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11. BASIC AND ADVANCED ANALYSIS OF ACOUSTIC EMISSION SIGNALS TO DISTINGUISH SIGNALS FROM DIFFERENT SOURCES GENERATING ACOUSTIC SIGNALS IN POWER OIL TRANSFORMERS

11.1. Introduction

Presented in this paper, research on the use of the AE method to identify various acoustic sources in power oil transformers is a continuation of the research carried out at the Department of Optoelectronics of the Silesian University of Technology for over a dozen years on the use of the acoustic emission method in the power industry [1-4], and in particular for several years of research on partial discharges in power oil transformers [5-10].

Partial discharges (PD) occurring in electro-insulating systems of power devices significantly affect the reliability of these devices. Long-term operation of PD can lead to breakdown of the insulation, which may result in short circuits, costly interruptions in the operation of these devices, and even fire. Hence, when assessing the condition of insulation, it is important to detect partial discharges, to determine the degree of their advancement, and in particular to locate the areas of PD occurrence.

In power oil transformers, AE signals coming from PD are accompanied by acoustic signals caused by other phenomena occurring in the tested object [11]. In particular, they are phenomena related to the process of magnetization of ferromagnetic materials, magnetostrictive phenomena, noises related to oil circulation, and other medium noise as well as disturbing signals. Due to the acoustic nature of these phenomena, they should be identified in detail.

One of the main problems with the development and application of the AE method is the correct analysis and interpretation of the obtained results. The recorded AE signals differ from the AE pulses generated in the sources, as the elastic AE waves generated in the sources undergo changes during propagation in the medium and during the detection and processing of the recorded signal [12]. Elastic AE waves during propagation in the real medium are absorbed,

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they can also be reflected, refracted and scattered. This reduces the amplitude (attenuation) of the wave, as well as changes the signal transmission band along the propagation path, which hinders the correct analysis of the results [11, 13, 14]. The analysis of the AE signals recorded as part of the research is therefore of key importance in the interpretation of the obtained results and the identification of signals from various sources generating acoustic signals in power oil transformers.

In this work, advanced AE descriptors are used to identify and locate AE sources [1, 11]. These descriptors are not based on the absolute values of the recorded signals (amplitude, energy of AE signals, etc.) and take into account the limitations of acoustic measurement methods. The discussed descriptors give the AE signals a degree of advancement, which is related to the degree of advancement of the deformation processes taking place in the tested objects. Additionally, carrying out the analysis of AE signals with the use of descriptor maps (discussed in chapter 2) in appropriately selected frequency bands allows to distinguish signals from different sources generating acoustic signals in power oil transformers.

11.2. Research method

To record AE signals in the investigated power oil transformer, the author's measuring system EA DEMA-COMP [11] has been used. It can be used both for research conducted in a laboratory and measurements taken during normal operation of power transformers. Fig. 1 shows a general view of the measuring system.

Fig. 1. General view of the measuring system EA DEMACOMP: 1 – apparatus set of DEMA, 2 – PCI-610E measuring card and CB6-TP measuring terminal, 3 – PC computer, 4 – oscilloscope, 5 – preamplifier, 6 – AE measuring sensor

Rys. 1. Widok ogólny systemu pomiarowego EA DEMA-COMP: 1 -zestaw aparaturowy DEMA, 2 – karta pomiarowa PCI-610E i terminal pomiarowy CB6-TP, 3 - komputer PC, 4 – oscyloskop, 5 – przedwzmacniacz, 6 – czujnik pomiarowy EA

AE signals recorded by the measuring system are analysed by the author's system for AE signal analysis [11]. The analysis includes the calculation of basic characteristics and amplitude distributions of signals, defined AE descriptors with ADP, ADC, ADNC acronyms [1, 15, 16, 17], determination of maps of descriptors on side walls of transformers, and next location of sources of AE signals as well as the analysis of the properties of the signals recorded at the points located in the neighbourhood of the identified sources. Fig. 2 presents example characteristics belonging to the basic description of the AE signal recorded in the power oil transformer.

Time waveforms of AE signal (Fig. 2a) are subjected to multiple analysis in discrimination threshold (U). The results of these analyses are amplitude distributions of: AE count rate, signal power, and AE normalised activity of counts. Properties of amplitude distributions of AE (made in logarithmic scale) can be described by means of specially defined AE descriptors. The descriptors were defined as follows.

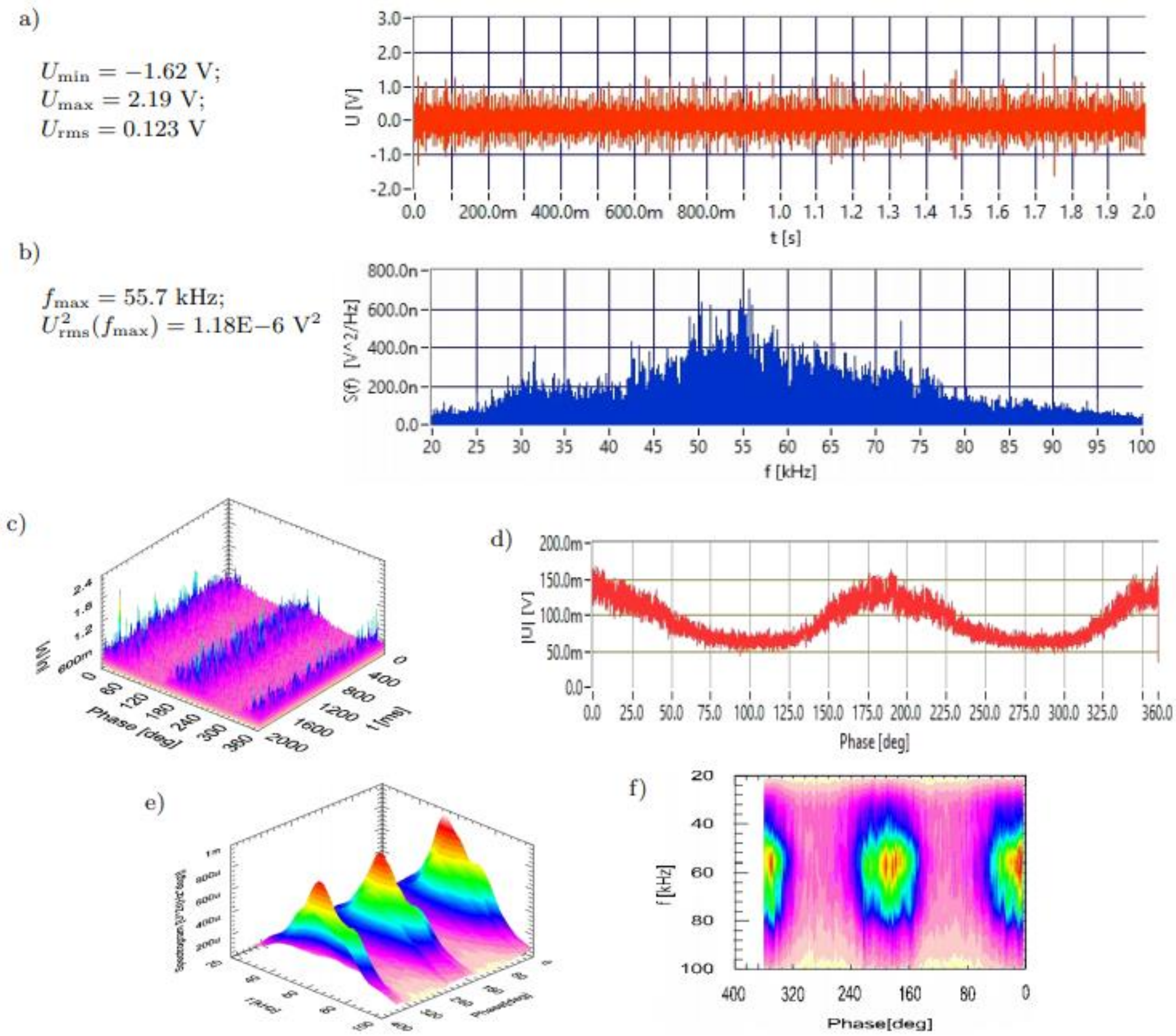

Fig. 2. Basic description of an exemplary AE signal coming from PDs: a) signal after filtration, b) frequency characteristic, c) phase-time characteristic, d) averaged phase characteristic, e) and f) STFT spectrograms

Rys. 2. Wstępny opis przykładowego sygnału EA pochodzącego od WNZ: a) sygnał po filtracji, b) charakterystyka częstotliwościowa, c) charakterystyka fazowo-czasowa, d) uśredniona charakterystyka fazowa, e) i f) spektrogramy STFT

At first, one should mark a fragment of an amplitude distribution curve which corresponds to the range of the discrimination threshold (U_d, U_g); value of U_d is determined by the minimum of amplitude distribution derivative against the discrimination threshold, whereas U_g is 90% of the maximal value of the recorded signal. The determined fragment of the curve is approximated by a straight line (2.1):

$$\ln\left(\frac{dN(U)}{dU}\right) = AU + B \tag{2.1}$$

whereas the descriptor connected with the amplitude distribution is equal to slope of the straight A. ADC descriptor is connected with **A**mplitude **D**istribution of AE **C**ounts, ADP descriptor is connected with **A**mplitude **D**istribution of AE signal **P**ower and ADNC descriptor is connected with **A**mplitude **D**istribution of AE **N**ormalized activity **C**ounts.

So defined descriptors do not base on the absolute values of the recorded signal. A larger descriptor value (the flatter part of the curve) means a more advanced deformational process.

Fig. 3 shows the example amplitude distributions of the count rate calculated in the framework of the advanced analysis (Fig. 3a, c), the derivatives of these distributions with respect to the threshold of discrimination (Fig. 3b), and corresponding values of the ADC descriptor (Fig. 3d) for two families of AE signals – those coming from sources of partial discharges (PDs) (Fig. 3d, signals 1–5) and the noises associated with the measuring channel (Fig. 3d, signals 6–10). One can see a fundamental difference between the descriptor values in those two families, which confirms the assumption of the possibility of recording and identifying AE signals coming from different sources.

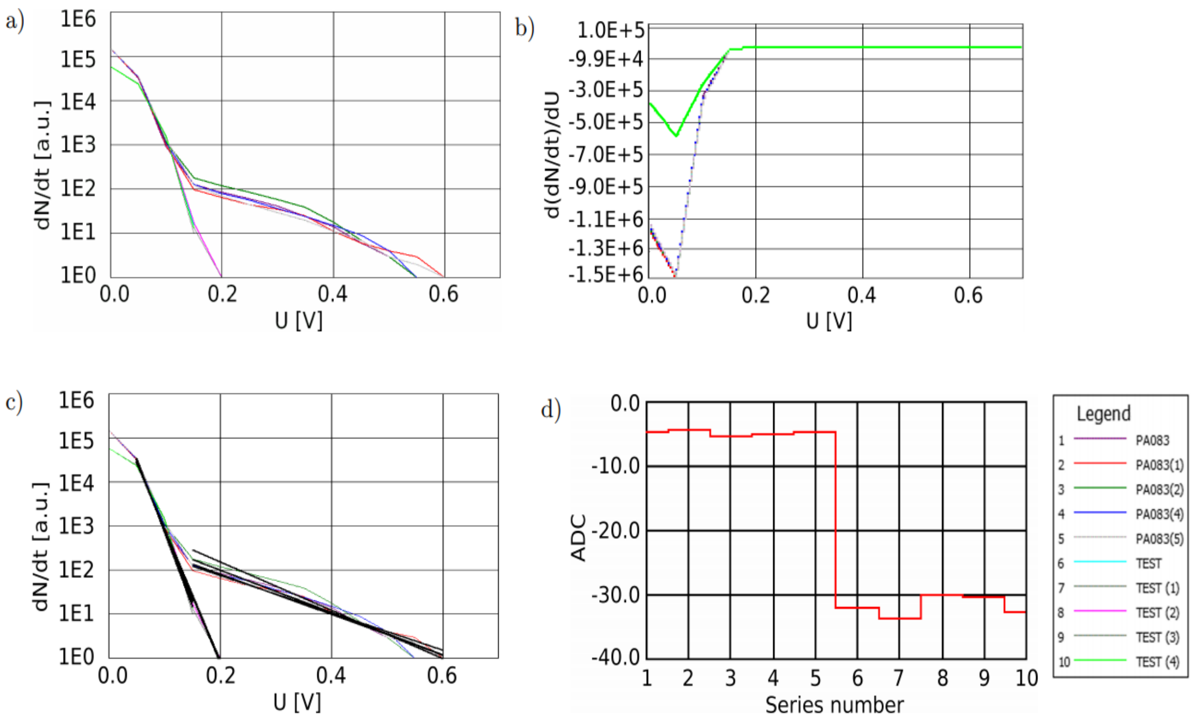

Fig. 3. Investigation of amplitude distributions by means of AE descriptor methods (calculation and visualization of amplitude distributions and descriptors): results for the family of AE signals coming from PD (signals 1–5) and the family of noise within measuring line (signals 6-10)

Rys. 3. Badanie właściwości rozkładów amplitudowych metodą deskryptorów EA (obliczanie i wizualizacja rozkładów amplitudowych i deskryptorów): wyniki dla rodziny sygnałów pochodzących od WNZ (sygnały 1-5) oraz rodziny szumów związanych z torem pomiarowym (sygnały 6-10)

The maps of descriptors on the side walls of the investigated transformer tank are determined from the obtained descriptors with the use of the kriging method. On the maps, there are local maxima. Fig. 4 shows an exemplary map of an ADC descriptor calculated for the frequency band of 20–200 kHz (the entire analysed frequency band). However, ADC descriptor maps are developed for different selected frequency bands. On these maps, one can determine the areas with local maxima. This enables the analysis of AE signals recorded in selected areas aiming at identification of signals coming from different acoustic sources in power oil transformers and location of these sources in the investigated transformers.

