TransGrid

Audible coronal noise study

Investigating audible noise from transmission lines in Australian climates

November 2025

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TransGrid

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WSP acknowledges that every project we work on takes place on First Peoples lands.
We recognise Aboriginal and Torres Strait Islander Peoples as the first scientists and engineers and pay our respects to Elders past and present.

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Glossary

Term	Definition / description
Decibel, dB	The decibel (dB) is a logarithmic scale that allows a wide range of sound pressures to be represented in a more comprehensible range, typically 0 dB to 120 dB. The decibel is ten times the logarithm of the ratio of sound energy (i.e. power squared, or pressure squared) relative to a reference level squared. The reference level for sound pressure is typically 20 µPa which is the approximate threshold of human hearing.
Decibel (A-weighted), dBA	A-weighting was devised to attempt to account for human response to sound not being equally sensitive at all frequencies; it consists of an electronic filter in a sound level meter, which attempts to build in this variability into the indicated noise level reading so that it will correlate, approximately, with human response.
Sound Power Level, L_w or SWL	The sound power level is the inherent noise of the source and is the total power radiated by the source, in dB. Sound power level does not vary with distance from the noise source or within a different acoustic environment.
Sound Pressure Level, L_p or SPL	The sound pressure level of a source, in dB, varies with distance from the noise source and with the environment in which it is located.

Abbreviations

Acronym	Description
ACN	Audible Coronal Noise
AS	Australian Standard
BPA	Bonneville Power Administration
dB	Decibel
dBA	Decibel (A-weighted)
DPHI	The NSW Department of Planning, Housing, and Infrastructure
EPA	Environment Protection Authority
EPRI	Electric Power Research Institute
HV	High Voltage
NSW	New South Wales
RFI	Radio Frequency Interference
SVG	Surface Voltage Gradient
SWL	Sound Power Level

Executive summary

Purpose and context

TransGrid commissioned this study to improve the prediction, monitoring and mitigation of Audible Corona Noise (ACN) from high voltage transmission lines in NSW, in accordance with conditions of approval for the EnergyConnect Eastern Project. While international ACN models are well established, their accuracy under Australian climatic conditions remains uncertain. This report combines literature review, field monitoring, and model evaluation to identify key environmental drivers and recommend best practice assessment and mitigation approaches.

Approach

Two monitoring sites were selected to represent typical humid NSW conditions: Lismore (330 kV) and Martinsville (500 kV). Continuous unattended and attended monitoring was undertaken between April and May 2025 using SiteHive remote noise monitoring units, NGARA Type 1 noise loggers and Davis Vantage Vue weather stations. Acoustic and meteorological data were processed in accordance with the methodology outlined in Section 5.1 to isolate ACN events and compare results with predictions from the EPRI and BPA methods, derived from the *EPRI Transmission Line Reference Book 200 kV and Above, Third Edition (2005)*. The rationale for selecting these two prediction methods, including their suitability for Australian climatic conditions, is discussed further in Section 2.3.

Key findings

- Rainfall and humidity were confirmed as the dominant meteorological drivers of ACN.
- The EPRI model considers rainfall rate as a direct input, while the BPA model includes an altitude correction and treats conditions as wet or dry.
- International models aligned with the higher voltage line but tended to overpredict for the lower voltage site, highlighting the need for field verification.
- Fog and mist can elevate ACN under calm saturated conditions, but their occurrence is highly site specific and cannot be reliably predicted across an alignment due to dependence on local terrain and specific local humidity / dew point conditions. In addition, the occurrence of fog and mist conditions are not recorded by the Bureau of Meteorology.

Implications for NSW practice

No single model adequately represents NSW conditions. Using both EPRI and BPA provides a more reliable prediction framework, with each compensating for the other's limitations. Field verification remains essential, particularly for lower voltages and sites influenced by localised weather conditions. Given ACN's low frequency character and outdoor propagation, effective mitigation should focus on line design and surface treatments rather than receiver controls.

Recommendations

- For high voltage transmission line assessments in NSW, it is recommended that both the EPRI and BPA prediction methods be applied to provide a conservative and robust estimate of ACN across the state's diverse climatic and topographic conditions. The EPRI model better captures the influence of rainfall rate, while the BPA model accounts for altitude effects, making their combined use the most reliable approach for representing the range of conditions experienced across NSW.
- Noise measurements showed strong correlation with the 500 kV line predictions but a notable overprediction for the 330 kV line. While lower voltage systems were expected to generate less ACN, the disparity observed was greater

than anticipated, underscoring the importance of field verification, particularly in cases where predictions indicate potential noncompliance or where mitigation may be required.

- Although fog and mist were observed to elevate ACN levels, their occurrence remains highly site specific and cannot be predicted using a generic model input or available meteorological data. Instead, fog risk may be assessed qualitatively based on typical local humidity, dew point depression and terrain indicators, verified by targeted monitoring where relevant.
- Where exceedances of noise criteria are predicted, mitigation planning should be evidence led, focusing first on conductor and hardware selection, management of surface gradients and span configuration before considering typical noise management solutions which account for the low frequency and outdoor propagation characteristics of ACN.
- Tonality was not observed, in accordance with the characterising features outlined in the NSW EPA Noise Policy for Industry (NPfI). In the instances where tonal features were present, their contribution was modest and did not dominate the overall A-weighted SPL. Accordingly, the application of tonality adjustments should not be assumed by default but instead be supported by evidence from attended measurements.

Next steps

Future work should expand field validation across a wider range of NSW climates, refine model inputs for lower voltage transmission lines and integrate evidence based mitigation strategies into design. These steps will strengthen predictive confidence, reduce community noise risk and support to the maintenance of a sustainable transmission network.

1 Introduction

1.1 Background on audible corona noise

An operating transmission line can create environmental disturbances such as noise and radio or television interference, primarily due to a phenomenon known as corona discharge (or the corona effect). This occurs when the air surrounding the transmission line becomes ionised, resulting in the emission of Audible Corona Noise (ACN) and Radio Frequency Interference (RFI). ACN is typically perceived as a subjective “crackling” or “buzzing” sound and may be accompanied by a violet glow.

Research indicates that ACN is influenced by both transmission line characteristics and meteorological conditions, with adverse weather known to increase noise levels. ACN can also include a tonal noise element, making it potentially more intolerable to humans. In addition, its low-frequency noise components are less attenuated by standard building facades, presenting further challenges for effective noise mitigation.

1.2 Study objectives and scope

It is important to have an efficient method for predicting, monitoring and mitigating ACN in transmission lines at sensitive receivers, to reduce noise-related complaints and potential disruptions in transmission line operation. Understanding the factors influencing the frequency and Sound Power Level (SWL) of ACN is critical for achieving this.

The NSW Department of Planning, Housing and Infrastructure (DPHI) has issued operational conditions of approval to Transgrid for the EnergyConnect Eastern Project. Among these is a requirement to develop and carry out a dedicated research program, in consultation with the Environment Protection Authority (EPA), which must be submitted to the Planning Secretary for approval prior to the commencement of operations. The purpose of this program is to enhance scientific and engineering understanding of corona discharge noise and to investigate best practice approaches for its mitigation.

This project aims to further investigate transmission line characteristics and climatic factors to improve understanding of their influence under varying Australian meteorological conditions. While extensive global research has been conducted into ACN, the specific impact of local meteorological conditions on ACN levels and frequency of occurrence is often not comprehensively addressed in existing studies.

1.3 Purpose of this report

Following the completion of the study's preceding scope items (refer to Figure 1-1), this report summarises the work undertaken as part of the study and presents the key findings.

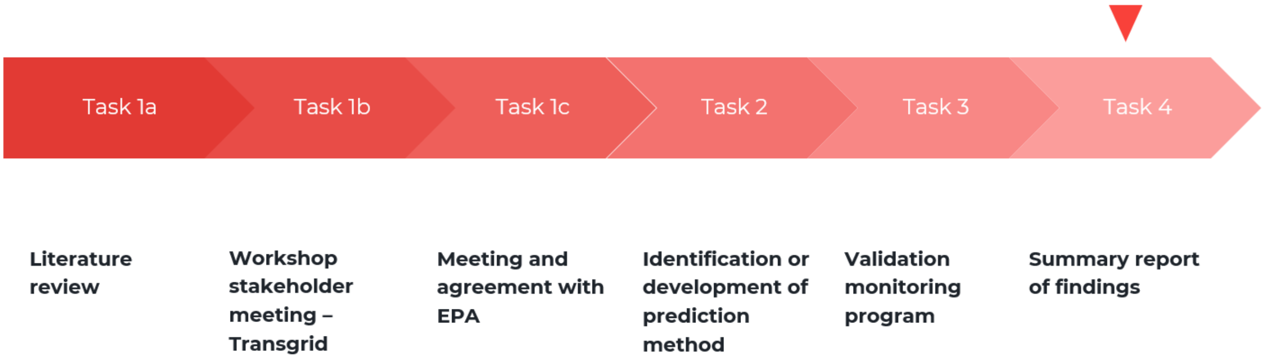

Figure 1-1 Project scope

This report includes the following key components:

- A summary of the literature review outlining the current state of knowledge on ACN, its governing mechanisms and the applicability of international prediction models to Australian conditions. This is presented in Section 2.
- A description of the study framework, monitoring program and analytical approach adopted to evaluate ACN under representative NSW climatic conditions. This is outlined in Sections 3 and 4.
- Analysis of measured ACN behaviour and its relationship with rainfall, humidity, fog, mist and altitude, including evaluation of the EPRI and BPA prediction methods. These results are presented in Section 5.
- Recommendations for ACN prediction, assessment and mitigation for NSW transmission lines, based on comparative model performance and field validation outcomes. These are provided in Sections 6

2 Summary of literature Review

This section provides a summary of the previously issued literature review, with a copy included in Appendix A.

2.1 Overview of corona noise mechanisms

Corona noise is generated when the electric field strength around a high-voltage (HV) conductor exceeds the ionisation potential of air, causing a breakdown of the surrounding air molecules. This process, known as corona discharge, results in the emission of light, heat, and sound. The audible component, referred to as ACN, is typically described as a crackling or hissing sound, and it originates from the rapid compression of air caused by corona current pulses. These sound emissions are strongest at voltages above 345 kV and are more prominent during wet or humid conditions, where water droplets or fog enhance the formation of corona sources on the conductor surface.

The acoustic character of ACN includes both broadband components and tonal elements, the latter typically occurring at harmonic frequencies of the power line's operating frequency, such as 100 Hz and 200 Hz. The perceived tonal nature of ACN contributes to its perceptual annoyance, particularly in rural areas with low background noise. Several physical factors influence the magnitude and frequency spectrum of ACN, including the Surface Voltage Gradient (SVG), conductor surface condition, contamination, altitude, and weather. Aged or polluted conductors tend to emit higher noise levels due to increased surface irregularities and droplet formation, which act as concentrated discharge points. These mechanisms are complex and vary spatially and temporally, necessitating robust models to predict and manage ACN emissions effectively.

2.2 Review of international and Australian studies

Internationally, extensive research has been undertaken to characterise and predict ACN, particularly in the United States, Europe, China, and Japan. Methods developed by organisations such as Bonneville Power Administration (BPA), Electric Power Research Institute (EPRI), and Hydro-Québec Research Institution (IREQ) have led to empirical and semi-empirical models for predicting ACN based on line geometry, voltage, and weather conditions. These models are typically derived from full-scale test lines in environments with well-defined meteorological profiles. Research has also examined the impact of altitude, conductor treatment, and ageing on corona discharge intensity, with results showing clear links between conductor condition and noise output. For example, studies confirm a logarithmic relationship between corona current and A-weighted noise levels, forming a basis for numerical and analytical models.

In Australia, relatively few targeted studies have been conducted, and most predictive methods have been adopted from overseas research. While tools such as SESEnviroPlus and PDCAD FACE apply BPA and EPRI methods, the extent to which these models reflect Australian climatic conditions remains uncertain. Field studies and monitoring campaigns have been limited, and many assumptions used in international models, including rainfall rates, ambient humidity, and conductor age, may not translate effectively to local conditions. As a result, there is limited local data available to validate or adjust these prediction methods.

2.3 Limitations of existing prediction methods in varied climates

Although several international corona noise models exist, the BPA and EPRI methods have emerged as the most appropriate options for application in Australian climates. Both consider a comparatively larger set of site-specific inputs, allowing them to better account for the diverse environmental conditions encountered across NSW. By contrast, simpler methods such as the IREQ method rely on only a small number of inputs and were primarily developed for higher voltage systems, typically 345 kV and above, making them less suitable for the Australian context where a wider range of line voltages and climatic conditions must be represented.

While empirical and semi-empirical models such as those developed by BPA and EPRI are widely adopted, their suitability across varied climates is not well understood. These methods were developed using long-term measurements collected in specific environmental settings, primarily in North America or Europe. As such, embedded assumptions regarding rainfall type, pollution levels, or surface treatment performance may not hold under significantly different meteorological patterns. For example, regions experiencing intermittent mist, tropical humidity, or high wind shear may trigger corona events in ways that standard models do not predict, resulting in inaccurate ACN estimates.

In the Australian context, where transmission lines traverse alpine regions, coastal corridors, and arid inland plains, these limitations become particularly pronounced. Most international models rely on broad meteorological categories and therefore do not capture local factors such as fog frequency, dew point depression, or high-humidity microclimates. Furthermore, few methods account for tonal characteristics or low-frequency components, which tend to be more intrusive and are less attenuated by lightweight Australian building façades. Without appropriate adaptation, the application of these models may lead to inadequate noise impact assessments, misinformed mitigation strategies, and an increased risk of community complaints. This highlights the need for locally calibrated or hybrid prediction approaches tailored to Australian transmission assets and climatic variability.

