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Potential reduction of audible noise from new and aged overhead transmission line conductors by increasing their hydrophilicity

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SUMMARY

In the context of audible noise from high voltage overhead lines, an increase of hydrophilicity is frequently suggested in literature as a means to reduce A-weighted noise emissions. Laboratory tests with hydrophilic coatings of new conductors within the project CONOR (a consortium formed by utilities from Austria, Germany and Switzerland, a Swiss authority and further institutions) executed at the authors' institute showed very promising results, especially concerning the reduction of the humming component of audible noise. Hence it was desirable to evaluate hydrophilic coatings as noise-reducing remedies on operational high voltage lines, especially with a view to clarifying the importance of conductor ageing, which was not tested in the previous laboratory experiments.
Indeed, the beneficial effects of conductor surface ageing with respect to corona have been known for over half a century. But as the impact of conductor ageing compared to hydrophilic coatings on audible noise was unknown, field tests with the coatings have been initiated on overhead lines with well aged cables. A first opportunity to do this offered itself with a line crossing the Swiss Alps with conductors aged well over 50 years. The measurements of the field test revealed not only low noise levels for the coated span but also low levels of the uncoated section of the line. Temporary de-energisation of the line permitted one more access to the conductors themselves so that their hydrophilicity could be assessed: The wettability was found to be fairly good on the treated as well as on the untreated conductors. The increase of hydrophilicity of the conductor cables resulting from ageing proved to be high. A second field test in a rural environment of southern Germany on a line with conductor cables of about 20 years of age supports the findings of the first field test that the coating of aged cables does not noticeably reduce audible noise emissions.
Even though artificial ageing of conductors at the manufacturing stage is suggested in literature, a viable method has not yet been given. But other methods to increase the hydrophilicity of new cables, such as sandblasting, are conceivable as well. This method was applied in connection with a refit of a line to different conductor bundles by one of the project partners. In the case of low surface gradients the results show a clear reduction of the audible noise emissions compared to reference lines with the same conductor bundles and new conductor cables which had not been sandblasted.
The presented findings indicate that the hydrophilic coating of a well aged conductor will in general be superfluous, while the coating or other surface treatment of new conductors – for refit or a new line – can be recommended to bring about a noise performance comparable to that of aged conductors.

KEYWORDS

Corona, audible noise, ageing, conductor, hydrophilicity

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1 INTRODUCTION

In the context of audible noise from high voltage overhead lines, an increase of hydrophilicity is frequently suggested in literature as a means to reduce A-weighted noise emissions [1-5]. New conductors show a relatively poor wettability; a typical example is shown for an Aldrey (AAAC) conductor in Figure 1. The sessile water drops are elongated in the electrical field due to their dielectric behaviour. As the drop deforms, the electric field strength itself is also increased. If this happens to a certain extent, the so-called Taylor-cone is formed and the point of Taylor-instability is reached. The latter results in a water jet ejected from the tip of the drop [6]. With the excessive field strength in this process, corona discharges may set in. Only certain types of these discharges contribute relevantly to audible noise [7].

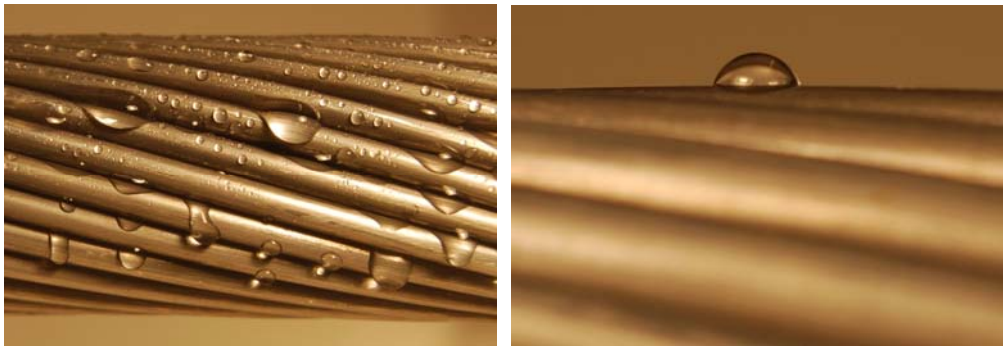


Figure 1: Wetting of a new, uncoated AAAC-conductor (600 mm^2 cross section) with a spray from above (*left*) and with a single 5 µl drop deposited with a pipette (*right*). The pictures are also representative for cleaned new ACRS-conductors. If remainders of drawing grease are not removed, wettability of new ACRS-conductors may even be poorer.

