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Author(s):
Hedtke, Sören; Xu, Pengfei; Pfeiffer, Martin D.; Zhang, Bo; He, Jinliang; Franck, Christian

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HVDC Corona Current Characteristics and Audible Noise during Wet Weather Transitions

S. Hedtke, P. Xu, M. Pfeiffer, B. Zhang, J. He, C.M. Franck

***Abstract*—For the connection of remote energy sources, HVDC offers higher efficiency and flexibility compared to conventional HVAC. As the acceptance for overhead lines in Europe is often low, the detailed understanding of its environmental effects, such as audible noise is of crucial importance. Still, only few experimental studies have investigated HVDC corona. Recent publications have demonstrated, that existing prediction models for DC audible noise show strong deviations when extrapolated for higher surface gradients. While audible noise is considered negligible in rain, research has shown that the discharge amplitudes increase significantly during transitions from dry to wet weather and vice-versa.**

In this study, the corona current and audible noise are investigated for a large range of surface gradients and rain rates. A special focus is set on the behavior during rain onset and dry-off. While the corona current increased during rain, the measured audible noise was significantly higher during the transitions before and after the steady state. The duration of these transition periods varied with rain rate and surface gradient. The observed effects are explained using corona pulse patterns and UV data. Compared to these measurements, existing audible noise prediction models were found to overestimate the sensitivity regarding the electric field.

***Index Terms*—Corona effects, HVDC, Audible noise, Partial discharge,**

I. Introduction

Transmission system operators (TSO) currently face the challenge of integrating remote renewable energy sources such as offshore wind power or pumped storage hydro power. However, the construction of new overhead lines (OHL) is often delayed due to public objection [1]. As an alternative, utilities are discussing the conversion of conventional alternating voltage (AC) overhead lines to direct current (DC) to increase bulk transmission capacity and reduce losses [2]. Also the conversion to hybrid AC/DC overhead lines with both systems on the same tower is discussed in various countries like Germany, China, Switzerland and the US [3]–[6]. In practice, OHL conductor surface gradients are designed to stay below the critical electric field strength in air assuming a smooth conductor surface. However, the critical field is often exceeded on the conductor surface due to precipitation, pollution or scratches, causing corona discharges and secondary effects such as audible noise [7]. Therefore, the achievable transmission capacity upgrade through a DC conversion is often limited by the requirement to reduce corona effects to an acceptable limit [1].

S. Hedtke, M. Pfeiffer and C.M. Franck are with the ETH Zurich High Voltage Laboratory (HVL). P. Xu, B. Zhang and J. He are with the State Key Lab of Power Systems at Tsinghua University, China

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While there is plenty of experience in AC corona effects [7], [8], DC corona phenomena are fundamentally different [9]. With AC corona, the ions oscillate in alternating fields, causing a humming audible noise component [10]. With HVDC instead, there will be a constant ion drift along the DC field to ground, causing an increase in the Poisson electric field at ground [11]. In contrast to AC audible noise, which is worst in heavy rain, DC audible noise is known to drop in case of precipitation [9] and depends on seasonal weather and pollution [12]. The same is true for radio interference [9], which is caused by the individual corona current pulses. The sum of these corona current pulses equals the corona loss current, which is equal to the total DC current for the case of an unloaded line. The ionization energy of these individual pulses will heat up the air and also cause single acoustical pulses [13], which sum up as the widely-reported broadband crackling and hissing audible noise [14]–[16].

Previous studies of the authors have shown that the average DC corona current increases with rain rate (RR) [17]. Additionally, an investigation varying the water supply in a single-drop setup has shown that the amplitude of pulses decreases with water supply rate while the number of pulses and average current increases [18]. A coupled electro-optical study has investigated the different corona current and radio interference of two different conductor types [6]. It was observed that the corona current increases after rain onset as expected, while the radio interference drops drastically. The transition time to a steady corona current and partial discharge (PD) level was usually longer than thirty minutes. The opposite behavior occurred in the dry-off phase after stopping the rain where the corona current decreases steadily while the PD level increased. In contrast, the audible noise from AC corona is known to decrease during dry-off [8], [19].

As the audible noise is of crucial interest for the public and an important design parameter for an HVDC conversion [1], [7], [9], this transient characteristic after rain onset and during dry-off is also investigated. While researchers agree that the DC audible noise is lower in rain, data is scarce and it is not entirely clear by how much the level drops during rain. Furthermore, previous observations of the corona current during different rain intensities in [17] raise the concern, that the observed transient behavior might vary significantly with regard to transition time and amplitudes for different rain intensities. Existing experimental studies are also usually limited to a certain range of surface gradients. A case-study for hybrid tower geometries in Europe and the US has revealed that the surface gradients of a converted tower might be well above the common range as the geometry might be

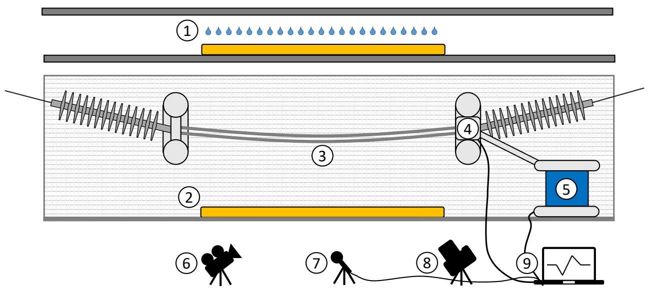


Fig. 1. Indoor corona test setup including rain simulator and movable crane (1), damping foam (2), horizontal double bundle (3), oscilloscope (4), HVDC source (5), UV camera (6), Sound Level Meter (7), SLR camera (8), Data acquisition (9)

fixed for mechanical reasons [5]. For these cases, there is a very strong deviation between existing prediction formulas regarding audible noise when extrapolated to high electric fields. Therefore it is also of high interest to explain the corona characteristics for a larger range of field strengths.

