Overhead Conductor Condition Monitoring

Milestone Report 1

Prepared by Dr Lakshitha Naranpanawe, Dr Hui Ma and Professor Tapan Saha

Power & Energy Systems Research Group

School of Information Technology & Electrical Engineering

The University of Queensland

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THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

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Milestone 1 - Progress Report

Produced by

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Power & Energy Systems Research Group
Axon building (#47), Staff House Road, St. Lucia Campus
The University of Queensland
Brisbane, QLD 4072 Australia
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Tony Stevens (SA Power)		

Executive Summary

Energy Networks Association (ENA) member utilities have almost 800,000 circuit kilometres of overhead conductor in service, valued at several billion dollars. Many of this critical infrastructure are ageing with some already reaching 70 years.   Current conductor condition monitoring practices are mainly visual inspections and conductor replacement is usually driven by the frequency of conductor failures. Reliable and cost-effective methods to assess the likelihood of a conductor failure have not yet been developed.

This project investigates the effective ways of monitor and assess the condition of overhead conductor for an improved asset management of conductors in Australian distribution networks. The objectives are:

- Review of conductor failure modes, degradation mechanisms, and ageing parameters, which are primarily responsible in influencing conductor degradation; and current Australian industry practices to test, operate, inspect, and asset manage overhead distribution conductors.
- Define the criteria for quantifying conductor condition and its end-of-life, and subsequently determine the probability of conductor failure and estimate its remaining useful life.
- Identify the core areas of research and development for improving condition assessment of conductors in Australian DNSPs' networks.
- Survey state-of-the-art conductor condition monitoring techniques (e.g. smart sensor and other advanced tested and validated techniques in overseas) that could be used to monitor distribution conductor condition without having to de-energise the distribution network. Assess the practicality and economics of applying these techniques and evaluate their suitability for Australian networks.

This project was started on June 20, 2018. Having been working closely with project industry partners in the past six months, the research team has reviewed conductor population in Australian Distribution Network Service Providers (DNSPs) circuits including the types, failure modes and geographical locales of conductors. A comprehensive study has been performed to understand the conductor degradation mechanism and parameters that affect each type of degradation mechanism. The focus of the investigation has been on the root causes of Australian conductor deterioration. The research team has also reviewed the current Australian

DNSP's practice on conductor asset management and their requirements for a proactive yet cost-effective conductor condition monitoring.

In the past six months, the research team has carefully reviewed the ENA 2015-2016 conductor survey and individual utility surveys, open source databases, IEEE, IEC and CIGRE standards and recommendations and other literature. The research team has consulted two industry experts Colin Lee and Keith Callaghan on distribution conductor failure mechanisms and condition monitoring. From the above review and study, the team has identified core areas of research and development for an improved condition assessment of conductors in Australian DNSPs' circuits. They are:

1) Statistical modelling for determining overhead conductor failure probability considering the age and geographical location of conductors. The model can be used to define end-of-life criteria for overhead conductors in Australian DNSPs' networks.
2) Dynamic conductor temperature modelling with the incorporation of environmental conditions, load fluctuations, elevated temperature and fault/reclose operations. The model can be used to determine the loss of tensile strength of overhead lines accurately due to annealing.
3) Smart sensory technologies that are suitable for condition monitoring of conductors in Australian DNSPs' networks.

At the next stage of the project, the research team will explore suitable modelling techniques for quantifying conductor condition and estimating its probability of failure. The team will also investigate the state-of-the-art commercially available conductor monitoring system and emerging smart sensor based system for Australian DNSPs' networks.

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1 Introduction

ENA members have almost 800,000 circuit kilometres of overhead conductor in service. This represents an asset, which is conservatively valued over several billion dollars. Overhead conductor asset can be of different metal types, different sizes and capacities, and is employed in all climatic zones including tropical, temperate, arid, and highlands. Many conductor assets are ageing with some already reaching 70 years. Though many advancements in technology have been achieved throughout these years, approaches to cost-effectively monitor condition of bulk of conductors have not substantially changed. Existing conductor condition monitoring practices are still visual inspections and conductor replacement is usually driven by the frequency of conductor failures. Reliable and cost-effective methods to assess the likelihood of a conductor failure have not yet been developed for the Australian distribution network service providers (DNSP) networks.

On June 20th 2018, ENA approved a research project proposal submitted by the University of Queensland team, led by Professor Tapan Saha & Dr Hui Ma. The project is aimed at investigating how to effectively monitor and assess the condition of overhead conductor for an improved asset management of conductors in Australian distribution networks. The project has been conducting research for:

1) An establishment of a knowledge base of overhead conductors in Australian distribution network and subsequently the identification of the current core areas of research and development for an improved conductor condition assessment;
2) A methodology for quantifying conductor condition and estimating the remaining useful life of conductor; and
3) Identification of state-of-the-art commercially available conductor monitoring system and emerging smart sensor-based system and possibly evaluating a smart sensor(s) with data collection methods including their communication modules.

This report is the first six-month milestone report, which includes:

1) A review on Australian DNSPs experiences of conductor failure modes with the relevant information (conductor type, installation, operation, maintenance, and failure location);

2) A literature survey of methodologies for defining the criteria for quantifying conductors' condition and its end-of-life and subsequently determining the probability of conductor failure and estimating its remaining useful life;
3) A proposal on the possible areas of research and development for improving conductor condition monitoring and asset management in Australian DNSPs' networks.

To complete this report, a number of sources have been explored. They are:

- datasets provided by Australian DNSPs (listed in Table 1),
- publicly available Australian power network asset management reports
- other online resources such as Regulatory Information Notices (RIN) data,
- publications from international science and technology societies including IEEE, IET, IEC, and Cigré, etc.

Table 1 Australian DNSPs

DNSP	State
ActewAGL	ACT
AUSGRID	NSW
Essential Energy	NSW
Transport for NSW	NSW
AusNet Services	VIC
United Energy	VIC
Jemena	VIC
Energex & Ergon Energy (Energy Queensland)	QLD
Horizon Power	WA
Western Power	WA
SA Power Networks	SA
TasNetworks	TAS

The remaining of this report is organized as follows. Part 2 is a review on overhead conductor manufacturing process. This provides some fundamental knowledge for the research works of this project. Part 3 summarises the Australian DNSPs experience on overhead conductor failures and condition monitoring. A comprehensive literature review on degradation of overhead conductors and condition monitoring is presented in Part 4. Part 5 of the report presents the possible areas of research that needs to be conducted to improve the condition assessment of overhead conductors in Australian distribution network. Finally, the conclusion of the report is presented in Part 6.

2 A Brief Review of Overhead Conductor Manufacturing Process

Overhead conductors are designed to withstand strong mechanical stresses throughout the 50-60 year lifetime. The manufacturing process of overhead conductors has a direct relationship with the strength of the final product and some of its degradation mechanisms e.g. corrosion and annealing. Hence, this section provides an overview of overhead conductor manufacturing process.

Conductor manufacturing process starts with a cold drawing of the redraw rods. The wires in a conductor are usually drawn from a redraw rod having a standard diameter. It is common practice for wire manufacturers to use annealed 9.5 mm diameter draw rod for aluminium type conductor, up to 3.5 mm draw rod for aluminium-alloy type conductor, and 12.7 mm draw rod for thicker wire conductor. Copper wires are often drawn from 8 mm rod. During the cold drawing process, diameter of the redraw rods is reduced to a desired size by pushing through a set of dies [1, 2].

The above cold drawing process that used to manufacture conductors destroys the long-range order of the crystals, reduces the size of the sub-grains and increases the stored energy. The increase in energy is a result of imperfections in the lattice structure i.e. stacking faults, twins, point-defect vacancies, interstitial atoms and precipitates. The smaller the diameter of the drawn wire the greater the initial tensile strength. Moreover, greater the degree of cold drawing process the greater the loss of strength for a given temperature and time duration. During the wire drawing, the increase in temperature initiates some recovery and energy is stored at the boundaries of the sub-grains, which may be highly oriented. Furthermore, at any time, if the drawn wire is subjected to elevated temperature levels, energy starts to recover. During the recovery, tensile strength and hardness decrease significantly with the increase of time duration and temperature. After fully recrystallized, the metal becomes soft as it was before cold working [2, 3].

3 Australian DNSPs Experience with Conductor Failure Modes with Respect to Conductor Type, Installation, Operation, Maintenance and Location

3.1 Conductor Types in Australian Distribution Network

3.1.1 Aluminium Conductor Steel Reinforced (ACSR) Conductor

The conventional ACSR conductor consists of a steel core surrounded by up to three layers of aluminium strands. Typically, the steel core consists of 1, 7, or 19 galvanized steel strands. ACSR conductors have a high tensile strength and good electrical conductivity. They are frequently supplied with greased steel core wires to inhibit corrosion. ACSR conductors widely used on distribution lines may have 1, 3, 4 or 7 strands of steel wires (e.g Apple 6/1/3.0, Banana, 6/1/3.75, Cherry 6/4.75, 7/1.6 and Raisin 3/4/2.5)

3.1.2 Copper Conductor

Hard drawn copper conductors are also available in different sizes ranging from a single strand to 61 strands. However, the most common sizes of the copper conductors in Australian distribution network are hard drawn 7/.064 (seven strands with each strand of 0.064 inches in diameter), 7/.080 and 7/.104 installed in 1960s. Table 2 summarizes the metric parameters of hard-drawn copper conductors. Copper has an excellent conductivity and good corrosion resistance. However, copper is more expensive than aluminium and steel. Thus, nowadays the hard drawn copper conductors are rarely used in the overhead networks.

Table 2 Properties of Hard-Drawn Copper Wires [4]

1	2	3	4	5	6	7	8
Standard diameters			Cross-sectional area†	Mass per km†	Minimum breaking load†	Minimum ultimate tensile stress	Maximum d.c. resistance per km at 20°C†
Nominal	Max.	Min.					
mm	mm	mm	mm^2	kg	kN	MPa	Ω
1.00	1.010	0.990	0.7854	6.98	0.361	460	22.6
1.25	1.263	1.238	1.227	10.9	0.558	455	14.5
1.75	1.768	1.733	2.405	21.4	1.07	445	7.39
2.00	2.020	1.980	3.142	27.9	1.38	440	5.66
2.50	2.525	2.475	4.909	43.6	2.11	430	3.62
2.75	2.778	2.723	5.940	52.8	2.52	425	2.99
3.00	3.030	2.970	7.069	62.8	2.97	420	2.51
3.50	3.535	3.465	9.621	85.5	3.94	410	1.85
3.75	3.788	3.713	11.04	98.1	4.47	405	1.61

† Tabulated values are based on nominal diameters given in Column 1 and are provided for information only.

3.1.3 Steel Conductor

High-strength and extra-high-strength galvanised steel conductors are commonly used on Single Wire Earth Return (SWER) lines in distribution networks and as overhead earthwires on sub-transmission and transmission lines. These conductors consist of 3 or 7 strands of steel and their strand diameter varies from 2.0 to 3.75 mm. Table 3 summarizes parameters of steel conductors. Galvanising (zinc coating) can improve the corrosion resistivity of corrosion-susceptible steel. However, the zinc coating tends to deteriorate when exposed to corrosive environments.

