ASSESSMENT OF UTILITY OF THE CORONA AUDIBLE SIGNAL IN THE DIAGNOSTIC PROCESS OF THE TECHNICAL CONDITION OF UHV TRANSMISSION LINES

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The paper deals with application of neural network techniques to recognition of typical damages of the transmission circuit elements in UHV power lines. The damage indicator is the acoustic signal generated by the corona effect, the intensity of which increases as a result of damage or contamination of the conductor surface. The primary difficulty in the diagnostic process is the necessity to distinguish between the signals generated by the surface damages and contaminations. The problem can not be solved neither by the analysis of RF interference signal nor by the classical methods of the acoustic signal analysis.

Particular attention has been focused on the parametrization of the acoustic signal of corona effect and selection of distinctive features, which could be useful in distinguishment of the origins of the increased corona effect in dry conductor surface conditions. For that task the aggregation analysis has been applied, in particular the possibilities offered by "Statistica"$^{\circledR}$ software package. The data used in the analysis has been obtained from laboratory studies in Institute of Power Engineering in Warsaw, where typical surface damages and contaminations of the transmission line elements have been simulated.

Keywords: corona noise, diagnosis, acoustics, cluster analysis, neural network.

1. Introduction

The noise generated by the corona effect near a working UHV transmission line is observed when the value of electric field E at the surface of a conductor or any other transmission circuit element is higher than a critical value E_0. In such a situation the micro-discharge phenomena occur, which, in addition to the noise, also generate other adverse phenomena like RF interference, conductor vibrations, ozone and nitrogen oxides production.

In general the lines are designed in such a way, that the maximum value of E varies in the range between 14 and 18 kV/cm, while the critical field value E_0 in fair weather

conditions locates in the range 19–20 kV/cm. In bad weather conditions the critical value may drop down even below 12 kV/cm. This is because the critical value E_0 depends not only on the line's design parameters but also on the ambient conditions and the technical state of the transmission line elements. In bad weather conditions (rain, drizzle, fog, wet snow) the intensity of corona effect increases as a result of the presence of water droplets at the conductor surface and because of increased humidity and air ionization. In dry conditions practically the only source of the corona effects are inhomogeneities on the surface of conducting elements. The presence of these inhomogeneities, and thus also the corona effect, may result from contaminations as well as surface damages on the conductors, isolators etc. [1]. Therefore the studies of the corona effects intensity in fair weather conditions may be helpful in evaluation of the technical condition of the transmission line elements.

The effect of the conductor surface condition on the intensity of corona process has been analyzed in many works, including the Project UHV works [4]. In those works the conductors aging effects have been mainly studied. The surface of a new conductors is completely greased – thus the water droplets distribute evenly on the whole surface. After some aging time the surface exhibits local degreased areas, similar to the results of detergent application and then the water droplets become big and concentrate below the conductor. Such a change in their behavior considerably affects the intensity and nature of the corona effect, particularly in the increased air humidity, drizzle or fog conditions as well as in the "after rain" periods. On the other hand in fair weather conditions, when the conductors are dry, the reasons of increased corona effects may be various surface defects, independent of the conductor's age.

Among the methods presently applied for detection of the line damages are the measurement of RF interference signal and application of special video cameras, able to visualize the corona discharge even during daytime. However it should be mentioned that the acoustic signal is usually the first symptom detected during the line inspections. The RF interference signal measurement in real field conditions is rather difficult for practical realization, while the necessary video cameras are very expensive. Therefore the possibility of using the acoustic signal as the symptom of line damage seems very attractive. The primary difficulty in the utilization of acoustic signal is the problem of proper attribution of the signal to its original source – i.e. finding the answer to the question: what type of damage or surface contamination is responsible for the increase of the corona effects. Another problem is the contribution from the environmental background signal, which is usually enhanced in the fair weather conditions. The methods based on the measurement of RF interference cannot distinguish between the surface damages and contaminations either, but they do not have to cope with the environmental background signal.