II. Experimental setup & procedure

The test line as shown in Fig. 1 consists of a horizontal double bundle which is the typical arrangement for the 400 kV AC system in Switzerland and other European countries. The conductors are new and untreated ACSR 265/35 conductors which are widely used in Europe. The active length of the conductors exposed to rain and not shielded by the toroids is 4.70 m. The bundle is strung up in the air with a minimum clearance of 2.65 m and a maximum sag of 0.12 m.

The average DC corona current, representing corona loss, is measured using an Extech Ex540 Multimeter on high potential via wireless transmission. The audible noise A-weighted equivalent sound pressure level as well as the third octave frequency bands are measured using a Norsonic Nor118 sound level meter behind the safety fence in 4.47 m separation with a temporal resolution of 1 Hz. Additionally, the raw sound files are captured for 10 s once per voltage step. The individual current pulses are measured using a TiePie Handyscope HS5 Oscilloscope with a battery pack on high potential connected via an optical fibre USB extension at a sampling rate of 500 MS/s. Based on test measurements, a 200 Ohm shunt resistor is placed in the toroid in series before the line to allow a current measurement. The corona activity on the bundle is observed using a Nikon D5300 single lens reflex camera with 30 s exposure time. This camera is automatically taking one photo every 60 s to give an overview of the number and intensity of the corona sources. Additionally, the transient corona behavior is recorded on a narrow section of the conductors through a CoronaScope UV-camera. Before every test, the conductors are wiped with ethanol. Then, possible remaining corona sources are burned off during a preconditioning phase at 400 kV for 30 minutes. Rain of different intensities is applied using the rain simulator implemented and used in previous studies [6], [10]. To ensure a clear start and end of the rain period, an overhead movable crane with an additional rain reservoir can be placed below the rain simulator. The rain intensity is controlled with a valve and flow counter while the movable crane is positioned below the rain simulator. After a waiting period of 10 minutes, the rain was verified to be constant. Then, the crane is moved away and the rain sets on instantly on the conductor at the desired intensity. During Phase A, the rain intensity is kept constant for 60 min. In a few cases this phase was extended as the corona behavior did not reach the steady state within 60 min. In Phase B, the dry-off behavior is observed. Therefore, the crane is moved back in position below the rain simulator and the valve is closed. This permits to guarantee no more drops to reach the conductor. Damping foam on both reservoirs at ground and on the movable crane allow to minimize the rain background noise to around 32 dB, which is considered negligible during both phases compared to the actual corona noise. The noise caused by the AC transformers does only affects the very low frequencies, which have a negligible contribution to the presented A-level audible noise and DC corona only causes noise in higher frequencies. Therefore, the presented values do not include additional filtering to remove the remaining background noise. While the measurements are conducted in a closed laboratory with air condition, the relative humidity can vary by some ten percent. An estimation by the authors has shown, that while air humidity influences sound propagation, the variation at the point of measurement is very small for rather extreme cases of relative humidity and therefore does not affect the presented phenomena.

The quoted electric field strengths were calculated as the average value of the maximum electric field strength on the individual bundles, the so-called average maximum surface gradient [20]. This was done in accordance with various existing studies regarding the prediction of audible noise. Accordingly, the calculation was conducted under the typical assumptions of an infinitely long cylindrical conductor without strands and surface protrusions above a plane ground and neglects the effect of space charge [9], [12].

III. Experimental results & discussion

A. Effect of electric field on transient corona characteristics

1) Measurement results:

The transient characteristics of the DC corona current (CC) and audible noise (AN) are shown after the start of constant rain in Fig. 2(a). To study the influence of the surface gradient, the measurement was repeated for various gradients between 14 and 40 kV/cm. Through the use of a wide range of surface gradients extending to values above typical gradients of up to 25 kV/cm, the measured values are also applicable to HVDC conversion projects, as a conversion can result in enhanced surface gradients on existing bundle infrastructure [5]. The lowest possible rain rate of 0.5 mm/h was selected to reach a small but homogeneous number of corona sources. Besides representing the situation of very mild rain, this situation could also represent the case of pollution in dry weather with only few corona sources [9].

Regarding the corona current, the general behavior can be divided in two different groups. For the highest surface gradient of 40 kV/cm, corona is already strongly present in dry conditions, manifesting in a high corona current. Still, the corona current shows a steep increase directly after the rain onset, until a saturated level is reached after roughly 90 min. All other corona current trends can be summarized in a second group showing no measurable corona current before the rain onset. As soon as rain drops reach the conductor, a corona current is measured. Both, the rate of rise of the current as well as the maximum steady state level increase with the surface gradient.

The audible noise after the rain onset shows a very different trend for the same measurements. In general, the behavior can be divided into three different groups: For the surface gradient of 40 kV/cm, there is already corona AN without any rain as can be seen also for the corona current. After the rain onset, the AN shows a strong decay, reaching its steady state level after more than 90 minutes. The second group of gradients from 18 to 30 kV/cm shows low to no corona AN in the dry state before rain. If the rain sets on, the AN jumps to a higher value, which is again followed by a decline until reaching the steady state after more than 60 minutes. For the third group of the lowest surface gradients of 14 and 16 kV/cm, the audible noise level is equal to the background level before the onset of rain. After the rain onset, however, there is no immediate measurable change in AN. With increasing time, the audible noise level rises slowly until reaching steady state. As for the corona current, the audible noise level increases with the surface gradient. In the same measurement, the rain is stopped after the steady state phase using the movable crane in order to investigate the corona characteristics during the dry-off. The observed trends for the DC corona current and audible noise are displayed in Fig. 2. During the dry-off phase, the corona current trend for various field strengths can be separated in two groups. For the highest field strength of 40 kV/cm, the corona current decreases directly after the rain stops and reduces within 90 min to the current level reached before the start of rain. At this point, no more drops were observed on the conductor. Secondly, all field strengths equal and below 30 kV/cm show a very similar trend in corona current during the dry-off phase. The stop of rain is immediately followed by a steady decrease in corona current until reaching zero current. After this point, no measurable DC current was detected. Regarding the time to dry, no clear impact of the electric field can be observed. It should be noted that the bundles are only loaded with the corona currents and are not heated externally. Therefore, the conductors are at room temperature below typical operating conditions of OHL. The absolute drying-off times might be significantly lower at higher conductor temperatures. However, the authors are convinced, that this will not influence the general trends and dependencies shown in this study.

