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Audible noise of hybrid AC/DC overhead lines: Comparison of different prediction methods and conductor arrangements

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***Abstract*—The concept of partial conversion of existing tower phase arrangements to hybrid HVAC/HVDC overhead lines has become an attractive solution to meet the demand for higher power transmission capacity. Due to mutual AC/DC coupling effects, corona phenomena such as audible noise can be affected and have thus to be predicted accurately. In this paper, existing empirical equations are used to predict corona audible noise for several hybrid AC/DC tower geometries and conductor arrangement scenarios.**

For some of the examined conductor arrangements, the surface gradient on the AC conductor is significantly affected by a DC bias from an adjacent pole, leading to a possible increase in audible noise. Furthermore, for some of the investigated scenarios, very high surface gradients on the DC conductors occur, resulting in remarkable DC fair and even foul weather audible noise levels. Large deviations between different prediction methods are observed and discussed. Depending on the conductor arrangement, the foul weather DC audible cannot be neglected for hybrid towers and contributes to the AC noise.

***Index Terms*—hybrid transmission lines, tower conversion, HVAC/HVDC overhead lines, corona, audible noise, coupling effects**

I. Introduction

A. Motivation for hybrid overhead lines

To meet the increasing demand for transmission capacity and to integrate large scale decentralized hydro and wind power plants, high voltage direct current (HVDC) transmission is a promising technology to realize long-distance bulk transmission at high efficiency. Long planning times due to low public acceptance are major difficulties in the construction of new overhead lines. The conversion of existing multi-circuit high voltage alternating current (HVAC) transmission towers to hybrid AC/DC towers is an option to increase power transmission capacity within a shorter time-frame with presumably lower public resistance. At least one AC system would be kept for easy tap-off and to continue to support the AC grid. The DC system could be operated at a higher effective voltage (with the same insulation distances). Additionally skin effect losses do not occur and reactive power compensation is not required.

As shown by Straumann and Franck as well as by Lundkvist et al., the possible increase factor of transmission power is in the range of 2.2 per system and 1.6 for a double-circuit AC tower (for the conversion of one AC system from a double-circuit 400 kV tower to a 500 kV bipolar DC system without a neutral conductor) [1, 2]. While the skin effect for typical conductor diameters between 20 and 35 mm increases the AC resistance only by about 3-5 %, the main reason for the higher transmission capacity is the possibility to increase the DC voltage significantly. This is in part due to the fact that, contrary to AC, the crest voltage, which controls the insulation requirements, coincides with the r.m.s. voltage, which is proportional to the power transmitted.

B. Different corona phenomena in steady and alternating fields and weather conditions

While the visual changes of a converted system are expected to be negligible, the presence of DC voltages leads to mutual coupling effects. This includes electrostatic induction, capacitive and inductive coupling, as well as DC ion current coupling [3]. Mutual surface field induction can influence the ionization processes on the conductor surfaces and therefore the corona effects can be altered. Since the concept of hybrid overhead lines is based on the assumption of higher public acceptance, environmental effects caused by corona have to be kept at a minimum.

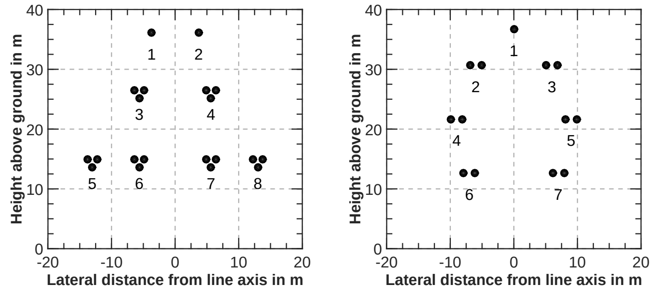
One major effect of overhead lines is the audible corona noise (AN). The noise can be divided into two different components. The energy created by the ionization process causes a spontaneous heating of ambient air, causing a sound emission at individual point sources. This results in a broadband hissing and crackling component, contributing to the A-weighted sound pressure level. The second component is created by the periodic movement of the ions created in each half-cycle of the AC system. This transfers energy to the surrounding neutral gas molecules and causes a low frequency humming noise at twice the power frequency [4, 5]. The first component is present in AC as well as DC transmission, whereas the second one only occurs in AC. According to [6], the humming component is less annoying compared to the A-weighted broadband component of the same sound pressure level. Generally, only the A-weighted level is specified by industrial noise regulations, sometimes complemented by an additional constant for the hum component.