2.4 Literature review conclusions

The reviewed literature confirms that ACN is a complex function of conductor surface voltage gradient, surface condition and meteorological influences such as rainfall, humidity and altitude. International studies have established strong empirical and analytical frameworks for predicting ACN, with the EPRI and BPA methods emerging as the most promising for use in Australian conditions. These methods are well established and widely validated overseas, yet their performance under the diverse climatic conditions found across NSW remains uncertain. Wet weather events, including rain, snow, fog and mist, consistently amplify noise emissions, while tonal peaks near 100 Hz and low frequency energy increase the potential for perceptual annoyance, particularly in quiet rural settings.

Available prediction software such as SESEnviroPlus and PDCAD FACE implement these methods effectively for wideband sound levels but are limited in their ability to represent low frequency and tonal components in a format suitable for environmental noise assessment in NSW. Studies indicate that the most effective mitigation measures are those applied at the source, including conductor bundling, surface coatings and grading ring optimisation, whereas receiver treatments offer limited benefit for low frequency noise. Overall, the literature supports adapting the EPRI and BPA methods as the preferred framework for predicting ACN in NSW, to be refined and validated through field monitoring under representative local meteorological conditions.

3 Study area and environmental context

3.1 Geographic and climatic features of NSW

NSW exhibits substantial climatic diversity driven by its varied topography and geographic extent. The state spans coastal, mountainous, and inland regions, each with distinct weather patterns. Along the eastern seaboard, the climate is predominantly humid subtropical, characterised by high humidity, warm temperatures, and frequently rainfall in summer months. Moving inland, the climate becomes increasingly dry, with parts of the western regions experiencing arid conditions, marked by hot summers, low annual rainfall, and large daily temperature variations. Elevated areas, such as the Southern Tablelands and Snowy Mountains, exhibit cooler conditions, with regular frost, seasonal snow, and pronounced shifts between summer and winter.

These regional climatic differences are directly relevant to corona discharge behaviour and ACN generation. Key meteorological factors such as temperature, humidity, rainfall, dew point depression, and air pressure vary significantly across NSW and can affect both the onset and intensity of ACN. For example, increased humidity and precipitation are known to enhance corona discharge activity, while cooler, drier conditions may suppress it. Understanding these climatic gradients is therefore critical when assessing the environmental performance of HV transmission infrastructure across the state.

3.2 Site selections

Two monitoring sites were selected for this study: Lismore and Martinsville, both located in the eastern half of NSW. These locations were chosen to capture environmental and climatic variability within regions known to support HV transmission infrastructure, and where meteorological conditions are favourable for the occurrence of ACN. Together, the two sites capture a range of climatic conditions relevant to ACN, supporting validation of prediction methods and improving confidence in modelling and mitigation of noise impacts across NSW and similar environments.

The site selections are shown in Figure 3.1.

Figure 3-1 Site selections

Source: [AEMO Map]

3.2.1 Lismore

Situated in the Northern Rivers region of NSW, Lismore experiences a humid subtropical climate. The area is characterised by warm to hot summers, high humidity, and significant rainfall, particularly during the summer and early autumn months. Frequent periods of elevated relative humidity and rainfall events create conditions conducive to corona discharge activity. Lismore's proximity to existing transmission infrastructure and its climate made it an ideal candidate for observing ACN behaviour under persistently moist atmospheric conditions.

Table 1 Typical climate characteristics - Lismore

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max Temp (°C)	29.2	28.9	27.4	25	22	19	18	20	22	24	26	28
Min Temp (°C)	20	19.5	18	15	11	8	7	8	10	13	16	18
Rainfall (mm)	150	180	160	100	75	90	70	60	50	90	120	140
Rain days	11	11.8	12	10.3	9.4	7.4	5.1	5	4.8	7.2	9.8	11.2

1) Represents long-term monthly averages, calculated as multi-year means (i.e., arithmetic averages) based on historical climate data from 1991–2020.

The site is located adjacent to a **330 kV** transmission line in a rural area with low background noise levels and sparse vehicle movements, providing favourable conditions for capturing and analysing corona-related noise events. The Lismore survey location is shown in Figure 3-2.

Figure 3-2 Lismore survey location

3.2.2 Martinsville

Located in the lower Hunter region near the Watagan Mountains, Martinsville also experiences a humid climate but with slightly more temperate conditions than Lismore. The site is influenced by both coastal and orographic effects, resulting in relatively high rainfall and cooler average temperatures compared to the northern part of the state. Its location at the base of a forested escarpment provides an opportunity to study ACN in a sheltered valley environment, where meteorological conditions such as fog, dew, and temperature inversions may influence sound propagation.

Table 2 Typical climate characteristics - Martinsville

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max Temp (°C)	28.7	28.1	26.8	24.3	21.3	18.5	18.5	20	22.8	24.3	25.9	27.5
Min Temp (°C)	17.9	17.4	16.1	12.1	8	6.6	5.1	5.3	8	11	14.1	16.1
Rainfall (mm)	109.6	132.5	156.3	107.8	56.6	94.8	70.5	48	61.9	90	103.2	84.7
Rain days	12.2	13.4	15.5	14.4	13.5	15	12.1	9	10.5	13.2	12.6	12.6

1) Represents long-term monthly averages, calculated as multi-year means (i.e., arithmetic averages) based on historical climate data from 1991–2020.

The site is located adjacent to a **500 kV** transmission line in a quiet rural setting with generally low background noise levels and limited vehicle activity, offering suitable conditions for observing corona noise under varied meteorological conditions. The Martinsville survey location is shown in Figure 3-3.

Figure 3-3 Martinsville survey location

3.3 Line configurations

To evaluate the BPA and EPRI prediction models under local conditions, TransGrid provided detailed configuration data for the HV transmission lines at both study sites, summarised in Table 3.3. Key parameters such as operating voltage, SVG, conductor type, bundle configuration, phase spacing and line height above ground were included, as these directly influence the corona discharge potential. This information formed the primary inputs to the ACN prediction models and ensured results were representative of the actual HV transmission line configurations.

Table 3.3 Site details and line configuration

Site details and line configuration	Lismore	Martinsville
TransGrid line / tower	TL89 - 694-693	5A1/2 - 33
Latitude, longitude	-28.905461, 153.180348	-33.066695, 151.421290
Line voltage (kV)	330	500
Altitude (m)	12	23
Bundles	3	6
Average maximum conductor surface gradient (kV/cm)	15.85 to 16.51	15.12 to 15.77
Number of sub-conductors in each phase bundle	2	4
Sub-conductor diameter (cm)	2.715	2.94
Bundle diameter (cm)	38	66

4 Field measurements

Field investigations were undertaken at the two study locations, Lismore and Martinsville, to characterise ACN under varying meteorological conditions. The monitoring program was designed to capture both acoustic emissions from transmission lines and the concurrent environmental parameters that influence corona discharge activity.

Environmental noise surveys were conducted in accordance with *AS 1055:2018 – Acoustics – Description and Measurement of Environmental Noise*, using a combination of unattended and attended monitoring.

Unattended monitoring was conducted at each site between 3 April and 21 May 2025 using noise loggers and a SiteHive remote monitoring unit. All acoustic instrumentation was fitted with windshields, with field calibration checks completed before and after deployment, and at two week intervals, confirming no drift within ±0.5 dB.

Attended measurements were also undertaken at each site to better understand local conditions, verify logger placement and identify background noise contributing elements such as fauna activity, vegetation movement and distant traffic.

Meteorological data were collected concurrently using on-site weather stations.

4.1 Monitoring instrumentation

To ensure robust and representative data collection, a combination of acoustic and meteorological instruments was deployed at each study site:

- A **SiteHive remote monitoring unit** provided continuous, real-time acoustic measurements and video footage accessible remotely, allowing surveillance during ACN activity and identification of periods of elevated noise.
- A **Davis Vantage Vue weather station**, capable of continuously recording meteorological parameters including air temperature, relative humidity, rainfall, wind speed, and wind direction, was deployed to provide long-term unattended monitoring with high temporal resolution. The unit also ensured data redundancy in the event of power or communication interruptions affecting the remote monitoring system.
- A **NGARA noise logger**, a Type 1-accredited instrument capable of capturing audio and third-octave band data, was deployed to provide long-term unattended noise recordings with high temporal resolution. The unit also ensured data redundancy in the event of power or communication interruptions affecting the remote monitoring system.

This combined monitoring approach provided a robust dataset for identifying and characterising corona-generated noise under a range of meteorological conditions.

Details of the noise monitoring equipment are provided in Table 4.1, with calibration certificates available upon request.

Table 4.1 Survey equipment

NSA	Survey Method	Manufacturer and Model No.	Serial No.	Calibration
Martinsville	Unattended measurement	Ngara	878099	Current
	Weather station	Davis Vantage Vue weather	Vue 3	N/A
	Attended measurement	NTi XL2	A2A-05707-E0	Current
Lismore	Unattended measurement	Ngara (NM01)	878235	Current
		Ngara (NM02)	878236	Current
	Weather station	Davis Vantage Vue weather	Vue 2	N/A
	Attended measurement	NTi XL2	17705	Current

4.2 Site layouts

4.2.1 Lismore

The site layout, including the position of the survey equipment in relation to the transmission line, is shown in Figure 4-1. NM01 served as the primary unattended measurement location. NM02 was deployed as a control position to capture ambient noise levels compare against levels measured at NM01. However, the wet conditions at the site resulted in elevated local fauna noise such as insects and frogs, and background levels at the control position were strongly influenced by proximity to individual fauna rather than by the transmission line or distant noise sources.

There was also an intention to measure noise levels at the mid span between the towers, but access was not possible due to waterlogged and swampy ground. Instead, measurements were undertaken at the base of the tower and along the fence line, which offered the only accessible points that were raised slightly above the surrounding low-lying terrain. This approach is considered conservative, as it is well established that the highest ACN levels typically occur adjacent to tower structures rather than at mid span.

Figure 4-1 Lismore site layout (Google Earth Imagery, captured 25 January 2024)

4.2.2 Martinsville

The site layout and the position of the survey equipment relative to the transmission line are shown in Figure 4-2.

Access to the mid span was restricted by fencing, preventing measurements between the towers. The base of the tower provided the most appropriate and accessible position for obtaining representative noise levels.

Figure 4-2 Martinsville site layout (Google Earth Imagery, captured 1 January 2025)

4.3 Meteorological data collection

Meteorological data were continuously recorded at both the Lismore and Martinsville sites using site-specific weather stations. The measured parameters included:

- Air temperature (°C)
- Relative humidity (%)
- Rainfall (mm)
- Wind speed (m/s)
- Barometric pressure (hPa)
- Dew point / dew point depression (°C)

These variables were selected for their known influence on corona discharge activity and ACN generation. All parameters were logged at regular intervals throughout the monitoring period to enable direct correlation with acoustic measurements. Relative humidity, rainfall and temperature were of particular interest, as elevated humidity and precipitation are known to increase corona onset and noise emissions. Wind speed was primarily used to identify periods above 5 m/s for exclusion from the processed dataset, and in combination with temperature and dew point to help identify fog and mist events. Barometric pressure provided additional context for changes in sound transmission, while dew point was specifically included to characterise conditions conducive to fog and mist, which can enhance corona activity and influence both the generation and propagation of ACN.

In addition to the meteorological data, the SiteHive monitoring camera was used to visually identify and verify fog and mist events, providing confirmation of conditions where elevated ACN levels were expected.

4.4 Summary of monitoring periods and conditions

Monitoring was conducted at Lismore and Martinsville over discrete periods to capture a representative range of weather conditions and corona activity.

- **Lismore** - Acoustic and meteorological monitoring was conducted from 3 April 2025 to 21 May 2025, capturing a total rainfall of 410.2 mm over the 50-day period. The average daily maximum temperature was 19.2 °C, with relative humidity consistently above 70 % during the majority of ACN events.
- **Martinsville** - Monitoring was undertaken from 4 April 2025 to 20 May 2025, with total rainfall of 235.0 mm recorded. Average daily maximum temperature during the 48-day period was 17.5 °C, and high humidity events (above 80 %) coincided with the most significant ACN observations.

These periods were selected to include seasonal weather patterns conducive to corona formation, including extended periods of high humidity and rainfall. The captured dataset provided a robust basis for analysing the relationship between atmospheric conditions and ACN emissions at each site.

4.5 ACN example spectrum

A targeted attended measurement was undertaken at the Lismore site (330 kV transmission line) during misty rain conditions on 3 April 2025. The mist was sufficient to fully wet the conductor surfaces yet light enough to avoid audible interference from direct rainfall noise. The measurement was conducted from the roadway directly beneath the conductors during a period of no traffic to minimise interference from extraneous noise sources such as insects and frogs. The resulting third-octave band spectrum is presented in Figure 4-3.

