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Developing a cost-effective solution for detecting the breakage of low voltage AC distribution overhead conductors

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***Abstract*—The reliability of low-voltage AC distribution networks is critical for ensuring uninterrupted power supply to residential and small commercial consumers. Overhead conductors in these networks are highly vulnerable to breakage due to environmental factors such as strong winds, falling trees, corrosion, and mechanical wear. Traditional fault detection methods are often expensive, slow, or ineffective in accurately identifying conductor breakage, especially in rural and semi-urban areas.This project proposes the development of a cost-effective and efficient solution for detecting the breakage of low-voltage AC distribution overhead conductors. The system utilizes affordable sensing components, such as current and voltage sensors, integrated with a microcontroller-based monitoring unit. By continuously analyzing line parameters, the system can quickly identify abnormal conditions that indicate a conductor breakage. Upon detection, the system triggers an alert mechanism, which may include visual indicators, alarms, or remote notifications using wireless communication technologies such as GSM or IoT platforms.**

***Index Terms*—Low Voltage Distribution System, Overhead Conductor Breakage Detection, Fault Detection, AC Distribution Network, Microcontroller, Electrical Safety, Real-Time Monitoring, Cost-Effective Protection System.**

I. INTRODUCTION

The electricity distribution network carries electric power over the last distance from transformers to consumers, i.e., households, commercial buildings, industries, etc. Accord ing to the Australian Energy Regulator [AER], the power distribution network serves approximately 10.7 million in dividuals 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 com mon 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 (Kan danaarachchi 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 compo nents is crucial to withstand the various loads they expe rience. There are several national and international de sign 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 infrastruc ture can still be found. The State of the Infrastructure Report 2020/2021, pub lished by Western Power Company, indicates that there were

1,169 instances of unassisted phase conductor fail ures in distribution lines within five years from July 2016 to June
2021 (Western Power, 2021). Western Power owns which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited. Journal of Civil Engineering and Management, 2025, 31(4), 338–361 a distribution network with a circuit length of approxi mately 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).

II. PROCEDURE FOR PAPER SUBMISSION

These electric overhead lines are constructed over different types of terrain and exposed to varying weather conditions. Continuous exposure to ad verse weather conditions and mechanical stresses induced by wind can cause deterioration of components (Aggarwal et al., 2000). This degradation process may initiate crack ing, corrosion, and a reduction in the capacity of the con ductors, 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 re duce failures. Initially, conventional visual inspection meth ods 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 Insti tute, 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 catego rized 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 over head power distribution conductors. In respective sections, it covers conductor types, design aspects, failure modes, condition assessment techniques, and reliability assess ment methods. 339 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, conduc tors can be categorized as bare conductors or aerial bun dled 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 Aus tralia & Standards New Zealand, 2000) can be used which covers aluminium and copper conductors. Further to that, AS 1531-1991 (aluminium and aluminium alloy conduc tors) (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 stand ards provide detailed specifications regarding construc tion 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 eco nomic considerations (Evoenergy, 2020). The most used bare conductor strands in the Australian electrical distribu tion 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

manufac tured using alloy designations of 1120 and 6201A, respec tively (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 con ductors, 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 ar eas (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 – 7 340

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monitoring of overhead power distribution conductors 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 avail able 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 advan tage of higher ultimate tensile stress compared to alu minium, resulting in higher breaking loads for both types of steel conductors (Standards Australia, 1992a). The steel wires are produced through a hot dip galvanizing pro cess. 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 con ductors that are reinforced with steel. This matrix includes the combination of aluminium or aluminium alloy conduc tors (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 con ductor 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, cop per exhibits good th

