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REVIEW OF THE DESIGN AND CONDITION MONITORING OF OVERHEAD POWER DISTRIBUTION CONDUCTORS

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Abstract. Bushfires, also known as wildfires in some parts of the world, is a major hazard with significant risks to communities and the environment. Such fires can initiate from a number of sources including lightning. However, one of the possibilities for initiating bushfires is faults in the power system. Faults in conductors can happen overtime and monitoring is essential for effective maintenance and avoiding unnecessary power failures. Simultaneously, assessing conductor reliability is critical for powerline asset management. This paper comprehensively reviews conductor design and monitoring in the distribution network. Various conductor types and applications are described using population statistics from the Australian power distribution network. Furthermore, the design approach in the Australian Standard is briefly explained and further design methodologies are assessed, emphasizing the progress of innovative approaches. Additionally, potential conductor failure modes in Australia's distribution network are identified. The paper also outlines different condition assessment methods and explores their advancement. Finally, possible models for evaluating conductor reliability are examined, underscoring their benefits in accounting for weather-induced impacts.

Keywords: wind load, design aspects, deterioration, failure identification, reliability, current practice.

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1. Introduction

The electricity distribution network carries electric power over the last distance from transformers to consumers, i.e., households, commercial buildings, industries, etc. According to the Australian Energy Regulator [AER], the power distribution network serves approximately 10.7 million individuals comprising both residential and non-residential users over a regular asset base of $82.6 billion (AER, 2022). The overhead power distribution network is the most common network type over thousands of square kilometers and consists of several essential components, including conductors, poles, cross arms, insulators, transformers, and substations.

Australia is a country which has experience with large-scale bushfire events. History reveals that these bushfires often occur due to high temperatures coupled with dry periods (Bandara et al., 2023). In the southern portions of Australia, the summer months are often hot and dry, which, combined with a high fuel load (dry vegetation), provides a very high bushfire risk. In contrast, faults in the power distribution components or infrastructures can initiate wildfires specially during elevated fire risk situations (Kandanaarachchi et al., 2020). The main causes are failure of aged components, vegetation-related problems, electrical apparatus malfunctioning, pole and cross-arm failures, and line failures (Jazebi et al., 2019). Therefore, it is crucial to have appropriate design and employ adequate condition monitoring, and surveillance of components in the power distribution network.

The structural design of power transmission components is crucial to withstand the various loads they experience. There are several national and international design codes available. For example, the AS/NZS 7000:2016 standard (Standards Australia & Standards New Zealand, 2016) for overhead line design provides relevant design parameters that consider the expected working life of the system. However, incidents of failures in power infrastructure can still be found.

The State of the Infrastructure Report 2020/2021, published by Western Power Company, indicates that there were 1,169 instances of unassisted phase conductor failures in distribution lines within five years from July 2016 to June 2021 (Western Power, 2021). Western Power owns a distribution network with a circuit length of approximately 94,000 km. Another company, Tasnetwork, that owns over 20,000 circuit kilometers of overhead network reported some 450 conductor failures during the period from 2001 to 2014 (Tasmanian Networks, 2015). Further, the failure rate of the conductors also increased with time (Naranpanawe et al., 2018). These electric overhead lines are constructed over different types of terrain and exposed to varying weather conditions. Continuous exposure to adverse weather conditions and mechanical stresses induced by wind can cause deterioration of components (Aggarwal et al., 2000). This degradation process may initiate cracking, corrosion, and a reduction in the capacity of the conductors, eventually leading to their ultimate failure. Existing literature suggests that frequent power outages are often attributed to ageing assets, with a significant number of interruptions occurring in the distribution power networks.

Various methods have been proposed and employed to monitor the condition of overhead conductors to reduce failures. Initially, conventional visual inspection methods such as ground patrol and helicopter routines were commonly used before the advent of advanced techniques involving unmanned aerial vehicles (UAVs) and advanced mobile robots. With the advancement of technology, non-destructive testing techniques including the ultrasonic pulse velocity (UPV) method, image processing techniques, stress wave analysis, and vibration-based techniques have been proposed and utilized (Electric Power Research Institute, 2006; Rajeev et al., 2022; Naranpanawe et al., 2018). Power distribution companies utilize the results obtained from the condition assessment of conductors to effectively maintain and manage the power network. As the network is constantly exposed to various environmental conditions and potential causes of failure a risk assessment process becomes crucial to ensure the continued reliability and performance of the network.

The concept of reliability evaluation in power systems was emphasised by Billinton and Allan (1984). In the power network hierarchy, the distribution infrastructure is categorized as hierarchical level III, which poses a challenge for evaluation due to its involvement in all functional zones: generation, transmission, and distribution. Mathematical simulation models such as the direct analytical method and the Monte Carlo method were proposed for the reliability evaluation of distribution infrastructure. It is recognised that establishing a risk assessment process within power distribution companies is crucial to identify the damage level of conductors and reduce the occurrence of sudden failures in the network. However, the lack of a complete data system to make a solid decision based on effective health monitoring procedures is a disadvantage.

This paper presents a comprehensive review of overhead power distribution conductors. In respective sections, it covers conductor types, design aspects, failure modes, condition assessment techniques, and reliability assessment methods.

2. Type of conductors

A conductor refers to a wire or a combination of wires that carries an electric current, without insulation between them. In the context of overhead power networks, conductors can be categorized as bare conductors or aerial bundled conductors. For electrical aerial bundled conductors used in distribution networks with working voltages up to and including 1.2 kV, AS/NZS 3560.1:2000 (Standards Australia & Standards New Zealand, 2000) can be used which covers aluminium and copper conductors. Further to that, AS 1531-1991 (aluminium and aluminium alloy conductors) (Standards Australia, 1991b), AS 1222.1-1992 (Steel galvanized conductors) (Standards Australia, 1992a), AS 1222.2-1992 (aluminium clad steel conductors) (Standards Australia, 1992b), AS 3607-1989 (aluminium conductor Steel reinforced) (Standards Australia, 1989), and AS 1746-1991 (copper conductors) (Standards Australia, 1991a) are available for different types of applications. These standards provide detailed specifications regarding construction type, rib details, voltage designation, direction of lay, testing requirements, delivery process, and other relevant information.

The selection of a specific conductor material type, such as steel or copper conductors depends on various factors including environmental, electrical, mechanical, and economic considerations (Evoenergy, 2020). The most used bare conductor strands in the Australian electrical distribution network include:

- All Aluminium Conductors (AAC);
- All Aluminium Alloy Conductors (AAAC);
- Steel (ST);
- Aluminium Clad Steel (ACS);
- Aluminium Conductor Steel Reinforced (ACSR);
- Copper Conductor (CU).

2.1. ALL aluminium and aluminium alloy conductors (AAC & AAAC)

AAC/1350, AAAC/1120, and AAAC/6201A are manufactured using alloy designations of 1120 and 6201A, respectively (Standards Australia, 1991b). AAC/1350 conductors are constructed using high-purity aluminium (designation 1350) and consist of multiple stranded wires without any steel reinforcement. To differentiate them from other conductors, blue-coloured threads are incorporated within the strands of AAAC/1120 conductors, and AAAC/6201A conductors are identified by incorporating red-coloured threads within the strands. The strength and corrosion protection is higher in AAAC conductors (Reinke et al., 2020).

These conductors are known for their lightweight and excellent conductivity, making them suitable for various overhead power distribution applications in urban areas (Sun et al., 2022). AAC strands of Libra (7/3.0 – seven strands aluminium of 3.0 mm diameter), Mars (7/3.75 – 7 strands of aluminium of 3.75 mm dia.), Moon (7/4.75 – 7 strands of aluminium of 4.75 mm dia.), and Pluto (19/3.75 – 19 strands of aluminium of 3.75 mm dia.) are commonly used in the Australian distribution network (Naranpanawe et al., 2018). Different stranding configurations are available for AAC/AAAC strands according to the number of wires in the conductor as shown in Figure 1.

2.2. Steel and aluminium clad steel conductors (SC/GZ & SC/AC)

Part I of the AS 1222-1992 specifies the requirements for galvanized steel conductors (SC/GZ) that have the advantage of higher ultimate tensile stress compared to aluminium, resulting in higher breaking loads for both types of steel conductors (Standards Australia, 1992a). The steel wires are produced through a hot dip galvanizing process. Aluminium clad steel conductor (SC/AC) consists of steel rod and aluminium cladding. The aluminium coating contributes to the overall conductivity of the conductor while utilizing the high strength and durability of the steel core. This combination allows for enhanced mechanical properties and electrical performance. In aluminium clad steel conductors (SC/AC), the lowest possible thickness of the aluminium cover is typically 10% of the radius of the steel strand. This translates to roughly 25% of the cross-sectional area (Naranpanawe et al., 2018).

2.3. Aluminium conductor steel reinforced (ACSR)

Australian Standard 3607-1989 (Standards Australia, 1989) specifies nine types of aluminium and aluminium alloy conductors that are reinforced with steel. This matrix includes the combination of aluminium or aluminium alloy conductors (Grade 1350, 1120, and 6201A) with either zinc-coated (GZ), aluminium coated (AZ), or aluminium clad (AC) steel wires. The inner cores of these conductors can be made of either aluminium-coated (aluminized) steel or aluminium-clad steel, and the reinforcing wires may be positioned in the central area. Aluminium provides high conductivity, lightweight, cost-effectiveness, and corrosion protection, while steel wires contribute strength to support the conductor as overhead lines and reduce deflection (Farzaneh & Savadjiev, 2006; Than, 2022). As per the standard, Apple (6/1/3.0 – 6 aluminium strands and 1 steel strand, each 3.0 mm in dia.), Banana (6/1/3.75 – 6 aluminium strands and 1 steel strand, each 3.75 mm in dia.), Cherry (6/4.75+7/1.6 – 6 aluminium strands of 4.75 mm in dia. and 7 steel strands of 1.6 mm in dia.), Almond (6/1/2.5 – 6 aluminium strands and 1 steel strand, each 2.5 mm in dia.), and Raisin (3/4/2.5 – 4 aluminium strands and 4 steel strands, each 3.0 mm in dia.) are few ACSR/GZ (Zn coated) conductors widely used on distribution lines. The combined ratios of aluminium wires and steel wires are properly defined in the standard and some of the configurations are shown in Figure 2.

