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ANALYSIS OF PARAMETERS INFLUENCING THE NOISE EMITTED BY HIGH-VOLTAGE POWER TRANSMISSION LINES

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The paper deals with the phenomena of the noise emitted by high voltage overhead power transmission lines. It contains an analysis of technical parameters of the transmission line: voltage, voltage gradient, configuration as well as technical conditions of the bundle of conductors. Test results for various weather and environmental conditions have been presented, and their influence upon the level and character of the emitted noise spectrum has been discussed. The atmospheric conditions have been pointed out which essentially influence the acoustic climate of the environment. Special attention has been paid to the noise emitted during intensive corona effect, and to the second harmonic of the power transmission line which appears then in the acoustic spectrum.

1. Introduction

The problem of noise emitted by overhead transmission lines of alternating current exists under bad atmospheric conditions only. Level of the emitted noise can then increase even by 15 dB or more and reach a value exceeding 50 dB [1]. In the noise emitted by an operating transmission line two characteristic components can be distinguished: 1) broad-band noise described alternatively as the sound of "frying" or "crackling" or "hissing" [6] and 2) a pure tone of the second harmonic of the transmission line frequency, being heard as a "hum". Broad-band noise is produced by electric discharges on the surface of the lines. Hum noise is generated by the discharge frequency of the given source. It appears in the case of regular discharges and makes the line noise arduous. Bad atmospheric conditions, such as rain, drizzle, snow and considerable humidity reduces the threshold of microdischarges.

An operating transmission line is a source of numerous nuisances for the environment (radio and television interference, ionization of air), but the most troublesome of them is noise, its effecting range being the greatest. It is now treated as the main nuisance in designing new transmission lines of alternating [7] and direct current, particularly in the countries a high degree of urbanization.

2. Sources of noise emitted by transmission line

Noise emitted by high voltage transmission lines is directly connected with the phenomenon of corona effect. When the voltage surface gradient of the line exceeds the critical value, called also "rupture gradient", random microdischarges occur. Each of them generates an acoustic wave, causes radio and television interference and loss of electric power.

According to Peek, the loss of active power due to the corona effect can be expressed by the following formula (for $f = 50$ Hz and $\delta = 1$):

$$\Delta P = 0.18 \sqrt{\frac{r}{b_{\mathrm{av}}}} \left(U_f - U_{\mathrm{cr}}\right)^2.$$

In practice these losses are of the order of several kW/km to dozens kW/km in the case of the transmission lines of voltage exceeding 1.000 kV.

The critical value of the voltage gradient is strictly dependent upon the phase critical value of the line u_{cr}, which can be expressed by the following formula:

$$U_{\mathrm{cr}} = 48.9\, m_a\, m_p\, \delta\, r \log \frac{b_{\mathrm{av}}}{r},$$

where U_{cr} — critical phase voltage of the line kV, m_a — coefficient dependent upon wheather conditions, ranging within the limits from 0.8 to 1 for bad and fair weather, respectively, m_p — coefficient dependent upon the state of the surface of the conductor, δ — relative air density, r — radius of the conductor for the bundle conductors an effective radius, [cm], b_{av} — average geometrical distance between the individual conductors, [cm].

The number of the microdischarges depends upon:

— technical parameters of the line (the voltage and voltage surface gradient of the conductors, design of the bundle of conductors, surface condition, etc.),

— atmospheric conditions,

— environment conditions (dirt covering the conductor surface, impurities of air, etc.).

Technical parameters of the line determine the voltage surface gradient of the conductor, whose maximum value determines, in turn, the corona effect intensity. It can be calculated from the following relationship [3]:

$$E = \frac{U}{\sqrt{3}\; nr \ln \dfrac{b_{\mathrm{av}}}{\sqrt[n]{rc^{n-1}}}} \left[1 + \frac{c}{r}\left[2(n-1)\sin\frac{\pi}{n}\right]\right],$$

where E — voltage surface gradient of the conductor, [kV/cm], U — line-to-line voltage, [kV], r — conductor bundle radius, [cm], n — number of the conductors in a bundle, c — distance between adjacent sub-conductors in the bundle, [cm], b_{av} — average distance between the adjacent conductors, [cm].

