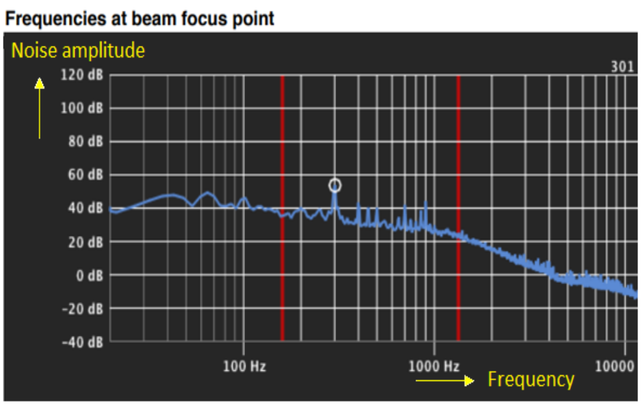

Fig. 10. Acoustic emission of transformer T-02 at 10% load.

4. Discussion

A. *Evaluating numerical measurements using the median*

Measurement of the acoustic emission was carried out over a period of 20 s. Noise values in dB were recorded every second for each frequency up to 20 kHz.

For the resulting display of the measured values, we used the median, i.e., the value that divides the sequence into two equally numerous halves according to the sizes arranged. The basic advantage of the median as a statistical indicator is the fact that it is not affected by extreme values. The advantage of the median over the arithmetic mean is that the influence of extreme values is excluded in the case of the median.

In this way, the median better represents the set and is more sensitive to the characteristic part of the set. The median-type charts were developed for dealing with outliers, contamination, or small deviations from normality. The median chart is particularly useful for monitoring long production runs [49], [50].

When looking for the median of an odd number of numbers, we simply choose the number that is exactly in the middle of the set. This describes the formula:

$$Me(X) = x_{(N+1)/2} \tag{1}$$

If we are looking for the median of an even number of numbers, we must calculate it as the arithmetic mean of the two numbers closest to the middle of the set ordered from smallest to largest, since an even group of numbers has no single number "in the middle". This describes the formula:

$$Me(X) = x_{N/2} + x_{(N/2+1)}\}/2 \tag{2}$$

where x is a chosen number and N is the quantity of all measured numbers [51].

Fig. 11 is an example of analysis of measured noise values for the selected frequency 1100 Hz in intervals of 20 s for the measured transformer with marking of the calculated median and trend flowline. The total measurement error with respect to the measuring device was 0.6%.

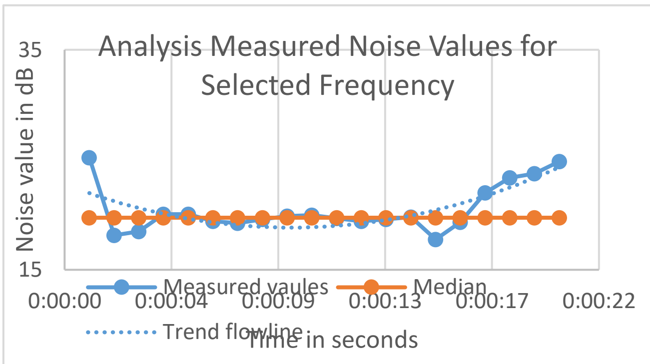

Fig. 11. Measurement analyses of noise depending on the time interval of 20 s.

B. *Results analysis of acoustic measurement*

By a suitable analysis of the experimental measurements, it was possible to find the source of the increased acoustic activity of a noisier transformer. Since the human ear is disturbed by noise mainly up to the tonal frequencies of 1000 Hz, our task was to analyze AE only in this frequency range.

Fig. 12 is a frequency comparison of the noise analysis for both transformers T-01 and T-02 with a calculated ratio to the fundamental noise harmonic component of 100 Hz.

When comparing the percentages of both transformers at the same 10% load, higher values of the frequency spectrum were measured for transformer T-01. According to Fig. 12, the increased values for frequencies 200, 400, 500, 600, 900, and 1000 Hz were considerable (above 20%).