Table 3 Properties of Galvanized steel wires [4]

1	2	3	4	5	6	7	8	9
Standard diameters			**Cross-sectional area***	**Mass per km***	**Minimum breaking load***	**Minimum ultimate tensile stress**	**Typical d.c. resistance per km at 20°C***	**Min. zinc coating mass †**
Nominal	**Max.**	**Min.**						
mm	**mm**	**mm**	**mm^2**	**kg**	**kN**	**MPa**	**Ω**	**g/m^2**
2.00	2.060	1.960	3.142	24.5	4.12	1310	60	215
2.75	2.833	2.695	5.940	46.3	7.78	1310	32	240
3.25	3.315	3.185	8.296	64.7	10.9	1310	23	250
3.75	3.825	3.675	11.04	86.1	14.5	1310	17	260

* Tabulated values are based on the nominal diameters given in Column 1, and are given for information only.
† For coating masses of non-standard wire sizes see AS 1650.

3.1.4 Aluminium Conductor

All-Aluminium conductor (AAC) is a conductor type consisting of aluminium strands of 1350 aluminium alloy. The most common AAC type in Australian distribution network is Libra 7/3.0, Mars 7/3.75, Moon 7/4.75, and Pluto 19/3.75 (mm). These conductors are typically installed in short span distribution lines in urban areas. For applications which require conductor with high tensile strength, for example, long span lines in rural areas, All Aluminium Alloyed Conductor (AAAC) type conductors, i.e. such as Iodine 7/4.75 and Neon 19/3.75 are used. Tables 4, 5 and 6 summarize parameters of the three typical type aluminium conductors. There are only a handful of overhead lines in Australia which utilise the 6201 alloyed conductors.

Table 4 Properties of Aluminium 1350 wires [4]

1	2	3	4	5	6	7	8
Standard diameters			Cross-sectional area*	Mass per km*	Minimum breaking load*	Minimum ultimate tensile stress	Maximum d.c. resistance per km at 20°C*
Nominal	Max.	Min.					
mm	mm	mm	mm²	kg	kN	MPa	Ω
2.50	2.525	2.475	4.909	13.3	0.859	175	5.76
2.75	2.778	2.723	5.940	16.0	1.01	170	4.76
3.00	3.030	2.970	7.069	19.1	1.20	170	4.00
3.25	3.283	3.218	8.296	22.4	1.37	165	3.41
3.50	3.535	3.465	9.621	26.0	1.59	165	2.94
3.75	3.788	3.713	11.04	29.8	1.77	160	2.56
4.50	4.545	4.455	15.90	42.9	2.54	160	1.78
4.75	4.798	4.703	17.72	47.8	2.84	160	1.60

* Tabulated values are based on the nominal diameters given in Column 1 and are provided for information only.

Table 5 Properties of Aluminium 1120 wires [4]

1	2	3	4	5	6	7	8
Standard diameters			Cross-sectional area*	Mass per km*	Minimum breaking load*	Minimum ultimate tensile stress	Maximum d.c. resistance per km at 20°C*
Nominal	Max.	Min.					
mm	mm	mm	mm²	kg	kN	MPa	Ω
2.50	2.525	2.475	4.909	13.3	1.23	250	5.97
2.75	2.778	2.723	5.940	16.0	1.49	250	4.93
3.00	3.030	2.970	7.069	19.1	1.77	250	4.14
3.25	3.283	3.218	8.296	22.4	2.07	250	3.53
3.50	3.535	3.465	9.621	26.0	2.31	240	3.05
3.75	3.788	3.713	11.04	29.8	2.65	240	2.65
4.50	4.545	4.455	15.90	42.9	3.66	230	1.84
4.75	4.798	4.703	17.72	47.8	4.08	230	1.65

* Tabulated values are based on the nominal diameters given in Column 1 and are provided for information only.

Table 6 Properties of Aluminium alloy 6201A wires [4]

1	2	3	4	5	6	7	8
Standard diameters			Cross-sectional area*	Mass per km*	Minimum breaking load*	Minimum ultimate tensile stress	Maximum d.c. resistance per km at 20°C*
Nominal	Max.	Min.					
mm	mm	mm	mm²	kg	kN	MPa	Ω
2.50	2.525	2.475	4.909	13.3	1.45	295	6.68
2.75	2.778	2.723	5.940	16.0	1.75	295	5.52
3.00	3.030	2.970	7.069	19.1	2.09	295	4.64
3.25	3.283	3.218	8.296	22.4	2.45	295	3.95
3.50	3.535	3.465	9.621	26.0	2.84	295	3.41
3.75	3.788	3.713	11.04	29.8	3.26	295	2.97
4.50	4.545	4.455	15.90	42.9	4.69	295	2.06
4.75	4.798	4.703	17.72	47.8	5.23	295	1.85

* Tabulated values are based on the nominal diameters given in Column 1 and are given for information only.

3.1.5 Aluminium Clad Steel (ACS)

Aluminium Clad Steel (ACS) overhead conductors are manufactured from aluminium coated high strength steel wires and have been used on SWER lines and overhead earthwires. In an ACS conductor, a layer of aluminium coating is solidly bonded to the steel surface through a metallurgical bond. The conductivity of the ACS conductor is proportional to the thickness of the aluminium layer. Typically, the minimum thickness of the aluminium layer is about 10% of the radius of the steel wire (about 25% of the cross-sectional area). Table 7 summarizes parameters of ACS conductors.

Table 7 Properties of Aluminium- Clad Steel wires [4]

1	2	3	4	5	6	7	8
Standard diameters			Cross-sectional area*	Mass per km*	Minimum breaking load*	Minimum ultimate tensile stress	Maximum d.c. resistance per km at 20°C*
Nominal	Max.	Min.					
mm	mm	mm	mm^2	kg	kN	MPa	Ω
2.75	2.791	2.709	5.940	39.1	7.96	1 340	14.3
3.00	3.045	2.955	7.069	46.6	9.47	1 340	12.0
3.25	3.299	3.201	8.296	54.7	11.1	1 340	10.2
3.75	3.806	3.694	11.04	72.8	13.8	1 250	7.70
4.25	4.313	4.186	14.19	93.5	16.7	1 180	5.98

* Tabulated values are based on the nominal diameters given in Column 1, and are given for information only.

3.2 Conductor Population in Australian Distribution Networks

Historically, galvanised steel conductors were commonly used in Australian HV overhead rural distribution networks, mainly in the single- wire earth return (SWER) networks. The main reason is due to the high tensile strength of steel that enables the conductors to be strung over longer spans, thereby reducing line costs. Copper was the most commonly used conductor for overhead lines in the early days of distribution network growth until about the 1960's , when it was slowly overtaken by ACSR and all aluminium conductors due to their lower mass, higher strength enabling longer spans, with an acceptable reduction in conductivity. These, in turn, were slowly overtaken by aluminium alloys for longer span uses, and specialist conductors, due to their lower all-up costs.

Table 8 summarizes the population of each major types of conductors in Australian distribution networks. Figure 1 present conductor circuit length (in km) in LV (< 1 kV) and HV Australian distribution networks.

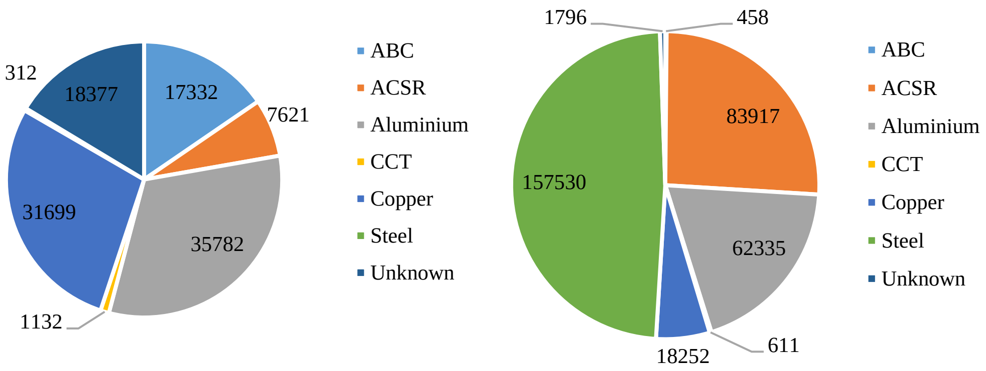


Figure 1 Conductor circuit length (in km) in LV (< 1kV) (left) and HV ((right) networks of Australian DNSPs listed in Table 1

Table 8: Information on Conductor population in various DNSPs [5-12]

	Copper	ACSR	Steel			Aluminium			Other	State
			AC/ GZ	SC/ AC		AAC	AAAC			
ActwAGL	18 %	7 %			10 %			54 %	11 %	ACT
Ausgrid	41.8%	12.3%	1.2%	0.0%	1.2%	31.8%	0.7%	32.5%	12.2%	NSW
Essential Energy	6.7 %	26 %			46 %			13 %	8.3 %	NSW
TransGrid	-	-	-	-	-	-	-	-	-	NSW
Transport for NSW	74.8 %	0.8 %			0 %			24 %	0.4 %	NSW
Energex	22 %	18.7 %			2 %			45.9 %	11.4 %	QLD
AusNet Services	4.5 %	23 %			49.5 %			17.2 %	5.8 %	VIC
Jemena	13.8 %	2.6 %			4 %			23 %	56.6 %	VIC
United Energy	9.5 %	19.4 %			3.3 %			27.4 %	40.4 %	VIC
TasNetworks	10.5 %	3.4 %			27.6 %			49 %	9.5 %	TAS
SA Power Networks	22.5 %	25 %			27.5 %			21 %	4 %	SA
Horizon Power	2.5 %	25.7 %			41.3 %			25.5 %	5 %	WA
Western Power	7 %	13 %	52 %	5 %		16 %	6 %		1 %	WA

In general, aluminium and copper conductor are the most widely used conductor types in Australian LV network. On the other hand, a steel conductor is the major conductor type installed in Australian power lines above 1 kV because of the utilities extensive rural networks.

These conductors are installed in different climate zones across Australia. As per AS/NZS 7000:2016 (Figure 2), these climate zones are categorised into three namely arid, temperate, and tropical. However, to be consistent with ENA definitions that are used in 2015-2016 ENA conductor survey report, conductor population locations are classified into four climate zones namely Coastal, Highlands, Plains and Arid. The definitions of the above four climate zones are as follows.

1. Coastal - humid climate. Typically within 100 km from the coast.
2. Highlands - typically mountainous areas with moderate rainfall.
3. Plains - typically low to moderate rainfall area.
4. Arid – barren, very low rainfall area.

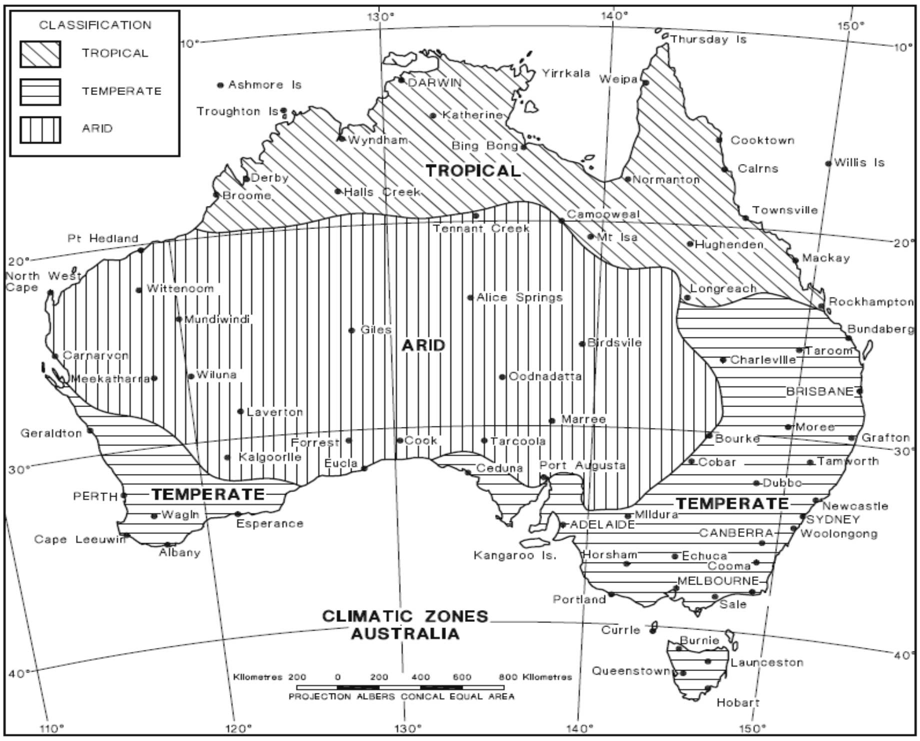


Figure 2 Climatic Zones for Australia as per AS/NZS 7000:2016

3.3 The Age Distribution of Conductors in Australian Distribution Networks

Australian distribution network consists of overhead conductors installed from the early 1920s to present. For an example, the periods of installation of different conductor types in Jemena network in Victoria are shown in Table 9. Further, a significant portion of the conductors installed more than 50 years ago are still in use (See conductor age profile of a NSW DNSP in Figure 3). Therefore, conductor ageing is becoming a major concern of Australian DNSPs.

