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Corona Discharge Pulse Pattern and Audible Noise on Hybrid AC/DC Transmission Lines under Electric Field Bias, Ripple and Ion Coupling

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Abstract

Hybrid AC/DC overhead lines offer a significant increase in transmission capacity compared to existing HVAC infrastructure. While corona phenomena and audible noise are crucially important for public acceptance, they are affected by mutual AC/DC coupling. While the underlying phenomena need to be clearly understood and predicted accurately, only few experimental studies exist. The corona effects are therefore studied in detail on a large laboratory setup under the influence of electric field bias, ripple and space charges. The results show a clear trend in the phase resolved partial discharge (PRPD) pattern and repetition rate which can explain the change in audible noise.

Keywords: corona effects; audible noise; partial discharge; hybrid tower; AC/DC transmission line; corona pulse characteristics

1. Introduction

Many utilities are faced with the challenge of large required grid reinforcements to cope with the rapid installation of renewable energy sources (RES). The concept of hybrid AC/DC lines is motivated by the possibility of increased power transmission capacity using existing tower geometries. Under the assumption of higher acceptance due to negligible visual change, a faster grid reinforcement can be achieved [1]. This offers a clear advantage in contrast to long regulatory procedures for new overhead line corridors or the high financial and technical effort of underground cable or gas-insulated lines. Hybrid AC/DC overhead lines benefit from the increased transmission capacity of the DC conversion due to higher voltages and lower active and reactive losses. At the same time, the remaining AC system allows to keep important nodes in populated areas and continues supporting the HVAC grid. Therefore, hybrid AC/DC lines are currently discussed in various countries [2], e.g. Germany [3], China [4], the United States and Switzerland [5]. While the visual impact of a hybrid conversion is assumed to be negligible, environmental effects, such as audible noise and electromagnetic fields caused by corona discharges will be altered.

If the electric field on the conductor surfaces exceeds the critical electric field strength due to field enhancements through water drops, pollution or scratches, a corona discharge occurs [6]. This corona current pulse manifests itself as an electromagnetic interference [7], as well as an acoustic pulse through the local heating of the air. Due to the usually high number of sources and pulses, as well as

Figure 1: Indoor hybrid AC/DC test using two parallel conductors with either round (u), spiky (v) or no artificial corona sources (o)

their random individual placement and occurrence, this causes radio interference (RI) and audible noise (AN), which can be perceived as a nuisance. Furthermore, an ion cloud will be generated in the electric field. Ions will move periodically in the conductor vicinity in alternating fields, causing the well-known hum component from HVAC overhead lines [8], while in HVDC these ions are repelled from the conductor of the same polarity and are attracted by the ground as well as adjacent conductors of different potentials. This steady DC ion drift causes a measurable DC ion current density and an increased Poisson electric field at ground level [6]. Thus, the hum component vanishes for HVDC overhead lines, as no periodic ion movement occurs [9]. Furthermore, the ion cloud is considered to be the cause for the drop in HVDC radio and audible noise for a high density of corona sources, e.g. during wet weather conditions [9, 10]. Experience from outdoor tests

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(a) Corona PRPD (DC = -240 kV)

(c) Corona PRPD (DC = 0 kV)

(e) Corona PRPD (DC = 240 kV)

(b) Corona activity (DC = -240 kV)

(d) Corona activity (DC = 0 kV)

(f) Corona activity (DC = 240 kV)

Figure 3: Comparison of AC corona PRPD and UV activity at 180 kV for positive, no and negative bias for 240 kV DC

at 16.2 kV/cm per 100 kV for both systems. The coupling through electrostatic induction is evaluated through the surface gradient of 2.3 kV/cm per 100 kV on the adjacent grounded conductor and then added based on the superposition principle. The relative bias and ripple ratios are calculated based on the electric field amplitudes instead of RMS to allow an easier comparison between AC and DC. To control the state of corona on both conductors individually, 21 artificial corona sources made of aluminum are placed equally spaced on the conductor surface. These artificial corona sources show similar results to real rain