An increase of the wettability of the cable is desirable, as it results in a better drip-off of the water and the drops thus formed are fewer in number and have flatter shapes. This results in a smaller enhancement of the electric field strength in the vicinity of these drops.
An extreme wettability or hydrophilicity can be reached by applying hydrophilic coatings. Laboratory tests with such coated new conductors within the project CONOR showed very promising results [8]. In contrast to the uncoated conductor of Figure 1, such coating effectively prevents the deposition of single water drops with a pipette, as the water spreads instantaneously and forms a water film. In the case of spraying, this water film is continuous, and if enough water is deposited, isolated large hanging drops are formed, which then drip off from the conductor. In the laboratory tests of the project CONOR, which was focused on the humming component (twice the mains frequency) of the audible noise, such coated conductors revealed reduced audible noise levels of this component [8, 9]. Hence it was desirable to evaluate hydrophilic coatings as noise reducing remedies on operational high voltage lines, especially with a view to clarifying the importance of conductor ageing, which was not tested in the laboratory experiments.
Indeed, the beneficial effects of conductor surface ageing with respect to corona have been known for over half a century [10, 11]. Cage tests [12] demonstrate tendencies observed in the comparison of new ("off the reel") and aged (after 6 years in service) conductors: On dry conductors, there is no difference between the new and aged state. In heavy rain there is little to choose between new and aged conductors as regards corona loss and acoustic power (A-weighted), while aged conductors are less noisy in light rain and dry sooner after rain. The greatest gain as regards sound emission is obtained with low surface gradients (16 kV/cm or

less), while all advantage is lost at high gradients (22 kV/cm). The reduction of audible noise emission with increasing age of a high voltage test line [1], actual lines [13] or of conductor bundles tested in corona-cage experiments [12, 14] are quite convincing; the exceedance level L_{50} of the test line was reduced by about 8 dB after almost 3 years in service [1].
Wettability of conductors exposed to the elements improves with age even when they are not energized [15] as manifested by visual observation of the wettability and reduction of drying time in corona tests of 8 kHz acoustic emission. To the authors' knowledge, [15] is the only reference showing the increase of wettability visually. The observations indicate a rather strong hydrophilicity of conductors aged up to 19 months [15], while the authors in Reference [1] "[…] felt that the conductors still do not have the truly hydrophilic property […]" after conductor-ageing of almost three years. As the quality of hydrophilicity due to conductor ageing and its impact on audible noise compared to hydrophilic coatings remained unclear, field tests with the coatings were initiated on overhead lines with well aged cables.
In this paper, these field tests will be discussed. Furthermore an alternative method to increase the wettability of new conductors, i.e. sandblasting, will be investigated. This method was successfully applied to an actual line by one of the project partners.

2 SURFACE TREATMENTS TO INCREASE HYDROPHILICITY

2.1 Assessment of Wettability

As a drop is sessile on a plane, a closed triple line is formed, where all three phases, air, water and solid, meet. In the triple line the so-called contact angle is defined by the tangent perpendicular to the triple line and the surface of the drop and its projection onto the plane (Figure 2). The contact angle θ is a measure for wettability or the hydrophilicity of the plane, which originates, as in the case of the surface tension, from the microscopic forces [16].
But only on perfectly smooth surfaces one single contact angle is given; for real, macroscopic planes, this is not the case [17]. This is shown by the example of the drop sessile on an inclined plane in Figure 2, where different contact angles are evident. The range of possible contact angles is limited by the extremes of the *receding* and the *advancing contact angles*, θ_r and θ_a respectively [17].

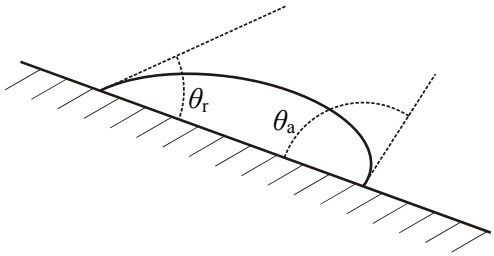


Figure 2: Schematic drawing of a water drop rolling along on an inclined plane. As the surface of the plane is not perfectly smooth and homogeneous, the plane at the lowest triple point constituted by water, plane and air is not instantaneously wetted. This limited wetting results in a slower or even halted run-off of the water drop and different contact angles along the triple line with the extremes of the advancing angle θ_a and the receding angle θ_r.