III. MATH

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 net work are typically constructed using Aluminium 1350. These conductors are insulated with X-90 (90 °C maxi mum 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 distribu tion network for working voltages ranging from 6.35/11 (12) kV to 19/33 (36) kV. The relevant standard govern ing this conductor type is AS/NZS 3675:2002, which out lines the properties related to the strands and their cov ers (Standards Australia & Standards New Zealand, 2002). Journal of Civil Engineering and Management, 2025, 31(4), 338–361 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 Aus tralian 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 insula tion material with an outer layer of high-density polyeth ylene (HDPE). The application of these conductors offers improved performance in polluted areas and allows for reduced clearance between phases and trees. The avail able 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 alumin ium alloy wires with steel wires, the properties are com parable to those of individual strands. It is worth noting that the properties of a single wire in aerial bundled con ductors (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 elas ticity, 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 in crease in the number of strands leads to a decrease in the direct current resistance of the conductor (Standards Aus tralia, 1991b). These properties play a crucial role in deter mining 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) Table 1. Material properties of a single strand (Standards Australia, 1991b) Conductor Density @ 20°C Resistivity @ 20°C (kg/m3) AAC/1350 AAAC/1120 AAAC/6201 SC/GZ SC/AC SC/AZ* CU 2.7×103 2.7×103

2.7×103 7.8×103 6.59×103 7.6×103 (μΩ.m) 0.0283 0.0293

0.0328 0.19 0.085 Modulus of Elasticity* (GPa) 68 68 68

193 341 (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 alu minium 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, espe cially in rural areas. Apart from steel conductors, aluminium 312 7.621 35.782 31.699 18.377 1.132 157.530 83.917 62.335 18.252
1.796 611 458 Steel ACSR Aluminium Copper Unknown CCT ABC Length /Circuit km Low voltage conductors High voltage conductors 17 Figure 3. Population of different conductor types (Naranpanawe et al., 2018) 36.1% 22.4%
20.9% 11.4% 4.6% 4.1% 0.4% Steel Aluminium ACSR Copper Unknown ABC Figure 4. Percentage availability of different conductor types (Naranpanawe et al., 2018) Constant Mass Temperature Coefficient for Resistance @ 20°C (per °C) 0.00403 0.00390 Coefficient of Linear Expansion (per °C) 23.0×10–6 23.0×10–6 0.00360 0.00440
162 0.15 8.89×103 0.01777 193 124 0.0036 0.0044
23.0×10–6 11.5×10–6 12.9×10–6 11.5×10–6 17×10–6
0.00381 342 S. Jayathilake et al. Review of the design and condition monitoring of overhead power distribution conductors 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 net work. 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 cur rent, 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 nor mally 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 snow fall 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 instal lation to control the sag between supports. However, it is important to note that the tension in the conductor dur ing service life would vary due to wind action, tempera ture 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). Ad ditionally, the direction of the wind also varies, indicat ing 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 min ute) 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 catego rized based on cardinal directions. The graphs clearly de pict 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 min ute) 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 con ductor, 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 con ductor (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 con ductor, it can lead to the generation of eddies or vorti ces on the side of the object facing away from the wind. Figure 6 visually demonstrates the formation of these ed dies 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 0 1000 2000 3000 4000 5000 6000 7000 8000
9000 0 10 20 30 40 Frequency Velocity (m/s) Mean wind velocity Maximum w Figure 5. Mean wind velocity distribution curve Figure 6. Formation of eddies in wind flow Journal of Civil Engineering and Management, 2025, 31(4), 338–361 aeolian vibration, which specifically denotes the vibration caused by the interaction between the wind and the con ductor (Whapham, 2012

IV. PUBLICATION PRINCIPLES

When a flow exceeds the limit velocity for the laminar f low, it creates vortices/eddies by transferring into a turbu lent 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 me chanical impedance of the conductor. Further, surrounding conditions such as terrain and wind conditions also influ ence 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 adhe sion of wet snow to powerlines poses challenges, particu larly 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 sur face 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) 343 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 conduc tors 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, gener ates opposing electromagnetic forces that act in opposite directions within the conductors (Khan, 2020). These op posing forces result in tension within the conductor, caus ing