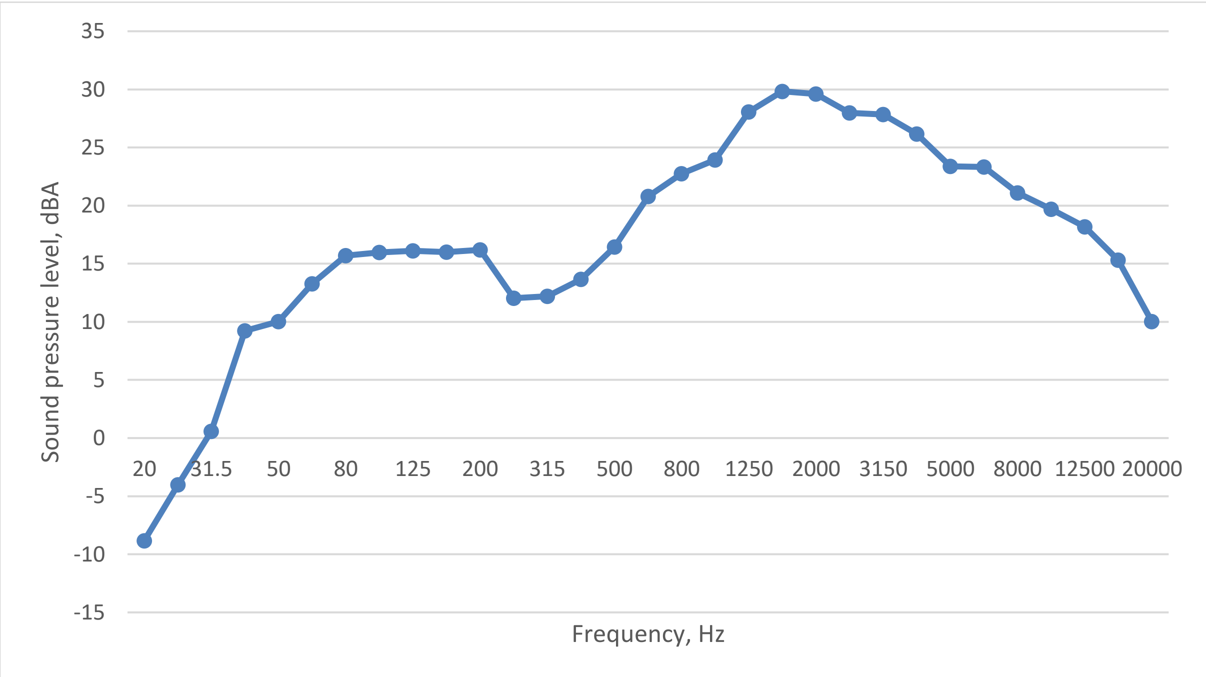

Figure 4-3 ACN example spectrum – Lismore

The measurement indicates that mid frequency components dominate the A-weighted levels. However, low frequencies propagate more effectively over distance, while higher frequencies are attenuated by ground and air absorption at a faster rate. As a result, the disparity between mid and low frequencies is expected to decrease with distance, with low frequencies become a stronger component of the overall level. Tonality was not observed, in accordance with the characterising features outlined in the NSW EPA Noise Policy for Industry (NPfI).

5 Results and discussion

The noise prediction formulas applied in the following section for the EPRI and BPA methods were sourced from the *EPRI Transmission Line Reference Book – 200 kV and Above, Third Edition (2005)*, which remains an accepted international reference for ACN prediction. The analytic approach for selecting and filtering measured ACN events, in combination with concurrent meteorological data and observations, has been undertaken in accordance with the methodology outlined in Section 5.1**.**

5.1 Analytical approach

By linking measured ACN emissions to site specific weather patterns, this study provides a direct evaluation of how international prediction methods perform under NSW conditions. The findings inform the suitability of these models for Australian applications and highlight areas where refinements may be required to improve predictive confidence and community impact assessments.

Acoustic and meteorological datasets were analysed in parallel to evaluate the performance of the BPA and EPRI prediction models under NSW conditions. Meteorological parameters including rainfall, relative humidity, wind speed, temperature, dew point, and dew point depression were aligned with acoustic measurements to identify periods most favourable for corona activity and to test the sensitivity of model predictions to local climatic drivers.

Captured audio was systematically reviewed to verify the presence of corona related noise. Periods immediately following rainfall were of particular interest, as surface droplets on conductors can intensify discharge activity until evaporation reduces their effect. Similarly, conditions with small dew point depressions, indicating saturated or near saturated air, were examined to capture events where fog or condensation increased surface wetting and supported sustained corona discharge. ACN during these periods was distinguished from background noise using audio recording, time domain inspection and spectral characteristics typical of corona noise.

To improve data integrity, recordings influenced by animal activity (e.g. insects, frogs) were processed using narrowband filtering and interpolation techniques, which allowed separation of extraneous tonal components from corona related emissions. The processed acoustic data were then compared against model predictions on both broadband and frequency specific bases, enabling assessment of overall prediction.

5.2 Rainfall intensity and ACN response

Rainfall intensity has a direct influence on corona activity, with higher rain rates generally associated with elevated ACN levels. Light rainfall can trigger intermittent discharges, while sustained or heavier rainfall often produces a more continuous and pronounced noise response. Of the two international prediction methods considered, the EPRI model incorporates rain rate as a key input variable, whereas the BPA model applies a simpler distinction between wet and dry conditions. This difference is significant for application in NSW, where variable rainfall regimes play a central role in shaping the occurrence and magnitude of ACN.

5.2.1 Lismore

A representative period between 2 and 9 May 2025 was selected for comparison of measured and predicted ACN levels. Over this interval, 35 mm of rainfall was recorded, with a typical (inter-quartile) rain rate between 0.8-2.4 mm/hr. A total of 146 ACN dominated events were identified, each lasting less than 30 seconds, thereby reducing the likelihood of contamination from extraneous environmental noise. No more than two events occurred within any 15-minute interval, ensuring coverage across a range of weather conditions. Following removal of insect interference, measured L_{Aeq} levels were compared with predictions from the EPRI and BPA models, with results presented in Figure 5-1.

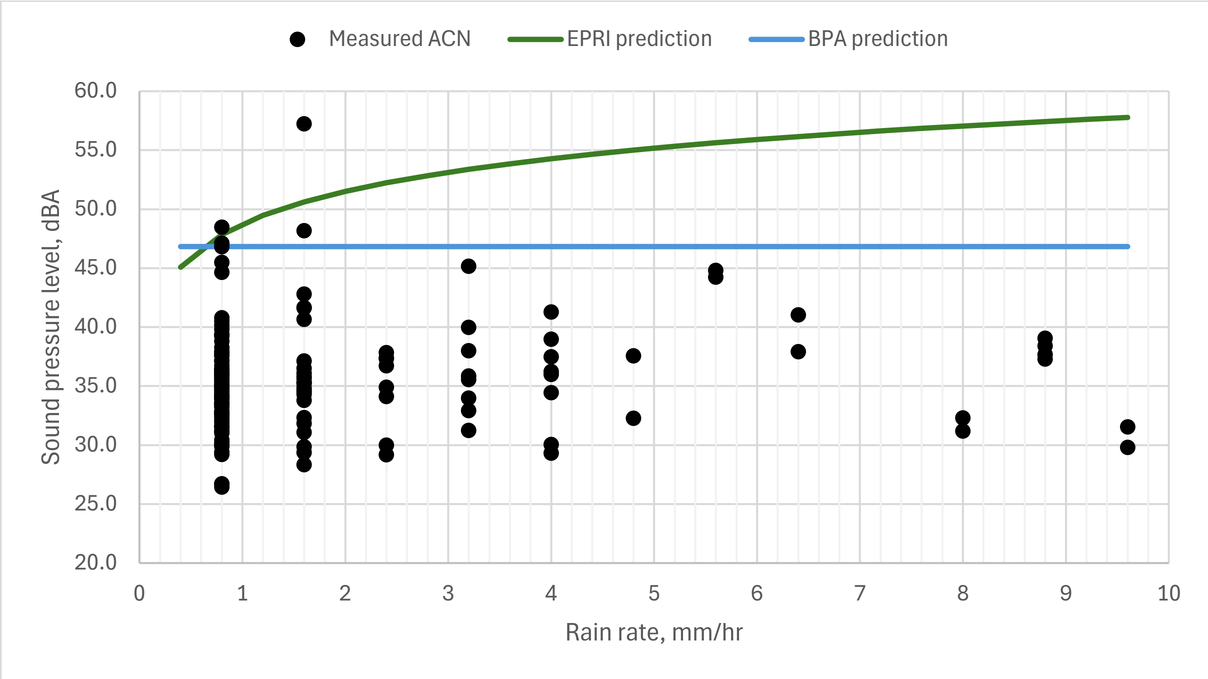

Figure 5-1 Rain rate vs ACN – Lismore

Note 1 The weather station records rainfall in fixed increments of 0.2 mm over each 15 minute interval. Rainfall rate has been extrapolated to mm/h, resulting in effective reporting increments of 0.8 mm/h.

The field measurements show substantial scatter, particularly at lower rainfall rates, with ACN levels ranging from approximately 25 to 60 dBA across the observed rainfall rates. No clear or consistent trend between rain rate and ACN level is evident, indicating that local factors beyond rainfall intensity are likely influencing measured Sound Pressure Levels (SPL). Variability may also reflect the influence of droplet size distribution, wind conditions, variable line load, and background environmental noise, which are not fully represented in predictive models.

Both the EPRI and BPA models consistently overpredicted relative to the field measurements, particularly EPRI at higher rain rates. This likely reflects the voltage of the monitored line, which at 330 kV produces less corona activity than the HV systems on which the prediction methods were originally developed. These results suggest that international models may overpredict when applied to lines below 500 kV, and caution is needed when assessing potential community noise impacts under these conditions.

5.2.2 Martinsville

A representative period between 14 and 21 May 2025 was selected for comparison of measured and predicted ACN levels. Over this interval, 190 mm of rainfall was recorded, with a typical (inter-quartile) rain rate of 0.8–5.6 mm/h. A total of 338 ACN dominated events were identified, using a consistent selection and processing approach to that applied at Lismore. Measured L_{Aeq} levels were then compared with predictions from the EPRI and BPA models, with results presented in Figure 5-2.

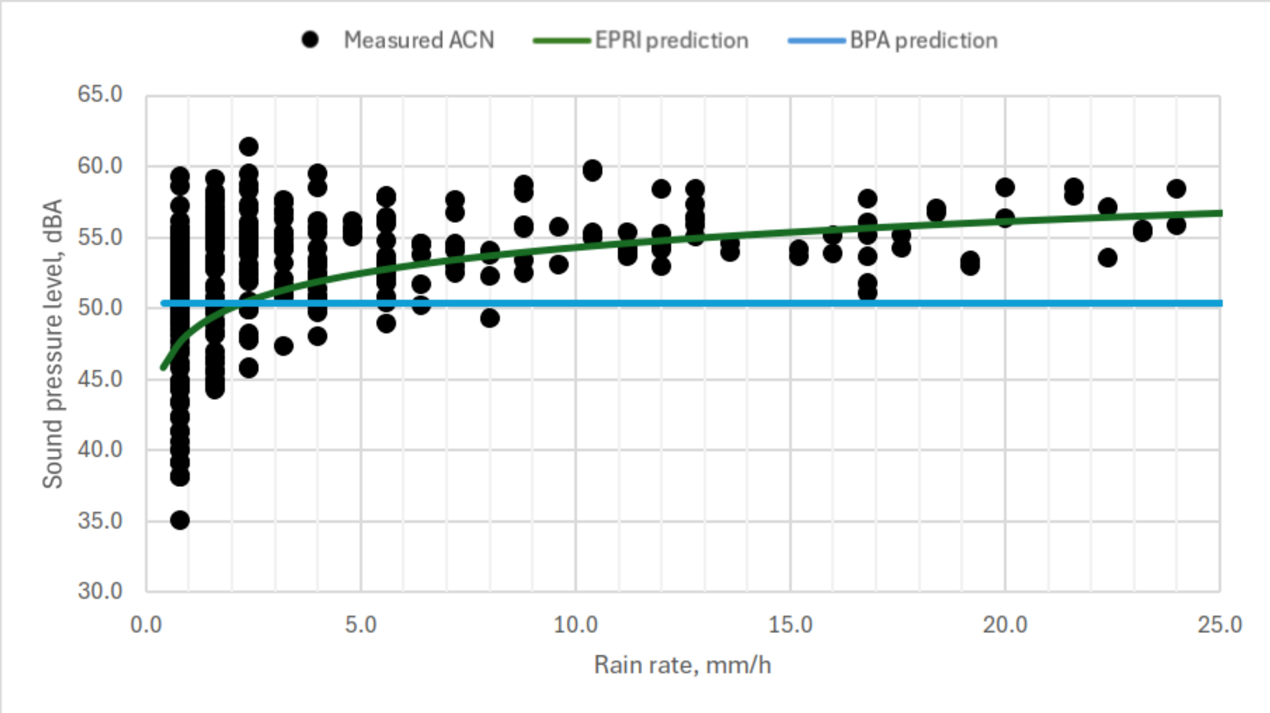

Figure 5-2 Rain rate vs ACN – Martinsville

Note 1 The weather station records rainfall in fixed increments of 0.2 mm over each 15 minute interval. Rainfall rate has been extrapolated to mm/h, resulting in effective reporting increments of 0.8 mm/h.

Field measurements at the Martinsville site show ACN levels ranging from approximately 35 to 60 dBA across the recorded rainfall intensities. A general increase in ACN with rain rate is apparent, particularly beyond about 5 mm/hr where levels tend to stabilise between 50 and 60 dBA. This pattern likely reflects the onset of more continuous corona activity as conductor surfaces become uniformly wetted under sustained rainfall.

Measured data show reasonable alignment with the EPRI prediction method, particularly at moderate to higher rainfall rates where modelled trends broadly match observations. At lower rain rates, greater variability is evident, likely due to intermittent wetting, local atmospheric fluctuations, and variable line load. The BPA method captured the overall relationship but underpredicted noise levels at higher intensities, indicating a lower sensitivity to increasing rainfall compared with field observations.

The filtered spectrum recorded across the identified ACN events are shown in Figure 5-3.

