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Audible Noise Management of Newly Reconductored Transmission Lines

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SUMMARY

Transpower New Zealand Limited has a programme of replacing transmission line overhead conductors that are reaching their physical end-of-life. Assurance is needed that the conductor chosen is appropriate from a power system, environmental and economic perspective. Two parallel 220kV lines have been reconductored in the North Island, each approximately 120 km long. This major project spanned a five-year construction period and the first section of the reconductoring was completed in the 2015-16 summer window.

Following the installation of the first new conductor section, Transpower received landowner complaints regarding audible noise (AN), which was perceived to be higher than the replaced conductor. The southern sections of the lines are close to and traverse through more populated areas where higher noise levels would be more obvious. As a result, Transpower commenced an investigation to understand the cause of the perceived higher audible noise levels.

The line voltage of 220kV is being maintained and the 30-year old conductor Goat, ACSR/GZ, 26mm diameter, and had been replaced with a larger capacity Zebra ACSR/AC, 28.6mm diameter. Both conductors have a steel core, however the aluminium stranding between the two vary. Old Goat has two layers of larger aluminium strands while the new Zebra has three layers of slightly smaller strand size. Comparatively the theoretical surface voltage gradient of the new conductor is less, and its electrically derived noise should have reduced.

This paper describes the research and development investigation undertaken by Transpower that included an international literature review, engagement with international industry experts, local and international conductor manufacturers, and laboratory and field trials and measurements.

As no defined laboratory test methodology could be found in the standards, a test method was progressively developed to provide a consistent format for identifying the audible noise of an electrical origin for a range of conductor types, including the existing and new conductor types, construction and surface finishes.

A high voltage laboratory test setup was designed at the University of Canterbury in Christchurch, New Zealand to emulate the audible noise created from the transmission line. Transpower worked with conductor manufacturers to trial various surface treatments of common conductor types, including surfaces created by cleaning and blasting in a production environment. The

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laboratory tests were benchmarked against the existing aged conductor noise levels and the various other conductor types were shortlisted to identify the best surface treatments based on their comparative noise levels. The associated field trials included manufacturing of modified conductor types, stringing trial sections on the line, and controlled field noise measurements.

The tests and field monitoring results have provided a significant basis for confirming the preferred conductor types and associated surface treatments, that minimise the production of audible noise of an electrical origin.

Key findings of our research are:

- Ageing of conductors reduces audible noise. The hydrophobic surfaces associated with new and highly greased conductors will result in wideband AN levels and 100 Hz tonality that exceed the values calculated using traditional calculation methods. These levels reduce over time as a result of natural weathering and ageing processes.
- Dulling new conductor surfaces to simulate accelerated ageing using glass bead blasting reduced the wideband AN level from the test samples but resulted in high long-term tonality that did not subside with natural conductor surface weathering.
- Field trial results demonstrated that detergent cleaning was the most effective method of mitigating the new conductor hydrophobic surface effects prior to stringing.
- Proprietary surface treatments for High Temperature conductors were also trialled in the field and demonstrated reduced wideband AN levels and improved tonality.

KEYWORDS

Corona, Audible Noise, tonality, reconductoring, hydrophobicity, conductor treatments.

1. INTRODUCTION

As part of prudent asset management, Transpower has commenced a programme of replacing overhead transmission line conductors that are reaching physical end-of-life criteria (due to advanced environmental corrosion). The most recent are two 120km long single circuit parallel 220kV lines strung with Goat stranding ACSR supported on 600 flat top steel lattice towers. They were originally installed in the 1950s and then reconductored around 1990.

Following replacement, Transpower received landowner complaints regarding audible noise (AN) being emitted from the reconductored line sections during wet conditions, which was perceived to be higher than the noise emitted from the replaced conductors. In particular, significant tonality was detected in the AN emissions. In response, Transpower commenced an investigation to further understand the cause of the perceived higher audible noise levels.

A review of research identified a number of factors that had the potential to affect conductor noise and led to the development of a bespoke factory conductor cleaning system. Testing of the acoustic performance achieved was initially undertaken in a high-voltage laboratory and for the more successful interventions, was confirmed in field trials.

2. BACKGROUND TO CORONA AUDIBLE NOISE

Audible noise from conductors can be generated from corona discharges (i.e. electrical source) or Aeolian vibration due to wind speed and direction (i.e. mechanical source).