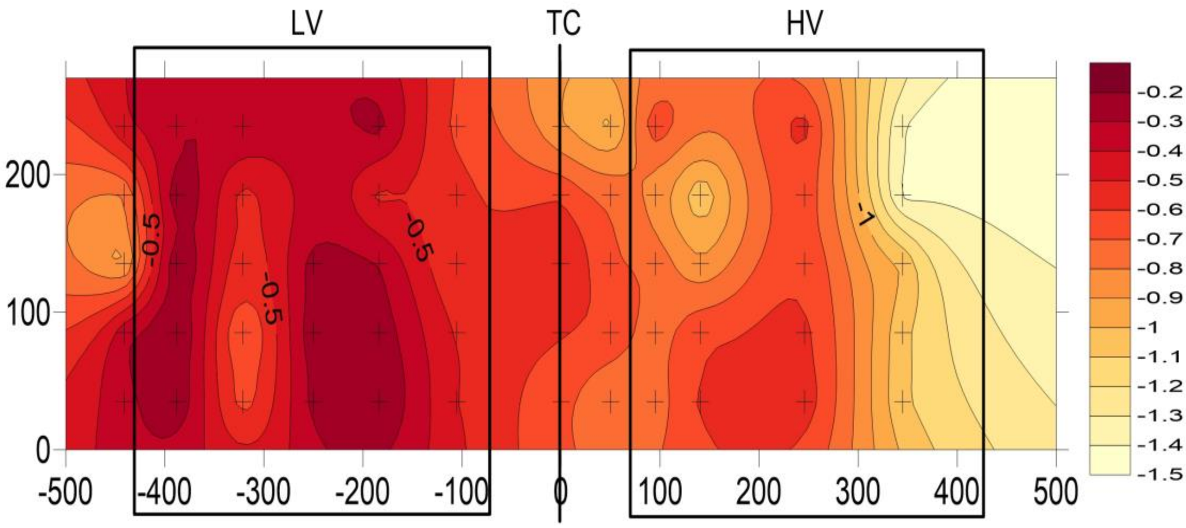

Fig. 4. Map of ADC descriptor on the side walls of the tested transformer tank for the analysis of signals in the range 20–200 kHz. (*X*, *Y*) coordinates of the transformer tank points (in centimeters): *X* – running position along the transformer tank, 0 – center of the tap changer (TC), positive values of *X* – part of the tank from high voltage side (HV), negative values of *X* – part of the tank from low voltage side (LV), *Y* – running height of the transformer tank, + – marked measurement points

Rys. 4. Mapa deskryptora ADC na ścianach bocznych kadzi badanego transformatora dla analizy sygnałów w paśmie 20-200 kHz. (*X*, *Y*) współrzędne punktów kadzi transformatora (wartości współrzędnych w centymetrach): *X* – położenie bieżące wzdłuż kadzi transformatora, 0 – środek przełącznika zaczepów, dodatnie wartości *X* – część kadzi od strony górnego napięcia (GN), ujemne wartości *X* – część kadzi od strony dolnego napięcia (DN), *Y* – wysokość bieżąca na kadzi transformatora, + - naniesione punkty pomiarowe

Due to the specific nature of individual deformation processes, in addition to the basic and advanced analysis of averaged AE signals, the selected parts of the AE signals of duration equal or shorter than one period of the reference voltage are additionally analysed. An exemplary analysis of the part of the recorded AE signal is shown in Fig. 5. In the analysis, there is a selected part of the whole recorded signal of the duration equal to one period of the reference voltage. This part is filtrated in a selected frequency band, and then there are separated single structures from the signal (Fig. 5a) for which the duration and frequency characteristics are determined (Fig. 5c, d).

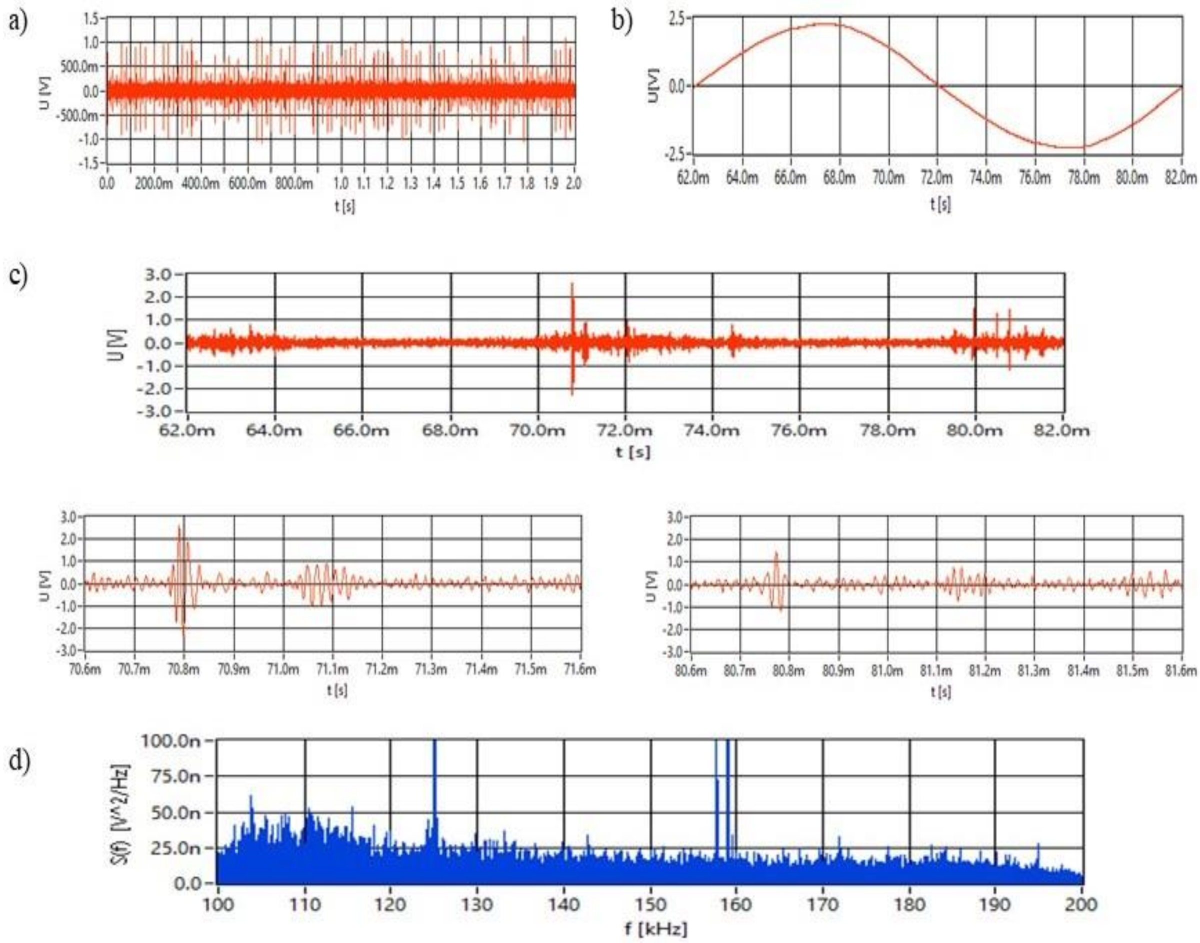

Fig. 5. Analysis of a selected part of the signal of duration equal to one period of the reference voltage, recorded at a chosen measurement point: a) the entire signal, b) the reference signal for the selected fragment of the signal, c) selected part of the signal after filtration with the indicated single pulses, d) frequency characteristic for the selected part of the signal

Rys. 5. Analiza wybranego fragment sygnału o czasie trwania 1 okresu napięcia odniesienia: a) cały sygnał, b) sygnał odniesienia dla wybranego fragmentu sygnału, c) wybrany fragment sygnału po filtracji wraz z wskazanymi pojedynczymi impulsami, d) charakterystyka częstotliwościowa dla wybranego fragmentu sygnału

11.3. Tested objects

As part of the work, six oil power transformers in different technical conditions were tested. The tested transformers were designated successively as T1 - T6 transformers. Table 1 presents basic information related to the tested transformers.

Table 1

Basic information related to the tested transformers

Name	Transformer rated parameters		Technical conditions	Measurement location	Type of AE sensors
	U_{1N}, kV	S_N, MVA			
T1	110/20/6	25	operating faultlessly for the whole operating life	power station - during normal transformer operation	D9241A
T2	110/20/6	25	it overheated several times; discharges led to its shutdown	power station - during normal transformer operation	D9241A
T3	110	25	operating faultlessly for the whole operating life; DGA test of oil - results in the range permitted by the standards	power station - during normal transformer operation	R6, WD
T4	110	25	several recent DGA tests of oil showed increasing levels of hydrogen and other gases dissolved in the oil, which indicated the existence of partial discharges	power station - during normal transformer operation	R6, WD
T5	110	16	DGA test of oil - hydrogen and other gases dissolved in oil, which indicated the existence of partial discharges	power engineering repair unit	R6
T6	220	400	new transformer with synthetic oil - electrical tests showed the occurrence of surface discharges with a charge of 1nC at a voltage of 1.7 U_n in the vicinity of the L2 phase	test station	D9241A

11.4. Basic and advanced analysis of acoustic emission signals to distinguish signals from different sources generating acoustic signals in power oil transformers

Based on the described in Chapter 2 maps of the ADC descriptor on the side walls of the investigated transformer tank, the areas for which the descriptor has local maxima of large values were determined. Signals recorded at measuring points located in such defined areas are characterized by a greater degree of advancement. For so selected recorded AE signals basic and advanced data analysis was performed.

On the basis of analyses in selected frequency bands, the AE signals from various sources generating acoustic signals in oil power transformers were distinguished. The following sources of AE signals have been distinguished: noise of the measuring path, partial discharges (PD), phenomena occurring during the magnetization of ferromagnetic materials and disturbing signals.

The subsequent sections present the results of the analysis of AE signals recorded in the tested transformers, the analysis being carried out with the aim of distinguishing signals from the above-mentioned types of sources generating acoustic signals in power oil transformers.

11.4.1. Noise of the measuring path

Three types of AE sensors were used in the research on AE signals recorded in power oil transformers (Table 1). These were Euro Physical Acoustics D9241A measuring transducers and Physical Acoustics Corporation AE sensors of WD and R6 types.

Figs. 6-8 show the basic characteristics of the signals recorded with the AE sensors used in the tests, before attaching the sensors to the tested transformer. These characteristics show examples of the noise of the measuring paths in three cases, when the measuring path contained respectively D9241A, WD and R6 AE sensors. Recorded signals have random character. The common feature of the presented characteristics is the presence of only local maxima of small amplitudes, which is typical for noise. The noise level introduced by the measuring paths is small. The ADC descriptor is small (about -25 ÷ -30).

