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Effect of electrostatic induction and space charges on the audible corona noise of hybrid AC/DC transmission lines

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SUMMARY

In contrast to an increasing demand for electric power transmission capacity, the public acceptance for new overhead lines is very low. The concept of hybrid overhead lines, combining high voltage alternating current (AC) and direct current (DC) transmission on the same existing tower infrastructure, allows to increase the transmission capacity without the need for new lines. However, the altered conductor arrangement with the possible consequence of small separation distances between AC and DC systems on the same side of the tower will influence environmental corona effects via coupling between adjacent bundles. One very important design criterion for high voltage overhead lines is the audible corona noise (AN), which is therefore investigated in this contribution with regard to hybrid AC/DC overhead lines.

Through electrostatic induction, the presence of an AC conductor will increase the maximum electric field on an adjacent DC conductor and vice versa. Furthermore, the bipolar ion drift between coronating AC and DC lines affects the space charge density in the conductor vicinity and, thus, also the electric field. Still, literature on these coupling effects with regard to AC and DC AN is very limited and some of the results were not consistently observed.

A hybrid laboratory test setup consisting of two parallel conductors was implemented to separate the influence of a pure electrostatic induction from the additional impact of space charge. Therefore, artificial defects on the conductors are applied to control the state of corona of both lines individually.

Regarding a pure positive DC bias on the adjacent AC conductor, the observed increase in AN was very significant around the AC corona onset. However, this effect was barely measurable in case the AC voltage was further increased above the onset voltage. Similarly, also a pure AC ripple caused the DC audible noise to increase. Again, the impact was highest around the DC corona onset voltage. Still, also for higher DC voltage a measurable increase was detected for a relatively low AC field ripple. For both, the AC and DC AN, the impact of an adjacent conductor was enhanced if both conductors were coronating and, hence, exposed to space charge in addition to the field coupling.

KEYWORDS

Hybrid tower, AC/DC transmission lines, corona, electrical effects, audible noise, ion current coupling

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1. Introduction

Concept of hybrid AC/DC overhead lines

The increasing demand for electric energy as well as the integration of remote renewable energy sources require higher transmission capacities. However, the public acceptance for the construction of new overhead lines is very low, leading to large delays in project realization. Hence, it is in the interest of the transmission system operators (TSOs) and the public to upgrade existing tower infrastructure to increase the transmission capacity. One promising option is the conversion of existing multi-system HVAC towers to hybrid AC/DC lines, as it is now proposed by the German TSOs Amprion and TransnetBW for a new 340 km HVDC corridor in Germany [1].

Converting one three-phase AC system of an existing tower to a bipolar DC line can increase the transmission capacity up to a factor of two while the remaining system keeps supporting the AC grid and permits easy voltage transformation [2]. Additionally, the DC converters can be used for power flow control. As the visual changes of such a hybrid conversion would be negligible, the public acceptance is assumed to be high compared to the construction of a new line. While the new DC line can be energized with higher effective voltages at the same insulation distance, the introduction of a DC bipole will considerably affect the adjacent AC phases and vice versa. Thus, the environmental effects due to corona discharges on the line are modified in a hybrid tower environment. In order to meet regulatory criteria and to minimize public annoyance to an acceptable level, these effects have to be critically investigated and demand for an assessment of the optimal system arrangement on the tower. One major reason for public disturbance is the audible noise of high voltage overhead lines, which will therefore be studied with regard to coupling effects on a hybrid tower in this contribution.

Corona phenomena & audible noise generation on high voltage AC and DC overhead lines

The separation distances on pylons as well as the conductor and bundle diameters are designed to prevent discharges under clean and dry conditions. However, in case of foul weather or pollution, the onset field strength of the conductors is considerably reduced due to local field enhancements by water drops and particles [3]. Thus, neutral air molecules are ionized in partial discharges on the line. This so-called corona leads to several effects generated by the ionization itself, but also due to the space charge drift.

The pulsating discharges on AC and DC lines cause radio interference and a broadband 'crackling' or 'hissing' audible noise due to the superposition of multiple sources and random occurrence. While the radio interference decreases with higher frequencies and mainly affects the outdated AM transmission, the audible noise causes annoyance and is a regular matter of public concern [3]. Therefore, it is treated as industry noise and has to meet governmental regulations.

Ions generated in the conductor vicinity drift along the electric field lines, as well as with the gas flow evoked by an external wind component [4]. These space charges affect the strength and direction of the electrical field in the conductor vicinity, there influencing the corona onset as well as the path of other ions. This ion movement is known to cause an overall heating of the air and acts as a force on neutral gas molecules [5]. In case of a periodic motion, as in AC electric fields, this contributes to an additional second harmonic frequency tonal audible noise component.

