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Publication date:
2005

Document Version
Accepted author manuscript, peer reviewed version

Link to publication from Aalborg University

Citation for published version (APA):
Bak, C. L., Mikkelsen, S. D., & Jensen, C. (2005). *Overhead line audible noise measurements and calculation model for snow and frosty mist*. Paper presented at International Symposium on High Voltage Engineering, Beijing, China.

ISH-05

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Abstract: Overhead line audible noise (AN) performance is gaining increased public interest and transmission system operators (TSO) needs to take AN performance of existing and new overhead lines into consideration. Existing AN models are empiric and only valid for rainy conditions. In Denmark this is less interesting as AN during weather conditions of low anbient noise as eg. snow, frosty mist and hoar frost are the causes of public complaints. This paper presents measurements of AN during snow and frosty mist, followed by a discussion of the results concerning metheorological dependencies, the most propable generation mechanism and an adjustment of an existing AN model to fit these measurements is proposed.

INTRODUCTION

Power transmission by means of high voltage overhead lines has gained an increased attraction of attention in the public opinion nowadays. Transmission system operators are met with environmental demands when building or refurbishing overhead lines concerning the "looks" and the emission of audible noise and magnetic and electric fields. Calculation of the magnetic and electric fields in the environment generated by overhead lines normally requires a numeric FEM approach to be reasonably accurate. Such a FEM model of an overhead line is rather simple to create and will easily give access to magnetic and electric field at eg. ground level and maximum conductor surface gradient. Calculation of audible noise is less strictly based on fundamental physical laws and audible noise calculation models are empiric and based on laboratory and/or full scale field measurements of the audible noise during rain. Such empiric formulas depends on a number of parameters (in general all geometric properties of the phase conductors) and are only available for rainy conditions. This is a problem as AN during ambiently, quiet conditions during snow, frosty mist and hoar frost is the major cause of public complaints in Denmark.

This paper will present AN measurements for a 420 kV duplex overhead line with Finch 636 mm^2 ACSR phase conductors during snow and frosty mist and the adaption of an existing AN model to fit these AN measurement data with the purpose of getting an AN design tool for use when considering new layouts of OH lines.

AUDIBLE NOISE CALCULATION MODELS

Different, but originally equal, empiric equations [1], [2], [3], [4] have been proposed and accepted widely. Such models rely on an empirically determined audible noise generated power A, [W/m] for each phase conductor, which gives rise to sound pressure waves propagating towards the surroundings of the overhead line. The sound pressure P in [dB(A)] is related to a reference sound pressure P_0 and expressed in terms of spherical sound waves at a distance R [m] from the source of generation, [1]

$$P_{\mathrm{dBabove}P_0\mu\mathrm{Pa}} = 10\log(A) + 10\log\left(\frac{\delta \bullet c}{4}\right) - 10\log(R) - 0{,}02(R) - 20\log(P_0) \qquad (1)$$

where δ is the air density and c is the velocity of propagation. As can be seen from (1) the audible noise present at a distance R from a phase conductor depends on the generated audible noise A of the phase conductors. All methods for calculating audible noise are for rain, [1]pp. 278, although the methods may vary as to what levels in rain are calculated. Audible noise from overhead lines consists of two components; a broad band noise and a 100 Hz hum. Generated acoustic power A depends on whether one is concerning the broad band noise or the hum and in both cases A must be determined by measurements. The generated acoustic power A will strongly depend on the metheorological conditions, i.e. the precipitation intensity and/or ice/water accumulation on the conductors.

$$A = n^2 \bullet \left(\frac{d}{3{,}8}\right)^{4{,}4} \bullet A_1 \bullet K_n \quad [W/m] \quad \text{or} \qquad (2)$$

$$10\log(A) = 20\log(n) + 44\log(d) - 85{,}5 + A_1 + K_n \quad [\mathrm{dB}_{\mathrm{above}1\mu W/m}]$$

with A_1 given as

$$A_1 = 46,4 - \frac{665}{E} \qquad [\mathrm{dB}_{\mathrm{above1\mu W/m}}] \qquad (3)$$

and $K_n = 7,5$ dB for n=1, $K_n = 2,6$ dB for n = 2 and $K_n = 0$ for $n \geq 3$.