Although AC and DC corona effects are created by the same phenomena, there are two major differences regarding audible noise. Whereas the corona loss current increases both with pulse amplitude and repetition rate of discharge impulses, audible noise is dominated by their discharge amplitude [7]. Therefore, the acoustic power generated by positive onset streamers, which have a high pulse amplitude and low frequency, is significantly higher than the emission from negative Trichel streamers, which have a low pulse amplitude but high frequency. Additionally, EPRI investigations have shown that corona sources, such as particles and insects in the air, are often charged negatively and are therefore attracted by the positive pole [8]. For DC transmission systems, the audible noise contribution from the negative pole is therefore neglected while in AC systems the superposition from all three phases needs to be considered.

The second main difference relates to the formation of ion space charge clouds around the conductors in DC systems. Unlike in AC, the space charges created around a DC conductor do not vanish periodically. Field enhancements, such as particles and water drops, are shielded by ions of the same polarity as the conductor. While foul weather corona is the worst case for AC audible noise, summer fair weather is more critical for DC [8–11]. On wet DC conductors, stable discharges from water drops lead to high mutual space charge shielding, which results in low pulse amplitudes and low audible noise. In fair weather, the separation between adjacent particles or insects is higher so that shielding effects are decreased.

Additionally, also the shape of corona sources has a high impact on their effects. According to Akazaki et al., sharp drops produce corona with high repetition rate but short impulses due to their very inhomogeneous field distribution. This results in a high corona current and lower audible noise (described as a hissing sound)[12]. Such sharp drops are frequently created by the strong fields on DC conductors and are called Taylor cones [13]. Since their frequency of appearance is highly dependent on the surface of the conductor [14], the conductor type is expected to have an influence on DC audible noise and radio interference as well.

Concerning the concept of hybrid AC/DC overhead lines, only a few studies exists in which possible coupling effects are investigated in an outdoor test arrangement [3, 15, 16]. All studies agree that the influence of the AC ripple created by electrostatic induction on the electric field on the surface of DC conductors has a negligible effect. In contrast, the DC bias on the electric field on the surface of AC conductors may have an effect, although it has been interpreted differently by different investigators.



(a) US design (b) Swiss design

Fig. 1: Geometry of the two implemented tower models from EPRI and ETH (average height)

The investigations of [15] show that a nearby negative pole is likely to increase the AC foul weather noise due to an enhancement of the positive half-cycle surface field gradient. Similarly, a positive pole decreases it. In contrast, EPRI's hybrid tower study indicates an increase with both positive and negative bias. However, it was found that both cause only a slight increase in audible noise, even for a relative bias of almost 100 % of the AC surface gradient, leading to the conclusion that this effect is negligible [3]. Hence the existing approaches treat the capacitive coupling differently. This will therefore be critically discussed for different conductor arrangements.

II. Calculation methods & tower scenarios

A. *Tower geometry*

In order to investigate possible difficulties of a hybrid tower conversion, two different structures, as shown in Figure 1, were selected as test cases. For each tower structure, a number of different conductor arrangement scenarios were considered. ETH provided a tower arrangement similar to the ones used in Switzerland, herein referred to as Swiss tower. EPRI proposed a different tower geometry, herein referred to as US tower.

There are some obvious differences between both designs. Compared to a lower operating voltage of 420 kV instead of 500 kV, the lowest conductor level of the Swiss tower has a higher separation to ground. This is partially due to the very strict regulations for the magnetic field levels in Switzerland (1 μT at ground level). As the magnetic field is optimized through a symmetric tower arrangement with the current flowing in opposite directions, the electric field is increased and thus, the structural height has to be enhanced. In case of a hybrid conversion, the symmetry and hence, the magnetic compensation is lost. To meet the regulations, a compaction of the remaining AC system as proposed by Pfeiffer et al could be implemented [17].