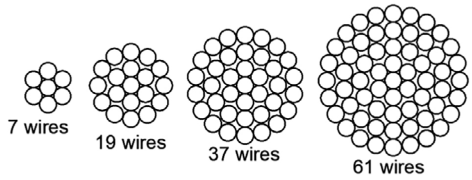

Figure 1. Different stranding configurations for AAC/AAAC strands (Zainuddin et al., 2020)

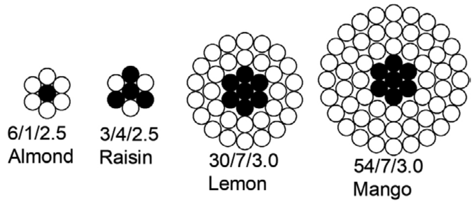

Figure 2. Different stranding configurations for ACSR/GZ strands (Zainuddin et al., 2020)

2.4. Copper conductors (CU)

These conductors are made from hard-drawn copper wires using a high conductivity copper alloy, typically 110A or an equivalent material as per Australian Standard AS 1746-1991 (Standards Australia, 1991). Copper is chosen for its excellent electrical conductivity properties, as it is a highly conductive non-precious metal. Additionally, copper exhibits good thermal conductivity. In the Australian network, copper conductors were commonly installed in the 1960s, and among the most frequently used copper conductor configurations are 7/.064 (seven copper strands of 0.064 inches in dia.), 7/.080 (seven copper strands of 0.080 inches in dia.), and 7/.104 (seven copper strands of 0.104 inches in dia.) (Naranpanawe et al., 2018).

2.5. Aerial bundled conductors (ABC)

Aerial bundled conductors used in the distribution network are typically constructed using Aluminium 1350. These conductors are insulated with X-90 (90 °C maximum continuous temperature rating material) cross-linked polythene material, providing electrical insulation. The manufacturing process follows the guidelines set in AS/NZS 3560.1:2000 (Standards Australia & Standards New Zealand, 2000), which specifies the standard requirements for these conductors. Aerial bundled conductors can have 2 to 4 cores and are designed for working voltages up to and including 1.2 kV.

2.6. Covered conductors (CCT)

Covered conductors are utilized in the Australian distribution network for working voltages ranging from 6.35/11 (12) kV to 19/33 (36) kV. The relevant standard governing this conductor type is AS/NZS 3675:2002, which outlines the properties related to the strands and their covers (Standards Australia & Standards New Zealand, 2002).

The wire strands used in these conductors are made of Aluminium alloy 1120 and 6201, which correspond to AAAC/1120 and AAAC/6201 wire strands specified in Australian Standard 1531-1991 with some preference given to AAAC/1120 (Standards Australia, 1991b). However, the conductors themselves are covered with ultraviolet (UV) stabilized X-90 insulation material or X-90 insulation material with an outer layer of high-density polyethylene (HDPE). The application of these conductors offers improved performance in polluted areas and allows for reduced clearance between phases and trees. The available conductor sizes for AAAC/1120 conductor type are 7/2.75, 7/3.75, 7/4.75, and 19/3.50 which provide flexibility for various distribution applications.

2.7. Conductor material properties and utilisation

Table 1 provides a summary of the material properties of AAC, AAAC, ST, ACSR, and CU conductors, as outlined in the relevant standards referenced earlier. In the case of ACSR conductors, which combine all-aluminium or aluminium alloy wires with steel wires, the properties are comparable to those of individual strands. It is worth noting that the properties of a single wire in aerial bundled conductors (ABC) align with those of AAC/1350, as it is made from aluminium grade 1350. Similarly, the properties of single wire strands in CCT correspond to AAAC/1120 and AAAC/6201.

A significant aspect to consider is the modulus of elasticity, which varies depending on the number of strands in the conductor. A higher number of strands results in a reduction in the modulus of elasticity. Additionally, an increase in the number of strands leads to a decrease in the direct current resistance of the conductor (Standards Australia, 1991b). These properties play a crucial role in determining the performance and behaviour of the conductors in electrical applications.

Naranpanawe et al. (2018) published population data on different types of conductors in overhead distribution networks all over Australia. Statistical data were collected from twelve power distribution companies. The data was categorized based on the voltage levels of the in-service power distribution lines, with lines classified as either low voltage (less than 1 kV) or high voltage (higher than 1 kV) (Naranpanawe et al., 2018). Figure 3 provides a summary of the conductor population in the Australian network, based on collected data in 2018. The conductor population is measured in circuit km. Figure 4 provides the percentage availability of different conductor types.

Based on Figure 3, the data clearly indicates that aluminium and copper conductors are the most used types for low-voltage applications in the Australian power network. However, for distribution lines with voltages exceeding 1kV, steel conductors are the predominant choice, especially in rural areas. Apart from steel conductors, aluminium

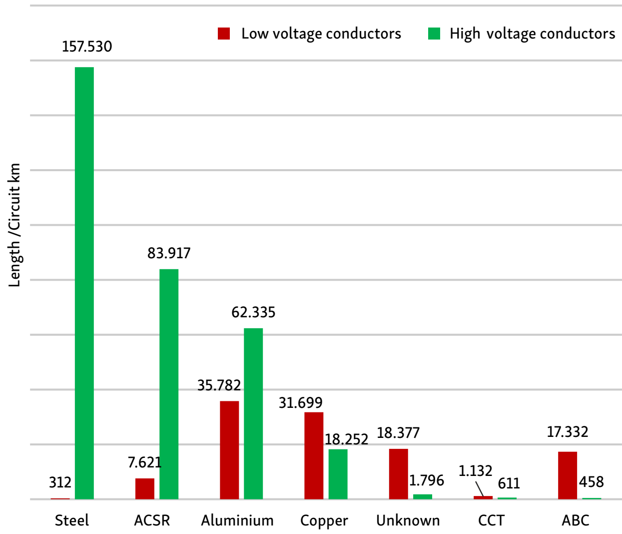

Figure 3. Population of different conductor types (Naranpanawe et al., 2018)

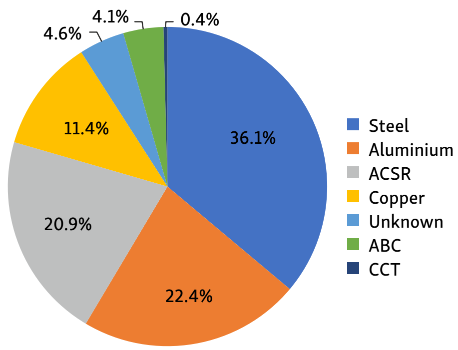

Figure 4. Percentage availability of different conductor types (Naranpanawe et al., 2018)

Table 1. Material properties of a single strand (Standards Australia, 1991b)

Conductor	Density @ 20°C (kg/m^3)	Resistivity @ 20°C (μΩ.m)	Modulus of Elasticity* (GPa)	Constant Mass Temperature Coefficient for Resistance @ 20°C (per °C)	Coefficient of Linear Expansion (per °C)
AAC/1350	2.7×10^3	0.0283	68	0.00403	23.0×10^{-6}
AAAC/1120	2.7×10^3	0.0293	68	0.00390	23.0×10^{-6}
AAAC/6201	2.7×10^3	0.0328	68	0.00360	23.0×10^{-6}
SC/GZ	7.8×10^3	0.19	193	0.00440	11.5×10^{-6}
SC/AC	6.59×10^3	0.085	162	0.0036	12.9×10^{-6}
SC/AZ*	7.6×10^3	0.15	193	0.0044	11.5×10^{-6}
CU	8.89×10^3	0.01777	124	0.00381	17×10^{-6}

and ACSR conductors also make a significant contribution to high-voltage power distribution. The data presented in Figure 4 indicates that steel conductors make up more than 36% of the total conductors in the distribution network. Aluminium conductors account for approximately 22.4%, ACSR conductors represent around 20.9%, and copper conductors contribute to approximately 11.4% of the conductors in service. These figures provide insights into the distribution and prevalence of different conductor types within the Australian power distribution network.

3. Possible loads and design methods

3.1. Loads on conductors

Conductors play a crucial role in carrying electrical current, while insulators ensure a safe distance is maintained between the charged conductors. The conductors must bear externally or internally induced static and dynamic loads without exceeding tension limits. Insulators are normally connected to cross-arms, which provide support for the conductors. Appropriate connecting hardware on the cross-arms transfers the load from the insulators to utility poles, effectively transferring the accumulated load from the power network to the ground. In addition to the self-weight, the overhead lines are subject to actions from wind and rainfall and depending on the location to snowfall and icy conditions.

3.1.1. Self-weight of conductor

The self-weight of a conductor in a powerline depends on several factors such as the type of conductor, the span of the powerline, and the sag of the conductor. Due to the constant self-weight acting along the entire length of the conductor, an initial tension is applied during installation to control the sag between supports. However, it is important to note that the tension in the conductor during service life would vary due to wind action, temperature changes, and the formation of ice and snow. These external influences can cause fluctuations in the tension and subsequently impact the sag of the conductor (Albizu et al., 2011; Xie et al., 2019).

3.1.2. Wind load

Wind velocities display variations throughout the year, exhibiting distinct seasonal patterns (Eso et al., 2021). Additionally, the direction of the wind also varies, indicating changes in both the magnitude and orientation of the wind. The Bureau of Meteorology (BOM) maintains both close to surface and upper air wind data sets (Jakob, 2010). Figure 5 depicts the curves for mean wind velocity (over 1 minute) and maximum wind gust velocity (over 1 minute) distribution patterns which are developed using wind data collected from the BOM for one location "Point Cook Raaf" in the year 2022.

The above graphs effectively illustrate the frequency distribution of wind velocities throughout the year 2022. However, please note that the velocities are not categorized based on cardinal directions. The graphs clearly depict the wide range of mean wind velocities (averaged over 1 minute) observed, varying from 0 to 24.3 m/s. Similarly, the occurrence of maximum wind velocities (within 1 minute) spans from 0 to 41.7 m/s.

One of the key considerations related to wind loading is induced vibration. When wind flows over a cylindrical object, like a conductor, it can lead to the generation of eddies or vortices on both sides of the object facing away from the wind as shown in Figure 7. These eddies develop alternately on the upper and lower surfaces of the conductor, resulting in alternating negative pressure patterns. Consequently, the conductor experiences periodic upward and downward forces. This phenomenon is referred to as aeolian vibration, which specifically denotes the vibration caused by the interaction between the wind and the conductor (Whapham, 2012).