Furthermore A will depend on the overall phase conductor geometry such as subconductor diameter d [cm], number of subconductors n, bundle diameter, applied voltage i.e. maximum surface field strength E [$\mathrm{kV_{RMS}/cm}$], normally taken as an average bundle value. For bundles with $n \geq 3$ bundle geometry plays a role concerning generated acoustic power, for instance will subconductor spacing change the level of A. This must be taken into consideration when $n \geq 3$. In this way the empiric equation for calculating broad-band generated acoustic power A [dB above 1 W/m] during heavy-rain (L_5) for overhead lines becomes [1]

$$A=20\log(n)+44\log(d)-39,1-\frac{665}{E}+K_n,(n<3)$$

$$A=20\log(n)+44\log(d)-46,4-\frac{665}{E} + \left[22,9\frac{(n-1)d}{D}\right] \quad (n \geq 3) \qquad (4)$$

All the dependencies, i.e. the factors present in eq. (4) are empirically determined on the basis of noise measurements of overhead lines in operation. Using eq (1) and (4) broad band AN for each phase conductor becomes, (in the case of n < 3)

$$P_{\mathrm{dBabove20\mu Pa}}=20\log(n)+44\log(d)-\frac{665}{E}+K_n +75,2-10\log(R)-0,02(R), \quad (n<3) \qquad (5)$$

Summarizing for all m phase conductors gives total AN for any measuring point near the OH line

$$P_{\mathrm{Total}}=10\log\sum_{i=1}^{m}10^{\frac{P_i}{10}} \qquad (6)$$

Equation (6) gives the broad band noise in heavy rain and the noise level during other intensities of rain will vary acoordingly. Wet conductor (L_{50}) is another well-known figure for the audible noise level originating from an overhead line. This level is calculated assuming another empirically determined generated acoustic power. Besides this 100 Hz hum has to be considered separately, because the generated acoustic power will be different and the propagating sound waves has to be added as vectors.

DISCUSSION OF AUDIBLE NOISE MEASUREMENTS DURING SNOW AND FROSTY MIST

Seen from local transmission system operators points of view AN calculation models should be used to predict and document the expected levels of AN from overhead lines in the design phase. Such expected AN levels are recommended to get a licence by the authorities to start constructing the line and for public opinion discussions. Therefore such AN models should reflect local practice concerning overhead line construction rather than be generally applicable for any number of subconductors between 1 and 12. In Denmark the highest voltage level is 420 kV and phase conductors are normally duplex or triplex with a diameter between $32,9 \leq d \leq 44,8$ mm and danish weather, which is very decisive for the noise generation, is in general different from e.g. american weather. Perception of the condition "heavy rain" will tend to be subjective and determined by local conditions. Another issue is the fact that the public annoyance concerning AN might not be the L_5 heavy rain level, because the AN noise will very much be "masked" by the naturally occurring sounds of the falling rain and the wind. People tend to be inside buildings during such weather and the ones outside do not expect silence and thereby feels no inconvenience of the AN. For people inside buildings (danish buildings are normally made by heavy materials as bricks and/or concrete) AN broad band noise will be heavily attenuated. This attenuation is [1]

$$\mathrm{Attenuation} = 10\log\left[1+\left(\frac{W \bullet f}{132}\right)^2\right] \quad \mathrm{dB} \qquad (7)$$

where W is the structure weight in kg/m^2 and f the frequency in Hz. Broad band noise will have a center frequency around 2 - 3 kHz in general.

Danish TSO Eltra have measured AN during different weather conditions. Two of these measurements (hereafter referred to as measurement 1 and 2) are presented in the following.

Measurements are performed underneath (ground level, at a hard plate to avoid reflections) the middle of the span (height 15,1 m, because of the sag). The line rated voltage is 420 kV, horisontal layout, duplex overhead line with Finch 636 mm^2 ACSR phase conductors, see figure 1. Measurement data are stored as 1 min averages and every 30 min will be recorded 1 min as a sound file for further analysis. Furthermore noise is measured at the tower in order to be able to subtract the tower/insulator noise from the noise measured underneath the middle of the span and thereby getting the "real" phase conductor noise. The measurements are continously supervised by man to avoid misinterpretation. Great effort has been put to assure that the measured sound levels are really originating from the overhead line. Therefore measurements are performed during the night at a very desolate place on the heath of Jutland. This gives rise to a very low and constant level of background noise in fair weather on app. 22 dB(A). Figure 2 shows the location of the measuring setup.

