Chapter 6

Testing of Partial Discharges and Location of Their Sources in Generator Coil Bars by Means of Acoustic Emission and Electric Methods

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Additional information is available at the end of the chapter

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1. Introduction

Although a leading role among testing investigations of partial discharges (PD) is attributed to electric methods [1], other complementary ones are developed permanently. One of them is acoustic emission (AE) method whose - using physical phenomena of AE - gives unique possibility to observe deformation processes [2,3]. Acoustic emissions have sufficient features so as to be an important measuring method, which may supply electric measuring methods of partial discharges. Basic disadvantages and limitations of acoustic methods (caused by changes of AE elastic waves generated by PD source during propagation within a medium, detection and handling data) can be eliminated by the choice of proper descriptors [4-6].

Authors are engaged in development problems of AE and its application for many years. During past years there were investigations of PD made by means of AE method. Authors worked out and built the original measuring system applied to record and analyze of recorded signals. The system is dedicated to testing of partial discharges by means of AE method. Measuring system enables us to record signals in real time within the band up to 500 kHz in laboratory and real conditions. Research method of acoustic signals bases on the software (written for this purpose); it enables us to describe signals and create AE descriptors. At present, the software contains programs for monitoring of signals, registration of data, basic and advanced analysis of registered data. This software can be developed if need be and creation of ideas concerning interpretation of measuring results will be created. Capability of the method designed to testing of AE signals, presented in the actual version, includes: filtration of signals within the given band, analysis of signals in domains of time, frequency and time-frequency, location of maximums at curves which are frequency characteristics of signals and averaging phase characteristics of signal modulus as well as testing of properties of amplitude distributions of an acoustic signal or a group of signals by means of AE method of descriptors, and finally - testing of properties of amplitude distributions of signal groups using Kohonen neuron network.

Authors made parallel testing of partial discharges in coil bars of the generator by means of AE and electric method. It is worth emphasis that results received from an electric method characterize the whole object - therefore they are global character. In turn, results received from AE method describe directly signals recorded at the given measuring point of the object (they are local character); connection of AE signals with these ones generated by AE sources needs knowledge of propagation conditions of AE impulses. Testing - carried out simultaneously - enable us to made independent analyses of described tested PD phenomena within a framework of particularly methods as well as to create description of phenomena common to both methods. Such a common description has an additional advantage - possibility to verify conformability of description received from both research methods.

2. The original system for recording of AE signals

In order to measure AE signals generated by PD, the original measuring system DEMA-COMP was designed and built [7,8]. It enables us to register signals in real time within the band of 20 - 500 kHz both in laboratory and real conditions. The measuring system contains four independently supplied measuring circuits. The maximum speed of 12-bit recording data to disk shall be 5 megasamples/second in each of the four channels. Software of measuring card was written in LabVIEW environment [9]. It contains programs for monitoring signals and registration data.

3. Basic analysis of recorded signals

Properties of recorded data in domains of time, frequency ad time-frequency are investigated in the frame of preliminary analysis of recorded signals. Analysis is made in the frame of activity of the program written for that purpose, named *AE+JTFA.* This program uses programming of LabVIEW environment.

Studied phenomena are of periodic and individual character. In view of the periodic nature of the investigated phenomena the authors analyze the recorded signals whose duration is many periods of the supply voltage – usually 2 seconds (i.e. 100 periods of the supply voltage). Particular signal characteristics are obtained over the periods of the supply voltage, and then averaged characteristics are calculated (Fig. 1).

In view of the individual nature of the studied phenomena (single deformation process), the authors perform an analysis of selected parts of the recorded signals.

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Description resulting from analysis of an example AE signal whose time duration is 2 seconds (100 periods of supply voltage) is presented in Fig. 1. These results are as follows:

–signal after filtration with its minimal, maximal and RMS values (Fig. 1a); for filtration the band pass filter of 5 order is used, filtration band is given as a frequency range at the frequency characteristic,

–spectral power density as frequency characteristic of the signal with the frequency for main maximum and spectrum value for this frequency (Fig. 1b),

–phase-time characteristic (Fig. 1c),

–averaging phase characteristic (Fig. 1d),

–three-dimensional STFT spectrogram (Fig. 1e),

–three-dimensional STFT spectrogram dropped to a phase-frequency plane (Fig. 1f).

In order to obtain characteristics presented in Fig. 1, it should be determined filtration band first of all. Minimal, maximal and RMS values of the signal in volts are calculated by turns (Fig. 1a).

After filtration, the signal is put a next analysis in domain frequency, time and time-frequency. Analysis of the signal in domain frequency includes calculation of fast Fourier transform and power density spectrum as a square of complex Fourier transform. Additionally, the frequency for main maximum and value of the spectrum for this frequency in the spectrum is determined (Fig. 1b).

Within a framework of analysis of the signal in domain of time Authors worked out: phase-time characteristic of signal modulus (Fig. 1c) and averaging phase characteristic of signal modulus (Fig. 1d). The way how calculate characteristics in domain of the time is presented in Fig. 2. Phase-time characteristic of signal modulus (Fig. 1c and Fig. 2c) is obtained as follows: the signal selected for analysis is divided towards periods of the reference voltage (Fig. 2e shows the reference voltage during one of periods, Fig. 2f shows a signal recorded during the time determined in Fig. 2e), signal modulus (Fig. 2h) is calculated for each of periods and this modulus is placed on a phase-time characteristic as „two-dimensional section" (Fig. 2g). The phase-time characteristic of signal modulus (Fig. 2c) is created by „sewing" such „two-dimensional sections". This characteristic reveals periodic and random character of registered data. Averaging phase characteristic of signal modulus (Fig. 2d) is result of averaging of all„two-dimensional sections" (Fig. 2g) towards a phase of the reference voltage.

Analysis in time-frequency domain is based on JFTA analysis (*Joint Time-Frequency Analysis*) of the firm National Instruments [9]. The base is calculation STFT spectrogram (*Short-Time Fourier Transform*) or Gabor spectrogram for successive fragments of a signal of reference voltage. Authors worked out a new three-dimensional form of spectrograms, where time has been replaced by a phase of reference voltage. These spectrogram are calculated as follows. First of all it should be calculated three-dimensional spectrograms for signals registered in successive period of reference voltage. Finally, one should calculate averaging spectrogram of the signal (Fig. 1e), resultant from all spectrograms calculated for successive periods of reference voltage, as well as its projection on phase-frequency plane (Fig. 1f). Such a presentation facilitates location of PD on phase-frequency plane

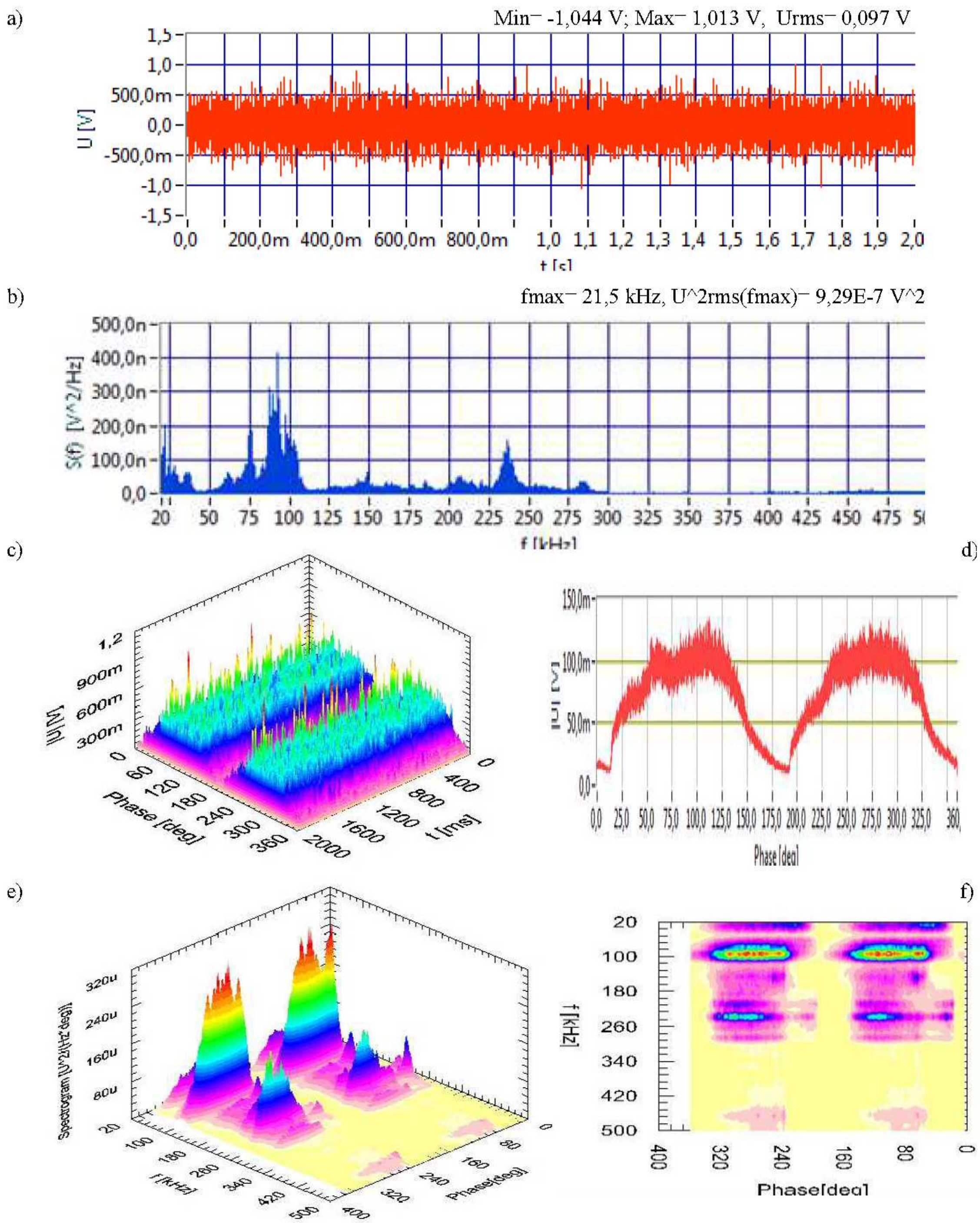

Figure 1. Introductory description of the example AE signal: a) impulse (after filtration), b) frequency characteristic, c) phase-time characteristic, d) averaging phase characteristic, e) and f) averaging STFT spectrograms; AE signal recorded in the following measuring conditions: measurement by means of WD sensor placed at P2 measuring point of „D" bar, the supply voltage of the bar 25 kV, measured value of the apparent charge 2.2 nC