The more the contact angles θ_a and θ_r differ, the more the run-off is impeded: in the situation of Figure 2 the plane could be inclined further until run-off occurs. If a better run-off is desired, the homogeneity of the surface should be increased [17].

As precise contact angle determination by use of elaborate equipment on site several tens of meters above ground on a large object such as a high voltage line is clearly impracticable, simpler, rougher methods had to be used:

- With a pipette single drops with a volume of 5 µl were carefully placed on the conductors. With the increase of the drop during the deposition up to the final 5 µl, the contact surface grows and an indication towards the advancing contact angle is obtained.
- The cable is wetted with a fine water spray, resulting in a continuous water film on the cable during the spraying operation. After spraying the water drips off and the remaining drops give an indication of the receding contact angle. This method is also suggested in the technical specification from IEC [18] used for measuring the receding contact angle on insulator surfaces.

In this way it was attempted to assess the advancing and receding contact angles on a rough and only qualitative basis. As the differences in wettability of the investigated conductors are considerable, this test method is assumed to be adequate.

2.2 Increase of Surface Roughness

Surface roughness has a substantial influence on the contact angle and can result in different deviations of the contact angles reached on a plane consisting of the same material but with perfectly smooth surface. According to Wenzel [19] the apparent contact angle θ' formed on rough surfaces is connected to the contact angle of the ideally smooth surface θ and the *roughness factor r* via

$$r = \frac{\cos\theta'}{\cos\theta} \quad , \tag{1}$$

while the roughness factor is given by

$$r = \frac{\text{actual surface}}{\text{geometric surface}} \quad . \tag{2}$$

Therefore, r of rough surfaces is greater than one. For contact angles $\theta > 90°$, the apparent angle is θ' is greater than θ, in the case of $\theta < 90°$, the apparent angle θ' is smaller than θ. Roughness can be used to increase the wettability of conductors, as for these the case $\theta' < \theta < 90°$ applies. Such improvement in the corona performance concerning audible noise is known in literature [1, 5]. This approach is further investigated in section 4 of this paper.

2.3 Hydrophilic Coatings

The evaluation of different coatings within the project CONOR resulted in a coating material based on TiO_2 particles suspended in water. This material is photocatalytically activated, i.e. the coated surface has to be exposed to ultraviolet irradiation, such as sunlight, to attain the (super-) hydrophilic state.

3 FIELD TESTS WITH CONDUCTOR COATING ON WELL AGED CABLES

To be able to compare an uncoated but aged span (*reference span*) with a coated span (*test span*) of the lines, two adjoining test spans were chosen in a similar cross-country stretch offering an environment quiet enough to permit useful noise measurement as well as aged conductors. A first opportunity to do this presented itself with a line crossing the Swiss Alps and a second in a rural environment in the southern part of Germany.

3.1 Procedure of Coating

Cleaning of the cables
The conductors were cleaned to remove dirt and enhance adhesion of the coating. In a first step the conductors were mechanically treated with a cleaning machine consisting of three metal brush rollers parallel to the cable, driven by an electrical drill. In the second step, the cables were cleaned with alcohol and a special cloth. This has to be done in dry weather, as any water intermixture resulted in a dark grey smeary layer covering the cables.

Coating of the cables
Providing a complete cover of the cable surface with a film of the coating material was required. As mentioned before, the TiO_2-based coating on the cables only develops its hydrophilic property after several hours to days of activation with natural ultraviolet solar radiation. Alcohol was added to the coating material, thus reducing the surface tension of the water [20] and increasing the wetting while applying the coating. The wetting was further improved by the increased surface roughness from the preceding cleaning process with the cleaning machine. Three layers of coatings were applied in the two field tests (see left side of Figure 3).

Location of the field tests
The first field test was carried out on the Swiss Lukmanier line near Sedrun in late summer 2007 during the annual de-energization period for maintenance. The Swiss line is a single 380 kV three-phase system (see right side of Figure 3). The conductor double-bundles consist of Aldrey (AAAC) cables with 550 mm^2 cross section cables, in service for over 50 years.



