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UNCERTAINTY OF L_{DEN} CALCULATION FOR CORONA NOISE FROM ULTRA HIGH VOLTAGE POWER LINES USING REFERENCE METHODS

T. WSZOŁEK

AGH University of Science and Technology
Department of Mechanics and Vibroacoustics
Al. Mickiewicza 30, 30-059 Kraków, Poland
e-mail: twszolek@agh.edu.pl

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Accordingly to the regulations contained in the European Noise Directive (END) and also in some legal acts being currently under legislative process in Poland, in the nearest future the L_{DEN} and L_{N} levels will be used as the basis for evaluation of corona noise from UHV power lines. The paper presents an example of combined uncertainty evaluation for estimation of long-term level ($L_{\mathrm{A,\,LT}}$) and L_{DEN} level for corona noise from UHV overhead power lines. Some specific features of that noise – large time variation of its level and spectral structure, dependent on the atmospheric conditions, and on the other hand often small distance from the background noise – are the reason that the evaluation of its estimation uncertainty is more difficult then for some other, better "determined" noise sources. The partial uncertainties related to the measurement system and prediction method according to the reference methods for industry noise were dealt with. The effect of the environment on the system and the measured quantity have been distinguished and quantitatively determined.

Key words: corona audible noise, day-evening-night level, power lines, uncertainty.

1. Introduction

The overhead Ultra High Voltage (UHV) power lines are sources of adverse environmental effects, what is often the reason of numerous complaints from the local population concerning their presence. In most cases the complaints consider the effects related to the corona process, in particular the radio frequency interference and audible noise in particular even though its level is relatively low e.g. in comparison of traffic noise. It causes that calculation of L_{DEN} is necessary. The corona process, and thus also the accompanying processes, essentially depend on the atmospheric conditions, in particular the precipitation occurrence. Therefore power lines emit intensified noise during so called bad weather conditions, among which rainfall, wet snowfall, fog and high air humidity are included.

In a properly designed power line during fair weather conditions (i.e. when the conductors are dry) the corona process should not take place, because the maximum conductor surface gradient is most often about 15–17 kV/cm, while the critical value (at which the corona process starts) is about 19–20 kV/cm. However during the bad weather conditions the critical value falls down even to 10–12 kV/cm [4], which is much below the maximum value of the “running” electric field. As a result an intensive corona process is started.

During fair weather the corona process is observed for significant surface irregularities, caused by contamination’s or insect carcasses on the surface, scratches or delaminations etc., and then the noise of power line can be clearly audible [3], sometimes even obnoxious.

Audible noise generated by corona may be considered to be composed of two major components: (1) the tonal components (hum noise) – the second and higher harmonics of the AC power frequency – and (2) the broad-band noise component in the band above 500 Hz [3]. While the noise component is rather stable, the tonal component exhibit considerable fluctuations both in space and time [4], even up to 20 dB. Additionally, not all AC corona modes create random noise and hum in the same proportion. In different weather conditions the relative magnitudes of random noise and hum may be different. For example, in rain, the broad-band component generally dominates, whereas under conditions of conductor icing a high, 100 Hz hum component may be accompanied by a relatively low level of broad-band noise. This is the reason of certain problems with their measurement. On the other hand the tonal components, according to ISO 1996 standard [7], are accounted for in the noise evaluation by introducing a 3 or 5 dB correction to the measured noise level.

Another item is the problem of the environmental disturbances, which are often hard to eliminate using classical methods [10].

Because of seasonal variation of the weather phenomena long-term levels should be taken as a basis for the noise assessment, according to the ISO 1996 standard. Also the Polish Standard PN-N-01339 [6] introduces the long-term values as the basis for the assessment. On the other hand in the American Standard IEEE Std 656 [7] the night-day levels are taken as basis for evaluation. However even if the introduction of both the long-term and night-day levels makes the evaluation more uniform, it does not allow the elimination of uncertainty related to the evaluation of actual periods of bad and fair weather conditions, the effect of environmental interference and the fluctuation of tonal components [8].

Accordingly to the regulations contained in the Directive [2] and also in some legal acts being currently under legislative process in Poland (so-called reference methods), in the nearest future the L_{DEN} and L_{N} levels will be used as the basis for evaluation of corona noise from UHV transmission lines. For calculation of these levels, in particular the L_{DEN} level, it is necessary to know the long-term values of 24 h noise distributions (L_{day}, L_{night} and L_{evening}).

