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doi:10.15199/48.2021.05.19

Analysis of Acoustic and Electromagnetic Emission of Traction Transformers

***Abstract**. The article analyzes the diagnostics of a high-voltage power transformer by means of an acoustic camera. It is one of the basic diagnostics and monitoring of remote measurement and analysis of acoustic emission. The high-voltage power transformer generates acoustic emission, thanks to which we can analyze the operating and fault states of the device. The article shows the use of the acoustic camera for operational monitoring and diagnostics of its life through noise from the source of the transformer winding and the ferromagnetic core. We performed measurements of acoustic emission on the traction transformers with parameters 5 MVA, 25/6 kV and 25 MVA, 110/3 kV that were in real operation. We studied the spatial distribution of the acoustical field as well as its spectra. Preliminary results have shown that acoustic analysis may be a useful alternative option for high-power transformer's health condition.*

Streszczenie**. . W artykule przeanalizowano diagnostykę transformatora mocy wysokiego napięcia za pomocą kamery akustycznej. Jest to jedna z podstawowych metod diagnostyki i monitoringu zdalnego z wykorzystaniem emisji akustycznej. Transformator mocy wysokiego napięcia generuje emisję akustyczną, dzięki której możemy analizować stany pracy i uszkodzenia urządzenia. W artykule przedstawiono zastosowanie kamery akustycznej do monitorowania eksploatacyjnego i diagnostyki poprzez szum pochodzący ze źródła uzwojenia transformatora i rdzenia ferromagnetycznego. Wykonaliśmy pomiary emisji akustycznej transformatorów trakcyjnych o parametrach 5 MVA, 25/6 kV i 25 MVA, 110/3 kV, które były w rzeczywistej eksploatacji. (**Analiza emisji akustycznej i elektromagnetycznej transformatorów trakcyjnych)

Keywords: transformer, acoustic camera, acoustic emission, acoustic source localisation
Słowa kluczowe: transformator mocy, diagnostyka, emissja akustyczna

1. Introduction

The quality of the insulating parts of the transformer in the oil-paper fabrication can deteriorate over a period of several years. At the power transformers, it is recommended to constantly monitor its mechanical and insulation condition to see if its parameters are changing. It is necessary to record faults in the power line that may adversely affect the operation of the transformer, such as inrush and short-circuit current, atmospheric overvoltage or weather. Evidence of adverse effects can tell us about the cause of a fault on the transformer, or tell us which method of diagnostics we can use. Based on the diagnostic analysis, we can identify a possible failure on the transformer.

At present, it is necessary to use non-contact measurements, which could, based on acoustic emissions (AE), identify a possible fault in the technical equipment. At present, such systems can be part of diagnostics and analysis for energy systems, especially in high and very high voltage transmission and distribution systems [1].

Acoustic and noise diagnostics can be an additional method for online monitoring of the transformer during its operation.

Among the significant sources of noise and acoustic emission in non-rotating electrical machines (power and measuring transformers and reactors) are vibrations in the winding and in the ferromagnetic core. Increased vibrations occur in the transformer mainly due to loose clamps on the sheets of the ferromagnetic core and loose contacts on the windings and coils. Among the basic operating sources of acoustic emission are phenomena in the ferromagnetic core, such as the Barkhausen effect (magnetoacoustic emission) and magnetostriction [2, 3].

During operation of the transformer, the vibrations in the winding and the ferromagnetic core produce acoustic emissions in a very audible low frequency range. This acoustic emission can acquire basic tonal sound with frequency of electric power. The fundamental frequency of electromagnetic forces and mechanical vibrations is usually twice that of a flowing electric current, i.e. 100 Hz in Europe, producing a spectrum of higher harmonics due to acoustic emission. [3].

Among other sources of acoustic emission may be due to aging in the insulation system of the transformer, which results in the formation of partial discharges. These mainly generate acoustic emission in the ultrasonic frequency range above 100 kHz [4, 5].