The perceived high level of audible noise from the reconductoring project was attributed to corona discharge during wet conditions.

Corona discharge [1] occurs when the conductor surface electric stress exceeds the dielectric strength of the air surrounding it. Overhead line conductors are generally designed to have a surface voltage gradient less than 16 kV/cm to limit the generation of corona discharge, but perturbations on the surface of a conductor (e.g. insects, pollution or water droplets) may enhance the electric stress sufficiently for corona to occur [9]. Part of the energy from each corona discharge is released as sound. Corona noise has two distinct components; a broad-band crackle, and a pure tonal hum of twice the power frequency (100Hz).

'Wet Noise' arises where water droplets on the conductor surface act as the source of corona discharge. Raindrops cannot be prevented from collecting on the conductor, and thus newly reconductored lines can be particularly noisy during and after rain [6].



Figure 1: Water droplet shape on different conductor surfaces.

The phenomenon of water formation on a conductor surface can be described as hydrophilic or hydrophobic and will affect the shape of the surface droplets formed, as illustrated in Figure 1.

Aged conductors have a hydrophilic surface, which together with the force of gravity channels surface droplets into the gaps between surface strands, resulting in relatively few, large pendant droplets on the underside of the conductor. It also smooths out the conductor surface and lowers the surface voltage gradient. Fewer larger droplets present fewer corona noise sources and thereby lower AN level. New, untreated conductors have a hydrophobic surface, which results in many small spherical droplets around the entire perimeter of the conductor surface. The increased number of droplets result in higher noise levels. These smaller droplets also appear to be relatively stable and thus AN levels can remain high for a considerable time after the cessation of rain, when ambient noise levels are lower.

The level of noise depends on the electric field at the surface of the conductor. AN issues can therefore be particularly problematic on simplex conductor arrangements, which have relatively high surface voltage gradients, even at lower line voltages. Reconductoring these lines with duplex or larger diameter simplex conductors, which would traditionally be used to resolve AN issues, may not be feasible due to significant foundation/structure strengthening requirements, consenting problems and property rights issues. The focus of this paper is associated with the influence of a conductor's surface nature and how that of a conventional new conductor differs from one operated from several years to decades. This is explored more in Section 5.

3. PROBLEM SOLVING APPROACH

The noise complaint issue was first tackled on the ground by the project team through discussions with affected landowners to understand the issue. This included audible noise measurements taken by professional acousticians to quantify the perceived noise.

A literature review of available research was carried out and international industry experts, other utilities, manufacturers and research institutes were consulted. The use of laboratory testing was explored, and the University of Canterbury was selected for such testing due to their high voltage test capability. Field trials were carried out and involved newly strung conductor with various surface treatments. Treatments included blasting techniques plus cleaning of the conductor in-

situ and in the factory (via hand and machine). Noise monitoring also commenced in the field at the sites of noise complaints with fixed monitoring stations and hand-held monitors.

4. LITERATURE REVIEW

4.1. Comparable Experience

A utility in Australia indicated that they have previously had AN issues on a new 500 kV line that was attributed to "over-greasing" of the conductor. They remedied the problem by manually cleaning the conductors with detergent to remove excess grease on the outer surface.

A United Kingdom technical advisory document discussed grease and drawing oil residue on the new conductor surface as being the primary cause of AN complaints on new transmission lines and recommended rag cleaning of the conductor before and during stringing.

4.2. International Research

The Electric Power Research Institute (EPRI) has reported on field trials that indicate conductor ageing, which is dependent on various environmental factors, reduces conductor hydrophobicity and thereby corona AN levels [5].

The Corona Noise Reduction (CONOR) project of the ETH Zürich has conducted extensive research on the effect of reducing conductor hydrophobicity on audible noise emissions from 380 kV and 220 kV transmission lines [8]. Working with an Austrian based cable manufacturer the research group reported on the efficacy of a surface dulling process and nanocoating (TiO_2) that is now marketed commercially. The reported research indicated that drawing oil residues on new conductors contribute to the new conductor's hydrophobicity and corona noise emissions. The drawing oil residues were first removed before applying the conductor surface treatments.