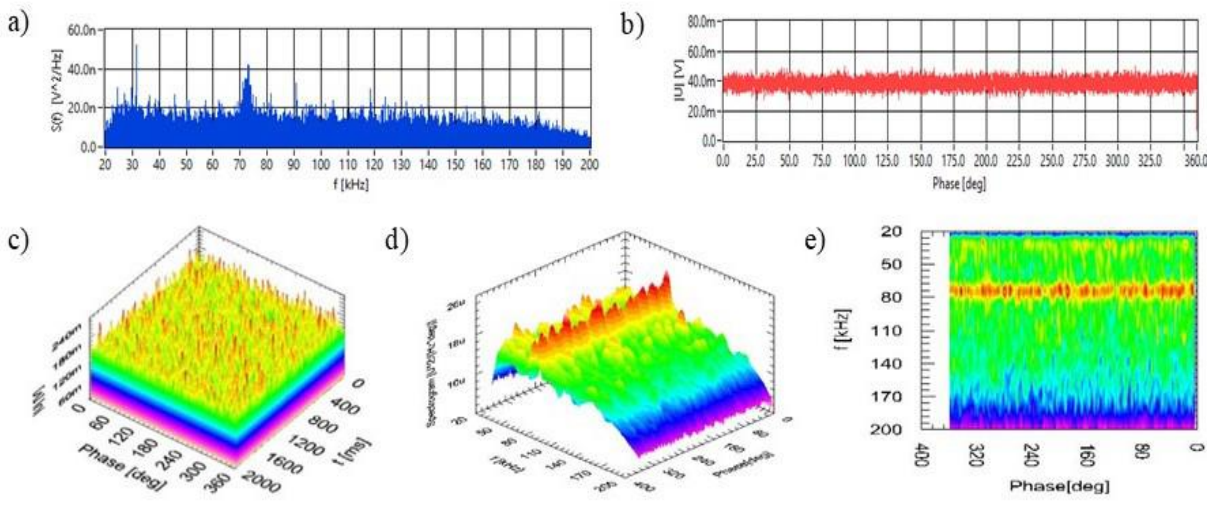

Fig. 6. Basic description of the AE signal recorded for the D9241A sensor with filtration in the 20-200 kHz band: a) signal after filtration, b) frequency characteristic, c) phase-time characteristic, d) averaged phase characteristic, e) and f) STFT spectrograms; ADC = -25.69

Rys. 6. Podstawowy opis sygnału EA zarejestrowanego dla czujnika D9241A przy filtracji w paśmie 20-200 kHz: a) sygnał, b) charakterystyka częstotliwościowa, c) charakterystyka fazowo-czasowa, d) uśredniona charakterystyka fazowa, e), f) uśrednione spektrogramy STFT; ADC = -25,69

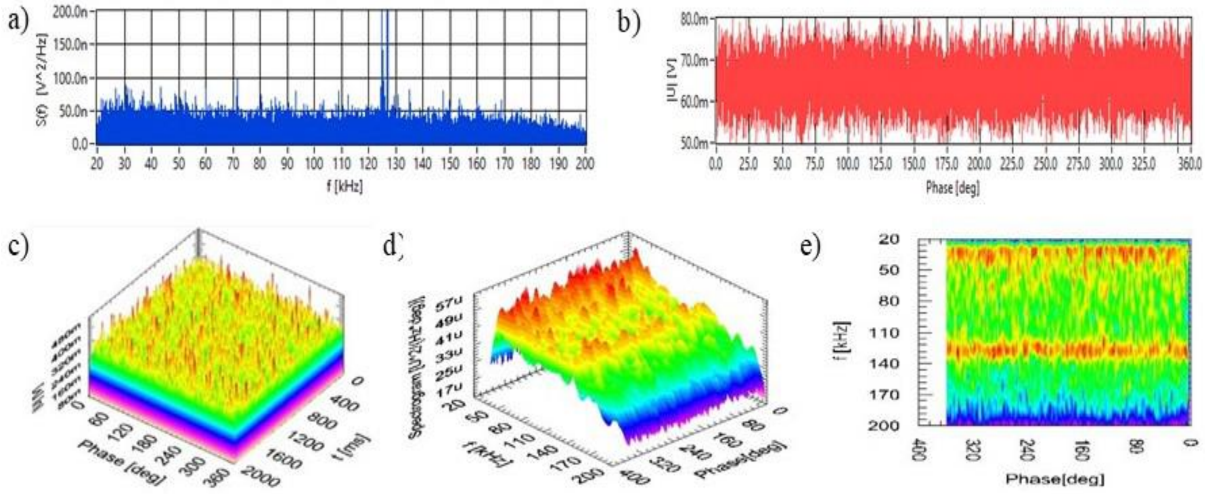

Fig. 7. Basic description of the AE signal recorded for the WD sensor with filtration in the 20-200 kHz band: a) signal after filtration, b) frequency characteristic, c) phase-time characteristic, d) averaged phase characteristic, e) and f) STFT spectrograms; ADC = -24.68

Rys. 7. Podstawowy opis sygnału EA zarejestrowanego dla czujnika WD przy filtracji w paśmie 20-200 kHz: a) sygnał, b) charakterystyka częstotliwościowa, c) charakterystyka fazowo-czasowa, d) uśredniona charakterystyka fazowa, e), f) uśrednione spektrogramy STFT; ADC = -24,68

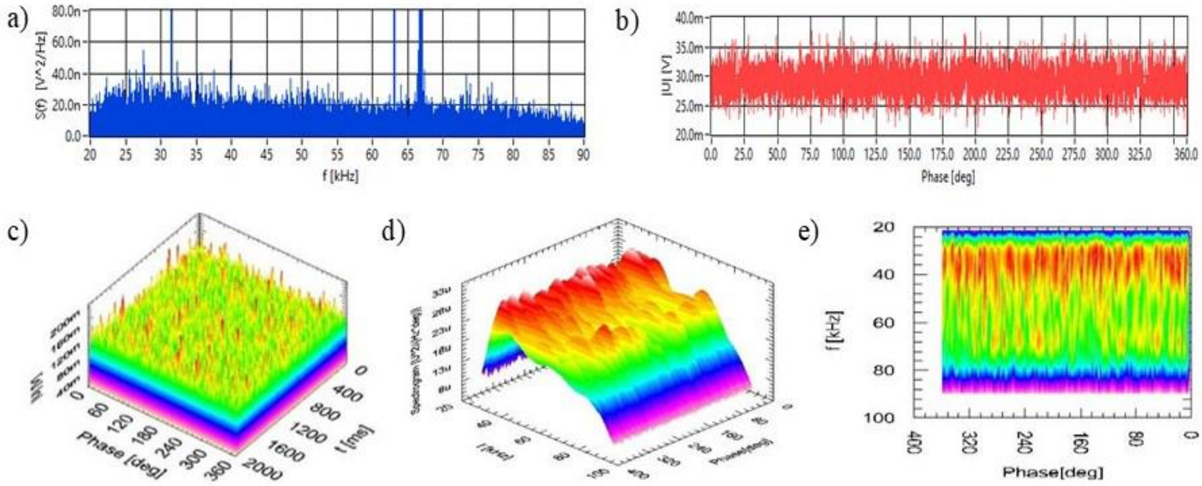

Fig. 8. Basic description of the AE signal recorded for the R6 sensor with filtration in the 20-90 kHz band: a) signal after filtration, b) frequency characteristic, c) phase-time characteristic, d) averaged phase characteristic, e) and f) STFT spectrograms; ADC = -29.17

Rys. 8. Podstawowy opis sygnału EA zarejestrowanego dla czujnika R6 przy filtracji w paśmie 20-90 kHz: a) sygnał, b) charakterystyka częstotliwościowa, c) charakterystyka fazowo-czasowa, d) uśredniona charakterystyka fazowa, e), f) uśrednione spektrogramy STFT; ADC = -29,17

11.4.2. Identification of partial discharges (PD) sources

Identification of PD sources in the tested transformer begins with the analysis of the ADC descriptor map calculated in the band 100(110)-200 kHz. On the map of the descriptor calculated in the band 100(110)-200 kHz, the areas for which the descriptor has local maxima of large values are marked. The results of the analysis of AE signals recorded at selected measuring points located in designated areas for selected transformers are presented below.

The maximum values of the ADC descriptor for the transformer T1 occur in the area at the bottom of the tap changer and these are values indicating the operation of the PD source responsible for the advanced deformation process. The basic characteristics of selected signals recorded in this area are shown in Figs. 9-10. They illustrate the properties of signals coming from the PD source located in the tap changer area.

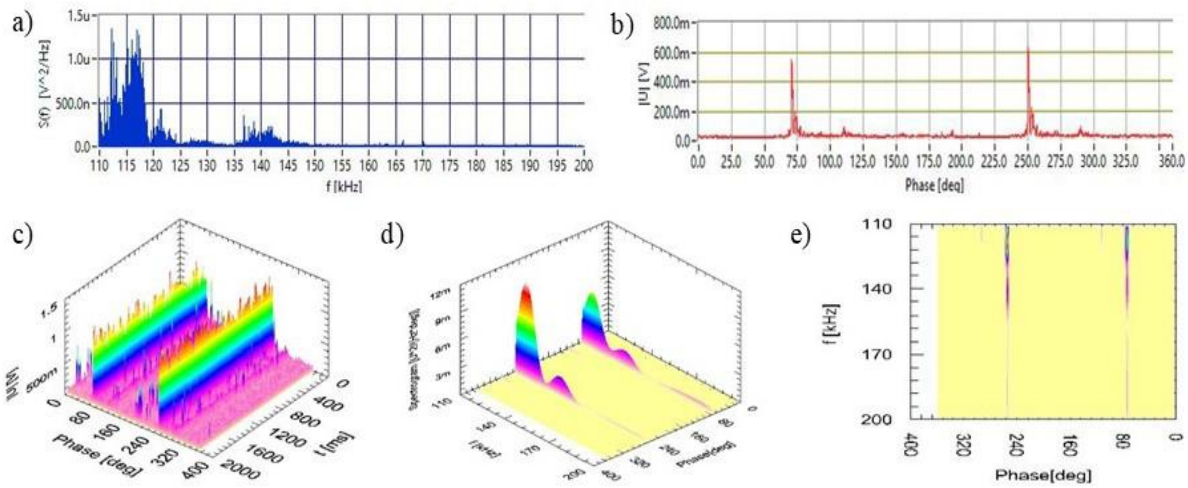

Fig. 9. Basic description of the AE signal recorded at the selected measuring point PA072 of the T1 transformer with filtration in the 110-200 kHz band: a) frequency characteristic, b) averaged phase characteristic c) phase-time characteristic, d) and e) averaged STFT spectrograms; ADC = -2.66

Rys. 9. Podstawowy opis sygnału EA zarejestrowanego w wybranym punkcie pomiarowym PA072 transformatora T1 przy filtracji w paśmie 110-200 kHz: a) charakterystyka częstotliwościowa, b) uśredniona charakterystyka fazowa, c) charakterystyka fazowo-czasowa, d), e) uśrednione spektrogramy STFT; ADC = -2,66

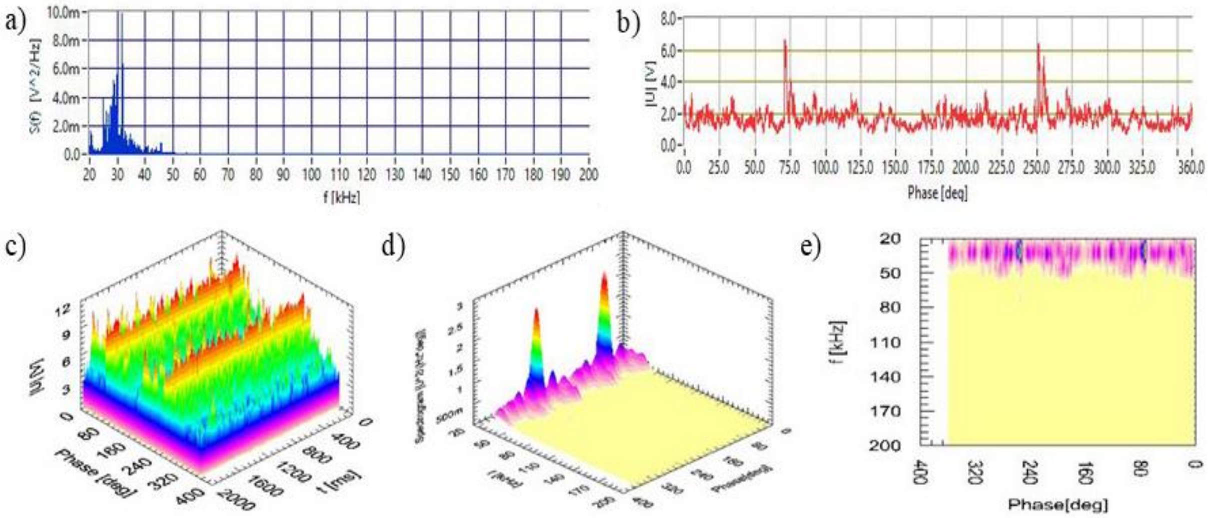

Fig. 10. Basic description of the AE signal recorded at the selected measuring point PA072 of the T1 transformer with filtration in the 20-200 kHz band: a) frequency characteristic, b) averaged phase characteristic c) phase-time characteristic, d) and e) averaged STFT spectrograms; ADC = -0.30

Rys. 10. Podstawowy opis sygnału EA zarejestrowanego w wybranym punkcie pomiarowym PA072 transformatora T1 przy filtracji w paśmie 20-200 kHz: a) charakterystyka częstotliwościowa, b) uśredniona charakterystyka fazowa, c) charakterystyka fazowo-czasowa, d), e) uśrednione spektrogramy STFT; ADC = -0,30

The signal recorded at the PA072 measuring point has the following properties: it is periodic, its main frequency bands are 110-125 kHz and 135-145 kHz, it occurs twice during one supply voltage period in phases differing by 180° and is very well located in phase. The periodic nature of this signal is shown by the "narrow" tunnels on the phase-time characteristic (Fig. 9b).

