PARTIAL DISCHARGES WITHIN THE BARS ASSIGNED FOR GENERATORS COILS

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The paper contains the analysis of PD investigations results (within the bars assigned for generators coils) obtained parallel on the ground of the electric method and acoustic emission method as well as unified eclectro-acoustic method. The analysis of results obtained by means of electric method characterizes kind and parameters of PDs. The analysis of results obtained by means of acoustic emission method contains acoustic description of AE signal and detailed analysis of amplitude distributions shapes which gives deformation processes description and PD sources location. Detailed analysis of amplitude distributions shapes has been carried out by means of two methods resultant from definition of AE descriptors and application of Kohonen neural network. The unified eclectro-acoustic method consists in parallel utilisation both methods to mutual verify obtained results.

Keywords: partial discharge, apparent charge, acoustic emission, amplitude distribution.

1. INTRODUCTION

Diagnostic problems relating to high voltage insulating systems are treated nowadays as fundamentals ones and investigations on partial discharges (PD) are of particular importance among theses problems [1-4]. That deals with both electric and non-electric investigation methods. In the second group, the acoustic emission (AE) methods are credible complementary operational methods used to measure and evaluate PDs in different insulating systems [5-8] because AE methods enables to localize PDs, distinguish and determine sources of PD.

PD investigations within the bars assigned for generator coils made by electric method [9, 10] give the typical PD level of order of nanocoulumbs. Such a level, admissible by relevant standards, is guaranteed by manufacturers but a merit of the matter is that bars are made using different and often competitive technologies. Thus PD investigations within the above elements have two goals: for one thing, cognitive, which specifies description of the phenomenon, and for another, practical, used to compare how bar properties are manifested within different technologies.

The paper is devoted to analysis of PD investigations within the bars assigned for generators coils carried out by means of electric method and AE method used parallel.

2. DESCRIPTION OF INVESTIGATIONS

In Poland, bars of generators are produced in a few firms - one of them is ENERGOSERVIS (in Lubliniec). Before applying, all produced bars are tested out on the stand used to study of PDs within bars of generators.

This time, the stand was extended with PD analysing system TE 571 and DEMA-COMP measuring system (Fig.1). Executed nvestigations were aimed at study of PD phenomena within generators coils bars basing on the electric and AE methods as well as the development of unified eclectro-acoustic method [14].

PD measurements by means of an electric method were carried out with using the digital PD analysing system TE 571, offered by the firm Haefely Trench. This PD detector is applied to evaluate intensity PDs in high voltage insulation in accordance with actual IEC recommendations. The TE 571 system is built according to conception worked out at Technical University in Delft [15]. Block scheme and view of PD measuring system are presented in Fig.2.

The PD measurements by means AE method were carried out with using measuring AE system DEMA COMP [16,17] which is unique, specialise and portable apparatus set which has been design and built by Authors. It enables us to make monitoring of input data, preliminary registration of selected AE signal parts in FIFO disk memory of PCI-610E measuring card, transmission of registered data (within frequency band up to 2.5 MHz in each from four measuring lines) introduced to disk memory of PC III Portable PFX-12 computer as well as advanced analysis of these signals in order to create chosen AE descriptors [11,12,16,17]. General view and block scheme of DEMA-COMP measuring system is presented in Fig. 3.

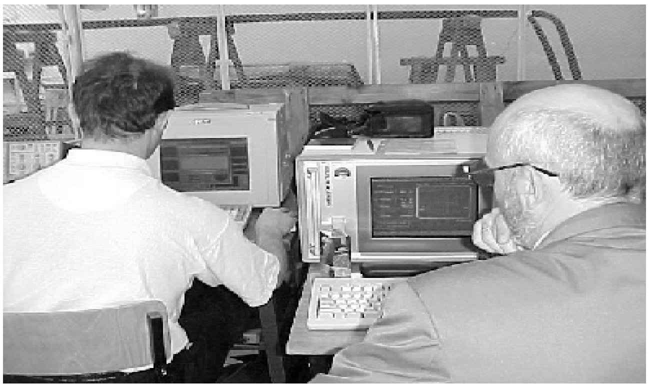

Fig.1. The measuring stand in the firm ENERGOSER-WIS (in Lubliniec) extended with PD analysing system TE 571 and DEMA-COMP measuring system

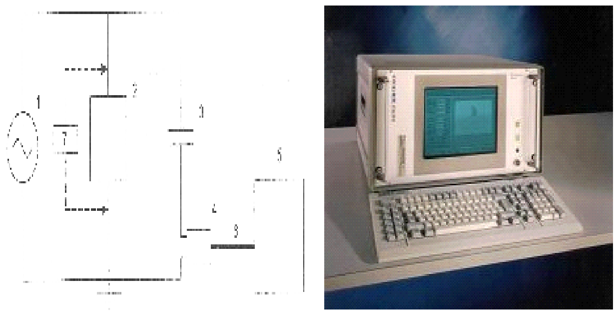

Fig.2 Block scheme of PD measuring system type TE 571 firm Haefely Trench: 1-PD source, 2-investigated object, 3-coupling condenser, 4-coupling qaudripole AKT 573, 5-"TE 571 system", 7-calibrator KAL 451 and view of PD measuring system.