The fluctuating nature of wind forces on a conductor makes it challenging to predict with absolute precision. However, standards and guidelines have been established to provide direction and recommendations for designing conductors in such conditions. On the other hand, when wind flows over a cylindrical object, like an electric conductor, it can lead to the generation of eddies or vortices on the side of the object facing away from the wind. Figure 6 visually demonstrates the formation of these eddies around a conductor due to wind flow. These eddies develop alternately on the upper and lower surfaces of the conductor, resulting in alternating pressure patterns. Consequently, the conductor experiences periodic upward and downward forces. This phenomenon is referred to as

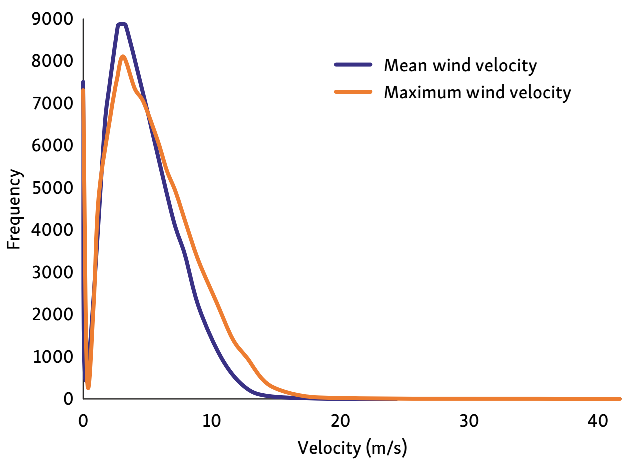

Figure 5. Mean wind velocity distribution curve

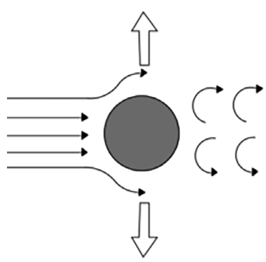

Figure 6. Formation of eddies in wind flow

aeolian vibration, which specifically denotes the vibration caused by the interaction between the wind and the conductor (Whapham, 2012).

When a flow exceeds the limit velocity for the laminar flow, it creates vortices/eddies by transferring into a turbulent behavior. Generally, the frequency of aeolian vibration is between 3 and 150 Hz and the amplitude is nearly 1–2 times the Conductor diameter (Li et al., 2017). The expected range of aeolian vibration majorly depends on the tension of the conductor, the span of the conductor, and the mechanical impedance of the conductor. Further, surrounding conditions such as terrain and wind conditions also influence the vibration (Whapham, 2012). Self-damping of the conductor is related to inter-strand friction. The increased tension exacerbates the vibration due to the reduction of the self-damping of the conductor (Guerard, 2011).

Current design standards cover the different aspects of wind loading on conductors and provide guidance for both serviceability and ultimate wind conditions.

3.1.3. Snow and ice loading

In regions where wet snow and freezing rain are common, electric overhead lines must be designed to withstand the weight and accumulation of icy coatings. The adhesion of wet snow to powerlines poses challenges, particularly when combined with strong winds, as it can result in the sudden accumulation of a large mass (Farzaneh & Chisholm, 2022). Figure 7 provides a comparison of this accretion process of wet snow around a conductor under low and high wind velocities. The distinction between low and high wind velocities is defined as wind velocity below 10 m/s and above 10 m/s, respectively (Rossi et al., 2020).

Once the accumulation of wet snow has fully formed around the wire, as depicted in Figure 7, the densification factor becomes a significant factor that contributes to the packing of the snow accretion. The wind-induced drag force acting on the wire is amplified due to the larger surface area presented by the increased diameter. The wind-induced drag force is counterbalanced by the tension in the conductor (Farzaneh & Chisholm, 2022).

3.1.4. Loading due to temperature variation

Extreme heat and high temperatures in specific locations present a considerable obstacle for power lines due to the thermal expansion of their construction materials. Prolonged exposure to elevated temperatures can cause the materials used in power lines to expand, resulting

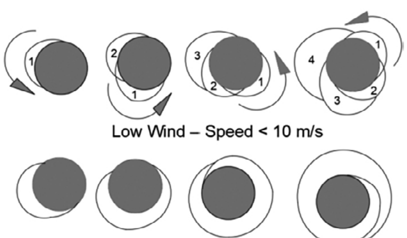

Figure 7. Accumulation of wet snow around a conductor (Wakahama et al., 1977)

in changes in their dimensions. This expansion, in turn, leads to an increase in sag, which helps reduce mechanical stress on the lines. However, it is important to note that as the temperature decreases, the opposite effect occurs in power lines (Kanálik et al., 2019). When the sag reaches the maximum permissible limit, power line crashes might occur (Alawar et al., 2005; Guo et al., 2021).

3.1.5. Forces due to short-circuit currents

In a flexible conductor system, the occurrence of a short circuit can have significant implications for the conductors involved. A short circuit happens when an unintended low-resistance pathway is formed between two points of differing electrical potential, causing a sudden surge of electrical current to flow through the system. This surge of current, which can be of extremely high magnitude, generates opposing electromagnetic forces that act in opposite directions within the conductors (Khan, 2020). These opposing forces result in tension within the conductor, causing it to experience mechanical stress and deformation. The magnitude of these tensile forces depends on several factors, including the magnitude of the fault current, the impedance of the electrical system, and the mechanical properties of the conductor itself (Yao et al., 2020).

3.1.6. Construction and maintenance loads

During the installation of the network, conductors may experience loads due to the process of lowering them, hanging equipment or accessories, and unexpected pulling forces. These loads can potentially affect the integrity and performance of the conductors. Furthermore, conductor maintenance load refers to the periodic maintenance activities performed on the power line to ensure their reliability and optimal performance (Stephen & Iglesias, 2023). Conductor maintenance load includes a range of activities such as periodic inspections, testing, repairs, and replacements as needed.

3.1.7. Other loads

Other loads on conductors can occur due to the falling of trees, branches, adjacent structures, and animals onto overhead lines (Wang, 2016). However, these loads are difficult to estimate as they are unpredictable. Some of the risks of such loads are minimised via maintenance such as period removal of overreaching vegetation from the vicinity of powerlines.

3.2. Design methods

3.2.1. Code of practices

There are many international standards that define the various loading and resistance models for various types of materials and structures. These include Australian Standards, ASCE (American Society of Civil Engineers), IEC (International Electrotechnical Commission), and CENELEC (European Committee for Electrotechnical Standardization) which cover the design, installation, operation, and maintenance of electrical power infrastructure.

In the Australian context, power distribution networks are designed in accordance with AS/NZS 7000:2016 (Standards Australia & Standards New Zealand, 2016) which refers to other Australian standards to cover specific aspects such as electrical or mechanical. Conductors in the powerlines are required to satisfy three conditions: Wind (Ftw), maintenance (Ftm), and every day (Fte). For wind loading, AS/NZS 1170.2:2021 is used (Standards Australia & Standards New Zealand, 2021).

While installing the conductor, only the self-weight acts as a permanent vertical action, and the tension of the conductor is controlled by the sag. As per Appendix R in AS/NZS 7000:2016 (Standards Australia & Standards New Zealand, 2016), Figure 8 illustrates one possible arrangement of a powerline in a network, where the conductors are suspended between two supports. This geometry can be either an inclined span or a level span.

The sag (D) of a conductor in a powerline is primarily influenced by various factors, including the tension applied at the two ends (T1 and T2), the resultant or inclined uniformly distributed load (W) on the conductor, and the span between the supports (L). Here, V and H are the vertical and horizontal components of the tension (T) respectively. The height between the two supports is denoted as h, while the chord length between the two supports in one span is represented as I. When the loads are applied to the conductors, tension is subjected to changes, and it can be calculated using Appendix R of AS/NZS 7000:2016 (Standards Australia & Standards New Zealand, 2016).

As per Clause DD1 of AS/NZS 7000:2016, areas located 800 meters above sea level or higher may experience occasional snow and ice loadings which is covered by AS/NZS 1170.3:2003 (Standards Australia & Standards New Zealand, 2003). In the design, load factors are applied to accommodate the uncertainties of loading as given in Table 7.1 of the AS/NZ 7000:2016 (Standards Australia & Standards New Zealand, 2016). Accordingly, conductor tension can be calculated for aforesaid loading conditions using appropriate load combinations and factors.

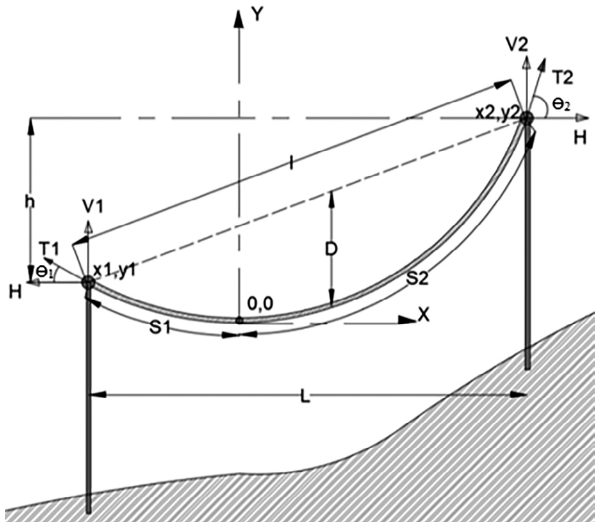

Figure 8. Geometry of a powerline

Conductor tensions due to the short circuit and failure contaminant loads are also considered when designing the powerline structure. According to clause C2 of AS/NZS 7000:2016 (Standards Australia & Standards New Zealand, 2016) incorporating the IEC 60865-1 standard, the tensile forces generated by the short-circuit current can be quite substantial and often exceed the maximum tension induced by wind loading on the conductor. Furthermore, Appendix AA provides guidance on the annealing effect in the design stage of different types of copper, aluminium, and steel conductors as conductors can operate at high-temperature levels. Further, Clause 7.2.7 in the design standard provides guidance in relation to the effect of breakages of conductors.