However, as these ions do not vanish in a steady DC field, the remaining space charge cloud around a coronating DC conductor shields adjacent corona sources. Therefore, DC AN is reduced above a critical density of corona sources, as it occurs in heavy rain. Thus, in contrast to AC, the worst case for DC AN is caused by particles and insects attaching in fair weather, where the public awareness is higher [6].

While corona effects tend to increase with electric field on the conductor surface, the audible noise and radio interference both mostly depend on the amplitude of the discharge itself and less on the repetition rate [3]. As the amplitude of the positive onset streamer discharge is much higher compared to a negative Trichel pulse, the negative polarity audible noise is of negligible influence in most cases. Likewise, the AC broadband noise mainly originates from the positive halfwave. For DC, this polarity effect is further enhanced as most of the particles and insects are charged negatively and, thus, attracted by the positive pole while the negative pole remains relatively clean [6].

Coupling effects on hybrid AC/DC overhead lines

Mutual coupling between close AC and DC lines were first investigated in the 1980s by BPA [7], IREQ [8] and EPRI [9], [10]. Through electrostatic induction, the alternating voltage of the AC system will

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cause an electric field ripple on the DC system. Similarly, a negative DC conductor induces a positive field bias on the AC conductor and vice versa for positive DC polarity. Due to the increased maximum electric field, the corona effects will therefore most likely be affected.

Additionally, an alternating current component will flow in the adjacent DC conductor due to capacitive and inductive coupling with possible impact on the converter transformers [11]. Regarding the ion current coupling, it was shown in [12] that space charges drift from a coronating DC line to nearby AC conductors, thus, inducing a direct current component. Similarly, ions from a coronating AC conductor are accelerated in the superposed DC field, leading to a steady DC current in the AC conductor. While this DC component can cause saturation effects in the AC transformer according to [13], the DC ions in the vicinity of the AC conductor should in theory also affect the electric field and, thus, broadband AN [8] and the hum component [2], [14]. Although it was shown numerically in [8] that the negative space charge drift enhances the positive bias on the AC surface gradient caused by pure electrostatic induction, existing experimental results from the literature are inconclusive.

Based on different hybrid tower scenarios from the literature, the separation distance between AC and DC bundles can be as small as 6 m in case both systems have to be arranged on the same tower [1]. Therefore, a DC bias of about 15 % of the AC peak surface gradient is determined as a realistic worst case scenario. Similarly, also the relative AC ripple on a DC bundle ranges from 10-15 % of the DC surface gradient.

According the BPA hybrid study [7], the measured AC AN showed a significant increase of up to 10 dB if an adjacent negative pole was energized. The same holds true for the radio interference voltage (RIV). Similarly, the DC conductor energized at positive polarity suppressed AN and RIV on the AC side. Therefore, [7] recommends to add the DC bias to the pure AC Laplace field for the AN prediction based on existing equations, while the impact of an AC ripple on the DC AN is considered negligible.

A second hybrid test series conducted by EPRI revealed an increase of 2-3 dB in the AC AN for a relatively small positive bias from a negative pole [9]. Also, a small decrease in the AC AN was observed when exposed to a negative bias from the positive pole. Due to the nature of an outdoor experiment, both conductors were coronating during rain. Thus, it could not be determined whether these effects were purely caused by the field bias or enhanced by space charge effects.

In a subsequent hybrid tower study [10], the effect of electrostatic induction was then investigated in more detail in a corona cage. In this setup, the AC AN again increased with a positive DC bias. However, this effect was also unexpectedly detected for a negative bias and the increase of about 2 dB for a relative bias of 30 % was quite small. The consideration of the same DC bias in the existing formulas according to [7] predicted more conservative results and was, therefore, considered inaccurate. Still, it is to be determined why the effect of the DC bias was independent of polarity and much smaller compared to previous investigations [7], [9]. However, in contrast to the former outdoor setup, the corona cage does not coronate and therefore only represents the influence of pure electrostatic induction.

Based on a theoretical investigation in [14], the predicted ground level AN was significantly increased by 4 dB for a realistic hybrid tower in case the DC bias was considered in existing formulas compared to the pure AC AN. While this is audibly significant, it does not include any space charge effects.