drops, as demonstrated by [10], while being very stable and easy to control. Additionally, this also enables to change corona pulse parameters and its repetition rate using different shapes as shown by [22]. Using this concept, corona sources can be designed to either generate a large ion current without significant audible noise, further-on referred to as v-shape (v), or vice versa generate high audible noise with small corona losses, the so-called u-shape (u), as demonstrated in [17] and shown in Figure 2. This design has shown to generate reproducible results and was also implemented in [16]. Also, in order to allow electro-

static coupling without ion current coupling, the conductor causing the coupling was not equipped with (v) or (u) type sources, but was kept clean, dry and free of corona sources and will be referred to as (o) case.

For each configuration, the voltage was ramped up automatically on one side with a total of 121 steps while the other side was kept at constant voltage. For each step, the voltage was kept constant for 60 seconds. During every step, a long exposure photograph of 30 s was taken with a Nikon D5300 digital single-lens reflex (DSLR) camera to monitor the state of corona and the number of active sources, as shown for example in Figure 3f. The camera was positioned at the edge of the safety cage with 5.9 m distance to the mid span in order to be as close as possible while still allowing to capture both conductors at the same time. Additionally, a corona camera was used from different angles to ensure that no PD occurs on the high voltage electrodes and connectors. The corona pulses are measured using the partial discharge measurement system Omicron MPD 600 with a measuring impedance in series with the coupling capacitor. The setup was calibrated using a pulse generator according to the IEC 60270 standard. The center frequency was chosen at 250 kHz within a range of ± 150 kHz. The device was set to auto-range, as otherwise saturation effects were unavoidable due to the large dynamics of the input signal at different voltage levels. The applied voltage was measured using calibrated AC and DC voltage dividers and recorded with a LabJack U3-HV A/D converter. To measure the audible noise of the conductors, two Norsonic Nor118 sound level meters with Class-1 free field microphones were placed on both sides behind the cage with 2.1 m distance to the AC and DC conductors, allowing to capture the A-weighted Sound pressure levels as well as the third-octave frequency bands.

2.1. Evaluation procedures

For every voltage step, a stream of 30 s is extracted from the MPD 600 recording, including the apparent charge and time stamp of every detected discharge. The raw data is then filtered with Matlab. From this stream, all discharges smaller than 0.1 nC are discarded, as their contribution to the audible noise is assumed very small compared to the other discharges of up to some ten nC. While the phase relation is not available as raw data, it is reconstructed based on the time stamps with the assumption that the maximum discharge detected is always positive and occurs at the maximum of the positive half-wave. Hence, the positive amplitude correlates with 5 ms or 90 degrees. The phase relation of all other discharges is then reconstructed based on their time stamp. For a separated evaluation of the pulses in the positive and negative half-wave, it is assumed that all pulses before 180 degrees or 10 ms respectively belong to the positive half-wave and all after 10 ms are part of the negative half-wave. For both half-waves, the pulse amplitude percentiles are evaluated, as well as the number of pulses per second as a representation of the repetition rate. For every individual voltage

step, a heat map is generated based on the phase shift and weighted by the number of pulses as in typical representations of PD patterns. To evaluate the trend of the repetition rate, the number of positive pulses per seconds is measured, e.g. in Figure 4b. Regarding the trend in pulse amplitude, the 99.9th percentile of the positive pulses is evaluated in order to track the behavior of the maximum pulse amplitudes as in Figure 4a.

Long-exposure photography highlighting the number of active corona sources and a qualitative evaluation of their activity, is used to detect the corona onset on both sides. For higher coupling ratios in case (o), corona onset was detected on the conductor although no artificial sources were attached. These voltage steps were consequently excluded in the post-processing, as they do not fulfill the assumption of no corona. This can occur, as the corona onset was tested prior to the measurements based on the energization of only the AC or DC system and can shift based on the hybrid energization as demonstrated in a previous publication of the authors [17].

