11145 Session 2022
B2 – OVERHEAD LINES
PS3 – ENVIRONMENTAL AND SAFETY ASPECTS FROM OHL

Correlation of the Surface Wettability and the Audible Noise Emission of Overhead Line Conductors

H. KIRCHNER
ETH Zürich
Switzerland
hkirchner@ethz.ch

C. M. FRANCK
ETH Zürich
Switzerland
cfranck@ethz.ch

SUMMARY

Given today's energy and climate policy, it is necessary to expand the power transmission capacity of our electrical network. This includes the new construction, expansion and modernization of existing high-voltage overhead line systems. However, this is made more difficult by many regulations, environmental requirements and the acceptance of the population. A potential for increasing the acceptance within the population lies in the reduction of audible noise emissions, which occur during foul weather, especially rain. The noise emission results from corona discharges, which are generated by water droplets on the conductor surface. The water droplets deform into Taylor cones in the electric field of the conductor and thus increase the electric field strength locally at the conductor surface. Previous investigations have shown that the deformation can be reduced by hydrophilic properties of the surface, which leads to a reduced electric field strength at the top of the droplet [1]. This in turn, leads to an increased corona inception voltage or, at a constant voltage, to a reduction of related corona discharges and thus decreases the noise emission. It has been suggested previously to use hydrophilic conductors to reduce corona noise emission and successful tests are reported [2, 3]. However, the detailed mechanism of noise reduction from full scale conductors is not explained and no clear definition of hydrophilicity on stranded conductors is given. Hydrophilic properties are commonly defined by the contact angle of water droplets on flat surfaces and must be smaller than 90°.
To investigate the correlation between hydrophilic surfaces and noise emission, several differently treated conductors are examined. The static contact angle of a single droplet on a conductor strand is measured and the behavior of the full conductor

with a completely wetted surface is investigated. The noise emission is measured on wetted overhead lines under AC stress as a function of the applied electric field strength.
The results show that the static contact angle of single droplets is no sufficient predictor for the audible noise behavior of the completely wetted surface. From the measurements it must be concluded that there is no correlation between hydrophilicity (measured by contact angle of single droplets) and noise emission. A reduction of the noise emission can only be measured when a complete water film is formed on the conductor surface. The missing correlation between the contact angle and the noise emission assume that other influences such as the droplet population, droplet size and the adhesion of the droplets to the surface also seem to play a major role in the discharge behavior of the corona discharges and thus in the noise emission.

KEYWORDS

Audible Noise, Corona Discharges, Hydrophilic Conductor, Surface Treatment

INTRODUCTION

The energy transition leads to the necessity to further expand the existing power transmission network in Europe. This means expansion, new construction and maintenance of existing infrastructure. The main focus is on high-voltage overhead lines, as they are a very cost-effective option compared to underground cables. However, political regulations, environmental regulations and public acceptance make the expansion of high-voltage overhead line systems difficult. One reason for the lack of public acceptance is the audible noise emission from overhead lines during bad weather, such as rain or fog. The noise emission is caused by corona discharges, which occur at the water droplets on the conductor surface. The droplets deform into Taylor cones in the electric field of the conductor and lead to an increased electric field on the surface [1, 4]. In the area of the increased electric field strength, external partial discharges can occur in ambient air around the conductor (Figure 1 shows photos of the UV-light emitted from the streamer discharges around a new (left) and an aged (right) conductor).

The occurring audible noise emission can be divided into two different components, a broadband and a $2f$-component (f being the power frequency). Streamer discharges on the water droplets result in a hissing or crackling noise, which has a broadband frequency range up to several kHz [2, 5]. The streamer discharges lead to space charges around the conductor which oscillate in the alternating electric field around the conductor. From these ion motion, energy is transferred to the neutral particles of the ambient air which forms the $2f$-component with a humming character. [2]

Studies in recent decades have shown that aged conductors have lower noise emissions than new ones [2, 3, 6, 7]. One explanation for this is the hydrophilic surface that forms on the conductor during the aging process. Due to the hydrophilic properties of a conductor surface, the deformation of droplets to Taylor cones is reduced and thus the increase of the local electric field strength [1]. As a result, less corona discharges occur at the water droplets which reduces the noise emission.