Preliminary studies carried out during the previous research project [6] have shown, that in some conditions there is a possibility of distinguishing between the sources of increased corona effect by application of artificial neural network methods. In order to increase the number of correct recognitions, and on the other hand to promote the applications of the elaborated neural models in real conditions, some additional experimental

studies have been carried out in laboratory conditions. It has lead to considerable enlargement of the database of results and in particular to improved determination of the vector of distinctive features, useful in the process of diagnosing the technical condition of the conductors.

The experimental studies in laboratory conditions have been carried out in Institute of Power Engineering in Warsaw (Poland), where various types of contaminations and typical damages of the conductors encountered in real conditions (scratches, delaminations) have been simulated. The applied conductor types and fittings were of original size used in 400 kV AC lines laid out in Poland.

In the analysis of the research results the main attention has been focused on the extraction of characteristic parameters of the corona acoustic signal, which could be regarded as insensitive to the external disturbances present both in the laboratory and environmental conditions. The tool used for assistance in the selection of the distinctive features of the studied phenomenon was the cluster analysis, realized in the "Statistica" software package.

2. General conditions of the study

The noise spectra observed during intense corona process are dominated by a broadband noise component, however also the tonal components, being the harmonics of the network frequency, are also observed. The broadband component origins from acoustic waves generated at random along the conductor. The tonal components are generated as a result of the ordered ion movements in the space surrounding the conductor and periodic discharge processes in the positive and negative half-periods.

In the corona process several phases can be distinguished, depending on the type of surface and voltage value, characterized by certain features in the RF interference signal, in the acoustic signal and even in the shape of the discharge cloud (the light effect of the discharge) [4]. In order to distinguish these features in the acoustic signal in the experimental studies the applied voltage has been varied in wide range of values, for various types and technical conditions of the surface of the transmission line elements. The examples of acoustic signal spectra measured in the initial phase of the intense corona process, for various surface conditions have been shown in Fig. 1.

The identification of the corona spectrum features in the measured acoustic signal does not present any serious difficulties, even in the conditions of enhanced noise level from the acoustic background [5]. The measurements carried out in the laboratory conditions have shown that the measurement of spectral components above 20 kHz [2] is particularly useful, because for these components high correlation with the RF interference signal has been found (see Fig. 2). Furthermore the high frequency components exhibit rather low intensity levels in the environmental noise.