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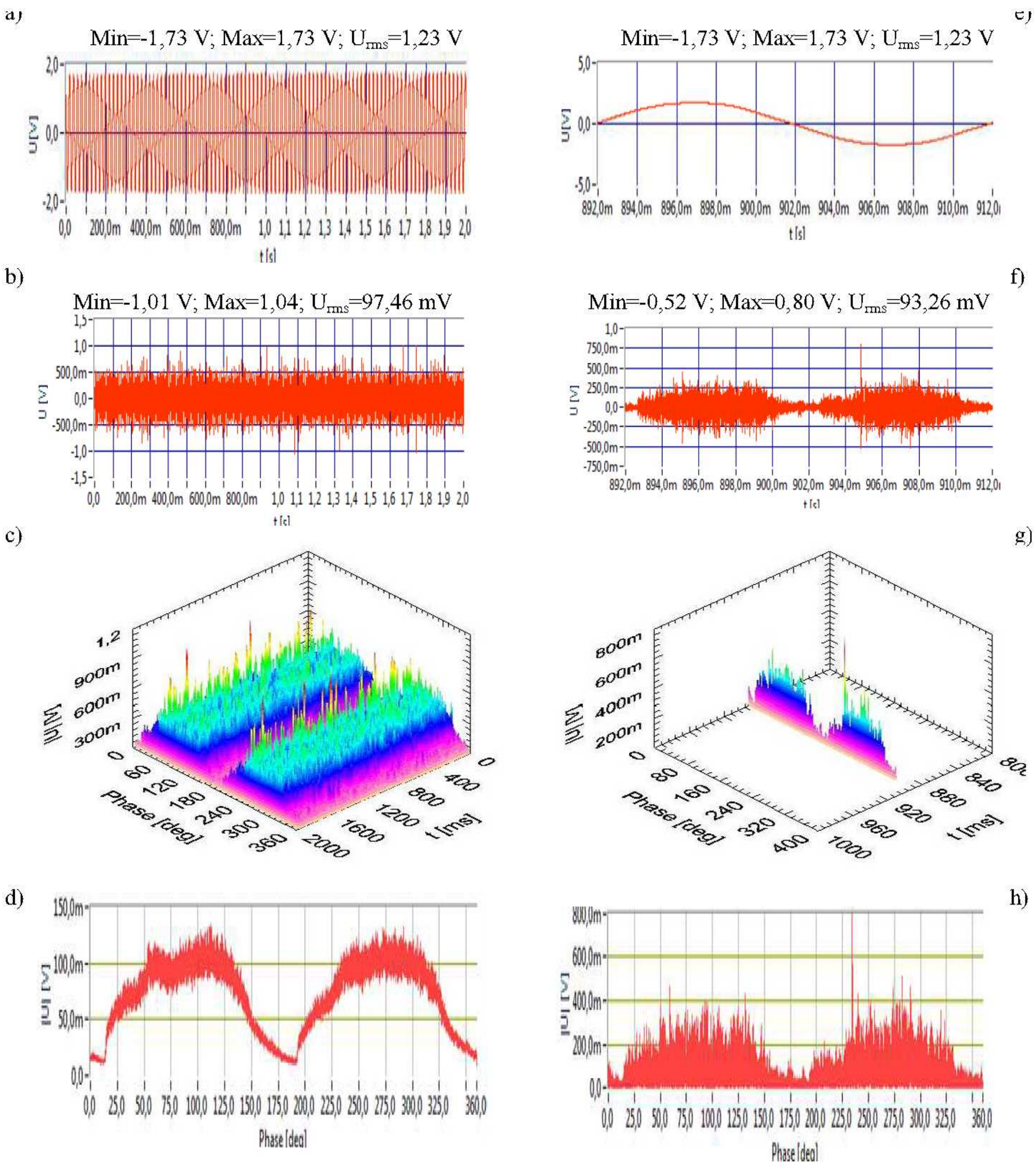

Figure 2. Preliminary analysis of registered data in time domain (for the signal from Fig. 1): a) reference voltage, b) signal after filtration, c) phase-time characteristic of signal modulus, d) averaging phase characteristic of signal modulus, e) reference voltage, f) fragment of signal registered during time given at the Fig. 2e, g) phase-time characteristic of signal modulus from the Fig. 2f, h) phase characteristic of signal modulus from the Fig. 2f

4. Advanced analysis of recorded signals

Within a framework of advanced analysis concerned recorded signals it is necessary to investigate recorded data in domain of discrimination threshold. This analysis includes calculation of amplitude distributions of AE signal power and AE counts in order to investigate their properties by means of the method of AE descriptors. Amplitude distributions of recorded signals are calculated by means of „*AE+JTFA*" program and next are visualized by means of other program named„AE amplitude distributions and descriptors", written for such a purpose.

Properties of amplitude distributions of AE counts and the power of AE signal (made in logarithmic scale) can be described by means of specially defined AE descriptors. The descriptors were defined as follows. At first, one should to mark a fragment of amplitude distribution curve which corresponds with the range of discrimination threshold (U_d, U_g); value of U_d is determined by minimum of derivative of distribution against discrimination threshold, whereas U_g is 90% of maximal value of recorded signal. Determined fragment of the curve is approximated by a straight line:

$$\ln(dN(U)/dt) = AU + B; \quad A = ADC \tag{1}$$

whereas the descriptor connected with the distribution is equals to slope of the straight A.

Described idea how define a descriptor for amplitude distribution of the power of AE signal is presented in Fig. 3. Descriptors defined in such a way are the base of the original advanced analysis of signals ascribing to acoustic emission signals AE descriptors with acronyms ADP (*Amplitude Distribution of Power of AE signal*) and ADC (*Amplitude Distribution of AE Counts*). Descriptors are calculated by means of the program„AE amplitude distributions and descriptors".

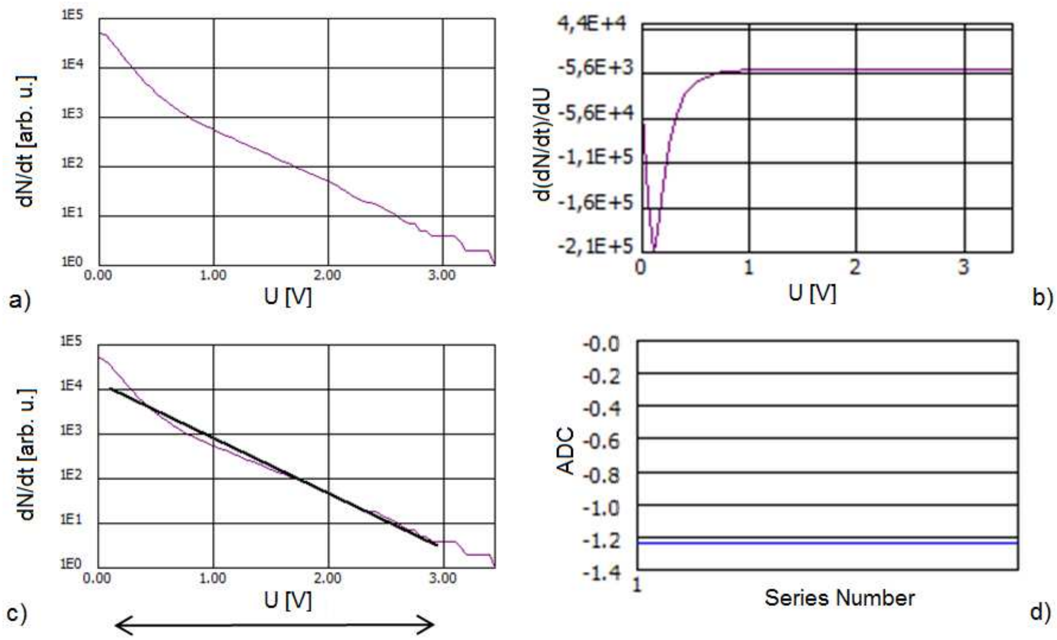

Figure 3. Illustration of ADC descriptor method calculation: a) amplitude distribution of counting rate, b) derivative of amplitude distribution of counting rate, c) amplitude distribution of counting rate with approximation curve and range of discrimination threshold (U_d and U_g), d) ADC descriptor for amplitude distribution from Figure 3a