One way to reduce noise emissions and thus improve public acceptance is to mimic the hydrophilic properties of aged overhead lines using surface treatments. Conductors with different surface treatments such as sandblasting for roughening or additional hydrophilic coatings have been produced for some years and are sold as so-called "silent conductors". The noise emission behavior of some of these surface-treated overhead lines has been investigated in former projects at TU Graz [3, 6, 7] and ETH Zurich (CONOR Project) [2]. However, the conductors are only classified by having either a hydrophilic or a hydrophobic surface [2, 3]. A precise statement on the behavior of water droplets on the surface is missing.

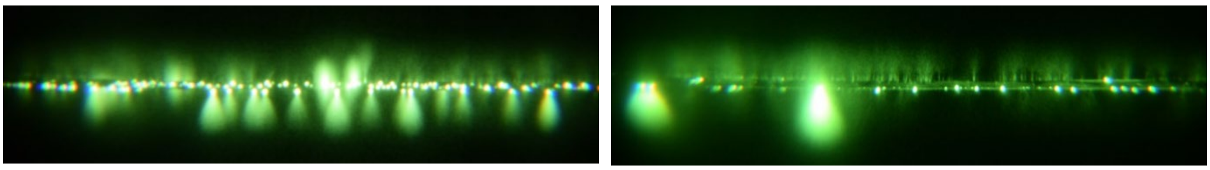


Figure 1: Corona discharges at a new (left) and an aged (right) conductor during rain (surface gradient: 27 kV/cm; rain rate: 3.5 mm/h)

Hydrophilicity is defined by the contact angle of a single water droplet at the contact point with the surface. If this angle is larger than 90°, the surface is described as hydrophobic, if the contact angle is lower than 90°, as hydrophilic [8-10] (cf. also Figure 3). However, the question is whether the determination of the hydrophilic properties based on the contact angle of single droplet on single strands is also sufficient to predict the noise emission behavior of the full conductors. For this reason, the static contact angle, as well as the behavior of droplets on the completely wetted conductor surface, are investigated in the present publication. In addition, this is compared to the A-weighted sound power level of the conductors as a function of the electric field strength.

METHODS AND MATERIALS

I: Set up for noise emission measurement

The noise emitted by overhead lines is investigated with the aid of a setup in the high-voltage laboratory at ETH Zurich. A picture of the setup is shown in Figure 2. The laboratory and equipment is free of partial discharges in the voltage range of the experiment. The conductor samples are also free of partial discharges up to approx. 24 kV/cm in the dry state. Thus, influences on the noise emission due to discharges on the surface without droplets can be excluded during the measurements up to this electric field strength. In order to simplify the electric field strength distribution on the conductor surface, single conductors are investigated first. The overhead line (1) with a length of 8 m is suspended at a height of 2.5 m. The suspension points are shielded with toroids (2). With the help of a rain simulator, the conductor is wetted over a length of 6 meters, whereby the rain rate can be variably adjusted.