The behavior of the audible noise is again quite in contrast to the trends of the corona current. As for the rain onset, the behavior during dry-off can be divided into three groups of surface gradients: For 40 kV/cm, the corona AN increases slowly after the rain is stopped and reaches a stable saturated level after 120 minutes similar to the level before the start of rain. The second group of gradients from 18 to 30 kV/cm shows a similar increase of the AN with time during the dry-off phase. However, after a couple of ten minutes, the noise drops rapidly to the background noise level of the laboratory. In addition to the A-weighted audible noise levels in Fig. 2, also the third-octave frequency bands are shown for the case of 25 kV/cm and 0.5 mm/h in Fig. 3 for different time instants during the rain and dry-off phase respectively. It is observed that with the onset of corona, the most significant change after corona onset occurs in the bands above 400 Hz with the peaks occurring around 2 to 4, as well as 12 to 16 kHz. This trend is true for both the rain and dry-off phase. The additional low frequency peaks around 100 to 400 Hz are considered transformer noise and are mostly constant besides variations in load and background noise and therefore irrelevant for the DC noise.

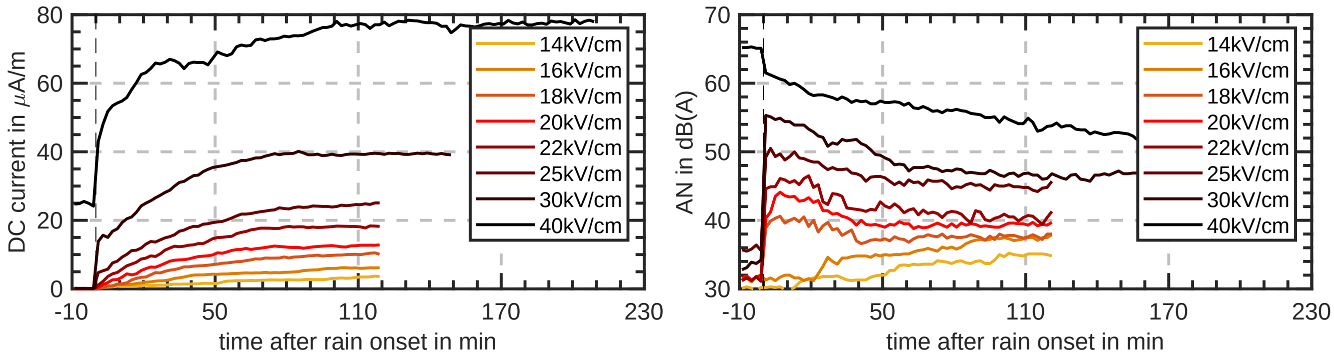
As an additional reference to explain the observed behavior, the individual corona current pulses were captured once per minute. Therefore four example snapshots of the current pulses are displayed in Fig. 4 for a surface gradient of 25 kV/cm at a rain rate of 0.5 mm/h, representative for the rain onset (a), during the transient phase (b), in the steady state (c) and during (d) and shortly before the end of the dry-off phase (e).

Likewise, the corona sources are captured by long-exposure photography in the near UV spectrum for the same instants in time in Fig 4. While only a few corona sources are active after the rain onset, a significantly higher number of drops are active in steady state. Also, all corona sources in steady state are clearly facing downwards while the corona sources after the rain onset are mostly placed on the upper side or facing the side of the conductor. Although the quality of the optical data does not allow for a quantitative analysis, the streamers on the upper side appear to be wider and more elongated compared to the lower side streamers. While more discharges seem to occur in steady state from the drops hanging down from the conductor, their streamers seem to be relatively short and very confined. However, for the drops during dry-off, the streamers on the downside appear to be again more elongated while much smaller in number.

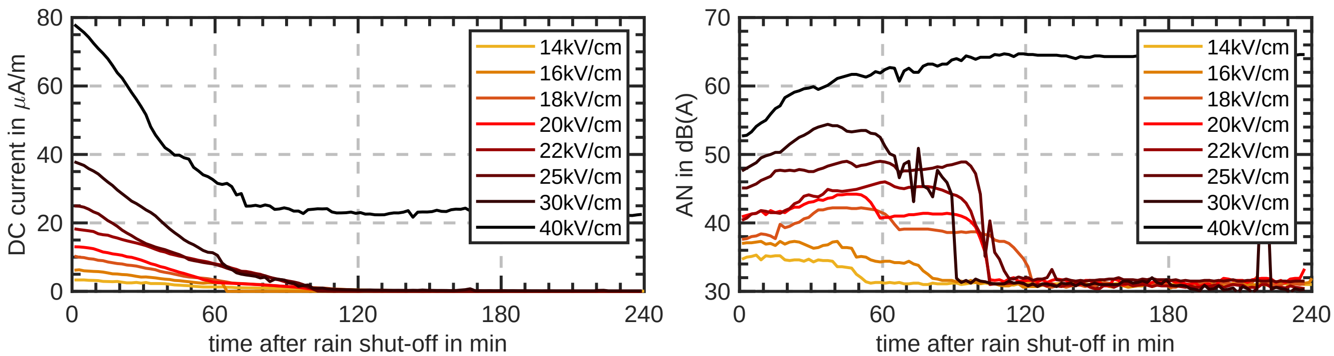
For the pulse patterns, it is obvious that there is a clear trend from few very strong pulses after rain onset towards very small pulses of high repetition rate in the steady state. The contrary behavior is observed during dry-off, when the pulse repetition rate is clearly reduced while rising again in amplitude.

