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Application of Signal Processing Elements for the Characteristics of Acoustic Emission Pulses Generated by Partial Discharges

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The subject matter of this paper refers to the issues connected with the application of modern numerical methods in processing and analysis of the signals measured by the acoustic emission method (AE) during high-power experiments carried out in laboratory conditions in the setups modelling basic partial discharge forms (PDs). The detailed cognitive aim of the research work was determining the possibilities and the application range of the short time Fourier transform (STFT) and wavelet transform in the analysis of the AE pulses generated by basic PD forms that can occur in oil insulation systems of such appliances as transformers, measuring transformers, bushing insulators, switchgears, and power condensers.

The time – frequency analysis was carried out for the particular PDs from the point of view of determining differences and indicating common features for the frequency structures determined, for the positive and negative voltage polarizations separately. The research concentrated mainly on the following types of PDs: point-plane, multipoint-plane, multipoint-plane with a layer of pressboard, surface, generated in gas bubbles and on the indeterminate-potential particles moving in oil.

In calculations using wavelet transformations basic types of analyzing functions, the so-called basic wavelets, were applied. When determining amplitude spectrograms of the AE pulses measured various types of observation windows were used. Moreover, for the approximation runs determined and for the particular details the autocorrelation functions (ACF) were calculated, and the probability density functions (PDF) were calculated to determine statistical properties. Also, frequency spectrum runs for the AE pulses measured and the diagrams corresponding with the details analyzed, which visualize the size of energy transferred at the particular decomposition levels, were determined.

The paper presents the results of measurements and analyses of the AE pulses generated by the PDs in oil in the multipoint-plane with a layer of pressboard system.

Keywords: acoustic emission (AE), partial discharges (PDs), STFT (Short Time Fourier Transform), discrete wavelet transform (DWT) , continuous wavelet transform (CWT).

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Introduction

At present, from the technical point of view, the electric, gas chromatography and acoustic emission (AE) nondestructive methods are used for evaluating electric discharges. Also, comparative measurements of an estimation character are taken of the amount of the heat obtained, of the light emitted and the changes of pressure in the area of PD generation. They were worked out based on the physical phenomena that accompany the occurrence and development of PDs [20, 27].

The starting point for the work on application of the AE emitted by electric discharges for evaluating the condition of power appliance insulation were metrological difficulties occurring during diagnostic measurements taken in industrial conditions using the electric method. In normal working conditions of power appliances the measurement of PDs using the electric methods, due to the high level of electromagnetic disturbances, is not possible, and information on the occurrence, intensity and location of PDs in insulation systems are of basic significance in evaluating the condition of a power appliance and therefore for predicting its further failure-free operation. However, determining the expected time of possible operation of the appliances under study is strictly bound not only with a scientific aspect but also, first of all, with economic and financial aspects.

Owing to the results obtained from the almost 25-year research, the AE method is now a significant supplement of other measuring methods used in diagnostics of insulation systems of transformers, current and voltage measuring transformers, power condensers, and bushing insulators. It is possible to broaden the application of the AE method on other high-power objects such as separately with SF_6 insulation.

The most significant merit of the AE method is the possibility of its application in very difficult conditions of power appliance operation, in which taking the PD measurements using other methods has been impossible so far. It enables detection, i.e. tracing the PD occurrence direct in insulation of the power appliance in operation. This way the AE method fills the gap that existed in PD metrology of high-power appliances, but it requires continuous improvement in the area of interpretation of the results obtained. Based on the results obtained using the AE method it is possible to locate the places of PD generation in insulation systems. To do so, calculation algorithms are applied using in the analysis the measurement results obtained through the auscultation method, that is the highest noise level or the triangulation method. However, the significant issue is the measurement of intensity and the size of PDs applying the AE method. It is due to the occurrence of the AE signals generated by PDs of many insulation layers, mostly of various values of suppression and acoustic wave reflection coefficients on the propagation path. In measuring practice the problem lies in correct making a relatively accurate scheme of the substitute acoustic setup of the power appliance insulation measured.