Corona AN research at the University of Manchester was conducted in 2013 as part of a PhD Thesis in a laboratory environment using a corona cage [4], which permitted the application of a lower applied voltage to achieve the actual line's surface voltage gradient on test conductor samples. The research investigated the impact of conductor surface hydrophobicity on water droplet size and distribution, and the correlation of these parameters to low frequency conductor hum properties. The research concluded that hydrophobic conductor surfaces result in the formation of smaller average droplet sizes with increased low-frequency hum emissions.

4.3 Cable Manufacturers

Transpower contacted cable manufacturers in New Zealand, North America, Europe and the Middle East. Research carried out by these manufacturers included the effects of water droplet size, strand shape and surface treatments on AN performance.

5. PROBLEM DEFINITION

Transpower's desktop review of international experience and research was able to confirm the following findings being applicable to our situation:

- Ageing of the conductor reduces the audible noise levels. The ageing period varied between 6 months to approximately 5 years depending on environmental conditions.
- Residual drawing oil on the conductor surface breaks down and is removed as part of the ageing process due to exposure to environmental elements and ultraviolet light.
- Conductor grease that migrates to the surface in between the outer strands will cause excessive audible noise. This is more difficult to remove and may require cleaning.
- The conductor surface oxidises over time forming a dull hydrophilic surface, reducing AN.

These key findings were the basis of conductor surface treatments and accelerated ageing processes we chose to investigate further in laboratory and field trials.

6. CONDUCTOR TREATMENTS

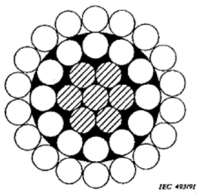


Figure 2: Fully greased conductor

Transpower have generally specified new conductor to be fully greased to IEC 61089, case 2. i.e. all the conductor strands are greased except the outer layer (figure 2).

Several conductor surface treatments were trialled in the laboratory and field, based on the findings of the literature survey. Laboratory test samples were manufactured by reducing greasing by one layer, using different drawing oils and/or cleaned with different media and processes. Cleaning processes that were developed included cleaning the whole conductor as well as individually cleaning the outer strands only. Based on the initial lab test results, a conductor cleaning rig was developed and integrated into the manufacturing process of a local conductor manufacturer.

Surface dulling using glass bead blasting was also trialled in both the laboratory and the field. Various bead sizes were trialled in the lab and it was concluded that bead size 2 (90 µm to 150 µm) produced the optimal hydrophilic effect on the aluminium strand surface, which was field trialled.

Finally, several conductor samples with proprietary surface treatments were trialled in the laboratory. One of these was then selected for field trials.

7. LABORATORY TESTING

Thirteen rounds of laboratory testing with >200 samples have been conducted in high voltage labs at the University of Canterbury (UC), New Zealand and University of Manchester (UoM), UK.

A cylindrical corona cage test setup was developed where conductor samples were tensioned between a supporting frame located centrally. The UC test setup utilised acoustic panelling to limit reverberations and the voltage supply was acoustically insulated to reduce ambient AN level in the laboratory. The UoM experiments were conducted inside an anechoic chamber (Figure 3).

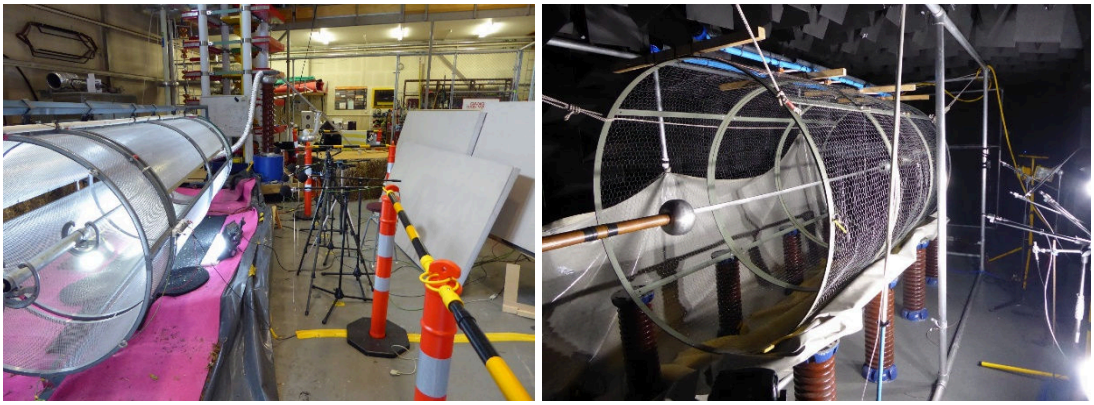


Figure 3: Corona Audible Noise Test Cage developed at the University of Canterbury Engineering School (left), University of Manchester (right).