Figure 3: Coating of the conductors (*left*) in the on-site-test of with hydrophilic coatings in the Swiss Alps, i.e. location of the first field-test (*right*).

The second field test was performed in a rural environment in the southern part of Germany on the line Herbertingen-Bundesgrenze in the summer of 2008. The German line combines a 380 kV and a 220 kV three-phase system. The double bundle of the 380 kV-system consists of ACSR conductors with a cross section of (Al/St) 435/55 mm^2 and an age of about 20 years.

3.2 Acoustic Field Measurements

In the case of the tonal component of the audible noise (twice the mains frequency), the emissions of the single phases are correlated. Hence they form a complex interference pattern, with maximum values of sound pressure when the waves of the single phases coincide, and with the lowest values when the contributions of the phases cancel each other out. These variations are large; in the example of [21] differences of 20 dB are observed. Therefore, the interference pattern has to be accounted for as requested by the IEEE standard [22].
In the first field test (Swiss Alps), audible noise was measured over several periods with corona or precipitation respectively. The resulting average sound pressure levels out of these measurements are summarized in Table 1.

For both components of the audible noise, the broadband as well as the tonal component, the measured values have to be processed to account for the different distances to the line from the points of measurement and, in case of the tonal component, the interference pattern has to be accounted for. In Table 1, the measured values from the test span were converted through calculation to the situation of the reference span. Therefore, these levels can be directly compared.

Table 1: Comparison of the audible noise from the on-site test in the Swiss Alps with untreated cables aged more than 50 years and coated cables.

Span	**L_p(A) [dB(A)]**	**$L_{p\ 100\ Hz}$ [dB]**
test span, coated	50.6	48.0
reference span, uncoated	50.3	47.6

The values from Table 1 reveal similar noise levels on the test and reference spans. Therefore, no reduction of audible noise from corona due to coating could be demonstrated.
The second field test in a rural environment in the southern part of Germany supports the findings of the first field test that the coating of aged cables does not noticeably reduce audible noise emissions.

3.3 Field Tests of Wettability

The interpretation of the findings of the noise measurements together with literature on ageing of the conductors seems quite clear. Ageing provides wettabilities comparable to those of coatings. To clarify the picture the wettability tests were performed on site.
Temporary de-energisation of the line permitted one more access to the conductors at the location of the first field test (Swiss Alps) so that their hydrophilicity could be assessed (Figure 4). Furthermore another section in southern Germany in a rural environment could also be assessed (Figure 5).

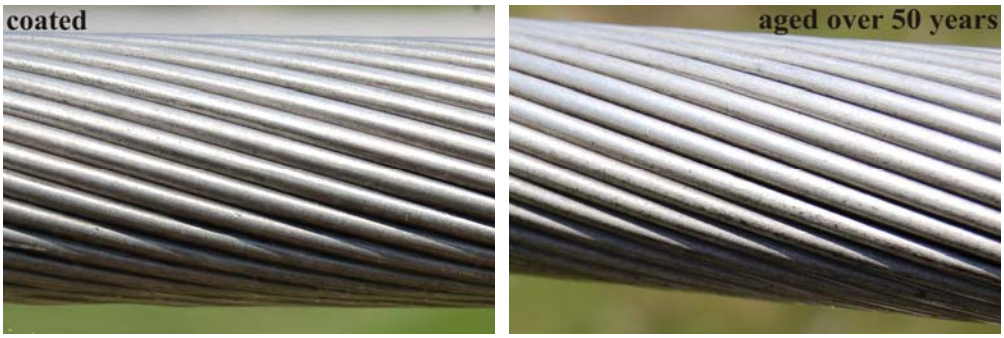


Figure 4: On-site test of wettability with water spray on the conductors of the first field test (Swiss Alps); the Aldrey 550 (AAAC) conductors are either aged over 50 years (*right*) or coated (*left*).

The spray tests of Figure 4 indicate a fairly good wettability on the treated as well as on the untreated conductors as there is a continuous water film present. The hydrophilicity is so high that the deposition of single drops is not possible; the water applied by pipette on the conductors spreads immediately to form a water film. The quality of the hydrophilicity is obvious when compared to that of the new conductor depicted in Figure 1.