The range of the AE method application can be limited by the following factors: high level of acoustic interference, complex geometry of the objects measured, which makes the mounting of measuring transducers on their surface impossible, using dielectrics or insulation systems of a low elasticity coefficient and of complex geometric structure.

So far the research on the AE method application in diagnostics of power appliance insulations has focused mainly on the issues dealing with explanation and mathematical description of the phenomena connected with generation and propagation of acoustic waves emitted by PDs in various types of dielectrics and complex insulation systems. The research has also been connected with the choice of the measuring apparatus, especially measuring transducers for receiving AE signals from PDs in various power appliances. It has also dealt with work on numerical ways of registration, analysis and interpretation of the measurement results obtained. Detailed analyses of the AE pulses from PDs measured have been carried out as well, based on the runs of characteristics determined in time and frequency domains. From among a wide group of parameters that can be used to characterize the AE pulses registered, a group of 5 descriptors that make it possible to identify basic PD forms in oil insulation systems have been selected, however, it refers only to laboratory conditions and experiments made in strictly defined metrological conditions.

Currently, it is necessary to solve still many particular issues connected with the AE method, such as carrying out a complex analysis in the time and frequency domains and, consequently, identifying the possible sources of disturbances occurring during the measurements using the AE method; carrying out the analysis and determining what part of the energy generated during the PD occurrence falls on the particular types of the radiation waves occurring; the choice of the computer software and numerical methods to analyze and interpret the measurement results registered of the AE generated by PDs [5-7,9,17,18,21,25-27].

The aim of the research carried out by the author of this paper is determining comparative standards, the so-called fingerprints for each of the basic PD form in such a way that by carrying out the comparative analysis of the AE pulses measured generated by PDs in insulation systems of power appliances, it will be possible to identify them uniquely. Apart from determining the place, intensity and size of PDs it is of basic significance in evaluating the condition of the insulation measured and the time of its further failure-free operation [10-13].

The aim of the research carried out the results of which are presented in this paper is to determine the range of application of the continuous and discrete wavelet transform and also the STFT in processing the AE pulses generated by six basic PD forms. Also, the possibilities of using the DWT in the analysis of the AE signals are indicated and the runs of the probability density (PDF), autocorrelation functions (ACF), diagrams illustrating the value of the energy transferred which were calculated separately for the particular details, are shown.

For comparison, also Power Spectrum Diagrams (PSD) runs calculated for the AE pulses for each of the PD forms under study have been presented. First of all, the character of frequency structure changes in time of the registered AE pulses generated in model setups was analyzed. Then the set of time approximation runs, and details at various levels obtained for the particular PDs forms underwent a comparative analysis.

Within this paper only the results obtained for the AE pulses generated by PDs of the multipoint-plane with a layer of pressboard system will be presented. In an analogous way the analyses were carried out separately in the negative and positive voltage half-times for the remaining five PD forms generated in insulation oil.

I. Characteristics of the setups used for measurement and analysis of the AE pulses generated by PDs

To generate basic PD forms in insulation oil spark gaps modeling the following PD forms were used: point-plane type discharges in oil, multipoint-plane type discharges in oil, multipoint-plane type with a layer of pressboard discharges in oil, surface discharges in oil, gas bubble discharges in oil, discharges in indeterminate-potential particles moving in oil and the brush. The model setups used were placed in special grips, which ensure the repeatability of the PD generation place and fluent adjustment of geometric sizes. The spark gaps made were placed in a transformer tub which was filled with transformer oil. To carry out the comparative analysis of the results obtained, the measurements of the AE pulses generated in each of the spark gaps under study were taken a voltage which was 80 % of the breakdown voltage. A detailed presentation of their supplying system spark gaps, geometric dimensions of the tub and the fixing constructions have been presented, among others, in the works [10-13].

To measure the AE pulses a piezoelectric wideband contact transducer series WD type AH 17 by the firm Physical Acoustic Corporation was used, which was placed on the surfaces of the side walls and the upper lid of the transformer tub. Its application made the measurement of the AE signals possible at a practically flat amplitude characteristics for the frequency in the range (0-15) MHz at the maximum value of amplitude drop equal to ± 5 dB. The AE signals measured were amplified and then were subject to initial filtration with a standardizing measuring amplifier Nexus type 26921 – OS1 by the Brüel and Kjær firm.