A comparison of the measured AN levels from the two experimental setups is presented in Figure 4 for untreated ACSR Zebra and ACSR/TW Curlew. The comparison indicates good agreement between the test setups and highlights the repeatability of the experiments.

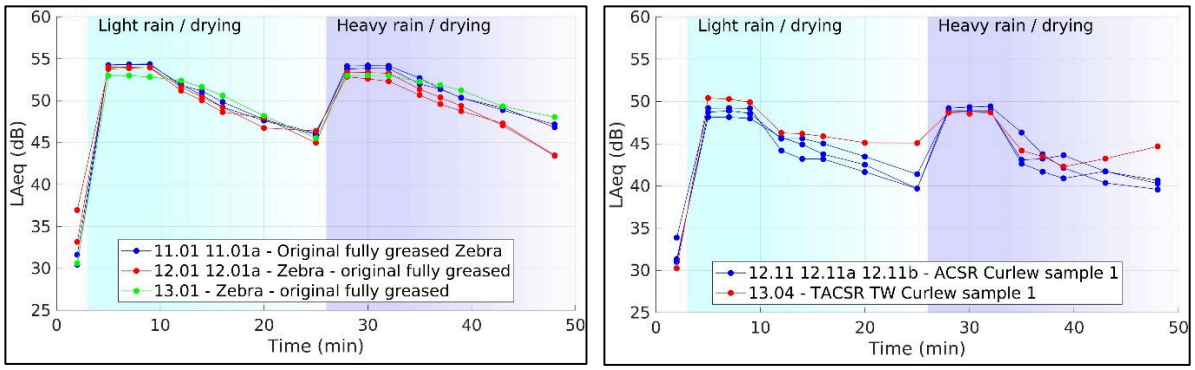


Figure 4: Comparison of measured AN levels for Zebra (left) and Curlew (right) between University of Canterbury (Rounds 1-12) tests and University of Manchester (Round 13).

A calibrated water sprinkler system was incorporated into the laboratory test setup. The two reported rain rates[2] used in the original University of Manchester research were applied to the test samples. The test procedure involved measurements taken during applications of continuous rain via the sprinkler system followed by measurements during a period of drying.

In both experiment setups, multiple microphones (placed in the same position relative to the sample) were used to measure the AN emission. The different microphone positions produced different tonal responses due to the acoustic properties of the experimental setup. This was accounted for with a logarithmic averaging process of individual microphones and repeated tests.

It was noticeable during the laboratory testing that the strong surface electric field deformed the smaller spherical water droplets that formed on hydrophobic conductors (e.g. new uncleaned or over-greased conductors) into sharp triangular peaks (figure 5a).

The larger droplets that had a flatter shape were not significantly deformed by the surface electric field (figure 5b).

For surface treated hydrophilic conductor samples, it was noticeable how the small water droplets didn't form on the conductor surface, but rather flowed along gaps between surface strands and formed a few large pendent droplets on the underside of the conductor (figure 5b).