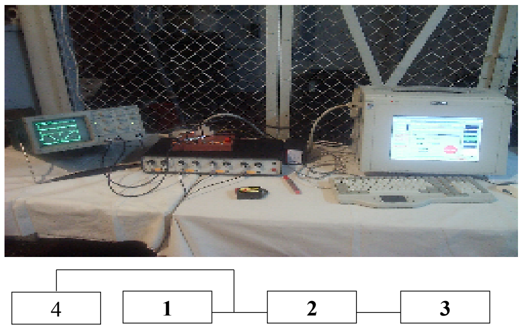

Fig.3. General view and block scheme of AE monitoring sys-tem DEMA-COMP: 1-set of DEMA instruments, 2–CB6-TP measuring terminal and PCI-610E measuring card, 3–PC III Portable PFX-12, 4–oscilloscope

Investigations carried out by means of electric method have been planned as follows:

a/ TE 571 system has been calibrated in charge units during the state without voltage and has been prepared to supply voltage measure in automatic mode;

b/ the tested bar has been energized by the voltage of selected values (5, 10, 15, 20, 25 and 30kV) for whose one sample of 120-seconds length PDs signals have been registered (this is the length of PDs signal which should be carry out according recommendations of the standard of analysis and TEAS modes);

Investigations carried out by means of AE method have been planned as follows:

a/ the measuring range accessible for AE measurements has been established within grooved part of the bar; in such a range, limited by additional earth electrodes, six measuring points (P1, P2, …, P6) have been uniformly displaced (Fig.4)

b/ the use of measuring lines:

- K0 line - monitoring of a reference voltage,
- K1, K2 and K3 lines – registering of AE signals - AE sensors of WD type and R6 type (made by the PAC), preamplifiers and DEMA (20dB amplification within DEMA);

c/ AE sensors (#1, #2, #3) have been placed at measuring points P1, P2, P3;

d/ the tested bar has been energized by the voltage of selected values (5, 10, 15, 20 ,25 and 30kV) for whose three to six samples of two-seconds length AE signals have been registered (sampling frequency of 1 MHz);

e/ AE sensors of R6 (#1,#2,#3) have been moved to the next measuring points ((P2, P3, P4), (P3, P4, P5), (P4, P5, P6), (P5, P6, P1), (P6, P1, P2) respectively) and all measurements were made again.

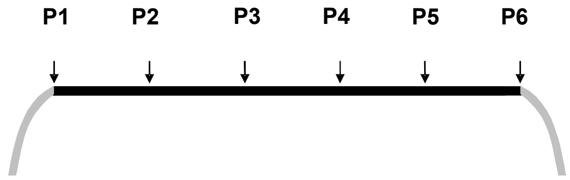

Fig.4 Arrangement of measuring points used in AE method during PD investigation in coil bars generator.

Bars of 120MW generator with U_N=13,8kV and 200MW generator with U_N=15,76kV were the domain of stydy. For each bar, measurements were carried out by means of both methods simultaneously.

The result of investigations together with their analysis for selected bar described as bar "D" (the bar of 120MW generator with U_N=13,8kV) are presented in the paper. Within the bar "D" are highly interesting PD sources which involve apparent charge with typical level of a few nanocoulombs but their apparent electric charge decreases with supply voltage increasing (see Table 1).

3. PD INVESTIGATIONS WITH AE METHOD

3.1. BASIC PROPERTIES OF AE SIGNALS

PD investigations within the bars were started with using both R6 type and WD type of AE sensor because their together frequency band is just as the frequency band of DEMA-COMP (20kHz-500kHz). Acoustic description of exemplary AE signal registered with measuring line with WD type AE sensor is presented in Fig.5. Each elements of that description is obtained after filtering of AE signal with 5-order band-pass filter (20kHz-500kHz). Figs.5c and 5d precise the dominant bands of AE signal as: (20kHz, 40kHz), 80kHz, 110kHz), 120kHz, 150kHz), 220kHz, 240kHz), and (270kHz, 290kHz).