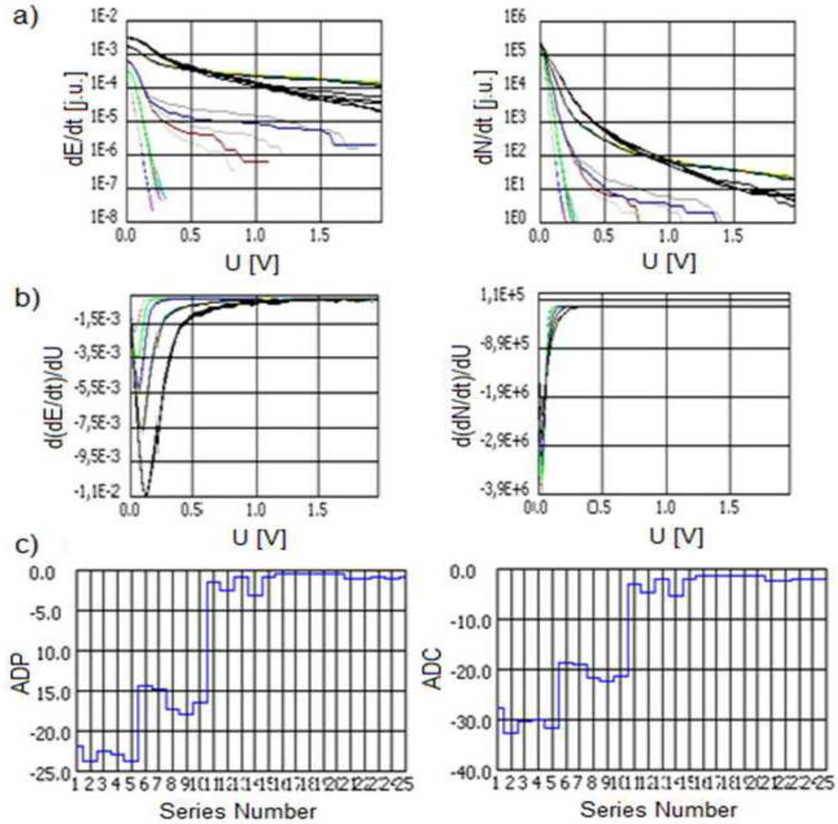

Figure 4. Test results concerned amplitude distributions made by means of the method of descriptors obtained with the program *Amplitude distributions and AE descriptors*: results for signal families recorded in measuring conditions differential only by applied voltages: U=10 kV (series 1-5), U=15 kV (series 6-10), U=20 kV (series 11-15), U=25 kV (series 16-20), U=30 kV (series 21-25))

Application of logarithmic scale on amplitude diagrams enables us to distinguish phenomena connected with propagation of an elastic wave in a medium and within an interconnected layer. Proposed definition of a descriptor and ascription of its value as the slope of a straight line, which approximates a chosen fragment of amplitude distribution, causes that descriptors are not based on values measured directly. Descriptors are negative values, and it is important that greater value of a descriptor is conform with flatter fragment of an amplitude distribution. Authors describe this property of defined descriptors as the so called advanced degree of AE signal, assuming that higher advanced degree of a signal is tantamount to greater value of a descriptor. Furthermore, Authors joint defined advanced degree of a signal with known advanced degree of deformation processes according to a rule that advanced degree of deformation process is described by AE signal generated in a source, whereas advanced degree of AE signal is described by a signal recorded at a measuring point (which is changed along propagation path). Test results concerned properties of amplitude distributions by means of the method of descriptors, for an example family of AE signal, is presented in Fig. 4. Authors have verified correctness of given hypothesis by analysis how are properties of many families of AE signals using the proposed method of descriptors [4,5,7,8].

5. Tested objects and description of tests

Tested objects were coil bars of the generator 120 MW, U_N = 13.8 kV (with outside control of electric field distribution [10]) and coil bars of the generator 200 MW, U_N = 15.76 kV (with outside and inside control of electric field distribution [10]).

Several hundred of generator coil bars are produced yearly in Poland. Each of these bars, before issuing of permit to work, is applied qualification tests. One of these tests consists in determination of PD level, carried out by means of electric method. Order of magnitude of admissible apparent charge in the case of considered objects is an order of nanoCoulombs.

Generator coil bar is a very interesting test object [11-15] because:

a. it is a complex insulating system (electrodes, semiconductor areas to control electric field distribution, complex insulating and conducting layers) where different PD sources typical for solid materials may appear,

b. AE sensors can be installed at many points of a tested bar which creates possibilities for identification of AE signals and location of PD sources.

Generator coil bars, produced by one of the factory, have been tested by means of AE method (using the original measuring system DEMA-COMP) and by means of electric method (using the computer measuring system TE 571 [8,16]). The purpose of these tests was analysis of PD phenomena appeared within generator coil bars resultant from two above methods applied simultaneously.

Within a framework of preparation for testing with the help of AE method it has been establish that tests concern only a slot part of the bar. This area is limited by additional earthed electrodes; between them there are six evenly distributed measuring points P1, P2,…, P6 (Fig. 5).

AE sensors (R6 and WD type, coming from the firm PAC[17]) have been placed at measuring points. Each tested bar was energized by the supply voltage which values were selected from the range of (0, $2U_N$); measurements have been carried out using two methods simultaneously. During measurements made by means of electric method, PD signals were detected by 120 seconds for each value of applied supply voltage (time period of data registration demanded to realize calculations made in analysis mode and by means of TEAS program). AE signals were recorded four times for each value of selected supply voltages within time periods of 2 seconds.

Many bars have been tested by the Authors. Measurement results and their analysis, presented in the article, deal with two selected bars (in which PD appeared) marked as:

–bar „D" (coil bar of the generator 120 MW, U_N=13.8 kV),

–bar „M" (coil bar of the generator 200 MW, UN=15.76 kV).

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a)

b)

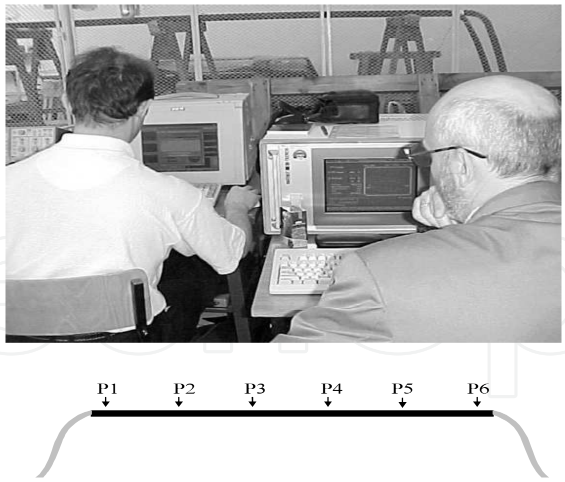

Figure 5. General view of the measuring stand to PD investigation in coil bars of generators with measuring systems DEMA-COMP and TE 571 (a) as well as arrangement of measuring points applied during PD testing by means of AE method in coils bars of generators (b)

U kV	Q nC	Diagnosis results received from TEAS program: Kind of PD source – correctness of diagnose (estimation by probability)
10	3.5	Inclusions near HV electrode (inside dielectric, near surface of the bar) – 0.57
15	3.8	Inclusions near HV electrode (inside dielectric, near surface of the bar) – 0.41 Inclusions near LV electrode (in upper part of dielectric) – 0.21 Inclusions inside dielectric – 0.15
20	2.2	Inclusions near HV electrode (inside dielectric, near surface of the bar) – 0.39
25	2.2	Inclusions near HV electrode (inside dielectric, near surface of the bar) – 0.44
30	2.0	Inclusions near HV electrode (inside dielectric, near surface of the bar) – 0.86

Table 1. Results of analysis of PD phenomena within the bar „D" (U_N=13.8 kV) - electric method

U kV	Q nC	Diagnosis results received from TEAS program: Kind of PD source – correctness of diagnose (estimation by probability)
10	2.2	External disturbances – 0.03
15	3.4	Superposition of inner discharges and corona (own analysis of Authors for lack of a standard in the library of profiles)
20	6.5	Discharge inside dielectric, 1% surface discharge – 0.12
25	70	Corona appeared at many points which dominates inner discharges – 0.21
30	26	Corona appeared at many points which dominates inner discharges – 0.26

Table 2. Results of analysis of PD phenomena within the bar „M" (U_N=15.76 kV) - electric method

6. Results of PD analysis received from electric tests

Results of PD analysis in the bars carried out after measurements made by means of electric method (using system TE 571) are presented in Tables 1 and 2. Two bars are interesting from the point of view of analysis of PD sources. Apparent charges introduced by PD sources in the bar ,,D" is order of a few or several dozen nanoCulombs. Their value increases as the supply voltage increases. Values of apparent charges introduced by PD sources to the bar ,,M" are anomalous (70 nC).

7. EA basic properties of AE signals coming from partial discharges in generator coil bars

Exemplary descriptions of AE signals recorded within bars ,,D" and ,,M" in the measuring channel with WD sensor are presented in Figs. 1 and 6. All elements of these descriptions have been received using signal filtration by means of pass-band filter of 5. order and signal band of 20 - 500 kHz.

The following bands in the signal spectrum are visible at the diagrams ,,b", "e" and ,,f" situated in Figs. 1 and 6: 20 - 40 kHz, 70 - 110 kHz, 120 - 150 kHz, 200 - 240 kHz, 270 - 290 kHz and 450-490 kHz. Analysis of descriptions registered at other measuring points and made for other values of the supply voltage proves representativeness of indicated frequency bands.

Characteristic c), d) and f) from Figs. 1 and 6 show analyzed quantities in dependence on a phase of the supply voltage. Characteristics d) and f) prove periodical character of PD in all cases, evolved by appearance of maximums of the tested quantity, twice during averaging period of the supply voltage.

Characteristics c) of mentioned Figures - this means phase-time diagrams, enable us to analyze values of AE signal amplitude for an established phase in successive periods of the supply voltage. They show two features: greater values appear for phase ranges (at the diagram are visible two ,,corridors") and phase diagrams of signal amplitudes show fluctuation of these values for successive periods of the supply voltage.

From Fig. 7 results that - for frequencies greater than 150 kHz - frequency characteristic of a measuring channel is flat, therefore all characteristics of AE signals show entirely quantity properties of PD phenomena. Properties of investigated phenomena in the range of frequency from 20 to 150 kHz are ,,rescaled" by noise of a measuring channel.