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Among other sources of acoustic emission, an interthread short-circuit on the winding may also be possible.

It is therefore appropriate to check the acoustic emission of the monitored power transformers with new ones in order to identify a possible failure or deteriorating service life of the equipment [2].

2. Diagnostics transformers using by measurement of acoustic emission

Many techniques have been applied for power transformers internal fault identification, being the main on-line methods based on the thermovission, dissolved gas analysis (DGA) or in the AE analysis (AEA) [6].

All the techniques aim at performing with low cost, high efficiency and fast diagnosis. Among these methods and measuring techniques, the AEA method stands out, for allowing a non-invasive analysis, which can be performed during the equipment's operation [5].

In literature, several researches combine the results of the AEA method with computing techniques to create a diagnostic expert system, which can identify and locate partial discharges that happen during the transformer operation.

Acoustic emission analysis for the purpose of supporting diagnostics and analysis of power transformers has certain disadvantages and shortcomings. The transformer winding and the core are immersed in a metal housing filled with insulating oil, which in turn affects the measurement of acoustic emission [8].

Another disadvantage is the effect of acoustic emission from the environment, or from other nearby electrical equipment. These effects can affect the accuracy of the noise and acoustic emission measurements of a given monitored device.

Due to these shortcomings, several important scientific works were recorded in the acoustic analysis and diagnostics of power transformers, especially for the identification of partial discharges. [2], [4], [5].

In works [7] and [8] it was found that the measurement of acoustic emission on the transformer can be used to monitor and monitor the mechanical and fastening parameters of the device.

The correct analysis of the acoustic emission on the transformer is based on several methods: parameterization, segmentation, acquisition and recognition [2].

3. Subject and Methods

Phase field signal processing is one of the most widely used techniques for AE remote monitoring and measurement of industrial equipment. The acoustic camera [10] is a modular system enabling the acquisition and processing of an acoustic signal with a phase field, thus enabling the location of sources on the basis of the visualization of the acoustic field and the emission.

The basic arrangement of the acoustic camera has a built-in microphone array, software for data processing and a recorder of measured data. Multi-channel processing of audio signals from the microphone field allows spatial filtering of the 3D acoustic field. Therefore, the AE system is able to focus on a specific point of the sound field and measure the spectro-temporal variations of acoustic waves at any point of the monitored space of the industrial plant. The frequency/space resolution depends on the arrangement and size of the microphone array.

The application of an acoustic camera for measuring and monitoring power transformers has two significant advantages:

- the location of the source of the possible failure can be identified,
- it is possible to direct the microphone field to a specific location of the device,
- it is possible to use sound field analysis.

Diagnostic analysis of power transformers using AE was performed by a Nor848A acoustic camera consisting of a microphone field and a digital system for spatial and spectral analysis of the acoustic field and noise map generation. The microphone array contains up to 128 microphones arranged in concentric circles on a circular disk with a diameter of 0.4 m (Fig. 2).

Using the mentioned microphone field system, it is possible to locate acoustic sources and visualize the noise map in the frequency range 0.316 - 15 kHz [11].

Fig. 2 View the measuring tools - acoustic camera Nor848A

We performed measurements on the traction transformers 25/6 kV, 5 MVA and 110/3 kV, 25 MVA that were in real operation. Both transformers were in good mechanical and insulating conditions.

The transformers supply power for traction security devices and lines. Such transformers may be susceptible to possible failure by short-circuit currents (inter-thread short circuit, moved winding, loose clamps in taps) [12].

The measurement was carried out at ambient temperature of 5 °C and humidity of 80 %. The measuring equipment (the disc with microphone array) was placed 9 meters from the transformer. The captured signal of the duration of several seconds was stored on Mac computer and further analysed by special software (a part of the acoustic camera Nor848A). The set-up is shown in Fig. 3.