In the spectra shown in Fig. 1 it can be noticed that there are some differences in the envelope curves, depending on the type of surface deformation. The differences can be noticed both in the tonal and noise components of the spectra. It can be also noticed
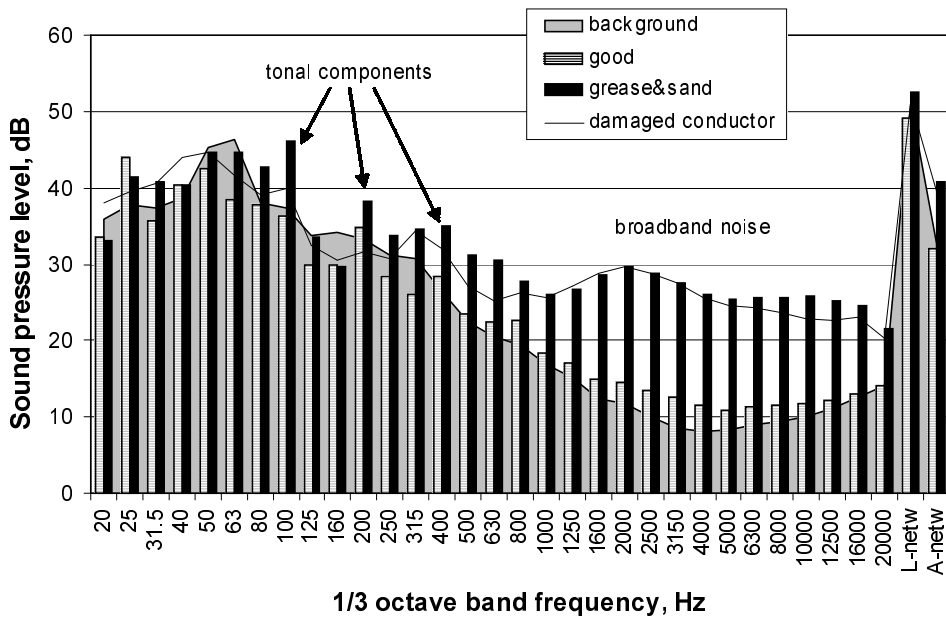
Fig. 1. Examples of acoustic spectra measured in the initial phase of corona process for the cases of clean, polluted and damaged conductor surface.
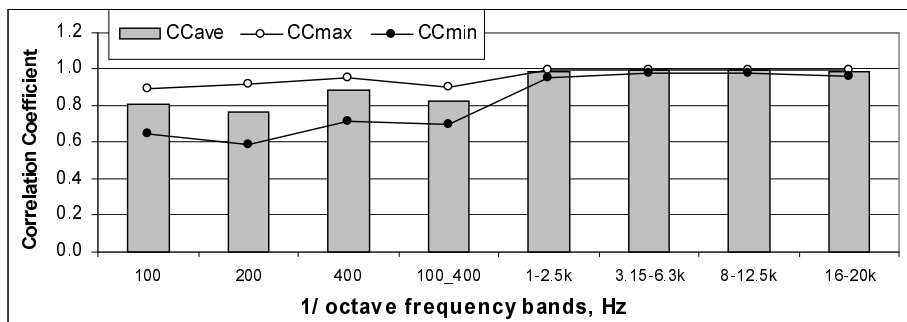

Fig. 2. Dependence of average values (bars) and the maximal and minimal values of the correlation coefficient between the acoustic signal of corona effect and RF interference signal in the range of tonal components 100, 200, 400 Hz (and their sum in the 100–400 Hz range) and the noise components in four frequency bands 1–2.5 kHz, 3.15–6.3 kHz, 8–12 kHz and 16–20 kHz.

that in the noise part of the spectra the signal distance from the acoustic background is the highest.

The tonal components, however easily distinguished in the spectra, are difficult to measure because of the environmental noise in the low frequency range and high fluctuations of these components in time and space [3]. In the environmental noise there are also components, which contribute to the high frequency part e.g. the voices of singing

birds, but they are mostly localized below 8 kHz [6]. Therefore the 8 kHz component, treated in many works as the best correlated with the A weighted level, is not always the best symptom for identification of acoustic signal of corona process. In the laboratory studies [6] the 10 kHz component exhibited somewhat better correlation with the RF interference signal therefore it can be assumed that also in the environmental conditions that component will be a good symptom of the process. However in the diagnostic procedure carried out with application of neural networks both the tonal (100, 200 and 400 Hz) and the noise components (1 to 20 kHz), best correlated with the RF interference signal, have been used. A working hypothesis has been assumed (based on the physical features of the corona effect), that in the noise component frequency range there are also some characteristic features, which after extraction can be used for distinguishing between the damages and contamination of the conductor surface.

3. Experimental studies

The measurements were carried out in laboratory conditions in the Institute of Power Engineering in Warsaw, where contaminations and typical surface damages encountered in real conditions (scratches, delaminations) have been simulated for a double and triple circuit line with original dimensions. The damages and contaminations of the conductor surface were distinct, even sometimes overdone, however they were always contained in a selected conductor section, which was 1–3 m meters in length. The studied voltage range covered the transition from the corona-free phase (low voltage) to intense corona phase (high voltage). In order to eliminate any external disturbances the supply voltage has been connected using hollow conductors of considerable diameter (so called corona-free conductors).

The list of experimental conditions and the conductor's damage and contamination descriptions can be found in the Table 1 and 2.

