Abstract: On high voltage overhead transmission lines foul weather usually results in audible noise with a broadband crackling and a tonal component at twice the mains frequency (2f). In the 1960s to 1980s, when the implementation of UHV-AC transmission with voltages up to 1500 kV was being considered, an intensive research into the broadband noise was initiated. However, only a scant amount of literature investigates the mechanism of the tonal component. Recently, an explicit theory together with a procedure to calculate the levels was suggested by one of the authors of this paper. In the work presented here, this procedure is applied to one UHV-AC line design used in the new Chinese 1100 kV UHV pilot project. The resulting 2f-levels are compared to those of the broadband component determined by the method from EPRI. The levels of both components indicate rather low levels.

1. INTRODUCTION

Foul weather like rain, fog, snow and hoar frost can lead to corona on high voltage overhead transmission lines. While under ideal conditions the conductor cables are free of corona-discharges, protrusions such as water drops on the cable enhance the electric field in the vicinity of the drop to a size where corona can set in.

These corona-discharges are perceivable as a broadband crackling and hissing noise, situated mainly in the frequency range of one up to several kilohertz [2]. In such situations the audible noise is generally complemented by an additional component of a low tone at twice the mains frequency (2f, i.e. mostly 100 Hz) and its higher harmonics. In early research this component was ascribed to background noise first [3]. In the 1960s to 1980s, when the implementation of UHV-AC transmission with voltages up to 1500 kV was being considered, an intensive research into the broadband noise was initiated, beginning, to the authors' knowledge, with [3]. Thereafter the intensity of research in this topic decreased but never completely stopped, and it has not lost its topicality.

In the different national regulations, the fundamental assessment criterion is normally the A-weighted noise level [4], which accounts for the different sensitiveness of the human ear towards sounds of different frequencies. Through the A-weighting the 2f-component loses 19 dB (for 100 Hz) of its level, which results in a marginal contribution to the overall A-weighting noise level by this 2f-component.

As the low-frequency tonal noise only contributes a minor share to the A-weighted level, it went largely unnoticed or uncommented. Nevertheless, the tonal 2f-emission can present a significant problem because such low frequency noise is less subject to attenuation by building structures and tonal noise is generally perceived as more annoying than a stochastic signal of the same strength [5]. This latter fact is often taken into separate account by national regulations by adding a supplement to the measured A-weighted overall noise level [6].

Together with this significance in national noise regulations, the 2f-component of the audible noise can present an additional problem because such low frequency noise is less subject to attenuation by building structures.

The broadband noise is formed by single pulsative corona-discharges. These result in the emission of single acoustic pulses [7]. The bigger the energy released in the discharge, the bigger is the emitted acoustic pulse and the lower is its middle frequency [8]. The latter is the reason why the measured frequencies of the acoustic pulses emitted by Trichel-discharges are measured in the ultrasonic range [9]. Thus, for the broadband level, only strong pulsative corona-discharges are relevant.

In corona the types of discharges to be found are Trichel-discharges, Glow and, only in the positive half-wave, Onset- and Breakdown streamers [10]. As Glow is pulse-less and the Trichel-discharges are mainly in the ultrasonic frequency range, only Onset- and Breakdown streamers are of relevance for the broadband AN.

There exist vast numbers of methods and formulas for forecasting the A-weighted levels of the broadband component of the AN from high voltage overhead
transmission lines. One of the best known may be the procedures of the Transmission Line Reference Book [11].

In a part of the experimental assessment of the audible noise, the 2f-component is noted passim. The scant literature [7] and [12-15] suggesting a mechanism of this 2f-emission is either vague or controversial. The mechanism of the emission of this 2f-component has therefore remained unclear until recently.

To the authors’ knowledge a quantitative description of the mechanisms leading to 2f-emissions was proposed for first time in [16]: While the high-frequency crackling and hissing component of corona noise emissions dominating the A-weighted level has its immediate origin in the corona-discharges themselves, the 2f-emissions arise from the movement of ions left behind by the discharges. These ions move in the drift-zone, where they scatter. Thereby they transmit heat and in the sum a force to the neutral gas. Both quantities—heat as well as force—are sources of 2f-emissions. Both can give rise to 2f-levels of similar magnitude depending on the situation. The computation of the emitted levels presupposes the knowledge of the warmth and the force evoked by the ions around the conductors.