We deal with real object, thus AE waves are damped during their propagation in the manner the damping is higher for waves with higher frequency. So the analysis of AE signal in higher band-pass should give more precisely location of PD sources as for higher frequency only AE waves coming from PD sources located in near neighbourhood of sensor reach the area where AE sensor is placed.

Figs.5 show the diagrams of different features, calculated from registered two-seconds length AE signals, versus supply voltage phase. Two maxima in diagrams from Fig.5b prove periodical property of AE signals. Two “corridors” of maxima in diagram from Fig.5a prove simultaneous periodical and random properties of AE signal. So Fig.5 prove AE impulses are generated twice during one period of the supply voltage but PD appearing time is random quantity, connected with local conditions of PD development.

AE signals properties depend on supply voltage values and measuring points thus planned and realized investigations give possibilities of deformational processes analysis and PD sources location.

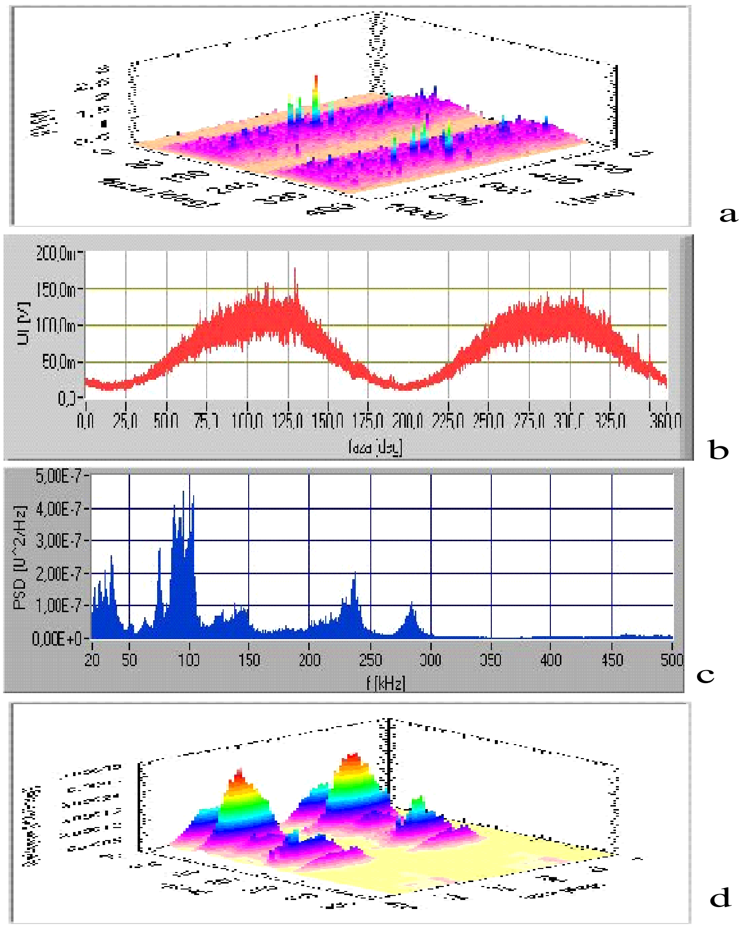

Fig.5 Acoustic description of AE signal registered in measuring conditions: bar „D”, 30 kV, 2 nC, measuring channel K3 (20 dB, WD), measuring point P1(a/ phase-time characteristic, b/ averaging phase characteristic, c/ frequency characteristic, d/ averaging STFT spectrogram).

3.2. AMPLITUDE DISTRIBUTIONS OF AE SIGNALS

Each of elements of analysed acoustic PD image can be a point of way out to a detailed analysis of AE signal properties. It has been demonstrated that amplitude distributions of AE signals, prepared to analyse their shapes, can be the basis of a detailed analysis – first of AE signal and then of AE source properties.

We have started from calculating the amplitude distribution for each registered AE signal. Amplitude distributions were calculated after filtering of AE signal with 5-order band-pass filter (150kHz-500kHz). Calculated AE distributions were grouped in the families for AE signal registered at PI measuring points.

Below we present quality analysis of amplitude distributions families calculated for AE signal registered at P2 and P4 points and quantity analysis for all measuring points made by means of two methods: definition of AE descriptors and application of neural network of Kohonen.

The amplitude distributions families for AE signals registered at P2 and P4 points are presented in Figs.6a and 7a respectively. They are amplitude distributions of AE signal power in discrimination threshold domain. The families describe the extreme types called by Authors as "simple distributions" (at P4) and "complex distributions" (at P2).

Within the framework of "simple distributions" the amplitude distribution calculated for different supply voltage form disjoint groups in the following manner: the more flat amplitude distribution curve is related with the higher supply voltage.