2. Uncertainty factors of corona noise assessment

As has been mentioned above the corona noise strongly depends on the atmospheric conditions and for the case of 400 kV transmission line in fair weather it varies around

30–35 dB at the distance of 30 m from the line (lateral conductor), but in some situations it may be completely inaudible. In rain conditions its level increases up to 50 dB and more, depending the line arrangement, geometrical layout of the conductor bundle and the rain rate [3, 12].

Fig. 1. Landscape with typical overhead power line arrangement in Poland.

Averaged experimental noise data for a 400 kV power lines with double and triple conductor bundles – 2×525 mm^2 and 3×350 mm^2 respectively, has been shown in Table 1 [12].

Table 1. Average measurement results of corona noise from 400 kV power lines in Poland.

Average measurement results $L_{\mathrm{Aeq,\,av}}$ of corona noise from 400 kV power lines in fair and foul weather condition, in lateral distance from outside phase – 15, 30 and 60 m											
Towers	Parameters	fair weather			foul weather						Bundle and line arrangement
					all conditions			stable rain			
		15 m	30 m	60 m	15 m	30 m	60 m	15 m	30 m	60 m	
Y52	st. dev.	3.40	3.10	2.80	3.80	3.90	3.80	1.90	2.30	2.70	2×525 mm^2, single circuit line
	$L_{\mathrm{Aeq,\,av}}$	37.2	34.2	31.7	49.4	46.5	43.7	51.4	48.6	45.7	
Z52	st. dev.	3.96	3.74	3.61	4.07	4.08	3.24	2.01	1.81	1.66	2×525 mm^2, double circuit line
	$L_{\mathrm{Aeq,\,av}}$	38.8	36.0	33.2	51.1	49.2	46.7	52.9	51.1	48.6	
Z33	st. dev.	2.4	2.3	2.3	3.1	2.9	2.8	1.2	1.4	1.2	3×350 mm^2, double circuit line
	$L_{\mathrm{Aeq,\,av}}$	35.0	32.9	31.6	44.5	41.6	38.9	45.3	42.4	39.7	

The experimental data listed in Table 1 are characterized by relatively large dispersion, particularly in fair weather conditions. The origins of this effect lie in variable state of atmospheric conditions and technical condition of the line, in particular its surface contamination, which is usually bigger in the long dry periods, especially nearby the transportation routes, urban areas etc. In practice quantitative evaluation of the effect of these factors can be carried out only by its multiple measurements and calculation of the standard deviation.

Depending on the weather conditions the spectral structure of corona noise signal also varies, still one can always identify in the spectrum the tonal components, with its basic frequency equal to the doubled power network frequency, and the noise component in the frequency band above 1 kHz [5].

The tonal components (100 and 200 Hz), however "mildly" affecting the A weighted noise level, are sometimes the reason of considerable dispersion of measurement results, because of their large fluctuations in time and space [8].

Examples of acoustic spectra of corona noise in both fair and bad weather conditions have been shown in Fig. 2.

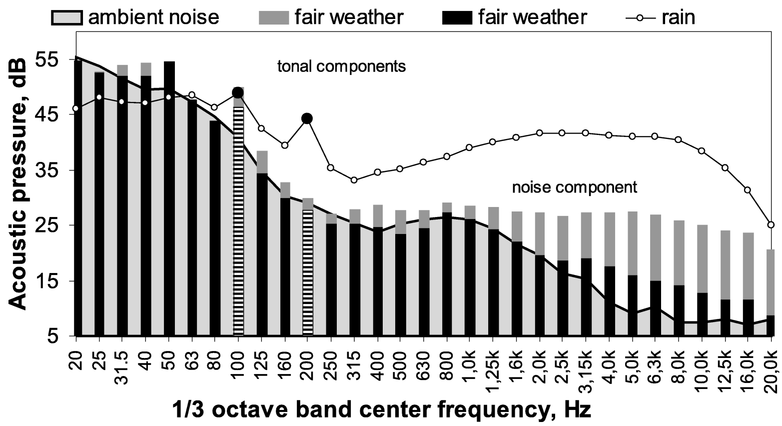

Fig. 2. Typical corona noise spectra in various weather conditions and state of conductor surface (in fair weather).