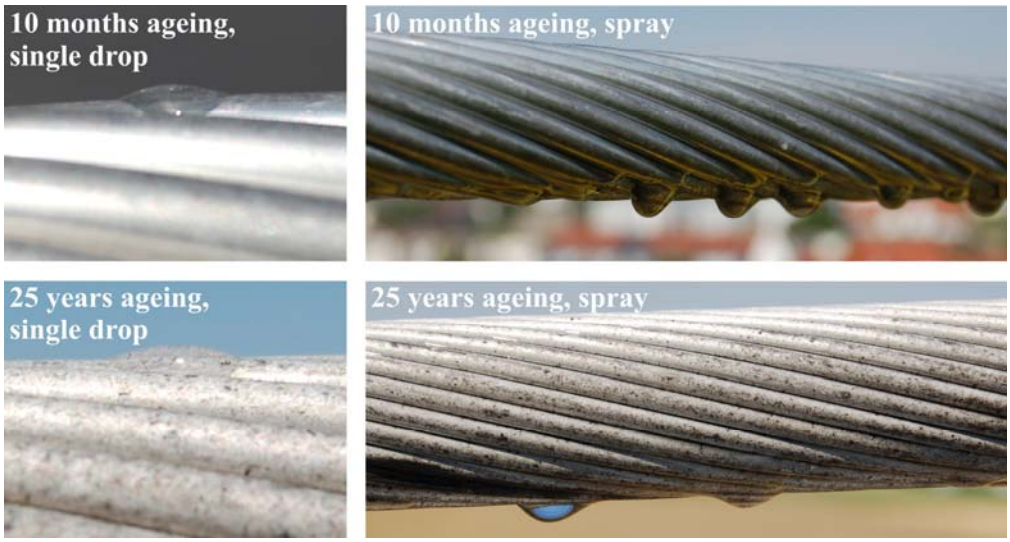


Figure 5: On-site test of wettability with water spray on conductors of a line in the southern part of Germany. Examples of spray test (*right*) and single-drop test (*left*) are depicted on the ACSR conductors (Al/St) 265/35 with 10 months of ageing (*top*) and (Al/St) 380/50 with about 25 years of ageing (*bottom*).

The pictures in Figure 5 also indicate a rather good wettability of the conductor aged for about 25 years, although some few drops in the single-drop test did not spread instantaneously when applied, as they did in the tests quoted in Figure 4. The conductor aged for only 10 months, however, suggests a less perfect wettability for newer conductors, even though it already seems a lot better than that on a new conductor such as depicted in Figure 1. The increase of hydrophilicity of the conductor cables resulting from ageing proves to be high.

3.4 Cause of the Ageing Effect

Considering the facts reported in the still fairly sparse literature on the causes of the increase of wettability due to ageing, it can only be concluded that the favourable performance of the uncoated spans on the test lines must be due to the considerable age of the conductors, presumably suffering mild surface corrosion due to hydrogenation of aluminium oxide. Thus, the aluminium oxide (Al_2O_3) film formed within milliseconds is gradually covered by aluminium hydroxide and aluminium oxide hydroxide which are more polar and micro-porous. These properties, polarity as well as porosity, may increase the hydrophilicity.
Furthermore, the decomposition of the traces of drawing grease remaining from the original manufacturing of the cables is a *sine qua non* for that ageing effect to work.

4 MEASURES FOR NEW CONDUCTORS

Due to lack of ageing, higher audible noise levels have to be expected when reenergizing a line fitted/refitted with new cables. As one of the project partners, a German utility, faced such a situation – audible noise levels of a 380 kV-line with quadruple bundles were higher with new ACSR 560/50 than with aged ACSR 265/35 conductors – measures for treating new cables were considered to anticipate the effect of increased hydrophilicity of aged cables.
Even though [1] advocates artificial ageing of conductors at the manufacturing stage, a viable method cannot yet be given. However, methods other than coating to increase the hydrophilicity of new cables are conceivable as well. One possibility, though not as perfect as hydrophilic coatings with regard to wettability, is sandblasting [1, 5]. As it was expected that a purely mechanical treatment of cables would be easier to implement in an industrial treatment process for new cables, this method was considered.

If due to its roughness the surface is very inhomogeneous, the difference between the advancing and receding angle is great and the run-off behaviour is impeded according to section 2.1. To avoid this, special care in manufacturing a homogeneous surface roughness is required.