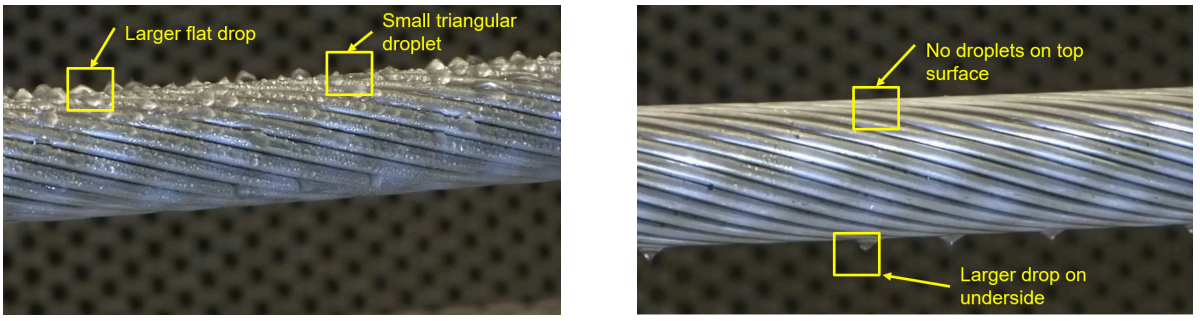


Figure 5a and 5b: Photographs of rain droplets on a hydrophobic conductor surface (5a, left) and a hydrophilic conductor surface (5b, right) during corona cage testing.

Throughout the testing, comparisons were made to samples of the existing 30-year old Goat, ACSR/GZ conductor in terms of AN levels and tonal qualities (specifically 100Hz) with subsequent rounds narrowing down the selection of better performing conductor samples. Figure 6 shows the L_{Aeq} and tonal performance for 106Hz (note: The ac voltage was applied at 53Hz to reduce interference form 50Hz noise sources). The data presented here is comparable to real world 100Hz.

[2] 21 mm/hr (simulated light rain) and 60 mm/hr (simulated heavy rain)

A sample was identified as a suitable replacement for the aged Goat (magenta lines in Figure6) consisting of a steel reinforced, trapezoidal shaped aluminium strand conductor (ACSR/TW) with a propriety abrasive treated outer surface. It has a nominal outer diameter of 28.7mm (same as Zebra) and is code named Curlew. The Curlew performed reasonably well both in wideband (L_{Aeq}) and tonal performance as compared with the aged Goat while being electrically and mechanically similar to the Zebra.

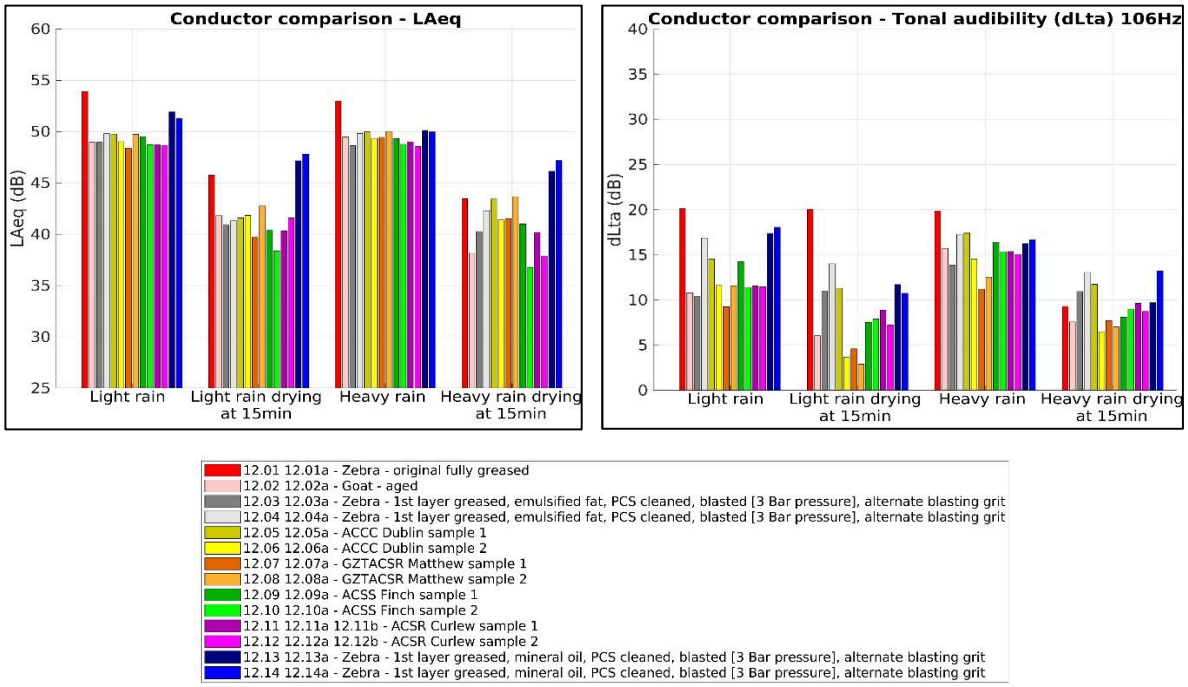


Figure 6: L_{Aeq} (left) and Tonal audibility (right) comparisons between conductors.