As it may be seen from the relationship given above, the voltage gradient depends directly upon the voltage and geometry of the bundle of sub-conductors. It increases with increasing voltage and decreases with increasing both the number of the sub-conductors and the effective bundle radius. Formulating the calculation procedures in order to predict the noise level, the research centres assume various forms of relationships which describe the influence of the line parameters on the phenomena under study. Table 1 presents the influence of the most essential line parameters on the level of the emitted noise and the forms of the calculation procedures employed by various research centres. These empirical procedures are based on the measurement data for both the test lines and the existing lines, the first data being called the cage data.

Table 1. Comparison of calculation procedures of noise of the existing AC-lines

Method	Voltage surface gradient	Conductor diameter	Number of sub-conductor in a bundle
BPA	$130\log E/E_0$	$44\log d/d_0$	$10\log n/n_0$
Westing-house	$120\log E/E_0$	$60\log d/d_0$	$10\log n/n_0$
Ontario Hydro	$100\log E/E_0$	$40\log d/d_0$	$10\log n/n_0$
ENEL	$85\log E/E_0$	$45\log d/d_0$	$18\log n/n_0$
IREQ	$72\log E/E_0$	$48.5\log d/d_0$	$22.7\log n/n_0$
EdF	$2.5\,(E-E_0)$* $1.5\,(E-E_0)$**	$4.5\,(d-d_0)$	$15\log n/n_0$

* — $15<E<20$ kV/cm
** — $20<E<25$ kV/cm

The procedure given above are valid for rain conditions. The maximum discrepancies result from considering the voltage gradient and number of sub-conductors in a bundle. Greater influence of the gradient of electric field on the conductor surface is obtained, if the procedure based on the data for the existing lines are replaced by procedures employing the data for the test lines.

The non-uniformity of the surface of the conductors is also an important factor: at sharp curvatures of the surface one can observe a greater accumulation of electric charges being a source of micro-discharges. In the case of a perfectly smooth surface of the conductor, the discharge phenomenon does not occur during fair weather. But in practice, line conductors consist of wires with definite curvature radii and definite surface smoothness. For the existing conditions the smoothness factor is equal to about 0.75. The surface conditions of the conductors are also directly dependent upon the environment conditions, such as dirt, accumulated insects, etc., as well as on the technical conditions of both the conductors and other elements of the transmission track. On the conductor surfaces there exist often scratches, stratification caused by improper assembly (pulling the conductors). Damages of conductors, insulators and switch gear, which are caused by wear and ageing processes, can also be sources of discharges. The discharge itself damages the surface of conductors because it contributes to the creation of nitrogen compound. Under fair weather conditions the noise level is strongly dependent upon roughness of the surface of the conductors or other high voltage elements (particularly insulators). To the elements of considerable rough surfaces belong fittings, particularly the insulators used frequently on the corner and tension poles (ON type poles) of overhead transmission lines.

For the given design data of an overhead transmission line, the noise level is dependent upon the atmospheric conditions. When the air is dry and the weather is fair, the number of microcharges is small but during rain it increases for two reasons: 1) The rain droplets result in the appearance of irregularities on the conductor surfaces, 2) the threshold at which discharge takes place (so-called "rupture gradient") is falling off. During fair weather single discharges occur at the voltage surface gradient of the order of 15 – 17 kV/cm. When the conductor is wet, the critical value of the voltage gradient is falling off to a level of about 12 kV/cm, whereas during rains it is falling off even below 10 kV/cm. According to [8], additional reduction of critical voltage gradient occurs in transmission lines with spiral vibration dampers; damping of mechanical vibration amounts to about 11 kV/cm for wet conductors and to about 8 kV/cm for rainy weather.

The number of microdischarges influences directly the level of the emitted noise. Fair weather is the weather with no rain and normal air humidity within the range of 60 to 70%. As a bad weather there will be regarded fog, drizzle, rain or snow. From the point of view of the influence of the noise of the transmission line on the environment, the most essential is the rainfall intensity, since the noise produced during heavy rain by the falling droplets is comparable with the noise generated by the transmission line itself. Also important are the conditions after the rain. The conductors are then wet, but there are no droplets on their surfaces. Such conditions exist during fog and drizzle. In foggy weather the maximum noise level is usually observed after saturation of conductors with moisture, which usually occurs after several hours.