In this work a specific UHV-Line design is investigated concerning both components of audible noise. To determine the broadband levels, the procedure of the Transmission Line Reference Book is used [11]. The evaluation of the 2f-levels is conducted according to [16]. This method is sketched passim during the determination of the levels. Finally, the levels are compared.

2. THE UHV-LINE UNDER CONSIDERATION

The geometry, phase arrangement, bundle geometry of the UHV-line for which the audible noise is calculated is shown in Figure 1.

The design corresponds to one of the new Chinese 1100 kV UHV-AC pilot project. The electric fields used to calculate the broadband noise are determined by means of an FEM-software. The average electric surface gradients on the conductor bundles amount to 11.5 kVrms/cm for the phases L1, L3 and 12.1 kVrms/cm for the phase L2. Due to the relatively massive bundle geometry, the electrical fields on the conductors are rather small.

3. CALCULATION OF THE A-WEIGHTED AN WITH EPRI’S FORMULA

The resulting average-maximum bundle gradients E (arithmetic mean of the maximum gradients in rms of the individual conductors in the bundle) add up to 13.8 kVrms/cm for the phases L1 and L3 while that of the phase L2 is 14.53 kVrms/cm.

The sound levels are calculated with the method of the Transmission Line Reference Book by EPRI [11]. The exceedance levels L50 and L5 resulting from this calculation procedure are depicted in Figure 2. According to [11] the procedure applies to moderately aged cables. Therefore, higher levels have to be expected at the time of commissioning the line.

4. CALCULATION OF TONAL COMPONENT

4.1. Drift of the ions and the corona-current

Water drops are elongated in the electrical field due to their dielectric behavior. With the deformation of a drop, the electric field strength itself is increased again. If the elongation of the drop is increased to a certain extent, the so-called Taylor-cone is formed and the point of the Taylor-instability is reached. The latter results in a water jet ejected from the tip of the drop [17]. With the excessive field strength in this process, corona-discharges may set in. As mentioned before, these can be the types of Trichel-discharges, Glow and Onset- and Breakdown-Streams. Corona-discharges are not confined to water drops, so henceforth the more general term protrusion will be used.
If a corona-discharge occurs, one can distinguish two regions: the ionization-region and the drift-region (Figure 3).

![Corona-discharge regions](image)

**Figure 3:** Schematical representation of a corona-discharge, where the ionization- and the drift-region are sketched.

The ionization-region, where the field strength is sufficiently high so that ionization of the gas dominates, is typically constricted to diameters less than 1 mm. Attached to this zone is the drift-region, where attachment of the electrons dominates; hence negative ions are formed. These drift together with the positive ions in the electric field \( \mathbf{E} \) with the velocity \( \mathbf{v} \) according to

\[
\mathbf{v} = \mu \mathbf{E} ,
\]

where \( \mu \) is the mobility of the ions [18]. In the simulation the mobility is chosen to be \( \mu = \pm 1.7 \text{ cm}^2/\text{Vs} \), which according to [18] is a typical value. Starting from the conductor, ions can drift over distances of several decimeters during a half-wave.

The drift is the average motion of the ions, which is actually dominated by collisions in the neutral gas. These collisions have two consequences. A single ion with the charge \( q \) evokes in the average a force \( q \mathbf{E} \) acting on the neutral gas on the one hand and, on the other hand, an energy transfer according the rate \( \mu q E^2 \).

Simple examinations show that this power is mainly transferred to a rise of warmth [16].

These two quantities may act as sources of sound emission. As, due to the discharge activity, these quantities arise twice per period of the mains voltage, these sources bear a major \( 2f \)-component.

4.2. **Tonal emission**

The consequence of this force \( f \) and the enthalpy \( h \), concerning the sound pressure \( p \) are described with the wave equation [16]

\[
\frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} - \Delta p = -\text{div} \mathbf{f} + \rho_0 \left( \gamma - 1 \right) \frac{\partial^2 h}{c^2 \partial t^2} ,
\]

where \( t \) is the time, \( \rho_0 \) and \( c \) the density and the speed of sound in air respectively; \( \gamma \) is the heat capacity ratio. With known sources, the sound pressure is determined.