Fig. 10 shows the basic characteristics of the signal in the band 20-200 kHz. In this frequency band, on the averaged phase characteristic, the maxima occur twice during one period of the supply voltage in phases differing by 180° and they are well located in the phase. It is important that the averaged phase characteristics in Figs. 9b and 10b are similar for the phases for which there are maxima. For the phases with values outside the maximum (in Fig. 10), larger fluctuations of the graph around the mean value are visible. Similarities of the same type appear in the phase-time characteristics (Figs. 9c and 10c). When analysing the signal in the band 20-200 kHz, the main frequency band for the signal is 20-40 kHz.

The combined analysis of the properties of the signal recorded at PA072 (carried out on the basis of the characteristics shown in Figs. 9 and 10) leads to the conclusion that in the entire analysed frequency band, i.e. 20-200 kHz, the dominant role is played by the harmonic components of the signal from the PD source, which are in the bands: 20-40 kHz, 110-125 kHz and 135-145 kHz.

AE signals from the identified PD source were further analysed, in which selected parts of the signals recorded at the PA072 measurement point of duration equal to one period of the reference voltage were analysed. The results of this analysis are shown in Fig. 11.

In the fragment of the signal recorded at the PA072 measurement point shown in Fig. 11a, two main structures can be distinguished, marked as 2 and 3, and an additional structure marked as 1. The main structures are shifted in time by half of the supply voltage period. These structures have a complex structure, which can be described as follows: the basis are two consecutive fragments that repeat after approx. 150 µs and 300 µs; subsequent repetitions have lower amplitudes; the total duration of both fragments during the first recording is approx. 80 µs. Such a complex structure of structures is well explained by the following description: the PD source generates a signal consisting of two structures lasting approx. 80 µs, which reach the measuring point as the first fragment of the recorded signal; the signal generated in the source is reflected and at the measuring point successive fragments of the structure shifted by approx. 150 µs and 300 µs, having smaller and smaller amplitudes, are recorded. The structure marked as 1 is in the form of a single pulse with a duration of approx. 40 µs.

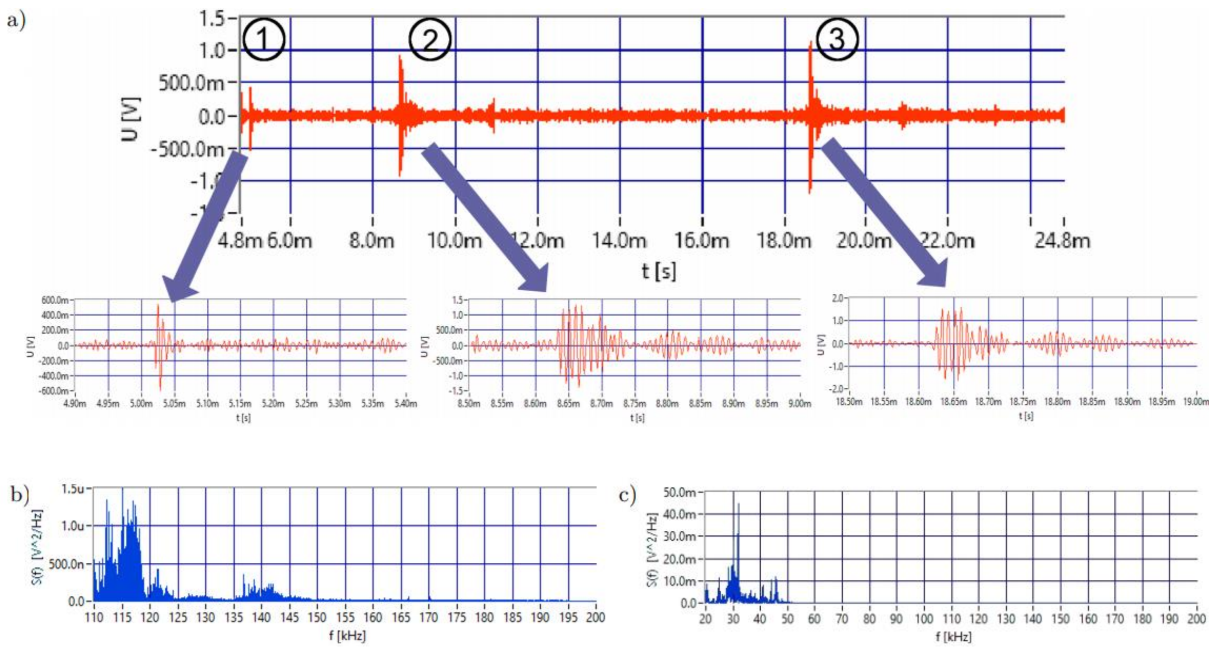

Fig. 11. Analysis of a selected part of the signal recorded at a measurement point PA072 of duration equal to one period of the reference voltage: a) selected part of the signal after filtration together with the shown single pulses, b) frequency characteristics for the selected part of the signal in the frequency range 110-200 kHz, c) frequency characteristics for the selected part of the signal in the frequency range 20-200 kHz

Rys. 11. Analiza wybranego fragmentu sygnału zarejestrowanego w punkcie pomiarowym PA072 o czasie trwania wynoszącym 1 okres napięcia odniesienia: a) wybrany fragment sygnału po filtracji wraz z wskazanymi pojedynczymi impulsami, b) charakterystyka częstotliwościowa dla wybranego fragmentu sygnału dla częstotliwości 110-200 kHz, c) charakterystyka częstotliwościowa dla wybranego fragmentu sygnału dla częstotliwości 20-200 kHz

In the case of the T4 transformer on the map of the ADC descriptor calculated in the 100-200 kHz band, the ADC descriptor takes the highest values in the area from the upper voltage side with the coordinates X = 130-150 cm, Y = 180-190 cm - around the measurement point T1G01 (X = 143 cm; Y = 186 cm). Fig. 12 shows the basic characteristics of the AE signal recorded at the T1G01 measurement point for the 100-200 kHz frequency band. These characteristics show the following characteristics of the signal: it occurs regularly and periodically - twice during each period of the supply voltage, the phase bands of the signal occurrence in each of the supply voltage periods are narrow (Fig. 12c), it has a dominant frequency band of 100-120 kHz and large amplitudes.

Fig. 13 shows the basic characteristics of the AE signal recorded at the T1G01 measurement point for the 20-100 kHz frequency band. These characteristics show the following characteristics of the signal: it occurs regularly and periodically - twice during each period of the supply voltage, where the phase bands of the signal occurrence in each of the supply voltage periods are arranged in "corridors" (Fig. 13c), it has the dominant frequency band of 40-80 kHz and very large amplitudes.

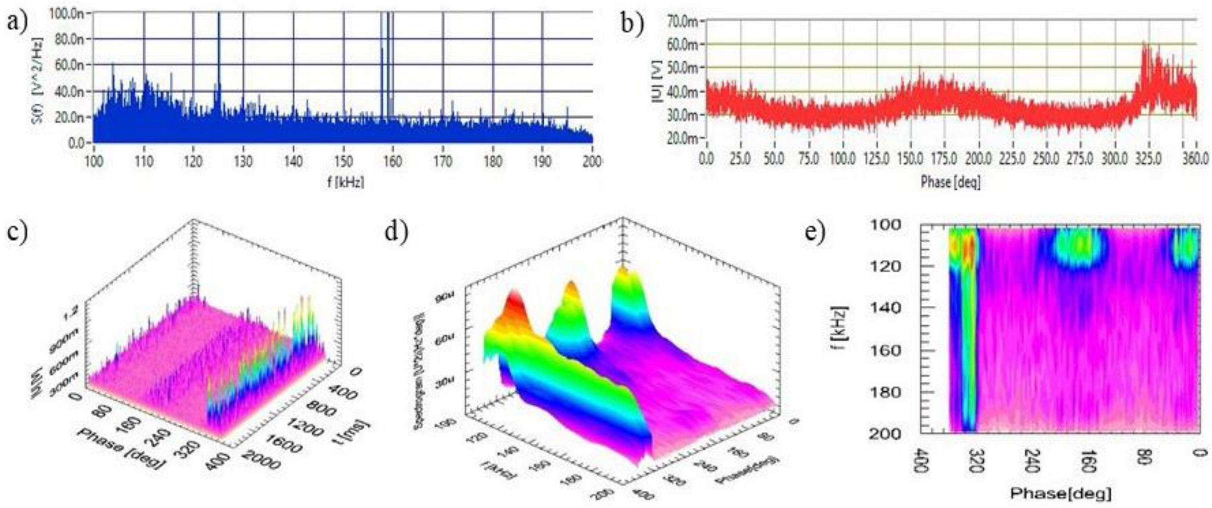

Fig. 12. Basic description of the AE signal recorded at the selected measuring point T1G01 of the T4 transformer with filtration in the 100-200 kHz band: a) frequency characteristic, b) averaged phase characteristic, c) phase-time characteristic, d) and e) averaged STFT spectrograms; ADC = -3.06

Rys. 12. Podstawowy opis sygnału EA zarejestrowanego w wybranym punkcie T1G01 transformatora T4 przy filtracji w paśmie 100-200 kHz: a) charakterystyka częstotliwościowa, b) uśredniona charakterystyka fazowa, c) charakterystyka fazowo-czasowa, d), e) uśrednione spektrogramy STFT; ADC = -3.06

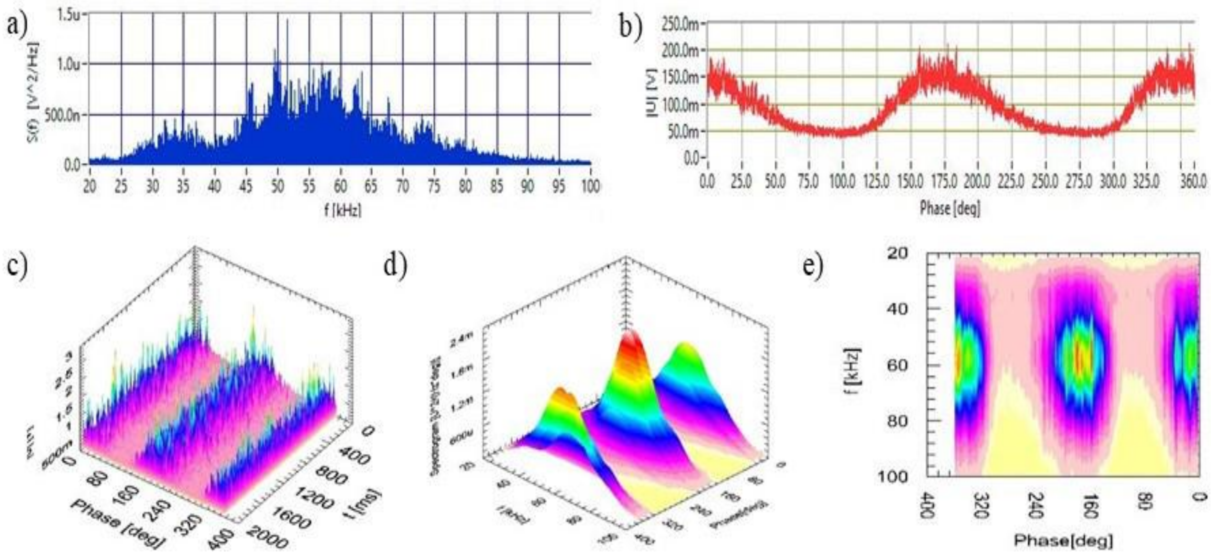

Fig. 13. Basic description of the AE signal recorded at the selected measuring point T1G01 of the T4 transformer with filtration in the 20-100 kHz band: a) frequency characteristic, b) averaged phase characteristic, c) phase-time characteristic, d) and e) averaged STFT spectrograms; ADC = -1.80

Rys. 13. Podstawowy opis sygnału EA zarejestrowanego w wybranym punkcie pomiarowym T1G01 transformatora T4 przy filtracji w paśmie 20-100 kHz: a) charakterystyka częstotliwościowa, b) uśredniona charakterystyka fazowa, c) charakterystyka fazowo-czasowa, d), e) uśrednione spektrogramy STFT; ADC = -1,80

The comparison of Figs. 12c and 13c is significant, showing that the "corridors" in Fig. 13c include the PD described in Fig. 12c. Such a comparison shows that in the 40-80 kHz band there are components both from PD and other acoustic phenomena, and the phase of PD phenomena occurrence falls within the phase area typical for other acoustic phenomena.