To distinguish quantitative features of AE impulses two descriptors, resultant from properties of amplitude distributions of AE impulses, have been proposed by Authors [8, 9]. These descriptors are signified by acronyms ACD and ADP. They are defined as the slope of straight line approximating the amplitude distribution of AE counts (ACD) and power of AE signals (ADP) The approximation is made within discrimination threshold range: the lower value of the range is treated as such discrimination threshold value when the first derivative of basic AE distribution reaches its minimum; the upper value is determined by 90% of maximum value of registered AE impulses. It is worth insisting on the following features of proposed descriptors:

- they are not connected directly with a measured quantity,
- logarithmic scale on diagrams of basic amplitude distributions brings about distinction of individual (single) deformational process and eliminate changes of thickness of interconnected layer (because of multiple assembly of AE sensors).
- The higher descriptor value (more flat fragment of a curve) signifies more advanced deformation process described by means of AE method [15-17]. Approximation curves

for "Simple distributions" curves from Fig.6a (see Fig.6c) have very good correlation factors σ=0,99.

The values of ADP descriptors (Fig.6b) increase with increasing supply voltage. It means the level of advance of deformational processes increases with supply voltage increasing. Families for AE signals registered at P6 point have similar properties.

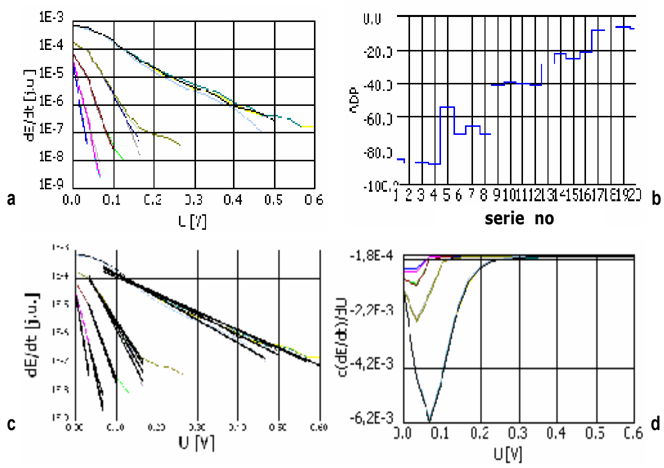

Fig.6.Features of amplitude distributions of AE signals power for a family sets (4 sets for each supply voltages 10, 15, 20, 25 and 30kV) registered in following measuring conditions: bar „D", measuring channel K3 (20dB, WD), measuring point P4, (a/ amplitude distributions, b/ ADP descriptors calculated for relevant files, c/ amplitude distributions with approximation curves d/ derivative of amplitude distribution of signal power).

"Complex distributions" (Fig.7a) point out different properties. It is impossible to separate the family into disjoint groups for different supply voltage. There are large fluctuations within the group calculated for selected supply voltage. Approximation curves have weak correlation factors σ=0,87. For supply voltage values 10, 15, 20, 25 and 30kV amplitude distributions are composed of two different "simple distributions". So, registered AE signals are generated by different PD sources with very different level of advance of deformational processes; What's more, for supply voltage values 10kV the level of advance of deformational processes is very high and doesn't change for supply voltage value 15, 20 and 25kV.