Additionally, the Swiss transmission system operator (TSO) is obliged to design the tower structure for very heavy ice loads per conductor since they traverse alpine regions. Therefore the bundles consist of only two 28 mm

TABLE I: List of the simulated conductor arrangements for the US and Swiss tower (the AC phases are designated with R, S and T and the neutral DC conductor with DC N, positions as indicated in Figure 1)

Position	**US tower design**			
(f.l.t.r.)	**US-A**	**US-B**	**US-C**	**US-D**
1	GND 1	GND 1	GND 1	GND 1
2	GND 2	GND 2	GND 2	GND 2
3	DC N	DC +	DC +	DC -
4	AC R	AC R	DC -	DC N
5	DC -	DC -	DC N	DC +
6	DC +	DC N	AC R	AC R
7	AC S	AC S	AC S	AC S
8	AC T	AC T	AC T	AC T
	Swiss tower design			
	CH-I	**CH-II**	**CH-III**	
1	GND	GND	GND	
2	AC R	DC +	DC +	
3	DC +	DC -	DC -	
4	AC S	AC R	DC N	
5	DC -	DC N	AC R	
6	AC T	AC S	AC S	
7	DC N	AC T	AC T	

conductors with a bundle spacing of 40 cm to omit mechanical problems whereas the US bundles consist of three 38.2 mm conductors with 45.72 cm spacing. The more compact Swiss tower is operated with only one ground wire, whereas the broader US design is protected by two wires. The average sag at midspan over different weather conditions was assumed to be equal to 8 m for both structures, resulting in an average height of $2/3 \times 8$ m = 5.33 m below the suspension point.

The investigated conductor arrangement scenarios are listed in Table I. The examined scenarios include several cases in which the DC and AC systems are on separate sides of the tower, as well as cases in which they are mixed. The cases therefore include different degrees of mutual coupling and conductor field strengths. For the Swiss tower scenarios, an additional study of the effect of varying the DC voltage from 400 to 500 kV was conducted. Out of this large number of combinations, the scenarios with the most interesting results were chosen to be discussed in detail in this publication.

B. Determination of the surface gradient

The Laplacian (space charge free) electric field strength on the conductors is a parameter for the empirical audible noise equations. It was calculated by both EPRI and ETH using different methods. EPRI uses the Method of Multiple Images applied to equivalent bundle diameters as explained in [9] while ETH has implemented the Charge Simulation Method (CSM) as presented in [18] with 150 charges and test points per single conductor. Additionally, the distance between charges and test points was set equal to the gap between two adjacent charges to improve the

TABLE II: Calculated bundle surface gradients for Scenario US-C. According to the IEEE definition in [19] these values are the averages of the maximum gradients on the surface of the subconductors of the bundle.

	Peak Electric field (in kV/cm)			
	AC only	**DC only**	**AC + bias**	**AC − bias**
GND 1	0.88	-8.10	-	-
GND 2	1.44	8.10	-	-
DC +	1.47	23.83	-	-
DC -	0.99	-23.83	-	-
DC N	3.38	-1.67	-	-
AC R	19.38	-1.34	18.04	20.73
AC S	20.48	1.35	22.33	19.64
AC T	19.75	1.68	21.44	18.07

CSM accuracy. In a comparison of the average maximum bundle gradients both methods showed good agreement with maximum deviations of 1 % having only a very small impact on the resulting audible noise levels.

Since electrostatic induction affects the surface gradients, it is expected to have an influence on the audible noise. The pure AC and DC components of the surface gradient of the AC conductors are calculated separately and superimposed to determine the biased AC field for both the positive and negative half-cycle. The same procedure applied to the DC conductors allows the determination of the AC ripple on the DC surface gradients. As mentioned above, the literature agrees that the latter effect is negligible and is therefore disregarded.