While design standards provide detailed guidance for the design of overhead powerlines, there are sometimes limitations and complexities which require additional information (Papailiou, 2017). In such cases, specific testing or modelling is undertaken as discussed below.

3.2.2. Wind tunnel testing

Several studies have been conducted to predict wind-induced aeolian vibration and galloping on powerlines by using scaled-down wind tunnel models to cater to the actual environmental effect in the component of the power overhead line network. As an initiation, Farquharson and McHugh (1956) investigated the behaviour of a conductor in a wind tunnel under a steady wind stream and calculated the total energy in the conductor. Later, several researchers such as Brika and Laneville (1996), Hardy and Van Dyke (1995), Kraus and Hagedorn (1991), Liang et al. (2015), Meynen et al. (2005), Noiseux et al. (1988), Qi et al. (2019), Rawlins (1983), Wardlaw et al. (1975), and Xie et al. (2017) carried out several wind tunnel testing for predicting the wind-induced aeolian vibrations of conductors in the powerlines.

Shan et al. (1992) demonstrated the conductor drag coefficient acquired in open air is matching well with wind tunnel drag measurements in the wind velocity spectrum of field data. Using a tunnel-like test setup, they developed an experiment to directly calculate conductor drag coefficients in the open air. Loredo-Souza and Davenport (2001, 2002) performed wind tunnel tests on two parallel conductors to investigate their dynamic behaviour in high winds and presented a novel method for modelling transmission power lines in wind tunnels. These data show that there is a high level of agreement between observed values and theoretical predictions derived using the influence line statistical method. Later, Bartoli et al. (2006) also conducted the same kind of wind tunnel testing on steel strand conductors to identify the conductor drag coefficient in different Reynolds numbers. Kikuchi et al. (2003) examined the heavy rainfall conditions and wind load in a wind tunnel to simulate the usual wind conditions. This study figured out that the design drag coefficient for heavy rainfall is not negligible. Later, researchers used those wind tunnel test data for their numerical model validation as well (Fu et al., 2019). Chabart and Lilien (1998) evaluated a small section of the power line in a wind tunnel using a typical eccentric ice shape model. This study's major goal was to track the powerline's attack angle and galloping behaviour while subjected to wind stress. Later, full-scale wind tunnel tests were developed by researchers to discover the galloping behaviour caused by ice and snow build up in different types of conductors (Flaga et al., 2020; Lu et al., 2019; Matsumiya et al., 2018; Xin-min et al., 2017; Yan et al., 2016; Zhou et al., 2016).

It should be noted that the research is focused on electrical transmission lines. While wind tunnel tests provide highly valuable data, numerical modelling offers an attractive cost-effective alternative.

3.2.3. Computer-based numerical simulation

The finite element method has been applied using computer software to predict the mechanical behaviour of conductors under various load conditions. The most often used computational fluid dynamics (CFD) simulation is based on wind and ice since they are the most frequent environmental conditions near the powerline. Furthermore, the thermal effect is also predicted by CFD modelling as the temperature varies in the surroundings as well as inside the conductor due to current flow. Additionally, it is possible to forecast the structural dynamic responses of the powerlines utilising static and dynamic analysis using commercial software (Zhao et al., 2023).

Research has been conducted with computer-based numerical modelling for designing and planning powerlines with optimal configurations and parameters. Worldwide, 80% of the weather-associated failures in transmission powerlines are due to downbursts and tornados (Dempsey & White, 1996), and 90% in Australia (Li, 2000). Therefore, CFD models have been developed to determine the reaction of the transmission powerlines under such extreme conditions (Aboshosha, 2014; Aboshosha et al., 2015; Aboshosha & El Damatty, 2012; Hangan et al., 2003; Kim & Hangan, 2007; Shehata et al., 2005; Stephen & Iglesias, 2023; Wood et al., 2001). However, the application of CFD for power distribution lines is not as prevalent in the literature.

The effect of ice-shedding on two-span powerlines was evaluated by Jamaleddine et al. (1993) using commercial software ADINA (automatic dynamic incremental nonlinear analysis) and it was validated with a small-scale physical model in a laboratory. Fekr and McClure (1998) used the same software to predict both static and dynamic effects on the power conductors due to different ice-shedding scenarios including the variables of ice thicknesses, powerline span, number of spans, etc. Keyhan et al. (2013) included the fluid-structure interaction (FSI) analysis to predict a more accurate representation of forces in a moving conductor due to wind conditions, and both ice and non-ice conditions were also proposed to be considered in this analysis. Furthermore, it was found that neglecting wind-conductor interaction leads to an overestimation of pressure on conductors. The aerodynamic behaviour of an iced conductor has been evaluated by Dong et al. (2022) using the CFD interface in ANSYS Fluent. Here, the influence of ice thickness, conductor diameter, section shape, and angle of attack are investigated to predict the dynamic performance of the conductor. Li et al. (2023) also developed a CFD simulation to evaluate the conductor tension due to ice accumulation at instantaneous wind velocities.

Computer-based simulations have also been developed to understand the performance of conductors when subject to temperature changes. Gómez et al. (2011) performed CFD analysis with ANSYS-Fluent software to identify the thermal behaviour of conductors under different operational conditions. Jia et al. (2022) developed a CFD model to investigate the heat-transferring performance of a fixed conductor with the relevant turbulence models. Furthermore, the study was extended to address the thermal and fluid-dynamic behaviour with different working conditions. Furthermore, a finite element model was developed by Guo et al. (2021) to investigate the sag-tension behaviour of an ACSR conductor. This study focused on the stress variation due to the maldistribution of temperature, creep strain, and initial tension of an ACSR conductor.

4. Failure modes of conductors

Failures in the power distribution network conductors can be classified into two categories: assisted failures and unassisted failures. Assisted failures refer to breakdowns caused by phenomena that are beyond the control of the power distribution company. Unassisted failures, on the other hand, occur due to factors that can be controlled by the company (Naranpanawe et al., 2018). Unassisted failures in the power distribution network can be attributed to various factors such as fatigue, vibration, annealing, clashing, corrosion, joints, and ties. They can also be caused by external factors including extreme weather events, animals, fire, human error, vegetation, lightning, and third-party impacts.

4.1. Statistic data on failures

Power distribution companies monitor their conductors and record all the failures and their causes. Failure data were collected from two power distribution companies in Australia during the period of Jan 2020 to Sep 2022 are depicted in Figure 9. According to the graph above, the majority of failures were caused by corrosion in the conductors from prolonged exposure to the environment. As wind is a common environmental condition, it also leads to significant failures. A sizable portion of breakdowns in the power distribution network are also caused by fatigue, vibration, and clashing. However, the most interesting observation in this data set is the failures of different components such as clamps, connectors, sleeves, and ties.

Figure 10 explains the percentage of failures related to different types of conductors during the aforementioned period. Percentage failures are normalized with the conductor population data given in Figure 3.

The cause of failures in those conductor types is evaluated in Figure 11. Here failures related to different components such as sleeves, ties, clamps, insulators, and dead-end grips are considered as failures of associated components for easy reference.

In total, conductor corrosion and wind are the major causes of failures in steel conductors while failures in ACSR and aluminium conductors are not highly affected by corrosion and wind according to Figure 11. But in copper and ABC conductors, corrosion accounts for considerable failures although it is not the critical cause of failure. Connection breakages and failures in associated components caused a higher effect in copper conductor failures, and it is around 18% of all kinds of conductor failures. Similarly, it was the major issue in ABC conductors, and it claims around 20% of total conductor failures. The most frequent failure for aluminium and ACSR is the failure of related parts such as ties, clamps, insulators, sleeves, and distribution grip dead ends. However, vibration is a significant factor in these conductor failures as well. It should be noted that unidentified other causes claim considerable failures in every type of conductor.

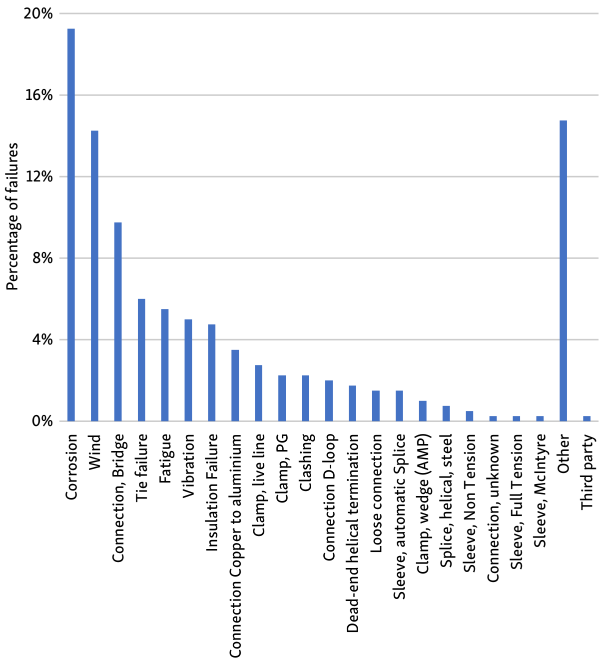

Figure 9. Percentage of failures attributed to different causes

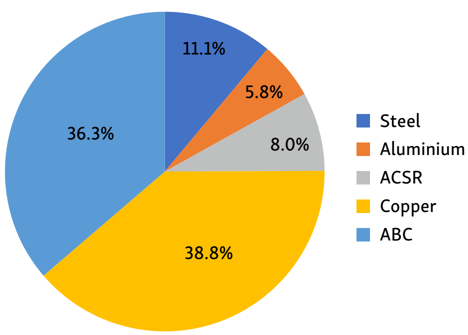

Figure 10. Percentage of failures of conductors based on conductor type

Naranpanawe et al. (2018) published data on powerlines in overhead distribution networks and their failures. According to their study, Figure 12 shows the percentage of conductor unassisted failures for steel, copper, aluminium, and ACSR that were observed in different geographical zones. Because a large proportion of conductors in the Australian distribution networks are located along close to shore (within 100km of the coast), corrosion may be the primary mode of failure.