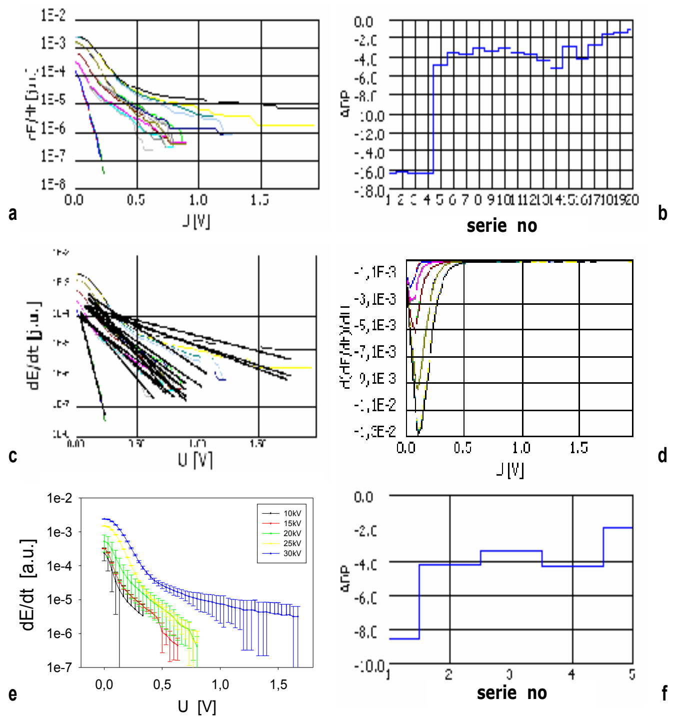

Fig.7 Features of amplitude distributions of AE signals power for a family sets (4 sets for each supply voltages 10, 15, 20, 25 and 30kV) registered in following m. conditions: bar „D", m.. channel K3 (20dB, WD), m.. point P2, (a/ amplitude distributions, b/ ADP descriptors calculated for relevant files, c/ amplitude distributions with approximation curves d/ derivative of amplitude distribution of signal power, e/ averaging amplitude distributions for supply voltages, f/ ADP descriptors for distributions from Fig.7e).

The quantity analysis includes all amplitude distributions for all measuring points and all supply voltage values. The amount of amplitude distributions is 144 because we have 6 measuring points with 6 different supply voltage values (0, 10, 15 20, 25 and 30kV) with 4 AE signal registered at each points with each supply voltage values. Amplitude distributions were calculated after filtering of AE signal with 5-order band-pass filter (150kHz-500kHz). The quantity analysis was made by means of two methods: definition of AE descriptors and application of neural network of Kohonen.

The analysis results for AE descriptors method are presented in Figs.8a and 9a. The ADP descriptors for all registered AE signals are in Fig.8a. Fig.9a shows the family of average ADP descriptors versus supply voltage values. Each of points on diagram denotes means value and standard deviation of ADP descriptors. One can see: - "simple distributions" pattern for AE signal registered at P4 and P6 measuring points, - "complex distributions" pattern for AE signal registered at P2 and intermediate pattern for AE signal registered at P5, P3 and P1 measuring points.

Amplitude distributions of AE impulses are images (built in domain of discrimination threshold values) for a considered neural network of Kohonen. Input vectors (learning data) for Kohonen network are built with four amplitude distributions of AE amplitudes in the following order: amplitude distributions of AE signal power, derivative of AE signal power, amplitude distributions of AE counts, derivative of AE counts. Values of amplitude distributions are features for Kohonen network. Single vector of features contains amplitude distributions calculated for a given measuring situations. The set of vectors of features describes all measuring family selected to analyse. Prepared data are scaled separately in each group of amplitude distributions. Such scaling keeps dependences occurring between particular measuring situations within one amplitude distributions and prepares images for neural network (every four amplitude distributions are equally important). Learning data prepared in such a way contains all features of amplitude distributions of registered 144 AE signals (the same as it was for AE descriptors method).

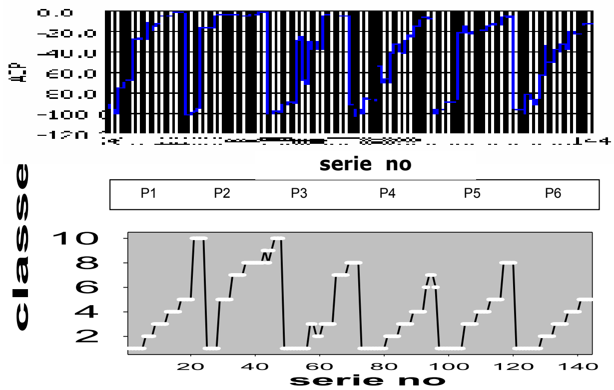

Fig.8 Statement of ADP descriptors and class assigned by Kohonen network for amplitude distribution of AE signals family registered at measuring points P1-P6 in the following measuring conditions: bar „D”, measuring channel K3 (20 dB, WD), analysis in the band 150-500 kHz; the family is composed with 144 AE signals – 24 signals for each measuring points (4 sets for each supply voltages 10, 15, 20, 25 and 30 kV)

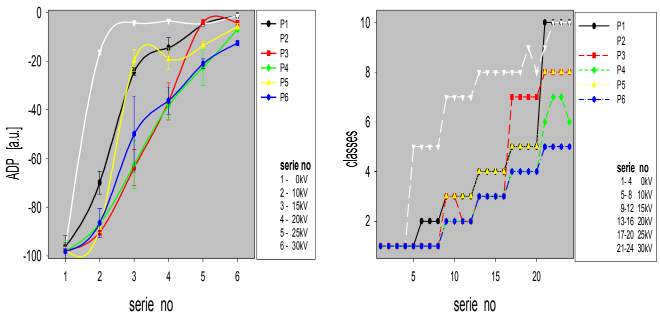

Fig.9 The families of ADP descriptors and classes assigned by Kohonena network for family from Fig.8 (for measuring points P1-P6 versus supply voltages for bar „D”, analysis in the band 150-500 kHz)