Figure 1 [5] shows the influence of the rainfall rate on the dependence of the level of the emitted noise on the voltage surface gradient. From these investigations an

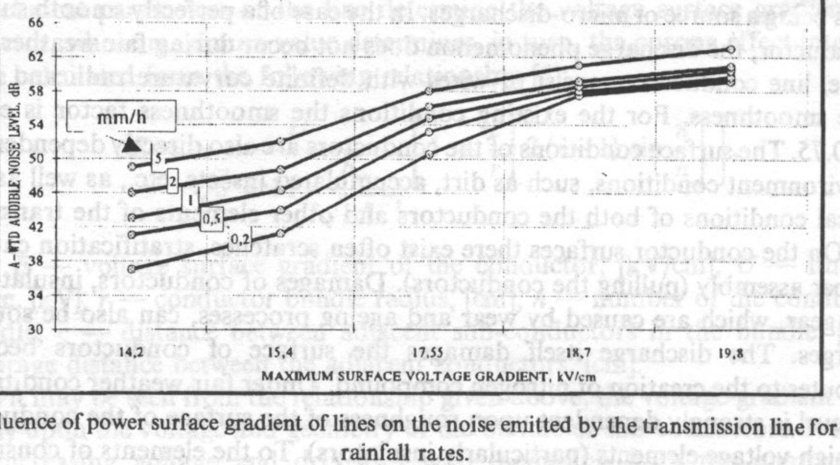

Fig. 1. Influence of power surface gradient of lines on the noise emitted by the transmission line for various rainfall rates.

essential conclusion can be drawn that sensitivity of the transmission line to the rainfall rate diminishes with increasing voltage gradient.

Noise during snow fall has a very wide range and depends upon the rate and kind of the falling snow.

Still another influence upon the noise level have the conditions of conductor surfaces connected with its age (Fig. 2 [10]). New conductors have somewhat greasy surface what leads to formation of drops during rain over the whole surface of the conductor. On the contrary, aged conductors have already degreassed surface like that after the use of detergents. Due to this, the drops accumulate in the bottom part of the conductor only [9], what leads to a smaller number of discharges. The age of the conductors is especially important during small rain falls drizzle and fog. The difference between the emitted noise decreases with increasing rainfall rate.

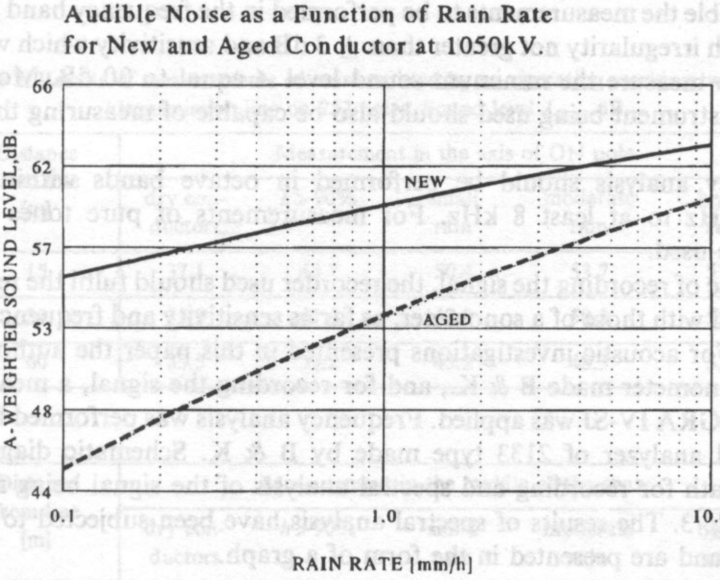

Fig. 2. Influence of the age of lines on the level of emitted noise for various rainfall rates.

3. Result of investigations in existing conditions

Investigation of the noise produced by an operating transmission line have been carried out on a double-circuit 400 kV line on poles of series Z52 between Tarnów and Byczyna. Investigations were performed under various atmospheric conditions by a short-term method, that is for short time intervals of characteristic weather conditions.

In Poland there are now no special regulations determining the methods of investigation of the noise emitted by power transmission lines. Such measurements are performed on the basis of the existing standards relating to general measurements in natural environment. Developing the measuring methods, the authors of this paper have additionally taken into account the standards ANSI/IEEE Std 6558 – 1985 concerning measurements of the noise emitted by overhead transmission lines.