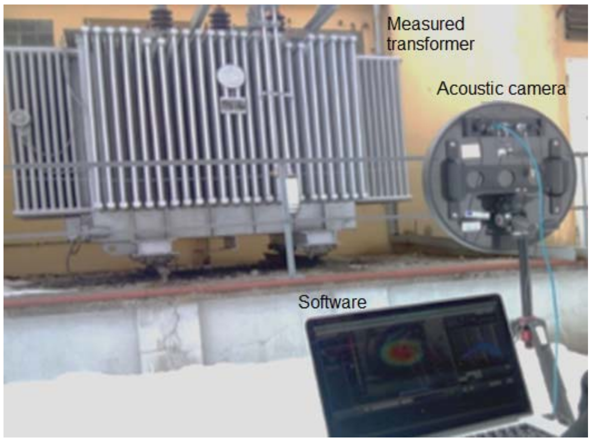


Fig. 3 View of the measured traction transformer 5 MVA, 25/6 kV with acoustic camera

In addition, experimental analysis of electromagnetic field (EM) was realized by the spectral analyser HP7402A, RFI Meter with a special selective micro-voltmeter, which uses superheterodyne principle (Fig. 4).

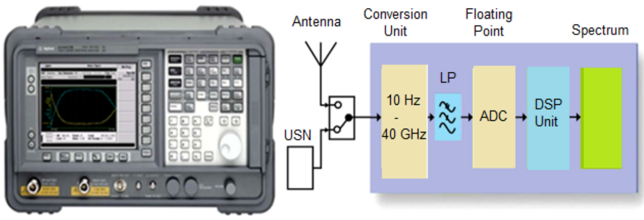


Fig. 4 Measuring apparatus of electromagnetic field

4. Discussion

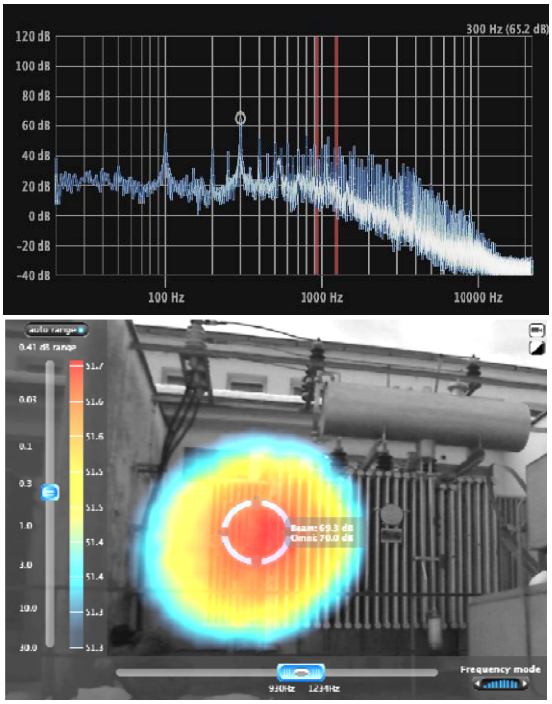
In Fig. 5 and Fig. 6 are shown screenshots from the measurements on the traction transformer 25/6 kV, 5 MVA and traction transformer 110/3 kV, 25 MVA in operation, respectively.

The Fig. 5a and 6a show graphs of the spectrum of acoustical signal in the given point of the acoustic field. From the graph, the fundamental frequency of 100 Hz and its higher harmonics are clearly visible. Some of the odd harmonics related to frequency of 50 Hz (150 Hz, 250 Hz, …) are present but with more varied levels than even harmonics.

The AE spectral envelope of the transformer 25/5 kV, 5 MVA has almost constant level up to 3000 Hz. In the second case (110/3 kV, 25 MVA), the spectrum envelope is flat up to 1200 Hz. Over this frequency, spectral level decreases with slope of about 20 dB per octave.

Note that the upper limit of the frequency range of the acoustic camera is 20 kHz therefore this type is not able to measure AE from particle discharge.