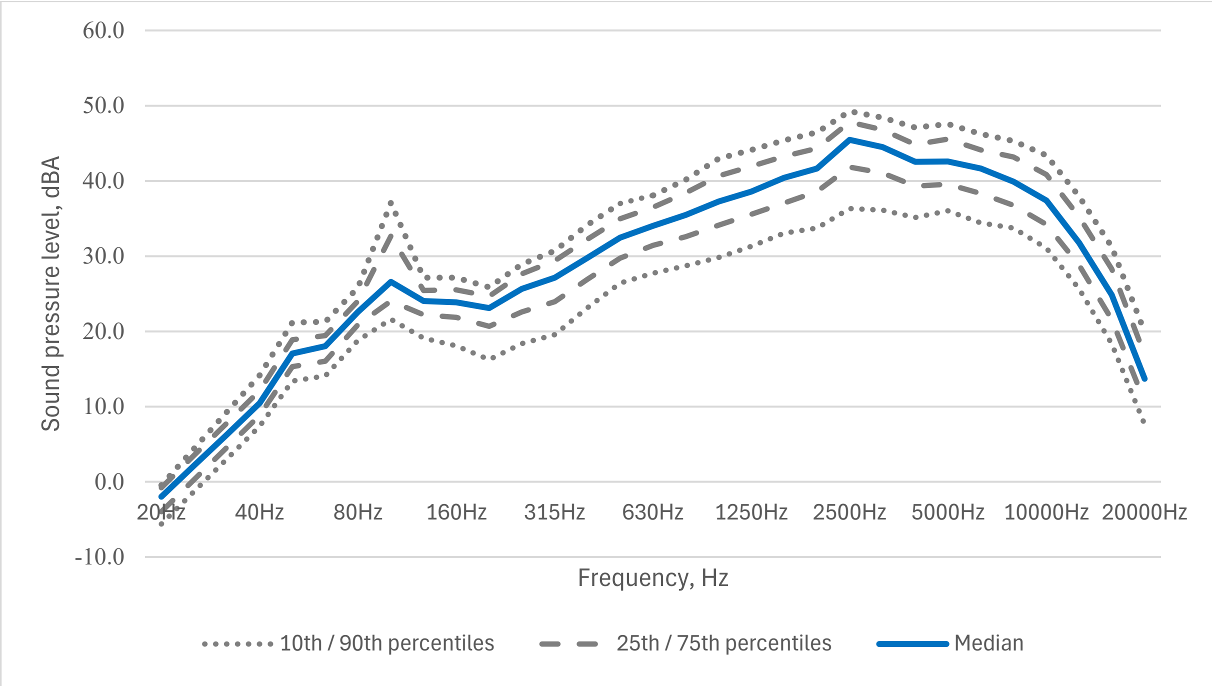

Figure 5-3 Measured spectrum – Martinsville

Tonality was not observed, in accordance with the characterising features outlined in the NSW EPA NPfI. In the instances where tonal features were present, their contribution was modest and did not dominate the overall A-weighted SPL. Accordingly, the application of tonality adjustments should not be assumed by default but instead be evidence led through attended measurements.

5.3 Influence of fog and mist on ACN

A review of noise levels at the Lismore site during periods of fog and mist was undertaken to assess their influence on ACN. Periods of fog or mist were manually identified using the SiteHive camera, supported by concurrent meteorological data. During these events, the typical conditions were relative humidity of 95% or greater, wind speeds of 0 m/s, and dew point depressions between 0 and 0.8°C. Fog was most observed between 6:00 am and 7:00 am, corresponding with the period of minimum overnight temperature and peak surface saturation. Observations were limited to this time window, as daylight constraints prevented reliable visual confirmation of fog or mist events prior to 6:00 am.

For consistency, measured noise levels during fog and mist were compared with clear, dry conditions over the same time window. Results shown in Figure 5.4 showed a modest but consistent increase in ACN levels during fog and mist events, suggesting that surface wetting by microdroplets is sufficient to sustain partial discharges even in the absence of rainfall.

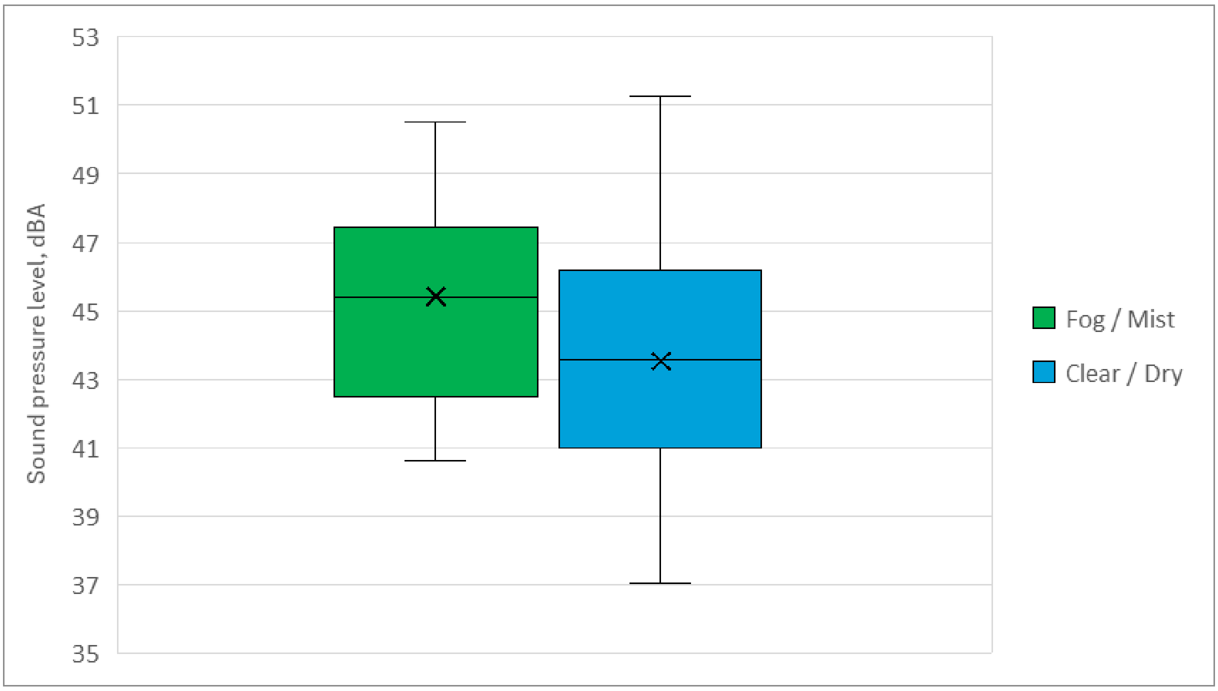

Figure 5-4 Influence of fog and mist on ACN – Lismore

The comparison results show a notable increase in measured noise levels at the 330 kV transmission line site, attributed to ACN. A representative third-octave spectrum recorded during these events is presented in Figure 5-5.

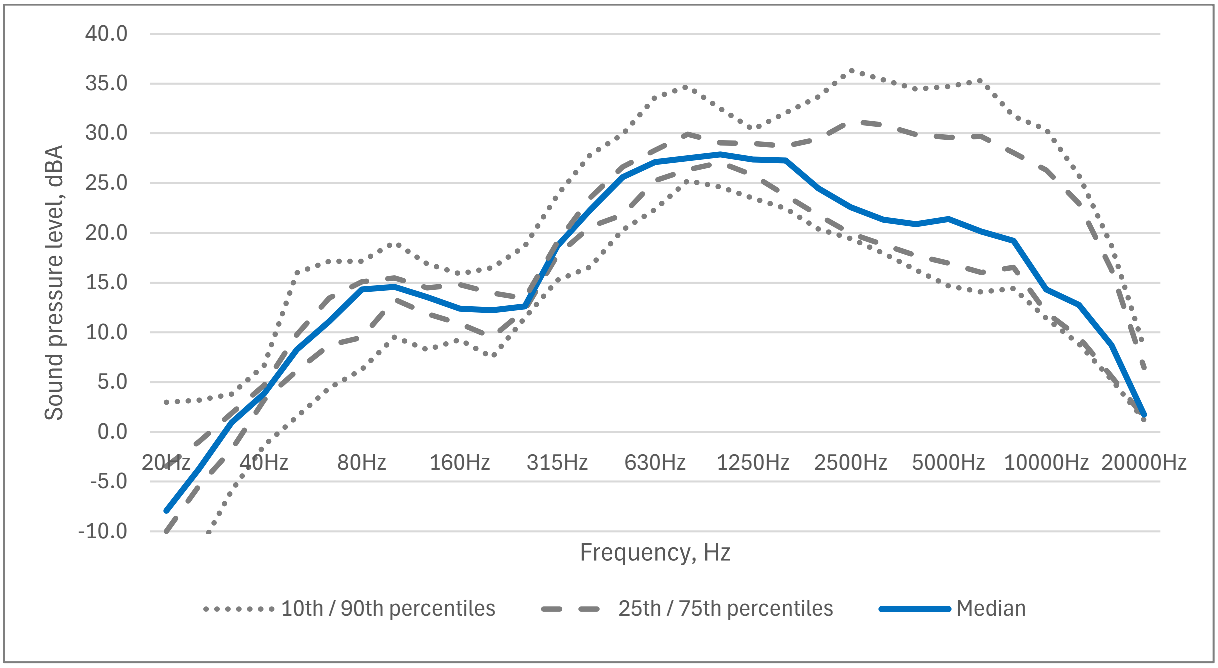

Figure 5-5 ACN example spectrum during fog and mist events

The spectrum shows that mid frequency components were dominant across measurements, with low and mid bands remaining relatively consistent between samples, while high frequency content exhibited noticeably greater variability. Tonality was not observed, in accordance with the characterising features outlined in the NSW EPA NPfI.

A similar analysis was planned for the Martinsville site, adjacent to the 500 kV transmission line; however, limited fog events were observed, resulting in an unreliable and low-volume dataset. It is anticipated that ACN during periods of fog or mist would produce elevated noise emissions, consistent with the increases observed during rainfall conditions.

The study by (Singh, Maheskumar, & Iyengar, 2022) highlights that fog formation is difficult to predict from meteorological variables alone, as localised factors such as terrain, soil type, and surface moisture conditions play a major role. This site-specific behaviour limits the ability to generalise fog-related ACN predictions using simple meteorological thresholds. Accordingly, while fog and mist are confirmed as contributing to enhanced ACN under calm, humid conditions, their occurrence and influence remain highly localised and dependent on microclimatic conditions.

5.4 Altitude effects on ACN

Altitude influences ACN primarily through its effect on air density, which alters the onset voltage for corona discharge. The BPA method explicitly accounts for altitude, applying a correction of approximately 0.3 dB increase in predicted noise level for every 100 m above sea level, reflecting the enhanced electric field intensity required to maintain discharge in thinner air. In contrast, the EPRI method does not include an adjustment for altitude, which may lead to under-prediction in elevated regions. This consideration is particularly relevant for transmission lines in parts of NSW that traverse high-altitude terrain and is discussed further in Section 5.5.

5.5 Comparative analysis of predictions methods

A representative case study was developed to demonstrate how predicted ACN levels vary with changes in rain rate and altitude when applying the EPRI and BPA prediction methods. The hypothetical site details and transmission line configuration, selected to reflect typical conditions for NSW transmission corridors, are summarised in Table 5.1.

Table 5.1 Hypothetical site details and line configuration

Site details and line configuration	**-**
Line voltage (kV)	500
Altitude (m)	0 to 1000
Bundles	6
Average maximum conductor surface gradient (kV/cm)	15.5
Number of sub-conductors in each phase bundle	4
Sub-conductor diameter (cm)	2.94
Bundle diameter (cm)	66

The case study ACN noise prediction results are illustrated in Figure 5-6. Predictions have been calculated along the transmission line centreline at a height of 1.5 m above ground level.

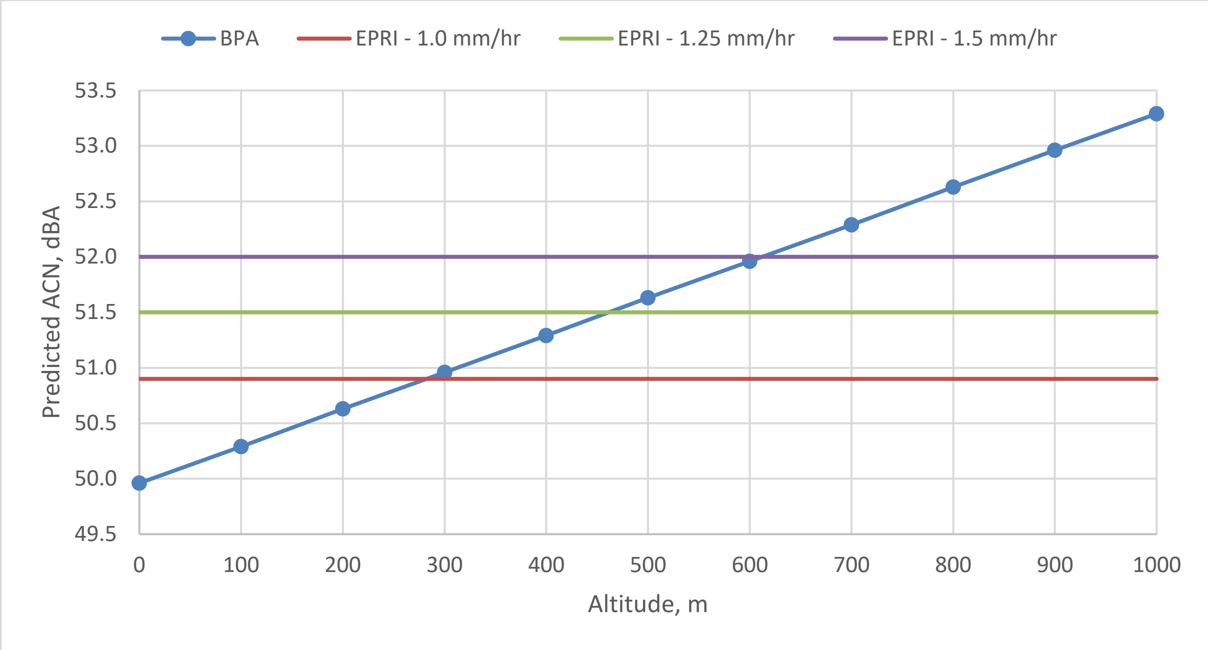

Figure 5-6 ACN predictions vs altitude

When considered together, the results show that the BPA and EPRI prediction methods diverge depending on whether altitude or rainfall is the dominant influencing factor. The BPA method more effectively captures the influence of altitude, whereas the EPRI method better represents the effect of rainfall rate. This suggests that BPA is the more suitable approach for assessing ACN along elevated transmission corridors, while EPRI is preferable in regions characterised by higher rainfall. For low-lying locations such as Martinsville and Lismore, where rainfall is the primary meteorological driver, the EPRI method may provide greater predictive accuracy. Conversely, as elevation increases along transmission routes, the BPA method becomes more applicable. Employing both approaches in tandem would likely yield the most reliable prediction framework for ACN across diverse environmental conditions.