Main instrument used for measurements of the noise intensity was the sonometer. It should enable the measurements to be performed in the frequency band from 20 Hz to 15 Hz, with irregularity not greater than ± 3 dB and sensitivity which would make it possible to measure the minimum sound level *A* equal to 30 dB. Moreover, the measuring instrument being used should also be capable of measuring the levels L_{eq} and L_{min}.

Frequency analysis should be performed in octave bands within the range from 31.5 kHz to at least 8 kHz. For measurements of pure tones 1/3 octave filters can be used.

In the case of recording the signal, the recorder used should fulfil the requirements identical used with those of a sonometer, as far as sensitivity and frequency bands are concerned. For acoustic investigations presented in this paper the authors used the 2231 type sonometer made B & K., and for recording the signal, a measuring tape recorder NAGRA IV-SJ was applied. Frequency analysis was performed by means of a wide band analyzer of 2133 type made by B & K. Schematic diagram of the measuring path for recording and spectral analysis of the signal being measured is shown in Fig. 3. The results of spectral analysis have been subjected to "computer processing" and are presented in the form of a graph.

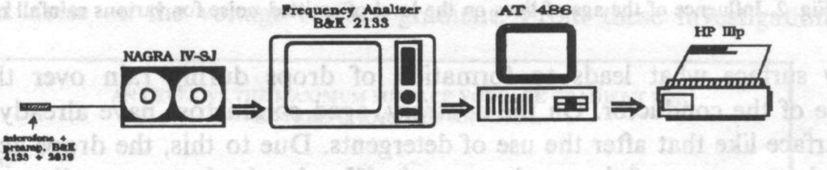

Fig. 3. Scheme of measuring channel for recording and spectral analysis of a noise signal.

Measuring points were situated at the distances of 15, 30, 60 and 120 m from the projection of the edge conductor. Measuring sections were situated in mid-span and in the axis of the pole of ON type, whereas in the case of measurements of noise distribution over the span, the measurements were performed in sections spaced 30 m from one another.

The results of investigations may be divided into two groups: 1) measurement of sound level *A* and 2) measurement of spectrum of 1/3 octave noise.

Measurements of the sound level *A* were performed mainly in order to determine the influence of acoustic phenomena on environment under various atmospheric conditions as well as the distribution of sound level along the span. Among the obtained results, five characteristic weather conditions have been distinguished:

— dry conductors (fair weather);
— considerable air humidity ($h > 90\%$),
— small rain or drizzle,
— moderate rain,
— heavy rain.

Averaged results of investigations of the sound level *A* for the particular atmospheric conditions for mid-span in the axis of the ON type pole are presented in Table 2.

Table 2. Results of measurements of noise emitted by an operating working two-track transmission line on 252 poles. Sound level $L_{A_{eq}}$, dB

Distance from line [m]	Measurement in the axis of ON pole				
	dry conductors	$h>90\%$	small rain	moderate rain	heavy rain
15	37.1	43.7	50.4	53.7	57.8
30	35.3	41.6	47.8	50.5	55.2
60	33.5	39.2	45.2	48.3	53.9

Distance from line [m]	Measurement in the middle of the span				
	dry conductors	$h>90\%$	small rain	moderate rain	heavy rain
15	35.1	41.4	48.5	53.5	57.5
30	33.2	39.0	46.1	51.5	55.1
60	31.4	37.1	44.1	47.2	52.7

1. Measurement results for moderate and intensive rainfalls are given in the form of average values of two series of measurements.
2. Distance is given from the projection of the edge line.

From the results presented in Table 1 the following conclusions may be drawn:

— noise level on tension pole axis (mainly the noise emitted by fittings) is slightly higher than in the middle of the span noise emitted by conductors;

— noise during intensive rainfalls is higher by about 20 dB as compared with the noise during fair weather;

— fluctuations of the level of noise emitted during rainfall change within the range of 8 to 9 dB.

Table 3 presents the results of measurements of sound level *A* on both sides of the transmission line in the case when the line is situated on a slops. They relate to the span 401—402 for a two-track line under good atmospheric conditions and average rain.

Table 3. Results of measurements of sound level $L_{A_{eq}}$, dB for an ascending and descending slope

Distance from the line [m]	Fair weather		Moderate rainfall	
	ascending slope	descending slope	ascending slope	descending slope
15	44.3	41.9	53.9	51.2
30	41.6	40.5	51.4	48.5
60	38.6	38.0	47.7	45.8

On a descending slope noise is lower by about 2.5 dB, and this difference decreases with increasing distance from the line. A dominating factor of such a sound distribution is the distance from the source.