As an example, in Table II the pure and mixed surface gradients are shown exemplary for Scenario US-C, which will be further discussed later on. Since the AC formulas require to input the r.m.s. field strengths, the resulting biased peak gradients were divided by $\sqrt{2}$. Comparing the different tower arrangements, it can be seen, that placing each pole on a separate side of the tower results in lower DC surface gradients. Hence, DC audible and radio noise are expected to decrease. The same is true for the ion current density and field strength on the ground. Still, this separation comes along with an increased coupling to the AC system with a rise of the surface gradient in the positive or negative half-cycle. Additionally, the DC ion current coupling to the AC phases causes a DC component in them. This can lead to transformer saturation according to Heindl et al. [20]. Due to the smaller bundles on the Swiss towers even a moderate DC voltage of 400 kV leads to very high surface gradients of 32 kV/cm exceeding 40 kV/cm for 500 kV. Thus, the DC corona effects are considerably increased as shown later on.

C. Formulas for AC foul and DC fair weather noise

Based on the calculated conductor surface gradient, the audible noise generation and ground distribution for each bundle are deduced. It is well known that the audible noise increases with the bundle surface gradient due to higher pulse amplitudes. While a higher number of bundle conductors or larger diameter does reduce the surface gradient, they increase the audible noise for the same gradient due to lower field decay around the corona source.

Various empirical formulas already exist, that have been derived from measurement data using corona cages and test lines. All of these equations consist of multiple terms that represent a fitting considering the number of bundle conductors and their subconductor diameter as well as the bundle gradient etc. [10, 21].

Due to the acoustic line characteristic of full-scale overhead lines, the sound pressure level decreases logarithmically with R_{dist}. While EPRI accounts for the absorption in air with an additional term, this is included in a higher C_5 for the BPA (Bonneville Power Administration) formula. Hence, the values at ground level can also deviate for equal acoustic power generation levels due to the different equations used for the sound propagation.

$$L_{\mathrm{w50}} = C_1 + C_2 \times \log_{10}(E_{\mathrm{am}}) + C_3 \times \log_{10}(n_{\mathrm{con}}) + C_4 \times \log_{10}(d_{\mathrm{con}}) \quad (1)$$

$$L_{\mathrm{p50}} = L_{\mathrm{w50}} - C_5 \times \log_{10}(R_{\mathrm{dist}}) + C_6 \quad (2)$$

with:

L_{w50} = Sound power level in dB(A) re 1 W/m
E_{am} = Average maximum bundle gradient in kV/cm
n_{con} = Number of subconductors in 1
d_{con} = Subconductor diameter in mm
L_{p50} = Sound pressure level in dB(A) re 20 μPa
R_{dist} = Distance to bundle
$C_{1..6}$ = Constants defined by empirical fitting

In [21] a lot of these available formulas are listed and compared with their deviation using real on-site measurements. According to the test study, the best results for foul weather noise were obtained with the EPRI [9] and the BPA method [10]. The EPRI method is especially popular with transmission system operators, as it contains a correction factor for a high range of rain intensities. In order to also examine the influence of mutual coupling between the adjacent systems on audible noise, the foul weather noise is evaluated for three different cases:

- AC foul weather EPRI classic according to [9]
- AC foul weather EPRI hybrid according to [16]
- AC foul weather BPA hybrid according to [15]

In the first case, the classic EPRI formula is used without accounting for a DC bias (henceforth referred to as 'no bias case').

In the second case, the same formula is used accounting for the DC bias as presented in [16]. In this case an adjacent negative pole will increase the AC noise in the positive half-cycle, while a positive pole would increase the noise in the negative half-cycle. As the negative Trichel pulses are reportedly emitting lower noise level, 4 dB have to be subtracted from the regular AC formula to calculate the noise in the negative half-wave. The final audible noise result for the biased AC conductor is considered to be equal to the highest of the noises measured during the positive and the negative half cycles. A positive DC bundle is therefore likely to reduce foul weather noise, but could also increase it due to a strong bias in the negative half-cycle.

For the last case, the BPA assumption from [22] was chosen. While the pure AC formulas of EPRI and BPA lead to quite similar results for the unbiased approach, Chartier et al. observed a decrease of foul weather noise for a negative DC offset and therefore neglected the noise emission during the negative half-cycle. Still both hybrid methods neglect any influence of space charge.