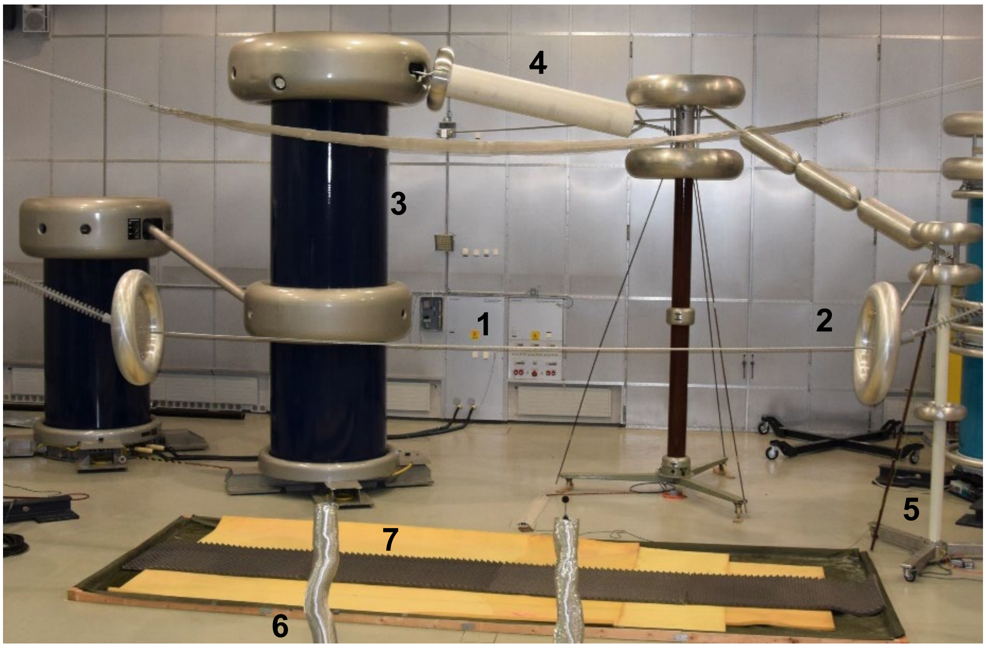


Figure 2: Experimental set up for noise emission measurement.

The line is energized by an 800 kV transformer cascade (3) and the measurement setup corresponds to a conventional PD measuring circuit according to IEC 60270 [11]. A blocking impedance (4) is connected between the AC voltage source and the test object. In addition, there is a coupling capacitor (5) in the test circuit, to which the measuring impedance for PD measurement is connected in series.

The sound emission of the conductor is measured with two shielded microphones (6) at a distance of 3 m from the conductor. The sound pressure level is measured in one-third octave bands in the range of 100 Hz - 20 kHz. To reduce the impact noise of the water droplets on the ground, the catch basin is covered with foam (7). Subsequently, the A-weighted sound power level is calculated from the measured sound pressure level according to ISO 3744 [12].

II. Investigation of the wettability of conductor surfaces

Two different approaches are used to study the wettability of the conductor surfaces. On the one hand, the wettability is determined with the static contact angle. For this purpose, individual droplets with a volume of 4 μl are applied to the conductor surface. The droplets are placed on the top of single aluminum strands or on the coating of the conductor (depending on the surface according to Table 1). As the contact angle of the droplet changes with time, it is measured after 1 min, 3 min and 10 min, as shown in Figure 3. Each measurement is repeated 10 times at different positions on the conductor surface and the median, minimum and maximum angle is evaluated.
On the other hand, investigations with several droplets under rain-like conditions are also carried out. These should help to achieve an understanding of the behavior of the water droplets on the entire conductor surface. The conductors are completely wetted around the entire circumference and water is also constantly added to simulate rain. The measurements are taken without an applied electric field strength to isolate the wettability behavior from the deformation of the droplets in the electric field.

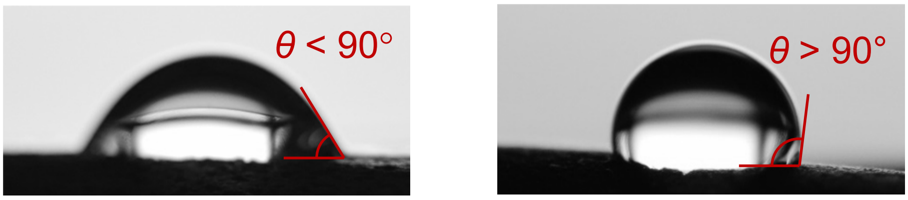


Figure 3: Static contact angle θ of droplets on a hydrophilic (left) and a hydrophobic (right) conductor surface according to [8]

III. Conductor surfaces

The surfaces of the conductors differ in their wettability due to different surface treatments. The different surfaces that are used for the investigations in the present contribution are listed in Table 1. The conductors each have the same diameter of 22.4 mm and, except for the coated conductor, the same geometrical structure (see Figure 4). The surfaces were not specially cleaned, but only wetted with water for a longer period of time around the total circumference.

Table 1: Investigated conductor surfaces

Conductor	Short form	Surface treatment
aged	ag	Aged over several years in operation
blank	bl	Untreated, new
colored	cl	Painted with a black color, new
coated	ct	sheathed with Polyolefin (approx. 3mm thickness), new
sand1	s1	Sandblasted, new
sand2	s2	Other sandblast treatment, new

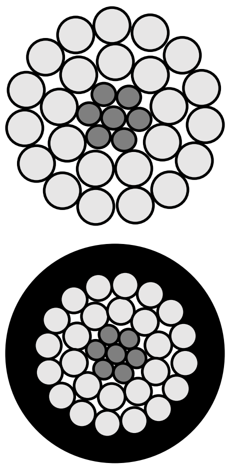


Figure 4: Geometry of investigated conductors, top: cross section of aged, blank, colored, and both sandblasted conductors; bottom: cross section of coated conductor