2) Discussion of Results:

The observed trend of the corona current in Fig. 2 can be explained by the increasing number of water drops on the conductor and thus corona sources with time. As corona occurs almost exclusively on water drops, they define the number of active corona sources. Furthermore, their size and shape influences the local electric field distribution and hence the corona activity. All curves below 40 kV/cm start at zero current as no corona occurred in dry and clean conditions. Although the first drops immediately reach the conductor after start of the rain, drops move slowly in the grooves of the stranded conductor until reaching the bottom of the conductor as shown in a previous publication of some of the authors [6]. This behavior is very similar to the AC corona loss increasing with time until reaching saturation as shown in [8]. The corona current is higher for higher surface gradients as it exceeds corona onset for a higher number of drops and corona pulses will occur at higher amplitude and frequency. After a certain



(a) rain onset



(b) dry-off

Fig. 2. Transient corona current and audible noise after rain onset (0.5 mm/h) and during dry-off for various surface gradients (in kV/cm)

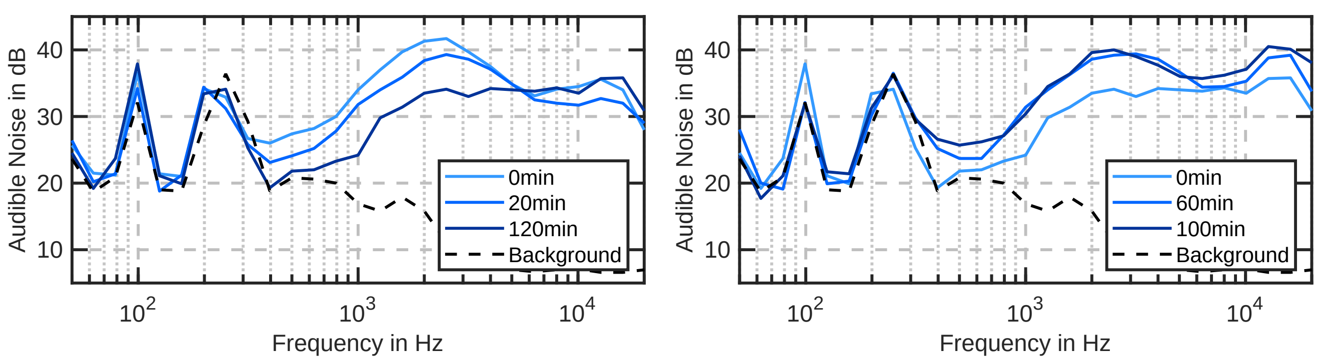


Fig. 3. Audible noise spectrum for 25 kV/cm at 0.5 mm/h for various times after rain onset (left) and dry-off (right) compared to the background noise (BG)

time, the water distribution on the conductor has reached a steady state, where the number of drops vanishing due to gravitation and water spilled by Taylor cones is equal to the water supplied from above. During the transition, the strong pulses clearly vanish while the number of pulses is increased (Fig. 4).

This can therefore explain the drop in audible noise while the corona current increases. While the mean DC current is just the sum of current pulses and therefore equally influenced by pulse amplitude and pulse frequency, this is not true for the audible noise. As discussed by Straumann in [21], the acoustical energy caused by a single current pulse will always exceed the energy-equivalent addition of two pulses of exactly half its energy. Therefore, single pulses of high amplitude will have a higher influence on the audible noise level than a high number of pulses of low amplitude. The general trend of the audible noise is consistent with the observations of [9] that DC audible noise drops in rainy conditions. However, while audible noise in typically reported to be higher for dry conductors, this is not true for laboratory investigations, as the number of possible particles and insects on the conductor is very low and therefore the conductor is mostly free from corona sources. Using the partial discharge amplitude as a reference for the audible noise level, this transient behavior was also shown in previous measurements in [6]. A possible explanation was introduced by [9] as the concept of the ”critical number of corona sources”. Accordingly, if the number or density of corona sources exceeds a certain level, the space charges created within the discharge will shield adjacent corona sources and therefore reduce their corona intensity.

Therefore, while counterintuitive, the audible noise decreases although the corona current increases with time. The higher number of active corona sources actually tends to reduce the activity of the individual sources. Also, while the drops grow in size while traveling in the conductor grooves, they can deform into Taylor cones on the lower conductor side. While the Taylor cones are known to have very high local electric fields, their field decay is very steep and typically causes discharges of low amplitude but high repetition frequency.

The resulting pulse patterns are therefore also a possible explanation for the observed trend in the third octave bands. The spectra show two elevated peaks which are caused by the transformer and also present if the same voltage is applied without any corona occurring on the dry conductor. The increase in broadband audible noise reaching to higher frequencies is typical for corona as shown by other researchers [9]. While all higher frequencies show clearly elevated levels in corona compared to the background noise, the transient development after rain onset and during the dry-off are not identical for all third-octave bands. As the number of water drops and there local electric field change with time, also the noise spectrum is subject to change after rain onset and during dry-off until a steady state is reached. Actually, the audible noise for the medium frequencies around 400 Hz to 4 kHz (Fig. 3) is highest after rain onset and at the end of the dry-off, but is observed to decrease in the steady state rain. Therefore, the audible noise of these frequency bands is actually highest for the lowest repetition rates and is reduced for the case of high repetition rate and number of pulses. On the other hand, the higher frequency bands above 10 kHz tend to increase after rain onset and hence with the number of drops and discharges. During dry-off however, this behavior is less clear, as also the high frequency bands increase after dry-off. Assuming equal pulse amplitudes, an increase in pulse repetition rate should theoretically also cause a shift towards higher frequencies in the audible spectrum. As the corona pulse repetition rate increases with the number of drops and is highest in steady state, this should generally increase the audible noise in higher frequencies, possibly including the ultrasound range. However, for the few but strong pulses after the rain onset and during dry-off, the repetition rate is low and so the dominant frequencies are in the lower frequency bands.