Figure 4 presents diagrams of sound level distribution along the span at a distance of 15.30 and 60 m from the extreme conductor for fair weather and moderate rainfall. From the presented diagrams it can be seen that during rain the transmission line is a more uniform source of noise than during fair weather. The corona effect under these conditions is determined mainly by: 1) reducing the critical intensity level, 2) deformation of the surface by rain drops, which is of the same form on the whole line. Also visible is a higher level of the noise emitted on the axis of ON type pole.

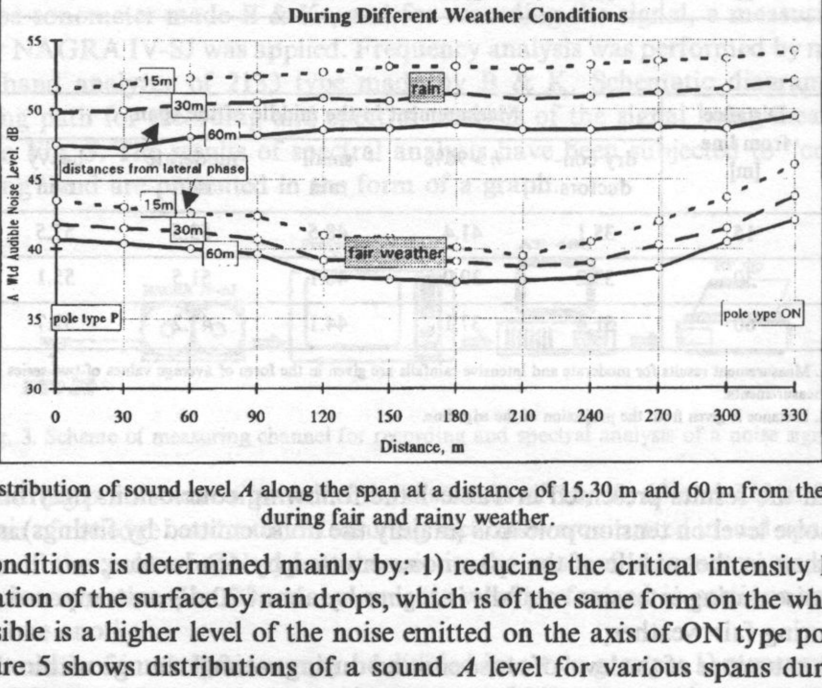

Fig. 4. Distribution of sound level *A* along the span at a distance of 15.30 m and 60 m from the edge line during fair and rainy weather.

Figure 5 shows distributions of a sound *A* level for various spans during fair weather. Three mutually exclusive tendencies can here be observed: raising or lowering the noise level in the middle of the span, or approaching its uniform distribution. An increase of noise in the mid-span indicates that the main sources of noise are the conductors, mainly dut to bad technical conditions of their surfaces. Such tendency was most often encountered in the transmission lines investigated by the authors.

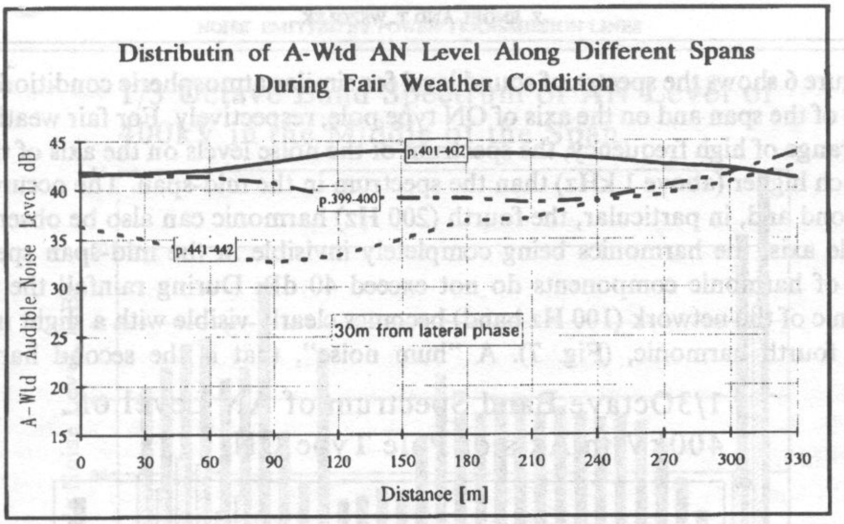

Fig. 5. Distribution of sound level *A* along various spans during fair weather. Measurements have been performed at a distance of 30 m from the edge line.