The registration of the AE pulses measured was done by means of the measuring card National Instruments type NI 5911 compatible with a PC computer. The card is equipped with an A/C transducer of a maximum sampling frequency at an adjustable resolution in the range from 8 to 21 bites and of 100 MHz. The AE pulses registered underwent the analysis in the time, frequency and time-frequency domains and were visualized by the computer programs: Mathcad 2001i and Matlab 6.0. A detailed presentation of the parameters of the particular elements that were used in the measuring line and the conditions in which the experiments were carried out have been presented in the works [10-13].

II. The results of the STFT and wavelet analysis of the AE pulses generated by PDs

The AE pulses generated by PDs are characterized by a wide frequency spectrum dependent on a discharge type. Moreover, they are characterized by a big change dynamics in the time domain. The methods of the acoustic signal analysis used so far were based on the analyses either in time or frequency domains [5-7,17,18,21,25-27]. This approach does not fully reflect the character of the AE pulses generated, thus the authors of the paper have suggested a Joint Time – Frequency Analysis (JTFA). The time – frequency analysis is a useful and required tool for examining non-stationary signals the parameters of which change in time, and that is why it is now used in the electric method of insulation measurement and it can be used for evaluation of the AE pulses generated by PDs [22-24,28-30]. The presentation of the AE pulses measured on a time – frequency ground enables not only a spectrum analysis resulting from time changes but it can also be a helpful tool used for determining the kind and size of the accompanying disturbances. Moreover, the use of the time – frequency analysis limits, to a great extent, the effect of a spectrum broadening connected with the application of the Fast Fourier Transform (FFT) without analyzing windows, which is caused by the phenomenon of overlapping of their fragments.

In the case of non-stationary signals the frequency analysis based on the Fourier transform makes it possible to determine a spectrum characteristics in a definite time range. Frequency resolution then depends on the width of the time range analyzed. Limiting the number of data of the time series is connected with the accuracy decrease of the frequency spectra being determined. The spectrum analysis provides information on average amplitude values or powers or energy size of frequency components which are present in a signal processed. The information on time changes of frequency structures, however, can be obtained by applying the spectrum analysis not to the whole time range but to a selected observation window, which is shifted in time. The change of its tracking enables narrowing or widening of time resolution of a spectrum being determined, which takes place at a simultaneous reverse impact on frequency resolution [1-4,8,14-16,19].

To analyze the AE pulses measured generated by the PD forms under study a continuous wavelet transform (CWT) with a base Morlet wavelet and a discrete wavelet transform (DWT) with an analyzing simlet wavelet 8. However, for the STFT analysis an observation Hanning window was used.

2.1. The results of the wavelet analysis of the AE pulses generated by the PDs in oil in the multipoint-plane with a layer of pressboard system

Fig. 1-2 show the time run and the wavelet distribution of the AE pulse series generated by PDs of the multipoint-plane with a layer of pressboard system

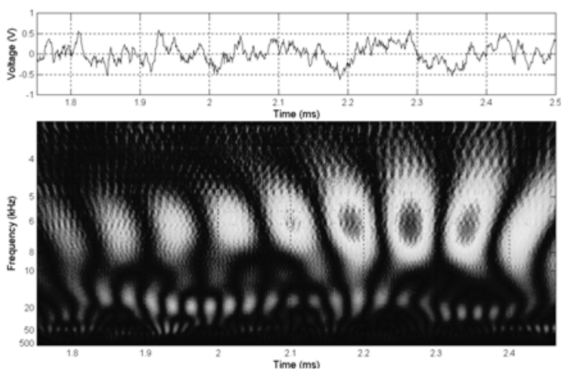

Fig. 1. CWT of a series of AE pulses generated by PDs in oil in the multipoint-plane with a layer of pressboard system during the positive voltage half-cycle and the time interval 1.75-2.5 ms.

for the positive (Fig. 1) and negative (Fig. 2) voltage polarization.