Table 9 Typical Periods of installation of different conductors in Jemena distribution network (VIC) [10]

Conductor type	Installation Years
Copper Conductor	1920 – 1960
Cadmium Copper	1960 – 1975
Steel	1960 – present
ACSR	1960-1975
Aluminium (AAC)	1975 - present

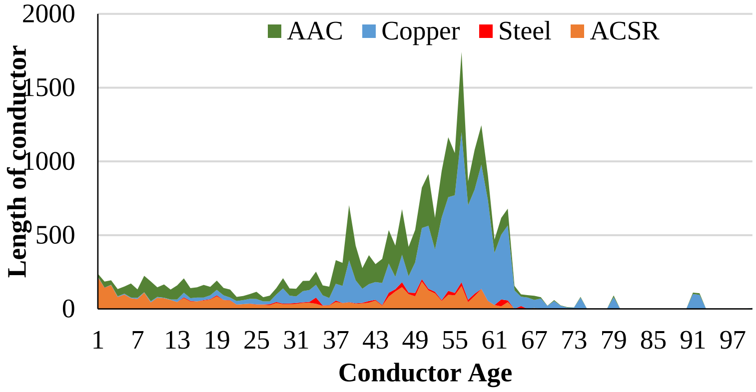


Figure 3 Overhead conductor age profile of a NSW DNSP

Figure 4 illustrates the average age of overhead conductors in Australian distribution networks. The data in Figure 3 are taken from the RIN response document. Amongst Australian DNSPs listed in Figure 4, Ausgrid and United Energy have an average conductor age below 50 years. Conductors in other DNSPs are well beyond 50-year-old and their average age is 58.3 years.

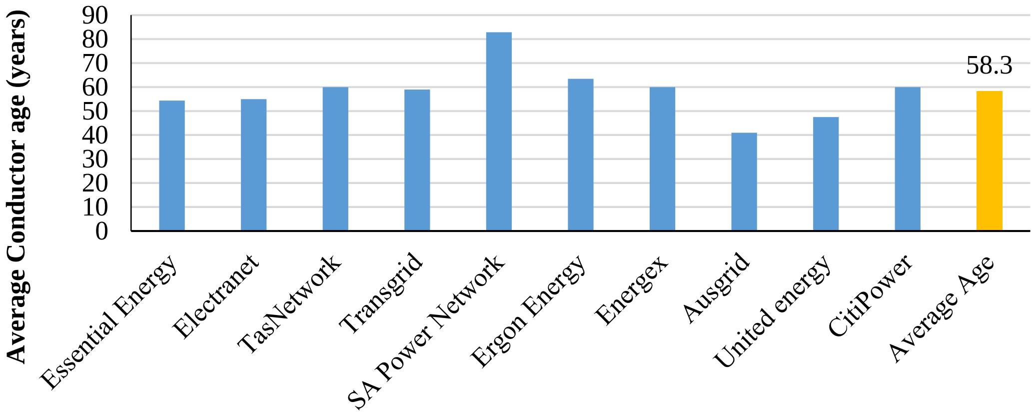


Figure 4 Average age of Overhead conductors in Australian DNSPs (Source: RIN data: https://www.aer.gov.au/taxonomy/term/1495)

After a long period of service, conductor ages and its material properties degrade. With ageing, conductors can eventually lose both their mechanical and electrical strengths. Due to the reduced mechanical strength, the conductors can have a higher probability of failure compared to unaged conductors. To minimize the risk of damage caused by conductor failure, DNSPs normally replace conductors, which may have reached end of their service life.

Figure 4 shows the typical conductor ages at the time the conductors are replaced in several Australian DNSPs. It can be seen that the typical conductor replacement age varies from about 40 to 77 years.

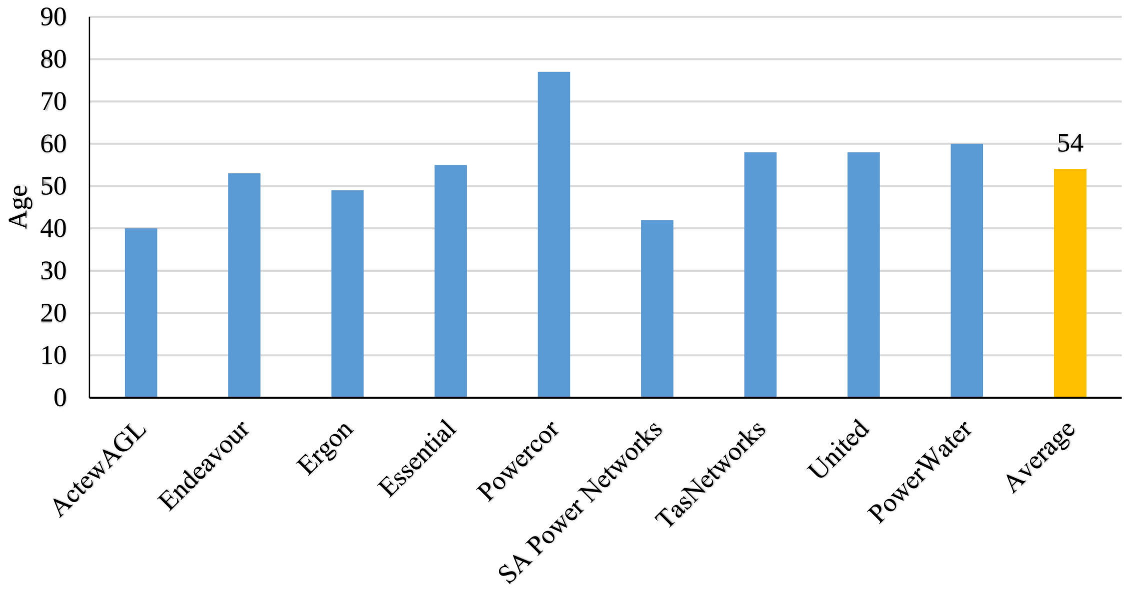


Figure 5 Conductor Replacement life in Australian DNSP's [7]

3.4 Modes of Conductor Failure in Australian Distribution Networks

According to the conductor failure data received from the Australian DNSPs listed in Table 1, two types of overhead conductor failure modes, "unassisted" and "assisted" were defined. Assisted failure is a failure caused by a phenomenon, which was not controllable by DNSPs such as third-party effects. Unassisted failures are caused by factors that are controllable or detectable by DNSPs. Typical examples of assisted and unassisted failure causes are listed in Table 10. Related statistics are discussed as follows.

Table 10: Overhead conductor failure modes [13]

Unassisted	Assisted
Annealing/ Overloading	Animals
Clashing	Extreme weather
Corrosion/ Rust	Fire
Fatigue	Human error
Splice/ Joint	Lightning
Ties	Secondary failures
Vibration	Third party impacts
	Vandalism
	Vegetation

Figure 6 summarises the percentages of different causes of failure in unassisted failures mode. It can be seen that corrosion contributes to about 30% of failures. It is the main cause of conductor failure. The other significant failure causes are Splice/Joint failure (19%) and fatigue (14%). It is noted that most of the above failure causes are sensitive to the environmental conditions.

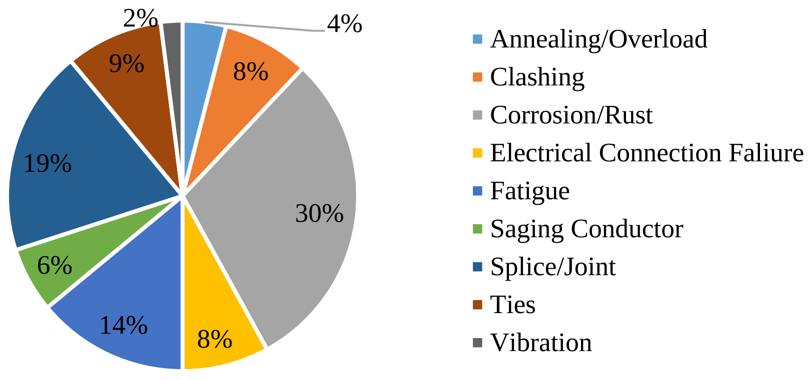


Figure 6 Different cause of conductor failure in unassisted failure mode

Figure 7 illustrates the percentage of copper, aluminium, ACSR and steel conductor unassisted failures recorded in each geographical zone. Since the majority of the conductors in Australian distribution networks are located in coastal areas (within 100km of the coast), one can suggest that corrosion may be the major conductor failure mode in Australian distribution networks. This can be clearly observed in the conductor failure statistics presented in Figure 7 .

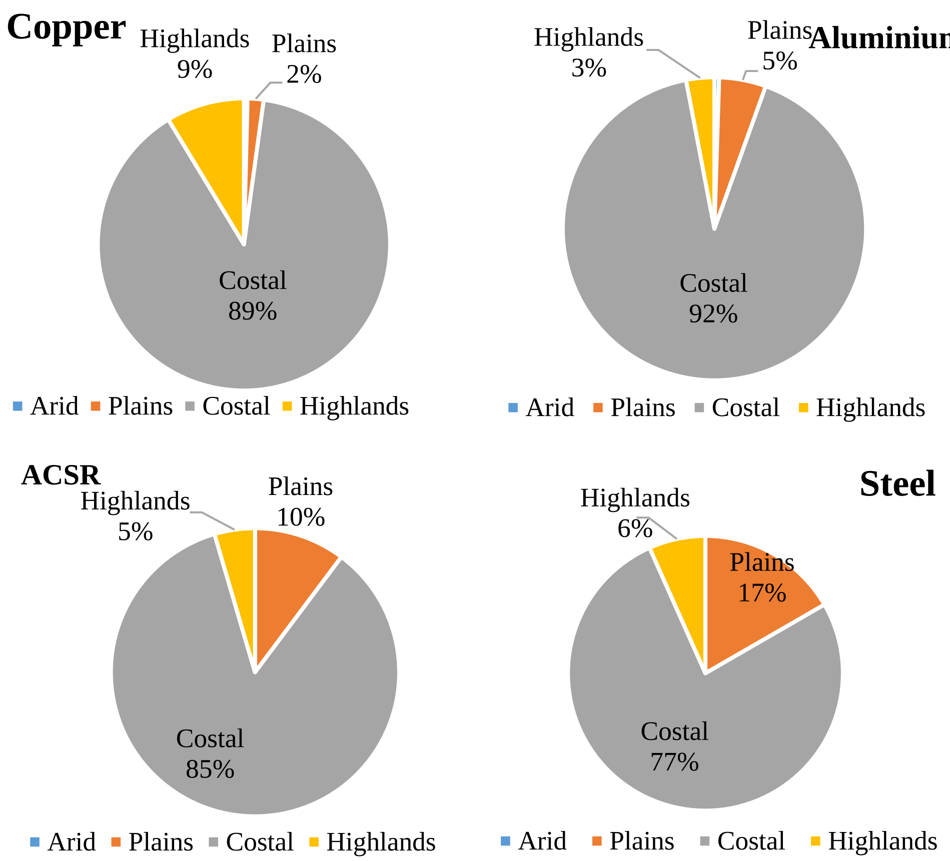


Figure 7 Overhead conductor failure statistics correspond to DNSPs in Table 1 in each geographical zone

3.4.1 Case Study of Conductor Failures in Energex Distribution Networks

Figure 8 illustrates the causes of overhead conductor failures recorded in Energex distribution system from 2012 to 2018. It can be seen that age and corrosion are the main conductor failure causes. Age and corrosion have contributed to about 34% and 38% of conductor failures. Further, vibration also contributed to 13% of overhead conductor failures.