Based on the above data and published data in the literature, a few causes of failures are identified as severe issues which can start powerline breakdowns. Those are corrosion, wind, vibration, fatigue, failure in connections, and associated components. However, most of these failures

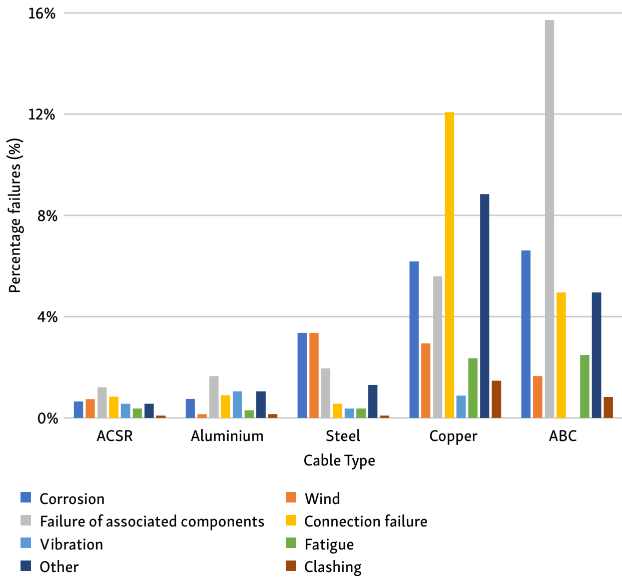

Figure 11. Summary of percentage failure based on conductor type

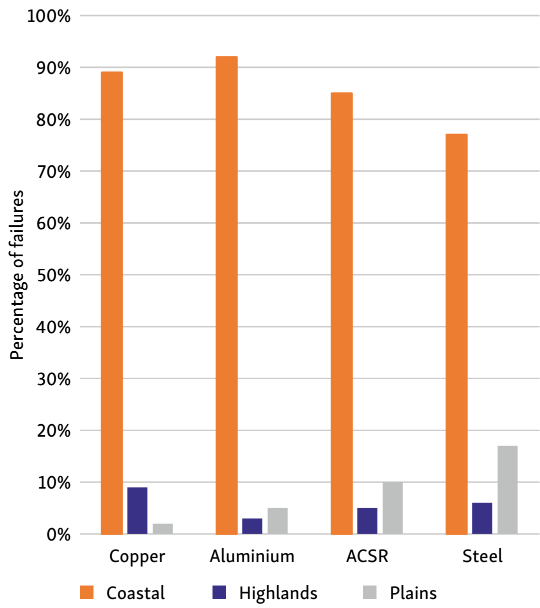

Figure 12. The percentage of conductor unassisted failures (Naranpanawe et al., 2018)

begin with the continuous conductor deterioration in the service lines. By considering all of the phenomena, three basic types of conductor degradation processes which are named annealing, corrosion, and fretting fatigue have been discussed in the literature (Naranpanawe et al., 2018).

4.2. Corrosion

Conductors can be subjected to different kinds of corrosion including atmospheric corrosion, galvanic corrosion, and crevice corrosion (Alstad et al., 1993; Popova & Prošek, 2022). Figure 13a illustrates a corroded steel conductor extracted from a power distribution network after 65 years of service and Figure 13b shows a corroded ACSR conductor.

a)

b)

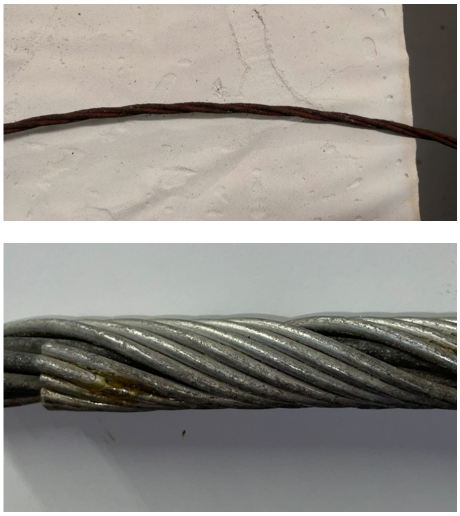

Figure 13. a – corroded steel conductor; b – corroded ACSR conductor

The most common conductors in overhead lines are comprised of aluminium and steel strands as shown in Figure 3. In general, aluminium is resistant to corrosion, even when it is exposed to water. A layer of aluminium oxide passivates the aluminium surface, which causes the corrosion process to halt (Vargel, 2020). The corrosion of aluminium is known to be facilitated by stray currents, either DC (direct current) or AC (alternative current), and this corrosion process necessitates a minimum current density (Büchler, 2020). A white powder and a smaller conductor cross-section can occasionally be seen when fixing damaged systems. Although its precise makeup is unknown, it is thought that this powder is a blend of aluminium corrosion compounds (van Deursen et al., 2019).

ACSR conductors frequently experience galvanic corrosion, which is a major cause of conductor failure. The loss of zinc from the galvanised steel strands is a crucial stage in this process because once the galvanising is lost, the aluminium strands are exposed to rapid galvanic corrosion (Jaffrey & Hettiwatte, 2014). Internal corrosion is a typical failure mode in power transmission systems that shortens the lifespan of ACSR conductors. Eddy current testing using the electromagnetic induction method detects zinc loss from the steel strands inside the ACSR (Bellemare et al., 2023).

4.3. Fretting fatigue

Although the sheer presence of Aeolian Vibration in distribution lines does not create trouble, fatigue or abrasion failures can generally occur over time when the conductor vibration occurs at considerably minimal mechanical stress (Kul'kov et al., 2021a). Aeolian vibration produces dynamic bending stress on the conductor, and it causes the fatigue failure of a bundle of conductors when it exceeds the endurance limit. The bending of the conductor causes the spreading of cracks initiated by fretting mechanisms, which is called fretting fatigue (Said et al., 2020). Figure 14 depicts fretting scars found on an old conductor's aluminium outer layer that was taken from the clamping zone.

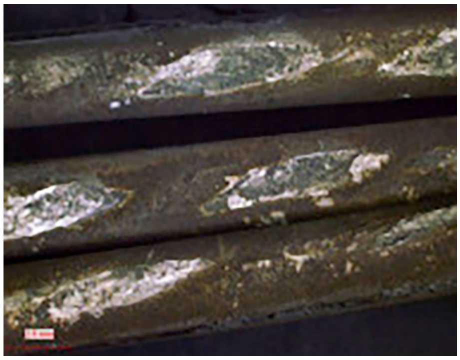

Figure 14. Possible fretting scars on the aluminium outer layer (Said et al., 2020)

Many studies have been carried out to identify the fatigue behaviour of conductors using single stands as well as whole conductors (Jiang et al., 2023a; Kalombo et al., 2015, 2016; Kul'kov et al., 2021a). However, fatigue is dependent on geometrical considerations, the influence of the conductor-clamp assembly, material behaviour, and the frictional contact of the conductor. Furthermore, the clamping zone has been identified as a key area where the bulk of failures take place (Said et al., 2020). Therefore, calculating the fatigue life of conductors is challenging due to the complexity of the mathematical formulation of this problem (Rocha et al., 2022).

In order to simulate the actual loading conditions in a laboratory setting, certain studies of conductors have been carried out using conductor-clamp assemblies (Fadel et al., 2012; Omrani et al., 2021). Several studies have also been conducted with numerical models to check the capability of accurate prediction of stress in conductors and fatigue analysis of assemblies used for clamping conductors (Frigerio et al., 2016; Omrani et al., 2021; Rocha et al., 2022; Thomas et al., 2022).

4.4. Thermal ageing and annealing

One of the main reasons conductors age is annealing brought on by high line temperatures. It may result in the networks' essential hardware failures (Manurung et al., 2023). During operation, overhead conductors are known to undergo both short-term and long-term annealing. Annealing is a process that leads to a reduction in the tensile strength of conductors and induces permanent elongation. This happens mainly due to the excessive heating of conductors with the high environment temperature, high resistance at the joints in conductors, etc. Morgan (1996) proposed a simple formula to predict the annealing loss of tensile strength of a hard-drawn conductor.

A new method for calculating conductor thermal ageing was put forward by Bhuiyan et al. (2010) combining load data from historical weather reanalysis and weather data interpolated to power line sites. Cimini Jr. and Fonseca (2013) experimented with ACSR conductors to establish a relationship between progressive wire rupture and the temperature of the conductor. However, all weather conditions including wind, ice, and rain were not considered in this model.

A thermal aging model was created by Hathout et al. (2018) to take aluminium strands' progressive annealing into account. Additionally, the integration of the thermal model with the fuzzy and reliability models allows for the investigation of the end-of-life of the overhead conductors. Yaqoob et al. (2022) developed a fuzzy dynamic thermal rating system with the consideration of mechanical and thermal stress. They used the fuzzy annealing degree of the conductor based on the Harvey model to simulate the loss of tensile stress.

As the aforementioned failures are continuously occurring in the power network, deterioration processes and their different signs have to be identified for proper maintenance. Visual inspection has traditionally been the principal method used to identify damage to overhead conductors. And those qualitative inspections are largely used to inform decisions about maintenance and replacement.

5. Conditions assessments

When making well-founded judgments about maintenance, replacement, and upgrading the overhead lines in the distribution network, conducting condition assessments using a mix of inspections, testing, and analysis is crucial. This means that the results of condition evaluation techniques can be qualitative or quantitative. Several methods of condition assessments can be carried out for the detection of damages in overhead lines. Especially, visual inspection, partial discharge (PD) detection, aerial inspection, infrared inspection, ultrasonic detection, sliding wear tests, fretting tests, measurement of corona pulse current inconsistency, radio noise detection, fibre optic applications, corona current monitor, aeolian vibration measurements and more tests are conducted for damage identification in overhead lines (Naranpanawe et al., 2018). In addition, smart sensing techniques with the use of smart plugs and cybersecurity also have been proposed to incorporate into the power systems monitoring.

5.1. Visual inspection

Visual inspection is the conventional method of detection of defects and can be done from the ground, using elevator work flatform, pole climbing, or helicopters. Discolouration of the surface, damaged/degraded joints, broken outer strands, excessive sag, and the clashed surface can be identified by visual inspection.

Visual inspection has some challenges as some defects cannot be detected visually until they become severe. Internal deterioration cannot be easily found by visual inspection. However, in case of severe internal corrosion, some of the byproducts can be seen on the surface of the conductor. Some of the broken conductors cannot be visualized due to the absence of physically unexposed damages (Rajan & Rudranna, 2013). Similarly, annealing and loss of strength cannot be revealed by visual inspection.