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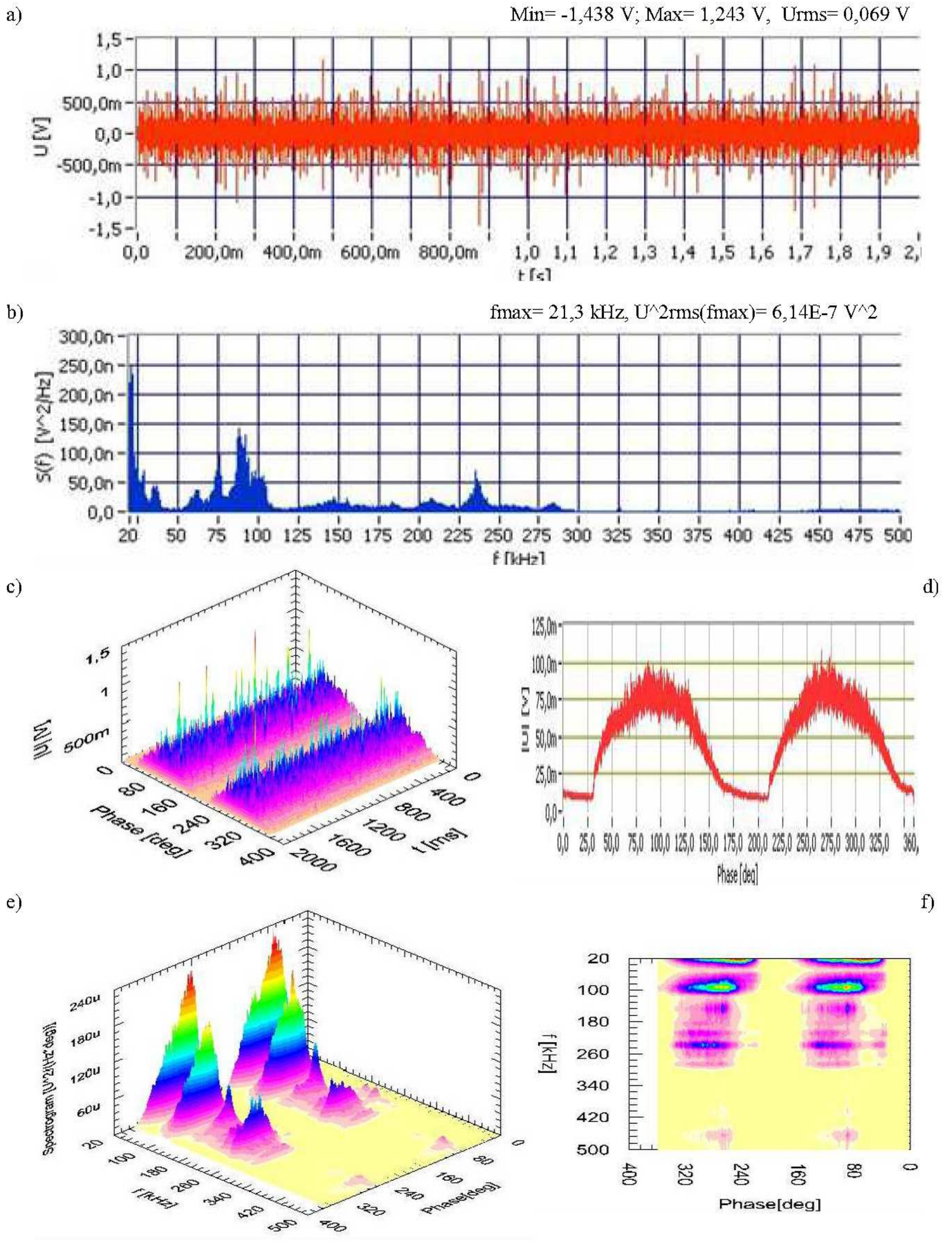

Figure 6. Description of AE signal recorded in the measuring conditions - measurement by means of WD sensor placed at P2 measuring point of „D" bar, the supply voltage of the bar 20 kV, measured value of the apparent charge 2.2 nC: a) impulse (after filtration), b) frequency characteristic, c) phase-time characteristic, d) averaging phase characteristic, e) and f) averaging STFT spectrograms

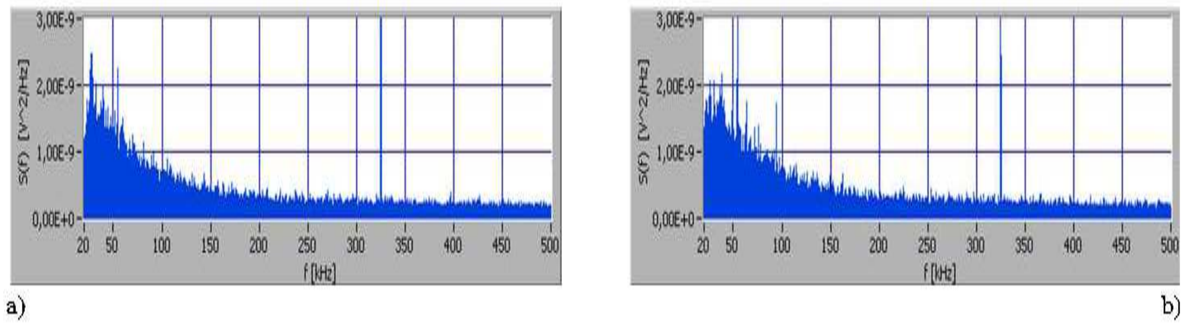

Figure 7. Frequency characteristics of noises in the measuring channel recorded in the following measuring conditions: bar „D", 0 kV, measuring point P1, AE sensor - WD: a) noises before measurements, b) noises after measurements

8. Location of PD sources by means of a method based on advanced degree of AE signals

8.1. Basis of location of PD sources by means of AE method

AE impulses are generated in PD source and propagate in the whole volume of a medium as AE elastic waves. They are subjected to phenomena connected with propagation of waves and particularly - dumping during propagation. In a such a way, AE signals which attained a given measuring point have amplitudes „weighted" by length of propagation path of a signal from PD source to AE sensor. Signals of less propagation path have more weight. This process depends also on frequency because AE elastic waves are damped during propagation and damping is stronger for higher frequencies.

From Fig. 2g results that - even in the frame of one period of the supply voltage – AE signals coming from many partial discharges reach EA sensor placed at one measuring point. Registration of AE signals requires multiple assembly of the sensor at chosen measuring points. In practice, that changes conditions of registration because – despite of repeatable procedure of mounting of the sensor – there is not certainty that the coupling layer will be stable and parallel.

From these reasons, even though a tested object should be treated as one-dimensional, Authors consider traditional methods of location of PD sources as insufficient ones. Instead of traditional approach the new method of location is proposed. Such a method is based on defined descriptors, calculated for recorded AE signals. In analyzed cases measurements were realized for each tested bars. That gives a set of 144 recorded AE signals (6 measuring points P1, P2, P3, P4, P5 and P6; 6 selected values of the supply voltage: 0, 10, 15, 20, 25and 30 kV; 4 AE signals recorded at each measuring point for each chosen value of the supply voltage).

The following activities are proceeded: choice of filtration band of recorded signals, filtration of all signals, calculation of amplitude distributions and AE descriptors.

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Now, the procedure is as follows: a) calculation of mean values and standard deviation of AE descriptor for signals recorded at a given measuring point and under determined value of the supply voltage, b) determination of dependencies of AE descriptor values on position of a measuring point for determined value of the supply voltage, c) search of maximums at received curves whose locate PD sources.

The presented way of location of PD sources was named by Authors as the method based on advanced degree of AE signal.

8.2. Location of PD sources in the band of [150,500] kHz by means of AE method

Location of PD sources on the basis of advanced degree of AE signal was begun from the band of 150 – 500 kHz. According to analysis presented at point 7, amplitude-frequency characteristic of the measuring system is plate within this band of frequency, then AE signals are not changed during their recording. Since „forced" damping along propagation path is expected so contribution from the nearest source should be dominant within recorded signals.

Diagrams of ADP descriptor values within Figs. 8 are expressed depending on of position of a measuring point for two tested bars and different values of the supply voltage. Maximums at each curve locate PD sources.

Results of location of PD sources with maximal activity for „D" bar are as follows:

a. when the supply voltages is 10 kV then PD source with maximal activity is situated near measuring point P2,

b. when supply voltages are 15 kV and 20 kV then PD source with maximal activity situated near measuring point P2 is still active, but there is also the second source near measuring point P5,

c. when supply voltages are 25 kV and 30 kV then local maximums remain identical as for 15 kV and 20 kV, but differences between local maximum and local minimum at the curve are considerable smaller (by comparison with curves for supply voltages 15 kV and 20 kV).

Statement of descriptor families for particular supply voltages gives additional information about location of PD sources. AE signals for lower supply voltages are recorded only at measuring points situated nearby PD sources, whereas AE signals for high supply voltages are recorded at all measuring points. In the last case „weighing" of AE signals enables us to locate PD sources as before. Elongation of propagation path of AE signals when the supply voltage increases is caused by differentiation of their power; AE signals recorded under supply voltages 25 kV and 30 kV have the power many times greater than the power of AE signals recorded under 10 kV. Greater amplitude of AE signal enables us to detect AE signals at measuring points situated farther from PD sources.

It is worth noticing that descriptors for repeatedly measured AE signals, which are noises of a measuring path (different bars and different measuring points), are similar values: about 100 contractual units.

Local maximums for the bar „M" appear in the vicinity of measuring point P3. They are distinct for supply voltages 10, 20, 25 and 30 kV. The second maximum appears near measuring point P5 (for supply voltages 10, 15 and 30 kV). From the supply voltage of 15 kV there are additional processes at one or two ends of the bar whose overlap to this picture.