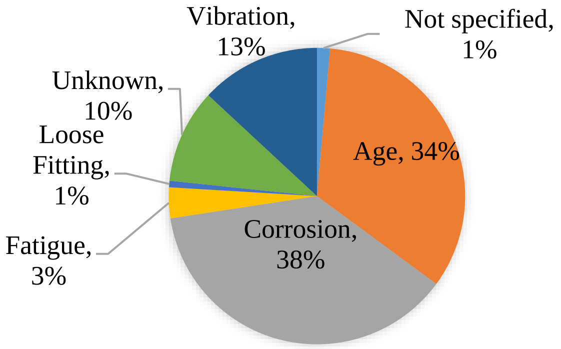


Figure 8 Causes of unassisted conductor failures in Energex distribution network in 2012-2018

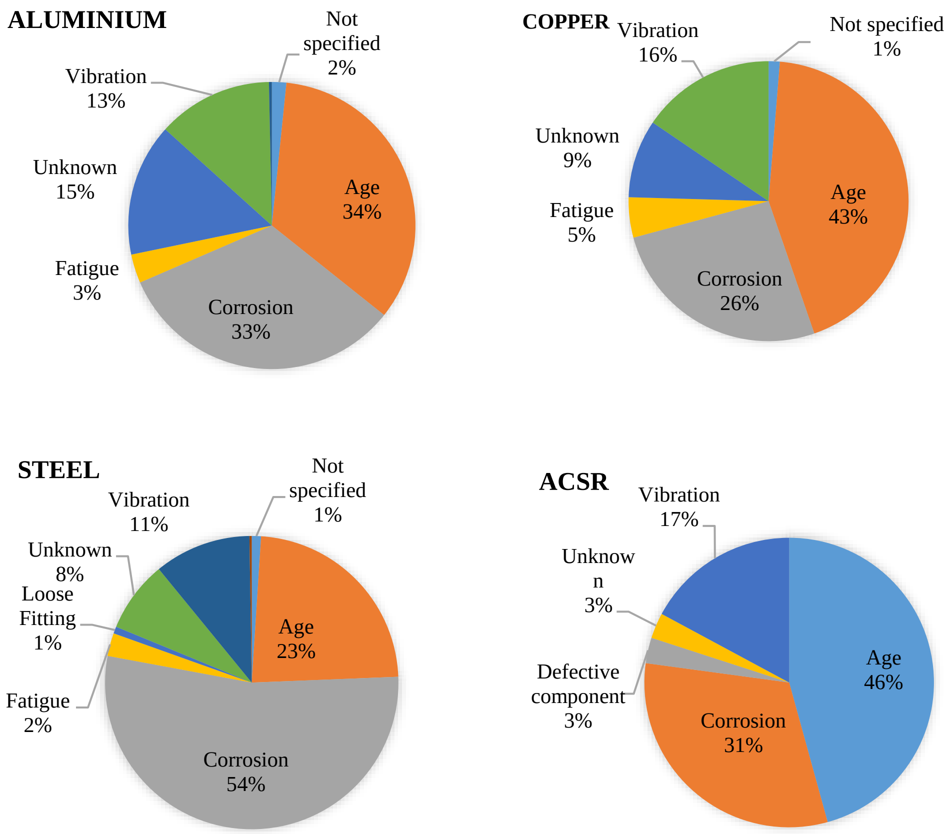


Figure 9 Unassisted failure by conductor type in Energex network (2012-2018)

Figure 9 illustrates causes of aluminium, copper, steel and ACSR conductor failures recorded in Energex network during the period 2012 to 2018. From Figure 9, it can be seen that service age is the major cause of failures in aluminium, copper, and ACSR cables. In contrast, corrosion is the major cause of steel conductor failures. It is suggested that failures due to service age may be associated with significant defects or loss of cross-section area of the conductor. This could be caused by lightning or vegetation impact, conductor clashing, annealing, degraded joints/spices, or cumulative fault and reclose operation.

3.4.2 A Case Study of Conductor Failures in TasNetwork's Distribution Networks (Based on Asset Management Plan: Conductor and Hardware – Distribution 2015)

TasNetwork distribution network consists of about 21,323 circuit kilometres of overhead conductors and Aerial bundled cables (ABC). More information on the conductor population data is listed in Table 11.

Table 11 Overhead conductor/cable lengths in TasNetwork network [11]

Conductor/cable type	Length (km)
Copper	1,288
Aluminium	8,436
Galvanized steel	5,888
ACSR	730
ABC	18
LV conductors	4,973
Total	21,323

The overhead conductors in TasNetwork system cover a wide range of age levels from few years to about 60 years. Figure 10 illustrates the age profile of the overhead conductors in TasNetwork. It can be seen that majority of the conductors are beyond 30 years. Further, a significant portion of the overhead conductors has reached 60 years.

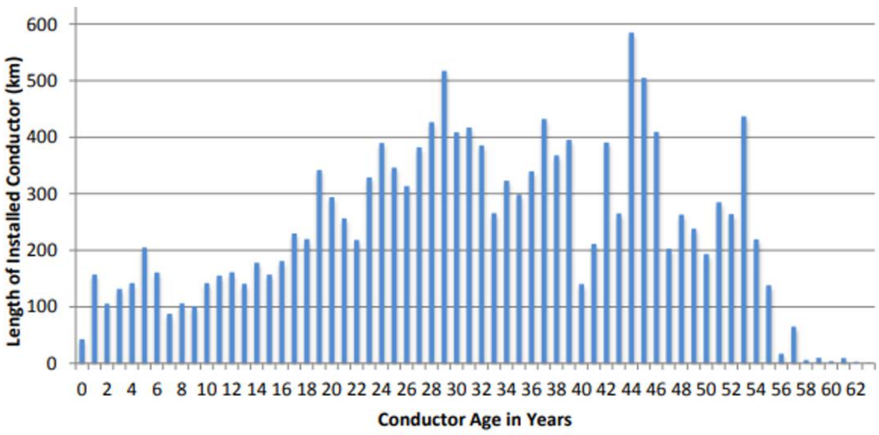


Figure 10 Age profile of the overhead conductors in the TasNetwork system [11]

The age profile of the copper conductors in the TasNetwork network is shown in Figure 11. From Figure 11, it can be seen that the age of copper conductors in the network range from 45 to 65 years old.

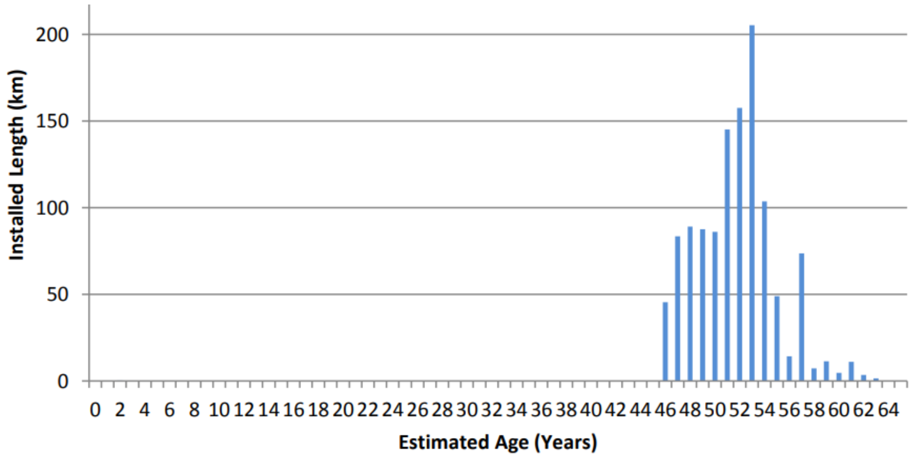


Figure 11 Age profile of the copper conductors in the TasNetwork network [11]

Failure statistics of copper conductors in the TasNetwork are presented in Figure 12. It can be seen that the number of copper conductor failures per year gradually increases with time, other than the exception during 2010-2012. The figure also reveals a relationship between conductor age and failure rate of copper conductors.

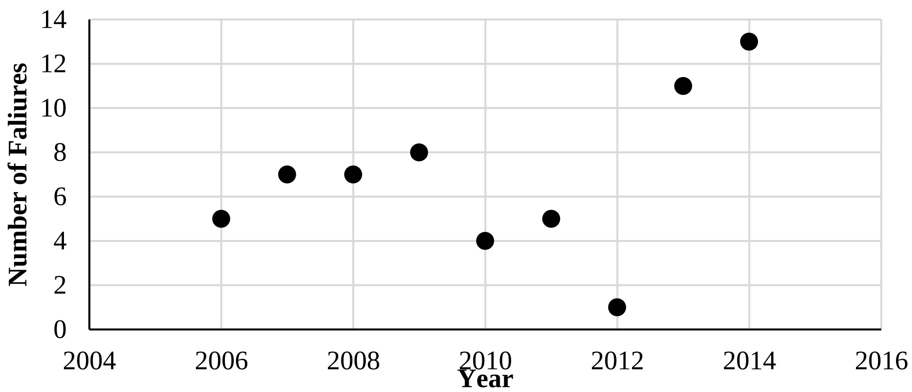


Figure 12 Copper conductor failure statistics by year [11]

Failure statistics of all conductor types in TasNetwork distribution system for the period from 2001 to 2014 are shown in Figure 13. From the figure, it can be seen that similar to the copper conductors, the failure rate of all other conductor types increases with time. According to the data presented in Figure 13, most of the failures occurred in steel conductors. The reason behind the higher number of failures in steel than copper conductors could be due to the higher circuit length of steel conductors in TasNetwork distribution networks. As shown in Table 11, in TasNetwork there are 1,288 km copper conductors and 5,888 km steel conductors.