RESULTS

I. Static contact angle

The measured static contact angles for the individual conductors with maximum deviations are shown in Figure 5 for the measurement times 1 min, 3 min and 10 min. The results show that the contact angle of the aged conductor is lowest compared to the other conductors at the measurement time 1 min. Moreover, it does not change much over time. The aged conductor is very hydrophilic with a contact angle smaller than 50°. The blank and the colored conductor exhibit very large contact angles. These decrease over time, but not as much as for the other conductors. According to the definition that a hydrophilic surface is present as soon as the contact angle is less than 90°, both conductors are hydrophilic after more than three minutes. The conductor with the polyolefin coating has the highest dispersion in the contact angle after one minute and exhibits hydrophilic behavior after only three minutes. The two different sand-blasted conductors exhibit similar behavior in the contact angle. After one minute, the contact angle is still greater than 90°, but decreases sharply with time. After 10 minutes, the contact angle is even smaller than that of the aged conductor.

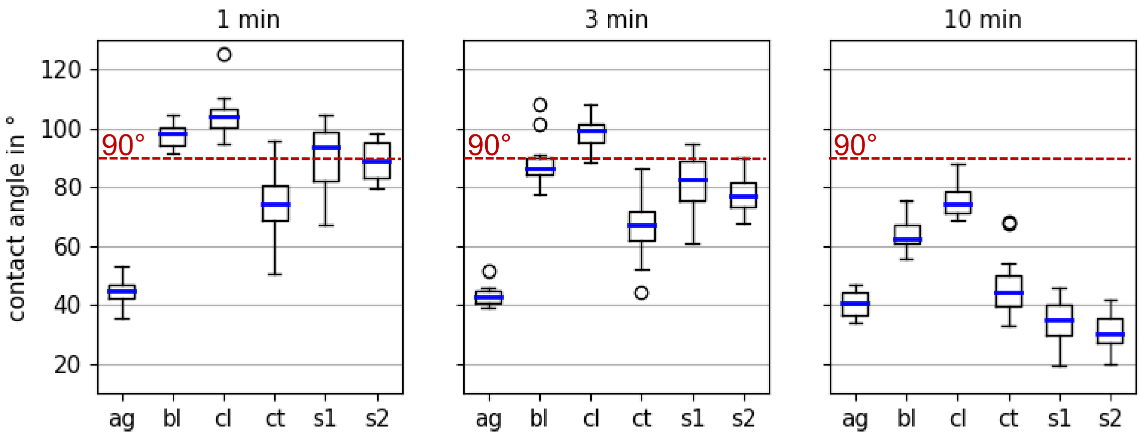


Figure 5: static contact angle of 4 µl droplets on different conductor surfaces after 1 min, 3 min and 10 min. The correct name for the short form can be found in Table 1.

II. Wettability of the total circumference of the conductors

In the next section, the results of the study of the behavior of the completely wetted surface will be presented. A summary can be found in Figure 6.
A film of water forms around the total circumference of the aged conductor when completely wetted. There are only very few locations where the water droplets form and drip off. The dripping-off locations are almost stable and do not move.
In the case of the blank conductor, it can be seen that there is no continuous film of water on the surface. Smaller droplets are visible around the entire circumference. Larger water droplets form on the underside of the conductor and then drip off. The water droplets are smaller than on the aged conductor. During the experiment, it was also found that most of the water does not flow within the spaces between the individual wire strands, but simply vertically downwards.
The results show that it is not possible to create a continuous film of water on the colored conductor. The water recedes very quickly and forms dry spots. In addition, it

can be seen that the water droplets do not hang centrally under the conductor. Two lines of water droplets forms on both sides and drip off from there.
Like on the aged conductor, a complete water film forms on the surface of the coated conductor. The water droplets hang centrally under the conductor. Compared to the aged conductor, significantly more water droplets form and they are very mobile due to the cylindrical and smooth geometry of the conductor surface.
The sandblasted conductor "Sand1" forms an almost constant water film on the surface. Although the water contracts into small drops after some time, it does not do so when watering is constant. The water mostly runs down in the spaces between the single wire strands. The water droplets that form on the bottom of the conductor are relatively small.
The sandblasted conductor "Sand2" does not form a water film. The water very quickly contracts into small droplets around the entire circumference of the conductor. The water moves along in the spaces between the wire strands and forms small droplets on the underside of the conductor. These droplets adhere very strongly to the surface compared to the blank conductor.