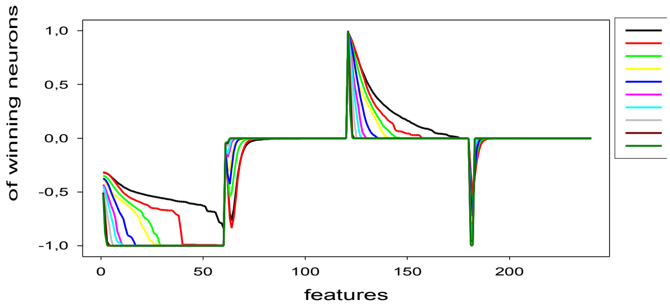

Fig.10 Winning neurons made by Kohonen network for family from Fig.8 (bar „D", measuring channel K3 (20 dB, WD), analysis in the band 150-500 kHz)

Kohonen network has been assigned a task to divide input objects into classes and construct pattern winner neurons. In order to better distinguish deformation processes, ten winning neurons have been searched. The wining neurons made by Kohonen network are presented in Fig.10. The results of classification the input vectors by built Kohonen network are presented in Fig.8b and 9b. It is worth to say that results given by Kohonen network method are more general in comparison with the results achieved with AE descriptor method. Comparison of diagrams from Figs. 9a and 9b show the similarity between the results of both methods: - "complex distributions" pattern for AE signal registered at P2, - "simple distributions" pattern for AE signal registered at P4 and P6 measuring points and intermediate pattern for AE signal registered at P5, P3 and P1 measuring points.

3.3. LOCATION OF PD SOURCES

AE signals are damped during their propagation, so amplitude of AE signals are "weighted" with due regard for the propagation path. With the view of doing the location we construct the families of amplitude distribution of AE signals registered at all measuring points for the same supply voltages. In each family AE signals have the same "weighting". Within each family the most advanced level of deformational processes or the highest class given by Kohonen network localize PD source with maximum activity. The above method of PD source location is called by author as "location by means of calculating the level of deformational processes"

3.3.1. AE DESCRIPTOR METHOD

Descriptors from Fig.9a are grouped into families depending on supply voltage values. They locally describe deformation processes, so within one family the maximum descriptor value locates PD sources with maximum activity. Statement of sources positions with maximum activity is following:

a/ for 10kV supply voltage family – PD source with maximum activity is located near P2 measuring point,

b/ for 15 and 20kV supply voltage families – the source located near P2 measuring points is still working, but there is another source located near P5 measuring point,

c/ for 25 and 30kV supply voltage families – both sources from are still located near P2 and P5 measuring points, but within family the difference between maximum and minimum is smaller (in comparison with the families for 15 or 20kV supply voltage).

Detailed analysis show that: - for 10kV supply voltage the AE signal are registered mainly in P2 measuring point, - for 15kV supply voltage the AE signal are registered mainly in P2 and P5 measuring points, - for higher supply voltage values AE signals are registered in all measuring points. For higher supply voltage values the power of AE signal is higher and AE waves generated within PD source are registered at many measuring points. We still have possibility to find local maximum within family because the amplitude of AE waves is "weighting" with due regard for the propagation path.

3.3.2. KOHONEN NETWORK METHOD

The families from Fig.9b were reconstructed to obtain the families of classes given by Kohonen network for amplitude distributions of AE signals registered at all measuring points for the same supply voltages. The results are presented in Fig.12 where each family contains 24 elements (4 sets for each measuring points). Statement of sources positions with maximum activity is following:

a/ all amplitude distributions of noises within measuring line have class 1,

b/ for 10kV supply voltage family – PD source with maximum activity is located near P2 measuring point,

b/ for 15 and 20kV supply voltage families – the source located near P2 measuring points is still working, but there is another source located near P5 measuring point,

/ for 25 and 30kV supply voltage families – both sources from are still located near P2 and P5 measuring points.