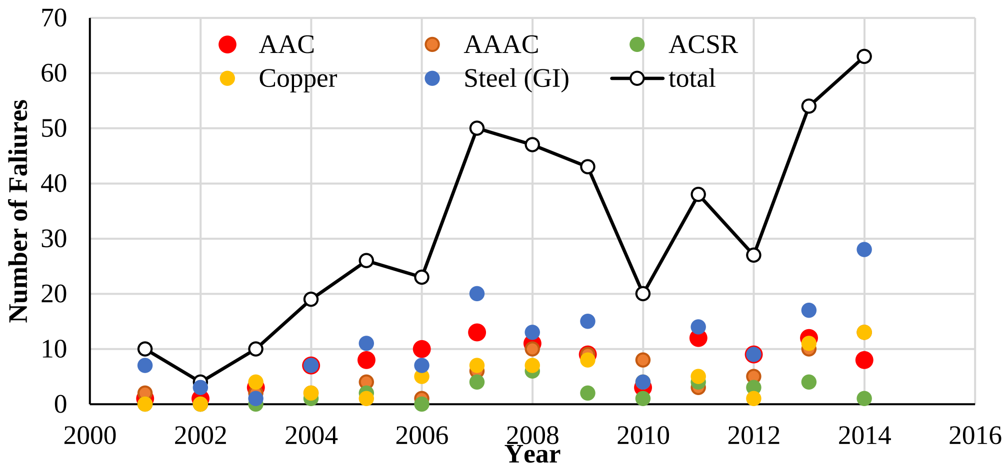


Figure 13 Overhead conductor failure statistics by year [11]

The conductor failure statistics in TasNetworks by the distance to the coastline is illustrated in Figure 14. It can be seen that the majority of the failures occurred in the conductors that were installed in the 0-5 km from the coastline. Further, steel and AAC are the conductor types that have the highest failures. This is because steel and aluminium are two metals susceptible to corrosion when exposed to marine environments. Further, it was assumed that the reason for the higher failure rates in >30 km from the coastline is the higher volume of conductors installed in inland compared to coastal areas.

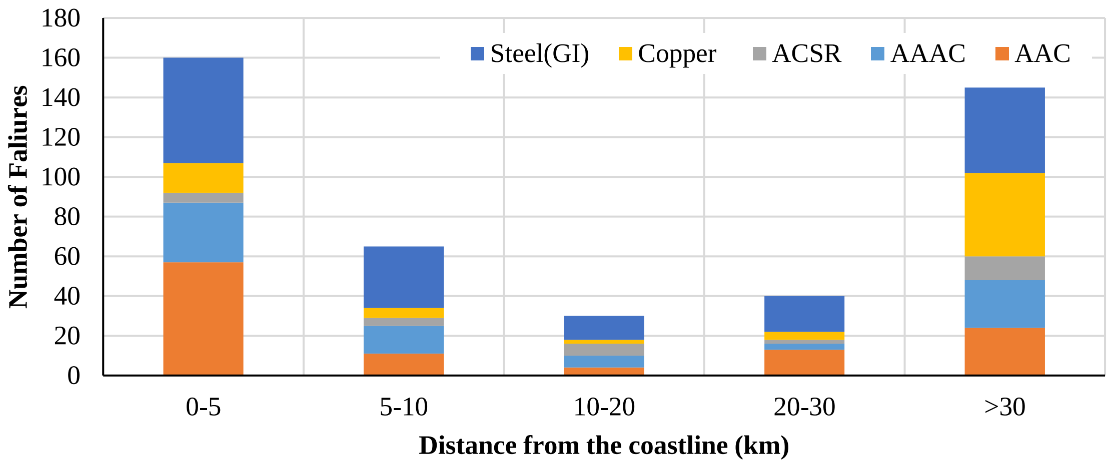


Figure 14 Conductor failure statistics by distance from the coastline [11]

3.5 Maintenance and Replacements Strategy in Australian DNSPs

Overhead conductor is a critical asset in the distribution network. Unexpected conductor failure could lead to safety hazards, loss of supply and possible environmental damages and capital losses. Hence, Australian DNSPs have adopted comprehensive maintenance strategies to reduce the risk of unexpected overhead conductor failures.

Current asset management practices heavily rely on visual inspections. Conductor replacement is driven by reactive response to the volume of conductor failure incidents. In general, preventive and predictive maintenance is carried out on the overhead conductor and related assets [8, 14]. The predictive methodology uses practical experience, current asset information, and technical knowledge to predict future asset condition, performance and risk of failure for network assets. On the other hand, time and/or usage-based predefined maintenance and inspection activities are used in predictive methodology for ensuring the remaining life of the asset.

3.5.1 Examples of Australian DNSPs Overhead Conductor Maintenance Practices

This section presents a summary of the maintenance procedures that Australian DNSPs have adopted. The summary is based on the information provided by the industry partners and from publicly available sources [5-14]

According to [12], Western Power conducts preventive and corrective maintenance on their overhead conductors and related accessories. Conductors and related asset are subjected to a four-yearly routine inspection. Condition based monitoring is also performed to address the defects during the routine inspections. The findings of the routine inspections are used to drive the replacement strategy for conductors and accessories. Some case studies on the critical issues in the Western Power network are presented in Table 12.

Table 12 Case studies based on [12] (Western Power Network)

Identified issue	Action recommended
0.3% (211 km) of distribution overhead conductor is beyond the 50 year design life. Some 42.8% (29,188 km) to exceed this age in 10 years.	Continue routine condition monitoring. Repair or replace where the defects become more prominent. Carry out routine inspection and condition-based maintenance.
In Extreme and High Fire Risk Areas, 16 km of distribution overhead conductor is beyond the 50 year design life. Some 9.5% (6,488 km) will exceed this age in 10 years.	Continue routine condition monitoring. Replace unserviceable items under Bushfire Mitigation Wires Down Program. Bundle work by geographic area and with other works to attain efficiencies. Replace 1,550 km of poor condition conductors
In Moderate and Low Fire Risk Areas, 195 km of distribution overhead conductor is beyond the 50 year design life. Some 33.3% (22,700 km) will exceed this age in 10 years.	Continue routine condition monitoring. Replace unserviceable items under Carrier Replacement Program. Work to be bundled by geographic area and with other works, if possible, to attain efficiencies. Replace 1,073 km of poor condition conductors

According to Energex regulatory proposal (October 2014), non-intrusive inspection based maintenance strategies are primarily used for ensuring the reliable operation of overhead conductors in Energex distribution network. A summary of the Energex overhead conductor maintenance and replacement strategies are presented in Table 13.

Table 13 Overhead Conductor Maintenance and Replacement Strategy – Energex [8]

Maintenance Strategy	Replacement Strategy
Standard activities: • Summer Preparedness Patrol • Aerial Inspections • Ground Inspections • Thermographic survey Activities carried out as required: • Line Profile Survey • Strength assessment • Fitting wear assessment • Broken strand assessment • Connection resistance test	Condition, end of life and obsolescence based assessment.

Energex's general overhead conductor maintenance tasks and their frequencies are listed in Table 14.

Table 14 Overhead Conductor Maintenance Tasks, Frequencies and Triggers [8]

Asset Category	Maintenance Task	Frequency
All overhead conductors	Standard Aerial or Ground Line Inspection	Aerial - 12 monthly on rural network Ground patrols are 12 monthly on critical feeders. All other conductor is inspected every 5 years.
	Thermal Survey Line Profile Survey Strength assessment Fitting wear assessment Broken strand assessment Connection Resistance Test	All these activities are carried out on an as required basis. The trigger would typically be defects found during inspections or an equipment population identified as potentially problematic.
Selected set of Overhead conductors	Summer Preparedness Patrol	This patrol is conducted annually on selected feeders. Feeders are selected based on one or more of the following criteria: • High bushfire hazard area • An outage is considered unacceptable • It supplies critical customer load.

Replacements of overhead conductors in the Energex network are mainly driven by predictive and preventive strategies. As per [8], a preventive approach based on the results of routine inspections is used for LV (≤ 1 kV) conductor replacement. However, HV (≥ 1 kV) conductor replacement is carried out based on both preventive and predictive strategies.

According to [6], Citipower/Powercor carry out conductor replacements based on two methodologies including

1. through inspection, asset failures or defect reports
2. proactively through risk-assessment using health indices

In the overhead conductor replacement plan of Powercor presented in [6], replacement timing and location of the conductor is decided based on condition assessment. Moreover, in [2] it was reported that there was a good agreement between the forecasted number of sections of overhead conductor to be replaced in the coming five years and the historic replacement data.

ActewAGL and most of the other Australian DNSPs use the LiDAR technology to monitor the vegetation along overhead conductor lines. The helicopter with LiDAR sensing devices flies at approximately 110-150 m and above 300 m above the overhead lines in rural and urban areas respectively. The collected data can be used for risk mitigation of unassisted conductor failure.

4 Conductor Degradation and Condition Monitoring – A Review

Ageing (degradation) of overhead conductors is becoming a considerable problem for DNSPs around the world. Hence, evaluating conductor condition and estimating conductor's remaining useful life is essential for conductor assets lifecycle management. As mentioned before, overhead conductors in the distribution network are installed in different geographical areas such as coastal, plains, highlands and arid. Further, environmental conditions such as high wind, corrosive environments in coastal areas, high-temperature operation and pollutions (acid rains) can accelerate the conductor ageing process.

This section provides a review of conductor degradation and condition monitoring. In Section 4.1 a comprehensive literature review on the conductor degradation mechanisms is presented. Finally, condition-monitoring techniques used to assess the condition of overhead lines is reviewed in section 4.2.

4.1 Conductor Degradation Mechanisms

There have been three main types of conductor degradation covered in the literature, being annealing, corrosion and fretting fatigue. These are covered in more detail below.

4.1.1 Annealing

Annealing is a process that can decrease the tensile strength of the hard drawn bare overhead conductors. Overhead conductors anneal when they operate at elevated temperature levels. Overload conditions, high resistance conductor joints, elevated environment temperature and multiple reclose operations are some of the common causes leading to conductor overheating. It has also been found that steel wires in ACSR conductors do not lose mechanical strength at temperatures up to 250 °C, though their zinc coating may suffer some damage. By comparison, copper and aluminium conductors can lose strength at temperature levels less than 100 ^{0}C

Several models have been proposed to model the percentage loss of tensile strength (*W*) with temperature (***T***) and time (***t***). Equation 1 is used to predict the percentage loss of tensile strength of a hard drawn conductor due to annealing [3].

$$W = W_a\{1 - e^{[-e^{(A + m\ln(t) + BT + C\ln(R/80))}]}\} \tag{1}$$

In Equation (1) W_a denotes the loss of strength in a fully annealed state and *A*, *m*, *B* and *C* are constants, and R denotes the percentage reduction in cross-sectional area during wire drawing. *R* is expressed as

$$R = 100[1-(D_W / D_0)^2] \tag{2}$$

Where D_w and D_0 are diameters of the draw rod and the drawn conductor respectively.

4.1.2 Corrosion

Corrosion is an electrochemical process that reduces the binding energy in metals. Metal corrosion generally occurs in the presence of water, acids, bases, salts and other solid and liquid chemicals.

Regardless of the rate of corrosion, it can eventually result in the loss of material in metal and potentially reduce the capability of the metal to perform its intended function. When an electrolyte such as water is present, metal atoms oxidise. As a result, metal atoms lose few electrons and they leave the metal surface. The lost electrons conduct from one site (anode) to another site (cathode) on the metal. Overhead conductors are subjected to two main types of corrosion, namely atmospheric corrosion and galvanic corrosion.

Atmospheric corrosion occurs when metals are exposed to substances such as oxygen, carbon dioxide, water vapour, sulphur and chlorine compounds. In atmospheric corrosion, both anode and cathode are on the same base metal. This type of corrosion primarily occurs in galvanised steel core of ACSR conductors and galvanised steel overhead ground wires. Both environmental conditions and physical characteristics of the conductors influence the corrosion process. For an example, the presence of high moisture, salt, sulphur and chlorine components are the environmental conditions that accelerate the corrosion process. On the other hand, physical characteristics such as how easily the conductor captures and holds the moisture and other pollutants also contribute to corrosion.