3. AC discharge behavior under positive and negative DC bias

3.1. Measurement results

The AC corona characteristics are investigated regarding the energization of an adjacent DC conductor with negative and positive polarity, respectively, inducing positive and negative DC bias. Furthermore, based on previous investigations [17], a distinction is made between DC energization with and without corona activity and hence ion current coupling. Consequently, the DC side was equipped with 21 artificial v-shape sources (v) for strong ion current coupling, while the conductor was clean, dry and free of corona for the cases without space charge effects (o). Exemplarily for the qualitative change in the PD pattern relative to phase, the PRPD patterns are shown for the two cases of strong coupling (240 kV_{DC} or a relative bias of 21.6% based on the AC amplitude) for positive (Figure 3a) and negative polarity (Figure 3e) compared to a grounded DC conductor (Figure 3c). While the AC corona behavior looks almost identical for both cases without bias, as expected, the number of pulses increases in the positive half-wave while decreasing in the negative half-wave for the case of positive bias (Figure 3a) and vice versa for the negative bias (Figure 3e). Also, the range of phase angles for which positive and negative pulses occur is enlarged or reduced for the respective bias.

As a quantitative manifestation of these phenomena, the pulse amplitudes and repetition rates responsible for the audible noise [20] are shown for all gradients and test cases over the relative coupling based on the PD apparent charge and number of detected pulses. For the case of positive bias in Figure 4a, the pulse amplitudes in the positive half-wave are increased. This is also true for the repetition rate in Figure 4b. The opposite could also be confirmed for the

(a) Max. pos. amplitude - pos. bias

(b) Pos. repetition rate - pos. bias

(c) Max. pos. amplitude - neg. bias

(d) Pos. repetition rate - neg. bias

(e) Max. pos. amplitude - AC ripple

(f) Pos. repetition rate - AC ripple

Figure 4: Positive corona pulse characteristics for varying relative coupling (in %) and applied AC field (kV/cm)

negative half-wave, where both amplitude and frequency are reduced. In the case of negative bias in Figure 4d, this behavior is reversed. The positive pulse amplitudes are clearly reduced with the relative bias Figure 4c, as well as their repetition rate. While the observed behavior is true²⁹⁰ for all AC surface gradients, the effect of relative coupling is found to be stronger for the lower AC gradients. In extreme cases, as for the lowest AC gradient, the negative coupling can even cause the positive discharges to extinguish. The optical corona activity is also evaluated quali-²⁹⁵

tatively for the two cases of positive and negative bias in Figure 3b and Figure 3f. It is obvious that no corona activity is observed on the DC conductor for the case of zero DC voltage. The energization of the DC conductor is visible for both cases, and the smaller negative Trichel discharges can well be distinguished from the positive Streamer discharges. Regarding the AC corona activity, all artificial corona sources are active in all cases for the selected AC gradients. While the image quality does not allow for a quantitative evaluation, the photographs still allow for a

qualitative comparison of the AC corona activity with and without bias. Regarding the positive bias (Figure 3b), the corona activity is brighter compared to the case of no DC corona (Figure 3d). The AC discharges appear to be longer and wider with the DC bias. On the contrary, the AC corona including negative DC bias (Figure 3f) clearly reduces the brightness and footprint of the AC discharges. As the measurement was subject to high background audible noise from the frequency converter, the corona audible noise is only presented for the highest voltage level to ensure a high signal to noise ratio. As a comparison of the trends of audible noise and corona pulses, the change in apparent PD charge Q_{max} , as well as in the A-level AN is demonstrated for the case of bias in Figure 5. For the positive bias, both the Audible Noise and the PD Amplitude increase. For the case of a strong negative bias, not only the PD characteristics decreased, but also the audible noise.