8. FIELD TESTING

Field testing utilised noise monitors at mid-span locations and beneath the centre phase of the lines. Transpower lines are located on and across privately owned land so landowner acceptance was required to place monitors. Locations away from significant noise sources such as urban areas and highways were required. Typical sites were remote pastoral land over flat terrain.

The monitors included a solar panel and battery and connection to the cellular network, to enable placement in remote locations. The site connectivity provided real time access to all continuously collected noise and weather parameters remotely via the web. A typical site set-up is shown below; the microphone was elevated on a pole 4-5 m above ground with the 220kV conductors in the region of 8m above. This elevated microphone position maximised the signal to noise ratio of conductor to other environmental noise. (Figure 7).

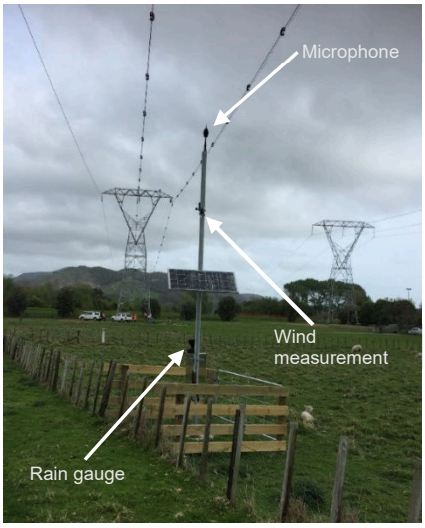


Figure 7: Field monitoring site setup

Sound was also able to be recorded allowing noise sources to be confirmed and sound qualities to be listened to. Recording of sound was triggered by rain gauge bucket tips, with 20 s recordings made upon a tip and each five-minute period thereafter for 15 mins. This allowed both wet and

drying conditions to be listened to. Sites were generally established at least a month before reconductoring to enable comparison of the noise performance of existing and new conductors.

For conductor assessment purposes, the continuously collected data was filtered by acousticians to eliminate, as far as possible, other noises in the environment. This included discarding all daytime data (7am to 10pm), windspeeds over 2m/s and where the L_{Aeq} and L_{90} were more than 2dB apart (conductor noise being reasonably continuous in any 15 min period). A rain gauge allowed wet and dry conductor conditions to be separated, each 15-minute period following rain was considered as wet condition as the conductor dries. This confirmed that elevated AN occurs in wet conditions. Tonality was evaluated using the simplified test method given in NZS 6802:2008, which compared the L_{eq} in a $^1/_3$ octave band with the arithmetic mean of the L_{eq} in each adjacent band. New conductor noise was found to have tonal characteristics in the 100Hz frequency and to a lesser extent its harmonics [7]. Data was routinely filtered and assessed to provide average L_{Aeq} and tonality values for periods of time, (the periods are somewhat determined by frequency of rainfall events). The acoustic performance trends became more evident as data built up over time.

Figure 8a below shows for initially strung untreated Zebra conductor the decline in noise level, (L_{Aeq}) and 100Hz tonality. In both cases the levels reduce with time but with considerable variation. Further research is required to understand the parameters which result in the variation, but migration of core grease in periods of conductor movement is most likely. Long term monitoring of aged conductor shows very little variation, (see aged Goat data in Figure 8b) so deposition of environmental contaminants is less likely to be a major contributor to the variation. The aged Goat had L_{Aeq} around 40dB and tonality less than 1dB so, for untreated Zebra conductor although there has been considerable reduction in noise over a 3-year period, it is anticipated that acoustic performance will continue to improve beyond this time.

100Hz tonality for a range of treated conductor types are shown in Figure 8b. Tonality is less influenced by background noise than L_{Aeq}, particularly for conductors that generate lower noise levels. Tonality is also thought to be more influential on public acceptance of conductor noise. The first 180 days following stringing is shown, this initial period of performance shapes public acceptability. Treated Zebra has performed around the margins of acceptable tonality initially but trended upwards, particularly cleaned and blasted conductor. The trapezoidal Curlew conductor with propriety surface treatment, again initially performed around the margins of acceptable tonality, but improved quite quickly within the first 6 months to a point where tonality became difficult to discern for most wet weather conditions.