Table 1.

No.	Type of conductor damage	Voltage range, kV	Conductor layout
1	A single wire wrapped around the conductor section of 1m length	130–300	1×525
2	Single wire wrapped around, section of 3m length	150–350	3×350
3	Foreign matter on the conductor	150–350	3×350
4	Conductor surface filed off and local delamination	150–350	3×350
5	Pins inserted into the conductor – 15 pins at section length 1.5 m	130–300	1×525
6	Fuzzy conductor surface	150–350	3×350
7	One wire cut, but not uncoiled	140–300	1×525
8	Grinding of the conductor	100–300	1×525
9	One wire cut and uncoiled	80–300	1×525

Table 2.

No.	Type of conductor surface contamination	Voltage range, kV	Conductor layout
1	Conductor greased with cup grease at section length of 3 m	150–350	3×350
2	Conductor greased with cup grease with file dust – length 3 m	150–350	3×350
3	Conductor greased with cup grease with fine sand – length 3 m	150–350	3×350
4	Conductor greased with cup grease with coarse sand – length 3 m	150–350	3×350
5	Grease + fine sand at the surface – length 1.5 m	130–300	1×525
6	Grease + sawdust at the surface – length 1.5 m	130–300	1×525
7	Grease + poplar seed fluff	130–300	1×525

In the laboratory conditions the primary device for measurements of the acoustic signal was a Norsonic RTA840 double-channel analyzer, accompanied by a system for measurement of RF interference level. The measurements of the acoustic and interference signal have been carried out concurrently. The acoustic signal was measured in 1/3 and 1/12 bands in the range from 20 Hz to 20 kHz, while the interference signal was measured in 0.5 MHz frequency band.

The measurements have been carried out for undamaged (clean) conductor and nine types of simulated various types of damages and contaminations of the conductor surface.

Photo documentation of selected damages and contaminations of conductors can be seen in Fig. 3.

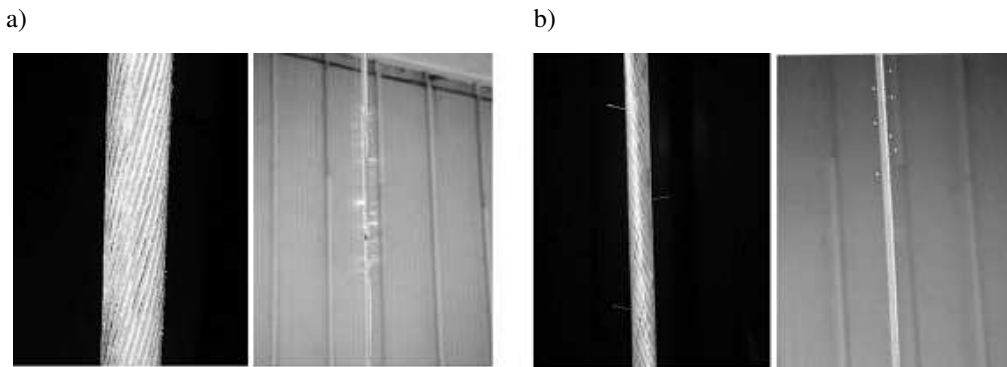a)   b)

Fig. 3. Photos of a conductor covered by grease and quartz sand (a) and with surface damaged by inserted pins (b). The images on the right show the visible light effects of the corona discharge.

The plots of average levels of the acoustic pressure, in bands best correlated with the RF interference, are shown in Fig. 4.