6 Recommendations

The results of this study provide practical insight into how international ACN prediction models perform under NSW climatic conditions. Field measurements confirmed that rainfall and humidity are the dominant factors influencing ACN generation, while fog and mist act as secondary contributors under calm, saturated conditions. The comparative analysis showed that the EPRI and BPA methods each capture different aspects of ACN behaviour, with EPRI more sensitive to rainfall rate and BPA better reflecting altitude effects. Together, they offer a complementary framework for predicting ACN across NSW's varied terrain and weather regimes.

Measured results also highlighted that while international models perform reasonably well for higher voltage systems, they tend to overpredict at lower voltages, emphasising the need for local validation and field verification. These findings support a combined approach to prediction and a focus on source level mitigation that considers line design, conductor configuration and surface conditions before applying conventional noise controls.

Based on these outcomes, the following recommendations are made to guide ACN prediction, assessment and mitigation for HV transmission infrastructure in NSW.

- For high voltage transmission line assessments in NSW, it is recommended that both the EPRI and BPA prediction methods be applied to provide a conservative and robust estimate of ACN across the state's diverse climatic and topographic conditions. The EPRI model better captures the influence of rainfall rate, while the BPA model accounts for altitude effects, making their combined use the most reliable approach for representing the range of conditions experienced across NSW.
- Noise measurements showed strong correlation with the 500 kV line predictions but a notable overprediction for the 330 kV line. While lower voltage systems were expected to generate less ACN, the disparity observed was greater than anticipated, underscoring the importance of field verification, particularly in cases where predictions indicate potential noncompliance or where mitigation may be required. No tonality was observed in the measured spectra, supporting that the differences were attributable to overall broadband levels rather than discrete tonal components.
- Although fog and mist were observed to elevate ACN levels, their occurrence remains highly site specific and cannot be predicted using a generic model input or available meteorological data. Instead, fog risk may be assessed qualitatively based on typical local humidity, dew point depression and terrain indicators, verified by targeted monitoring where relevant.
- Where exceedances of noise criteria are predicted, mitigation planning should be evidence led, focusing first on conductor and hardware selection, management of surface gradients and span configuration before considering typical noise management solutions which account for the low frequency and outdoor propagation characteristics of ACN.
- Tonality was not observed, in accordance with the characterising features outlined in the NSW EPA NPfI. In the instances where tonal features were present, their contribution was modest and did not dominate the overall A-weighted SPL. Accordingly, the application of tonality adjustments should not be assumed by default but instead be supported by evidence from attended measurements.

7 Conclusions

This study has advanced the understanding of ACN under NSW climatic conditions through a combination of literature review, field monitoring and model evaluation. The results confirm that ACN generation is primarily driven by rainfall, humidity and altitude, with fog and mist acting as secondary influences that sustain corona discharge under calm, saturated conditions. Field observations at the Lismore and Martinsville sites provided the first direct validation of the EPRI and BPA prediction methods in Australian environments, demonstrating that while both frameworks remain broadly applicable, each performs optimally under different meteorological regimes.

The EPRI model was found to better represent the effect of rainfall rate, while the BPA model more accurately captured altitude effects. Together, these methods form a robust and adaptable basis for predicting ACN across the diverse climatic and topographic regions of NSW. The study also showed that international models may overpredict at lower voltages, highlighting the importance of field verification and the need to refine prediction inputs to better reflect Australian transmission infrastructure.

Overall, the findings reinforce the value of locally validated prediction and monitoring approaches to improve the reliability of ACN assessments and guide practical, evidence-based mitigation strategies. These insights provide a foundation for future refinement of modelling tools and support TransGrid's ongoing commitment to responsible environmental management of HV transmission networks across NSW.

Appendix A

Literature review

TRANSGRID

AUDIBLE CORONAL NOISE STUDY

LITERATURE REVIEW

JUNE 2024

CONFIDENTIAL

Question today
Imagine tomorrow
Create for the future

Coronal Noise Study
Literature Review

Transgrid

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REV	DATE	DETAILS
0	26/06/2024	Draft for client review
1	21/11/2025	For Issue

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GLOSSARY

TERM	DEFINITION / DESCRIPTION
Decibel, dB	The decibel (dB) is a logarithmic scale that allows a wide range of sound pressures to be represented in a more comprehensible range, typically 0 dB to 120 dB. The decibel is ten times the logarithm of the ratio of sound energy (i.e. power squared, or pressure squared) relative to a reference level squared. The reference level for sound pressure is typically 20 μPa which is the approximate threshold of human hearing.
Decibel (A-weighted), dBA	A-weighting was devised to attempt to account for human response to sound not being equally sensitive at all frequencies; it consists of an electronic filter in a sound level meter, which attempts to build in this variability into the indicated noise level reading so that it will correlate, approximately, with human response.
Sound Power Level, L_w or SWL	The sound power level is the inherent noise of the source and is the total power radiated by the source, in dB. Sound power level does not vary with distance from the noise source or within a different acoustic environment.
Sound Pressure Level, L_p or SPL	The sound pressure level of a source, in dB, varies with distance from the noise source and with the environment in which it is located.
Statistical Noise Levels, L_n (L_{90}, L_{10}, L_{50}, etc.)	The noise level that is exceeded for the stated percentage of the noise measurement period. For example, L_{90} is the noise level that is exceeded for 90% of the noise measurement period. L_{90} is commonly referred to as the 'background' noise level. L_{10} is commonly referred to the 'intrusive' noise level. L_1 may refer to the 'average maximum" noise level.
L_{max}	L_{max} is the absolute maximum sound level recorded over the measurement period.
Rating Background Level, RBL	RBL is the 10th percentile L_{A90} which accounts for temporal variation of background noise levels and is typically used as the assessment background level.
Weighted Sound Reduction Index, R_w	Single number descriptor which characterises the airborne sound insulation properties of a material or building element over a defined range of frequencies from 100 Hz to 3.15 kHz. R_w values are calculated from 1/3 octave band measurements undertaken in a test laboratory under ideal installation conditions.

ABBREVIATIONS

ACRONYM	DESCRIPTION
ACN	Audible Coronal Noise
HV	High Voltage
RFI	Radio Frequency Interference
NPfI	NSW Noise Policy for Industry
NSW	New South Wales
SWL	Sound Power Level
AS	Australian Standard
dB	Decibel
SVG	Surface Voltage Gradient
EPA	Environment Protection Authority
dBA	Decibel (A-weighted)
L_{10}	Statistical noise descriptor: noise level not exceeded for 10% of the measurement period. Typically used to represent the upper noise level.
L_{90}	Statistical noise descriptor: noise level not exceeded for 90% of the measurement period. Typically used to represent the background noise level.
L_{eq}	Equivalent noise level: equivalent energy averaged noise level which over a defined time period would contain the same energy as the time varying signal over the same time period.
L_{max}	Maximum noise level: maximum rms noise level.
BPA	Bonneville Power Administration
EPRI	Electric Power Research Institute
RBL	Rating Background Level

1 INTRODUCTION

1.1 BACKGROUND

An operating transmission line can create environmental disturbances such as noise and radio and television interference [1], due to a phenomenon known as corona discharge (or corona effect). This effect is caused by the ionisation of air surrounding the transmission line and leads to the production of Audible Coronal Noise (ACN) and Radio Frequency Interference (RFI). ACN manifests as a subjective "crackling" or "buzzing" sound accompanied by a violet glow.

Research indicates that ACN is influenced by transmission line parameters and weather conditions, with adverse weather increasing the noise level [2-3]. It is also generally tonal in nature, making it potentially more annoying to people, and substantial low-frequency components are less absorbed by typical building facades, posing an additional challenge in addressing these noise issues.

1.2 PROJECT OVERVIEW

It is important to have an efficient method for predicting, monitoring and mitigating ACN in transmission lines at sensitive receivers, to reduce noise-related complaints and potential disruptions in transmission line operation. Understanding the factors influencing the frequency and Sound Power Level (SWL) of ACN is critical for achieving this.

The NSW Department of Planning, Housing, and Infrastructure (DPHI) has issued operational conditions of approval to Transgrid under the EnergyConnect Eastern project, and these include:

Condition C9 d)

— *Prepare and implement a research program and allocate $150,000 to this program, prepared in consultation with EPA, and be submitted to the Planning Secretary for approval prior to commencement of operation, which must provide further scientific and engineering understanding of coronal discharge noise and best practice noise mitigation measures.*

This project aims to further investigate transmission line parameters and climatic information to better understand these parameters under different Australian meteorological conditions.

There has been extensive global research into ACN; however, the impact of meteorological conditions in Australia on ACN levels and frequency of occurrence is often not fully addressed in these studies.

1.3 PROJECT PRELIMINARY SCOPE OF WORKS

The following preliminary scope of works has been prepared to address the initial aims of this Project:

- **Literature review (Task 1a)**
- Workshop stakeholder meeting - Transgrid (Task 1b)
- Meeting and agreement with EPA/DPHI (Task 1c)
- Identification or development of prediction method (Task 2)
- Validation monitoring program (Task 3)
- Summary report of findings (Task 4)

1.4 AIMS OF THIS REPORT

This document is a comprehensive literature review which has been prepared as Task 1a of this research program and will inform the final project goals and scope of works. The review has undertaken an in-depth analysis of current research with the following aims:

- Pinpoint any gaps in the knowledge of ACN (coronal noise) as it applies to Australian conditions and assessment in NSW
- The impact of transmission line design on ACN
- Identify environmental factors that influence coronal noise
- Evaluate the suitability of exploring methods for predicting Sound Power Level (SWL) under Australian conditions
- Evaluate reasonable and feasible techniques for mitigating ACN.

Broadly the literature review will evaluate the applicability of existing methodologies and tools, offering recommendations for their optimal utilisation check for in the Australian context. Furthermore, the review will outline a suggested course of action, as well as highlight potential opportunities and risks associated with the study. It will also examine current best practices for mitigating coronal noise, delving into the advantages and disadvantages of various mitigation options.

2 LITERATURE REVIEW

ACN presents a considerable challenge in high-voltage power systems, particularly in the context of transmission lines and substation equipment. Corona discharge is the process of ionising air molecules around high-voltage conductors, which leads to the creation of plasma and the release of energy in the form of light, heat, and sound. A precise understanding and calculation of this noise are imperative for the development of power systems that adhere to environmental and community noise regulations.

2.1 ACN INFLUENCING FACTORS

The assessment of the relationship between ACN and its impacting variables, such as transmission line parameters and meteorological factors, plays a pivotal role in comprehending coronal noise and ascertaining noise levels. This section provides an intricate analysis of the influence of transmission lines and meteorological factors on ACN levels.

2.1.1 TRANSMISSION LINE FACTORS

The current design selection of transmission lines, conductor, insulation, and line hardware generally considers the resulting electric field on the surface of the conductor, referred to as Surface Voltage Gradient (SVG), which is the primary factor influencing the resulting corona event and hence ACN.

It is understood that guidelines for SVG design are generally considered in accordance with the informative requirements of AS/NZS 7000 Overhead Line Design. Other factors influencing SVG are generally considered in accordance with design principles from Energy Networks Australia EMF Handbook and underlined by the occupation and general public guideline limits outlined by the Australian Radiation and Nuclear Science Agency (ARPANSA) [38].

- Other factors that may influence ACN include Surface contamination, like atmospheric pollution, significantly impacts the spectrum characteristics of ACN, with polluted conductors exhibiting higher noise levels than clean ones [5]
- Hydrophilic conductor surface treatments can reduce ACN, but their effectiveness diminishes with increasing surface gradient, leading to higher emission levels above a certain point [6]
- The altitude of the transmission line plays a crucial role, with a clear logarithmic relationship between the equivalent A-weighted sound level and the average corona current observed at high altitudes [7]
- The relationship between wire power supply current and audible noise is essential for understanding the noise generated by high-voltage direct current lines [8]
- Irregularities on the conductor's surface, such as nicks or sharp points, as well as airborne contaminants, can enhance the corona activity [8]
- Aging or weathering of the conductor's surface generally reduces the significance of these factors [10].

Extensive research work has been conducted on influence of transmission line parameters on ACN. Table 2.1 presents some critical literature on meteorological factors influence ACN.

Table 2.1 Insights of some critical literature on transmission line parameters influence on ACN

REF NO	ARTICLE TITLE	INSIGHTS
[5]	Interaction of Surface Gradient, Precipitation Rate and Conductor Surface Treatment on Corona Induced Audible Noise of AC Overhead Transmission Lines	— Surface gradient, precipitation rate, and conductor surface treatment influence coronal noise — Hydrophilic conductors reduce noise, the rate is affected by surface gradient and precipitation.
[6]	Corona current and audible noise characteristics of HV-DC transmission lines and their relationship at high-altitude	— Altitude increase intensifies the audible noise of HV-DC transmission lines — The study found a clear logarithmic relationship between A-weighted sound level and corona current.
[7]	Audible noise sensing method for HV-DC Transmission lines based on corona current detection	— Wire power supply current influences audible noise characteristics.
[8]	Influence of surface contamination of conductor on positive corona-generated audible noise spectrum characteristics of HV-DC system	— Surface contamination affects audible noise spectrum characteristics — Positive corona discharge produces higher audible noise levels than negative.
[9]	Effect of altitude on the audible noise level of AC power lines	— Audible noise level of AC power lines increases with altitude — Correction term of 2.85 dB/1000 m is recommended for altitudes above 3200 m.
[10]	Influence of aged conductor surface conditions on AC corona-generated audible noise with a corona cage	— Aged conductors generate a more intense corona discharge, resulting in a higher audible noise — Audible noise is 3 to 5 dB stronger in wet conditions.