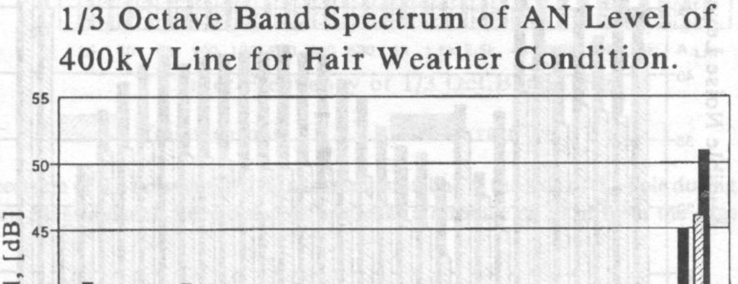

Fig. 6. Third spectrum of noise emitted by the transmission line during fair weather on axis of the ON pole and in the mid-span. Measurements have been performed at a distance of 30 m from the edge line.

Figure 6 shows the spectra of sound level for similar atmospheric conditions in the middle of the span and on the axis of ON type pole, respectively. For fair weather and in the range of high frequency, the spectrum of the noise levels on the axis of the pole are much higher (above 1 kHz) than the spectrum in the mid-span. The occurence of the second and, in particular, the fourth (200 Hz) harmonic can also be observed on the pole axis, the harmonics being completely invisible in the mid-span spectrum. Levels of harmonic components do not exceed 40 dB. During rainfall the second harmonic of the network (100 Hz band) becomes clearly visible with a slight increase of the fourth harmonic, (Fig. 7). A "hum noise", that is the second harmonic, is most easily observed in the middle of the span (Fig. 8). The sound level in the 100 Hz band increases then by about 16 dB what is accompanied by an increase of sound level *A*, also by about 16 dB. In both cases one can see a higher wide-band level which is far greater in the middle of the span. Also significant is the rise of the noise level of the fourth harmonic of the network (400 Hz). In both the cases, a rise of broad-band noise can be observed, which is considerably greater in the middle than in other points of the span.

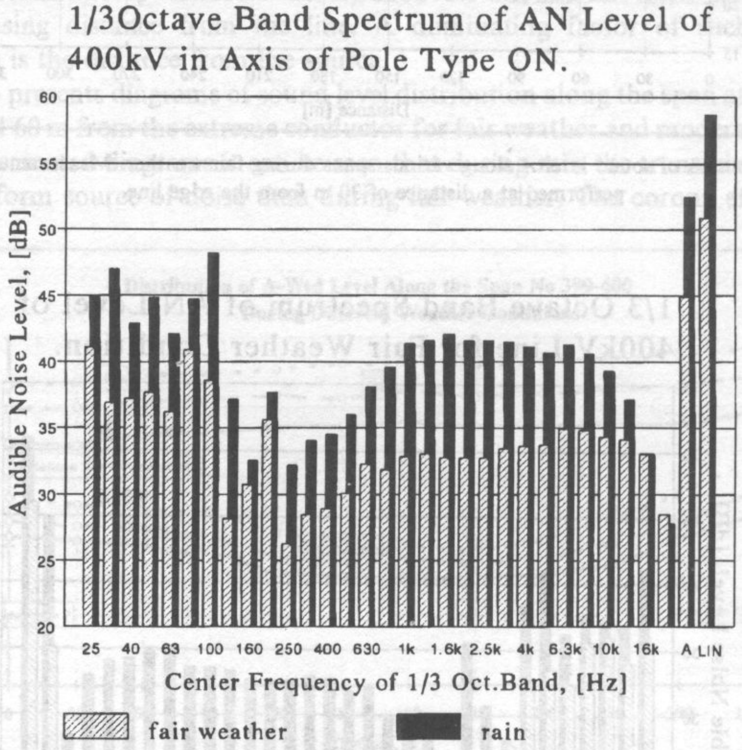

Fig. 7. Third spectrum of noise emitted by a transmission line in the axis of the pole during fair and rainy weather. Measurements have been performed at a distance of 30 m from the edge line.