Fig. 13 shows a percentage comparison of tonal frequency increase for the transformer T-01 to transformer T-02 at no load and at 10% load. The highest percentage increase for transformer T-01 to the quieter T-02 is over 30% at frequencies 400, 500, 600 and 1000 Hz. At 800 Hz frequency the higher value is with transformer T-01 at no-load to load following magneto-acoustic emission.

In the case of dry transformers, the most common fault in the change of acoustic emission may also be incorrect connection of the screws on the fastening structure or when connecting the windings. As a complementary method, a set of different contact measurements can be used, which can more accurately detect a fault in the insulation or the structural system of transformers.

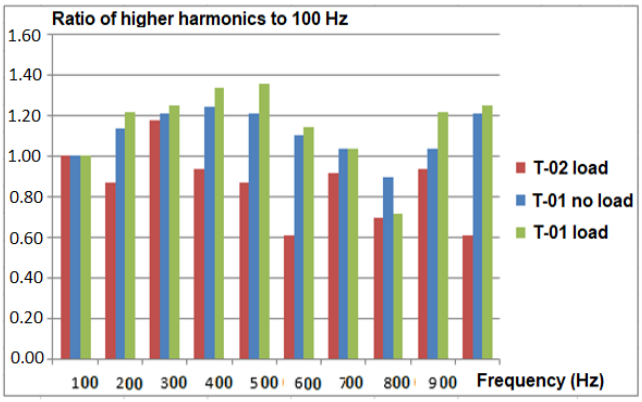

Fig. 12. Frequency comparison of noise analysis for both transformers T-01 and T-02 with a calculated ratio to the fundamental noise harmonic component of 100 Hz.

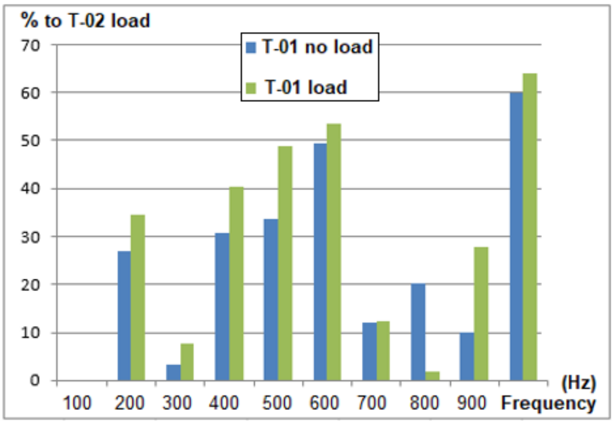

Fig. 13. Percentage comparison of tonal frequency increase for transformer T-01 to transformer T-02 at no load and at 10% load.

C. Additional offline measurement by the sweep frequency response analysis method

For the analysis of the correct connections and tightening of the screws on the dry transformers, it is possible to use the contact offline SFRA method with the Megger FRAX apparatus.

Acoustic emission analysis also shows an increased rate of harmonic acoustic components in the frequency range up to 1 kHz, and thermal emission analysis shows an increased rate of warming of the damaged site compared to other parts of the transformer.

The equivalent transformer RLC circuit used for the SFRA broadband frequency analysis includes electrical and magnetic bonds between individual transformer elements. Such RLC circuit has unique frequency characteristics for a specific geometry [52], [53].

The identified faulty dry transformer was out of operation and disconnected from the electrical network and then measured using the appropriate measuring equipment for SFRA analysis.

Fig. 14 shows the frequency analysis of the transformer attenuation before fixing the winding screw (red line) and after fixing the winding screw (blue line). The problem of insufficient or incorrect clamp-screw connection was shown in the source range of frequency above 200 kHz to 2 MHz.

In the area of highest frequencies above 2 MHz on larger machines, the response is less repeatable and is affected by the measurement setup, especially the grounding, which depends on the length of the bushing.

If the clamp on the ferromagnetic core was activated (analysis up to 10 kHz frequency), it would not be possible to detect such a defect with the SFRA method. In this way, the defect can be detected by the measurement only when monitoring at higher frequencies, where the importance of the transition resistance increases.