At BPA, the impact of space charge was studied using DC conductors of three different diameters - thick (corona free), thin (strong corona) and conventional [7]. Although the AC AN measured for the thin DC conductor was higher compared to the conventional conductor, the difference was considered relatively low and it was concluded that no effect of ions was observed. Regarding the difference compared to the thick non coronating DC conductor, no AN data was presented. Still, for the RIV, which is known to behave similar to AN [10], the presented data reveals lower AC radio interference in case the adjacent thick DC conductor was not coronating. Thus, this could be an indicator for space charge effects.

Regarding the DC AN, the impact of an AC ripple is considered negligible by most of the studies and, thus, not included in existing prediction formulas to the author's knowledge [7], [10]. However, although the BPA study did not investigate the effect of the AC ripple on the DC AN, the RIV data from the DC conductor shows a significant increase with the AC voltage [7]. Also the studies from EPRI revealed a higher DC AN with an increasing AC ripple, although it was considered to be small [9], [10]. Still, the impact of the energization of the AC conductor on the DC AN was 'enough to be immediately perceived by the human ear' [9].

As a result of these observations, this study aims to investigate the coupling effects on AC and DC AN.

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2. Hybrid AC/DC setup and development of test cases using artificial corona sources

Setup of the hybrid AC/DC test line

A hybrid AC/DC test setup was constructed to further investigate the effects of field induction and space charge on the AC and DC AN. In order to qualitatively study these effects in a controlled environment, a small-scale indoor setup was designed. This offers the possibility to vary single parameters while keeping control of the environmental conditions at low background distortion. Based on the experience of previous investigations, artificial defects were implemented to adjust the corona state on both systems independently.

A set of two standard profile ACSR 265/35 conductors with a span of 6.80 m were strung up 1.33 m above ground and suspended by four insulators, each having the outfacing side connected to a surrounding grounded fence as shown in Figure 1. For all presented measurements, the separation distance between the AC and DC conductor was set to 2.10 m. Using MWB elements, the DC line was energized using a 100 kV_{rms} transformer and a double stage Greinacher (Cockcroft-Walton) rectifying cascade permitting a maximum DC voltage of 280 kV_{avg}. The AC line was fed using a stack of two 100 kV_{rms} AC transformers enabling a maximum AC voltage of 200 kV_{rms}. However, in order to ensure corona-free operation of the cascade and to exclude wire corona, the realized voltages were considerably lower. Using the commercial finite element method tool COMSOL®, the surface gradient on the AC conductor for a typical operating voltage of 180 kV_{peak} was determined to be 30.4 kV_{peak}/cm. If the adjacent conductor is then energized at a negative DC voltage 150 kV_{avg}, this would cause a positive bias of 1.8 kV_{avg}/cm on the AC conductor, thus, resulting in a relative bias of 5.9 % compared to the pure AC field at peak voltage. Therefore, the realizable coupling in this study was relatively low.

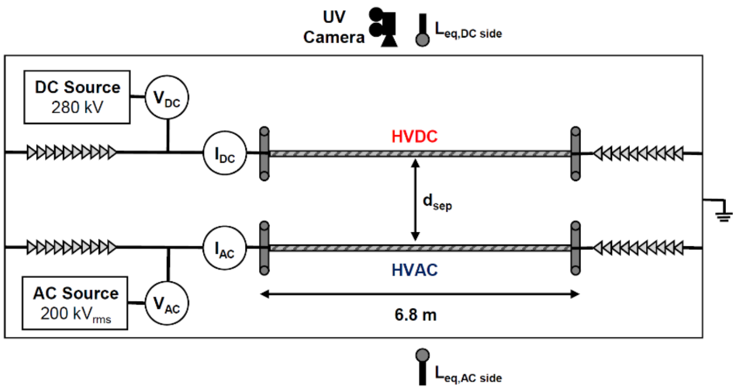

Figure 1: Hybrid AC/DC test setup

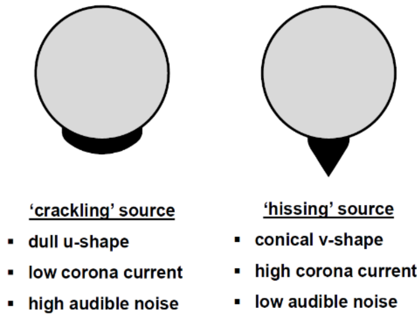

Figure 2: Shape of artificial sources

The currents on both conductors were measured using shunt resistors with ADCs and fibre optical connection on high potential. For the visual inspection of the corona state, a Forsyth Electro-Optics CoronaScope™ was used. Two identical Norsonic Nor118 Class 1 sound level meters with Nor1225 ½" free-field microphones were directed to the conductor midspan from both sides at the closest distance possible behind the grounded fence. Thus, the DC audible noise is measured from the DC side in 2.24 m distance, while the AC noise is based on the AC side microphone in 1.99 m distance of the conductor. Due to reflections on the acoustically hard walls, the laboratory does not permit to measure the absolute sound power levels. However, this study aims to quantitatively investigate the impact of different conditions on the corona noise, which can be very well stated using the undisturbed increase in dB. The background noise of the laboratory itself was quite constant at about 29.6 dB(A) and, hence, much lower than the audible noise measured in this investigation.