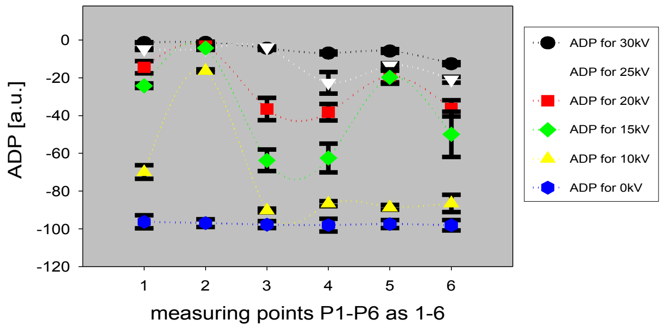

Fig.11 Families of AE descriptors (for AE signals registered by WD sensor at measuring points P1-P6, analysis in the band 150-500 kHz) for different values of applied voltage: bar „D", (maximum within family locates PD source with maximum activity)

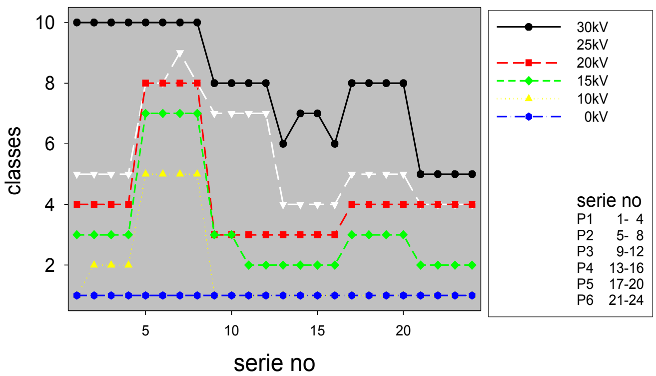

Fig.12 Classification results of input vectors (for AE signals registered with WD sensor at measuring points P1-P6, analysis in band 150-500 kHz) for different values of applied voltage: bar „D (maximum within family for each applied voltage locates PD source with maximum activity).

3.3.3. RECAPITULATION

Both methods give the same results for location PD source with maximum activity:

a/ the main source is located near P2 measuring point (we describe this source as S1),

b/ the second PD source appears near P5 measuring point beginning from 15kV supply voltage (we describe this source as S2).

The properties of AE signals generated by source are following (Figs. 13 and 14):

Source S1

1. averaging phase characteristic: trapezoid shape, amplitude and shape asymmetry within both half cycles of the supply voltage,
2. asymmetry within averaging STFT spectrograms,
3. frequency band: the main (230kHz, 240kHz), other (205kHz, 210kHz).

Source S2

4. averaging phase characteristic: gaussian shape, amplitude and shape symmetry within both half cycles of the supply voltage,
5. symmetry within averaging STFT spectrograms,
6. frequency band: the main (230kHz, 240kHz), other (280kHz, 290kHz).

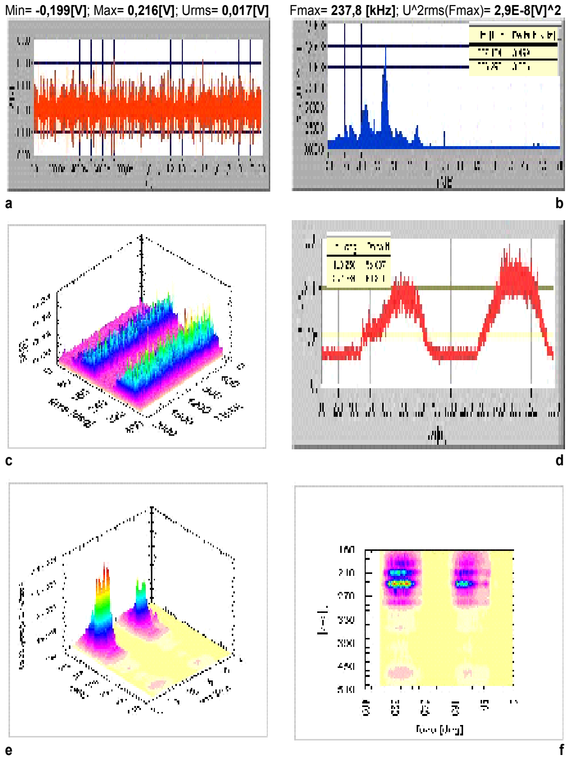

Fig.13 Acoustic description of the AE signal (a/ impulse, b/ frequency characteristic, c/ phase-time characteristic, d/ averaging phase characteristic, e/,f/ averaging STFT spectrograms) recorded in measuring conditions: bar „D", 11.8 kV, 3.8 nC, measuring channel K3 (20 dB, WD, measuring point P2; (S1 source).