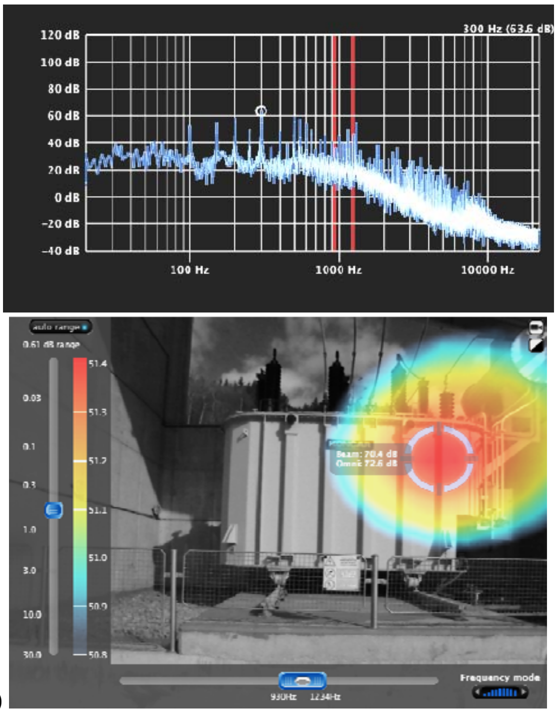
Fig. 5b and 6b show intensity of AE radiated by the transformers. From the figures it can be seen that the maximum intensity is located in different positions for different frequencies.



a)

b)

Fig. 5 AE spectrum of the 25/6 kV, 5 MVA transformer (a) and acoustic map of band-limited AE (b). The selected frequency band is marked by two red lines in the spectrum graph



a)

b)

Fig. 6 AE spectrum of the 110/3 kV, 25 MVA transformer (a) and acoustic map of band-limited AE (b). The selected frequency band is marked by two red lines in the spectrum graph

Fig. 7 is a comparison of the maximum values of acoustic signals - peaks on a transformer with a traction transformer 25/6 kV with a power of 5 MVA and a transmission transformer 110/3 kV with a power of 25 MVA. According to Fig, 7 is shown clear difference in peak values according to the magnitude of the transformer transmitted power.

For trouble-free operation at a minimum load of about 10%, the mutual noise difference of the measured transformers 5 MVA, 25/6 kV and 25 MVA, 110/3 kV is given in Table 1. The most difference between measured transformers is at frequency 100 and 900 Hz (30 dB).

According to the assumption, the frequency of 100 Hz causes significant electromagnetic noise and which also corresponds to twice the 1st harmonic of the excitation current at the value 50Hz. Due to the deformation of the excitation current due to saturation and the shape of the transformer's magnetic circuit, higher harmonics in the excitation are also manifested. Their image is then measured higher harmonic waveforms in the soundtrack and practically corresponds to frequencies of 200, 300, 400, 500, 600, 800 and 900 Hz.

The attenuation rate of the 200 Hz noise component is given by the current, for this reason the frequency 200 Hz, which is an even multiple of the basic supply frequency 50 Hz, still remains significantly represented. Even multiples of the fundamental frequency is given by the nature of the magnetic induction [13].

During the measurement we found out, that the precise localization of AE sources was very limited due to placement of the transformer in the enclosed tank. But the acoustic camera seems be able to localize maxima of the individual frequency modes on the tank surface. Thus, such remote contactless sensing might replace vibration sensors fixed to the tank surface.