Concept of artificial corona sources

The corona onset as well as the discharge impulse amplitude and repetition rate strongly depend on the shape of the corona source on the conductor surface. In [15] and [16] it was demonstrated that sharp metallical sources tend to produce 'hissing' corona with low impulse amplitude and a high repetition rate. This is due to the very local field enhancement, which strongly decays with distance. Thus, the corona onset is expected to be reduced, while the streamer propagation is suppressed after short distance. On the contrary, the onset voltage is increased for dull corona sources due to the lower electrical field,

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causing 'crackling' corona with a higher impulse amplitude. Therefore, two types of corona sources were designed - one conical (v-type) generating 'hissing' and another dull (u-type) producing 'crackling' corona. Using these different designs, as presented in Figure 2, it is possible to set the conductor to either produce high audible noise with low ion current or to generate a high ion current with a relatively lower sound pressure level.

Hybrid test cases

For the investigation of hybrid coupling effects on the audible noise, a set of test cases was designed to control the state of corona on both, the AC and DC conductor, individually. Therefore, 20 u-shaped corona sources with an axial distance of 20 cm were placed on the conductor, which AN shall be measured, in order to produce a high sound pressure level with low background distortion. To separate the pure electrostatic induction from the effect of space charge, the adjacent conductor was kept clean and dry and, therefore, neither producing audible noise nor space charges. To enforce additional space charge effects, 20 v-shaped corona sources were placed on the adjacent conductor to produce hissing corona, causing a high space charge density but negligible AN.

Thus, for the investigation of the DC AN, a clean AC conductor was energized in Case 1a in order to investigate the influence of a pure AC ripple as shown in Figure 3. This result is then compared to the additional impact of space charge from the hissing AC corona in Case 1b.

Similarly, the AC AN was investigated with regard to a pure positive DC bias through the energization of a clean and non-coronating negative DC pole in Case 2a. Regarding the effect of space charge in Case 2b, the DC conductor was set to produce hissing corona. In case 2c, the same effect was investigated for a strong ion current on both sides, creating a severe ion current coupling.

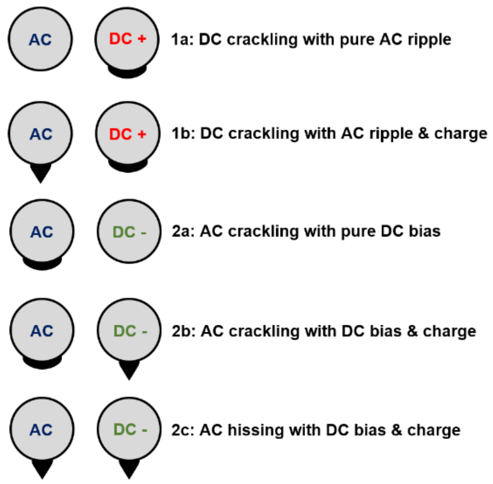

Figure 3: Hybrid test cases using artificial defects as corona sources

3. Measurement results

Prestudy of the corona sources

Based on the previously presented concepts, the discharge behavior of the corona sources and its reproducibility have to be demonstrated in a prestudy. In the main test series these sources were applied according to the test cases in Figure 3. If not stated otherwise, all presented sound pressure levels equal the A-weighted equivalent sound pressure levels averaged energetically over one minute.

In contrast to the main study, the prestudy was conducted in a symmetrical single-conductor setup in 1.20 m above ground and one microphone located behind a grounded fence in 1.70 m distance from the conductor. In a first series, the corona current is evaluated for both shapes, placing one specimen on the midspan of the conductor for an increasing energization DC voltage, as shown in Figure 4.

As predicted by theory, the DC onset voltage of 50 kV_{avg} is significantly lower for the sharp v-type, compared to about 140 kV_{avg} for the dull u-type source. In consequence of the strongly inhomogeneous field enhancement above the onset, also the corona current is considerably higher by a factor of two to four for the v-type. As can be seen by the overlap of the test results for three repeated series with different specimen, the behavior of both types has proven to be reproducible.