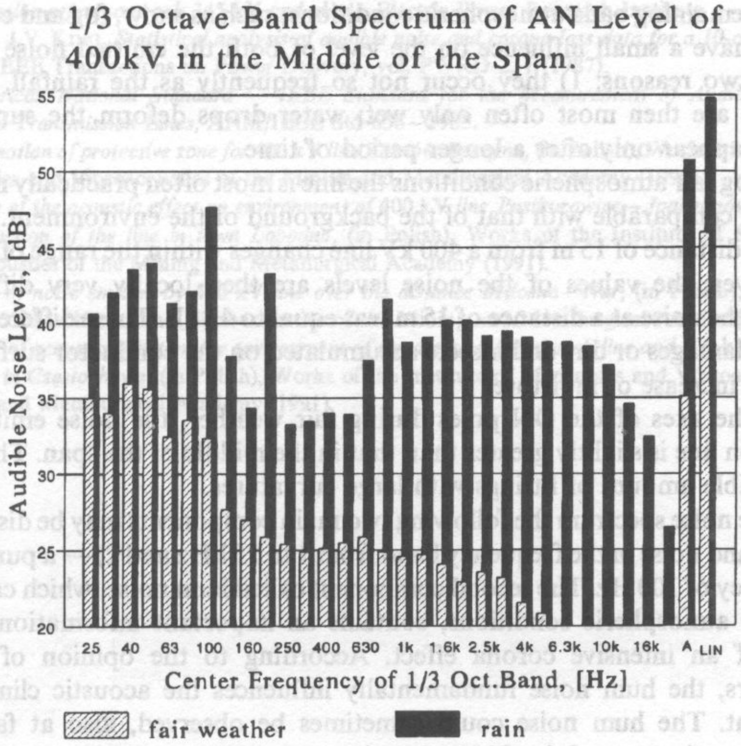

Fig. 8. Third spectrum of the noise emitted by a transmission line in the axis of the pole during fair and rainy weather. Measurements have been performed at a distance of 30 m from the edge line.

From the point of view of its influence on environment, the considerable rise of the noise level of the second harmonic during rain is of an essential since pure tones in the spectrum augment the subjective nuisance of the noise.

4. Conclusions

On the basis of the performed investigations, the following conclusions can be drawn:

1. High voltage transmission lines (400 kV and more) are intensive sources of noise during bad atmospheric conditions, such as heavy and moderate rain, drizzle and, to a lesser extent, fog, snow and considerable air humidity. During intensive rain, the noise produced by the rainfall itself is comparable with the noise emitted by the transmission already at a distance of 30 m from the lines. The level of noise of 400 kV lines at a distance of 25 m from an edge conductor during bad atmospheric conditions changes with in the range of 30 to 54 dB.

2. The remaining bada atmospheric conditions, such as snow, fog and considerable humidity, have a small influence on the level of both the emitted noise and power losses for two reasons: 1) they occur not so frequently as the rainfall, and 2) the conductors are then most often only wet; water drops deform the surface of the conductor appear only after a longer period of time.

3. During fair atmospheric conditions the line is most often practically noiseless, its noise being comparable with that of the background of the environment. The sound level *A* at a distance of 15 m from a 400 kV line changes within the range of 34 up to 36 dB. However, the values of the noise levels are then locally very differentiated; sometimes the noise at a distance of 15 m was equal to 45 dB. These differences can be caused by damages or dirt and insects accumulated on the conductor surface, as well as by local increase of moisture.

4. On the axes of the ON poles during fair weather, the noise emitted by the transmission line is slightly greater than that in the middle of the span. This is due to a considerable amount of fittings with large curvatures.

5. In the noise spectrum the following two main components may be distinguished: 1) broad-band noise in the frequency band from 1 to 15 kHz and 2) — a pure tone with the frequency of 100 Hz. The second component called hum noise, which can be heard during bad atmospheric conditions, contains an important information about the presence of an intensive corona effect. According to the opinion of numerous investigators, the hum noise fundamentally influences the acoustic climate of the environment. The hum noise could sometimes be observed, also at fair weather conditions on the axes of the ON type poles.

6. During bad atmospheric conditions, the noise emitted by aged lines and the induced power loss are lower than those produced by new lines.

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