For PDs of the multipoint-plane type with a layer of pressboard, the wavelet distributions (Fig. 1-2) were obtained for both voltage half-times, which indicate their different frequency structure. There can be observed three main components for the frequencies of the values 6, 18, 48 kHz. For the negative voltage half there occurs a bigger number of structures, which indicates an increase of the number of acoustic events. The relaxation time is, in both cases, close to the time of discharge duration and is around 0.5 ms. The characteristic feature is that the components of the pulses of the frequencies of 18 or 48 kHz do not occur simultaneously. Also, some kind of periodicity in the occurrence of these structures can be distinguished.

2.2. The results of the multiresolution analysis of

the AE pulses generated by the PDs in oil in the multipoint-plane with a layer of pressboard system

Orthonormal symlet base functions were used for multiresolution analysis. Symlet wavelets of a high order ensure the closest approximation at a given level of a precise symmetry and a linear phase. In the case of the analysis carried out, the minimization of the phase distortion was significant in order to keep true time relationships between the details of acoustic pulses, which is why the symlet wavelet 8 was chosen.

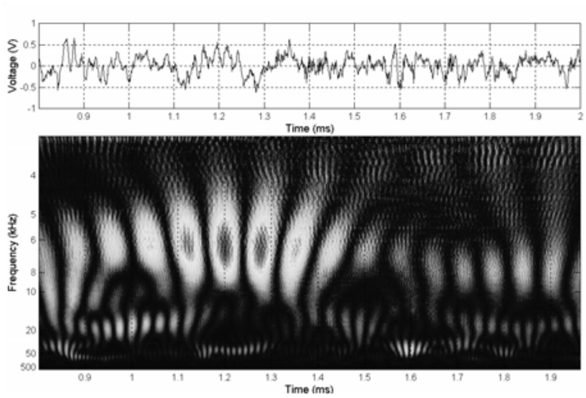

Fig. 2. CWT of a series of AE pulses generated by PDs in oil in the multipoint-plane with a layer of pressboard system during the negative voltage half-cycle and the time interval 0.8-2 ms.

The result of the multiresolution analysis application using a discrete wavelet transform, a set of time approximation runs, and details at various levels were obtained. The particular levels correspond to frequency ranges resulting from the bandwidth of the band-pass filter connected with an analyzing function. The runs obtained constitute a signal decomposition of the pulses measured [1-4,8,16,19,22-24,28-29].

The multiresolution analysis was carried out by means of the discrete wavelet transform (DWT) using the analyzing symlet wavelet. Compared with other wavelet families, which have the scaling function, the symlet wavelets of a high rank ensure the closest approximation of a precise symmetry and a linear phase on a given level of decomposition. In the analyses carried out the symlet wavelet 8 was selected due to the minimization of the phase deformation to obtain real time relations between the particular details of the AE pulses measured.

Figs 3-4 show original time runs of the AE pulses generated by PDs in oil in the multipoint-plane with a layer of pressboard system, approximation A at the 7th level of decomposition, and details D at the levels from 1 to 7 for the measured pulses. For comparison, also power spectrum density (PSD) runs and diagrams illustrating the value of the energy transferred by particular details have been shown.

For the multipoint – plane PDs with a layer of pressboard system similar shapes of amplitude spectra were obtained for both voltage polarizations, for which dominant frequency bands, at the discrimination threshold of 10 dB, occur in the range from 0 to 50 kHz. Moreover, for the AE pulses generated in the positive and negative voltage half-times the same character of energy size runs transferred on the decomposition levels under consideration was obtained. The biggest participation in the size of the energy transferred has level 7 (about 6000), and then level 6, the energy of which, however, is three times smaller (about 2000). The participation of the other decomposition levels is smaller – that of level 4 (about 1400) and of level 5 (1000). The influence of detail 4 on the decomposition run of the AE pulses generated y PDs of the multipoint – plane type with a layer of pressboard in the positive half-time (Fig. 3) can be observed, but the time structures are relatively disordered. On level 1, however, around 4 ms a short-duration series of the AE pulses of the duration time about 0.5 ms occurs. However, for the discharges in oil in the multipoint-plane with a layer of pressboard system in negative polarization (Fig. 4) the detail D4 is especially active, on which a set of acoustic events of a relatively disordered character can be observed. In this case the relaxation time is not defined clearly. The energy discharged is not distributed uniformly in the