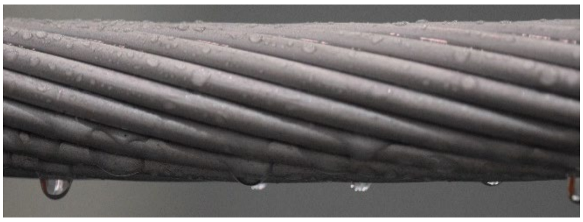
Aged: continuous water film on surface, few dripping points

Blank: no continuous wetting, droplets drip off at the lowest point of the conductor

Colored: no continuous wetting, droplets drip off in two lines, not centered

Coated: continuous water film on surface, droplets drip off at the lowest point of the conductor

Sand1: almost continuous wetting, recedes quickly, droplets drip off at the lowest point of the conductor



Sand2: no continuous wetting, droplets drip off in the center, droplets adhere to surface

Figure 6: Behavior of water droplets on total circumference of conductor during rain

III. Audible noise emission of overhead line conductors

Although the noise emissions of a conductor can be divided into two different noise components (broadband and 2*f*-component), only the A-weighted total sound power level is to be investigated in this case. Figure 7 shows the behavior of the sound power level of the different conductors as a function of the electric field strength at the conductor surface (the value given is the rms-value of the highest field strength on the conductor surface assuming an equivalent cylinder with similar radius). The investigated conductors all show an increase in noise emission with increasing electric field strength, although there is a difference in the slopes. At very low electric field strengths up to 12 kV/cm, the measurement data are not meaningful, since in this range the background noise in the laboratory, partly generated by the rain simulator and the transformer, is too high.

The aged and most hydrophilic conductor has the lowest sound power level at low to medium electric field strengths up to about 20 kV/cm and the highest at high electric field strength. This behavior confirms previous investigations [2, 3, 6, 7]. All other conductors exhibit a higher sound power level in the range of low electric field strengths and also a steeper increase in the sound power level up to about 17 kV/cm. Above this field value, the slope decreases and, depending on the conductor, an intersection with the sound power level of the aged conductor between 22 – 24 kV/cm is obtained.

The investigation also shows that the difference between the blank conductor and the sandblasted ones is very small, partially the sandblasted ones have even higher sound power levels. The colored conductor shows almost no difference to the blank conductor for low electric field strengths, but exhibits lower sound power levels at high electric field strengths. The coated conductor has a similar characteristic to the blank and sandblasted conductors, but the increase is lower. For this reason, along with the aged conductor, it has the lowest noise emissions in the entire range of electric field strength.