Moreover, in this case, the AE signals from the identified PD source were subjected to further analysis - selected parts of the signal recorded at the T1G01 measurement point of duration equal to one period of the reference voltage were analysed. The results of this analysis are shown in Fig. 14.

In the indicated part of the signal recorded at the T1G01 measurement point, several structures with duration from 30 μs to 50 μs can be distinguished. Examples of structures are highlighted in Fig. 14a. Further analyses of PD signals for the T4 transformer can be found in [16].

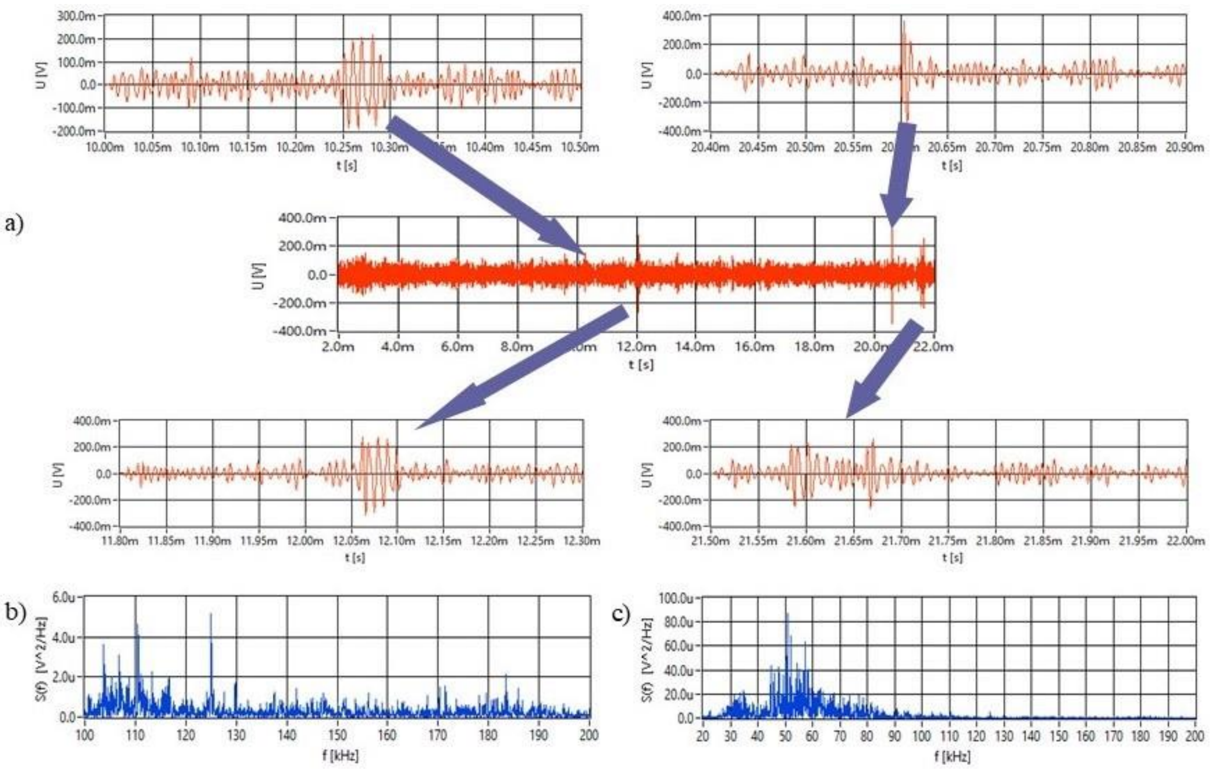

Fig. 14. Analysis of a selected part of the signal recorded at a measurement point T1G01 of duration equal to one period of the reference voltage: a) the entire signal selected part of the signal after filtration in the 100-200 kHz band with the indicated single pulses, b) and c) frequency characteristics for the selected part of the signal

Rys. 14. Analiza wybranego fragment sygnału zarejestrowanego w punkcie pomiarowym T1G01 o czasie trwania wynoszącym 1 okres napięcia odniesienia: a) wybrany fragment sygnału po filtracji w paśmie 100-200 kHz wraz z wskazanymi pojedynczymi impulsami, b) i c) charakterystyki częstotliwościowe dla wybranego fragmentu sygnału

It is worth adding that as a result of the performed tests, the transformer was inspected, which showed that near the T1G01 measurement point, the cables connecting the high-voltage terminals and the tap changer were too close to the transformer tank - not in accordance with the designed solutions. After restoring the correct distance, no PDs were found near this measurement point.

For the T6 transformer, which is filled with synthetic oil, the measurements were carried out for two cases. First, the AE signals were recorded with the supply of rated voltage U_N, and then the measurements were made at the voltage of 1.7 U_N, while the signals were recorded after the supply time of 90 minutes.

The analysis of signals registered at U_N voltage indicates that the descriptor take very small values, which means no PDs for this case. The ADC descriptor map for the second case shows very large descriptor values in the tap changer area and at the top of the transformer area. Such a distribution of descriptor values allows us to hypothesize that there are many PDs sources in the transformer. Bearing in mind the following facts: (i) no PDs sources in the first case, (ii) synthetic oil was used in the transformer, (iii) in gas inclusions in oil PDs are initiated in areas where the electric field strength is higher than the critical intensity, the following hypothesis was made: during the operation, in the oil used in the transformer "gassing" processes occurred. In the gas bubbles formed in this way and located in the areas where the local field strength is greater than the critical intensity, PDs are initiated. Transformer oil tests carried out using the DGA method showed the amount of hydrogen several times exceeding the permissible level.

The basic characteristics of an exemplary signal recorded in this measurement situation are shown in Fig. 15. They illustrate the properties of the AE signal coming from partial discharges in gas bubbles that appear in the tested transformer after a long time of operation in conditions of increased voltage (1.7 U_N).

The analysis of the selected parts of this signal (Fig. 16) proves that the AE signal recorded at the selected measurement point on the side wall of the T6 transformer tank is non-periodic. There are fragments of the signal where single pulses can be distinguished (Fig. 16a). Such a pulse shows the main structure as well as additional structures that may come from PDs in other gas bubbles or in the same bubble. The shape of these structures determines the spontaneous avalanche discharges in the gas bubbles. There are also visible parts of the analysed signal (Fig. 16b), for which individual structures cannot be indicated. However, in both cases the main frequency bands on the frequency characteristics are the same (Figs. 16c and 16d).

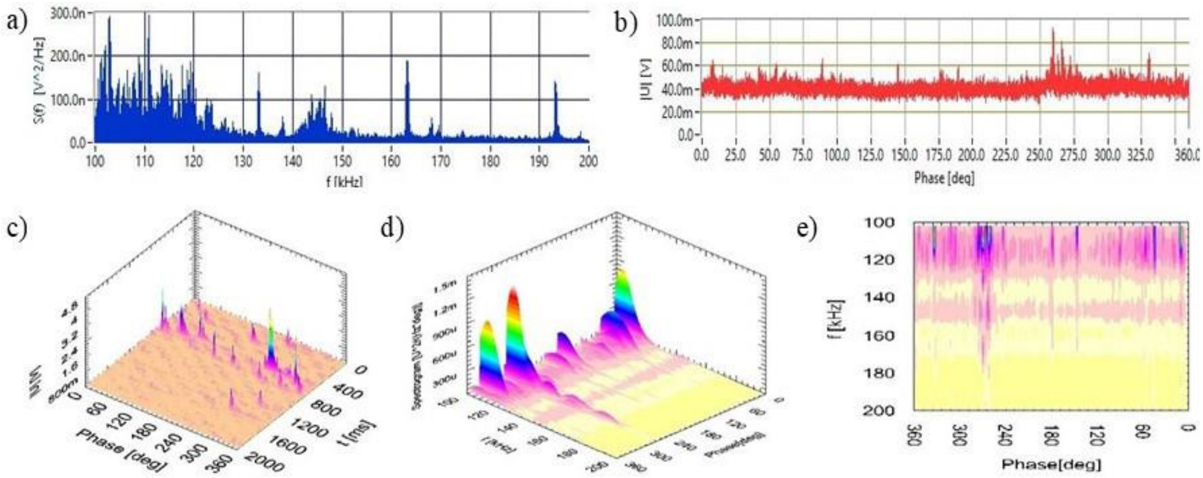

Fig. 15. Basic description of the AE signal recorded at the selected measuring point NB011BIS of the T6 transformer with filtration in the 100-200 kHz band: a) frequency characteristic, b) averaged phase characteristic, c) phase-time characteristic, d) and e) averaged STFT spectrograms; ADC= -1.41

Rys. 15. Podstawowy opis sygnału EA zarejestrowanego w wybranym punkcie pomiarowym NB011BIS transformatora T6 przy filtracji w paśmie 100-200 kHz: a) charakterystyka częstotliwościowa, b) uśredniona charakterystyka fazowa, c) charakterystyka fazowo-czasowa, d), e) uśrednione spektrogramy STFT; ADC= -1,41

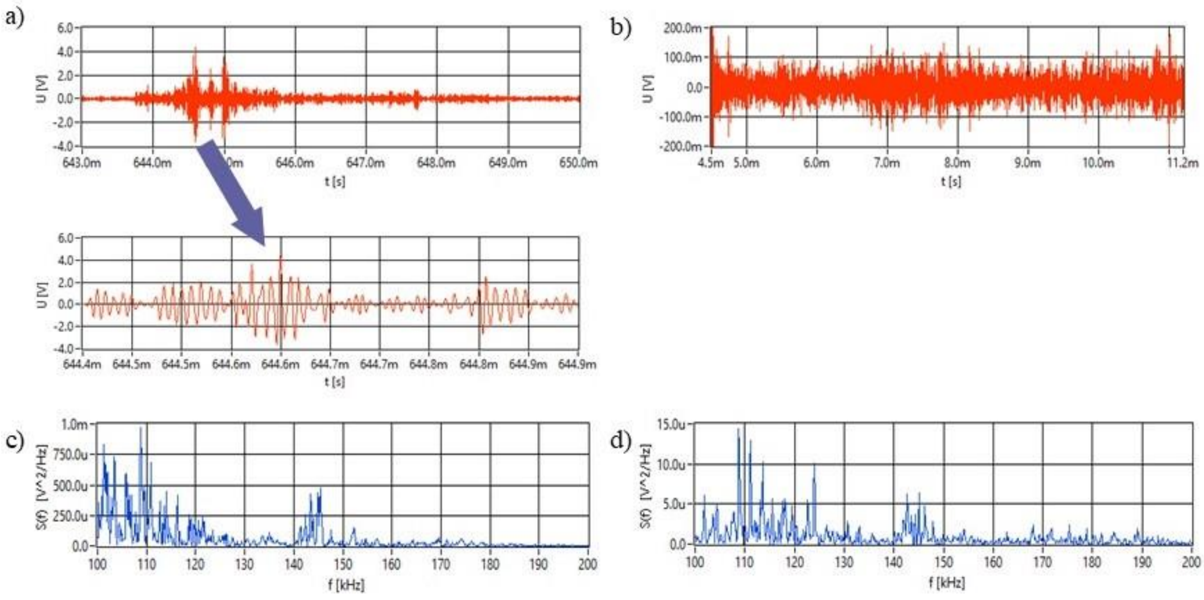

Fig. 16. Analysis of the selected parts of the signal recorded at the measurement point NB011BIS of duration equal to one period of the reference voltage: a) the first of the selected parts of the signal filtered in the 100-200 kHz band with the indicated single pulse, b) the second of the selected signal parts after filtration in the 100-200 kHz band, c) frequency characteristics for the signal part from Fig. 16a, d) frequency characteristics of the signal part from Fig. 16b

Rys. 16. Analiza wybranych fragmentów sygnału zarejestrowanego w punkcie pomiarowym NB011BIS o czasie trwania wynoszącym 1 okres napięcia odniesienia: a) pierwszy z wybranych fragmentów sygnału po filtracji w paśmie 100-200 kHz wraz z wskazanym pojedynczym impulsem, b) drugi z wybranych fragmentów sygnału po filtracji w paśmie 100-200 kHz, c) charakterystyka częstotliwościowa dla fragmentu sygnału z rys. 16a, d) charakterystyka częstotliwościowa dla fragmentu sygnału z rys. 16b

11.4.3. Identification of AE signals coming from the phenomena occurring during the magnetization of ferromagnetic materials

During the magnetization of ferromagnetic materials from which transformer core sheets are made, the phenomena of reversible displacement of domain boundaries, the so-called Bloch walls, irreversible displacement of domain boundaries (Barkhausen effect) and rotation of magnetization vectors towards the external magnetic field occur. As part of these processes, the processes of creating domain boundaries, movement of these boundaries and annihilation of boundaries occur, during which acoustic signals are generated, referred to as magnetoacoustic emission (MAE). According to literature data [18], the main frequency band of MAE signals is in the range 10 - 65 kHz.