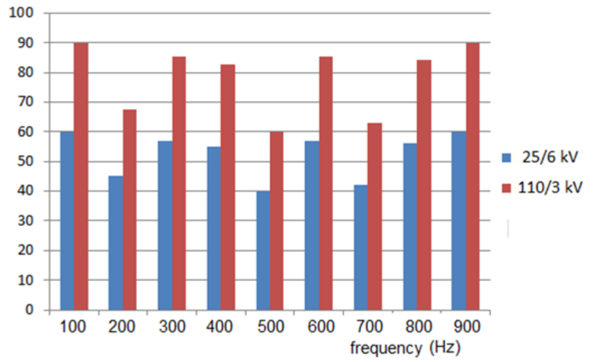


Fig. 7 Comparison of transformer peaks of the 25/6 kV, 5 MVA and 110/3 kV, 25 MVA according to voice acoustic analysis

Table 1. Noise acoustic comparison of measured transformers with power 5 (25/6 kV) and 25 MVA (110/3 kV) at about 10% load

Measured frequency	100, 900 Hz	200 Hz	300 Hz	400 Hz	500 Hz	600 Hz	700 Hz
Mutual difference	30 dB	24 dB	28 dB	28 dB	20 dB	17 dB	21 dB

With a minimum load of both transformers of about 10%, it is possible to observe a higher influence of higher harmonics due to the greater influence of the ferromagnetic core. In tab. 2 is supplemented by the ratio of even higher to 2nd harmonic, i.e. against 100 Hz for both measured transformers 5 and 25 MVA.

According to Table 2, it can be seen that the 5 MVA transformer has almost the same ratio of higher harmonics to 100 Hz as the 25 MVA transformer, i.e. they have almost identical load as a 5 MVA transformer – 10%.

For illustration, Fig. 8 shows screenshots from the measurements of EM radiation on the same traction transformer 5 MVA, 25/6 kV in operation.

Spectrum of EM radiation shows the same main peaks in frequency points as at the measurement with the acoustic camera, since the peaks naturally correspond with the higher harmonics of the fundamental frequency of the current (see Fig. 5 and 6), however, the spectral details (individual lines between harmonics) and overall spectral envelope may differ.

Table 2. Ratio the higher harmonics against 100 Hz of measured transformers with power 5 and 25 MVA at about 10% load

	200 Hz	300 Hz	400 Hz	500 Hz	600 Hz	700 Hz	800 Hz	900 Hz
5 MVA	0.73	0.95	0.92	0.67	0.95	0.70	0.92	1.0
25 MVA	0.76	0.94	0.91	0.67	0.95	0.69	0.92	1.0

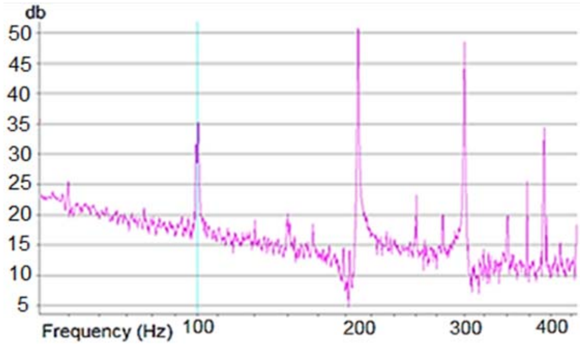


Fig. 8 View for measured traction transformer 5 MVA, 25/6 kV transformer with spectral analyser

The differences in the spectra are due to the fact that acoustic and EM radiations are affected by different phenomena. It follows from the above measurements that the acoustic analysis can be supplemented by an analysis of the EM field. Although, differences in EM and AE spectra is need further in depth analysis.

For the experiment carried out, only the transformers in good health conditions were at disposal thus, any classification or detection tasks on health conditions of the transformer cannot be performed. Suitability of AE analysis for transformer's health, and/or failure prediction issues is our ongoing research. We plan to compare the AE spectra of the transformers in various load conditions or with malfunctions.

5. Conclusions

Article presents analysis traction transformer 5 MVA 25/6 kV, by using with spectral emission with comparison of power transformer 25 MVA, 110/3 kV by acoustic camera and measuring apparatus of electromagnetic field (spectral analyser with RFI meter). Spectral maximums represent higher harmonics of its power supply of the basic frequency 100 Hz (200, 300, 400, ... Hz).