The plots shown in Fig. 5 exhibit some differences in the acoustic pressure curves in the noise and tonal components bands for the cases of surface damages and contamina-

Frequency band, Hz	100	200	400	100_400	1-2.5k	3.15-6.3k	8-12.5k	16-20k
Correlation	0.86	0.92	0.95	0.89	0.99	0.99	1.00	1.00

Reference levels:
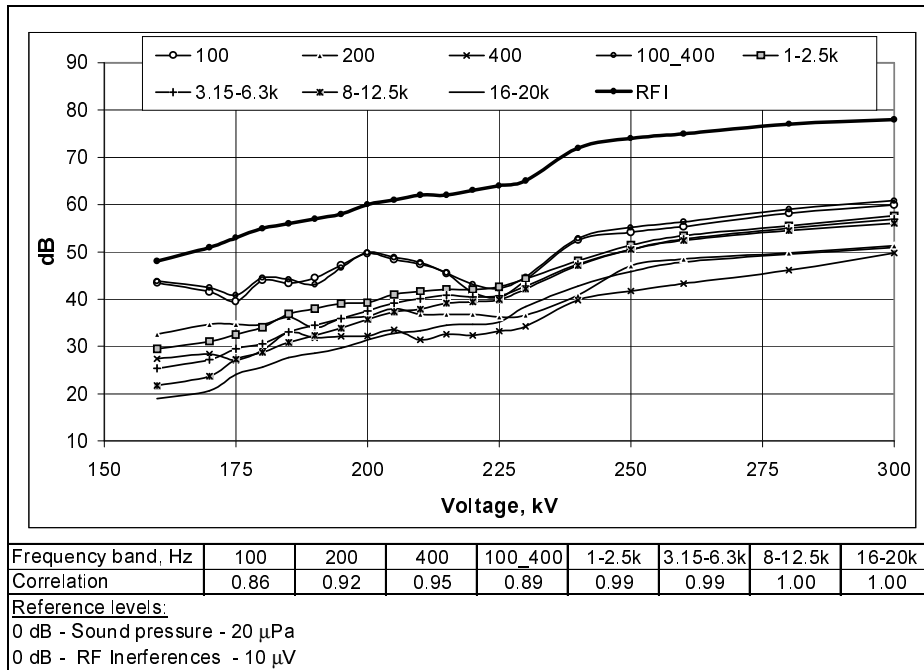0 dB - Sound pressure - 20 µPa
0 dB - RF Inerferences - 10 µV

Fig. 4. The dependence of selected components of the acoustic signal on the working voltage. The conductor with inserted pins.
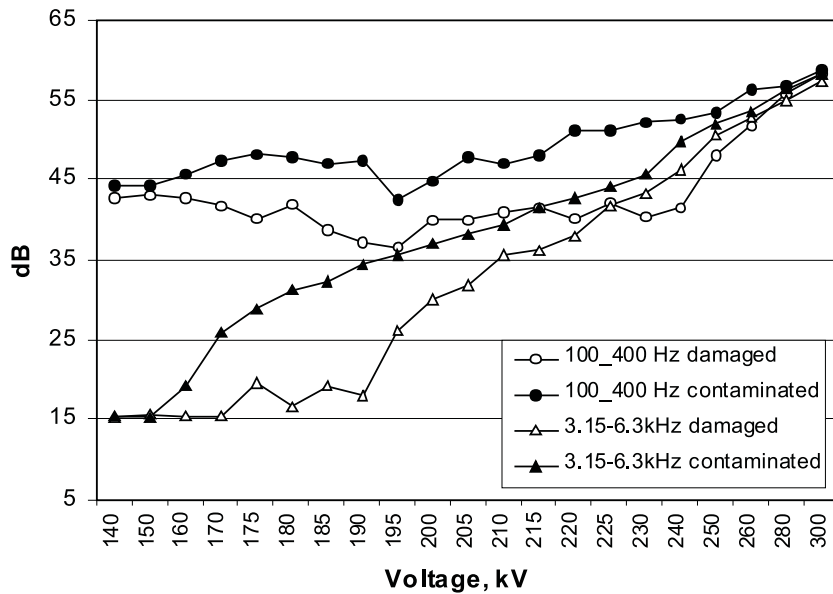

Fig. 5. The plots of tonal and noise components for the case of conductor damage (wire wound around) and contamination (grease + sawdust).

tions. The differences are more noticeable in the middle voltage range i.e. in the initial phase of the corona effect. Both in the low voltage range (when the corona effect is absent) and in the high voltage range (corona effect is observed on the whole surface of the conductor) the differences between curves are hardly visible. The results confirm the previously noticed [5, 6] tendencies in the distribution of the spectral energy density for the acoustic signal of corona effect, dependent on the origins of the process.