The identification of AE signals coming from the phenomena occurring during magnetization of ferromagnetic materials will be presented on the basis of the analysis of the AE signals recorded in the T1 transformer. Taking into account the fact that the lower limit of the frequency response of the measurement system used in the research is 20 kHz, the analysis will be performed in the 20-70 kHz band.

On the map of the ADC descriptor in the band of 20–70 kHz, the areas of the greatest intensity of the AE signals were determined provided that corresponding to them descriptor values in the range of 110–200 kHz were small. These areas determine the places in which MAE signals are dominant in the recorded signals. To identify the AE signals coming from these phenomena, there were performed analyses of the AE signals recorded in the area around one of transformer's cores (measurement points belonging to the family PA02y with coordinates X = 483 cm, Y = 60 ÷ 235 cm (y = 1, 2, . . . , 6 – numbering from bottom of the transformer). These points are evenly distributed along one vertical line on the transformer tank.

Basic characteristics were calculated for all AE signals recorded at the measurement points belonging to the PA02y family. These characteristics for the signals recorded at the measurement point PA026 in the band 20-70 kHz are presented in Fig. 17.

The properties of the recorded signal are as follows: signals are periodic; their dominant frequency band is 20-40 kHz; in each period of the supply voltage, bands of phases of signal occurrence are arranged in wide "corridors" (Fig. 17c); one can distinguish two or four ranges of phases of the reference voltage for which the signals are recorded (Fig. 17b).

To discuss the analysis results of the signals recorded at all measurement points belonging to the family PA02y, there were chosen: a) averaged phase characteristics, b) STFT spectrograms projected onto the phase-frequency plane. These characteristics were calculated after filtering the signal in the bands 20-70 kHz and 40-70 kHz. They are shown in Figs. 18 and 19.

The analysis of the properties of the averaged phase characteristics (Figs. 18a and b) when distinguishing two ranges of phases of the reference voltage shows for each range a fast increase in the values at the beginning of the range and a significantly slower decrease of the signal at the end of the range. In addition, when analysing the signal in the band of 20-70 kHz it can be noted that the first maximum values in the first of the two distinguished ranges are larger than the first maximum values in the second range; such a regularity does not occur when analysing the signal in the band of 40-70 kHz. In a more detailed analysis which leads to separation of individual curves within each range (obtained from distinguishing two ranges), one should first designate the envelope and then see this envelope as a superposition of two or three Gaussian-type curves. With this approach, in each of the ranges there can be seen one Gaussian-type curve in the initial part of the range and one or two such curves in the further part of the range. Location of the maxima and the values of the maxima of these component curves give summary curves of different shapes with one or many maxima. With this approach, the curve of Fig. 18a for the point PA021 although having one maximum in the range, consists of at least two Gaussian-type curves, the second of which has a much lower amplitude than the first one. It follows from the asymmetric shape of this curve. This explanation allows to see that for the average characteristics of phase (Fig. 18) there are two fragments within curve containing two maxima separated by a relative minimum. These fragments correspond to the increase and decrease of the magnetic field, the minima occur around the coercive field [19].

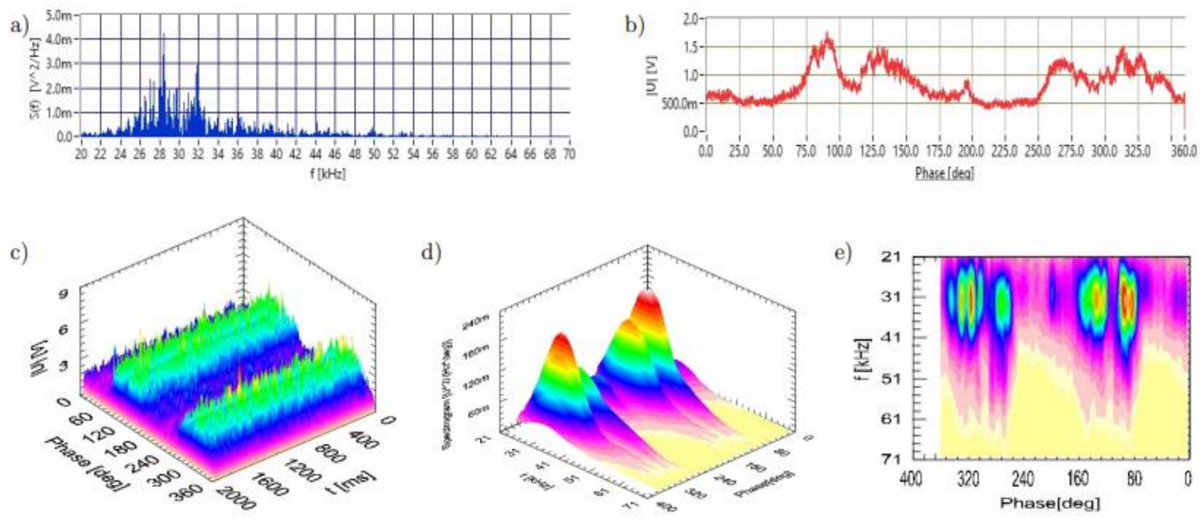

Fig. 17. Basic description of the AE signal recorded at the selected measurement point of the T1 transformer (PA026) for filtration in the band 20-70 kHz: a) frequency characteristic, b) averaged phase characteristic, c) phase-time characteristic, d) and e) averaged STFT spectrograms; ADC = -0.63

Rys. 17. Podstawowy opis sygnału EA zarejestrowanego w wybranym punkcie pomiarowym transformatora T1 (PA026) przy filtracji w paśmie 20-70 kHz: a) charakterystyka częstotliwościowa, b) uśredniona charakterystyka fazowa, c) charakterystyka fazowo-czasowa, d), e) uśrednione spektrogramy STFT; ADC= -0,63

A detailed analysis of the positions of the minimum in Fig. 18a for PA026-24 points gives results within the following phase ranges: (105°, 115°) and (285°, 295°). These values define, therefore, the phase of the coercive field of studies. It is worth emphasizing that the phases shown in the diagrams describe the phases of the power supply voltage used in the measurement system and do not specify the phase of current flowing in the winding, which induces magnetic flux in the tested core. Quantitative differences and qualitative differences in the shapes of the curves of the individual graphs in Fig. 18 contain information about the local magnetic properties of the tested materials. A similar analysis can be performed for STFT spectrograms shown in Fig. 19. The higher sensitivity of STFT spectrograms as compared to the averaged characteristics of the phase is visible. Such an approach to the averaged phase characteristics of Figs. 18 and 19 allows concluding that the magnetoacoustic emission:

- distinguishes between the processes of magnetization and demagnetization,
- distinguishes between the processes of magnetization and demagnetization at positive and negative values of the magnetic field,
- shows the local properties of transformer core sheets.

To further characterize the AE signals coming from the phenomena occurring during magnetization of ferromagnetic materials, the analysis of the signals after filtration in the bands of 70-100 kHz and 100-200 kHz was conducted. Results of this analysis are presented in the paper [20]. From the conducted analyses it follows that the main band for the phenomena associated with magnetization of ferromagnetic materials can be extended up to 90 kHz.

The analysis of the selected parts of the signals of 20 ms duration recorded at particular measurement points was also performed. The analysis results for the signals recorded at the measurement points PA021 and PA026 and the frequency band of 40-70 kHz are presented in Fig. 20. In both signals, the structures of duration of approx. 150-250 μs each were distinguished.

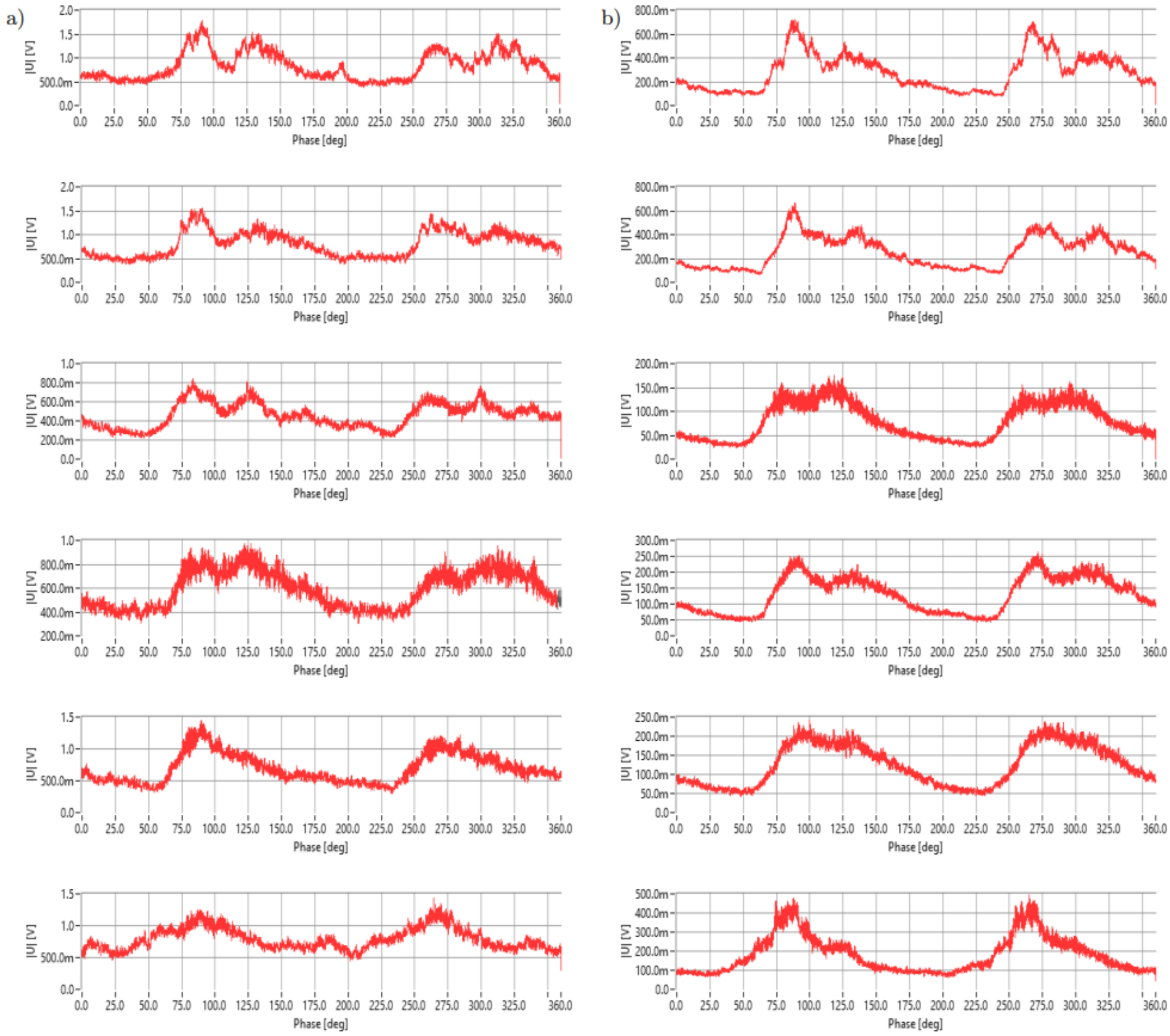

Fig. 18. Averaged phase characteristics for the family of AE signals recorded at the measurement points PA02y for the frequency band: a) 20-70 kHz, b) 40-70 kHz (numbering of measurement points from bottom to top: $y = 1, 2, \ldots, 6$)

Rys. 18. Uśrednione charakterystyki fazowe dla rodziny sygnałów EA zarejestrowanych w punktach pomiarowych PA02y dla pasma częstotliwości: a) 20-70 kHz, b) 40-70 kHz; (kolejne punkty pomiarowe liczone od dołu, y=1,2,…,6)