Regarding the two lowest surface gradients, the change in AN and CC is very small directly after rain onset, although drops are present on the conductor. Therefore, the corona onset condition is not fulfilled for water drops resting on the upper conductor side. However, the audible noise will start to raise after some ten minutes which coincidences with the time for the drops to reach the bottom of the conductor. This leads to the conclusion, that corona onset is quite different for the top-side resting drops compared to water drops hanging on the lower side of the conductor, possibly forming Taylor cones. As the size and shape of these Taylor cone drops is different, the local electric field will be higher and hence lead to an earlier onset. In the first couple of minutes, corona will only occur on top of the conductor between falling drops and the conductor if the background electric field is sufficiently high. Later-on, drops will hang from the lower side of the conductor, were corona was observed for all gradients, and contribute to the audible noise as well. As the increase in audible noise is delayed for the lower range of surface gradients, the corona onset for the lower side corona is assumed to be lower than the upper side corona.

Interestingly, the transition time to steady state tends to increase with the surface gradient. This can possibly be explained with the higher difference of surface gradient and critical field, leading to stronger corona on a larger number of drops. Therefore, it takes longer to reach an equilibrium at the lower side of the conductor as some drops might vaporize on the top and more water is lost by hanging Taylor cones.

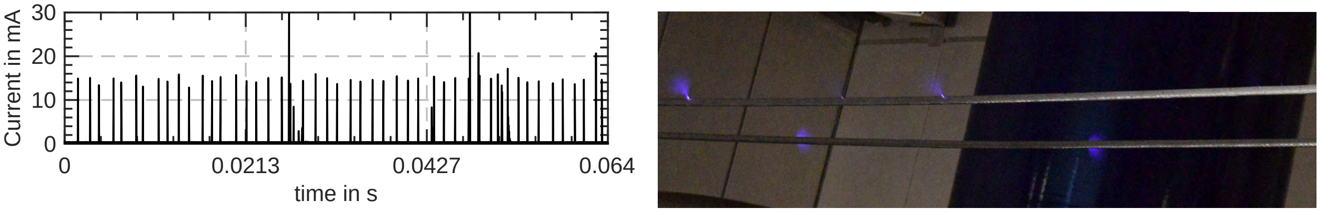
During dry-off, the corona current decreases slowly, while the audible noise increases. As the number of drops on the conductor decreases, less ions are generated on the conductor reducing the size of the surrounding shielding ion cloud. This allows the water drops to generate larger streamers and, thus, current pulses while the number of pulses and, hence, the average current decreases. In the end, only very few drops remain, generating significant pulses and audible noise. This also explains the quite fluctuating behavior as strong but very intermittent corona on single sources has a major impact on the audible noise. Based on the experience with AC corona, it is very remarkable that the audible noise from only two water drops in DC can exceed the audible noise generated by some ten drops per meter. This is also one reason why DC audible noise is complicated to quantify and possible deviations between different setups and laboratories can be large, as the worst case levels can be defined by a very small number of corona sources.

B. *Effect of rain rate on transient corona characteristics*

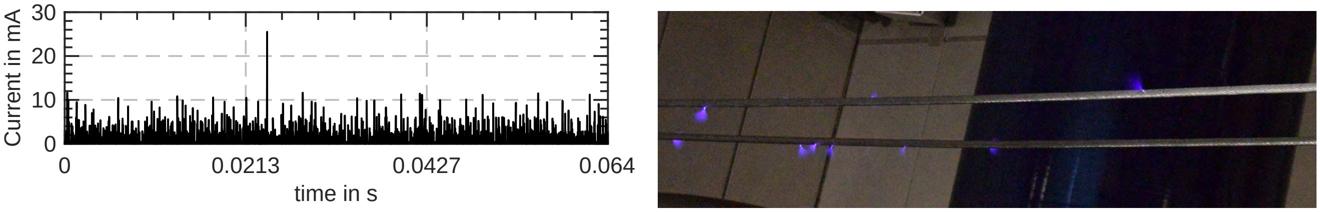
1) Measurement results:

In a second test series, the transient behavior of corona audible noise and corona current are investigated at constant field strength but for various rain rates. For typical operation conditions, a surface gradient of 25 kV/cm was chosen. The rain rate was varied from 0.5 mm/h to 4 mm/h, representing the lowest possible rain rate with the existing rain simulator and valve, as well as the highest rain rate with a homogeneous rain distribution. While 4 mm/h is a realistic assumption for strong rain in Europe, with significantly higher rates typically only occurring as very short peaks, the lowest rain intensity was selected as an approximation for corona on dry and polluted conductors with only a small number of corona sources per meter. For these different rain intensities, the corona current and audible noise are depicted in Fig. 5.

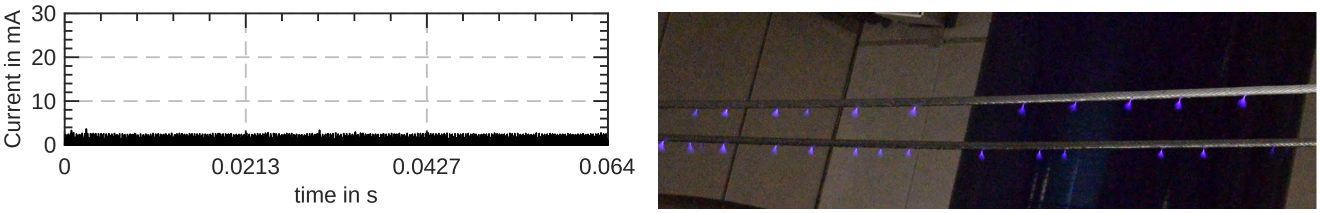
The corona current shows an increasing trend for all rain rates until reaching a stable level. The increase after rain onset is steeper for the higher rain intensities. Also, the time to reach a stable corona current is shorter for higher rain rates and the steady state corona current is highest for the highest rain rate. Also for the audible noise, the general trend is similar for all rain rates after rain onset. After a steep increase directly after rain onset, the audible noise level decreases for all rain rates until reaching a steady state. In general, the peak after rain onset is higher for lower rain rates. Also, the time until