In a second test, ten identical specimen were placed homogenously over the conductor to investigate the AN for both shapes and energization voltages. With a similar onset voltage compared to the first series, the DC AN of the ten v-type sources is significantly lower than for the u-type according to Figure 5. This is also true for alternating voltages.

However, the difference between the shapes is lower for AC energization, which might be explained by the shielding effect of the DC space charge, which is assumed highest for hissing corona, thus, reducing the DC AN for the v-shape. This same shielding effect was also observed in a previous investigation in case the axial distance between the sources was reduced in accordance with [15]. Regarding the planned hybrid test cases, for a typical DC operating voltage of 180 kV_{avg}, the worst case background distortion

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of the DC crackling noise from AC hissing corona at 150 kV_{peak} is assumed to be at least 9 dB lower and, thus, of negligible impact. The same holds true for the case of AC corona noise, as the negative polarity hissing AN is known to be very low [6] and, thus, considered of minor impact.

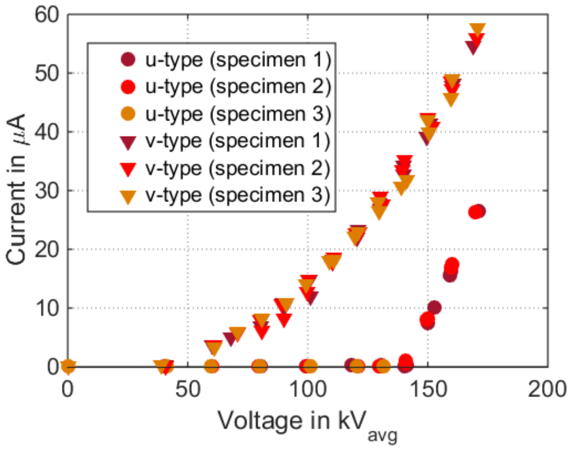

Figure 4: Reproducibility of DC corona current for the different specimen and shapes

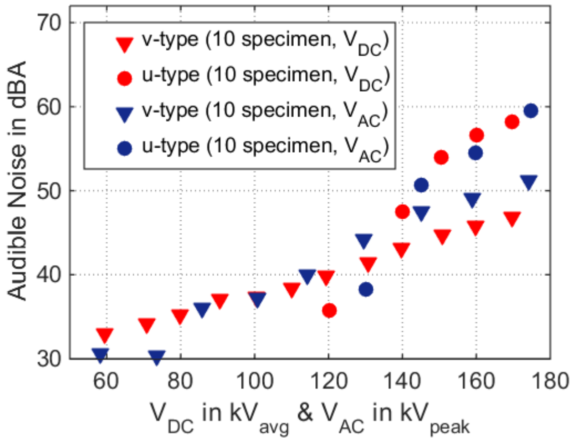

Figure 5: Difference in hissing and crackling audible noise for AC & DC voltage

Influence of pure electrostatic induction on AC and DC audible noise

To investigate the influence of a pure electrostatic induction on the adjacent conductor audible noise, one conductor was set in crackling corona while the adjacent energized conductor was dry and clean and, hence, not coronating. The state of corona was verified with the CoronaScope™.

The influence of an AC ripple on the DC AN according to Case 1a is presented in Figure 6. Three DC voltage levels were selected, with 140 kV_{avg} representing the case around the onset of the dull sources, while for 180 and 200 kV_{avg} most of the artificial sources are coronating. The maximum AC voltage of the adjacent conductor was limited to 150 kV_{peak} as wire corona was observed for higher voltages on the clean conductor. Otherwise, the assumption of a pure electrostatic effect would be no longer valid. All results are presented as the increase in the audible noise compared to the pure DC noise without any ripple.

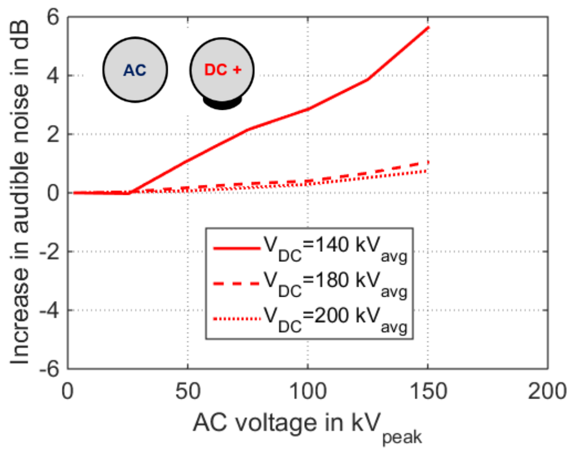

Figure 6: Effect of a pure AC ripple (Case 1a) on DC AN for different DC voltages