TABLE III: Calculated AN generation for Scenario US-C

	Generated acoustic power (dB above 1 W/m)					
	AC foul weather			**DC fair weather**		
	EPRI	EPRI bias	BPA bias	EPRI	CRIEPI	BPA
AC R	-63.20	-62.88	-65.38	-	-	-
AC S	-58.11	-54.38	-54.27	-	-	-
AC T	-61.96	-56.82	-56.41	-	-	-
DC +	-	-	-	-58.47	-58.99	-59.10

Various empirical equations were developed to predict DC line audible noise. It was decided to investigate the EPRI, BPA and CRIEPI (Central Research Institute of Electric Power Industry of Japan) methods which were based on a large amount of empirical data:

- DC fair weather EPRI according to [8]
- DC fair weather CRIEPI according to [23]
- DC fair weather BPA according to [10]

Based on the surface gradients in Table II, the sound power levels are evaluated and shown in Table III. It can be seen that the foul weather noise is affected by the DC bias for both hybrid approaches in a similar way close to the negative pole. Interestingly, while the positive pole increases the noise level using the EPRI method, the BPA method actually predicts a decrease.

D. Discussion of the influence of space charge

Regarding the ion current coupling, all approaches are based on the Laplacian surface gradient and therefore neglect the effect of space charges in DC or hybrid arrangements. Recently, Pfeiffer et al. discovered different mechanisms of current coupling in a hybrid reduced scale laboratory arrangement [24]. It was found that a DC current is coupled to the AC system via two mechanisms. The first one is due to a drift of ions produced at a DC conductor and collected at the AC conductor. The second one is due to ions produced at the AC conductor that are attracted by the DC conductor. If both AC and

DC conductors produce corona, as it would be the case during foul weather, measurements demonstrated that the resulting DC current in the AC system was much higher than the sum of both individual effects. Thus it has to be expected that under rainy conditions AC and DC corona effects are coupled via the ion current. Considering the audible noise of hybrid lines, there could thus be two additional effects besides electrostatic induction.

Firstly, the ionic space charge shielding on the AC conductor could be affected by DC ions drifting to the AC conductor. Depending on the emitting polarity, negative ions could recombine with the positive space charge around the AC conductor and therefore reduce the shielding effect in the louder positive half-cycle. Consequently also DC ions from the positive pole could decrease the DC surface gradient in addition to electrostatic induction effects.

Secondly, as a consequence of an increase of the corona current on the AC side due to adjacent DC corona, the space charge density around the AC conductor is increased. The low frequency humming component, which is caused by collisions between ions and neutral gas molecules [4, 9], could therefore be increased.

To the author's knowledge the only audible noise calculation approach dealing with space charge effects has been presented by Maruvada and Drogi in [25]. Based on their calculation of the ion trajectories, the DC bias on the AC conductors can be calculated via the Poisson equation including the space charge distribution. Depending on the tower structure their simulations revealed a bias increase of up to 3 kV/cm. Under this assumption, the predicted audible noise levels were about 2 dB higher compared to the case considering the bias without space charges. As the prediction approach of Maruvada and Drogi has not yet been compared with measurement data, the influence of space charge is still to be verified experimentally.

III. Simulation results

A. Influence of tower and conductor arrangement

When investigating the different scenarios, there is a high influence of the bipole arrangement on the surface gradients and thus on the emitted audible noise. In general, there are two different approaches: both poles can either be placed together on one side of the tower or they can be separated from each other on opposite tower sides.

While separating the poles on different sides of the structure will certainly reduce the surface gradients on the DC bundles, an arrangement close to the AC conductors increases mutual coupling effects. It becomes clear that the different corona effects are a coupled problem. A reduction of hybrid (AC/DC) coupling effects can be achieved at the cost of increased fair weather noise as well as higher ion current densities and field strengths at ground level.

Table IV shows the sound pressure level 15 m laterally from the outside phase in 1.5 m above ground for all Scenarios at a DC Voltage of 500 kV. The highest fair weather levels at a height of 1.5 m above ground were obtained for Scenario CH-I for the Swiss tower as well as for US-A for the US structure. In these two cases, the DC surface field strength is dominated by the small pole separation. By contrast, the highest impact of the AC audible noise due to a DC bias was observed for the US-C and the CH-III scenarios, in which the DC poles are situated on different sides of the tower and the AC and DC systems are close to each other.