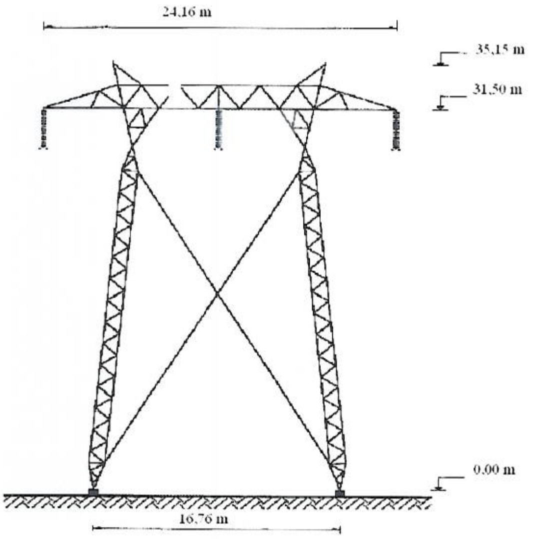

Fig. 1 400 kV tower of the investigated line

Fig. 2 Desolate location of the AN measurements

Measurement 1

The results of measurement 1 are presented in figure 3-5. Ambient temperature varied between -2°C and 2 °C, relative humidity 82 - 86 % and a wind speed of 1 - 5 m/s. From figure 3 is seen that the AN level depends very much on the weather condition "snow" or "no-snow" and the AN center frequency is around 2 kHz. Broad band noise will be attenuated approximately 60 dB (internal wall insulation neglegted) by a double brick wall and by a double window glass around 45 dB [1]. Therefore broad band AN will more or less be non-present inside buildings and the calculation of such levels of limited interest. Much more interesting is the 100 Hz hum because this will penetrate buildings more easily. Another issue is the fact that the hum tends to be more dominant during hoar frost and icing [1] pp. 267, where the ambient (wind, rain) noise is comparably low and the overall perception therefore seems to be that AN is much more annoying during quiet conditions as frosty mist. Narrow band analysis of measurement 1 in figure 3 shows pure tones as a multipla of 100 Hz, see figure 4.

Figure 5 shows that there is a good correlation between precipitation in the shape of snow and AN level. As the snow starts to fall a distinct increase of the AN is seen to take place. The snowing is intermittend and for each snowy period, the same maximum AN levels is reached.

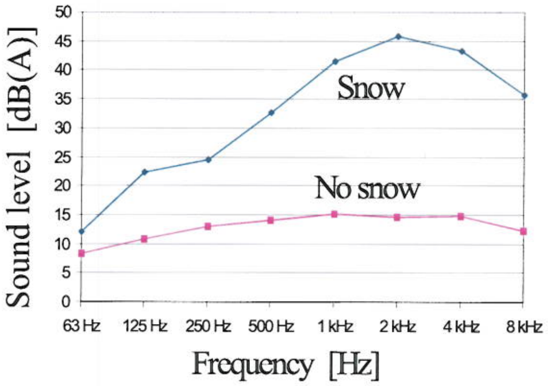

Fig. 3 Measurement 1. AN level versus frequency during snowfall/no snowfall

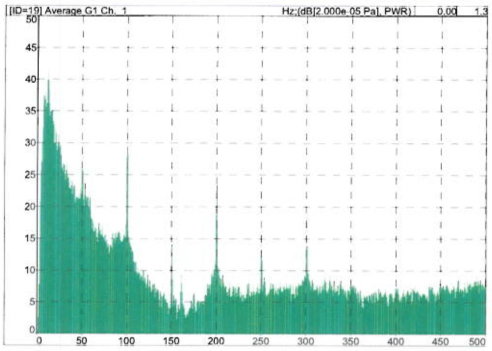

Fig. 4 Measurement 1. Narrow band analysis of AN during snowfall.

Measurement of transmission line AN is generally difficult to establish, because one wants to establish a reproducable condition such as for instance "frosty mist", "light snow" or "heavy fog" and the thereby connected AN broad band and 100 Hz level.

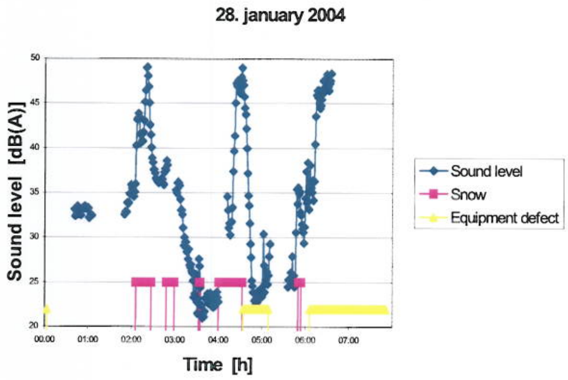

Fig. 5 Measurement 1. AN level as a function of time during intermittent snow.

Measurement 2

Another AN measurement (no. 2) at the line discussed above have shown the results during frosty mist fog presented in figure 6-8. Temperature between -2,8 °C and -0,4 °C, humidity 67 - 85 % and a visibility between 185 and 2000 m.