Galvanic corrosion or bimetallic corrosion is an electrochemical process, which occurs when metals with different electrode potentials are in contact in presence of moisture and electric potential. During this process, one metal becomes the anode and the other becomes the cathode. The anode is the metal that can easily release electrons. Hence, the corrosion of the anode will accelerate and the corrosion of the cathode will decelerate or stop. For an ACSR conductor with intact galvanizing, its zinc coating and aluminium act as the anode and cathode respectively. However, once the ACSR conductor’s zinc coating becomes exhausted and the aluminium is in contact with the steel, its aluminium becomes the sacrificial anode and begins to corrode at a higher rate while the rate of steel corrosion is reduced. The by-product of galvanic corrosion of the aluminium is a white powdery substance. In some extreme cases of galvanic corrosion, this white substance may be visible on the conductor surface.

4.1.3 Fretting Fatigue

Fretting occurs at the contact area between two materials, which are subjected to a miniature relative motion due to forces such as vibration. The fretting can reduce the fatigue strength of the materials. Fretting fatigue has been identified as one of the main causes of steel and aluminium conductor failure [15]. In overhead conductors, aeolian vibrations produced during relatively low wind speed may cause fatigue. Due to the connection arrangement between conductor and the other devices such as insulators, clamps, spacers, spacer dampers and stockbridge -type dampers, the failures frequently occur near these devices. Due to conductor fatigue, cracks can develop in the conductor strands, decrease the fatigue strength and eventually lead to conductor failures. Images of different stages of conductor fatigue are shown in Figure 15.

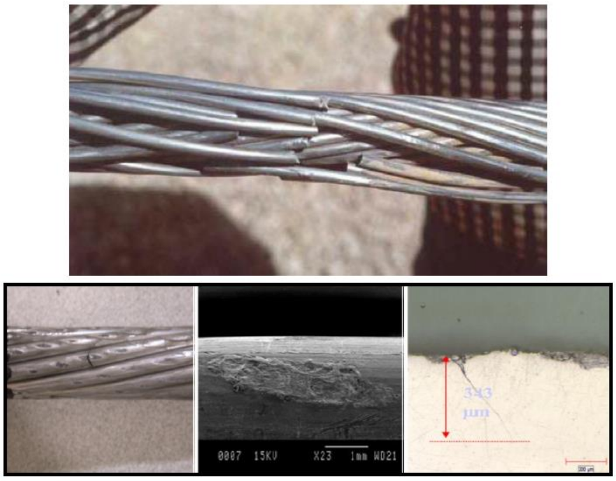


Figure 15 Different phases of conductor fatigue [16]

4.1.4 Additional Defects/Failures on Distribution Conductors

Distribution conductors are prone to defects and damage due to environmental effects (lightning, wind and vegetation impacts), conductor loading (long duration at elevated temperatures), short-term fault conditions (phase to phase clashing) and reclose operations where on some distribution lines can have up to 3 reclose operations after a fault.

Distribution conductors are often exposed to severe bushfires where temperatures can be in excess of 250 ^{o}C and this can significantly anneal and reduce the mechanical strength of the conductor.

Distribution conductors also tend to have many joints/splices and clamps on the conductor. These clamps and joints tend to degrade much faster than the conductor due to poor installation techniques and high resistance temperature operation. There are many preformed splices or repair rods on aged distribution conductors, which have been installed to repair conductors damaged by environmental effects. These splices/repair rods are known to be susceptible to becoming a hot joint where significant loss of conductor area can occur providing a point of failure of the conductors.

4.2 Condition Monitoring for Overhead Lines

Condition monitoring of overhead conductors is extremely important for ensuring an uninterrupted power supply while minimizing the risk of falling conductors. High-frequency partial discharges have been identified in the literature as the main symptom of degraded overhead transmission lines [17]. Also, localised heat generation has also been identified as another indication of overhead conductor degradation [17]. A list of techniques that are used to detect degradation in overhead lines are as follows:

1. Ultrasonic, Radio noise detection, Partial discharge detection.
2. Measurement of corona pulse current inconsistency.
3. Corona current monitor.
4. Infrared inspection of overhead transmission lines.
5. Fibre optic– strain gauges, FBG temperature sensors.
6. Audible noise meters.
7. Aeolian Vibration measurements.

The above techniques have shown some promising results. However, some practical limitations still exist limiting the deployment of these techniques in practical conductor condition monitoring. The localised nature of these techniques cannot provide an automatic means of conductor condition monitoring of a whole circuit, which may span over a hundred kilometres. Recently, aerial inspections using helicopters and Unmanned Aerial Vehicles (UAV) have been used to inspect complete overhead circuits.

4.2.1 Typical Overhead Conductor Condition Assessment Tests

a) Visual Inspection, Corona Cameras and Infrared Cameras

The visual inspections of overhead conductors are carried out from the ground or from a helicopter. The typical indicators of potential conductor failures that can be detected using visual inspections are [18],

- Broken outer strands
- Surface discolouration, possibly from internal corrosion
- Flashed/clashed surface
- Damaged or degraded joints/splices
- Excessive sag
- Overgrown vegetation.

However, unless the defect has become severe, detection of such defect through visual inspection is difficult. Specifically, the faults such as internal corrosion of ACSR conductors may not be detectable through visual inspection until the corrosion becomes severe and the by-products become visible on the conductor surface. Similarly, the defects such as broken strands may not be detectable until the defect become severe. Defects such as high resistance joints cannot be detected using visual inspections.

Infrared cameras can be used to capture the temperature profile of overhead lines. They are capable of detecting defects such as high resistance joints and broken strands, which can cause an increase in the conductor temperature [18]. Thermal imaging is effective for detecting high resistance joints; however, it is still challenging to use thermal imaging for detecting broken strands [18].

Corona cameras are used to detect corona in HV systems. This technology uses the UV light generated by the corona to create the corona images. Since the corona is generated due to excessive electric field stress, corona cameras can be used to detect conductor defects such as [18],

- Broken and protruding strands
- Bird-caging
- Severe surface scaring.

b) Corrosion Detection of ACSR Conductors

Though the steel core of ACSR conductors is galvanised, it is prone to galvanic corrosion that exhausts the zinc coating and eventually leads to bimetallic corrosion of aluminium and environmental corrosion of the steel core.

A number of technologies have been developed to detect corrosion of ACSR conductors. EPRI has developed a corrosion detection device, which adopts a non-destructive method and can be operated from the ground [16]. It uses two co-aligned lasers i.e. one with a wavelength of 637.3 nm (red) and another one with 822.0 nm (near infrared laser). The device is based on the reflectance properties of rust (refer to Figure 16). During its operation, the device shoots two laser beams on the ACSR conductor. Then it uses a telescope to capture the red and near-infrared signals reflected from the conductor. The captured signals are analysed and the ratio of red to near-infrared signal is used to estimate the severity of conductor corrosion.

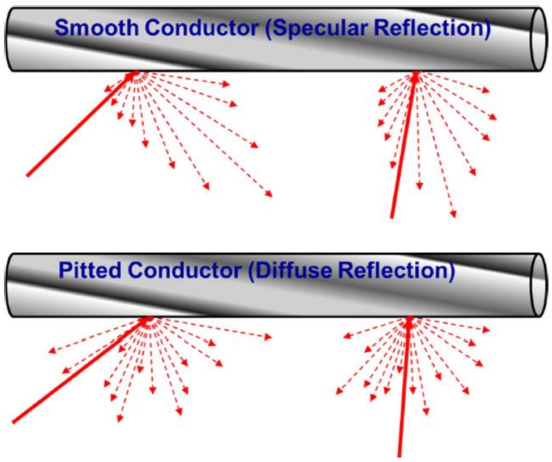


Figure 16 Laser reflection in a smooth and rough conductor [19]

According to [19], this device was designed to mount on a tripod and operated from the ground. Other mounting methods such as mounting on a moving vehicle is under review [19]. One of the main drawbacks of this method is its inability to detect the corrosion in the steel core strand.

Another non-destructive corrosion detection method is the electromagnetic induction method (Eddy Current testing) [20, 21]. Eddy current test instrument has a field coil that generates a magnetic field and a transducer that can detect eddy current flow. A high-frequency current is applied to the field windings. These field windings are placed closer to the ACSR conductor in such a way that the magnetic field generated by the field windings can generate eddy currents in each conductor strand. The defects in the surface (i.e. corrosion) of the conductor strands decrease the flow of eddy currents and hence affecting the impedance of the conductor. Some commercial products using the electromagnetic induction method are

- Cormon OHLCD technology [22]
- Fujikura's detector [3]
- Detection Services offered by ATTAR in Australia [1]

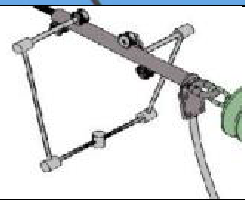
It should be noted that the electromagnetic induction method can not only detect conductor corrosion but also the loss of aluminium cross-section of conductor [18].

Time domain reflectometry (TDR) is also used to detect corrosion in overhead lines. In this method, a short step electrical pulse is transmitted along the conductor and the returning pulse is measured. If the load impedance matches the impedance of the line, no reflection will occur. When the travelling signal encounters a change in the impedance, portion of the transmitted signal will reflect. In [21], a conductor corrosion detection system was developed using TDR techniques. It was reported that the system could locate the corroded line segments in overhead conductors.

4.2.2 Mobile Robots for Distribution Overhead Line Inspection

Application of autonomous mobile robots for power line monitoring has become popular. One such example is Line Suspended Robotics. This type of robots is typically designed to mount on the overhead lines and can move along the line while performing overhead line condition assessment [23-26]. Whilst these devices have been designed primarily for use on transmission conductors, they are worth noting for their potential use in distribution line surveillance. Typical measurements that line suspended robots can perform include the condition assessment of steel core wires ACSR conductors, detection of broken wires, measurement of the cross-section of conductors, etc. Table 15 lists a number of representative products [24].

Table 15 Comparison of existing Line Suspended Robot products[24]

Product description	Capabilities	Limitations	
LineScout, Hydro-Québec (Canada)	work on live-lines of up to 765 kV equipped with a camera infrared inspection measure electrical resistance tightening and loosening bolted assemblies temporary repair of broken conductor Corrosion detection of ACSR conductors	cannot cross dead-end structures and jumper cables	
LineVueTM, Kinectrics Inc.(Canada)	inspect overhead steel ground wires detect corrosion pits locate broken steel core wires measure the remaining cross-sectional remotely controlled from the ground on-board camera	device weight about 32 kg Too heavy for use on distribution conductors	
Expliner, HiBot (Japan)	Can work on high-voltage transmission lines up to 500 kV Carbon fiber body, T shaped body can overcome obstacles		
AApe, Chinese Academy of Sciences (China)	Can work on high-voltage transmission lines up to 500 kV Can cross obstacles Can returning a broken strand back to the conductor fastening the broken location with a specialized clamp	device weight is about 42 kg Too heavy for use on distribution conductors	 AApe-A1
Power Line Inspection Robot (PLIR), University of KwaZulu-Natal and Eskom (South Africa),	Light weight (10 kg) can navigate around obstacles up to 650 mm in length		
Transpower (New Zealand)	Detect damage to transmission line conductors Can navigate on jumper loop		
Transmission Inspector (TI), EPRI (USA)	Can pass obstacles Wireless data communication Can measure wind speed, direction and temperature HD camera Lidar IR camera	Battery power	

LineROVer, Hydro-Québec (Canada)	infrared imaging measure the the electrical resistance of splices repair broken strands by installing temporary clamps de-ice ground wires ACSR corrosion detection probe		
Conductor Corrosion Assessment System (CCAS), Shannon Technology (Canada)	Measure the remaining zinc on galvanized steel core wires of ACSR conductors		

Almost all the above line suspended robots were designed for inspecting conductors on transmission lines. Since they cannot cross jumper loops, these robots may not be suitable for inspecting distribution overhead conductors. However, considering the lightweight construction (10 kg) and ability to navigate around obstacles, Power Line Inspection Robot (PLIR) developed by University of KwaZulu-Natal / Eskom (South Africa) and Transpower (New Zealand) may be suitable for inspection of overhead conductors in distribution networks.