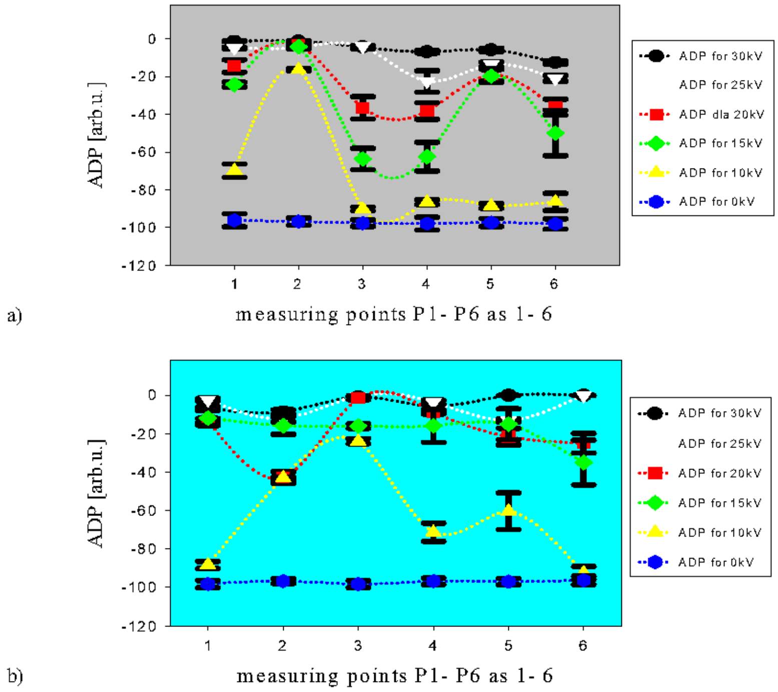

Figure 8. Location of PD sources made by means of method of advanced degree of AE signal (for AE signals registered by WD sensor at measuring points P1-P6, analysis in the band of 150 - 500 kHz) for different values of the supply voltage: a) bar „D", b) bar „M"

8.3. Location of PD sources in the band of [20,60] kHz by means of AE method

Amplitude-frequency characteristic of the measuring system is not flat within selected band of frequencies therefore AE signals are changed during recording. This input, coming from the measuring system, increases monotonically as frequency is decreased; it gives four times growth in spectrum characteristic of density of the power. Additionally (taking into account that damping of elastic waves is greater for higher frequencies) AE elastic waves coming from father distances can be also detected at measuring points within selected bands.

Suitable calculations have been carried out for two tested bars. Diagrams of ADP descriptor values (for signals recorded by R6 sensors) versus the position of a measuring point, for different values of the supply voltage, are presented in Fig. 9.

Location of PD sources within the band of 60 - 20 kHz, resultant from analysis of location of maximums at each curve presented in Fig. 9, gives the following results:

- „D" bar – PD sources are located near the measuring point P2 (under supply voltages of 10, 15, 20, 25 and 30 kV) and P5 (under supply voltages of 20, 25 and 30 kV);

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- „M” bar – PD sources are located near the measuring point P3 (appear under all values of supply voltages) and P5 (under supply voltages of 10, 15 and 20 kV), unilateral maximums appear under supply voltages of 25 and 30 kV.

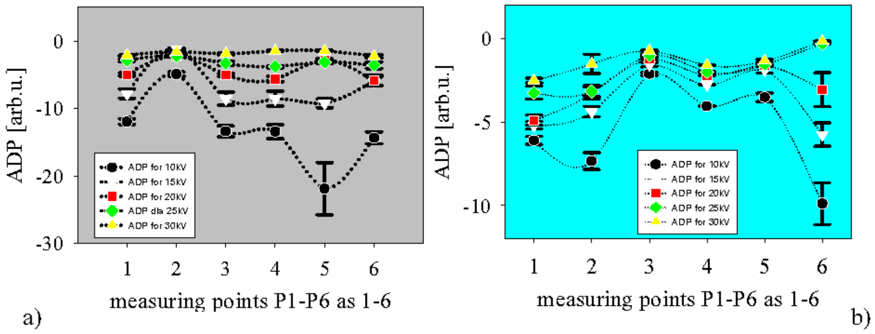

Figure 9. Location of PD sources made by means of the method of advanced degree of AE signal (for AE signals recorded by R6 sensor at measuring points P1-P6, analysis in the band of 20 - 60 kHz) for different values of the supply voltage: a) bar „D”, b) bar „M”

9. Location of PD sources using Kohonen network

9.1. Basis for location of PD sources using Kohonen network

Groups of amplitude distributions can be treated as sets of pictures, i.e. input vectors X. In order to describe these sets one should divide them into classes and build pictures representative for particular classes. A good tool for solution of such a task are neuron networks [18-21].

The assigned task imposes the choice of a network which ensures learning of classification without inspection, based on assembly of input data. Lack of information on attachment of input pictures to determined classes, established a priori, shows that searched network has self organization features, i.e. it finds by one-self standards within input data and codes them (in order to find of output). In the stage of selection of the network the following assumption has been made – only one output unity is in active state during learning at a given moment. Output unities compete with themselves in order to be within the incited state and are named unities type of „winner takes all” (WTA).

The above requirements fulfill the networks in which competitive learning without inspection has place [19,21], i.e. self-organized networks where the base is competition between neurons. These networks include input layer and self-organized one. Input layer is defined by dimension of input vector (N). Self-organizing layer contains M neurons with a structure defined during solution of specific problem. In practice, WTA algorithm has been replaced by winner take most (WTM) algorithms in which - besides a winner - neighbouring neurons actualize also their weights (the greater distance from a winner the less change of the value of neuron weights). An example of WTM algorithm is one of Grossberg-Kohonen. Authors have implemented Kohonen neuron network using a set of tools coming from DataEngine V.i. worked up on the base of LabView software. Operation of the network is realized by means of „Kohonen EA" program (written for this purpose) which realizes the following tasks:

–building of Kohonen network and standard pictures for the classes,

–labeling of classes,

–testing of input objects.

Kohonen network is built after introduction of input data (learning data) and after determination of number of features within input vector, number of layers and winning neurons. Input data make a set of input vectors. Single input vector (vector of features) has the following form:

$$\vec{X}^T = [A_1, A_2, ..., A_p, B_1, B_2, ..., B_q, C_1, C_2, ..., C_r, D_1, D_2, ..., D_s] \quad (2)$$

where $\vec{A}$ and $\vec{C}$ are amplitude distributions of AE counts and the power of a signal, whereas $\vec{B}$ and $\vec{D}$ are derivatives of $\vec{B}$ and $\vec{D}$ against discrimination threshold.

A single value of vector component X_α^T (single feature) is one of values of one of AE amplitude distributions or their derivatives for a given discrimination threshold U_T. Full definition of an input vector needs determination of parameters *p, q, r* and *s*. These parameters are determined during preparation of learning data – by means of „*AE amplitude distributions and descriptors*" program. Input vector includes amplitude distributions of a signal; input data describe signal families. Up to the present, an assumption has been put during analyses: contribution of each from amplitude distributions to a final result is the same. This assumption is realized by means of the same values of parameters *p, q, r and s* as well as by normalization of independent groups of particular amplitude distributions.

Implemented Kohonen network is built by two layers – input one and Kohonen layer. Number of neurons in input layer is a number of features characterized a given problem (*p+q+r+s*). Kohonen layer is many-dimensional table of neurons – number of dimensions 1, 2 or 3 is optional (number of neurons in Kohonen layer was established experimentally). Adaptation of weights is realized according to Grossberg-Kohonen algorithm; learning constant and neighbouring ray are changed during learning during successive input vectors are analyzed. This dynamic of the network aims at improvement of activity and organization of neurons during learning process. Such a dynamic of neuron network is written as an dependence of quantities $\vec{W}$, η and G versus t (time):

$$\Delta\vec{W}(t+1) = \eta(t)G(t)[\vec{X} - \vec{W}] \quad (3)$$

Final vector of weights of a given neuron reflects values of features of a vector representative for a given class; result describes ability to fragmentation of a set of input pictures to separable classes and creation representative standard pictures for these classes.

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Kohonen network may realize the task consisting in assignment of input vectors of particular classes. Input vectors can be learning data for realized network or any input vectors with identical structure of features. Input vectors are built by means of „AE amplitude distributions and AE descriptors" program. They are the form which is recognized by „AE Kohonen" program. Choice of features of input vector is essential problem for results obtained by built Kohonen network. Authors chose amplitude distributions ADC and ADP as well as derivative of these descriptions (against discrimination threshold), assimilating input data to problems of Newton dynamics. Additionally, concerning about discernment of pictures by Kohonen network, amplitude distributions are prepared in logarithmic scale. Owing to that, input pictures distinguish exponential character of many phenomena. It is worth addition that such a form of input data (which takes into account physical aspects of researched phenomenon) leads to a proper classification. „AE Kohonen" program normalizes input vectors (normalization is made independently within one distribution kind because it gives the same contribution of each distribution into realized input vector), classifies, builds winning neurons and enables us to classify input vectors.

9.2. Location of PD sources in the band of [150,500] kHz using Kohonen network

Results of classification of 144 input vectors (for each bar) made by Kohonen network, built for 10 winning neurons have been assembled to subgroups included input vectors for particular values of the supply voltage (0, 10, 15, 20, 25 and 30 kV). Each subgroup contains 24 series describing input vectors for AE signals, recorded at particular measuring points (4 measuring series for each measuring point - P1, P2, P3, P4, P5 and P6 successively). Assembled location results are presented in Fig. 10.