Figure 6 reveals that apparently no connection is to be found between visibility (which is a reasonable measure for the amount of water/ice/snow particles in the air) and AN level as both high and low levels of AN can be achieved for a visibility of app. 200 m.

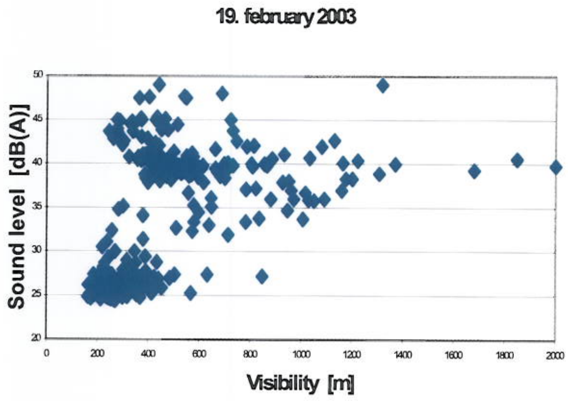

Fig. 6 Measurement 2. AN level as a function of visibility during frosty mist fog.

Figure 7 shows the visibility (recorded by means of a Vaisala hyperterminal) as a function of time and figure 8 the AN level as a function of time. It seems interesting that the AN level increases rapidly as the visibility increases, i.e. the water/ice particle content of the air decreases. This was not what was expected, because normally one associates a high density (and thereby low visibility) of water/ice particles with a high AN level. An explanation could be that the water particles have accumulated on the phase conductors when the frosty mist fog lifts away, because the AN level was very low (comparable to dry, good weather) when the visibility was low and therefore no particles can be assumed to have been present around or at the phase conductors. Another possibility is that the AN appears as a consequence of the frozen snow/ice particles moving in the air in the the vicinity of the phase conductors and discharges taking place between the particles (snowflake, ice fog particle) and the energized conductor, this hypothesis is supported by [1] pp. 181, which also states that snowflakes have been observed to stick more frequently to unenergized than energized conductors. This could explain the fact that AN was low during the period of measurement 2 where visibility was low and that AN increased when the frosty mist fog lifted off and the visibility increased, this was

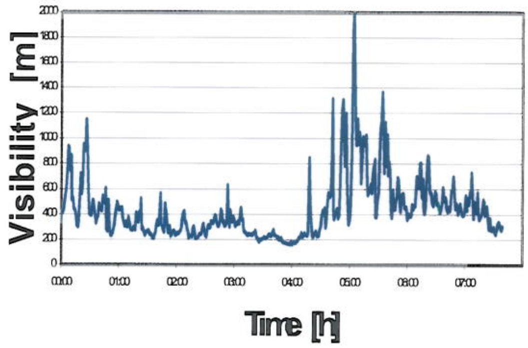

Fig. 7 Measurement 2. Visibility as a function of time during frosty mist fog.

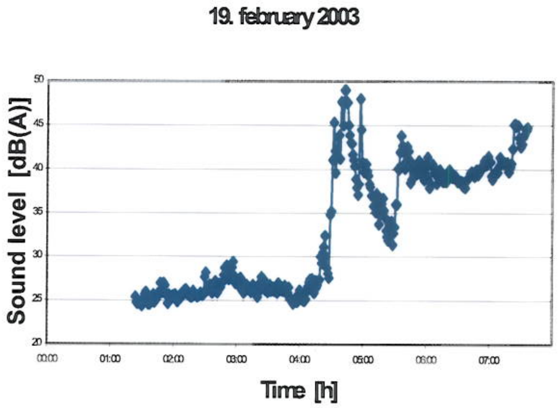

Fig. 8 Measurement 2. AN level as a function of time during frosty mist fog.

monitored both by measuring equipment and man. The ice fog particles and the snow (frozen - not sleet) are not likely to adhere to the surface of the conductors as the temperature was close to or below zero degrees and the AN therefore is likely to have been caused by the presence of the frozen particles moving in the high field region around the phase conductors.

Discussion

Measurement 1 and 2 shows that the AN level during snow and frosty mist fog are the same. This level is seen to be app. 49 dB(A) for both cases and this fact supports the hypothesis that the generation mechanism is due to the moving frozen particles in the vicinity of the phase conductors. The load of the line has been monitored and was found to be constantly very low during the measurement so thermal influence can be excluded. A narrow band analysis of the AN during measurement 2 was found only to contain an insignificant 100 Hz hum component, which normally would have been expected during icy conditions. This again supports that the AN has been generated by particles not present at the surface of the phase conductors, but in the high field region as 100 Hz tends to be dependent of particles (especially hoar frost icing) at the surface. The low, but detectable level of 100 Hz hum during snow (measurement 1) could be explained by some snowflakes attaching to the phase conductors [2].