TABLE IV: Sound pressure levels 15 m laterally from the outside phase for all scenarios at 500 kV

	Sound pressure level (in dBA)					
	AC foul weather			**DC fair weather**		
	EPRI	EPRI bias	BPA bias	EPRI	CRIEPI	BPA
US-A	44.6	44.4	41.4	47.1	52.2	43.3
US-B	44.3	43.5	42.0	37.8	36.5	36.5
US-C	44.0	48.0	46.7	39.9	39.9	37.9
US-D	44.0	45.7	44.4	41.9	40.2	40.0
CH-I	50.3	50.6	48.8	63.7	51.2	46.7
CH-II	49.4	50.3	46.4	61.2	47.3	45.0
CH-III	49.4	53.2	52.1	61.2	47.3	45.0

B. Impact of electrostatic induction on AN prediction

As an example of the influence of a DC bias on the noise level at ground, the audible noise lateral distribution for Scenario US-C is given in Figure 2. In this case the negative pole is close to the AC phases resulting in an increased surface gradient in the positive half-cycle. While the fair weather noise is quite low due to the higher placement of the DC conductors, both formulas that account for electrostatic induction show an increased noise level of up to 4 dB, which is audibly significant. A similar result was obtained for scenario CH-III at 500 kV, in which the relative bias is much higher because of the increase of the DC voltage (while the AC voltage remains constant). The DC bias of 23% in CH-III leads to a sound power level increase of more than 7 dB whereas a considerably lower bias of 12% in US-C does increase the generated acoustic power by about 4 dB on two AC conductors which hence sum up energetically.

This again demonstrates the importance of the superposed noise contribution of multiple bundles in AC foul weather noise. In certain cases a pronounced increase in generated acoustic power on one of the AC conductors can become negligible in the total sound pressure level at ground level. Smaller increases on more than one AC phase, however, can actually increase ground level audible noise. Even if such an influence might be below the audible sensitivity of the human ear, it is still measurable and could exceed regulation limits.

C. Deviations between the empirical approaches

In Figure 3 the audible noise lateral profile is plotted for Scenario CH-I in which both DC conductors are placed on the same side of the tower for 400 and 500 kV. Due to

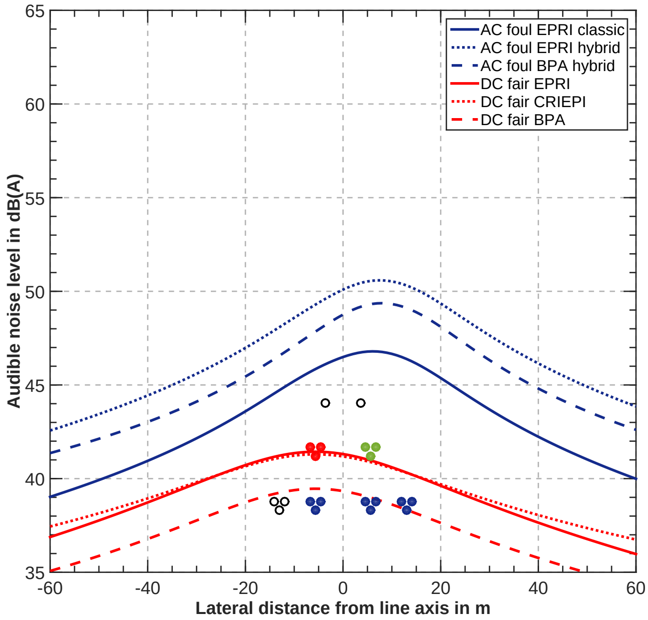


Fig. 2: Different results for the AC foul weather audible noise lateral distribution on the ground with and without bias for Scenario US-C with the AC system in blue, positive pole in red, negative pole in green and grounded bundles in white