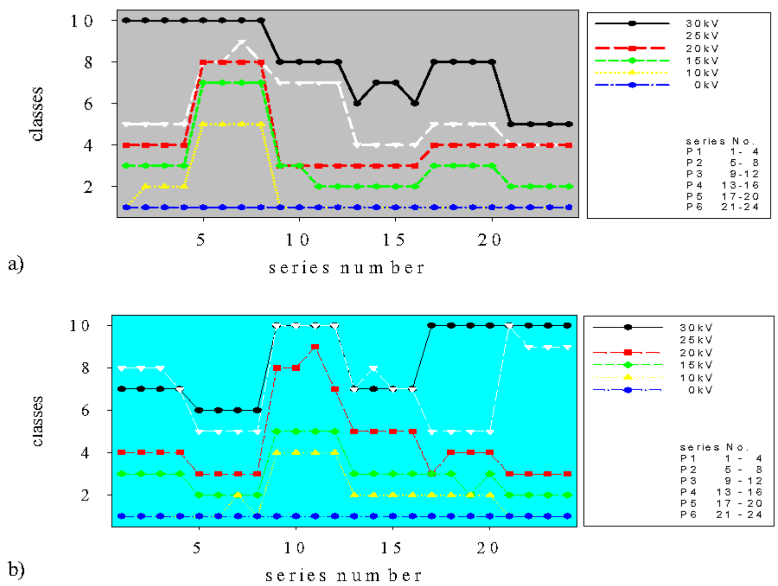

Figure 10. Classification results of input vectors (for AE signals recorded by WD sensor at measuring points P1-P6, analysis in the band of 150 - 500 kHz) by Kohonen network for different values of the supply voltage: a) bar „D", b) bar „M" (maximum within a subgroup locates PD source with maximum activity)

Location is made within subgroups (for particular supply voltages) by determination of the measuring point where local maximum appears. Higher class given by the network correspond with higher advanced degree of AE signal.

Results of location of PD sources for both bars by means of Kohonen network are as follows:

a. PD sources within „D" are located near measuring point P2 (for each values of the supply voltage) and near P5 (for supply voltages of 15, 20, 25 and 30 kV),

b. PD sources within „M" are located near measuring point P3 (for each values of the supply voltage) and near P5 (for the supply voltage of 20 kV), but from beginning of 15 kV additional processes appear at one or two ends of the bar (they overlap on this picture).

It is worth also noticing the following facts:

1. Kohonen network gives the lowest class (class 1) to input vectors for noises of a measuring channel,

2. Kohonen network gives classes which differ most of two ones to particular input vectors built for signals recorded at one point and under one supply voltage (it may recognize that deformation processes are stable),

3. there is conformability between location made by means of the method of descriptors and when Kohonen network is applied (Figs. 7 and 8).

10. Location of PD sources — Recapitulation

There are two PD sources within bar „D" near measuring points P2 and P5 whose were named as Z1 and Z2 respectively.

There are two PD sources within bar „M" near measuring points P3 and P5 whose were named as Z3 and Z4 respectively as well as two sources at ends of the bar named as Z5 and Z6.

Z1 and Z3 sources are active under supply voltages of 10, 15, 20, 25 and 30 kV. Z2 source is active beginning from supply voltages of 10 or 15 kV. Z5 and Z6 sources are active under higher values of the supply voltage 25 and 30 kV.

Results of location of PD sources coming from the method of descriptors and Kohonen network are identical in practice.

It is worth noticing the following information, included in Figs. 8 and 9:

a. signals generated by Z1 source in the band of 150 - 500 kHz may be detected up to distance of 1 m (for lowered bands the distance is longer),

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b. AE signals are recorded within the band of 20 - 60 kHz at all measuring points even under the supply voltage of 10 kV,

c. there are not different AE sources after changing of frequency bands.

Conclusions a) and b) result from physics of elastic waves. The conclusion c) proves that bars are „grateful" research material, in which there are not other significant acoustic phenomena masked of PD like, for example, in oil power transformers.

11. Description of AE impulses radiated by PD sources (band of [150, 500] kHz)

Description of AE signals coming from PD sources, named as Z1, Z2, Z3 and Z6, is presented in Figs. 11 - 14. Characteristics of these selected AE signals are beginning of data base describing AE signals generated by PD sources within coil bars of generators.

Properties of AE signals coming from particular sources are as follows:

- Z1 source – averaging phase-time characteristic is characterized by: trapezoid shape, asymmetry of amplitude and shape in both half of the period, asymmetry of amplitudes of averaging STFT spectrogram, frequency main bands of 230 – 250 kHz (main bands) and remaining bands of 280 – 290 kHz;

- Z2 source – averaging phase-time characteristic is characterized by: shape of Gauss curve, symmetry of amplitude and shape in both half of the period, symmetry of amplitudes of averaging STFT spectrogram, frequency main bands of 230 – 240 kHz (main bands) and remaining bands of 280 – 290 kHz;

- Z3 source – averaging phase-time characteristic is characterized by: triangle-trapezoid shape, asymmetry of amplitude and shape in both half of the period, symmetry of amplitudes of averaging STFT spectrogram, frequency main bands of 230 – 250 kHz and remaining bands of 280 – 290 kHz;

- Z6 source – averaging phase-time characteristic is characterized by: triangle shape, symmetry of amplitude and shape in both half of the period, symmetry of amplitudes of averaging STFT spectrogram, main frequency bands of 230 kHz – 245 kHz and remaining bands of 280 – 290 kHz.

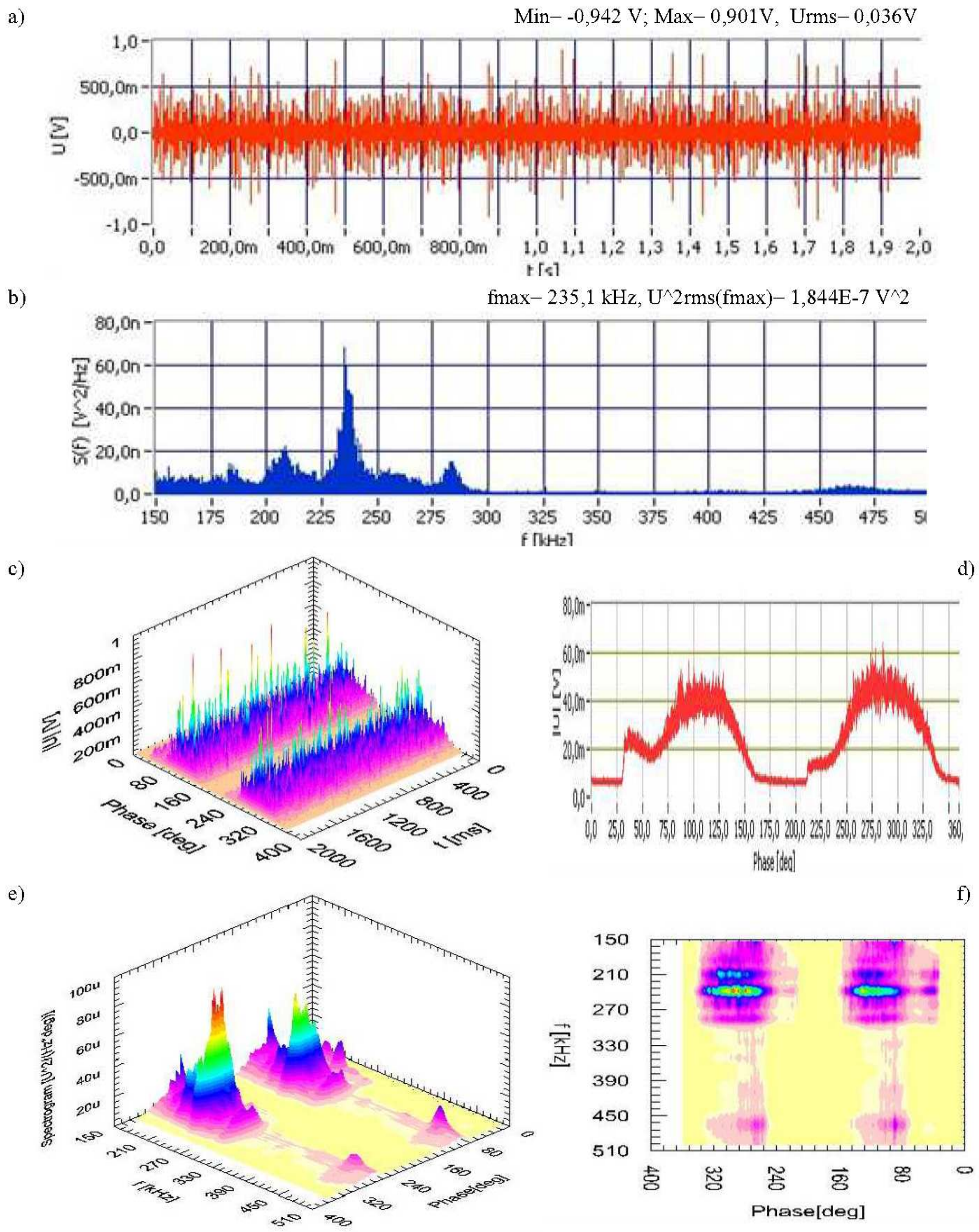

Figure 11. Z1 source: a) impulse (after filtration), b) frequency characteristic, c) phase-time characteristic, d) averaging phase characteristic, e) and f) averaging STFT spectrograms recorded in measuring conditions: measurement by means of WD sensor placed at P2 measuring point of „D" bar, the supply voltage of the bar 11.8 kV, measured value of the apparent charge 3.8 nC