Solving of (2) is simplest, if the sources are confined to line sources, i.e. the extension of the source \( d \) is much smaller than the wavelength \( \lambda \). The simulation shows that the main contribution of the drifting ions to the sources is close to the conductor cables. Constricting the spatially distributed force and power acting on the gas to one line for each phase is a good approximation for small bundles such as for example diameters of 40 cm. For the bigger bundle geometries like under investigation here, \( d \ll \lambda \) is not fulfilled to that degree anymore. However, with the idea to provide a rough estimation of the levels of the tonal component, this approximation is nevertheless made. For this reason, the thus calculated \( 2f \)-levels are rather too high.

The power describing the rate of introduced warmth is given by the corona-current itself [19]. This current can be measured and therefore the contribution of the warmth source calculated. This is not possible for the force, where measurement is not on-hand. Which of these sources dominates is not clear a priori. The calculation of the \( 2f \)-levels is made possible by the simulation of [16] sketched in the following section.

4.3. **Determination of the warmth- and force-sources with a simulation**

In literature on theoretical description of corona losses a critical surface gradient \( E_c \) is often used, as for example in [20]. To every surface condition (i.e. is for example water drops) a critical field strength \( E_c \) is defined, above which discharge (i.e. ions injected into the drift region) sets in. According to (1) these ions drift along the electrical field. Ions of the one polarity drift away from the conductor, those of the other polarity drift towards the conductor, where they are neutralized. The remaining ions, i.e. those drifting away from the conductor, reduce the surface gradient on the conductor. Within this ansatz the amount of injected ions due to discharges is such that the surface gradient on the conductor does not exceed \( E_c \).

For the simulation of [16] used here, not only a global value for \( E_c \) is needed, but the dependence on the polar angle \( \theta_c(\theta) \). The value of \( E_c \) changes with respect to \( \theta \), as larger drops occur mainly on the underside of the cable, while on the upper side only smaller drops with higher onset fields are present [16]. The values for Ec used here are depicted in Figure 4; they correspond to a new conductor-cable under rain between moderate and strong intensity (some mm/h) [16].

The results of the simulation are apparent powers at twice the mains frequency of 71 VA/m and 96 VA/m for the outside phases and phase L2 respectively. The
force at twice the mains frequency is 0.21 N/m for L1 and L3, while that of L2 amounts to 0.25 N/m.

Figure 4: Dependence of the critical surface gradient $E_c$ on the polar angle $\theta$ for moderate rain as used in the simulation.

4.4. Lateral profile of the 2f-levels

Solving the wave equation (2) for point sources and unbounded space and introducing the values for the sources of every phase mentioned in the previous section, the sound pressure field for unbounded space for every single phase is known.

While adding these fields together, the phasors of the single components must be accounted for. These consist of the dependence of the sources to the phase angles of the electric phases and of the delay due to the distance of travel to the point of interest. For sound waves of low frequency such as 100 Hz, the reflection on the ground is generally almost perfect. Thus the sound pressure near to the ground is doubled or the noise level increased by 6 dB.

The resulting A-weighted sound levels at twice the mains frequency for the sources mentioned in the previous section are depicted in Figure 5.

As the phasors of the sound waves from the single phases change differently along the lateral distance from the line, a complex interference pattern is formed, with maximum values of sound pressure, when the phasors coincide and with the lowest values, when the contributions of the phases cancel each other out.

Although the effect of the ions on the gas is small, it is obviously high enough to evoke noteworthy tonal emission all the same.

As the levels depicted in Figure 5 are calculated for new cables, they are expected to be reduced substantially with the ageing of the conductors: The mechanism of the tonal emission is directly connected with the process which also evokes the corona losses. Therefore it is not surprising that the 2f-emission and corona-loss are correlated in a noteworthy manner, as shown in [11] (p. 313). The reduction of corona-losses with conductor ageing is widely known and quite notable.

5. CONCLUSIONS

The relatively low surface field gradients of the investigated UHV-line indicate rather low A-weighted broadband- (Figure 2) as well as 2f-levels (Figure 3).

The direct comparison of the levels of the two components of audible noise are only of limited significance, as the broadband component is calculated for moderately aged cables, while the tonal component is determined for new ones. Nevertheless, the maximum values of the tonal component seem to be quite significant compared to the broadband component. These large 2f-levels decrease rapidly with conductor ageing.

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7. REFERENCES