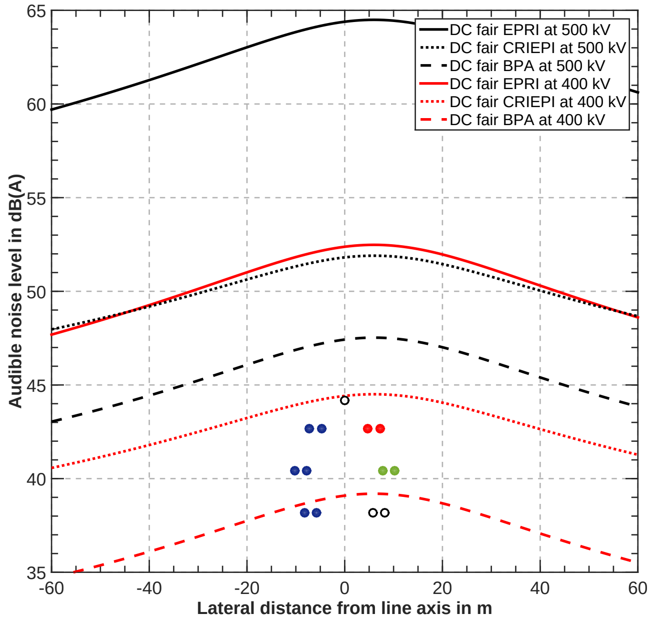


Fig. 3: Deviation between the results of empirical DC formulas at very high field strengths for Scenario CH-I with the AC system in blue, positive pole in red, negative pole in green and grounded bundles in white

the conductor arrangement the small bundles and low conductor diameters, the resulting DC surface gradients are extremely high with about 32 and 40 kV/cm. Regarding the fair weather prediction, the different formulas result in quite different noise levels for this case. Already at 400 kV the implemented methods differ by about 13 dB which increases up to nearly 20 dB for the 500 kV case. The deviation between the three formulas for the same case is higher than the increase in noise predicted for a voltage increase from 400 to 500 kV. This is remarkable and therefore discussions on the different methods are necessary in order to clarify which values are to be trusted.

The reason for this deviation is that all existing formulas are fitted to different sets of measurement data. High surface gradients in the order of 40 kV/cm were typically not considered to be of interest. Hence, there is good agreement for the various formulas at a typical range of 20-28 kV/cm, whereas for higher values they diverge due to their fitting functions. While the semi-empirical fair weather formulas of EPRI and BPA are based on measurement data for field strengths of around 20-28 kV/cm, the CRIEPI formula was fitted to an extended range of field strengths of up to 33 kV/cm for three and four conductor bundles and 40 kV/cm for two conductor bundles. To the author's knowledge this is the only formula that includes measurement data at such high field stresses, and is thus believed to deliver the best match above 28 kV/cm.

The maximum acceptable value that the surface gradient of a DC bundle should have, was suggested by CIGRÉ in [26] to be 25 kV/cm. Even if the audible noise at ground level would not exceed regional regulations, other corona effects, as for example ion current densities and field strengths on the ground, strongly increase with the gradient thus limiting the possible voltage increase.

Hence, to maximize the transmission capacity, an increase in the number or diameter of subconductors should be considered and the mechanical properties of the tower should be optimally exploited. One possible measure for the Swiss towers would be to convert the three AC duplex bundles to a positive and a negative triplex bundle without a neutral conductor. Besides a considerable decrease of the surface gradient, also the transmission capacity would increase as demonstrates in [1, 2]. However the neutral conductor would no longer serve as return conductor in case of a short-circuit with potential problems due to the earth return.

D. Overlap of AC and DC foul weather noise

Heavy rain and summer fair weather represent the worst case situation for AC and DC corona noise respectively. In hybrid transmission systems, where both systems are present, other weather conditions may need to be considered. As previously discussed, the conversion of existing AC structures to hybrid AC/DC will most probably lead to higher DC surface gradients than they would occur in newly designed DC systems.