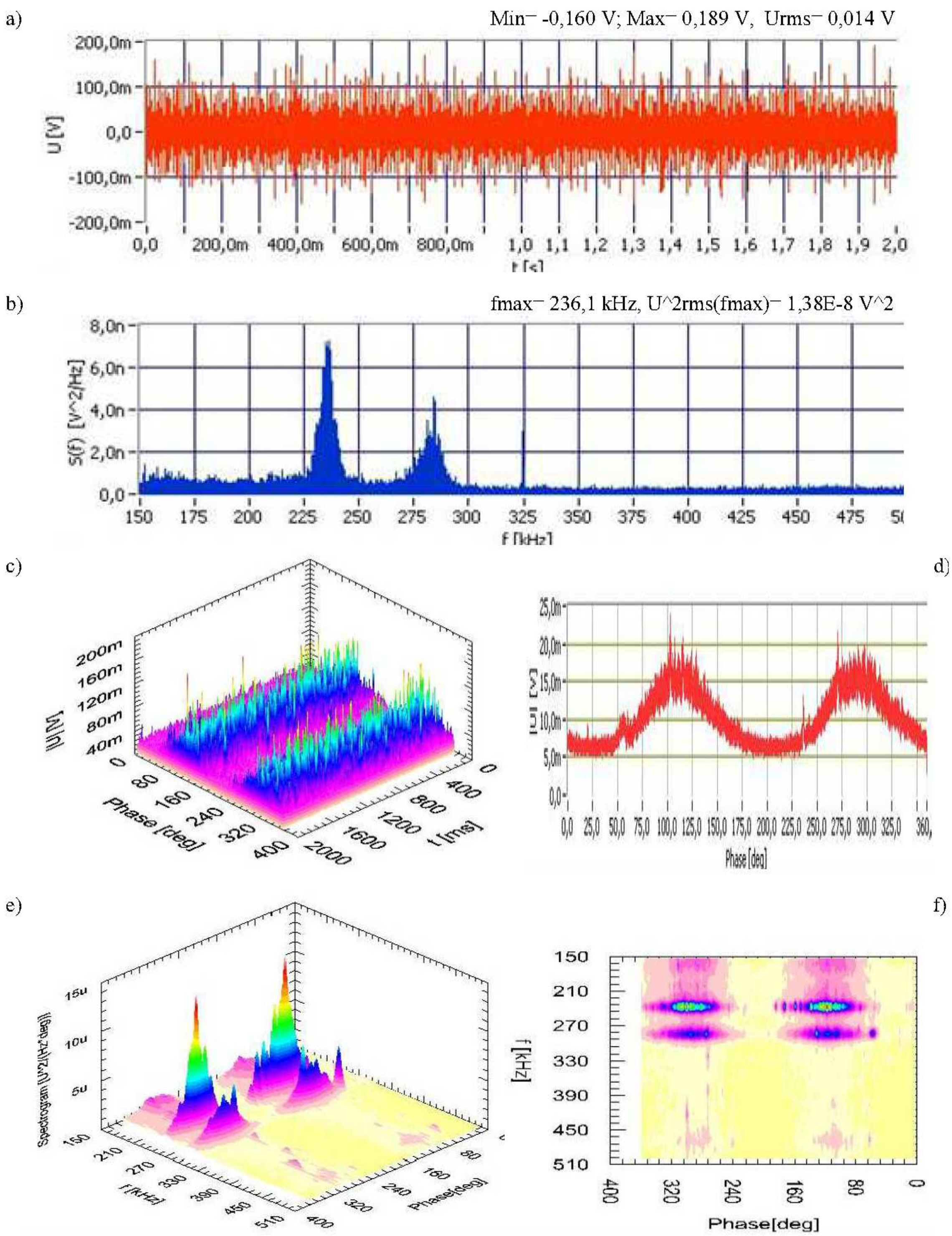

Figure 12. Z2 source: a) impulse (after filtration), b) frequency characteristic, c) phase-time characteristic, d) averaging phase characteristic, e) and f) averaging STFT spectrograms recorded in measuring conditions: measurement by means of WD sensor placed at P5 measuring point of ,,D" bar, the supply voltage of the bar 20.5 kV, measured value of the apparent charge 2.2 nC

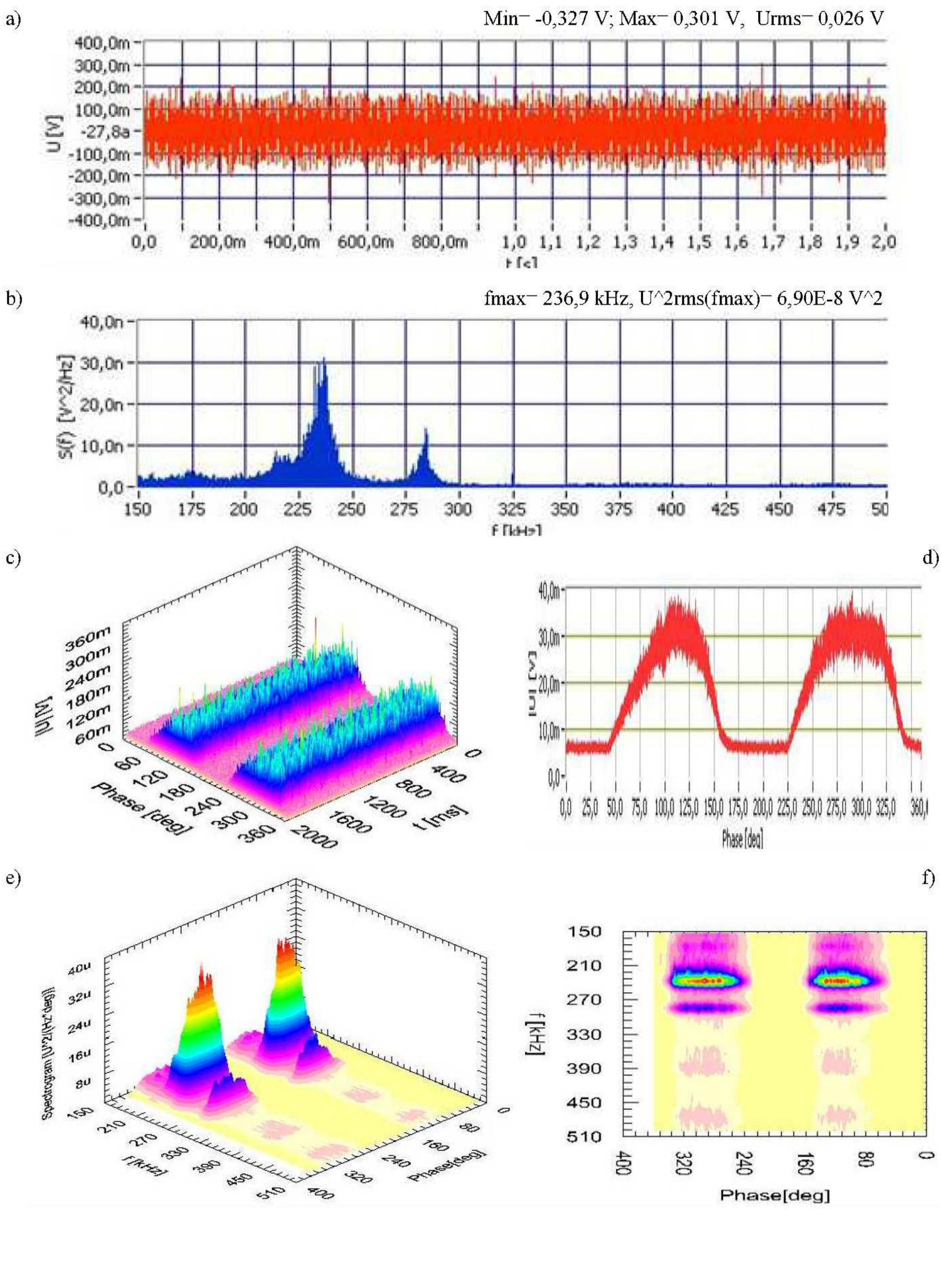

Figure 13. Z3 source: a) description of AE signal, b) frequency characteristic, c) phase-time characteristic, d) averaging phase characteristic, e) and f) averaging STFT spectrograms recorded in measuring conditions: measurement by means of WD sensor placed at P3 measuring point of „M" bar, the supply voltage of the bar 15.5 kV, measured value of the apparent charge 3.4 nC