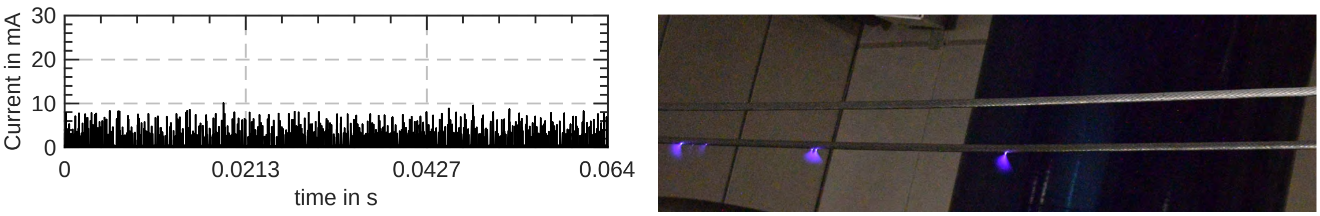
(a) 0 min after rain-onset



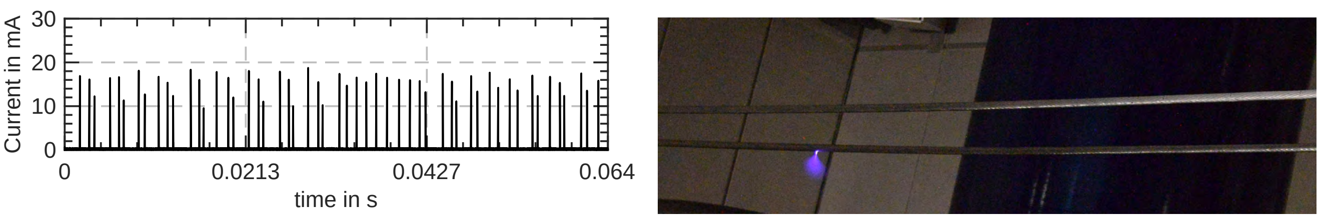
(b) 20 min after rain-onset (transient phase)



(c) 120 min after rain-onset (steady state)



(d) 60 min after rain-stop (dry-off phase)



(e) 100 min after rain-stop (end of dry-off)

Fig. 4. Corona current pulse patterns (left) and visual corona inspection (right) for various instants during rain and dry-off

a steady AN level is reached is longer for the lower rain rates. The steady state level is highest for the lowest rain rate. However, the differences between the other rain rates are small and there is no clear trend of a higher steady state audible noise with lower rain intensity. The corona characteristics during the dry-off are shown in Fig. 5 for different rain rates. All corona currents show a similar decreasing trend immediately after rain shutdown. However, while the current returns to zero for the lowest rain rate, a small current remains for the other cases. For these other cases, the current was zero before the rain was started.

During the dry-off phase, the audible noise increases similarly for all rain rates. For some of the cases, the audible noise shows a very fluctuating behavior, falling down to a lower level and jumping back up right after. While the audible noise falls down to the background noise and remaining constant for one of the rain rates, it stays relatively constant at a high level for a long time after the initial increase. This is the case for all rain rates with also a small corona current remaining after dry-off.

2) Discussion of results:

The corona current increases in steepness and steady state level with the rain rate. As more drops are present on the conductor for a higher rain intensity, even in steady state, the number of