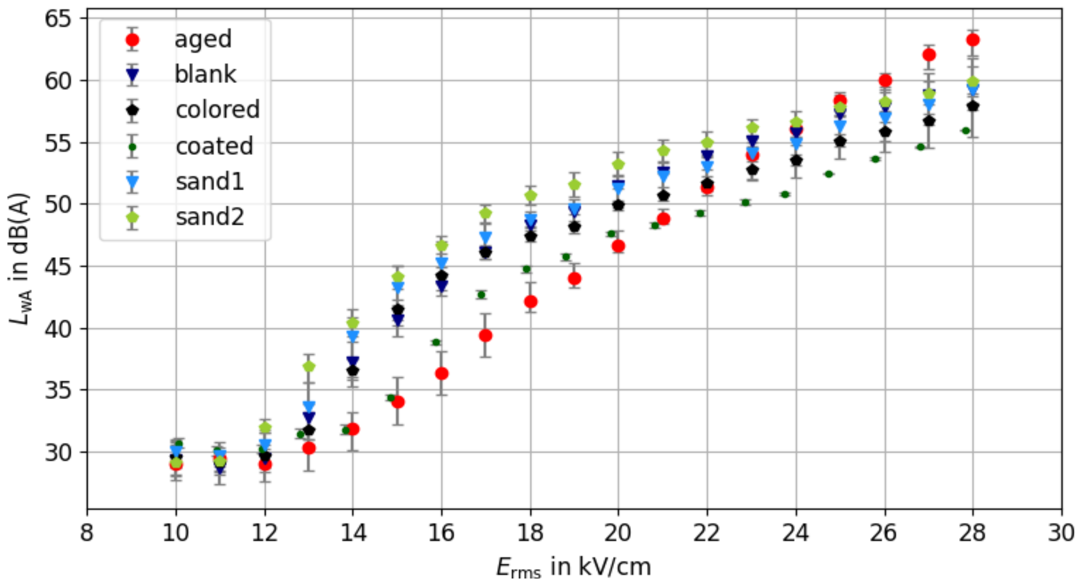


Figure 7: A-weighted sound power level as a function of the electric field strength at the conductor surface at a rain rate of 3.5 mm/h

DISCUSSION

I. Evaluation of wettability based on the behavior of single and several droplets on conductor surface

From Figure 6 it can be seen that some conductors exhibit a droplet distribution characteristic for hydrophobic surfaces, even though the static contact angle is less than 90°. After an elapsed time of 3 minutes, all the conductors except the colored one can be considered hydrophilic according to the definition of θ < 90°. Also the hanging droplets, shown in Figure 6, partly form smaller contact angles than 90° for some conductors.

On the surface of some conductors, however, the water film contracts again to small droplets, which rather speaks for a hydrophobic behavior. Despite a low static contact angle, complete wetting of the surface is not possible. This is clearly shown for the conductor "Sand2", which shows the lowest contact angle after 10 min, but corresponds to the blank conductor according to the droplet distribution according to Figure 6.

This behavior is clearly different from that of the aged and coated conductor. These form a water film that wraps around the conductor and are thus much more hydrophilic in behavior. Similarly, the sand-blasted conductor "Sand1", with its almost continuous water film, shows a much more hydrophilic behavior than the blank one and “Sand2”.

The behavior of the completely wetted surface should be the focus for defining the properties of the conductor surface, as this is closer to the conditions under rain.

II. Influence of the wettability on the noise emission

The measurements partly show the expected behavior from previous investigations. The aged conductor has the lowest noise emission at low to medium electric field strengths. Since the aged conductor has the lowest static contact angle after 1 and after 3 minutes, the result initially confirms the assumption that the more hydrophilic the conductor surface, the lower the audible noise emission. This is contradicted by the conductor "Sand2", which has a very low contact angle after several minutes, but a very high noise emission level. This phenomenon can also be seen in a weakened form with the conductor "Sand1". This shows that there is no correlation between the static contact angle of a single droplet and the noise emission level. However, it does show that the property of forming a continuous water film on the surface can contribute significantly to reducing noise emissions (aged and coated conductor).

The investigations presented here are not yet sufficient to provide detailed explanations for the relationship between the conductor surface, the behavior of the droplets on the conductor and the audible noise emissions. Nevertheless, some correlations can be identified. Thus, the droplet population seems to have an influence on the noise emission. The difference is noticeable between low droplet population (Aged) and high droplet population (Colored, Sand1 and Blank). A lower droplet population leads here to a lower noise emission level.

An additional correlation that could be observed during the investigations is the mobility of the droplets or, conversely, the adhesion of the droplets to the surface and the noise emission. The coated conductor has a relatively large number of large droplets on the underside of the conductor, but these can move flexibly along the conductor due to the cylindrical geometry. In comparison, the conductor "Sand2" has a similar droplet population to the blank one, but the droplets adhere strongly to the surface and do not drip off as quickly. The strong adhesion of the droplets leads to a higher noise level and the high flexibility to a lower one.

An influence of the droplet volume on the noise emission could not be determined during these investigations. It can only be clearly seen that the aged conductor has larger droplets than the others. However, further investigations are necessary for precise explanations.

CONCLUSION AND OUTLOOK

I. Conclusion

Previous measurements [2, 3] show that the more hydrophilic the surface, the lower the noise emission for small to medium electric field strengths. However, it is often not defined in these measurements how hydrophilic the conductors are. The investigations presented in the present contribution show that there is no correlation between the static contact angle, which classically defines the hydrophilicity of a surface, and the noise emission. It is therefore not possible to predict the noise emission behavior of individual conductor surfaces based on this contact angle.

However, if the condition that the conductor surface forms a continuous film of water around the entire circumference when completely wetted is added, it can be determined that a correlation exists here with the noise emission level. The noise emission of a conductor is reduced as soon as the surface forms a complete water film instead of droplets with dry spots in between.