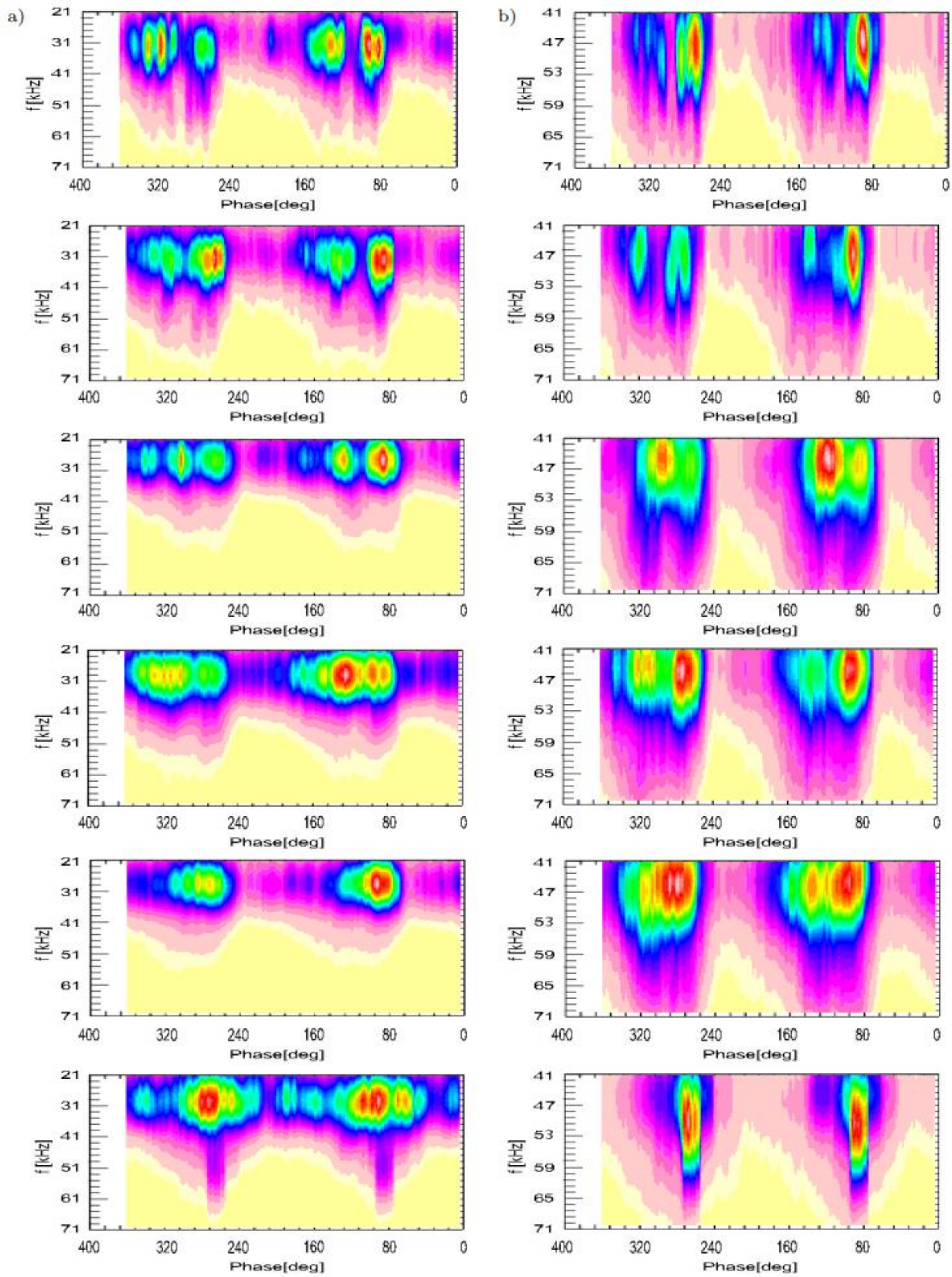

Fig. 19. STFT spectrograms projected onto phase-frequency plane for the family of AE signals recorded at measurement points PA02y for the frequency band: a) 20-70 kHz, b) 40-70 kHz (numbering of measurement points from bottom to top: *y* = 1, 2, . . . , 6)

Rys. 19. Spektrogramy STFT zrzutowane na płaszczyznę faza-częstotliwość dla rodziny sygnałów EA zarejestrowanych w punktach pomiarowych PA02y dla pasma częstotliwości: a) 20-70 kHz, b) 40-70 kHz; (kolejne punkty pomiarowe liczone od dołu, *y* = 1,2,…,6)

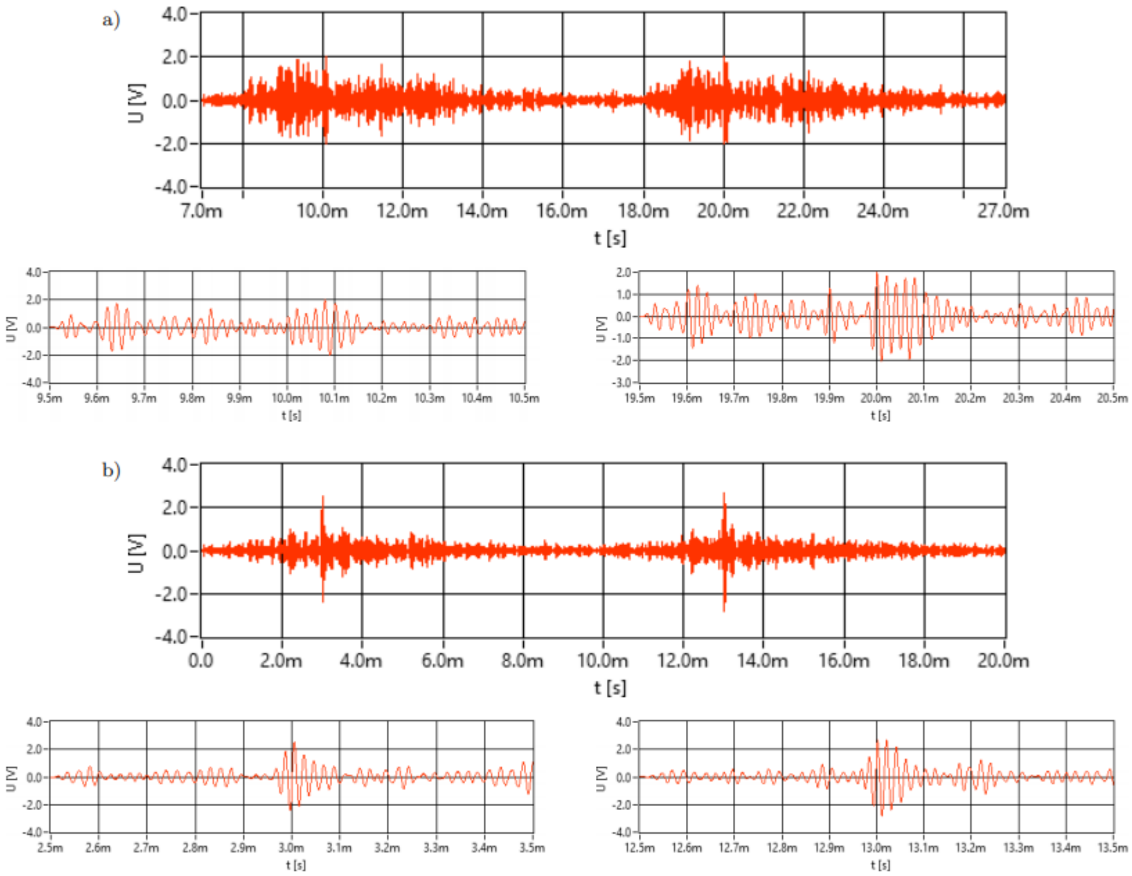

Fig. 20. Analysis of the selected parts of the 20 ms AE signals recorded at measurement points: a) PA026 (X = 483 cm; Y = 235 cm), b) PA021 (X = 483 cm; Y = 60 cm). The selected fragment of the signal after filtration in the band of 40-70 kHz together with the single structures

Rys. 20. Analiza wybranych fragmentów sygnałów EA o czasie trwania 20 ms zarejestrowanych w punktach pomiarowych: a) PA026 (X = 483 cm; Y = 235 cm) i b) PA021(X = 483 cm; Y = 60 cm). Wybrany fragment sygnału po filtracji w paśmie 40-70 kHz wraz z wskazanymi pojedynczymi strukturami

11.4.4. Identification of disturbing signals

Disturbing signals have an adverse effect on the recorded AE signals. They can significantly hinder the evaluation of the obtained results of the recorded AE signals analysis. The presence of disturbing signals may prevent the effective identification of PD sources, their location, and, consequently, lead to an incorrect assessment of the insulation condition of the tested transformer.

Due to the multitude of disturbing signals that may occur during tests in industrial conditions, this problem is important in terms of the correct identification of PD sources. Therefore, it is important to recognize and - if possible - eliminate disturbances occurring during measurements of AE signals in power oil transformers.

In the tests carried out on real power transformers, there were also disturbances in the recorded AE signals. In the following sections the analysis of sample disturbing signals, which have been identified in the tested units will be presented.

11.4.4.1. Disturbance brought by the measuring system and network

External disturbances are related to the technical and environmental conditions in the place of installation of the tested object. This type of disturbance was identified during the analysis of the AE signals recorded in the T2 transformer. The analysis of AE signals from various measurement points for this transformer showed that during the measurements there were disturbances affecting the recorded AE signals, which cannot be filtered out of the analysed signals.

First, the analysis on the AE signal recorded in the measuring path immediately before attaching the measuring sensor to the tested transformer was carried out. This signal, after filtration in the 20-200 kHz band, along with its frequency characteristics is shown in Fig. 21.

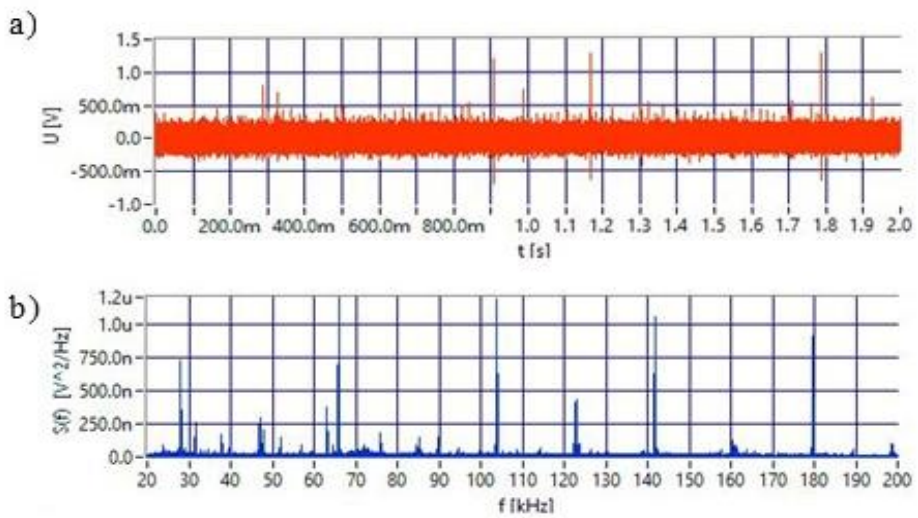

Fig. 21. AE signal recorded in the measuring path immediately before attaching the measuring sensor to the tested T2 transformer: a) signal after filtration in the band of 20-200 kHz, b) frequency characteristics for the signal from Fig. 21a

Rys. 21. Sygnał EA zarejestrowany w torze pomiarowym bezpośrednio przed przymocowaniem czujnika pomiarowego do badanego transformatora T2: a) sygnał po filtracji w paśmie 20-200 kHz, b) charakterystyka częstotliwościowa dla sygnału z rys. 21a

Fig. 21b shows that the measuring system has resonance properties. Each signal coming to the sensor gives a "ringing" response of the measuring system at resonant frequencies. The disturbance signal is carried along with each signal, which is visible from the time course and frequency characteristics of the recorded AE signals. Additionally, in these more difficult metrological conditions, the measuring system transfers the disturbances from the network visible in Fig. 22b-e as many peaks (Fig. 22b) having harmonic components in the whole band of analysed frequencies (Fig. 22d-e).