4. Vector of distinctive features for the corona noise

The above–mentioned characteristic features of the corona acoustic signal are yet too subtle to allow the distinguishment of origins of the enhanced intensity corona process in real conditions by application of classical analysis methods. Therefore it is difficult to come to definite conclusions concerning the possible conductor damages, not even mentioning the distinguishment of their types. Therefore the artificial neural network technique has been applied as a tool assisting in the process of recognizing the origins of the enhanced corona effects in fair weather conditions [5]. The acoustic signal of the corona effect has been parametrized, with special attention focused on the quality of the feature vector selection.

For construction of the feature vector the essential features of both static X1 and dynamic X2 spectra of the corona noise signal have been used, defined as follows:

$$\langle f_1, f_2, \ldots, f_6 \rangle = X1,$$

where f_i – averaged values in the i-th frequency band: 100, 200 and 400 Hz in 1/3 octave bands and 1–2.5, 3.15–6.3, 8–12.5 and 16–20 kHz, dB

$$\langle M_0, M_1, M_2 \rangle = X2,$$

where M_0, M_1 and M_2 – moments of the respective components in the spectrum frequency bands.

$$M_0(j) = \sum_{i=f_d}^{i=f_g} w_j^i \quad - \quad \text{0-th moment of the spectrum,}$$

where f_d, f_g – denote respectively the frequencies of the lower and upper 1/3 octave band, $w(i, j)$ – acoustic pressure level for the i-th band, j-th time interval.

$$M_1(j) = \frac{\sum\limits_{i=f_d}^{i=f_g} w_j^i \cdot i}{M_0(j)} \quad - \quad \text{weighted average frequency,}$$

$$M_2(j) = \sqrt{\frac{\sum\limits_{i=f_d}^{i=f_g} w_j^i \cdot i^2}{M_0(j)} - M_1^2(j)} \quad - \quad \text{dispersion of the spectrum.}$$

The obtained vector of features has been subject to aggregation analysis for selection of data possibly useful in the construction of the neural model, and on the other hand for rejection of the equivalent or useless data. In the first stage the agglomeration of individual cases has been carried out, irrespective of the working voltage applied to the conductor. This has been done in order to reveal the cases, in which the signal was too low, hardly distinguishable from the background, and the cases (in the high voltage range), where the saturation effect occurs – i.e. the further increase of the applied voltage does not result in the increased intensity of corona process.

In the cluster plot shown in Fig. 6 three primary groups can be distinguished:

Group one: the objects are grouped with the background cases. These objects have been rejected from further analysis, because the corona effect was negligible or was completely absent.

Group two: the data in the middle range (marked by the envelope frame). Clearly distinguished from the background and the other groups of signals. They can be attributed to the initial phase of the corona process, therefore it is highly probable that the respective effects take place near the damaged parts of the conductor.