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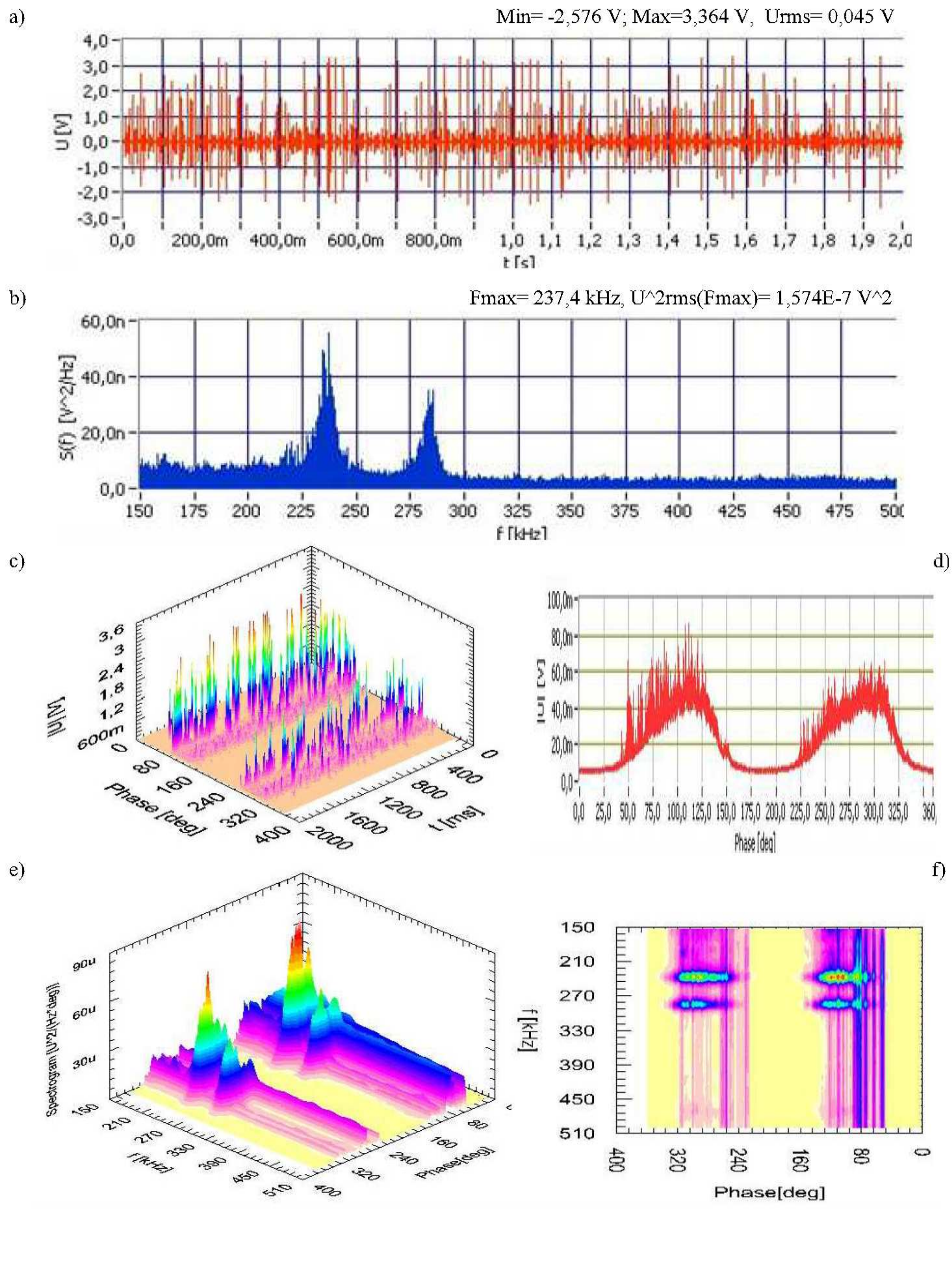

Figure 14. Z6 source: a) description of AE signal, b) frequency characteristic, c) phase-time characteristic, d) averaging phase characteristic, e) and f) averaging STFT spectrograms recorded in measuring conditions: measurement by means of WD sensor placed at P6 measuring point of „M" bar, the supply voltage of the bar 31 kV, measured value of the apparent charge 26 nC

12. Cumulative analysis of PD testing results made by means of joint electric-acoustic methodology

Results of analyses concerning testing of PD within ,,D" and ,,M" bar, received simultaneously from electric and AE method, are stated in Tables 3 and 4. The statement contains supply voltages and the following measured or calculated quantities for signals recorded under particular supply voltages: apparent charge, ADP descriptors for AE signal which gives maximum within the suitable group of AE signals (after analysis within bands of 150 – 500 kHz and 20 – 60 kHz) and properties of PD sources determine independently by means of electric and acoustic method. There are properties: kind of PD determined by means of expert diagnostic program TEAS (electric method) and location of PD sources (AE method). Such a statement enables us to obtain more complete information on the kind and the place in which partial discharges appear.

Electric method			AE method		
U kV	Q nC	Diagnosis results received from TEAS program: Kind of PD source – correctness of diagnose (estimation by probability)	ADP within bands of: [150,500] kHz	[20,60] kHz	Location of sources
10	3.5	Inclusions near HV electrode (inside dielectric, near surface of the bar) – 0.57	-16.3	-4.9	Z1 source – near P2
15	3.8	Inclusions near HV electrode (inside dielectric, near surface of the bar) – 0.41 Inclusions near LV electrode (in upper part of dielectric) – 0.21 Inclusions inside dielectric – 0.15	-4.2	-1.2	Z1 source – near P2 Z2 source – near P5
20	2.2	Inclusions near HV electrode (inside dielectric, near surface of the bar) – 0.39	-3.3	-2.2	Z1 source – near P2 Z2 source – near P5
25	2.2	Inclusions near HV electrode (inside dielectric, near surface of the bar) – 0.44	-4.0	-2.7	Z1 source – near P2 Z2 source – near P5
30	2.0	Inclusions near HV electrode (inside dielectric, near surface of the bar) – 0.86	-1.3	-1.6	Z1 source – near P2 Z2 source – near P5

Table 3. Statement of results of PD analysis made by means of electric-acoustic methodology for ,,D" bar (U_N =13.8 kV)

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The source of the most intensive partial discharges appears within „D" bar near measuring point P2. This source is created by inclusions near HV electrode (inside dielectric, near surface of the bar). Ignition of partial discharges at point P2 takes place already under the supply voltage of 7 kV (about 52% U_N). This source is created by inclusions near LV electrode. The most compose description of PD, given by expert diagnostic program TEAS (for the supply voltage 15 kV), corresponds with activity of Z1 source and growth of activity of Z2 source. Growth of apparent charge value is caused by properties of PD source which is located near point P2. Maximal value of ADP descriptor and maximal value of apparent charge was registered for the band of 20 – 60 kHz under the supply voltage of 15 kV.

Electric method			**AE method**		
U kV	Q nC	Diagnosis results received from TEAS program: Kind of PD source – correctness of diagnose (estimation by probability)	ADP within bands of: [150,500] kHz	[20,60] kHz	Location of sources
10	2.2	External disturbances – 0.03	-24.0	-2.1	Z3 source – near P3 Z4 source – near P5
15	3.4	Superposition of inner discharges and corona (own analysis of Authors for lack of a standard in the library of profiles)	-15.8	-1.6	Z3 source – near P3 Z4 source – near P5
20	6.5	Discharge inside dielectric, 1% surface discharge – 0.12	-1.4	-1.2	Z3 source – near P3 Z4 source – near P5
25	70	Corona appeared at many points which dominates inner discharges – 0.21	-0.4	-1.0	Z3 source – near P3 Z4 source – near P5 Z5,Z6 sources – near ends
30	26	Corona appeared at many points which dominates inner discharges – 0.26	-1.0	-0.7	Z3 source – near P3 Z4 source – near P5 Z5,Z6 sources – near ends

Table 4. Statement of results of PD analysis made by means of electric-acoustic methodology for „M" bar (U_N =13.8 kV)

The source of the most intensive partial discharges within „M" bar appears near measuring point P3. It is caused by inner discharges. Additionally, the source within area of measuring points P5 and P6 is active for supply voltages 25 and 30 kV. There is also a source near measuring point P5 within the band of 20 – 60 kHz. Acoustic method shows weak sensitivity for many-point corona discharge given growth of apparent charge up to value of 70 nC.

13. Recapitulation

The original method, worked out to analyze of AE signals at basic and advanced level, is presented. The basic analysis is made in domains of time, frequency and time-frequency, whereas advanced analysis describes properties of AE signals in domain of threshold.

The results of basic analysis are as follows:

–the signal after filtration with its minimal, maximal and RMS values (the band pass filter of 5. order is applied to filtration which band is given as a frequency range at the frequency characteristic),

–spectral power density as frequency characteristic of the signal with the frequency for main maximum and spectrum value for this frequency,

–phase-time characteristic,

–averaging phase characteristic,

–three-dimensional STFT spectrogram,

–three-dimensional STFT spectrogram dropped to a phase-frequency plane.

These quantities are calculated for AE signals recorded during 100 periods of the supply voltage and describes properties of AE signal for „averaging" period of the supply voltage. They define frequency of bands dominant within AE signals and describe random character of AE signals appearing in analyzed phenomena.

Results of advanced analysis are distributions of counting rate and power of the signal in function of discrimination threshold as well as ADC and ADP descriptors which describe quantitatively AE signals named as advanced degree of recorded AE signals. Descriptors are a base to locate PD sources by means of advanced degree of AE signals.

Investigations of partial discharges within generator coil bars, realized as simultaneous measurements made by means of electric and acoustic method. Electric method was applied to determine apparent charge, introduced by active PD sources, and kind of recorded partial discharges (by means of TEAS program). Analysis of test results is presented for two chosen bars, designed as „D" (bar of the coil of the generator 120 MW, U_N=13.8 kV) and „M" (bar of the coil of the generator 200 MW, U_N=15.76 kV). The both bars are interesting from the point of vue of analyze of PD sources. In the case of „D" bar, PD sources introduce apparent charges whose value is at the level of several nC; this value diminues when the supply voltage increases. Values of apparent charges introduced by PD sources into „M" bar reached suprising anomalous great value (70 nC).

AE measurements were made at six measuring points of each tested bar. Investigation results obtained from AE method determine the following frequency bands, dominant in AE signals: 20 - 40 kHz, 70 - 110 kHz, 120 - 150 kHz, 200 - 240 kHz, 270 - 290 kHz and 450-490 kHz. ADC and ADP descriptors calculated for recorded signals order theses signals according their advanced degree. They are a base for location of AE sources by means of the original method of advanced degree of AE signals.

In result of analysis of AE signals within the band of [150,500] kHz such a location od PD sources for different values of the supply voltage have been made; six PD sources were located and results of basic analysis for these sources were presented.

Obtained results were proved by location resultant from application of Kohonen network.

AE signals recorded within the band [20,60] kHz were analyzed additionally. Analysis of AE signals in different frequency bands showed the same location of PD sources and proved changes of AE signals during propagation.

The cumulative analysis of PD test results made by means of complex electric-accoustic methodology enables us to obtain more complete information about the kind and the place of occurrence of partial discharges.

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