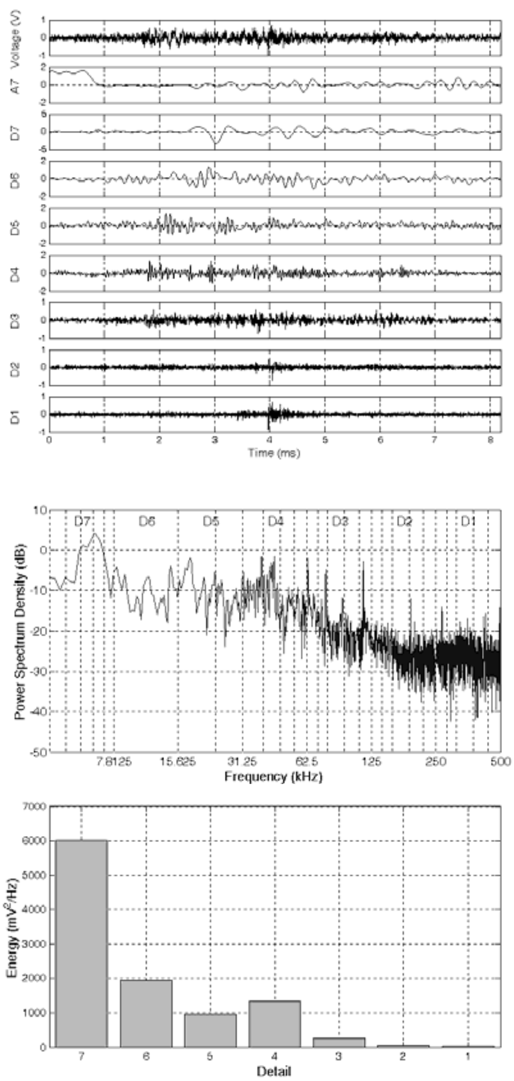

Fig. 3. DWT, PSD, the value of the energy transferred of a series of AE pulses generated by PDs in oil in the multipoint-plane with a layer of pressboard system during the positive voltage half-cycle.

whole range of the time analyzed.

In order to compare statistical properties and time

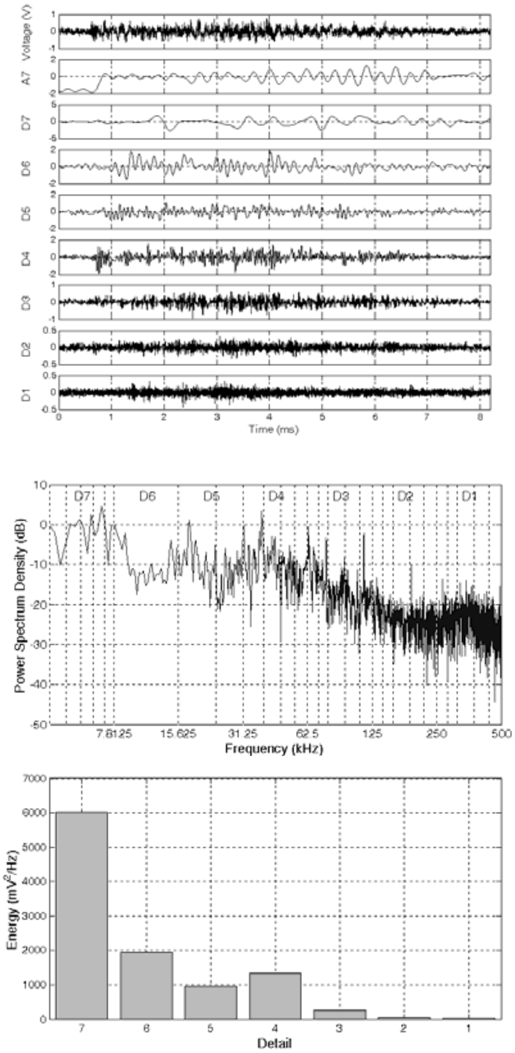

Fig. 4. DWT, PSD, the value of the energy transferred of a series of AE pulses generated by PDs in oil in the multipoint-plane system during the negative voltage half-cycle.