In the article was showed that analysis by acoustic emission generated by the magnetic field it is possible to diagnostics operating behaviour a power transformers and its mechanical and insulating conditions. In future we will plan to compare method of acoustic emission analysis with other diagnostic method.

Advantage of diagnostic of acoustic emission analysis is localization possible fault of mechanical and insulating part in power transformer. Disadvantage of the measuring method is sound interference from ambient and other acoustic emission from other high-voltage electric devices.

At short-circuit damage of winding, taps or core in transformer it possible to identify this fault and its size by using with emission camera. These anomalies it is possible to found in acoustic spectrum low frequencies.

Using acoustic analysis, it is also possible to detect and analyse the propagation of partial discharges (PD), by analysing the spectrum at higher frequencies (approximately 40 kHz). This makes it possible to assess the overall insulation condition of the power transformers.

A condition analysis of transformer is dependent from effects of magnetic and electric field of machine and was found by the acoustic emission by acoustic camera supplemented by the analysis of spectrum analyser using by spectral analyser. These measurements confirmed the accuracy of the results of the measurements and analysis using AE analysis.

Until now, however, the analysis of transformers using AE has not been standardized, which makes it possible to use experimental experience.

This work was partially supported by the Grant Agency VEGA from the Ministry of Education of Slovak Republic under contract 1/0471/20.

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REFERENCES

[1] Orman M., Pinto C.T., Usage of acoustic camera for condition monitoring of electric motors. In *IEEE International Conference TENCON 2013. IEEE*, 1-4. 2013.
[2] Bartoletti C., Desiderio M., Di Carlo D., Fazio G., Muzi F., Sacerdoti G., Salvatori F., Vibro-acoustic techniques to diagnose power transformers. In: *IEEE Transactions on Power Delivery,* 19(2004), No. 1, 221-229.
[3] Olszewska A., Witos F., Identification of Acoustic Emission Signals Originating from the Core Magnetization of Power Oil Transformer. In: *Archives of Acoustics*, 41(2016), No. 4, 799-812.
[4] Ramírez-Niño J., Pascacio A., Acoustic measuring of partial discharge in power transformers. In: *Measurement Science and Technology*, 20(2009), No.11.
[5] Boczar T., Cichon A., Borucki S., Diagnostic expert system of transformer insulation systems using the acoustic emission method. In: *IEEE Transactions on Dielectrics and Electrical Insulation,* 21(2014), No. 2, 854-865.
[6] Bacha K., Souahlia S., Gossa M., Power transformer fault diagnosis based on dissolved gas analysis by support vector machine, In: *Electric Power Systems Research*, vol. 83, 2012, pp. 73-79.
[7] Jin M., Pan J., Vibration transmission from internal structures to the tank of an oil-filled power transformer, In: *Applied Acoustics*, vol. 113, 2016, pp. 1-6.
[8] García B., Burgos J.C., Alonso A.M., Transformer tank vibration modeling as a method of detecting winding deformations-part I: theoretical foundation, part II: experimental verification, In: *IEEE Transactions on Power Delivery*, vol. 21, no. 1, 2006, pp. 157-169.
[9] Zhao M., Xu G., Feature extraction of power transformer vibration signals based on empirical wavelet transform and multiscale entropy, In: *IET Science, Measurement & Technology*, vol. 12, no. 1, 2017, pp. 63-71.
[10] Eric M. M., Some research challenges of acoustic, In: *9th Telecommunications Forum (TELFOR)*, Belgrade, Serbia, Nov 22. IEEE. pp. 1036-1039.
[11] Product data: Nor848A Acoustic Camera, online https://web2.norsonic.com/ product/324/
[12] Brandt M., Identification failure of 3 MVA furnace transformer," In: *Conference DEMISEE 2016*, Papradno, SR, 2016, pp. 6-10.
[13] Pokorný, V., Elimination of Noise Emission of Electrical Equipment, In: *Abstract of the doctoral dissertation*, VSB-TU Ostrava, 2013