In the above figure one can notice the definitely lower distance from the background noise in fair weather conditions (black bars) which sometimes might be quite large (grey bars) – e.g because of conductor surface contamination, and on the other hand a very high distance in bad weather (rain), what is very essential for the determination of uncertainty related to background effects both in fair and bad weather conditions.

3. Uncertainty of L_{DEN} calculation

In the evaluation of type B standard uncertainty it has been assumed that the standard deviations of individual partial uncertainties of measuring devices are equal to $1/\sqrt{3}$ of the limiting error values of these devices and that the respective errors exhibit normal distribution. In the cases where the distribution of possible errors is rectangular (e.g. for the reference standard uncertainty or for the type B uncertainty evaluation) it has been assumed that the partial standard uncertainty is equal to of the error's limiting value. For all the type B uncertainties mentioned in the paper, a rectangular distribution of possible values is assumed for simplicity, with its range described as $\pm a$. The standard deviation for such a distribution is:

$$U = \frac{a}{\sqrt{3}}. \tag{1}$$

The following uncertainty components are considered as type B:

- Calibration of the acoustic instruments, U_{B1}.
- Tolerances on the chain of acoustic measurement instruments, U_{B2}.

Factors affecting the values of these uncertainties are: calibration and the directional characteristics of the microphone – important because of the spectral structure of corona noise: predominant effect of frequencies higher than 5 kHz, for which the microphone directional characteristics ($1/2''$ microphone) becomes very important.

• Fluctuation of tonal components, U_{B3}.

The influence of tonal components (100 and 200 Hz) /tonality/ cannot be neglected, mainly because of their large fluctuation in time and space [8]. The amplitude of these fluctuations often reaches the level of 15 dB in the 100 Hz band and 10 dB in the 200 Hz band., however the total effect of these fluctuations on the A weighted level (because of its high attenuation in the 100 and 200 Hz bands: 19.1 and 10.9 dB, respectively). Another obstacle results from the absence of estimate for the actual period when the tonal components have been observed in a sense of ISO 1996 standard.

• Distance from the microphone to UHV line conductors, U_{B4}.

In the case of power lines, because of the varying shape of suspended conductors (chain curve), the distance error, depending on the line load and ambient temperature, will be of the order of 10%.

• Atmospheric absorption, U_{B5}.

It can be of great importance, because of the high contribution of the high-frequency components in the signal (Fig. 2). For the humidity change from 30% to 50% – measurement in fair weather conditions – the standard uncertainty in the distance of 30 m from the conductors will be equal to $U_{\mathrm{B5\,1f}} = 0.4$ dB, while in the distance of 60 m it will already reach 0.8 dB. In bad weather conditions, the humidity changes are negligible, but the contribution of the high frequency component is bigger.

The total uncertainty also includes the uncertainty related to the temperature variation and is calculated separately for bad (index b) and fair (index f) weather.

• Uncertainty related to changes of wind velocity and direction, U_{B6}.

Assuming measurements carried out in wind-free conditions or very low wind speed the wind do not affect the measurements (e.g. by using a wind shield) but only the sound propagation. For longer distances the wind can be of decisive importance in the total uncertainty budget.

• Uncertainty of acoustic background effects, U_{B7}.

In elimination of the acoustic background effect we use the formula:

$$L_{\mathrm{Aeq},\,em} = 10\log\left(10^{0.1L_{\mathrm{Aeq},\,m}} - 10^{0.1L_{\mathrm{Aeq},\,b}}\right), \tag{2}$$

where $L_{\mathrm{Aeq},\,em}$ – noise emission level (after subtracting the acoustic background), dB; $L_{\mathrm{Aeq},\,b}$ – acoustic background level, dB; $L_{\mathrm{Aeq},\,m}$ – measured noise level (total from the source and the background), dB.

In that case because of the shortage of necessary data the type A uncertainty (i.e. from the standard deviation) cannot be estimated, but with the knowledge of average levels of line noise and the acoustic background in the fair and bad weather condition and assuming the possible variation range of these values, one can estimate the standard uncertainty U_{B7}.

In fair weather relatively low distance from the acoustic background is observed, but on the other hand the fluctuations of the acoustic background itself are greater. In bad weather, when the distance from acoustic background is higher, the estimated uncertainty will be much lower.