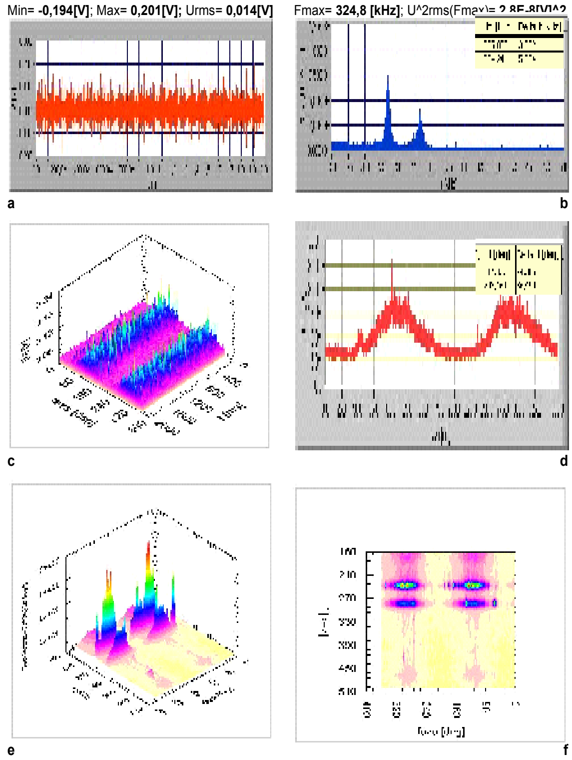

Fig.14 Acoustic description of the AE signal (a/ impulse, b/ frequency characteristic, c/ phase-time characteristic, d/ averaging phase characteristic, e/,f/ averaging STFT spectrograms) recorded in measuring conditions: bar „D", 20.5kV, 2.2 nC, measuring channel K3 (20 dB, WD, measuring point P5; (S2 source).

4. UNIFIED ELECTRO-ACOUSTIC METHOD

Unified electro-acoustic method PD investigation within bars assigned for generators coils proposed in paper [14] consist in parallel utilisation:

– the electric method (to characterize kind and parameters of Pds),
– the AE method (to measure intensity and location of Pds),
– both methods (to mutual verify obtained results).

Electric method gives apparent electric charge and character of discharges determined with professional diagnostic program TEAS.

Acoustic emission method gives location of PD sources and description of deformational processes in the way described in the paper.

Setting-up of PD investigation results obtained by means electric and AE methods for tested bar described as bar “D” (the bar of 120MW generator with U_N=13,8kV) are presented in Table 1.

Measuring method	U kV	q [nC] ADP[a.u.]	The results of analysis
Electric	10	3,5	cavity; fissure, HV electrode (with probability 0,57)
Acoustic		-16,3	S1 source near P2 measuring point
Electric	15	3,8	cavity; fissure, HV electrode (0,41) cavities: LV electrode-bouded (0,21) cavities:, dielectric-bounded (0,15)
Acoustic		-4,2	S1, S2 sources near P2 and P5 measuring points the level of ADP descriptor
Electric	20	2,2	cavity; fissure, HV electrode (0,39)
Acoustic		-3,3	S1, S2 sources near P2 and P5 measuring points
Electric	25	2,2	cavity; fissure, HV electrode (0,44)
Acoustic		-4,0	S1, S2 sources near P2 and P5 measuring points
Electric	30	2,0	cavity; fissure, HV electrode (0,86)
Acoustic		-1,3	S1, S2 sources near P2 and P5 measuring points

Tab. 1. Setting-up of PD investigation results obtained by means electric and AE methods

Electric method demonstrates the following properties of PDs occurring within tested object:

- PDs occur in inclusions located near HV electrode (for all supply voltage values),
- PDs occur in inclusions located near earthed electrode and inside insulating material for 15kV of supply voltage),
- apparent electric charge involved by PDs sources achieves the maximum value for 15kV of supply voltage and then decreases with increasing of supply voltage value.

Acoustic emission method:

- locates main PDs sources near P2 measuring point (for all supply voltage values),
- locates additional PDs sources near P5 measuring point (for 15kV and higher values of supply voltage),
- deformational processes occurring near P2 measuring point have complex pattern and produce above- mentioned dependence of apparent electric charge versus supply voltage.

The results coming from electric and AE method are compatible and give more general description of PDs within tested object.

5. CONCLUSION

In the paper are presented:

- acoustic description of registered AE signals,
- detailed analysis of shapes of amplitude distributions of AE signals,
- unified electro-acoustic method of PD investigation within tested bar assigned for geneator coil.

Detailed analysis of shapes of amplitude distributions of AE signals (made by means of two methods: definition of AE descriptors and application of neural network of Kohonen):

- gives new possibility for deformational processes analysis,
- is the base for new method location of PD sources defined in the paper and called as "location by means of calculating the level of deformational processes".

Unified electro-acoustic method of PD investigation within tested bar assigned for generator coil give more general description of PDs within tested object. Connection of proposed capacities of acoustic and electric method enhances considerable quality of information about PD sources and reduces the risk of results misinterpretation coming only from one measuring method.

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