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 pull ing forces. These loads can potentially affect the integrity and performance of the conductors. Furthermore, conduc tor 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 dif f icult 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 Stand ards, ASCE (American Society of Civil Engineers), IEC (In ternational Electrotechnical Commission), and CENELEC (European Committee for Electrotechnical Standardization) which cover the design, installation, operation, and main tenance of electrical power infrastructure. 344 S. Jayathilake et al. Review of the design and condition monitoring of overhead power distribution conductors In the Australian context, power distribution networks are designed in accordance with AS/NZS 7000:2016 (Stand ards Australia & Standards New Zealand, 2016) which re fers to other Australian standards to cover specific aspects such as electrical or mechanical. Conductors in the power lines 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 & Stand ards 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 arrange ment 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 primar ily influenced by various factors, including the tension ap plied 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 verti cal and horizontal components of the tension (T) respec tively. 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 (Stand ards 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 oc casional 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 fail ure 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 in duced by wind loading on the conductor. Furthermore, Ap pendix 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-tem perature 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 infor mation (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-in duced aeolian vibration and galloping on powerlines by using scaled-down wind tunnel models to cater to the ac tual environmental effect in the component of the power overhead line network. As an initiation, Farquharson and McHugh (1956) investigated the behaviour of a conduc tor in a wind tunnel under a steady wind stream and cal culated 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 predict ing 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 coeffi cients in the open air. Loredo-Souza and Davenport (2001, 2002) performed wind tunnel tests on two parallel conduc tors 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 sta tistical method. Later, Bartoli et al. (2006) also conducted the same kind of wind tunnel testing on steel strand con ductors to identify the conductor drag coefficient in differ ent 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 Journal of Civil Engineering and Management, 2025, 31(4), 338–361 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 tun nel 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 elec trical transmission lines. While wind tunnel tests provide highly valuable data, numerical modelling offers an attrac tive cost-effective alternative. 3.2.3. Computer-based numerical simulation The finite element method has been applied using com puter software to predict the mechanical behaviour of conductors under various load conditions. The most of ten 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 in side 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 power lines with optimal configurations and parameters. World wide, 80% of the weather-associated failures in trans mission 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 & Igle sias, 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, pow erline 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 mov ing 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 345 iced conductor has been evaluated by Dong et al. (2022) using the CFD interface in ANSYS Fluent. Here, the influ ence 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 devel oped a CFD simulation to evaluate the conductor tension due to ice accumulation at instantaneous wind velocities. Computer-based simulations have also been devel oped to understand the performance of conductors when subject to temperature changes. Gómez et al. (2011) per formed CFD analysis with ANSYS-Fluent software to iden tify 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,

V. UINT

the study was extended to address the ther mal and fluid-dynamic behaviour with different working conditions. Furthermore, a finite element model was de veloped 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 fail ures in the power distribution network can be attributed to various factors such as fatigue, vibration, annealing, clash ing, corrosion, joints, and ties. They can also be caused by external factors including extreme weather events, animals, f ire, 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 con ductors 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 ob servation in this data set is the failures of different compo nents 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 con ductor population data given in Figure 3. 346 S. Jayathilake et al. Review of the design and condition monitoring of overhead power distribution conductors The cause of failures in those conductor types is evalu ated in Figure 11. Here failures related to different compo nents such as sleeves, ties, clamps, insulators, and dead end grips are considered as failures of associated compo nents 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 cor rosion and wind according to Figure