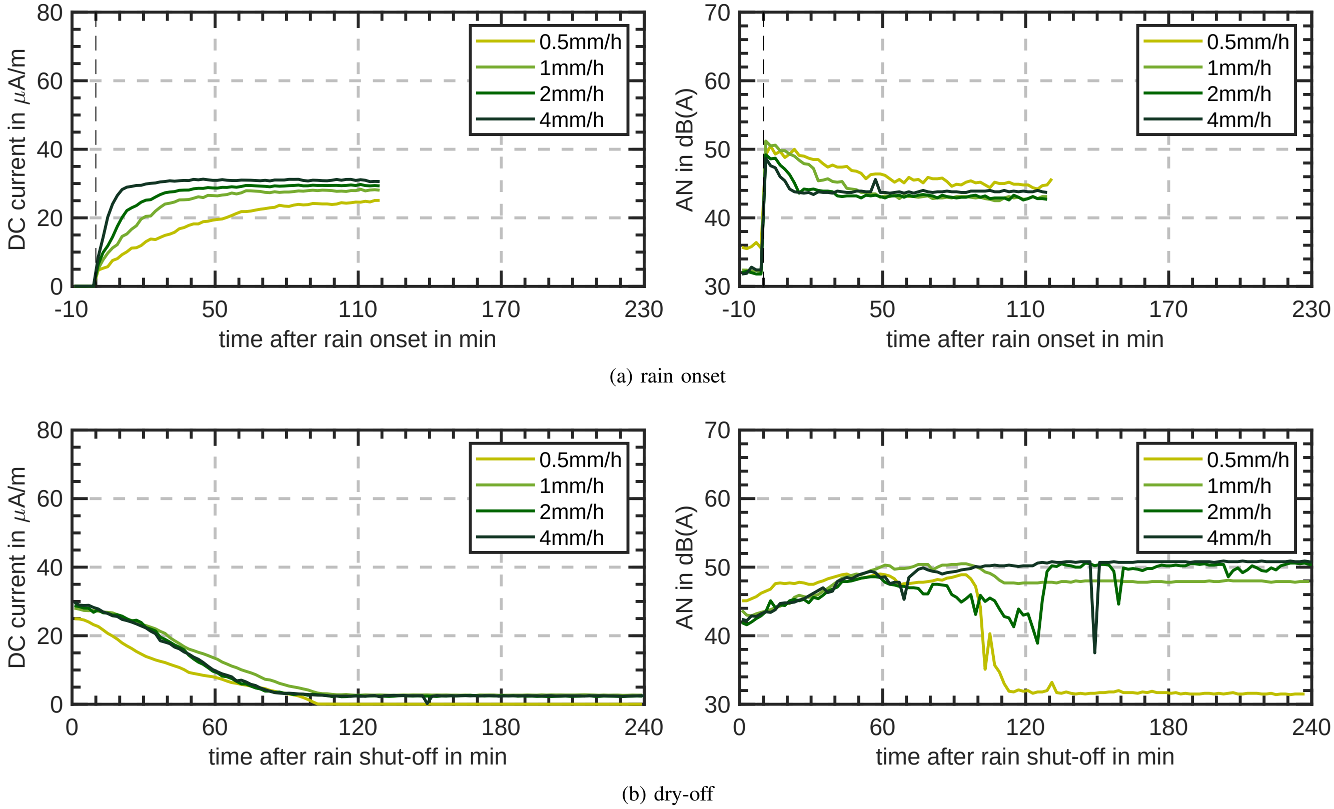


Fig. 5. Transient corona characteristics for 25 kV/cm after rain onset depending on rain rate in mm/h for corona current (left) and audible noise (right)

corona sources is higher. While the shielding of adjacent rain drops might result in a lower pulse amplitude, the total number of pulses, and hence, the integrated corona current is higher.

For the audible noise, the measured peak level after the onset is higher for the lower rain intensities. This includes the duration of the decay as well. This might be for two reasons. Firstly, if the water supply and rain rate are higher, drops might reach the lower side of the conductor earlier, while no single large drops can form on the upper side of the conductor. As seen before, the pulses caused by only few drops on the upper side tend to be higher than on the lower side and hence, should cause the audible noise. Secondly, the ion cloud caused by the rain drops might shield adjacent drops and therefore reduce their pulse amplitude. As incorporated by the concept of the ”critical number of corona sources” from [9], the number of corona sources on the conductor exceeds the critical number for an increasing rain rate. Therefore, the audible noise is equal or lower to the one with less rain rate. As the supply rate of drops is much lower for the low rain rates, also the time interval to reach steady state is higher, as it takes more time to fill the conductor grooves. In the final stage, almost no discharges were detected from the upper side of the conductor. This could be caused by two different factors. If many drops are coronating on the lower side of the conductor, this could possibly suppress significant discharges from the upper side to contribute to the audible noise. Furthermore, some time after rain-onset, enough water has accumulated on the conductor to form a rather film than individual drops, thereby reducing the local electric field below corona onset.

During the dry-off, there is no clear trend of a dependence of the corona current to the rain rate. While the time to reach a steady state is shortest for the lowest rain rate, this trend is not confirmed by the higher rates. This might be caused by the additional water loss due to Taylor cone corona [22], as discussed in [6]. While drying is assumed to be generally faster for less water and hence lower rain rates, Taylor cones which are present in a higher number for more water supply might accelerate this process. Furthermore, the current does not return to zero for some of the rain intensities. This is due to a very small number of corona sources remaining steadily during the dry-off. The authors are convinced, that this corona activity is caused by dust particles acquired during the dry-off phase and therefore not related to the rain intensity. As this occurrence is very stochastic, it is impossible to receive reproducible results, especially as the pollution in the laboratory is not enough to get a homogeneous level of particles on the conductor.

The dry-off behavior for the audible noise is very fluctuating and does not allow for a clear qualitative interpretation. This is mainly due to a very small number of drops generating intermittent corona of, however, very strong pulse amplitudes. Therefore while the drop in corona current is only very small compared to the audible noise level in the steady state, the audible noise level can jump by over 10 dB if only one single corona source exceeds or falls below its corona onset. As for the corona current, the audible noise remains quite stable above the background noise at the end of the drying stage. While the small number of dirt particles only produces a small amount of corona current, its strong pulses can contribute to significant audible noise. Still, this behavior is highly unreproducible and not within the scope of these measurements. However, in weather conditions with significant potential for pollution on the conductors, the behavior during dry-off is assumed to be quite similar.

The shown effect of rain rate on the transient corona characteristics can have quite direct consequences for the application of HVDC overhead lines. While audible noise during rain is often assumed negligible, it is shown that the audible noise for low rain rates will be significantly higher than for high rain rates. Therefore, further laboratory studies should focus on very low rain intensities to get closer to the worst case. Also, although the audible noise will drop for all rain rates, the transition time can be in the order of 45 min in which the audible noise is still higher. In contrast to the dry-off time, the time to steady state, if affected, should increase for higher conductor operating temperatures. Especially, when rain might rather occur in shorter showers than continuously, the lowest steady state levels might only be reached in laboratories. Finally, as with the dry-weather audible noise, the audible noise in light rain or transient periods might cause higher awareness as more people are outside.

C. Comparison of results to existing prediction models

Recent case studies have shown, that the variation between existing DC audible noise prediction formulas can be very large when applied for high field strengths which exceed their intended range. However, these high gradients could realistically occur when existing lines are to be converted without the possibility to exchange bundles for mechanical reasons [5]. As an approximation of polluted conductors with a small number of corona sources, the corona noise at very low rain rate (0.5 mm/h) is compared to the extrapolation of the existing formulas from EPRI [9] and BPA [12]. Therefore, the dependency of the DC AN on the surface gradient is compared to the presented measurement results in Fig. 6. From the measurements, the audible noise is extracted from three different states. Firstly, the audible noise which occurs in the first minutes after the rain onset is used, where only very few drops on the upper side are supposed to coronate. Secondly, the steady state AN is selected which was constant for over ten minutes. Lastly, although high fluctuating, the maximum of the audible noise during the dry-off phase is chosen as a final comparison. At this stage, only very few sources are active, which might also be the case in summer at the beginning of a pollution stage.