4.1 Methods Considered to Increase Surface Roughness

According to section 2, wettability is increased with the roughness of the surface. The most perfect surface would therefore be a fractal one, providing the largest surface roughness r. As the time framework for this investigation was limited, only relatively simple methods yielding quick results were investigated: treatment of the cable surface with sandpaper, steel wool, metal brushes mounted on an electric drill and sandblasting with different kinds of abrasives.
With sandpaper only the peripheral exposed parts of the surface of the cable were reached by the treatment. These parts revealed somewhat better wettability, but constituted only a fraction of the surface. The resulting wettabilities due to treatment with steel wool as well with the metal brush showed promising results, but they were topped by the results due to sandblasting. For the latter method, the quality of the surface is in fact little changed in the case of the single-drop test (θ_a), but almost perfect in the case of the spray test (θ_r). This indicates that with sandblasting very low receding contact angles are reached, while the impact on the advancing angle is low. To further improve the wetting, i.e. to reduce the advancing contact angle, the surface roughness should be more homogeneous (see section 2.2).
For this, different kinds of abrasives were compared. In preliminary tests glass beads showed better results than aluminium oxide abrasives. Thus it was suggested to consider different kinds of glass beads for the sandblasting, after remainders of drawing grease were removed by flame treatment before sandblasting. The test series consisted of glass beads with particle sizes of (1…50) µm, (50…100) µm, (100…200) µm, (200…400) µm and (400…600) µm. These series of treatments were performed in the factory of the Austrian cable manufacturer entrusted by the German utility with this treatment of the cables.
The tests of these samples revealed differences in wettabilities concerning receding contact angles (spray test). The best results were achieved by the two abrasives with glass beads of sizes within the range of (1…50) µm and (50…100) µm (Figure 6). For these abrasives the resulting wettabilities on receding contact angles were perfect; according to IEC [18] this would correspond to the highest wetting class WC7. Little difference between the resulting wettabilities from these two particle sizes was noticed.



Figure 6: Spray test on the cable after flame treatment and sandblasting with glass beads of the size (50…100) µm. The wettability on receding contact angles is high: With the spray from above the sample is not entirely wetted, because of the limited wettability on advancing angles; with spraying around the conductor practically perfect wetting is attained.

On the advancing contact angle no considerable difference could be discovered with the rough test method between the surfaces treated by the two sizes of abrasives. Even compared to an untreated, new cable, this treatment does not seem to significantly reduce the advancing

angles. Whether the advancing or the receding contact angle has greater effect on audible noise emission cannot be concluded from these measurements.

4.2 Reduction of Audible Noise with Sandblasting

This method was implemented on a 380 kV-line with quadruple bundles of ACSR 560/50 conductors. Measurements show a clear reduction of the audible noise emissions [13]:

- While the line with new ACSR 560/50 conductors reveals bigger noise levels than that with aged ACSR 265/35 conductors (also arranged in a quadruple bundle), the line with new ACSR 560/50 conductors sandblasted according the procedure explained in the previous section 4.1 revealed lower levels. The measured reduction from new to new but sandblasted ACSR 560/50 quadruple bundles is about 9 dB(A).
- This reduction of 9 dB(A) exceeds the measured reduction of audible noise from new to aged ACSR 265/35 quadruple bundles.

The tendency of lower impact on audible noise if wettability is increased for conductors with higher electric surface field strengths agrees with the observations from Reference [12] described in section 1 of this paper. The reduction of 9 dB(A) mentioned above is substantial and otherwise only attainable through considerable decrease in surface field strengths on the conductors (for example by increasing conductor-bundles with additional subconductors). Nevertheless, it cannot be concluded whether hydrophilic coating would result in a further decrease of audible noise or not.

5 CONCLUSIONS

1) In the case of low surface gradients, sandblasting, hydrophilic coating or ageing of new conductors cause substantial reduction of audible noise. For this case coating or sandblasting of new conductors can be recommended.
2) The findings presented indicate that the hydrophilic coating of a well aged conductor will in general be superfluous, as ageing results in comparable wettabilities.
3) Hydrophilic coating results in an optimal hydrophilicity. Whether the poor impact of the considered surface roughening on advancing contact angles influences the audible noise is not yet known. Thus it cannot be concluded if hydrophilic coating would result in a further decrease of audible noise than sandblasting.
4) Even though [1] advocates pre-ageing of conductors at the manufacturing stage, a viable method cannot yet be given.

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