5.2. Infrared inspection

The temperature profile of a conductor can be captured by infrared (IR) cameras and those captures are called thermal images. These images are commonly used to identify the conductor joints which have high resistance resulting in higher temperatures. Normally, high resistance is a symptom of weakening of the joint which could lead to mechanical failure.

Blazquez (1994) conducted studies on transmission lines using IR cameras which have a video system with a probe eye scanner with the ability to produce thermograph images and normal colour images. Stockton and Tache (2006) showed that accurate temperature measurements taken from thermal images were impossible to quantify. Furthermore, these images were also taken from short distances.

Montambault and Pouliot (2003) studied IR imageing techniques to detect probable defects due to corrosion in overhead line components. According to their research, it was understood that defects identified from the other methods can be confirmed by the videos and images collected from IR imageing. However, in this test, robot equipment was also used to carry out inspections. Although airborne thermal images can detect damage, it is difficult to get accurate temperature readings. Therefore, researchers moved to carry out studies on UAV surveys with the use of both thermal imageing and laser scanning (Jeong et al., 2023; Matikainen et al., 2016; Pagnano et al., 2013).

5.3. Robotic inspection

Studies on robotic inspection methods of power transmission lines were carried out continuously with the development of robotic technology. Aracil et al. (2002) studied the Telerobotics for live-power lines and introduced the ROBTET system. Rocha et al. (2022) took the first steps to carry out a study by targeting the development of a robot to inspect the electrical power conductors. Further, promising results were obtained in their study although the simplifying assumptions in modelling and linearization procedure were used. Li and Brown (2004) researched control systems for inspection robots. In this study, the obstacle-navigation control principle was used for the research and a prototype for the robot was developed to process the main functions of inspection tasks.

Zhou et al. (2005) presented the inspection robot with a control strategy in an expert system. This system can manage the robot to move along the overhead lines and negotiate various obstacles. Xiao et al. (2007) conducted research on inspection robots that can overcome obstacles for dynamic coupling simulation in overhead lines.

Pouliot and Montambault (2008) presented a mobile robotic platform called LineScout which can be used for overhead line inspection and maintenance. In their study, a third-generation prototype had been developed and validated under field conditions. Katrasnik et al. (2008) targeted the development of climbing and flying robots for power line inspection. This research shows that the concept is feasible from the practical point of view although a few specific challenges such as positioning on conductors and bandwidth of high communication links were observed. In further research, Katrasnik et al. (2009) identified that a climbing robot is slightly better than a flying robot. Although the design and construction of a flying robot are relatively straightforward, the inspection quality of a flying robot was much lower due to vibrations, greater distances, and limited area of view (when inspecting conductors).

Roncolatto et al. (2010) proposed a computer-controlled automatic elevator and a flexible telescopic robot for overhead line observation and maintenance. The proposed elevator with the small pick-up type of vehicle was shown as an interesting solution than the ladder. Further, it is reported that the proposed telescopic robot has a high accuracy allowing the inspections from ground level. Future improvements in the elevator were proposed in design and functionality before field application.

Pinto et al. (2010) carried out a study to develop a prototype of robotic equipment that can support extreme weather. The existing faults were correctly identified and located by this robot during both laboratory and field tests. Based on the continuum robot concept Finotto et al. (2012) developed a prototype of a telescopic robot with portable, lightweight, flexible, and dielectric features. The proposed robotic system has the capacity to reach heights over 9m and it allows to inspect from ground level. Further, it can transfer the motion by tendons and control the movement and positioning of the structure using actuators in the base platform. This prototype was tested by experimental results and validated allowing improvements in the application of inspection. However, considerable variation was reported in the positioning test.

Pouliot et al. (2012) presented a three-step file system for LineScout procedures to utilize the collected information as precisely as possible. These three steps are specifying the mission file, inspection (video and image recording), and developing an automated report file. Some improvements were identified in this system such as precise localization of the non-visible damages. Pouliot et al. (2015) continue the research on LineScout robotic platform. They included sensors and an arm with tools for repairing the broken conductor strands. This technology has engaged in teleoperated maintenance activities in the field as a successful method.

Velásquez and Lara (2016) developed a novel robot for powerline automatic inspection by minimizing the cost and enhancing the safety conditions for operation. This robot can move along the conductors fast and steadily by locomotion with wheels. This robot can reach locations with difficult access with geographic considerations as well. Gulzar et al. (2018) developed a prototype of a mobile robot with four wheels, sensors, two motors, cameras, etc. This robot can cross over the power line clamps as well. This system is capable of walking along the powerline. The inspection can be performed at the ground level in a live environment with the help of GPS.

Li et al. (2020) designed an inspection robot to identify the damages in aluminium conductor composite core (ACCC) wires based on NDT. This robot can climb at 35° angles and roll over the dampers and clamps in the powerlines. However, crossing the dampers and clamps cannot be performed at angles higher than 15° and 20° respectively. The field experiment was done for the proposed robot and the prototype met the requirements of detecting the damages in ACCC conductors.

Srivastav et al. (2021) developed a robot for the inspection of the faults in powerlines. This robot has ultrasonic sensors, Gyro for position control, cameras including IR, and motors. These motors are capable of changing the positions to be run based on the command received from the controlling person. This robot also allows to observe the conditions through the camera and travel along the conductor by overcoming obstacles. Here obstacles are cleared using the arms in the robotic system after sensing the distance by the sensor. However, this leads to a quick operation by avoiding delays due to obstacles.

Lovrenčič et al. (2022) conducted a study on a live-line robot for the asset management of the powerline. This robot can identify local breaks and deep pits within the steel core wires. Furthermore, it gauges the remaining cross-sectional area of the steel core wires in both ACSR and aluminium conductor steel-supported (ACSS) conductors. The line inspection robot has the capability of inspecting the individual conductors with overall diameters within 15 mm to 45 mm.

Wang et al. (2023) developed a novel inspection robot for the automation detection of flaws in the core of ACCC powerlines. This inspection robot is comprised of an X-ray NDT system to obtain X-ray images of the conductors. This robot is capable of identifying internal defects in ACCC wires quickly and accurately. However, the detection of damages in the multi-bundle wires is not efficient and it requires manual disassembling and installation as the robot can only one strand at a time.

5.4. Unmanned aerial vehicles

UAVs with sensors and imageing capabilities provide a safe and economical way to inspect electricity lines and related infrastructure. Numerous research studies have focused on developing advanced condition assessment methods using UAVs to precisely detect defects in powerlines. The study of visual control of UAVs for distribution power line inspection was started by Golightly and Jones (2005). The suggested system was tested in a lab setting using a 30:1 scale model of an overhead line with three conductors in this study. According to this research, the suggested rotorcraft can recover from a disturbance caused by blowing wind. However, it was suggested to velocity up image processing's response time and computation.

To find the anomalies along the power lines, Larrauri et al. (2013) developed the "RELIFO" technology. An autonomous aircraft was used in this study to inspect the lines, and antennas in a ground station used the signals it picked up to create fresh offline reports. According to this study, the suggested system was capable of using image processing to automatically determine distance and hotspots.

Nguyen et al. (2018) conducted a comprehensive review of the deep learning vision-based idea for inspecting power lines using specially designed autonomous UAVs. The problems with deep learning navigation and inspection have been noted and were addressed in this assessment. In order to achieve the aforementioned goal, Nguyen et al. (2019) proposed a unique automatic vision-based system that uses optical images as a data source and deep learning as a model for data analysis. The results of this study demonstrated that the suggested approach has a marginally improved ability to identify common problems in the power line components. Due to a shortage of training data, class imbalance of power components, and errors in the detection of minor components in power lines, this system faced a few obstacles. Therefore, multi-stage detection was proposed using a single shot multibox detector and deep residual network to detect small components and faults.

Vemula and Frye (2020) developed a real-time powerline detection technology for UAVs. This developed system is based on deep learning where the neural network simulation is involved. The system exhibits enhanced speed and minimum average precision. This technique can identify the components of the powerline as it has the ability to identify the boundaries with detailed pixel levels. Therefore, it helps to avoid mistakes and identify various components. Zheng et al. (2021) also developed a method to detect faults based on deep learning using UAVs. In this study, recognition and classification experiments were carried out with the collected images from drones. That study has confirmed the ability to use deep learning techniques to detect damages in the powerline accurately.

Bandara et al. (2024) carried out a review on faults and wildfires in power distribution systems with the understanding of the potential of initiation of wildfire due to failure of power components. This study highlighted the ability to use UAVs with advanced and automated techniques for data interpretation as it gives more reliable solutions with the required accuracy.

5.5. Partial discharge detection

The advancements in PD detection for the condition monitoring of overhead conductors have received a lot of attention. Partial Discharge can be divided into three categories; internal, surface, and corona PD (Majidi et al., 2015). Corona discharge is created by air ionisation near a high-voltage electrode. Surface discharge occurs at the surface of a dielectric material and frequently at the contact between two materials. Internal discharge occurs in weak dielectrics. However, surface discharge is one of the most common causes of conductor failure. This can be due to contamination and weather around the surface of the components. There are several PD testing methods can be found in the literature such as Off-line tests (including AC voltage test, VLF test, and damp AC test), online tests, and sensor applications (including acoustic emission sensors, high-frequency current transformers, ultraviolet imagers, etc.) for power line conductors (Zhang et al., 2021).

An online PD detection approach that works with wire-screened electrical power conductors was described by Ahmed and Srinivas (1998). Here wire-screened has a common conductive layer for electromagnetic shielding. This study focused on the use of spectrum analyzer techniques for on-site testing of PD detection in conductors at various frequency ranges and PD detector-to-conductor distances. The effectiveness of the VHF approach for PD detection utilising a spectrum analyzer was tested close to joints and terminations. In order to verify its accuracy and sensitivity, it was cross-checked by running two additional PD detection tests (high-speed digital oscilloscope and pulse phase analyzer) in a controlled setting. The output results demonstrated the capability of this technology to conduct field tests for capturing PD measurements in power connections.