relations for the signals obtained for the particular frequencies, the diagrams (PDF) and the autocorrelation functions (ACF) determined for the AE pulses generated by PDs of the multipoint – plane type with a layer of pressboard are presented separately for the positive (Fig. 5) and negative voltage half-times (Fig. 6). The PDF and ACF diagrams shown in Figs 5-6 are characteristic of a similar shape of runs obtained on the particular decomposition levels and for the signal measured for the positive and negative voltage polarizations.

2.3. The results of the STFT to analysis of the AE pulses generated by PDs in oil in the multipoint-plane with a layer of pressboard system

For graphic STFT visualization a spectrogram has been determined which defines changes of the spectrum density of a signal power in time, and the value of which has been calculated as a STFT module square. This method enables time location of the particular fragments

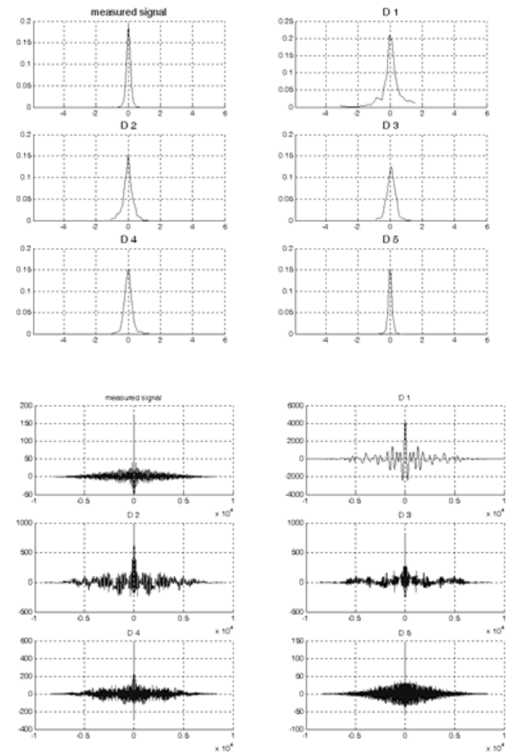

Fig. 5. PDF, ACF a series of AE pulses generated by PDs in oil in the multipoint-plane system during the positive voltage half-cycle.

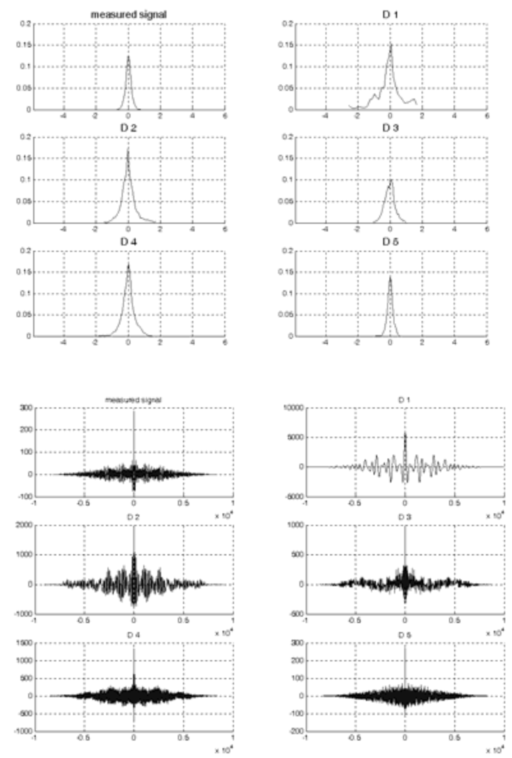

Fig. 6. PDF, ACF a series of AE pulses generated by PDs in oil in the multipoint-plane system during the negative voltage half-cycle.

of the signals analyzed, determining the influence of the value change of the AE pulses registered taking place in time on the values of the frequencies transferred, and considerably minimizes the effects connected with the interference of spectrum fragments.