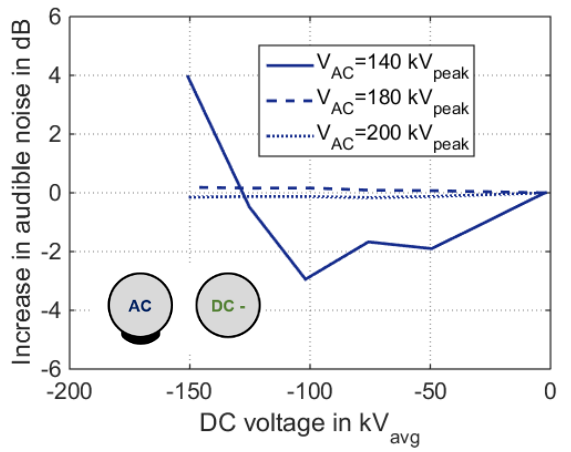

Figure 7: Effect of a pure DC bias (Case 2a) on AC AN for different AC voltages

Therefore, the DC AN is observed to increase with the influence of electrostatic induction in form of an AC field ripple. This effect is quite strong around the onset of the 'crackling' sources at 140 kV_{avg}. However, for higher DC voltages, this effect is considerably decreased.

While this effect is mostly considered negligible in the literature, this increase could be explained with the higher maximum surface gradient on the DC line. Thus, the maximum discharge amplitude is presumed to be higher, although it should stay the same in average. However, as the discharge impulse is of much higher importance for the AN than the repetition rate, the DC noise is expected to increase.

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Around the onset voltage, the effect of an AC ripple on the DC AN is assumed to be higher, as it increases the maximum surface gradient on the adjacent conductor and, hence, also the number of coronating sources contributing to the noise. However, for the higher voltage levels most of the sources are already coronating, which is why the measurable effect is lower. Still, for a relatively low maximum AC ripple of 5.9 and 5.3 % for DC voltages of 180 and 200 kV_{avg} respectively, the DC audible noise increases by about 1 dB. While this change is barely audible for the human ear, it still might be of importance when it comes to regulations. Furthermore, as previously discussed, the maximum AC ripple with AC and DC conductors on the same side of the tower is assumed to be significantly higher.
A similar behavior is also observed in Figure 7 for the AC AN affected by a positive DC bias from the adjacent negative pole, as investigated for Case 2a. There is a clear impact on the AC AN around the onset voltage, which is significantly reduced for the case of higher AC voltage, where most artificial sources are coronating without any bias. Additionally, one interesting effect is observed around the AC onset at 140 kV_{peak}. There, the AN is first reduced with the DC bias and then strongly increases.
As the negative corona onset is known to be lower than the positive [3], the AC conductor at onset is assumed to exclusively coronate in the negative halfwave, thus producing relatively low noise. This is in accordance with the optical observation where only negative Trichel pulses were detected. With a higher DC bias, the negative corona is then suppressed while the positive corona onset condition is not fulfilled. Accordingly, at a DC voltage of 100 kV_{avg}, the AC AN is equal to the laboratory background noise and no discharge is observed. If the bias is further increased, the AN increases by another 4 dB. While this is audibly significant, this case is mostly of scientific interest, as a typical AC line during rain is considerably above the corona onset. For both cases significantly above the AC onset at 180 and 200 kV_{peak}, the increase in the audible noise is barely measurable and considered negligible for the realized DC bias.

Effect of space charge on AC and DC corona noise

In addition to the pure electrostatic induction, the additional impact of space charge was investigated. Based on the results of the prestudy, the DC voltage was selected to 180 kV_{avg} for the investigation of Case 1b. This enables to energize the AC conductor up to 150 $kV_{peak,}$ where the audible disturbance due to the AC hissing is still considered negligible. On the contrary, the v-type sources will produce severe AC corona losses with negative space charges drifting from the AC conductor to the positive DC pole.
According to Figure 8, the DC crackling noise intensifies with pure electrostatic induction, as well as with additional AC corona. However, the increase including space charge is somewhat higher compared to the pure AC ripple. This holds also true for the 8 kHz frequency band, which is known to be representative for corona noise at low background distortion [7] and can, therefore, also be used for a consecutive outdoor investigation in case of higher environmental noise.
The stronger impact including AC corona can be explained due to the ion drift between the conductors. Space charges created in the negative AC half-cycle are attracted by the positive DC pole and can further enhance the maximum Poisson electric field in the vicinity of the DC line in addition to the ripple.