3.2. Discussion

The partial discharge characteristics and the audible noise are altered due to the coupling between AC and DC. All corona effects are closely connected to the surface gradient and will increase if also the maximum surface gradient is increased. Due to the energization of adjacent AC and DC bundles, the surface gradient is enhanced based on the superposition of various coupling phenomena which are discussed based on the model in Figure 6. Regarding AC corona, the DC energization will cause a DC bias through electrostatic induction shown in Figure 6(d). The DC bias causes a shift in the surface gradient on the conductor depending on the DC polarity. For one half-wave, the maximum field amplitude is increased and so is the time period for which the critical field strength is exceeded. Therefore, it is logical, that a positive bias causes an increased number and amplitude of positive pulses, while for negative pulses the phase range in which they occur as well as their amplitude are reduced. It can be assumed that the streamer integral is larger for pulses of one half-wave and that longer streamers can form, causing higher charge per pulse, and hence higher thermal and acoustic energy. In case of ion current coupling between both AC and DC, as shown in the case with v-type sources on both, the AC and DC conductor, multiple mechanisms exist, which will occur simultaneously and cannot generally be treated independently. If only the DC corona causes corona, e.g. due to increased pollution on the DC side, the DC ions will be repelled by the DC conductor and drift to the AC conductor with a superimposed oscillation caused by the AC field shown in Figure 6(a). This can be measured as a DC current in the AC conductor. Furthermore, the DC ions drifting to the AC conductor will cause a locally enhanced space charge density in the conductor vicinity. The drift of negative ions to the AC conductor should further enhance a positive bias on the AC surface gradient. Likewise, it is logical that positive ions will reduce the electric field in the positive AC halfwave, thereby supporting a negative

bias.

If only the AC conductor would be in corona, e.g. due to different conductor types or scratches on the conductor, still a DC ion current would flow, as the AC ions are attracted by the steady DC field (Figure 6(c)) as shown previously in [16]. This removal of space charge from the AC conductor should further enhance the effect of the DC bias, as the removal of positive ions will enhance the surface gradient in the positive halfwave, as the shielding effect is reduced. The same is true for the removal of negative ions for a positive DC polarity.

However, in most cases, precipitation as the main source of corona will cause discharges to occur on both, AC and DC, simultaneously. In this case, the bipolar ion flow will show different mechanisms, e.g. due to recombination of ions (Figure 6(b)), which has shown to further increase the corona current coupling according to [16] in the so-called 'Hybrid Effect'. Here the DC ion current in the AC bundle was observed much stronger than the superposition of only AC or DC corona with the consequence of higher DC current on the AC side and a higher density of space charges. For the example of a positive bias from a negative DC conductor, the negative ions close to the AC conductors are assumed to further increase the bias in the same direction as the purely electrostatic coupling without ion current coupling. As shown previously by Maruvada and Drogi [23], corona from the DC side can cause the bias to further increase by more than 200 % depending on the tower configuration. Therefore it is obvious, that the hybrid effect of simultaneous AC and DC corona should always force a change in the corona effects in the same direction as the electrostatic induction without space charge. This effect of the space charges was also shown to increase the audible noise in [17]. Based on Figure 4, it can also be seen, that the pulse amplitudes and repetition rates are more affected for the case of DC ion current coupling. In some cases, the hybrid energization caused a dry and clean conductor to cause corona as well, which could be verified with the UV and PD data. As in this case, the assumption of purely electrostatic coupling without ion current coupling would no longer be valid these points were excluded accordingly.

4. DC discharge behavior under an AC ripple

4.1. Measurement results

Based on the previously observed effect of an AC ripple on the DC audible noise in [17], the DC corona current characteristics are now studied in detail regarding an energization of an adjacent AC conductor. As DC corona noise is typically worst in dry weather due to pollution [9], it is assumed that in this case only the DC conductor is coronating, while the AC conductor only causes an electrostatic coupling. As an example for this case, the corona PRPDs are shown for the two cases of no ripple (Figure 7c) and a strong ripple of 19.5 % in (Figure 7d).

Figure 5: PD and AN characteristics for positive and negative bias

Figure 6: Theoretical model of induction and ion current coupling

The corona pattern shows three bands of PD activity with random appearance and does not show any phase dependency. In contrast, the PRPD pattern shows a clear phase dependency, when an AC ripple is applied.