For the discharges of the multipoint-plane type with a pressboard insulation layer the time – frequency distributions are shown in Figs 7 and 8 for both voltage polarizations separately. On the spectrogram determined for the AE pulses generated at the positive voltage polarization (Fig. 7) one group of components can be observed in the whole frequency range analyzed, which occurs at 3.8 ms, and the duration time of which is about 0.4 ms. Also another group of components generated for

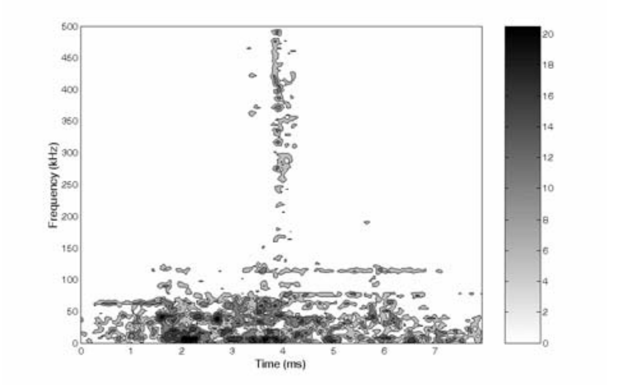

Fig. 7. Spectrogram calculated for the AE pulses generated by PDs in the multipoint - plane system in oil with a layer of pressboard, during the positive voltage half-period.

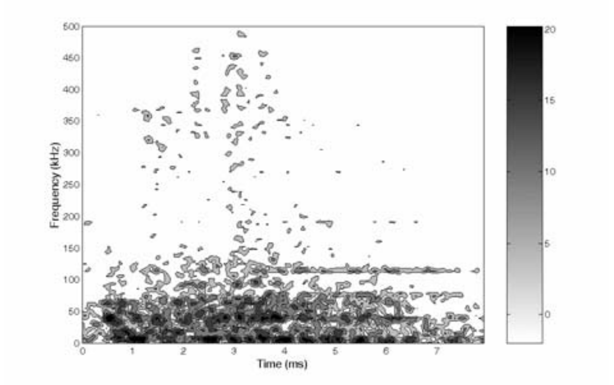

Fig. 8. Spectrogram calculated for the AE pulses generated by PDs in the multipoint – plane system in oil with a layer of pressboard, during the negative voltage half-period.

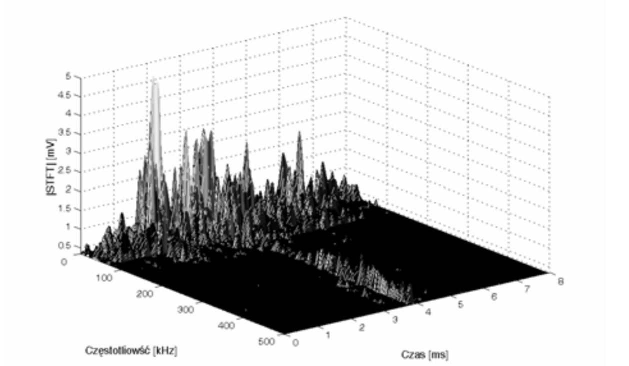

Fig. 9. Three-dimensional spectrogram of amplitude spectrum calculated for the AE pulses generated by PDs in the multipoint - plane system in oil with a layer of pressboard, during the positive voltage half-period.

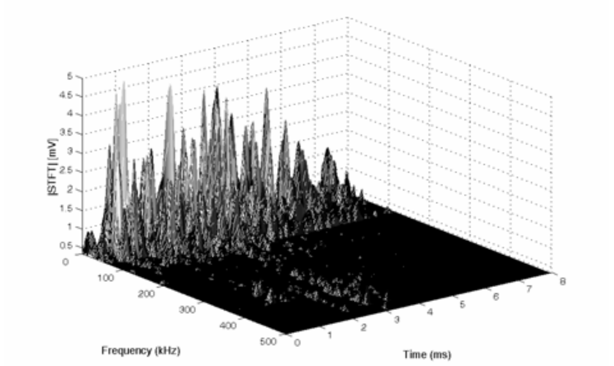

Fig. 10. Three-dimensional spectrogram of amplitude spectrum calculated for the AE pulses generated by PDs in the multipoint - plane system in oil with a layer of pressboard, during the negative voltage half-period.