Using an oscillating wave test system (OWTS), Gulski et al. (1999) evaluated the impact of PD measuring approaches in real-world settings. To reach the stated goal, tests in the lab and on-site were both carried out. The OWTS can be employed for accurate PD detection in the conductors under AC settings, according to the results. It has also been demonstrated that this oscillation technique can be utilised to activate discharge ignition at certain locations. In addition to the aforementioned, the precise discharge's location can be determined. To explore the full potential of the aforementioned strategy, however, several experiments were planned after this study. Further research was done by Gulski et al. (2000) on the Advanced PD diagnosis of the medium voltage (MV) power conductor utilising the OWTS, and they provided a three-step method for sensitively developing conductor diagnostics. This three-step process consists of gathering the PD measurements for various conductor sections, assessing the degradation process to create a database, and putting the diagnosis and knowledge criteria for various insulating materials into practice to test them in real-world settings. Brettschneider et al. (2002) performed three field tests to verify the sensitivity of PD detection by using the recently developed complex discharge analyzing (CDA) method using the OWTS. It was shown that the proposed method is capable of detecting PD failures accurately and efficiently under rough field conditions.

Gulski et al. (2005) proposed a PD diagnosis method at damped AC (DAC) voltages to detect the faults in distribution network conductors. It has been shown that the possibility of detecting PD discharge problems in two different types of conductor insulation (XLPE – cross-linked polyethylene and PILC – paper insulated lead covered). Gulski et al. (2007) extended this study to PD diagnosis on medium voltage power conductors and shown that the possibility of detection and localizing of defects in XLPE and PILC conductors. Petzold et al. (2008) conducted a field study on the aforesaid proposal and recommended applying this non-destructive technique to illustrate appropriate demands and an effective conclusion to enable asset management decision-making. Wild et al. (2013) continued the study on DAC technology for medium voltage conductors with longer lengths. It has been shown that the use of double-sided PD measurement on extended conductor length increases the sensitivity of PD detection by aiding in the localization of the PD source.

Steennis et al. (2016) employed an online PD monitoring system to track temperature variations in medium voltage conductors in order to locate problem locations. In this investigation, the location of the failure was precisely identified in the field. Furthermore, employing PD phenomena, this study extended to anticipate upcoming failures for XLPE conductor systems. The risk index scale is developed based on PD parameters to identify the urgency of the conductor replacement. Similarly, researchers moved on to reliability assessments on the power components to identify the remaining life or expected period of failure.

A novel technique based on PD signals has been invented by Wong et al. (2019) using the directional antennas installed on the poles to detect the early damage of conductors. This study performed both laboratory and field tests to check the ability to detect damages in conductors based on PD signals generated by initial detects. Based on the results, it was identified that the identification of early vegetation contact with power lines becomes possible when protective relays can detect fault currents below 0.5A and quickly initiate a response. For each fault, the PD signal resulting from vegetation contact can be detected using a directional antenna positioned externally to the test rig.

Researchers combined the machine learning approaches with PD techniques to obtain optimum outcomes from new technology. Venkatesh et al. (2020) used the machine learning approaches to detect PD patterns in powerlines. A dataset containing PD patterns in powerlines has been published by the University of Ostrava. This dataset was used for the prediction of machine learning models for PD. Later, Rivas et al. (2022) used machine learning techniques in PD diagnostics for the detection of faults. A publicly available dataset containing PD measurements on covered conductors from power lines is utilized to develop models through automated machine learning. However, the results were not compared with other similar models as the exact datasets for training and testing were different.

Jiang et al. (2023b) proposed an automated powerline PD detection system for the online identification of PD. This study was focused on multi-scale one-dimensional convolutional neural network modelling to combine with the PD detection technique. Convolutional neural network plays a crucial role in the field of computer vision. When dealing with time series data, such as signals or sequences, the convolutional operation is performed in one dimension. Therefore, this study has used one-dimensional convolutional neural network modelling. However, this study has not shown understandable fault information due to a lack of large training data which increases the training cost as well.

5.6. Other methods

Smart sensing technology is under continuous evolution, and new methods are being proposed to improve the techniques of monitoring distribution networks. In respect, smart plugs, and cyber-physical systems also play their role in improving power distribution monitoring. Smart plugs measure voltage, frequency, and power quality for condition monitoring. Furthermore, it facilitates real-time data collection about conductor performance that assists in the monitoring, assessment, and management of power loads effectively (Dhaou, 2023; Kayastha et al., 2014; Suryadevara & Biswal, 2019). These devices convey information to servers where it is analysed for gauging the stability of the grid and identifying issues. The data gathered over parameters like voltage and frequency enables the smart plugs to help in early fault detection (Biswal et al., 2011). Apart from that, smart plugs support monitoring the energy flow in both directions with conductor condition monitoring in real-time, considering supply and demand. Smart plugs support the monitoring of grid stability management while there is effective power flow management in both directions (Padhi et al., 2021).

Cybersecurity is a major concern because the integration of a large number of Internet of Things (IoT) devices within the grid opens it up to many dangers, unauthorized access, and breaches in data (Suryadevara & Biswal, 2019). These Cybersecurity procedures enable the secure transfer of this data, defending against possible attacks and preserving the integrity of the grid's condition monitoring systems. Standard methods of cybersecurity include data encryption, authentication protocols, and microservice architectures that manage data flow for sensitive monitoring data to remain secure (Biswal et al., 2011). While this concept is mainly applied to microgrid components, their application on the higher end of the hierarchy in the Energy ecosystem, such as substation, utility, microgrid, and grid level is still open (Suryadevara & Biswal, 2019).

The results of the condition assessment of each component of the system are used by power distribution firms to maintain and operate the power network. Although every overhead component is checked and maintained effectively, greater attention should be devoted to the reliability of the power distribution network, which is constantly threatened by numerous environmental conditions and reasons. As a result, it is worthwhile to implement a risk assessment approach for the power distribution network.

6. Reliability assessments

The examination of the reliability of power distribution components is an important part of guaranteeing the overall stability and continuity of electrical power supply systems. It includes assessing the performance and dependability of various power distribution network components. Several factors such as weather effects, dependent failures, loading models, security limits, etc. were considered for reliability evaluation (Li, 2002). Several studies were carried out to assess the risk of the infrastructure in overhead transmission and distribution networks. Three functional zones were defined for the adequacy assessment of the power system by Billinton and Allan (1984) as shown in Figure 15.

Accordingly, hierarchical level I (HLI) is solely concerned with generation facilities. In an assessment of consumer load point sufficiency, hierarchical level II (HLII) covers both generation and transmission facilities, and HLIII includes all three functional zones. Therefore, evaluation of HLIII can become very complex in this system. For the reliability assessment of HLIII, Billinton and Allan (1984) proposed different primary indices such as expected failure rate, average failure duration, and annual outage time at the actual consumer load point. In 1988, Allan and Billinton published a review of the concept of reliability evaluation of power systems and proposed to apply aforesaid reliability indices using different mathematical models such as the Monte Carlo simulation (MCS) and direct analytical method (Allan & Billinton, 1988).

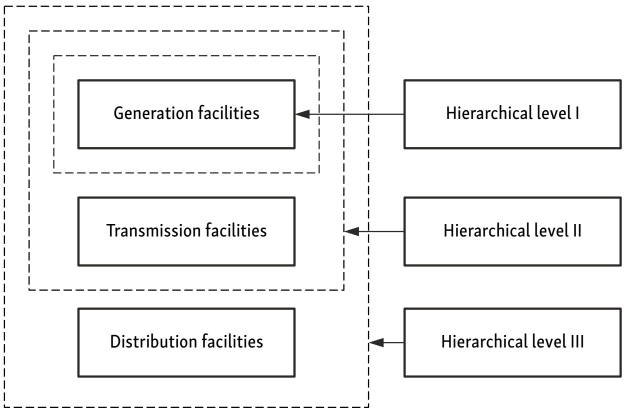

Figure 15. Three functional levels according to Billinton and Allan (1984)

The direct analytical approach analyses power system reliability indices using mathematical solutions, whereas the MCS estimates it by modelling the actual process and random behaviour of the power system. These methods have different advantages and disadvantages and those are summarised in Table 2.

Table 2. Advantages and disadvantages of both direct analytical approach and MCS (Allan & Billinton, 1988; Allan, 2013)

Method	Advantages	Disadvantages
Direct Analytical Approach	1. Faster for small and medium power systems. 2. Less computational effort. 3. Exact Solutions for specific systems.	1. Impractical for large power systems. 2. The actual process cannot be achieved with assumptions.
Monte Carlo Simulation	1. Practical for large-scale power systems. 2. Ability to incorporate the different indices. 3. Providing a more comprehensive idea of the system.	1. High computational effort. 2. Results depend on iterations. 3. Developing a proper model is challenging and time-consuming.

Researchers continue to employ the MCS for assessing power system reliability, despite its shortcomings. Especially, a hybrid approach was also employed for different models by combining MCS and a numerical technique (Billinton & Wenyuan, 1991). Furthermore, as computer resources improve, researchers start to use high-performance computing to run more extensive and refined MCS. Pereira and Pinto (1992) proposed a new computational tool namely, CREAM for reliability assessment in power systems. This new tool is based on MCS sampling. Later this concept is referred by researchers to develop a reliability analysis method for composite systems such as both power generation and transmission systems (Sankarakrishnan & Billinton, 1995; Ubeda & Allan, 1992).

Not only power systems, but also failure of the electrical components also having a relationship with time, and several research have been carried out to identify the effect of age on the components and the other external parameters like dynamic effects, corrosion, excessive heating, etc. Havard et al. (1992) carried out a study about the prediction of the remaining life of aged ACSR conductors in Ontario Hydro's overhead power system. This study focused on three factors to represent the mechanical status of the ASCR lines for the transmission network. Experimental work was carried out to identify corrosion level, loss of tensile strength, and loss of ductility behaviour of the Conductors with the age of it. According to the ACSR conductors used in this study, galvanised steel core wires are corroding, and galvanising loss measurements utilising a corrosion detector provide an early warning of catastrophic mechanical property loss. It was also discovered that torsional ductility tests on conductor samples provide a more sensitive assessment of remaining useable life. Later Florea et al. (2005) used the same set of curves to check the life span left for ASCR conductors after exposure to excessive heating, wind vibrations, and corrosion during functioning.