4.2.3 Obstacle Traversing

Obstacle traversing is critical when developing line suspended robots. The main obstacle that a line suspended robot needs to cross is the crossarm. Existing literature propose several obstacle traversing mechanisms. Among them, the mechanism used in Hydro-Quebec's LineScout is illustrated in Figure 17.

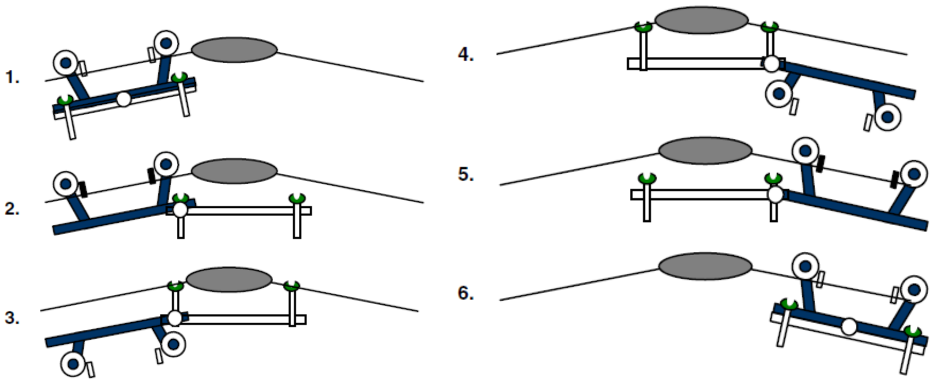


Figure 17 The LineScout obstacle clearing sequence [27]

The LineScout is composed of three independent frames namely "wheel frame" (blue coloured), "arm frame" (white coloured) and "centre frame" (white circle). The centre frame links the arm frame and wheel frame together. LineScout obstacle traversing sequence is explained in Table 16 [27]. According to [27], the obstacle traversing sequence can be completed within two minutes.

Table 16 LineScout obstacle traversing sequence

Step 1	First LineScout stops in front of the obstacle. Clamp the robot firmly to the conductor using the “Safety Rollers” (two small rectangles) next to the wheels.
Step 2/3	The “Arm Frame” and “Centre Frame” slide forward. Hinge two “Auxiliary Arms” (two vertical rectangles with “Gripper” tips) either side of the obstacle.
Step 4	“Centre Frame” slide and pivoting underneath the obstacle.
Step 5	In step 5, flipping mechanism brings the wheels back onto the conductor. “Safety rollers” release the LineScout from the conductor.
Step 6	“Arm Frame” and “Center Frame” return to their initial position. Vehicle is ready to continue rolling down the line.

4.2.4 Unmanned Aerial Vehicles (UAVS)

In general, aerial overhead conductor monitoring equipment operated by a trained officer on board an aerial vehicle (i.e. helicopter) has been used to monitor overhead lines. Such methods overcome the practical limitations in monitoring the entire length of the line on ground. However, such methods could be expensive and may not be suitable for use in urban areas.

On the other hand, Unmanned Aerial Vehicles (UAVs) are compact and can monitor long spans overhead conductor lines in both urban and rural areas. UAVS enable the utility companies to perform visual inspections of conductors and other overhead components using different types of cameras. However, deployment of UAVS to monitor overhead line inspection has several risks and limitations. As per [24] examples of such limitations and risks are as follows,

- Risk of UAV crash on live overhead lines due to sudden changes in environmental conditions such as wind gusts and equipment failure.
- Concerns of invasion of privacy
- Limitations in flying UAVs imposed by aviation agencies

Information of some of the UAVs designed for overhead line monitoring purposes is listed in Table 17.

Table 17 Information on UAVs used in overhead line monitoring [24]

Fixed-Wing Aircraft	Helicopter	Multicopter
Fast recognition in case of break-down LIDAR applications. Topography Vegetation managing	Intensive inspection in long section of OHTL (75 towers per day) RGB videos corona inspection IR inspection	Specific inspection in any component of OHTL (1 or 2 towers per day). RGB videos corona inspection IR inspection
 AAI Aerosonde (Cruise Speed 27 m/s, Payload 8 kg)	 UAR 45 Red Eléctrica de España (take-off weight is between 25 kg and 100 kg)	 Hexacopter

4.3 Condition Assessment of Overhead Lines

The condition measurements discussed in section 4.2 can provide a number of parameters that reflect the health condition of overhead conductor. The challenges are how to make use of the measurement results to evaluate conductor's health condition and predict conductor's probability of failure and remaining useful life.

4.2

4.3.1 Conductor Health Index

Health Index is a complex index that indicates the condition of an asset. The health index is calculated using a set of parameters that represent the asset characteristics. Each of the parameters has a different influence on the overall asset health. Hence, it is required to rank the parameters and assign weights. The parameters that have greater contribution to asset degradation are given higher weights [28].

Two types of health indexes for overhead conductors namely basic and comprehensive are proposed in [28]. Both are based on the following formulas.

$$HI = \frac{\sum_{m=1}^{\forall m} \alpha_m (CPS_m \times WPC_m)}{\sum_{m=1}^{\forall m} \alpha_m (CPS_{m.\max} \times WPC_m)} \times DRF \tag{3}$$

$$CPS = \frac{\sum_{n=1}^{\forall n} \beta_n (SCPS_n \times WSPC_n)}{\sum_{n=1}^{\forall n} \beta_n (SCPS_{n.\max} \times WSPC_n)} \tag{4}$$

Where,

CPS - Condition Parameter Score

WCP - Weight of Condition Parameter

CPS_{max} - Maximum Score for Condition Parameter

α_m - Data availability coefficient

SCPS - Sub-Condition Parameter Score

WSCP - Weight of Sub-Condition Parameter

$SCPS_{max}$ - Maximum Score for Sub-Condition Parameter

β_n - Data availability coefficient

DRF - De-Rating Factor

When calculating the basic health index proposed in [28], conductor-physical condition and field observation data are used as given in Table 18.

Table 18 Basic health index parameters and weights

m	Condition Parameter	WCP_m
1	Physical Condition	1
2	Service Record	2
DRF	Repairs/Splices	90%

The physical condition of the conductor refers to the conductor’s surface condition, which is obtained from field inspection. The conductor age is also considered. Any previous conductor repairs and splices is used as de -rating factors. However, as field inspections are primarily visual inspections conducted at a distance, they may not reflect the true condition of the overhead conductor.

In the comprehensive health index, the condition parameters and weights used are listed in Table 19.

Table 19 Comprehensive health index parameters and weights

m	Condition Parameter	WCP_m
1	Mechanical Properties	6
2	Physical Condition	2
3	Service Record	1
DRF	Repairs/Splices, remaining tensile strength	

Mechanical strength (properties such as torsional ductility and tension) is a critical parameter of overhead conductors. It is addressed under “Mechanical Properties” parameter. As mechanical strength is closely related to the remaining life of a conductor, it is given a higher weight than the rest of the parameters. Rest of the parameters have similar definitions as the basic health index formulation.

Another practical use of conductor health index method for assessing the health of overhead conductors in the Romanian power system is presented in [29]. Their conductor health assessment method is primarily based on the method proposed in [30], which is based on a set of curves that relate conductor age and mechanical properties namely breaking stress-age, torsional ductility-age and corrosion rating-age curves. However, the age curves presented in [30] are based on conductor samples collected from various climate zones in Canada. Hence, the Romanian researchers use set of breaking stress-age and torsional ductility-age as curves for conductors in Romania (See Figure 17).

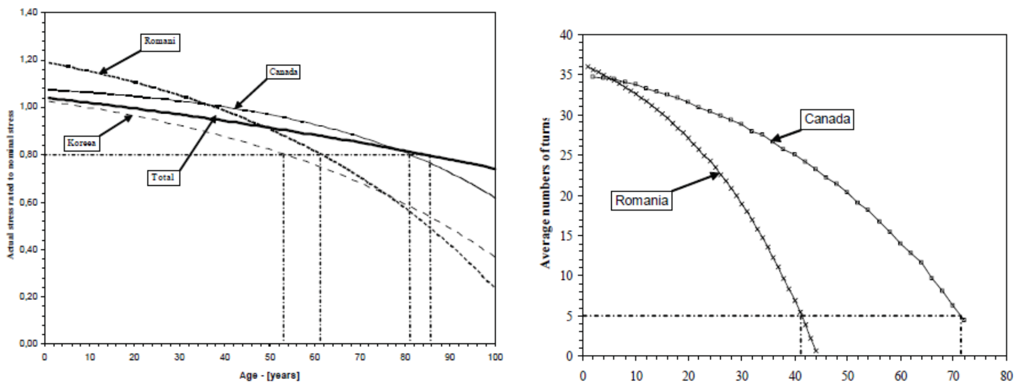


Figure 18 Actual breaking stresses rated to the nominal ones for ACSR conductors (left) and Torsional ductility of outer layers of steel core in Romania and Canada (right)

4.3.2 End-of-life Criteria for Overhead Conductors

Defining an end of life failure criteria or conductor retiring/replacing strategy is another research area. In [28], the aforementioned conductor health index has been used to determine the remaining life of overhead conductors as follows.

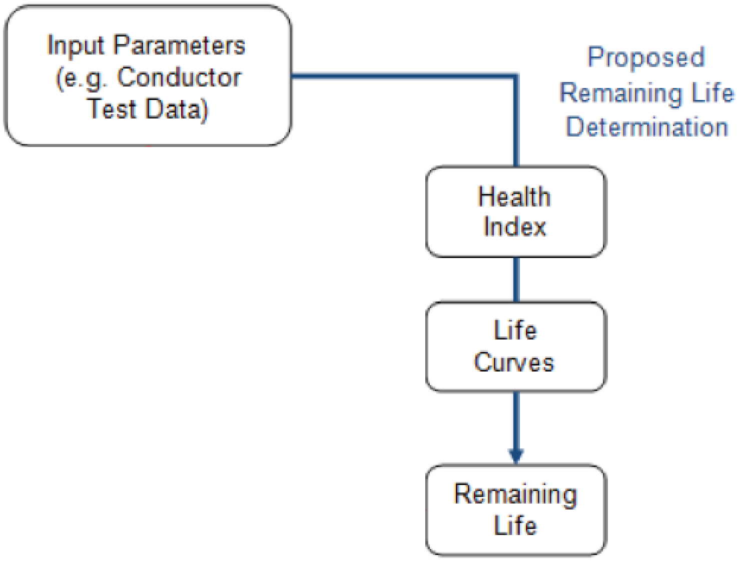


Figure 19 Estimating remaining life of overhead conductors [28]

In Figure 19, “life curves” are the curves that represent the probability of a conductor failure with reference to the conductor age. Typically, these curves are generated using a large number of conductor failure data. Due to the lack of adequate amount of such data, life curves in [28] have been developed by modelling using Gompetz- Makeham law of mortality on a small size of dataset. Finally, the developed life curves (Figure 20) are used to determine the conductor end of life.