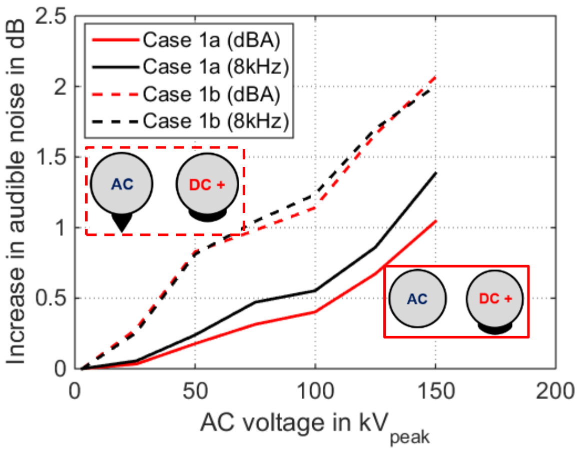

Figure 8: Impact of AC corona (Case 1b) on DC AN in comparison to a pure AC ripple (Case 1a), V_{DC} = 180 kV_{avg}

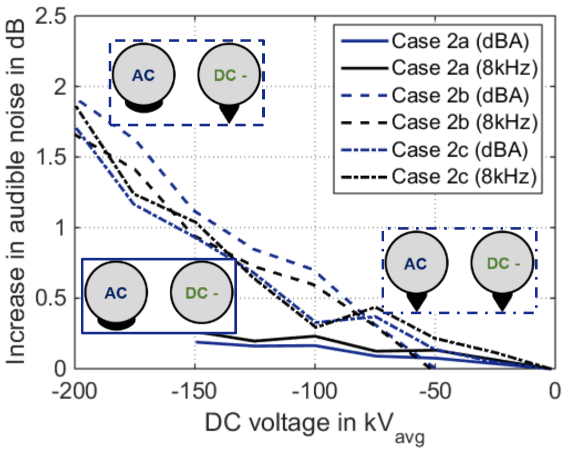

Figure 9: Impact of DC corona (Case 2b & 2c) on AC AN in comparison to a pure DC bias (Case 2a), V_{AC} = 180 kV_{peak}

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In Figure 9, the influence of negative DC space charge drifting to the AC conductor on the AC AN is presented in comparison to the pure bias from the DC energization. For comparability reasons, the AC voltage for this case was also selected to 180 kV_{peak}. However, as the negative pole was verified to produce negligible noise, the DC voltage could be increased up to -200 kV_{avg}. While previously, the impact of the DC bias was very low for a strongly coronating AC conductor, the increase in AC AN is more pronounced with additional negative space charges. This is also true for Case 2c, where the crackling u-type sources on the AC conductor are exchanged for 20 v-type hissing corona sources. Both cases show a very similar increase in AN of up to 2 dB with the DC voltage.
Again, this additional impact can be explained based on the assumption of negative space charges emitted by the DC pole, increasing the electric field in the positive half-wave, which is most relevant for the AC AN. While the hissing AC corona in Case 2c is much higher above the onset compared to Case 2b, also the ion current coupling is higher due to the stronger AC corona in accordance with [12]. Although the increase in AC AN of about 2 dB is not very significant in total, as the sensibility of the human ear is about 2-3 dB, the maximum field bias of 7.9 % is about half of the expected worst case.

4. Conclusion & Outlook

Conclusion

It was shown that artificial corona sources with different shapes offer the possibility to control the corona state on adjacent conductors individually. Based on this concept, the audible noise of AC and DC conductors in a hybrid tower environment was investigated with regard to the effects of pure electrostatic induction and space charges from an energized and coronating adjacent conductor.
Based on the observations, both, the AC and DC AN, are strongly affected around their corona onset by pure electrostatic induction coupled from an energized adjacent conductor. However, this impact was considerably reduced in case the examined conductor was energized significantly above the corona onset voltage. Still, regarding the AC AN, the impact of a pure DC bias was barely measurable.
However, this effect was significantly enhanced if the adjacent negative pole was set to produce strong corona, as it occurs in foul weather and, thus, is relevant for the worst case of AC AN. While this effect was expected for the DC bias, this study revealed that the main impact is due to the DC ions and not only the pure electrostatic induction.
Furthermore, the DC AN did not only increase with a pure AC ripple, but was additionally enhanced in case the AC conductor was coronating and, thus, affecting the space charge cloud in the DC conductor vicinity. This is a very interesting results, as this effect is mostly considered negligible and of less interest than the DC bias. While corona on the AC conductor rarely occurs in summer fair weather, the DC AN can also be affected by a pure AC field ripple based on the observations.
Therefore, the impact of field induction and space charge on the audible noise cannot be generally negligible and should be considered in the hybrid tower design in order to meet regulatory criteria.