Measurement 1 and 2 have shown that AN measurements on practical overhead lines can be fairly difficult to perform as one gets levels of AN not easily associatable with a well-defined metheorological condition. Furthermore the presence of either broad band noise and/or 100 Hz hum can be difficult to associate with a specific type of weather.

APPLICATION OF EXISTING AUDIBLE NOISE MODEL TO FIT SNOW/FROSTY MIST

Since wintertime conditions like snow and frosty mist fog is much more "interesting" concerning AN in Denmark and no AN models valid for such conditions are available it is proposed to modify the existing L_5 broad band AN model to fit these conditions. Generated acoustic power acc. to eq. (2) and (3) must be lower during snow as the emitted AN is lower than during L_5 rain. Generated acoustic power A is a function of number of subconductors, n, subconductor diameter, d, bundle geometry, K_n and A_1, which depends on maximum E-field strength so one could state that $A = A_1 \cdot f(n,d,K_n)$ and $A_1 = f(E)$. Assuming the same functional dependency $A_1 = f(E)$ within the range of practical interest, $13 < E < 20$kV/cm [2] one could adjust the figure 665 in eq. (3) to fit the measured AN level of 49 dB(A) during snow and frosty mist fog by means of eq. (5) and (6). This gives generated acoustic power A_1 during snow or frosty mist

$$A_{1,\text{snow}} = 46,4 - \frac{803}{E} \quad [\text{dB(A)}] \tag{8}$$

Figure 9 shows the approach within the practically interesting range $13 < E < 20$ kV/cm for E.

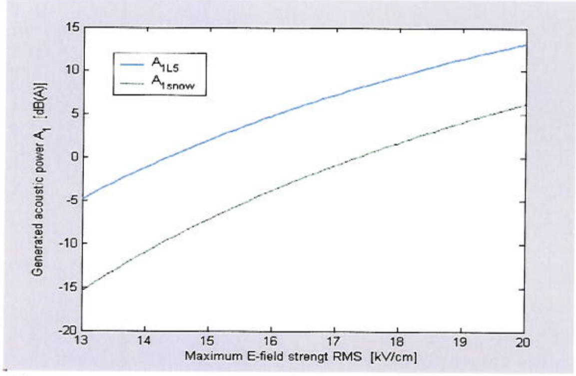

Fig. 9 Acoustic power A_1 for snow and heavy rain as a function of field strength E.

The assumption that the functional dependency of A_1 for heavy rain vs. snow is the same, based on one measurement point is strictly insufficient, but one or two measuring points for other tower/phase conductor types with different E could confirm this or give rise to a slight change in the empiric function, eg. on the basis of the method of least squares. The complete eq. (2) for A takes phase conductor layout (n, d, bundle diameter) into consideration as different layouts ("larger" phase conductors will generate a higher level of AN for constant E than "smaller" ones) will give rise to different levels of stored E-field energy and thereby varying ability to generate AN. The same procedure is applicable concerning the 100 Hz hum. 100 Hz AN during snow is seen from figure 2 to be 35 dB(A) and this figure could be used to calculate generated acoustic 100 Hz power as suggested above. Formulas for this, which are alike the ones for broad band noise, are available in [1] pp. 305-306.

CONCLUSIONS AND FURTHER WORK

Measurements of wintertime AN performance of a 420 kV overhead line, single circuit, horizontal layout with duplex Finch 636 mm^2 ACSR phase conductors has been performed and the following conclusions can be drawn:

- AN level 49 dB(A) measured at ground level underneath the middle of the span during snow or frosty mist.

- Generation mechanism of broad band noise is most likely due to the presence of the moving frozen particles in the high field region in the vicinity of the phase conductors.

- Generation of 100 Hz hum is most likely due to snow/ice particles at the surface of the phase conductors.

- Adaption of existing AN calculation model to fit snow/frosty mist conditions is achieved by adjusting the empiric generation equation.

Suggestions concerning further work could be:

- Supervision of phase conductor surface conditions during AN measurements during snow and/or hoar frost by means of camera in the tower with the purpose of explaining the presence of the 100 Hz hum.

- Further AN measurements for other phase conductor types with varying number and diameter of subconductors with the purpose of validating/adjusting further the empiric generation equation.

Finally it would be of great experimental value to measure the AN during heavy hoar frost with substantial rime on the phase conductors as especially this condition is the major cause of public complaints. Unfortunately this has not yet been practically possible.

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