The ACN generated by AC transmission lines exhibits greater severity at higher altitudes compared to lower altitudes, thereby impacting the structural design of power lines and their environmental impact assessment [9]. The analysis conducted in this study suggests that the actual audible noise correction values are marginally lower than the Bonneville Power Administration's prescribed term of 1 dB/300 m at altitudes below 3200 m. Consequently, a correction term of 2.85 dB/1000 m is recommended for a more precise evaluation when assessing altitudes above 3200 m. It is noted that Mount Kosciuszko is the tallest mountain peak in mainland Australia at 2,228 meters and as such, this correction is not applicable within Australia.

Bian et al [10] investigated the effects of surface conditions on corona-generated audible noise for long-term aged AC conductors. A comparison was made between audible noise on typical aged conductors and new ones. The aged conductors had been in service for 12, 15, and 20 years, and their surface morphology, composition, and roughness had been analysed. **The study found that the audible noise of the aged conductors was much higher (2.2 to 6.7 dB) than that of the new conductors in dry conditions and even more pronounced in wet conditions, with the audible noise being 3 to 5 dB stronger.**

It is important to note that UV radiation and chemical pollution gradually degrade the residual oil and grease layers over time, causing a transition to a hydrophilic outer conductor surface. This hydrophilic surface hinders the formation of droplets and subsequently results in conductors with minimal corona sources. Moreover, the migration of grease from the conductor core to the surface, coupled with the filling of gaps between adjacent surface strands due to mechanical torsion forces on the conductor, prevents the shedding of surface water, leading to an increase in ACN generation. This process has the potential to persist over an extended period, often spanning many years [10, 23, 32].

The utilisation of a new conductor with a hydrophobic surface under wet conditions has shown potential to influence tonal characteristics in transmission lines. Surface treatment involving the application of grease on the steel core strands for corrosion protection, along with residual drawing oil from the cable manufacturing process, contributes to the development of a hydrophobic surface on the outer strands of the conductor and in the gaps between adjacent outer strands. This hydrophobic nature of the conductor's surface leads to the formation of small droplets when exposed to rain, mist, or fog. Remarkably, these droplets do not readily move downwards through the valleys and gaps between conductor strands due to the hydrophobicity of the surface, defying the forces of gravity and capillary action. The presence of numerous small droplets around the conductor surface acts as concentrated sources of corona activity, resonating at harmonic frequencies of 50 Hz, notably 100 Hz and 200 Hz, under the influence increased corona activity [10, 23, 32]. It is recommended that the extent of this factor is investigated further in subsequent project phases.

2.1.2 METEOROLOGICAL FACTORS

The degree or intensity of the corona discharge and the resulting audible noise are affected by air conditions, humidity, air density, wind, and water in the form of rain, drizzle, and fog. Water increases the conductivity of the air, thus increasing the intensity of the discharge. As such, in wet/humid weather conditions, corona discharges can be produced by the presence of water droplets, fog, and snow. Table 2.2 presents some critical literature on meteorological factors influence ACN.

Table 2.2 Insights of some critical literature on meteorological influence on ACN

REF NO	ARTICLE TITLE	INSIGHTS
[3]	HV-DC corona current characteristics and audible noise during rain	— Rain intensity influences HV-AC audible noise level — The sensitivity of the generated noise level to the rain rate decreases under and applied electric field.
[11]	HV-AC corona current characteristics and audible noise during wet weather transitions	— ACN is significantly higher during transitions before and after steady state rainfall — Corona discharge is increased during rain.
[12]	Corona discharge characteristics for fittings of AC transmission line under rainy conditions	— Audible noise increases substantially at inception corona voltage in dry conditions — Audible noise increases gradually with voltage in rainy conditions.
[13]	Computation of audible noise from a 1200 kV UHV power transmission line	— Wet/humid weather (rain, snow, fog, haze) aggravates audible coronal noise — Rain generates higher levels of ACN than snow or fog.
[14]	Corona phenomena for long-term operating conductor under different weather conditions	— Rainy weather distorts electric field, intensifies ACN — Heavy rain reduces the deviation between old and new conductors.
[15]	Audible noise analysis of 750-kV AC transmission line in high-altitude area under different weather	— Audible noise increases during periods of rainfall and snowfall — A pure tone at 100 Hz is more prominent during rainy and snowy weather.

It is found from research studies [3, 11-15] that wet/humid weather (rain, snow, fog, haze) aggravates ACN. Rain is one of the most influencing factors for higher ACN level. One study [11] investigated corona current and audible noise for a wide range of surface gradients and rain rates, with a focus on behaviour during rain onset and dry-off. The results show that corona current increased during rain, and the measured audible noise was substantially higher during transitions before and after the steady state of rain. A research investigation [15] found that the pure tone at 100 Hz was observed to be more pronounced during rainy and snowy weather conditions.

Rainfall intensity plays a crucial role in influencing the audible noise level, with a higher rain rate usually expected to cause a louder noise level. However, the sensitivity of noise level to rain rate decreases where an electric field is applied to the conductor [3]. This effect occurs because of a distortion of the electric field around the conductors under rainy conditions, affecting corona discharge intensity, affecting both audible noise and radio interference levels significantly compared to dry weather [12-13]. **Overall, weather conditions, especially rain, increase the ACN levels emitted by high voltage transmission lines.**

2.2 ACN CALCULATION

ACN calculation methods are based on the measurement or calculation of corona current waveforms, noise reduction processing, solving 1/3 octave spectrum data, and then calculating sound pressure levels based on correlation models [16-17]. Both experimental and computational techniques are utilised to simulate sound pressure pulses resulting from corona discharge. The findings generally indicate a consistent agreement between calculations and measurements, suggesting an association between an increase in noise pulse frequency, the presence of more corona sources, and higher voltages [18-20].

Investigations into the directivity and lateral profiles of coronal noise from a single source demonstrate a reduction in sound pressure levels with distance, thereby confirming a propagation model that incorporates ground absorption/reflection and air attenuation [19]. Additionally, a method for analysing audible noise from DC single wire corona discharge involves the construction of random sound pressure pulse waveforms and the examination of noise at various spatial points [21]. Where these methods have been validated, the calculation models indicate that all assessed approaches provide generally accurate predictions of ACN.

Accurately calculating the SWL of ACN involves using complex models that consider the physical and electrical properties of the system. Three key methods for this purpose are empirical models, analytical models, and numerical models. To ensure reliability of ACN calculations, these methods need to be validated against field measurement involving sound level measurement and assessing local environmental/meteorological conditions. A summary and insights of most relevant literature has been presented in Table 2.3.

Table 2.3 Summary and insights on ACN calculation

REF NO	ARTICLE TITLE	INSIGHTS	METHOD TYPE
[16]	Design and application of indirect detection software for audible noise	— Software based calculation of ACN based on corona current measurement data — Utilises C# Net and MATLAB for audible noise calculation.	Numerical
[17]	Audible noise indirect detection method	— Indirect detection method using corona current waveform data — Calculates audible noise level based on corona current spectrum data.	Analytical

REF NO	ARTICLE TITLE	INSIGHTS	METHOD TYPE
[18]	Time-domain performance of audible noise for positive dc corona: Numerical simulations and measurements	— Proposed acoustic source model and computational technique for sound pressure simulation — Calculations of sound pressure is in reasonable agreement with measurements.	Numerical
[19]	A numerical model of acoustic wave caused by a single positive corona source	— A model based on fluid equations to interpret coronal noise generation mechanisms — . The experiment findings showed that the amplitudes of the sound wave and the corona current are also correlated, suggesting that the strength of the sound wave is influenced by the intensity of the corona current	Numerical and Analytical
[20]	Finite Element Method Assisted Audible Noise Detection for Overhead Line Conductors Using the Cage Experiment	— Optimisation of detection points using finite element method for accurate measurements. — Considered the optimal alignment of the measurement microphone with the noise source for optimal audible noise calculation.	Numerical
[21]	DC single wire corona discharge audible noise analysis method	— This method was found to measure, disperse, construct, and calculate DC coronal noise accurately — Utilises intrinsic features of transmission lines (e.g. distribution of sources, current fluctuations, and waveforms) for precise analysis of corona discharge noise.	Analytical
[22]	Analytical Method for Calculating Corona Noise on HV-AC Power Line Carrier Communication Channels	— This method calculates coronal noise level from HV-AC power line carriers — Coronal noise is evaluated in carrier frequency range. with any given bandwidth, and in terms of quasi-peak, RMS, or average value, enhancing the precision of noise predictions	Analytical
[13]	Computation of audible noise from a 1200 kV UHV power transmission line	— Computes tonal noise from 1200 kV transmission line — Finds that tonal noise may be a health concern due to low frequency perception.	Numerical
[23]	Interaction of Surface Gradient, Precipitation Rate and Conductor Surface Treatment on Corona Induced Audible Noise of AC Overhead Transmission Lines	— This paper developed a new prediction method to understand varying emission levels from surface gradient and precipitation rate — Found that hydrophilic conductors reduce audible noise emissions under wet/humid weather conditions.	Empirical
[24]	Research on the correlation between corona current spectrum and audible noise spectrum of HV-DC transmission line	— Found that audible noise is closely related to corona current on HV-DC lines — Established a mathematical expression for corona current and audible noise spectrum prediction.	Empirical

REF NO	ARTICLE TITLE	INSIGHTS	METHOD TYPE
[6]	Corona current and audible noise characteristics of HV-DC transmission lines and their relationship at high-altitude	— Identified that higher altitude intensifies audible noise of HV-DC transmission lines — Found a clear logarithmic relationship between A-weighted sound level and corona current.	Empirical
[27]	Coronal noise on a 400 kV overhead power line: Measurements and computer modelling	— Undertook measurement of coronal noise spectrums density under different weather conditions.	Empirical & Numerical

2.2.1 *MEASUREMENT OF ACN SWL AND FREQUENCY SPECTRUM*

Corona discharge induced noise typically becomes a design concern for transmission lines at 345 kV and above and is less noticeable from lines that are operated at lower voltages [33]. It was found that the sound level of ACN can be increased by 15 dB under certain conditions and can reach a value of more than 50 dB. The ACN emits two components: a constant broad-band noise signal and pure tone component. The broad-band noise is generated by electric discharges on the surfaces of the line while the pure tone is generated by discharge frequency of the given source [1].

A few research papers focused [23-25] on understanding the complex mechanisms of ACN generation from HV-DC and HV-AC lines. The understanding these mechanisms is crucial for developing effective noise mitigation strategies. The research studies looked at the characteristics of ACN in time and frequency domains and the correlation between sound and discharge. It is found that the sound power level of ACN in transmission lines is influenced by various factors such as corona current, altitude and voltage levels.

2.2.1.1 CORONA CURRENT

Corona discharge produces corona current pulses that compress the air around the conductor. The corona current on transmission lines has two components: the current created by the movement of electrons drawn into the discharge point, and the current induced by the change in positive charge levels on the surface of the discharge point. However, the latter can often be disregarded due to the low intensity of corona discharge and minimal changes in capacitance between transmission lines and the ground [6-7, 23].

A clear logarithmic relationship between the equivalent A-weighted sound level and the average value of the corona current was established, indicating that as the corona current increases, the audible noise level also increases in a predictable manner. [6]. Pischler et al. [23] presented the correlation between corona current and audible noise in the context of ultra-high-voltage (UHV) DC transmission lines. It describes how experimental data was used to establish a correlation and formula between the frequency-domain characteristics of corona current and the A-weighted sound level of audible noise. The results presented here could be a foundation for further research into the connection between corona current and audible noise, with potential implications for estimating audible noise.

Another work [24] studied the relationship between audible noise and corona current on a high voltage direct current (HVDC) transmission line. This work explained the internal reasons for the statistical regularities observed in the measured corona current and audible noise data by establishing a mathematical expression between the audible noise spectrum and the corona current spectrum. The frequency-domain characteristics of corona current play a crucial role in determining the audible noise level, with a correlation formula established between the spectrum characteristics of corona current and the A-weighted sound level of audible noise [26].

2.2.1.2 CORONA VOLTAGE

The repetition frequency and amplitude of ACN increase with the number of corona discharge points and applied voltage levels, highlighting the importance of these parameters in determining the sound power level of coronal noise in

HV-DC lines [13]. The tonal component generated due to corona discharge was measured during bad weather. The tonal component of the audible noise was calculated for an 8 sub-conductor bundle conductor of a 1200 kV transmission line, resulting in a sound pressure level of 80.9 dB at a distance of 5.81 meters in a corona cage study with a wetting length of 18 meters.

2.2.1.3 CONDUCTOR CONFIGURATION

Perry et al. conducted [28] testing on a three-phase test line with different conductor configurations energized at 525 kV. The results showed that **different conductor configurations and phase spacings considerably impact the audible noise levels. For example, for twin Mango conductor bundle the ACN level varies from 15 dB to more than 22 dB compared to heavy rain ACN level [32].**

2.2.1.4 WEATHER CONDITIONS

Mujčić et al. [27] presented experimental research on coronal noise on a 400 kV overhead power line. They measured the power spectrum density and relative coronal noise within a power frequency period, finding that the **noise levels are significantly higher in wet/humid weather conditions compared to dry/fair weather conditions, with maximum peaks exceeding the root-mean-square noise level by 7.95 dB in wet/humid weather and by 2.9 dB in dry/fair weather.**

2.2.2 PREDICTION METHODS AND SOFTWARE OF ACN

2.2.2.1 EMPIRICAL AND SEMI-EMPIRICAL FORMULAS FOR PREDICTING AUDIBLE NOISE LEVEL

Numerous empirical and semi-empirical methods are available for predicting ACN for a transmission line. Engel et al. [1] presented table of different methods Bonneville Power Administration (BPA), Westing-house, Ontario Hydro, IREQ (Hydro-Quebec Research Institute) from different research centre. Other published methods are developed by National Electricity Board (ENEL) in Italy, France Electricity (EDF) in France, FGH in Germany, Electric Power Research Institute (EPRI) in USA, Central Research Institute of Electric Power Industry (CRIEPI) in Japan and China Electric Power Research Institute (CEPRI) in China [1, 30, 32-33]. Some these methods were only derived from tests on lines with operating voltages exceeding 400 kV. In this section, BPA and EPRI methods, which are mostly used in Australia, have been discussed.