Outlook

A consecutive laboratory study is scheduled to analyze the observed effects more in detail. Therefore, also a wider range of gradients with a higher relative coupling is of interest as well as the behavior of the tonal noise component.
With regard to the severity of these effects for realistic hybrid overhead lines, a series of outdoor investigations is planned. Thereby, the impact of varying weather conditions on these phenomena is to be studied for realistic voltages and separation distances.

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BIBLIOGRAPHY

[1] B. Rusek, C. Neumann, S. Steevens, U. Sundermann, K. Kleinekorte, J. Wulff, F. Jenau, and K. H. Weck, “Ohmic coupling between AC and DC circuits on hybrid overhead lines,” in *Cigre Auckland Symposium*, 2013.

[2] U. Straumann and C. M. Franck, “Discussion of Converting a Double-Circuit AC Overhead Line to an AC/DC Hybrid Line with Regard to Audible Noise.” 2011.

[3] P. S. Maruvada, *Corona Performance of High-Voltage Transmission Lines*. Research Studies Press Ltd., 2000.

[4] T. Guillod, M. Pfeiffer, and C. M. Franck, “Improved Coupled Ion-Flow Field Calculation Method for AC/DC Hybrid Overhead Power Lines,” *IEEE Trans. Power Deliv.*, vol. 29, no. 6, pp. 2493–2501, Dec. 2014.

[5] U. Straumann, “Berechnung und Reduktion der tonalen Geräuschemission von Hochspannungsfreileitungen,” ETH Zurich, 2007.

[6] Electric Power Research Institute, “HVDC transmission line reference book,” p. 684, 1993.

[7] V. L. Chartier, S. H. Sarkinen, R. D. Stearns, and A. L. Burns, “Investigation of Corona and Field Effects of AC/DC Hybrid Transmission Lines,” *Power Appar. Syst. IEEE Trans.*, vol. PAS-100, no. 1, pp. 72–80, 1981.

[8] P. S. Maruvada and S. Drogi, “Field and ion interactions of hybrid AC/DC transmission lines,” *IEEE Trans. Power Deliv.*, vol. 3, no. 3, pp. 1165–1172, Jul. 1988.

[9] Electric Power Research Institute, New York Power Authority, and General Electric Company, “Hybrid Transmission Corridor Study: Volume 2: Phase 2--Full-Scale Tests,” vol. 2, no. November, 1991.

[10] Electric Power Research Institute, General Electric Company, and Ohio State University, *Hybrid Tower Study: Volume 3: Phase 3 -- Scale Model Development and Full-Scale Tests*. 1994.

[11] E. V Larsen, R. A. Walling, and C. J. Bridenbaugh, “Parallel AC/DC transmission lines steady-state induction issues,” *Power Deliv. IEEE Trans.*, vol. 4, no. 1, pp. 667–674, 1989.

[12] M. Pfeiffer, C. M. Franck, and J. Schmutz, “DC ion-currents in AC conductors in hybrid AC/DC transmission systems,” in *11th IET International Conference on AC and DC Power Transmission*, 2015, p. 048 (10 .)–048 (10 .).

[13] M. Beltle, M. Schühle, and S. Tenbohlen, “Influences of Direct Currents on Power Transformers Caused by AC-HVDC Interactions in Hybrid Grids,” in *International Symposium on High Voltage Engineering (ISH), Pilsen, Czech Republic*, 2015.

[14] S. Hedtke, M. Pfeiffer, C. M. Franck, L. Zaffanella, J. Chan, and J. Bell, “Audible noise of hybrid AC / DC overhead lines : Comparison of different prediction methods and conductor arrangements,” in *EPRI’s High-Voltage Direct Current & Flexible AC Transmission Systems Conference*, 2015, vol. 1, pp. 1–8.

[15] M. Akazaki, “Corona Phenomena from Water Drops on Smooth Conductors under High Direct Voltage,” *IEEE Trans. Power Appar. Syst.*, vol. 84, no. 1, pp. 1–8, Jan. 1965.

[16] T. W. Liao, W. A. Keen, and D. R. Powell, “Relationship Between Corona and Radio Influence on Transmission Lines, Laboratory Studies I-Point and Conductor Corona,” *Trans. Am. Inst. Electr. Eng. Part III Power Appar. Syst.*, vol. 76, no. 3, pp. 530–538, Apr. 1957.

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