This shows that previous measurements on the noise emission behavior of OHLs are confirmed as long as the static contact angle is not used to determine the hydrophilic properties of the conductor, but the behavior of the completely wetted conductor surface.

In the case of new construction or replacing of old conductors, it is therefore recommended to use a conductor that forms a water film to reduce the noise emission level. Based on the investigation with 6 different types of conductors presented here, this would be the coated conductor. However, this is not an alternative as long as the same diameter is required, since the transmittable power is reduced due to the smaller current-carrying cross-section.

II. Outlook

The measurements carried out on different conductors provide an initial overview of the correlation between the surface properties of conductors and their audible noise emissions. For detailed explanations of how the surface wettability and thus the droplet population, droplet size, the adhesion of the droplets, the drying time, etc. (cf. Figure 6) influence the noise emission, further investigations must be carried out. What has also not been discussed in this study is the exact discharge behavior depending on the surface properties. This includes the intensity of the corona discharges from single droplets and their interaction (direct and via the generated space charge). Another point that has not yet been addressed is the exact consideration of the noise emission as a function of the electric field strength. Above a certain electric field strength, the hydrophilic aged conductor has a higher noise emission level than the less hydrophilic conductors and an explanation for this has not yet been found [3].

ACKNOWLEDGEMENT

The authors would like to thank Dr. Benjamin Schröder and Dr. Saskia Möllenbeck from Amprion GmbH for the different overhead line conductors they provided and also for their input and the technical discussions. Further thanks go to Ivan Cheptiakov, who performed some of the noise emission measurements as part of his bachelor thesis and Dr. Christos Stamatopoulos for his help in studying the contact angles. The work is financially supported by Amprion GmbH.

BIBLIOGRAPHY

[1] C. Stamatopoulos, P. Bleuler, M. Pfeiffer, S. Hedtke, P. Rudolf von Rohr, and C. M. Franck, “Influence of Surface Wettability on Discharges from Water Drops in Electric Fields,” Langmuir, vol. 35, no. 14, pp. 4876–4885, Apr. 2019.

[2] U. Straumann, “Berechnung und Reduktion der tonalen Geräuschemission von Hochspannungsfreileitungen“, Doctoral Thesis No. 17408, ETH Zürich 2007.

[3] O. Pischler, “Zum Geräuschemissionsverhalten von Leiterbündeln bei Wechselspannungsbeanspruchung in Drehstrom- und Hybridfreileitungen“, Doctoral Thesis, TU Graz 2020

[4] G. Taylor, “Disintegration of water drops in an electric field,” Proc. R. Soc. London, Ser. A, Mathematical Phys. Sci., vol. 280, no. 1382, pp. 383–397, 1964.

[5] . F. Ianna, G. L. Wilson and D. J. Bosack, ”Spectral Characteristics of Acoustic Noise from Metallic Protrusions and Water Droplets in High Electric Fields“, IEEE Transactions on Power Apparatus and Systems PAS-93.6, S. 1787–1796., 1974.

[6] O. Pischler, U. Schichler, B. Zhang, “Interaction of Surface Gradient, Precipitation Rate and Conductor Surface Treatment on Corona Induced Audible Noise of AC Overhead Transmission Lines”, IEEE International Conference on High Voltage Engineering and Application, 2020.

[7] O. Pischler, U. Schichler, “Influence of Hydrophilic Conductor Surface Treatments on OHL Audible Noise“, 12th IEEE International Conference on the Properties and Applications of Dielectric Materials, 2018.

[8] J. C. Berg, “Wettability”, CRC Press, an imprint of Taylor and Francis, first edition, 1993.

[9] K. Y. Law, “Definitions for hydrophilicity, hydrophobicity, and super-hydrophobicity: Getting the basics right”, Journal of Physical Chemistry Letters, 5, 2014.

[10] Working Group B2.44, “Coatings for Protecting Overhead Power Network Equipment in Winter Conditions”, TB 631, 2015

[11] IEC 60270:2000, “High-voltage test techniques – Partial discharge measurements”, 2000.

[12] ISO 3744:2010, “Acoustics — Determination of sound power levels and sound energy levels of noise sources using sound pressure — Engineering methods for an essentially free field over a reflecting plane”, 2010