The BPA empirical method is widely applied for predicting ACN levels. BPA has developed general formulas based on full-scale line data to predict A-weighted audible noise during rain for AC lines. The method is mostly used for single circuit lines at 500 kV with large sub-conductors. It provides L_{50} exceedance levels at an unspecified rainfall rate and a generic 3.5 dB correction factor for L_{50} exceedance levels. This method is specifically designed for aged or weathered conductors and is developed from long-term measurements on several full-scale operating or test lines. It considers phase configuration, typical operating voltage, height above mean sea level, number of conductors in a bundle (if applicable), conductor diameter, and height above ground at maximum conductor sag [30-32].

The EPRI methodology encompasses equations to forecast the audible noise from empirical measurements. The model's accuracy hinges upon the precision of the original measurements and the input parameters, such as the specific elevation of the transmission line at a given location. The resulting field plots typically align within a few percentage points of the actual value for the conditions being modelled. EPRI's research has brought to light the impact of pollution and conductor aging on audible noise levels. In regions with low pollution, the lifespan of aging conductor may be extended by up to three years, as delineated in the EPRI reference book. This finding underscores the importance of addressing these issues through regular maintenance. Furthermore, the EPRI reference book emphasizes the substantial variance in ACN levels during fair weather and the extent of surface pollution [30, 32-33].

Research centres use various other calculation procedures to analyse noise levels in transmission lines to establish the relationship between line parameters and the corona phenomenon. These empirical calculation formulas have been developed, based on field data obtained from test locations adjacent to both operating transmission lines and full-scale test spans. These formulas demonstrate correlations between wideband ACN level and surface voltage gradient (SVG), sub-conductor number, sub-conductor diameter, and the distance between the conductors and the measurement point. These empirical formulas do not account for some variables, such as weather and pollution conditions. It is important to note that these formulas are specific to the design philosophy of the transmission utility and the characteristic weather of a given region [30, 32].

Consequently, the empirical constants used in these formulas may vary among individual transmission utilities and national industry bodies. The empirical formulas are also designed for a specific rainfall condition (i.e., L_{50} exceedance levels). For instance, the semi-empirical EPRI (USA) formula was generated from measured data on a full-scale test span with a specific rainfall rate, which may differ across regions. This formula incorporates conductor bundle arrangements and provides an SVG based on a rainfall rate correction factor, enabling sound pressure level calculation at a 100 Hz tone and includes a correction for a new conductor effect. Semi-empirical calculation formulas are typically derived from three-phase and single-phase test cage data. While they predict heavy rain L_5 exceedance levels, they also offer correction factors for various rainfall rates [28, 32-33].

2.2.2.2 SOFTWARE AND PRODUCTS USED FOR MONITORING/SIMULATING ACN

Various software applications have been developed to predict and analyse corona discharge and related noise (ACN) in HV transmission lines. These software programs provide valuable insights into understanding and easily forecasting ACN in power systems. Examples of such software include SESEnviroPlus, PDCAD FACE, COMSOL Multiphysics, ANSYS Maxwell, CDEGS, MATLAB, and Finite Element Analysis (FEA) Software.

SESENVIROPLUS

SESEnviroPlus is designed to evaluate corona-related parameters based on various assessment methods such as EDF, IREQ, EPRI, BPA, CRIEPI, ENEL, and FGH. It allows users to specify their own calculation methods and takes into consideration factors such as power frequency, surface effects, proximity effects, conductor surface conditions, and earth characteristics when assessing corona and line parameters. Additionally, SESEnviroPlus can account for corona onset gradients, ion mobilities, ion recombination, and system configurations for HV-DC lines.

This software package was used in the Beca [31] report. They used BPA (empirical) and EPRI (semi-empirical) methods in the software. They found that the EPRI and CIGRE methods were the most appropriate methods for calculating wideband ACN level and RFI level respectively. However, it is noted that these packages do not provide sound pressure level calculations for low frequency or tonal characteristics.

PDCAD FACE

PDCAD FACE (Field and Corona Effects) is a simulation tool that predicts the field and corona effects of high-voltage transmission lines, including audible noise, corona loss, radio interference, electric and magnetic field distributions beneath transmission lines, ionized fields, ion charges, and ion currents. It evaluates the overall environmental effects of high-voltage AC, DC, or AC/DC hybrid transmission lines using empirical formulas and semi-analytical methods.

COMSOL MULTIPHYSICS

COMSOL Multiphysics is a comprehensive simulation platform that utilizes the Finite Element Method (FEM) to solve multi-physics problems, encompassing electromagnetic and acoustic phenomena. It is employed for detailed simulations of electric fields, ionization processes, and coronal noise in high-voltage systems.

ANSYS MAXWELL

ANSYS Maxwell is specialized electromagnetic field simulation software that employs FEM for analysing electric and magnetic fields. It is well-suited for modelling electric field distributions around conductors and predicting corona inception and noise generation.

CDEGS

CDEGS (Current Distribution, Electromagnetic Fields, Grounding, and Soil Structure Analysis) is a software package developed by Safe Engineering Services & Technologies Ltd (SES), featuring modules for electromagnetic field analysis and grounding system design. This software is used for analysing electric fields around high-voltage transmission lines and substations, aiding in corona discharge and noise calculations.

MATLAB

MATLAB a high-level programming language and environment for numerical computing and visualisation, is frequently utilized to implement customized algorithms for coronal noise prediction, process experimental data, and validate theoretical models against measurements.

In addition, general-purpose FEA software packages such as Abaqus or NASTRAN can be adapted for electromagnetic field analysis to study corona discharge and noise generation phenomena. These tools offer comprehensive capabilities for understanding ACN in power systems.

2.3 MITIGATION

Where corona noise is predicted to exceed recommended or mandatory noise impact criteria, mitigation of noise impacts may be required. Mitigation measures of transmission line coronal noise can be grouped into four general categories:

1. Mitigation measures that alter the location of the source
2. Mitigation measures that alter the noise level of the source
3. Mitigation measures that affect the path of noise transmission between the source and the receiver
4. Mitigation measures that alter the receiver.

The following subsections will further discuss these categories and some examples of these mitigation measures.

2.3.1 SOURCE LOCATION MITIGATION MEASURES

One of the most straightforward and effective means of mitigation is to relocate the transmission lines to an area far enough away from sensitive receivers to comply with local noise impact criteria. However, this must be undertaken in consideration of other potential engineering or property constraints and may not be reasonable and/or feasible under certain circumstances.

2.3.2 AT-SOURCE NOISE MITIGATION

Where the relocation of the transmission lines is not feasible, at-source mitigation is an effective measure that can be used to reduce surrounding noise impacts. By taking preventative measures to avoid ACN transmission line factors such as those detailed in section 2.1.1, as well as measures that result in protecting transmission lines from meteorological factors such as those listed in section 2.1.2, noise emissions from overhead transmission lines can be significantly reduced. These can be broken down into active measures such as limiting the current passing through the transmission lines during periods when noise impacts on surrounding properties may be higher, and passive measures such as modifications to the transmission line design which reduce the SWL of the source or the frequency of coronal discharge events.

Active measures such as **limiting current at certain periods of the day may reduce the SWL and frequency of ACN**, however these may result in other operational constraints and would need to be considered in conjunction with broader design parameters.

As a result of this, passive measures may form a more viable at-source mitigation approach. The majority of passive measures focus on modifying the configuration of the conductor bundles, treating the conductor surface or additional transmission tower components near the transmission lines. At source mitigation measures currently include the following measures where reasonable and feasible:

- Conductor bundle configurations
- Conductor coatings

- Insulator grading rings/corona rings
- Line type

The effectiveness and relevance of these measures under Australian conditions will be further investigated during future project phases.

A common coronal noise mitigation method it the implementation of bundling in transmission conductor lines. A bundled conductor, also known as a bundled transmission line, represents a configuration of multiple conductors or cables grouped together to form a single transmission line. This configuration is frequently utilised in high-voltage power transmission systems. The bundling of conductors is a common method to reduce the surface electric field intensity, thereby lowering the likelihood of corona discharge and subsequent noise generation. **The effectiveness of this approach may be influenced by factors such as the number of sub conductors, their diameter, and the spacing between them.** Studies have shown that increasing the number of bundles and the diameter of sub conductors can significantly reduce audible noise, although the influence of spacing is negligible [32, 36, 37].

Pischer et al. [23] studied the effectiveness of hydrophilic treatment on conductors, aiming to reduce noise by influencing the formation of water droplets. The treatment promotes the generation of smaller, more dispersed water droplets, thereby minimizing them as a corona discharge source and reducing audible noise emissions. **The study found that while hydrophilic treatment reduces noise levels, its effectiveness is inversely related to the SVG**. Treated transmission lines may emit higher noise levels under certain conditions, underscoring the need for a better understanding of the limitations of hydrophilic conductors.

Li et al. [34] investigated an alternative conductor treatment in 2023. Specifically, they examined the effectiveness of applying a superhydrophobic coating to the conductor lines, as opposed to a hydrophilic coating. This superhydrophobic coating functions by repelling water droplets that can lead to coronal arcing and subsequent ACN. The study found that superhydrophobic coating on the transmission line repelled droplets, thereby reducing ACN SWL and frequency. It also noted that the force exerted on nearby droplets and their range of influence increased with the electric field. However, the paper primarily focuses on water droplet movement and discharge, without addressing durability, effectiveness, or practical cost of such treatment in real-world scenarios. Additionally, the sample size and duration of the experiments may not fully cover potential practical applications.

There is a likelihood that the effectiveness of these conductor coatings can decline with age and as such may require more frequent maintenance through re-application. This needs to be confirmed by further investigation.

Yang, Peng, and Liao [35] examined the use of insulator grading rings to adjust the voltage distribution and electric field strength along a conductor, specifically focusing on their impact on reducing corona discharge around transmission tower insulators. Grading rings, (also known as corona rings) which are electrically connected to the insulator, assist in distributing the voltage and field strength evenly along the insulator strings, thereby reducing the strength of the electric field and minimising coronal arcing. The study utilized a full-scale 3D simulation of a strain type transmission tower to model the voltage distribution and electric field of porcelain insulators, both with and without grading rings of varying physical properties. The findings underscored the influence of grading rings on voltage distribution and field strength. The researchers concluded that by adjusting specific grading ring parameters such as placement, shielding depth, ring diameter, and tube diameter, the design could be optimized to reduce ACN and maximize system efficiency and improve power transmission.

The study mainly focuses on optimizing insulator grading rings for double circuit tension towers in ultra-high-voltage UHV 1000 kV AC transmission lines. However, it is important to note that this study's findings may not be fully applicable to current and future transmission networks in NSW. UHV transmission lines are not used in Australia at this time and the study was limited to simulations which did not validate the modelled result. Additionally, the study does not cover economic feasibility, environmental impact, sustainability considerations, or the long-term durability and operational lifespan of the optimized grading ring design or its application to standard HV transmission configurations.

2.3.3 SOURCE-RECEIVER NOISE PATH MITIGATION

Where source relocation and at-source mitigation measures are unfeasible or provide insufficient mitigation for nearby receivers, measures that focus on mitigating or altering the noise path between the source and the receiver may be considered. Increasing the height of transmission line towers provides a negligible increase in source to receiver separation distance and is not a reasonable mitigation measure. Likewise for elevated transmission lines, the size of any effective noise barrier would make this a typically unfeasible solution.

However, the placement of transmission lines underground will eliminate ACN impacts and may form a reasonable and/or feasible solution in some locations.

2.3.4 AT-RECEIVER MITIGATION

When all other types of mitigation have been deemed unfeasible or found to be insufficient at reducing noise impacts at nearby noise-receivers below local noise impact regulation, mitigation at the receiver would typically need to be considered. This would usually take the form of at-property treatment of building facades through the installation of acoustic treatments such as double glazed windows, upgrade of façade and roof construction type, under floor treatment, solid core doors, fresh air ventilation paths, etc.

Difficulties with this approach include that noise from coronal arcing events is typically dominant in low frequency ranges where façade treatments are less effective. Additionally, this method does not provide a reduction in externally noise levels and its effectiveness is reduced where doors and or windows are open. For buildings with light-weight facades, measures short of faced replacement may not adequately reduce the internal noise impacts due to the low frequency noise component.

As such, the most effective mitigation methods against coronal noise are likely to usually be those that involve source mitigation, rather than those targeting the receiver.

2.4 RADIO FREQUENCY INTERFERENCE

Electromagnetic fields produced by overhead transmission lines, also known as Radio Frequency Interference (RFI) are emitted in a spectrum of frequencies, including in frequency ranges used for television and radio communications. Australian Standard AS2344 defines RFI limits in the 0.15 - 3000MHz frequency band for urban and non-urban areas for the protection of TV and radio reception against subjective annoyance caused by transmission line RFI.

The limits applicable to NSW are summarised in Table 2.4 below.