Increased rain rates can potentially affect the perception of conductor noise, particularly in built up areas with hard surfaces. But monitoring indicates that some tonality and low frequency noise may still be perceptible, even in heavy rain. Site data shows that high rain rates occur very seldomly and so have little bearing on the impact of corona induced line noise.

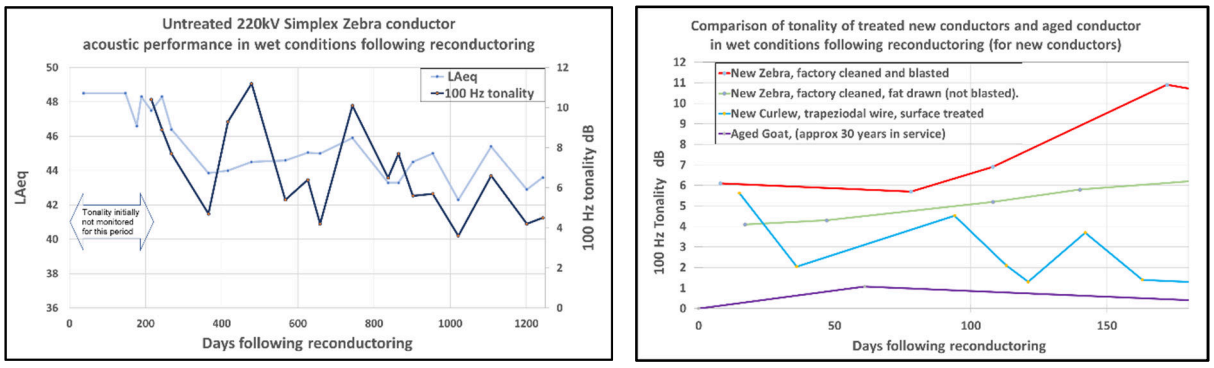


Figure 8a and 8b: L_{Aeq} (8a) and Tonal audibility (8b, dLta) comparisons between different field-tested conductors.

9. COMPARISON OF CALCULATIONS, FIELD DATA AND LABORATORY DATA

Transpower has historically used the EPRI semi-empirical calculation method [2] for estimating the wideband Audible Noise level of a new or reconductored transmission line.

Field measurements of an aged 30 years old simplex Goat ACSR conductor were compared to the EPRI calculations prior to the reconductoring of the 220kV single circuit line. The nominal measured wet conductor wideband AN level for the aged Goat conductor was 42.8 dBA, which correlated well with the 41.9 dBA EPRI calculated value. Tonality calculations were not carried out as part of the assessment as was difficult to predict. Further research is needed in this area.

A section of the same line was reconductored with simplex new Zebra ACSR conductor with no surface treatment applied to the new conductor. The initial measured wideband wet conductor AN under the reconductored line was 48.6 dBA (7 months after stringing). This was a 5.8 dB increase in AN level. An initial tonality value of 10.4 dB was also measured.

Samples of the aged Goat ACSR conductor removed from the reconductored line and samples of the new, untreated Zebra ACSR conductor were tested under simulated rain conditions in the laboratory corona cage. The results of the testing indicated a maximum 5.2 dB variance in wideband AN level between the aged Goat and new Zebra samples under simulated light rain conditions. This variance reduced to 3.5 dB under simulated heavy rain conditions. It was speculated that the simulated heavy rain conditions in the laboratory testing represented the maximum rain rate conditions on the actual line and that the simulated light rain conditions in the laboratory were more representative of the average rain conditions in the field. The relative increase in wideband AN level in the simulated light rain laboratory testing correlated well with the field measurement results.

Similarly, the tonal audibility results from the lab testing indicated a maximum 9.0 dB variance in 100 Hz tonality between the tested aged Goat and new Zebra test samples under simulated light rain conditions. This variance reduced to 4.0 dB under simulated heavy rain conditions. The correlation to the 10.4 value measured in the field was considered good and further supported the theory that the simulated light rain conditions in the laboratory were more representative of the average rain conditions in the field. However, for treated conductors, the lab tonality poorly represented the field tonality experience.