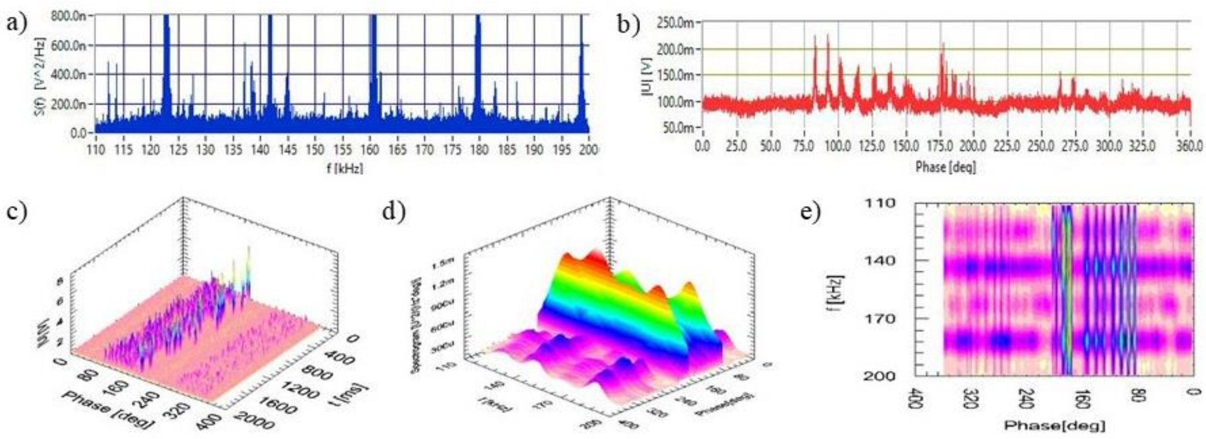

Fig. 22. Basic description of the AE signal recorded at the selected measurement point of the T2 transformer (J073) for filtration in the band 110-200 kHz: a) frequency characteristic, b) averaged phase characteristic, c) phase-time characteristic, d) and e) averaged STFT spectrograms; ADC = -0.63

Rys. 22. Podstawowy opis sygnału EA zarejestrowanego w wybranym punkcie pomiarowym transformatora T2 (J073) przy filtracji w paśmie 110-200 kHz: a) charakterystyka częstotliwościowa, b) uśredniona charakterystyka fazowa, c) charakterystyka fazowo-czasowa, d), e) uśrednione spektrogramy STFT; ADC= -0,63

The presence of the identified disturbance may be related to the applied temporary solution, designed to fit the sensor (Dual BNC) to the preamplifiers. This temporary solution is based on replacing the dual BNC output of the D9241A sensor with two BNC outputs so that the signal goes to the preamplifiers. In the new solution of the 8A-PD measuring and research system, the D9241A sensors are connected to the preamplifiers with the original Dual BNC output - tests carried out in laboratory conditions show a much greater resistance to disturbance.

The occurrence of disturbances caused by the measuring system and the network significantly hinders evaluation of the results of the analysis of recorded signals, therefore already at the stage of measurement, the possibility of such disturbances should be eliminated or as much as possible limited.

11.4.4.2. Corona discharges

In a strong electric field, the value of which, under given atmospheric conditions, exceeds the initial intensity of ionization in the air, partial discharges called corona discharges occur. The phenomenon of corona in issues related to the operation of power devices is undesirable. Corona discharges generate acoustic and electrical disturbances.

The acoustic signal generated by the corona discharge is a source of noise, the intensity of which strongly depends on the weather conditions and the surface condition of the power line conductors. Acoustic disturbances in the form of AE from external partial discharges due to differences in air impedance and piezoelectric ceramics are practically irrelevant in PD tests using the acoustic emission method [21].

The influence of electromagnetic noise originating from corona discharges on the PD measurement using the AE method can be limited by careful shielding of the measuring system. At the stage of analysis of the recorded data, signals from PD and disturbing signals coming from the corona discharges can be distinguished.

In Figs. 23 and 24 an example of effective identification of the corona discharge peaks is presented. It concerns the AE signals recorded in the T5 transformer near the measurement point C192 (X = -140 cm; Y = 160 cm). The analysis showed that in this area, in addition to the partial discharges, there was an additional disturbing signal generated by the corona discharge.

Basic characteristics (Fig. 23) confirm the different nature of the peak originating from the corona discharge in relation to the properties of the AE signals from the internal PD recorded at this measurement point. The disturbing signal has much larger amplitude, and its frequency spectrum covers the entire range of analysed frequencies.

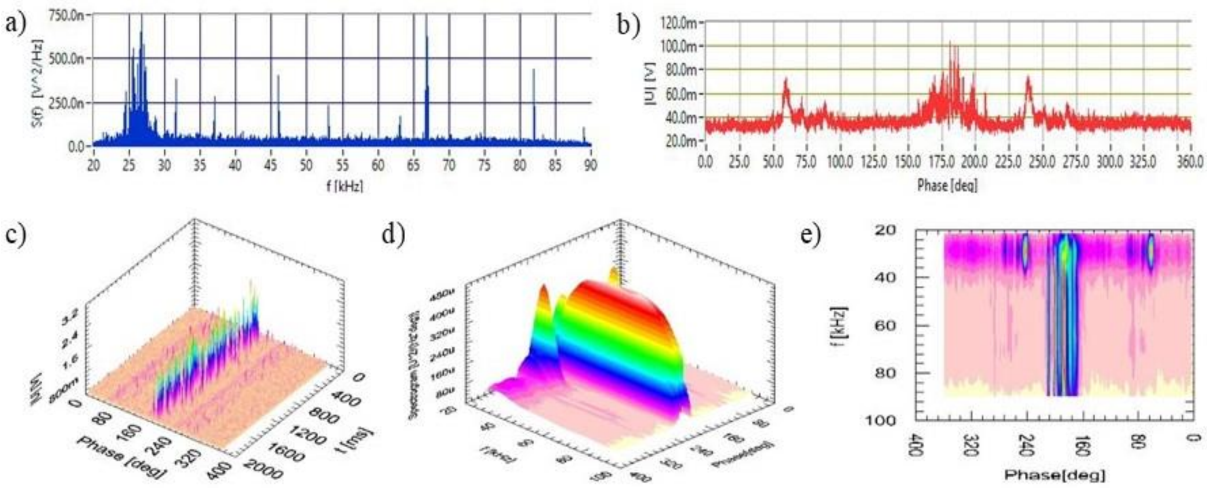

Fig. 23. Basic description of the AE signal recorded at the selected measurement point of the T5 transformer (C192) for filtration in the band 20-90 kHz: a) frequency characteristic, b) averaged phase characteristic, c) phase-time characteristic, d) and e) averaged STFT spectrograms; ADC = -0.91

Rys. 23. Podstawowy opis sygnału EA zarejestrowanego w wybranym punkcie pomiarowym transformatora T5 (C192) przy filtracji w paśmie 20-90 kHz: a) charakterystyka częstotliwościowa, b) uśredniona charakterystyka fazowa, c) charakterystyka fazowo-czasowa, d), e) uśrednione spektrogramy STFT; ADC= -0,91

As part of the analysis of the signal of duration equal to one period of the reference voltage, it was possible to distinguish three structures in the signal (Fig. 24). The waveforms and frequency characteristics for structures 1 and 2 are the same and indicate the occurrence of PDs. Structure 3 is of a different nature, which allows it to be identified as a disturbance.

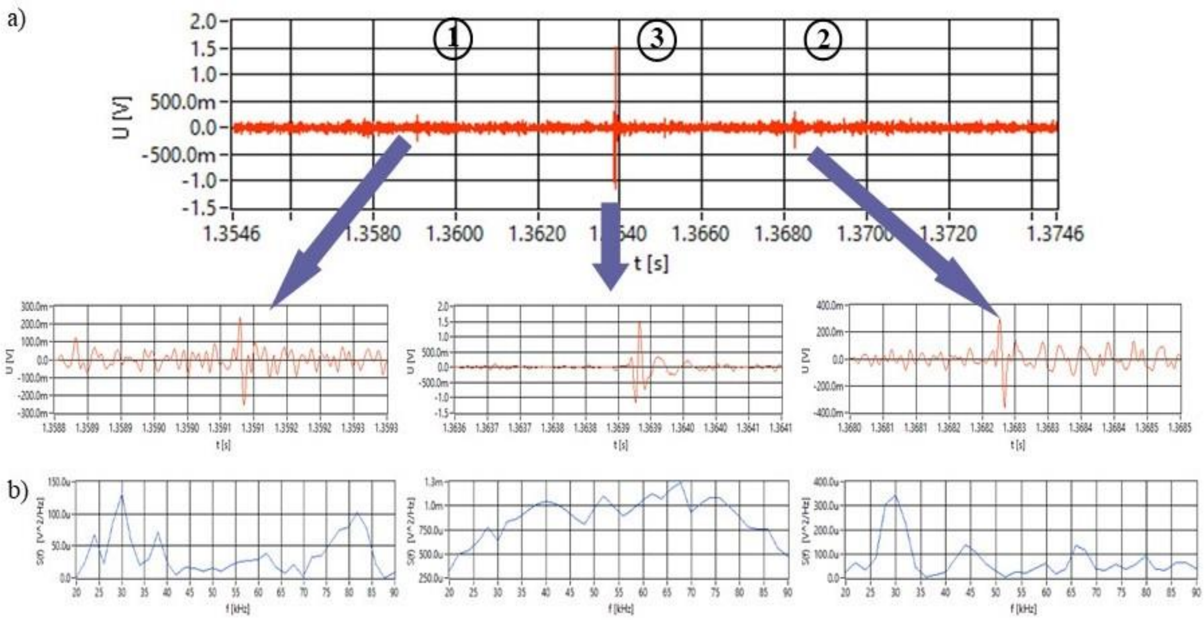

Fig. 24. Analysis of a selected part of the signal recorded at the measurement point C192 of duration equal to one period of the reference voltage: a) the selected part of the signal after filtration in the 20-90 kHz band with the indicated single pulse marked as 1, 2, 3, b) frequency characteristics for the structures marked as 1, 2, 3

Rys. 24. Analiza wybranego fragment sygnału zarejestrowanego w punkcie pomiarowym C192 o czasie trwania wynoszącym 1 okres napięcia odniesienia: a) wybrany fragment sygnału po filtracji w paśmie 20-90 kHz wraz z wskazanym pojedynczymi impulsami oznaczonymi jako 1, 2, 3, b) charakterystyki częstotliwościowe dla struktur oznaczonych jako 1, 2, 3

The ability to distinguish individual components of the signal recorded at this measuring point is also confirmed by the values of the ADC descriptor calculated for the signal parts corresponding to the individual distinguished structures (Table 2). The corona discharge signal component (marked as structure 3) refers to a significantly higher value of the ADC descriptor (in relation to the value of this descriptor for structures 1 and 2 derived from PD) and it has a greater influence on the value of the ADC descriptor calculated for the whole signal.

Table 2

ADC descriptor values for the parts of the signal recorded at the C192 measurement point, shown in Fig. 24

Part of the signal	**Time *t*, s**	**ADC, a.u.**
one period of the reference voltage	1.3546 ÷ 1.3746	-0.88
structure 1	1.3588 ÷ 1.3593	-8.34
structure 2	1.3680 ÷ 1.3685	-5.98
structure 3	1.3636 ÷ 1.3641	-0.44

The conducted analyses have shown that corona discharges have an influence on the recorded AE signals from partial discharges. Due to the fact that the corona discharge peaks overlap with the PDs image, they cannot be filtered out of the analysed signal. However, it is possible to effectively identify this type of disturbance in detail, which is essential in the context of evaluating the insulation condition of the tested transformer.

11.5. Summary

Presented in the paper, the analysis of AE signals recorded in the tested power oil transformers was based on:

- the determination of, on the maps of the ADC descriptor on the side walls of the investigated transformer tank (calculated in different frequency bands), the areas for which the recorded signals were characterized by a greater degree of advancement,
- the analysis of the properties of AE signals registered in the identified areas, in particular:
  - the calculation of constituting the basic description of the signals, the phase-time characteristics, the averaged phase characteristics and averaged STFT spectrograms,
  - the analysis of the selected parts of the AE signals of duration equal or shorter than one period of the reference voltage.

Analysis of the signals recorded at various measurement points located in the identified areas for filtration in the 100 (110)-200 kHz band, led to the identification of PD sources and the determination of the properties of the recorded AE signals.

The analysis of signals from the areas of the highest intensity on the ADC descriptor map in the 20-70 kHz band, provided that the corresponding descriptor values in the 110-200 kHz band are small, led to the identification of signals originating from the phenomena occurring during the magnetization of ferromagnetic materials.

During the study of signals coming from PDs, additional sources of AE signals were identified. The conducted analyses allowed to state that the source of these signals are disturbances caused by the measuring system and the network, as well as corona discharge.

In conclusion, in the tested power oil transformers, separate identification of sources originating from partial discharges, phenomena occurring during magnetization of transformer cores and disturbing signals were made.

The presented research results led to the determination of the properties of the AE signals originated from signal sources in power oil transformers and identified during the analyses.

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