11. But in copper and ABC conductors, corrosion accounts

for considerable fail ures although it is not the critical cause of failure. Con nection 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. Simi larly, 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 distribu tion grip dead ends. However, vibration is a significant fac tor in these conductor failures as well. It should be noted that unidentified other causes claim considerable failures in every type of conductor. 0% 4% 8% 12% 16% 20% Corrosion Wind Connection, Bridge Tie failure Fatigue Vibration Insulation Failure Connection Copper to aluminium Clamp, live line Clamp, PG Clashing Connection D-loop Dead-end helical termination Loose connection Sleeve, automatic Splice Clamp, wedge (AMP) Splice, helical, steel Sleeve, Non Tension Connection, unknown Sleeve, Full Tension Sleeve, McIntyre Other Third party Percentage of failur Figure 9. Percentage of failures attributed to different causes 11.1% 5.8% 8.0% 38.8% 36.3% Steel Aluminium ACSR Copper AB Figure 10. Percentage of failures of conductors based on conductor type Naranpanawe et al. (2018) published data on power lines in overhead distribution networks and their failures. According to their study, Figure 12 shows the percentage of conductor unassisted failures for steel, copper, alumin ium, and ACSR that were observed in different geographi cal 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 lit erature, a few causes of failures are identified as severe is sues which can start powerline breakdowns. Those are cor rosion, wind, vibration, fatigue, failure in connections, and associated components. However, most of these failures 0% 4% 8% 12% 16% ACSR Aluminium Steel Copper ABC Percentage failures (%) Cable Type Corrosion Wind Failure of associated components Connection failure Vibration Fatigue Other Figure 11. Summary of percentage failure based on conductor type 0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100% Copper Aluminium ACSR Steel Percentage of failures Coastal Highlands Pla Figure 12. The percentage of conductor unassisted failures (Naranpanawe et al., 2018) Journal of Civil Engineering and Management, 2025, 31(4), 338–361 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 corro sion including atmospheric corrosion, galvanic corrosion, and crevice corrosion (Alstad et al., 1993; Popova & Prošek, 2022). Figure 13a illustrates a corroded steel conductor ex tracted from a power distribution network after 65 years of service and Figure 13b shows a 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, ei ther 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 dam aged systems. Although its precise makeup is unknown, it is thought that this powder is a blend of aluminium corro sion compounds (van Deursen et al., 2019). ACSR conductors frequently experience galvanic corro sion, 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 us ing 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 dis tribution lines does not create trouble, fatigue or abrasion failures can generally occur over time when the conduc tor 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 ex ceeds the endurance limit. The bending of the conduc tor 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. Many studies have been carried out to identify the fa tigue behaviour of conductors using single stands as well as whole conductors (Jiang et al., 2023a; Kalombo et al., 347 a) b) Figure 13. a – corroded steel conductor; b – corroded ACSR conductor Figure 14. Possible fretting scars on the aluminium outer layer (Said et al., 2020) 2015, 2016; Kul'kov et al., 2021a). However, fatigue is de pendent 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, cal culating 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 capabil ity of accurate prediction of stress in conductors and fa tigue 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., 348 S. Jayathilake et al. Review of the design and condition monitoring of overhead power distribution conductors 2023). During operation, overhead conductors are known to undergo both short-term and long-term annealing. An nealing is a process that leads to a reduction in the tensile strength of conductors and induces permanent elonga tion. 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 age ing 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 Fonse ca (2013) experimented with ACSR conductors to establish a relationship between progressive wire rupture and the temperature of the conductor. However, all weather condi tions 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 conduc tors. Yaqoob et al. (2022) developed a fuzzy dynamic ther mal 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 oc curring in the power network, deterioration processes and their different signs have to be identified for proper main tenance. Visual inspection has traditionally been the princi pal method used to identify damage to overhead conduc tors. And those qualitative inspections are largely used to inform decisions about maintenance and replacement.

VI. CONCLUSION

assessments When making well-founded judgments about mainte nance, replacement, and upgrading the overhead lines in the distribution network, conducting condition assess ments using a mix of inspections, testing, and analysis is crucial. This means that the results of condition evalua tion 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 dam age 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 el evator work flatform, pole climbing, or helicopters. Discol ouration 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. In ternal deterioration cannot be easily found by visual in spection. 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 visu alized due to the absence of physically unexposed dam ages (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 symp tom of weakening of the joint which could lead to me chanical 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 dis tances. 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 col lected from IR imageing. However, in this test, robot equip ment was also used to carry out inspections. Although air borne 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 transmis sion lines were carried out continuously with the develop ment 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

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