Group three: the signal has been obtained for high working voltage. It is clearly distinct from the other two groups. In that voltage range the corona effect takes place irrespectively of the conductor's condition and practically along its whole length. The data has been classified as completely useless for further analyses.
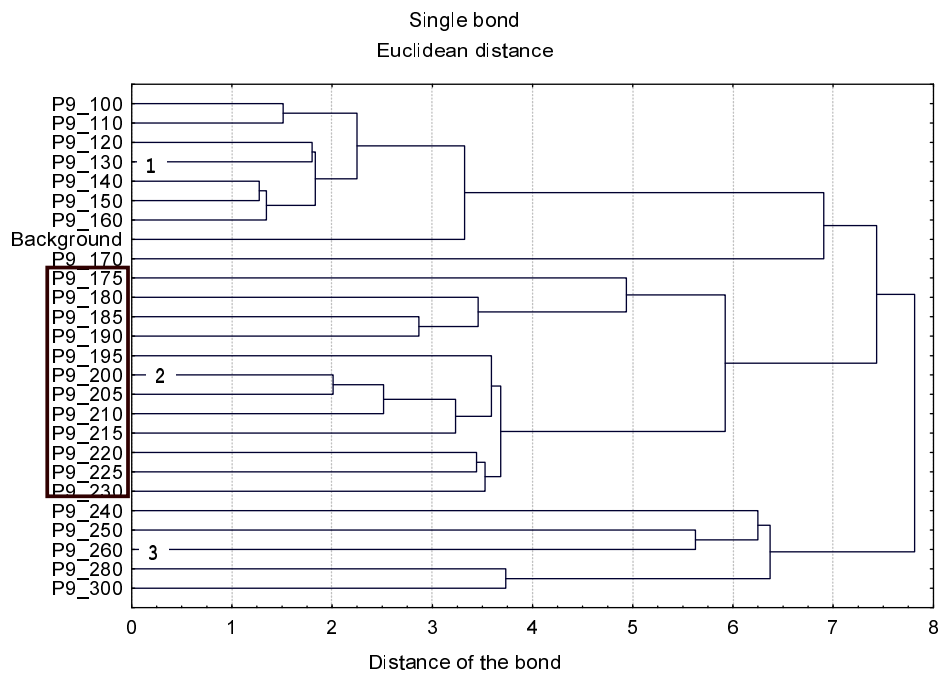

Fig. 6. Cluster analysis. Damage of a single wire in the conductor. The wire sticks out from the conductor surface (item 9 in Table 1).
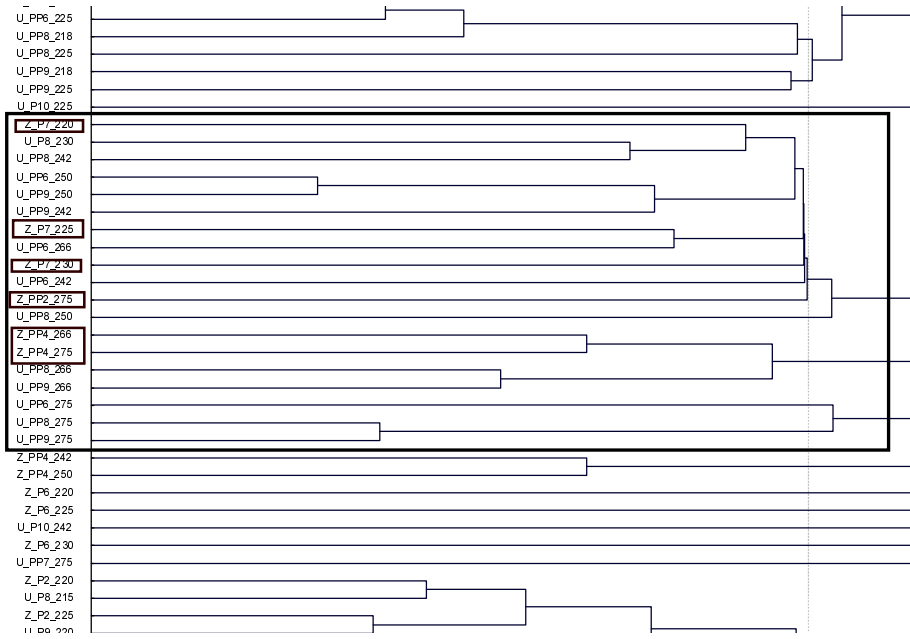
Fig. 7. Part of the agglomeration plot with an exemplary contents of contradictory data (in the small box), within the whole group enveloped by the big frame.
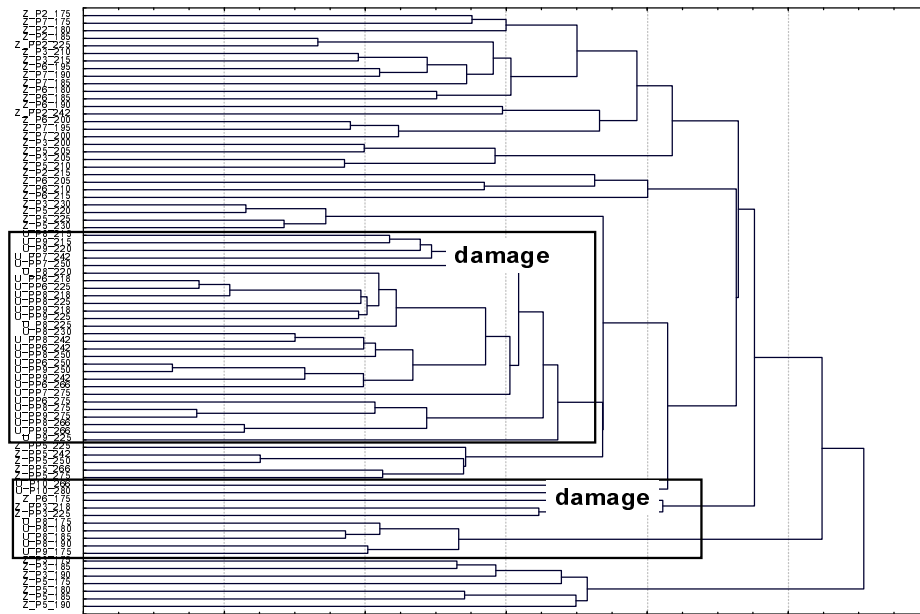