As quantitative evaluation, the effect of relative ripple is displayed for the pulse amplitude (Figure 4e) and repetition rate (Figure 4f). Both these parameters show an increase with relative ripple. The same is true for an increase in the applied DC voltage and surface gradient instead of an AC ripple.

The corona activity is shown for DC energization in Figure 7a, as well as for hybrid energization in Figure 7b. As no artificial sources are fixed on the AC conductor, no AC activity is visible in both figures. While some DC sources are already active for pure DC energization without coupling, they do not show the same degree of corona activity, as some sources are brighter than the others. In the case including the AC ripple, the number of active sources has clearly increased. Also, the DC discharges appear qualitatively brighter and longer. Furthermore, their activity seems more homogeneous.

4.2. Discussion

The DC corona has proven to be generally less stable than AC corona and shows more interference between adjacent corona sources, which is attributed to the effect of the space charge shielding adjacent sources as discussed in [9]. Therefore, also the corona UV example in Fig-

ure 7a and Figure 7b does not show a very homogeneous activity. This is also a possible explanation for the three bands of corona activity in the PRPD plot in Figure 7c and Figure 7d. As the different corona sources show different optical activity, it is logical that also the amplitude and repetition rate should be different. Another explanation would be the automatic range function of the PD sensor leading to concrete bands, however other PRPD plots for the same setup show discharges over the whole range, depending on applied voltage and AC ripple. Therefore, the authors are convinced, that the different bands of partial discharge are rather caused by the different state of corona on the single sources. This can also occur, as the u-type shape allows discharges to occur on different spots, with corona not always having the exact same onset conditions. The electrostatic induction in Figure 6(d) should cause an AC ripple on the DC conductor. As the worst-case is assumed to occur in dry weather with only DC corona, the other mechanisms based on the ion current coupling do not play a role in this example, but can of course also affect the DC corona in the case of rain, when the audible noise is lower. Based on the PRPD pattern in Figure 7d, the number of discharges as well as their amplitude is strongly reduced during the positive AC half-wave (equivalent to the negative half-wave of the ripple), as the surface gradient is reduced due to the lower potential difference between the AC and DC conductor. Thereby, the difference between the applied electric field and the critical electric field is increased in the negative half-wave, allowing the formation of longer streamers and allowing more pulses to occur. If the applied electric field is only slightly above the critical electric field, the ripple can push the corona further above the onset, resulting in a strong increase of the number of pulses, as seen in Figure 4f. This trend can also be confirmed looking at the images of the corona activity in Figure 7b, where the activity of the DC corona sources appears more homogeneous, as the AC ripple pushes more sources above the offset.

(a) DC corona activity for 0 kV AC

(b) DC corona activity for 150 kV AC

(c) DC Corona PRPD for the 0 kV AC

(d) DC Corona PRPD for 150 kV AC

Figure 7: Comparison of DC corona PRPDs and UV activity at 180 kV for no ripple and 150 kV AC

5. Conclusion & outlook

Based on a large series of small-scale experiments with typical overhead line conductors and realistic gradients and relative coupling, the AC and DC corona effects of hybrid AC/DC lines were investigated regarding DC bias or AC ripple caused by an adjacent bundle. It was demonstrated that the corona characteristics are effected by the relative coupling from the adjacent bundle. The PRPD patterns clearly show a change in corona activity in both halfwaves and allow to explain the observed trends in audible noise. Both, the repetition rate as well as the maximum pulse amplitudes are increased through relative coupling with respect to polarity. The optical investigation of the number and activity of the corona sources qualitatively confirm these results. In consequence of the altered corona activity, also the audible noise is affected. Therefore, the audible noise on a hybrid tower can be increased through a positive DC bias or AC ripple, but also possibly be reduced through a negative DC bias in some cases and therefore allows to design an optimized conductor arrangement for an improved corona performance. In order to confirm these results for a full-scale overhead line under real weather conditions and pollution, a series of outdoor tests is scheduled on a recently constructed test line [24].

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