10. CONCLUSIONS

Our research and development investigation concluded with four key findings, three relating to performance and one to method, are listed below:

- Ageing of conductors reduces audible noise. It was demonstrated by field testing that the hydrophobic surfaces associated with new and highly greased conductors will result in wideband AN levels and 100 Hz tonality that exceed the values calculated using traditional calculation methods. These levels reduce over time as a result of natural weathering and ageing processes. Our experience and other research shows that this ageing period can vary between 6 months to 5 years depending on environmental conditions. A modified AN calculation method that accounts for the initial hydrophobic surface effects is required.
- Dulling new conductor surfaces using glass bead blasting to simulate accelerated ageing reduced the wideband AN level from the test samples but resulted in high long-term tonality that did not subside with natural conductor surface weathering. Test results also indicated that hydrophobic conductor surface coatings only reduced the wideband AN levels and improved tonality only under heavy rain conditions, but not light rain.

- It was determined from the field trial results that the most effective method of mitigating the new conductor hydrophobic surface effects was detergent cleaning of the new conductor prior to stringing. A conductor cleaning process was developed and integrated into a conductor production line. Proprietary surface treatments for High Temperature conductors were also trialled in the field and demonstrated reduced wideband AN levels and improved tonality.
- Laboratory testing with a corona cage was used to determine comparative merits of different conductor types and surface treatments for the field trials but required a logarithmic averaging process of the multiple microphone locations to achieve a reasonable variance in tonality for a single test sample. There was also an observed dependence on simulated rain rates that requires consideration when simulating environmental conditions for a specific transmission line.

11. FUTURE WORK

Additional research is required to improve the laboratory test setup and develop a generation function for the corona cage data [3]. This can help facilitate the prediction of transmission line AN performance, including 100 Hz tonality, for new hydrophobic conductors using corona cage test data and improving correlation of these levels with measured field data. The developed generation functions can then be used to improve calculation methods currently used to predict new conductor AN performance for future reconductoring projects.

12. GLOSSARY

L_{90}: the sound level exceeded for 90% of the measurement interval, reflecting background sound.
A-Weighted: weighting of measured sound frequencies to reflect of the human ear to noise.
L_{Aeq}: A-weighted equivalent continuous sound level in decibels measured over a 15 mins.
ACSR: Aluminium conductor steel reinforced
ACSR/TW: Aluminium conductor steel reinforced / trapezoid wire.

13. BIBLIOGRAPHY

[1] Peek, F.W. *Dielectric Phenomena in High Voltage Engineering*, McGraw-Hill Book Company, Inc.: New York, NY, USA, 1929.
[2] Electric Power Research Institute. EPRI AC Transmission Line Reference Book – 200 kV and Above, 3rd ed.; Electric Power Research Institute: Palo Alto, CA, USA, 2005.
[3] Trinh, N.G.; Maruvada, P.S.; "A method of predicting the corona performance of conductor bundles based on cage test results", IEEE Trans. Power Appar. Syst. 1977, 98, 312-325.
[4] Li, Q.; Rowland, S.M.; Dupere, I.; Shuttleworth, R.; "Acoustic noise evaluation for overhead line conductors using an anechoic chamber", IEEE Trans. Power Deliv., 2017, 32, 1835-1843.
[5] M.G. Comber and R.J. Nigbor, "Audible Noise Performance of Regular and Asymmetric Bundles and Effect of Conductor Aging on Project UHV's Three-Phase Test Line" IEEE Trans. PAS, vol. 98, no. 2, 1979, pages 561-572.
[6] D.W. Tong, G.L. Wilson, I. Johansen, "Effects of surface wettability on audible noise and capillary absorption as a noise reduction scheme", IEEE 1975 PES Summer Meeting, San Francisco CA, USA 1795, pages A75 566-0/1-7.
[7] U. Straumann, J. Fan, "Tonal component of the audible noise from UHV-AC Transmission Lines", 16th International Symposium on High Voltage Engineering, Cape Town, RSA, 2009.
[8] M. Semmler, "Tonal noise levels during precipitation", ETH Power System and High Voltage Laboratories, Annual Report, 2005, pages 63-65.
[9] AS/NZS 7000:2016, "Overhead Line Design", Australian/New Zealand Standard, page 44.