Li (2002) carried out a study about two types of probability distribution models (using both normal and Weibull distribution) for the unavailability of ageing failures in electric components in power systems. Here, the probability of ageing failure can occur within a specific period of its lifetime and the component can be survived for further years (Billinton & Allan, 1992). In this study, eight underground 230 kV conductors were used to check the performance of the proposed two models to predict the unavailability of ageing failures. This study showed that the impact of ageing failures significantly reduces system reliability, especially in already-aged systems. A similar Weibull probability distribution model was applied by Li (2004) to estimate the mean life and end-of-life failures of power equipment such as reactors, transformers, and underground conductors.

The Life cycle cost analysis (LCCA) concept is also the first proposed model for checking the reliability of the powerlines. This LCCA concept is targeted to consider the technical, economic, and other reasonable strategic measures to have a sustainable achievement. Zhu et al. (2016) used this concept to carry out an analysis for the comparison of three types of powerline conductors – aluminium alloy, copper, and overhead conductor. In this study, failure cost was considered as a main parameter for the LCCA, and a model for the risk assessment of components was developed with a probability distribution model using the MCS method.

Vasquez et al. (2017) proposed an advanced ageing failure model by considering the effects of both loading and weather conditions. Here, the Weibull distribution function has been modified by incorporating the Arrhenius relationship to consider the loading and weather effect together in aluminium conductor steel reinforced (ACSR) conductors. The Arrhenius relationship is a method to model the lifetime of a conductor using the effect of temperature. Further, the lifetime of the component can be used as a scale parameter in the Weibull distribution method (Awadallah, 2014). According to the results of this study, it was shown both loading and weather conditions can make a great effect on the ageing failure of conductors when the temperature of the conductor reaches to a higher value than the maximum operating temperature of the conductor (Vasquez et al., 2017).

Velásquez and Lara (2018) have identified the key features essential for determining the required electrical and specialised tests to diagnose and assess the remaining life of powerlines through a health index process. They proposed three sets of remaining lives for the conductors, i.e., chronological age, prediction from basic health index, and comprehensive health index. The basic health index just uses age and visual inspection. The comprehensive health index uses in-depth details including age, more accurate visual inspections, maintenance records, and test results. However, maintenance based on the basic health index leads to unnecessary replacements.

Liu et al. (2018) also considered the health index of overhead powerlines to evaluate the health standing. They considered the factors such as electrical, mechanical, and insulation performance. Furthermore, external features such as natural factors, human factors, improper operation, and maintenance were also considered. However, frequent inspections are still recommended due to the different climatic conditions. Similarly, Naranpanawe et al. (2020) proposed a health index for the conductors in the Australian overhead power distribution network. They also considered the geographical locations of conductors, meteorological data, conductor metallic measurements, network operating circumstances, and industry knowledge. The proposed health index was validated via the testing done for aged aluminium and copper conductors. Furthermore, a correlation between the probabilistic failure and the proposed health index was developed using the field test data.

Kul'kov et al. (2021b) developed a method to evaluate the damage degree of a conductor based on the fatigue strength. This was achieved by measuring high-frequency electrical resistance and accounting for the accumulation of defects in the crystal structure and surface layer cracking of the metal conductor.

Rácz and Németh (2021) proposed a novel and economical way of monitoring and evaluating powerlines. It is called the dynamic line rating method which is developed for the enhancing of current carrying capacity of conductors considering the environmental conditions and the powerline considerations. It has shown that the expert system yields more cost-effective outcomes compared to the traditional static line rating. The study has suggested that incorporating dynamic line rating into an expert system not only enhances transfer capacity but also directly contributes to the safety and security of power lines, offering additional advantages. In 2022, they improved the dynamic line rating method by introducing artificial neural network parameter settings (Rácz & Németh, 2022). This new method enhances the ability of thermal tracking and powerline rating, and it determines line ratings without relying on sensory measurements after a specified period.

A fire growth model was examined by Sayarshad and Ghorbanloo (2023) to understand the increment of probabilistic failure of ageing in powerlines. Different factors such as various landscapes, topography, weather conditions, and fuel variables were considered for developing the mathematical model. One of the advantages of this model is the ability to rank the critical areas around the power conductors according to the fire risks. The study found that up to 7% of increment can occur in the aging probabilistic failure where the 7000 min of simulated wildfire event under the high temperature. Therefore, consideration of the wildfire effect in the life prediction models is crucial, especially in areas where conductors are situated in fire-prone environments.

Other than the aforementioned methods, Dynamic Thermal Rating (DTR) technology has become increasingly important over the years for the reliability and efficiency of distribution power conductors, as utilities can dynamically assess and optimize network capacity. Conductor thermal ratings have traditionally been estimated to prevent overheating which leads to underutilization of the assets. In contrast, DTR allows the system for real-time monitoring of conductor temperature and optimises the conductor load-carrying capability based on environmental parameters such as wind speed, ambient temperature, and solar radiation (Lai & Teh, 2022; Yang et al., 2024).

Evidence from numerous literature (e.g., Teh et al., 2017; Yang & Teh, 2023) shows that DTR technology improves the thermal impact on conductors. However, it is very critical to run variable loads without overloading the equipment and subsequently causing failure. Real-time adaptability for more strategic asset utilization: DTR technology may allow higher conductor utilization in favourable weather conditions. Furthermore, it allows for delay and reduction in expensive infrastructure replacements (Abas et al., 2024). DTR provides more accurate predictions of failure probability by including high-temperature loading effects and natural ageing processes utilising the Arrhenius and Weibull models. This capability of prediction is essential in maintenance planning because it extends the life of the conductor by eliminating unnecessary thermal stresses.

The bushings will further facilitate this efficiency, as they are capable of maintaining stable current flow and reducing the chances of developing faults that would require costly repairs and downtime. Combined, DTR and high-quality bushings facilitate practical grid planning through better capacity forecasting, thermal degradation minimization, and flexibility extension in both operational and long-term planning stages. These technologies reduce the intermittency in power flows within the integration of wind farms, safer, more reliable, and more cost-effective expansion of variable generation in the power distribution grid (Daminov et al., 2021; Molina Gómez, 2020).

DTR technology enables higher operational flexibility, especially within AC/DC hybrid distribution systems where the presence of renewable energy sources and dispatchable resources introduces variability in loads (Su & Teh, 2022; Su et al., 2023b). With DTR, dynamic changing of conductor capacities contributes to the mitigation of network obstruction and better integration of distributed generation like solar and wind. This flexibility offered by DTR permits dynamic response to real-time grid conditions through the balancing of power flow in various directions within the conductor network by allowing key contribution during peak demand periods.

Additionally, DTR plays a key role in hierarchical and distributed management systems (Su et al., 2023a). The final relies on DTR for managing the conductor capacity at various levels from the distribution system by incorporating cloud and edge devices to further the control function over distributed energy resources. This complex, dynamic strategy creates an efficient network that is critical for delivering consistent service, especially in hybrid networks with significant electric vehicle adoption and other fluctuating loads. Likely, DTR enhances short- and long-term reliability in power distribution by allowing better, adaptive management of the thermal loads on conductors. Such dynamic control would optimise asset utilisation and enhance grid resilience to fluctuating demands, allowing flexibility in immediate operations and strategic, long-term infrastructure planning.

While the aforementioned methods give direct approaches to the reliability of overhead power conductors, the involvement of smart plugs and cybersecurity is a novel concept which is proposed to reshape future power distribution system reliability. Smart IoT devices, such as smart plugs, support utilities in balancing demand across the network by collecting real-time load data. This stress reduction on all types of conductors helps to avoid thermal overloads and extends the conductor life span in highly demanded areas. Furthermore, cybersecurity within IoT for the power systems secures both operational data and infrastructure-important to avoid unauthorized access (Majhi & Mohanty, 2024).

Wang et al. (2022) investigate the overall infrastructure that may impact resilience in the distribution network, considering distributed energy resources (DER) deployment, data management, and consumer interaction roles within smart grids. It also discusses how the integration of DERs, like solar panels and electric vehicles, into the grid involves intensive data collection, communication, and control throughout the full distribution grid. Further, sensors and IoT-enabled devices can improve the reliability and security of the grid by conducting monitoring of several system components and enabling the detection of possible cyber threats that could indirectly influence physical components, such as conductors. However, the capability of the IoT to optimise energy distribution, preventing failures by predictive maintenance, including cybersecurity. This can help avoid cyber threats and improve resilience, thereby indirectly supporting the reliability of the infrastructure components like overhead conductors that reduce stress in a system and enhance safety measures (Bedi et al., 2018).

Bandara et al. (2024) conducted an evaluation of infrastructure connected to power distribution networks, describing the need for reliable access to each power component, including conductors. This study emphasises the significance of using high-impact, low-probability extreme weather scenarios in power networks. Similarly, all the preceding studies emphasise the significance of having adequate reliability estimation of power systems, including power distribution conductors. It specifies the ability to employ advanced ageing failure models with the application of the Arrhenius relationship to address hybrid impacts on weather-related catastrophes that can give practical scenarios with reasonable accuracy.

7. Conclusions

Conductors serve a critical function in the electrical power distribution network by transporting current to users. It can have a varying number of wires and be built of various materials depending on the usage. Because the power network is subjected to a variety of weather conditions, including high winds, rain, snow and temperature variations conductors have to resist a variety of loads in addition to their self-weight. There are national and international standards which support the structural design of conductors. However, for some situations, additional information may be required via testing or specific simulations. Wind tunnel testing is an option to predict the effect of loads under various wind and ice conditions. However, it is an expensive approach. As another alternative, computer-based numerical simulation approaches using CFD software can be used to solve wind, snow, and temperature effects on conductors.

Conductors can experience different types of failures due to continuous exposure to different weather and operating conditions. Most failures in the Australian distribution network are due to corrosion of steel conductors while other causes such as wind, vibration, fatigue, and failures of associated components also contribute to a considerable percentage. Condition assessment techniques such as non-destructive testing including PD detection, visual inspection, infrared inspection, and robotic and UAV inspection detect the faults in the conductors. Reliability assessment of conductors is important for decision-making in relation to the overall network. The use of advanced ageing failure models in conjunction with appropriate probability models such as the Weibull and Arrhenius relationship is key to tackling hybrid impacts including weather actions. Consideration of parameters such as corrosion, temperature changes, incidences of severe winds, fatigue effect, operation circumstances, etc in the development of reliability models has a significant influence on the probabilistic failure prediction of powerline conductors. Furthermore, incorporating the artificial neural network into the reliability modelling offers a novel approach to power conductor asset management.

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Author contributions

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