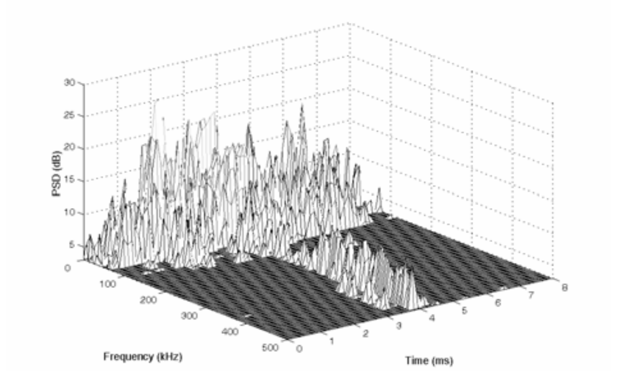

Fig. 11. Three-dimensional spectrogram of power spectrum density calculated for the AE pulses generated by PDs in the multipoint - plane system in oil with a layer of pressboard, during the positive voltage half-period.

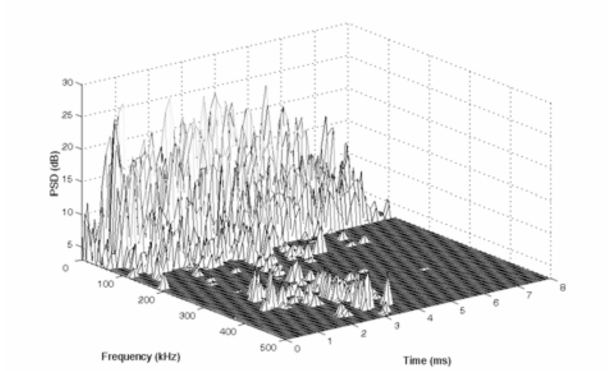

Fig. 12. Three-dimensional spectrogram of power spectrum density calculated for the AE pulses generated by PDs in the multipoint - plane system in oil with a layer of pressboard, during the negative voltage half-period.

the time of 1.8 ms and the duration time of about 0.7 ms occurs in the frequency range not exceeding 120 kHz. Moreover, from the time of 3.8 ms on there occurs a group of structures of a narrow-band noise character of the frequency of 130 kHz, which are suppressed after the time of 3 ms.

For the AE pulses generated at the negative voltage polarization (Fig. 8) three groups of structures can be observed, which occur about every 0.5 ms, from 1.2 ms on. Their frequency bands are of various ranges, which for the first group are within the range (250-370) kHz, for the second group from 320 to 470 kHz, and for the third structure they occur in the whole band analyzed.

For both voltage polarizations the area in the range of low frequencies not exceeding the value of 60 kHz is active. It can be observed on two-dimensional spectrograms (Figs 8 and 7) and on three-dimensional spectrograms, which are presented in Figs 9-12, on which the power of the low-frequency noise is by a dozen or so dB bigger than the power of the high-frequency components, which occur at the time of the biggest number of the AE pulses.

Summary

At present, as the computer and informatics technology develops, advanced numerical procedures are used more and more widely for signal processing, which make a fuller and fuller evaluation of the PDs measured possible.

The results presented in this paper, which were obtained by using the statistical tools and the correlation and time – frequency analyses, are a supplement and, to a great extent, enlarge the information base on basic PD forms that can occur in insulation systems of power transformers. They can also be a useful tool in identifying interfering signals occurring during insulation measurements taken in industrial conditions using the AE method. Moreover, the use of the time – frequency analysis makes it possible to relate time runs to the corresponding frequency ranges, which is not possible when a standard Fourier transformation and analysis are used only in the time domain.

For the registered AE pulses generated by basic PD forms varying distributions of frequency structures and PDF and ACF runs calculated for the particular decomposition levels were obtained. Therefore it is possible to use the results obtained as descriptors for basic PD form identification.

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