Fig. 8. The final shape of agglomeration of the data set selected for construction of the neural network model for construction of the system for diagnosing the technical condition of the conductor surface in UHV transmission lines.

Figure 7 presents a zoomed selection from the collective agglomeration (all the cases – damaged and contaminated conductors together with the data from the study carried out in 1999 [6]). It can be notices that not all the objects grouped into one cluster belong to the same class (the, "u" symbol in front of the case number denotes the damage cases, while the symbol "z" denotes the contamination). Among the cases described as damage there are cases labeled as contamination (located within the border frame). They are much less frequent, therefore they have been qualified for removal. In such a way the pure branch of objects describing the damage cases has been obtained. The other grouped agglomerations have been treated by the same procedure. In order to avoid possible selection errors (accidental qualification of cases to the wrong groups) the whole cleaning process has been repeated several times.

5. Conclusions

The considered problem of the recognition of conductor damages in the overhead UHV transmission lines by application of neural networks exhibits both diagnostic and ecological aspect, related to the prediction of possible environmental hazards.

High correlation of the noise component of the acoustic signal with the RF interference signal indicates great utility of the method in recognition of corona effects origins on the elements of UHV transmission lines.

In the spectral structures of the signal multi-varied distribution of the spectral density can be noticed both in the tonal component and the noise component frequency range, dependent on various factors initiating the corona effect in dry surface conditions. That observation enabled the selection and grouping of features of the acoustic signal of corona effect, which are characteristic for damaged and contaminated conductor surfaces.

The aggregation analysis turned out to be particularly useful in elimination of contradictory and useless data in the data set selected for construction of the neural network model.

For the cases of low intensity corona effect (low voltages) or very intense corona effects (high voltages) the data could not be grouped, therefore they cannot be useful in the process of diagnosing the technical condition of the conductor surface.

The presented results indicate a possibility of constructing a system for diagnosing the UHV line damages, with application of the acoustic signal of corona effect, as a system alternative or accompanying the systems based on the measurement of RF interference, particularly in the task of distinguishing between the cases of conductor surface damage and contaminations.

Acknowledgment

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