In case of relatively high DC fair weather noise, as it is predicted for Scenario US-A, the question arises whether DC foul weather noise can still be neglected. According to the investigations of BPA and EPRI in [10] and [8], the DC noise emission in wet or rainy conditions is roughly 6 dB lower than the summer fair weather levels. Depending on

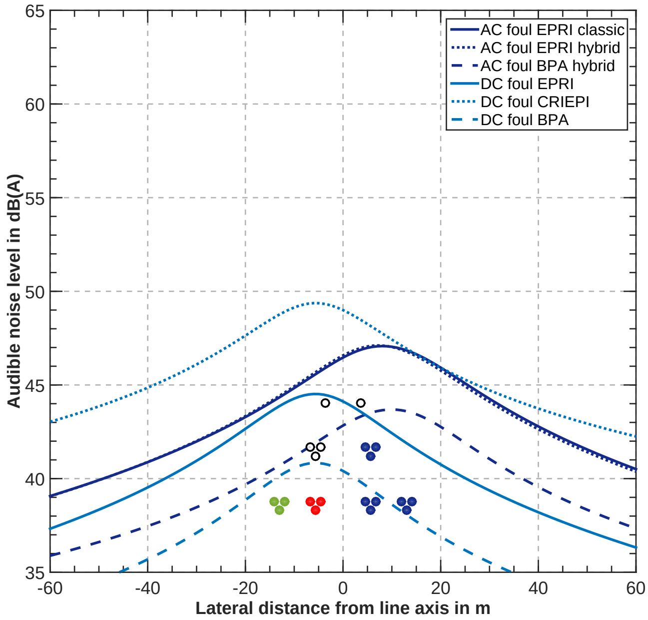


Fig. 4: Overlap of AC and DC foul weather noise distribution for Scenario US-C with the AC system in blue, positive pole in red, negative pole in green and grounded bundles in white

the season, IREQ in [11] predicts a decrease of only 1-4 dB in foul weather. In light of the dependence of the DC corona current on rain intensity as shown in [27], it can be expected that DC noise may also be affected by rain intensity. Therefore this deviation is expected to be caused by different rain intensities and regional differences in fair weather noise. In contrast to the rain rate correction factor established for AC in [9], no approach of this type is available for DC foul weather noise.

To study the DC noise in rain, 6 dB were substracted from the predicted fair weather values (the most conservative value from the above discussion). The results are shown in Figure 4. The result demonstrates that in certain situations even DC foul weather noise can reach levels equal or above those of the adjacent AC system. Due to the superposition of both AC and DC noise in foul weather, the level would hence be increased by 3 dB or more for DC levels equal to or above the AC noise in rain.

While HVAC overhead lines are designed in a way that a clean conductor is not in corona, still, particles and insects can attach to it, resulting in fair weather AC noise. According to [9], audible noise could be measured during fair weather periods but it is still a minor problem. The difference to foul weather noise during heavy rain is typically around 10-15 dB but decreases with increasing surface gradient and can even become zero at extremely high gradients [28]. Since typical AC r.m.s. surface gradients are usually around 15 kV/cm the authors believe that the AC fair weather noise will be negligible in most cases. DC fair weather on the other hand may become important because fair weather noise can cause higher annoyance and stricter noise limits may be specified [8].

IV. Conclusion & outlook

A. Conclusion

Environmental effects are likely to be affected by hybrid tower design using existing geometry.

DC field strengths can reach critical levels in case tower strength does not allow new bundles. At such high field strengths a high deviation between the empirical prediction formulas was observed when their applicable range was exceeded. An increased separation distance of the DC poles reduces the bipole surface gradients but leads to a high DC bias thus affecting AC foul weather audible noise.

Based on existing empirical models, a bias at the investigated DC voltages can lead to an audibly significant increase of the noise level. Due to superposition of audible noises from different bundles, a major bias on one bundle can be less critical than minor coupling on multiple conductors.

While DC foul weather noise may be negligible in non-hybrid arrangements, it can have a considerable influence in certain hybrid conductor arrangement scenarios.

B. Outlook

The voltage of the DC circuit of a hybrid tower may be increased significantly to increase the transmitted power while at the same time respecting the insulation strength requirements. However, this may occur at the expense of fair weather DC audible noise which may impose a severe limitation requiring reconductoring.

The effect of a DC bias on AC audible noise is not clear and requires further investigation, particularly regarding the role of space charge. Since a tower optimization to decrease audible noise directly affects DC ion currents both at ground and induced in the AC phases, a coupled study has to be conducted to attain a compromise.

To clarify these issues, EPRI and ETH are conducting a cooperative research program that involves both calculations and measurements.

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