The uncertainty of the acoustic background can be also estimated as type A uncertainty, when the required number of experimental data has been collected and the standard deviations of the background level $L_{\mathrm{Aeq},\,b}$, and the measured corona noise (with the background) $L_{\mathrm{Aeq},\,m}$ are known.

In such a case the type A standard uncertainty can be calculated using the uncertainty propagation law, thus:

$$U_y = \sqrt{\sum_1^n \left(\frac{\partial f}{\partial x_i}\right)^2 U_{x_i}^2}, \tag{3}$$

In the case considered the formula for calculation of the (net) emission level uncertainty, after background subtraction according to Eq. (2), will take the following form:

$$U_{\mathrm{A},\,em} = \sqrt{\left(\frac{\partial L_{\mathrm{eq},\,em}}{\partial L_{\mathrm{eq},\,m}}\right)^2 U_m^2 + \left(\frac{\partial L_{\mathrm{eq},\,em}}{\partial L_{\mathrm{eq},\,b}}\right)^2 U_b^2}. \tag{4}$$

- Combined uncertainty of the result of long-term $U_{\mathrm{C},\,\mathrm{LT}}$ and L_{DEN} calculation

According to the Directive [2] the L_{DEN} is calculated using A-weighted long-term levels, as defined in ISO 1996-2:1987 [7], determined over all day (day, evening and night) periods of a year. The value of long-term levels can be determined according to the formula below (3) [9]:

$$L_{\mathrm{Aeq,\,LT}} = 10\log\left(t_f 10^{0.1L_{(\mathrm{Aeq})f}} + t_b 10^{0.1L_{(\mathrm{Aeq})b}}\right), \tag{5}$$

where $L_{(\mathrm{Aeq})f}$ – the averaged noise level in fair weather, dB; $L_{(\mathrm{Aeq})b}$ – the averaged noise level in bad weather, dB; t_f, t_b – average percentage values of periods of fair and bad weather conditions, respectively.

Taking into account that in practice in most countries it is assumed that the bad weather conditions occur during 5–10% of the year, the error that can be made by assuming inaccurate period of these conditions is found to be in the 1–3% range. In Poland the average year periods of fair and bad weather conditions are assumed to be 90% and 10%, respectively. Assuming that the standard uncertainty $U_{\mathrm{A,\,LT}}$ will be determined from the formula (3), for average levels $t_f = 90\%$, $t_b = 10\%$, $L_f = 35$ dB, $L_b = 50$ dB, $\sigma_f = 3$ dB, $\sigma_b = 1.2$ dB the obtained standard uncertainty for $n = 24$, the combined uncertainty $U_{\mathrm{C,\,LT}}$ will be 1.76 dB. The listing of all the partial uncertainties can be found in Table 2.

As one can notice from the above results the source changeability affects the most to the total uncertainty of long-term level prediction as well as to the L_{DEN} level. The listing of the calculated L_{LT} and L_{DEN} with standard uncertainties for typical support series of 400 kV power lines can be found in Table 3.

Table 2. Gathered examples of evaluated values of standard uncertainty components in case of corona audible noise.

Component	Possible typical range (at 95% confidense)	Possible typical standard uncertainty
Calibration	± 0.3 dB	0.2 dB
Measurement system, U_{B2}		
microphone directivity, U_{B22}	± 0.52 dB	0.29 dB
instrument, U_{B21}	± 0.34 dB	0.2 dB
U_{B2}	± 0.62 dB	0.36 dB
Tonalty, U_{B3}	0.3 dB	0.17 dB
Distance, U_{B4}	0.41 dB	0.24 dB
Atmospheric absorption, U_{B5}		
humidity fair weather, $U_{\mathrm{B5\,1f}}$	± 0.7 dB	0.4 dB
humidity bad weather, $U_{\mathrm{B5\,1b}}$	± 0.2 dB	0.1 dB
temperature (fair and bad weather), U_{B52}	± 0.25 dB	0.15 dB
$U_{\mathrm{B\,5f}}$ (fair weather)	± 0.9 dB	0.5 dB
$U_{\mathrm{B\,5b}}$ (bad weather)	± 0.3 dB	0.2 dB
Wind speed and directiopn, U_{B6}	± 0.5 dB	0.3 dB
Backgroung, U_{B7}		
fair weather, $U_{\mathrm{B\,7f}}$	± 1.0 dB	0.6 dB
bad weather, $U_{\mathrm{B\,7b}}$	± 0.2 dB	0.1 dB
Long-term $U_{\mathrm{A,\,LT}}$		
fair weather, $U_{\mathrm{A,\,LTf}}$ (std. dev., t-Student distribution, $n = 24$)	± 6 dB	2.15 dB
bad weather, $U_{\mathrm{A,\,LTb}}$ (std. dev., t-Student distribution, $n = 24$)	± 2.4 dB	0.86 dB
Combine uncertainty, $U_{\mathrm{C,\,LT}}$	± 4.9 dB	1.76 dB