Based on the results, the sensitivity to the electric field is generally higher for both the EPRI and the BPA formula. However, this sensitivity is significantly stronger for the EPRI formula as shown in [5] leading to large deviations between the different predictions for high field strengths. The results from the onset phase are closest to the BPA curve while the steady state values as well as the dry-off levels are even less sensitive. Therefore, the authors question the extrapolation of existing measurement data for higher field strengths this leads to significant deviations of more than 10 dB in extreme cases.

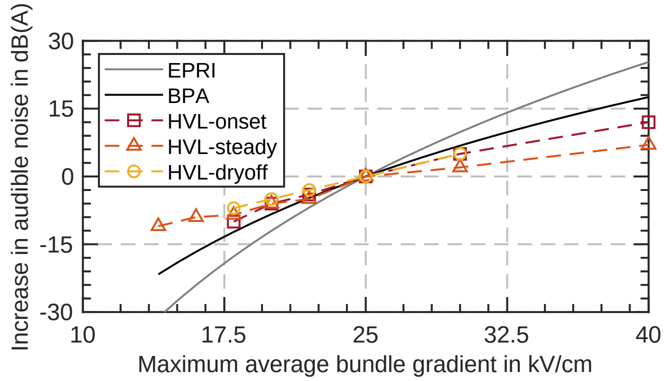


Fig. 6. Increase of DC audible noise as comparison of the BPA and EPRI formula with measurement results after rain onset, during steady state and the maximum reached during dry-off

However, while the measurement results were obtained in a controlled laboratory setup, the corona behavior at low rain intensities might be somewhat different to corona from insects, grass particles and other sources. Partly, this lower sensitivity of the audible noise for the electric field could be explained with the deformation of water drops in electric fields while other corona sources like scratches should stay mostly constant or burn away as bio particles.

IV. Conclusion & Outlook

The audible noise and corona current pulses were investigated for a high range of surface gradients in various rain intensities. The transient behavior of the corona characteristics during the rain onset and dry-off were studied. Both these phases show a significantly higher audible noise level compared to the steady state rain case in contrast to the corona current. This is explained based on the significant decrease in the amplitude of the single corona pulses as well as the change in number and location of the corona sources using additional optical investigations. Furthermore, the duration of the transient phases has shown to increase with the surface gradient and decrease with rain intensity. The decrease of DC audible noise during heavy rain and the high audible noise during dry summer is explained with the small amount of corona sources and the consequently reduced shielding and enhanced corona activity. This is confirmed based on the increase of audible noise for lower numbers of corona sources in the transient phases and at low rain intensities. As an approximation for the corona in dry summer weather, the corona characteristics at low rain intensity and during the transients are compared to fair weather prediction levels. Here, the existing prediction models were more sensitive to the electric field compared to the presented measurements. The observed effects are scheduled to be investigated in more detail on a recently constructed outdoor test line [23].

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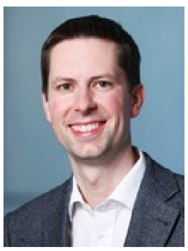
Sören Hedtke was born in 1988 in Neuwied, Germany and studied Electrical Engineering and Information Technology at TU Darmstadt (Germany) and Grenoble INP (France). Since he received his M.Sc. degree in 2014, he is with the High Voltage Laboratory at ETH Zurich (Switzerland). His current Ph.D. research focuses on hybrid AC/DC overhead lines with a special interest on the influence of coupling effects on corona phenomena and audible noise.

Pengfei Xu Pengfei Xu was born in Qingdao, Shandong Province, China, in 1991. He received the Bachelor's. degree in Electrical Engineering in North China Electricity Power University in 2013, and the Ph.D. degree in Electrical Engineering from Tsinghua University in 2018. His main research topics are corona effects on HVDC and HVAC overhead lines. Currently, he is working at Global Energy Interconnection Development and Cooperation Organization, Beijing.

Martin Pfeiffer was born in Cotonou, Benin, in 1986. He received the M.Eng. degree in Engineering and Business Finance from University College London, UK, in 2008, the M.Sc. degree in Energy Science and Technology from ETH Zurich, Switzerland, in 2012 and the Ph.D. degree in electrical engineering from ETH Zurich in 2017. His main research topics are corona effects on HVDC overhead lines and their impact on potential hybrid AC/DC transmission lines.

Bo Zhang (M'10, SM'16) was born in Datong, China, in 1976. He received the B.Sc. and Ph.D. degrees in theoretical electrical engineering from the North China Electric Power University, Baoding, China, in 1998 and 2003, respectively. Currently, he is an Associate Professor in the Department of Electrical Engineering at Tsinghua University, Beijing. His research interests include computational electromagnetics and EMC in power systems.

Jinliang He (M'02–SM'02–F'08) was born in Changsha, China, in 1966. He received the B.Sc. degree in electrical engineering from Wuhan University of Hydraulic and Electrical Engineering, Wuhan, China, in 1988, the M.Sc. degree in electrical engineering from Chongqing University, Chongqing, China, in 1991, and the Ph.D. degree in electrical engineering from Tsinghua University, Beijing, China, in 1994. Currently, he is the Chair of the High Voltage Research Institute at Tsinghua University, Beijing, China. He is the author of five books and 300 technical papers. His research interests include overvoltage and electromagnetic compatibility in power systems and electronic systems, lightning protection, grounding technology, power apparatus, and dielectric material.



Christian M. Franck (M'04-SM'11) received a diploma in physics from the University of Kiel, Germany in 1999 and the Ph.D. degree in physics from the University of Greifswald, Germany in 2003. He was with the Swiss corporate research center of ABB from 2003-2009 as a Scientist and Group Leader for gas circuit breakers and high-voltage systems. Currently, he is Professor for High Voltage Technology at the Swiss Federal Institute of Technology (ETH) in Zurich, Switzerland.