Table 2.4 RFI limits applicable to NSW areas as per AS2344

FREQUENCY (MHz)	MAGNETIC FIELD STRENGTH (dBµA/m)		ELECTRIC FIELD STRENGTH (dBµV/m)
	Urban Areas [1]	All Other Areas	
0.15-0.3	-1.5	-15.5 to -28.5	n/a
0.3-0.5	-15.5	-15.5	n/a
0.5-1.7	-1.5	-15.5	n/a
1.7-3	-15.5	-15.5	n/a
3-30[2]	-15.5 to -28.5	-15.5 to -28.5	n/a
30-230	n/a	n/a	30
230-1000	n/a	n/a	37
1000-3000	n/a	n/a	60

(1) Areas where a population of greater than 2000 people are serviced by local broadcast stations

(2) Limit decreases linearly with the logarithm of the frequency range

Compliance with the limits must be verified by testing in accordance with CISPR TR 18-2, with measured levels at appropriate locations at the edge of the line easement required to comply with RFI limits with 80% confidence for a minimum of 80% of the time.

Typically, a reduction in the SWL or frequency of ACN is linked to a comparable reduction in RFI effects.

3 OTHER RELEVANT FACTORS

3.1 NSW ASSESSMENT LEGISLATION

Assessment of ACN in NSW is guided by the Noise Policy for Industry (NPfI). The assessment procedure outlines two components:

- Controlling intrusive noise impacts in the short-term for residences
- Maintaining noise level amenity for land uses for residences and other land uses.

In assessing the noise impact of ACN, both components must be considered for residential receivers. As ACN may occur at any time through the 24-hour day period, the night-time criteria are typically the controlling time criteria.

3.1.1 PROJECT INTRUSIVENESS NOISE LEVEL

The project intrusiveness noise level for residential receivers prescribed in the NSW NPfI is summarised as:

$$L_{eq\ (15\ minute)} \leq Rating\ Background\ Level\ (L_{90}) + 5\ dBA$$

The project intrusiveness noise levels are typically determined through noise monitoring, however in rural areas are commonly limited by prescribed minimum Rating Background Levels (RBLs) detailed within the NPfI. Where the measured RBL is less than 30 dBA for the evening and night periods, it is set to 30 dBA. When it is found to be less than 35 dBA for the day period, it is set to 35 dBA. The NPfI also recommends that evening criteria is set no higher than the day criteria and the night criteria should not be set any higher than the evening criteria.

3.1.2 PROJECT AMENITY NOISE LEVELS

To limit continuing increases in ambient noise levels (i.e. background noise level creep), the maximum amenity noise level within an area from industrial noise sources should not normally exceed the amenity noise levels prescribed in the NSW NPfI.

The recommended amenity noise levels represent the objective for total industrial noise from all sources at a receiver location, whereas the project amenity noise level represents the objective for noise from a single industrial development at a receiver location, defined as the recommended noise levels listed below (Table 2.2 of NPI) minus 5 dBA.

The amenity criteria applicable to residential receivers is based on their indicative land use designation and are presented in Table 3.1.

Table 3.1 Residential project amenity noise levels

TYPE OF RECEIVER	RECOMMENDED AMENITY NOISE LEVEL (ANL) dB $L_{AEQ,PERIOD}$[1]		
	Day	**Evening**	**Night**
Residential – Rural	50	45	40
Residential – Suburban	55	45	40
Residential – Urban	60	50	45

(1) Day: the period from 7 am to 6 pm Monday to Saturday; or 8 am to 6 pm on Sundays and public holidays; evening: the period from 6 pm to 10 pm; night: the remaining periods.

3.1.3 PROJECT NOISE TRIGGER LEVELS

In assessing the operational noise impact of the project on surrounding residential receivers, both the intrusiveness and amenity criterion must be considered. In most cases, only one criterion will become the limiting criterion and form the project noise trigger levels (PNTL) for the industrial source under assessment.

To standardise the time periods for the intrusiveness and amenity noise levels, the following conversion between $L_{eq\ period}$ and $L_{Aeq\ 15\ min}$ is applied (as per Section 2.2 of the NSW NPfI):

$$L_{Aeq(15\ min)} = L_{Aeq(period)} + 3\ dB$$

In accordance with Section 3.1 of the NSW NPfI, all project noise trigger levels and limits are expressed as $L_{eq(15min)}$, unless otherwise expressed.

3.1.4 MODIFYING FACTORS FOR ANNOYING CHARACTERISTICS

Certain noise characteristics have a higher potential to cause annoyance, generally requiring additional considerations during assessment. Tonality, low frequency emphasis may arise because of ACN. These characteristics are generally considered to be attention-drawing noise characteristics and can cause greater disturbance. For tonal noise and low frequency noise, as per NPfI modifying correction factor is 5 dB to 10 dB maximum [4].

3.1.5 MAXIMUM NOISE LEVEL ASSESSMENT AND SLEEP DISTURBANCE

The potential for operational noise impacts resulting from transient maximum noise level events and sleep disturbance during the night-time period is detailed in the NPfI. Maximum noise impacts may cause awakening events, while maintained elevated levels of noise may reduce the quality of sleep.

As ACN is typically characterised by a steady medium term noise source, the assessment of short term L_{Amax} maximum levels is not relevant to this study. The assessment of potential sleep disturbance impacts is based on the consideration of $L_{Aeq(15\ minute)}$ noise levels, however under the NpFI methodology, these criteria are always equal to or less than the calculated PNTLs and as such the consideration of sleep disturbance is not considered further in this study.

3.1.6 ADVERSE METEOROLOGICAL FACTORS

The NSW NPfI requires the consideration of adverse meteorological conditions where they occur more than 30% of the time. However, it is stated in Appendix C that this is applicable to meteorological conditions affecting the propagation of noise and not the occurrence of noise. As such, assessment of transmission line noise impacts would typically be required during the loudest 15-minute period, which would typically be during conditions conducive to the production of ACN.

It is also noted for future consideration that in NSW, these conditions are typically during rainfall where elevated levels of background noise may mask the extent of ACN or under conditions of fog, where the transmission of noise is substantially reduced. However, the NPfI makes no allowance for these considerations.

3.2 METEOROLOGICAL FACTORS WITHIN NSW

NSW contains a diverse range of climatic regions, covering a wide range of weather patterns and conditions that are primarily influenced by the geographical landscape, altitude / altitude, and distance from the coast. The following major climatic regions are considered in this study:

3.2.1 COASTAL REGIONS

Coastal regions of NSW experience a temperate climate influenced by the ocean and includes the state largest population centres. Rainfall is relatively evenly distributed throughout the year, with around 100-150 days of rainfall annually. Misty conditions are common, especially during the cooler months, as moist air from the ocean interacts with the land, this creates a mild and often foggy atmosphere along the coast.

3.2.2 NORTHERN AND SOUTHERN TABLELANDS

Located in the central northern areas of NSW, the Northern Tablelands region experiences a more variable climate. Rainfall tends to be higher compared to the coastal areas, with around 150-200 days of rainfall per year. Misty conditions are frequent, particularly in elevated areas where moisture-laden air can form clouds and fog.

3.2.3 CENTRAL WEST

In the central parts of NSW, the climate is typically characterized by semi-arid conditions. Rainfall is lower compared to coastal and mountainous areas, with approximately 50-100 days of rainfall annually. Misty conditions are less common due to the lower moisture content in the air, although fog can occasionally form in valleys and low-lying areas, especially during winter mornings. Clear skies and sunny days are typical.

3.2.4 WESTERN NSW

Further west, the Outback region of NSW experiences a desert climate with hot, dry summers and cool winters. Rainfall is scarce, with less than 50 days of rainfall per year on average. Misty conditions are rare in this arid landscape, as the low humidity levels inhibit the formation of fog. Instead, clear skies dominate throughout much of the year.

3.2.5 SNOWY MOUNTAINS

The Snowy Mountains region is defined by an alpine climate. Snowfall is common during the winter months and rainfall is moderate, with around 100-150 days of precipitation annually. Misty conditions are prevalent, especially around the higher peaks, where moisture-laden air can create thick fog and low visibility, particularly in the mornings.

It is noted that the Australian Bureau of Meteorology (BoM) does not typically track the number of misty days at its weather stations and as such this parameter will be difficult to confirm at most assessment sites.

4 DISCUSSION

The Australian power transmission network is widespread and often remote infrastructure necessitates the construction of HV transmission lines across vast distances, encompassing areas characterised by diverse climatic conditions. The propagation of such ACN may pose a significant concern for residents, this may be increased in rural or semi-rural locales where ambient noise levels are typically lower. Residents living near transmission lines may report the noise as a nuisance, leading to complaints and demands for mitigation measures. Corona discharge induced noise typically becomes a design concern for transmission lines at 345 kV and above and is less noticeable from lines that are operated at lower voltages.

The existing literature indicates that ACN is function of the voltage of the line, the diameter of the conductors, the locations of the conductors in relation to each other, the elevation of the line above sea level, the condition of the conductors and hardware, and the local weather. Specifically, higher elevation, wet conditions (mist, fog), and rainy days can elevate the ACN level, potentially exceeding the noise criteria in the local area.

ACN produces a wideband sound with significant high frequency content, as well as very narrowband tones, with the 100 Hz tone being the most prominent. Noise sources with narrowband tonality may be annoying to people, and to account for this, the noise limits set by the NSW NPfI are reduced by 5 dB if the tones are significant.

There are several existing empirical and semi-empirical methods available for predicting ACN for transmission lines. Most of these methods typically only predict a wideband sound pressure level, while a small number consider low frequency or 100 Hz tonality. These methods are based on local meteorological databases from the locality where they were developed, which may limit their applicability for general use in Australia (however this will be further investigated in future phases of this project). The BPA and EPRI methods are commonly used to calculate ACN levels in various software packages, such as SESEnviroPlus and PDCAD FACE. Some studies have indicated that using multiple empirical methods and cross-validating with field data leads to more reliable predictions of ACN in transmission lines.

Extensive research has been conducted about calculating ACN and finding suitable methods. Some studies have developed specific acoustic power formulas for HV-DC and HV-AC and UHV AC lines. These formulas have been verified with long-term statistical data and have shown improved accuracy compared to traditional methods. To our knowledge, there are currently no UHV transmission lines (above 800 kV) in Australia. Therefore, methods focusing on UHV transmission lines may not be applicable in the Australian context at the moment.

In cases where the ACN level is expected to exceed recommended or mandatory noise impact criteria, it is necessary to mitigate noise impacts. One effective way to do this is by relocating transmission lines however, this may not always be a reasonable or feasible solution. The next step in mitigation would involve at-source measures, which could include treating the surface of the conductors (e.g., hydrophilic treatment, superhydrophobic coating) and using grading rings. These measures are sometimes challenging to implement due to the complex relationship between engineering constraints, conductor surfaces and weather conditions. The placement of transmission lines underground will eliminate ACN impacts and may form a reasonable and/or feasible solution in some locations. Where at property treatment is required, management of the low frequency tones, which are less attenuated by houses' windows, doors, and lightweight walls, makes it more complex to address noise issues.

5 RECOMMENDATIONS

Review of the findings outlined within the document indicate that development of a method for predicting the Audible Coronal Noise (ACN) of HV transmission lines is likely not required as numerous existing algorithms already exist. Any final methodology should be incorporate a consideration of potential low frequency and tonal characteristics, predict noise levels under neutral and adverse weather conditions at the transmission line location (in this case, in NSW, Australia), and implement a user-friendly interface to enable simple data input and processing.

However, it appears that a single calculation method has not yet been established which provides all these features and any solution may require a combination of methodologies.

As such, the following recommendation for future objectives are provided for discussion with Transgrid:

- Investigate specific inputs and outputs associated with each prediction method for their suitability to Australian, and specific NSW assessments. This will require Transgrid to provide WSP with typical transmission lines parameters relevant to this study, likely including transmission lines, conductor, insulation, and line hardware, but specifically referenced within AS/NZS 7000 Overhead line design.
- It is proposed that both the BPA and EPRI methods are widely used however have limitations when applied to generalised meteorological conditions. It might be beneficial to adapt both methods and validate them using field data. It is recommended that their compatibility and the viability of this solution is further investigated. Specifically, the format of outputs, the consideration of meteorological conditions and the ability to calculate tonality and low frequency components should be reviewed further.
- The SESEnviroPLus software has been used in different cases, but also has limitations in calculating tonality and low frequency noise. This method should also be investigated further.
- It is noted that one solution to the lack of 1/3 octave results (and therefore the ability to consider tonality and low frequency noise components) could be to calculate tonality using a separate method or consider using another promising software package such as PSCAD FACE. Alternatively, where it can be shown that a low frequency and/or tonal noise is common to all transmission line configurations, a 'worst case' approach could be taken whereby tonal penalties are routinely applied. This will be further investigated in subsequent stages. As such, a consideration of these two options should be further investigated in any subsequent investigation.
- Any implications of increase noise masking ACN or reduced noise propagation under conditions generating ACN should be further investigated. It is noted that under the existing NPfI, no allowance for a relaxing of criteria or assessment requirements for meteorological conditions is provided and some change to the existing guidelines may be required to adequately consider these implications.

Following the formation of agreed pathways to address the factors outlined above, it is proposed that a simple spreadsheet-based methodology will be developed to calculate the SWL of ACN in a format suitable for consideration in NSW environmental assessments. Validation of the developed SWL calculation method will be conducted with an unattended noise monitoring program.

As such, the preliminary scope of works outlined in Section 1.3 has been refined and minor changes made:

- **Literature review (Task 1a)**
- Workshop stakeholder meeting - Transgrid (Task 1b)
- Meeting and agreement with EPA/DPHI (Task 1c)
- Further study and provision of an initial investigative report identifying a suitable prediction method (Task 2)
- Validation monitoring program (Task 3)
- Summary report of findings (Task 4)

These recommendations will be discussed and agreed with Transgrid before finalisation of the next study phase.

6 LIMITATIONS

This Report is provided by WSP Australia Pty Limited (WSP) for Transgrid (Client) in response to specific instructions from the Client and in accordance with WSP's proposal agreement with the Client (Agreement).

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