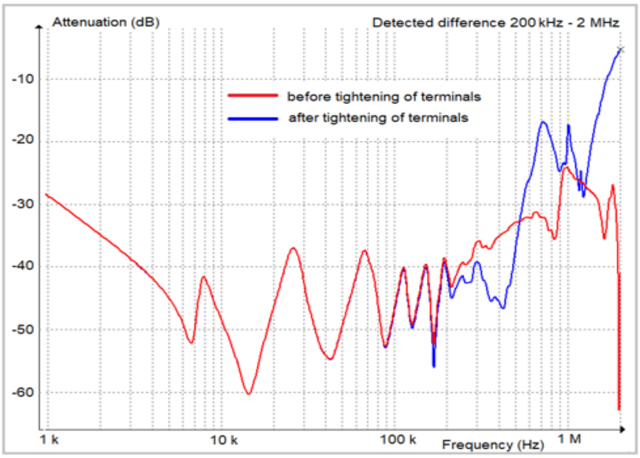

Fig. 14. Measurement on dry transformer T-01 for analysis of attenuation depending on the frequency before tightening of winding terminals (red line) and after tightening of terminals (blue line).

If it is a case of insufficient connection of the terminals, starting from Fig. 14, one can add an analysis of the purely resistive component in the frequency band if one measures just before tightening of winding terminals (red curve) and after tightening of terminals (blue curve) according to Fig. 15, where a significant difference between the red and blue curves can be observed due to the increased transition resistance at the relaxed coil terminal.

Such a measurement is suitable, e.g., for comparing the curves of individual phases of a three-phase transformer.

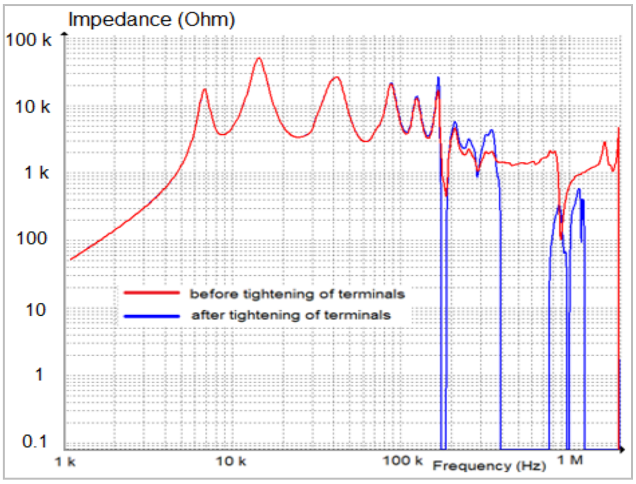

Fig. 15. Measurement on dry transformer T-01 for analysis of resistance depending on the frequency before tightening of winding terminals (red line) and after tightening of terminals (blue line).

5. CONCLUSION

The use of the above diagnostic methods is significant for the detection of aging phenomena and their effects on the analysis of the mechanical and structural parts of power dry transformers during operation. The above methods, when properly used, are resistant to interference and can be easily applied directly at the transformer installation site.

The use of a non-contact method using acoustic emission measurement is a good starting position for the analysis of the transformer, thanks to which it is possible to propose a different, but contact, offline diagnostic method. The advantage of the microphone acoustic systems is that thanks to the displayed frequency spectrum, it is not necessary to use an external frequency filter, which is used by some measuring devices for noise measurement.

In the long run, the progressive contact frequency method SFRA is most useful because it provides enough information about the structural condition of the transformer. Data obtained from the manufacturer or before commissioning is considered a reference and can be used for comparison with data during operation of a specific transformer. However, the disadvantage of the contact method is the shutdown of the power transformer from the network. Therefore, to ensure the supply of electricity, a second parallel machine must be used to power the operation during the test measurement.

If the clamp on the ferromagnetic core was activated (analysis up to 10 kHz frequency), it would not be possible to detect such a defect with the SFRA method. In this way, the defect can be detected by the measurement only when monitoring at higher frequencies, where the importance of the transition resistance increases.

Both mentioned methods (acoustic emission and SFRA) contribute to a better understanding of the structural state of the power transformer and to the exclusion of an incorrect diagnosis of a possible fault.

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