Table 3. L_{LT} and L_{DEN} results with combine uncertainty (U_{C}) in distance 15 m from lateral conductor for 400 kV power lines.

Support serie	L, dB	U_{C}
Long-term level L_{LT}		
Z52	42.9	2.5
Y25	41.3	2
Z33	35.7	1.8
Day-evening-night level L_{DEN}		
Z52	49.3	2.2
Y25	47.7	1.9
Z33	42.1	1.7

4. Conclusions

• The corona noise is characterized by large variation in time, affecting both its level and spectral structure, depending mainly on the weather conditions but also on the technical condition of the line.

• Large variability of the noise level is expressed by relatively high dispersion of the results, particularly in fair weather conditions, but also in bad weather as a consequence of varying intensity of the accompanying phenomena (varying precipitation rate, fog density etc.). As a result the standard uncertainties of the corona noise variation in long-time periods are equal from almost 2 dB (in the steady rain conditions) up to more than 4 dB in the other weather conditions.

• The high-frequency nature of the corona noise spectrum leads to relatively high values of the uncertainty related to the directional properties of the microphone, especially that the intensity of corona discharge increases with the increasing air humidity values, and the measurements have to be carried out both in fair and bad weather conditions.

• As a whole the combined expanded uncertainty at the 95% confidence level of long-term level, and the L_{DEN} level will be equal respectively to 1.8–2.5 dB and 1.7–2.2 dB depending on the line layout.

• The source's (corona phenomena) changeability has the main influence on the total uncertainty of corona noise measurement and prediction in opposite to measurement system which influence is less relevant.

References

[1] Acoustics – Description and measurement of environmental noise. Part 2. *Acquisition of data pertinent to land use*, International Standard ISO 1996-2:1987 (1987).

[2] Directive 2002/49/CE of the European Parliament and of the Council of 25 June 2002, relating to the assessment and management of environmental noise, Official Journal of the European Communities 18.7.2002.

[3] Transmission Line Reference Book 345 kV and Above, Second Edition, Electric Power Research Institute, Palo Alto, CA, 1982.

[4] ENGEL Z., WSZOŁEK T., *Audible noise of transmission lines caused by the corona effect: analysis, modeling, prediction*, Applied Acoustics, **47**, 2, 149–163 (1996).

[5] *Guide to the expression of uncertainty in measurement ISO*, 1995.

[6] HARTOG VAN BANDA E., STAPELFELDT H., *Implementing prediction standards in calculation software – the various sources of uncertainty*, International INCE Symposium "Managing uncertainties in noise measurements and predictions: a new challenge for acousticians", Le Mans, France 26–29 June (2005) (CD).

[7] IEEE Standard for the Measurement of Audible Noise From Overhead Transmission Lines, IEEE Std 656–1992 (1992).

[8] TANABE K., *Hum noise performance of 6, 8, 10 conductor bundles for 1000 kV transmission lines at the Akagi test site: A comparison study with cage data*, IEEE Transactions on Power Delivery, **6**, 4, 1799–1804, October (1991).

[9] PN-N-01339. Noise. Methods for the Measurement and Evaluation of Audible Noise From Overhead Transmission Lines Polish Standard [in Polish], 1999.

[10] WSZOŁEK T., TADEUSIEWICZ R., WSZOŁEK W., IZWORSKI A., *Attempt of the sound level evaluation for the corona noise of UHV transmission lines in the intensified interference conditions*, INTERNOISE'99, Ft. Lauderdale, Fl., USA, Proceedings of IN99, 91–94 (1999).