In [31] an advanced end-of-life failure model for overhead transmission lines in proposed. This model is capable of incorporating the loading effects and weather conditions when calculating the failure probability. In [31], the relationship between conductor life and temperature is modelled using Arrhenius relationship. The conductor life is then used as a scale parameter of the Weibull probability distribution. The parameters of Arrhenius and Weibull distributions are calculated based on conductor failure data corresponding to ACSR conductors.

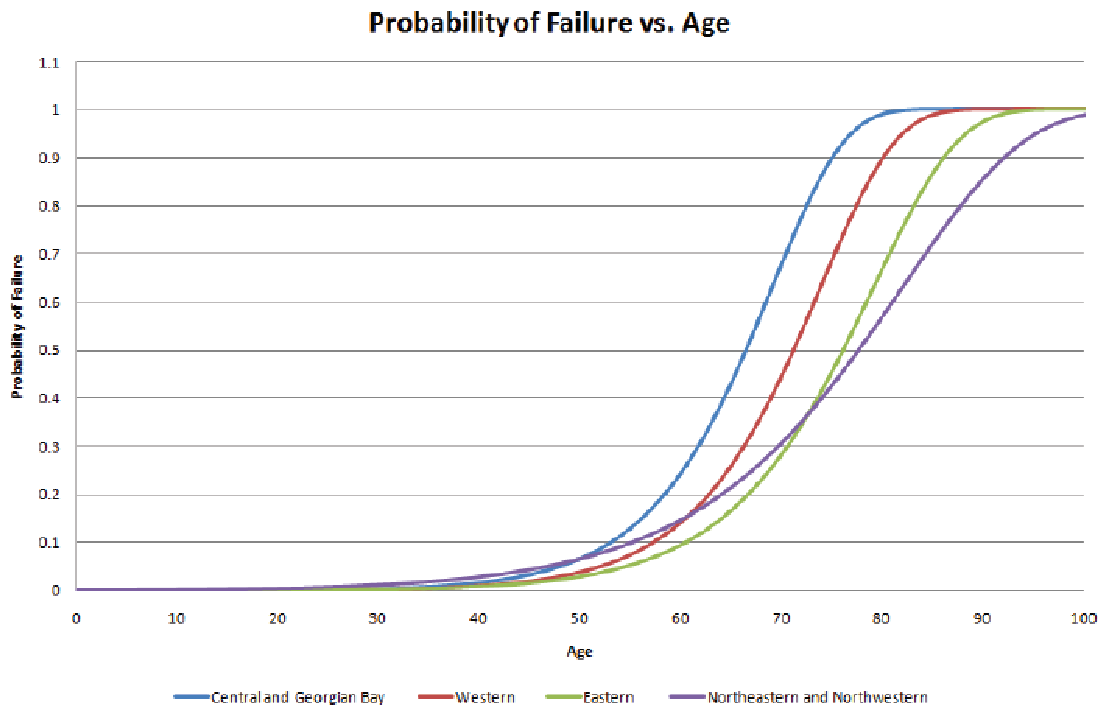


Figure 20 Life curves of overhead conductors correspond to different geographical zones in Canada [28]

5 Possible Areas of Research and Development for an Improved Conductor Condition Monitoring and Asset Management in Australian DNSPs' Network

Electric power utility companies operating worldwide are keen to know the probability of failure and remaining life of overhead conductors. Australian DNSPs are interested in developing a reliable model for estimating the probability of failure and the end of life of the aged overhead conductors. A comprehensive analysis of the overhead conductor failure data in Australian distribution network has not been conducted to this date. As a result, a failure probability/end of life model for overhead conductors in Australian distribution network has not yet been developed. In order to improve the condition assessment practices of overhead conductors in Australian distribution networks, the following short-term and long-term research plans are proposed.

5.1 Short-term Research Plan

The short-term research plan will be looking into solving two main knowledge gaps in condition assessment of overhead conductors in Australian distribution network. The short-term research plan can be executed during the remaining duration of the current project and will lay the groundwork for the long-term research proposed in next section.

1. Statistical modelling of conductor failure data collected from different geographical zones of Australia. The main purpose of this work is to develop a statistical model for determining overhead conductor failure probability considering the age and geographical location. The outcomes will be used to define an end-of-life criteria for overhead conductors in distribution network.
2. Dynamic conductor temperature calculation. Environmental conditions, fluctuations in load, elevated temperature and fault/reclose operations need to be incorporated or considered in the calculations for better accuracy. The calculated dynamic conductor temperature can be used to determine the loss of tensile strength of overhead lines due to annealing accurately.
3. Identifying the sensing technologies that are suitable for condition monitoring of conductor in distribution system. Firstly, information on sensing technologies that are

already in use will be gathered from industry partners. Applicability of these technologies to accurately condition assess overhead lines will be investigated. Hardware limitations of the sensors will also be identified. The knowledge will then be used to propose suitable sensing technologies for Australian distribution network.

5.2 Long-term Research Plan

The long-term research plan is a continuation of the short-term research plan. As illustrated in the flowchart in Figure 21, the proposed research plan has five stages.

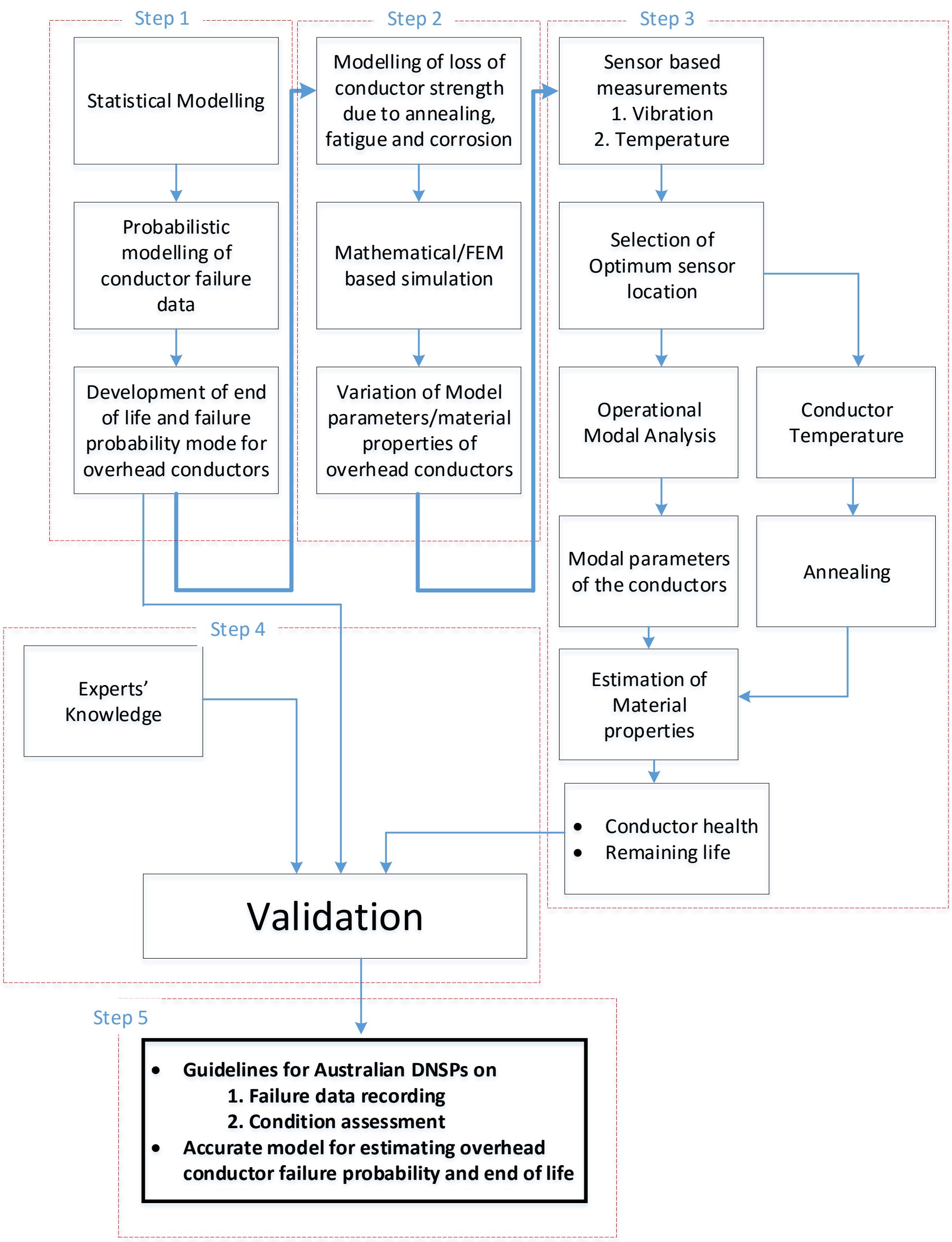


Figure 21 Identified possible areas of research and development for an improved conductor condition monitoring

5.2.1 Statistical Modelling of Failure Data (Step 1)

Statistical analysis of overhead conductor failure data gathered from Australian DNSPs. The conductor failure data should contain information on:

1. conductor type
2. conductor age when it fails
3. geographical location
4. the main cause of failure (e.g annealing, corrosion, fatigue)
5. other contributing factors (e.g lightning damage, elevated temperature, conductor clashing, joint/splice, fault and reclose history)

Weibull/normal probability distribution will be used to model the overhead conductor data. To model the relationship between conductor life and other parameters such as temperature and fatigue, Arrhenius relationship can be used. By modelling conductor failure data collected from different climate zones, effect of geographical location on the conductor failure probability will be incorporated into the model.

5.2.2 Modelling of Conductor Temperature with Time (Step 2)

Mathematical/Finite element modelling (FEM) based simulations conducted for

1. calculating the dynamic temperature of overhead conductor

Temperature of overhead conductors are sensitive to load and environmental conditions such as rain and wind.

2. modelling the reduction of conductor tensile strength due to annealing and vibration

As discussed in section 4.1.1, annealing is directly related to the temperature of overhead conductors and operating history (long-term loading, and short-term fault and reclose operation). Hence, the dynamic line temperature calculated in the previous step can be used to determine the loss of tensile strength of overhead lines due to fluctuating load and environmental conditions.

As discussed in section 4.1.3, fatigue caused by Aeolian vibration decreases the tensile strength of overhead conductors. Hence, mathematical modelling will be used to estimate the loss of tensile strength of overhead lines due to fatigue.

3. Identifying the relationship between annealing, fatigue and mechanical defects in conductors with respect to their modal parameters (Natural frequencies, Mode shapes and damping ratios)

Finally, FEM bases simulations will be used to identify the relationships between annealing, fatigue and mechanical defects in conductors and the corresponding modal parameters. The results will be used to evaluate the applicability of accelerometers for evaluating conductor ageing status. Results of a preliminary FEM simulation conducted to relationship between natural frequency of 7/.064 copper conductor (see Figure 22) and mechanical defects are listed in Table 20 and Figure 23. From the results, it can be seen that natural frequencies of the overhead conductors are sensitive to the mechanical defects.

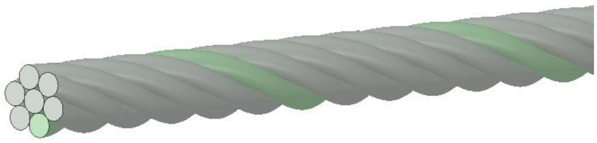


Figure 22 3D CAD model of the 7/.064 copper conductor used for preliminary FEM simulations

Table 20 First ten natural frequencies of 7/.064 copper overhead conductor and mechanical defects

	Natural Frequency (Hz)			
Mode	*A* - Healthy	*B* - Broken centre strand	*C* - Broken outer strand	*D* - 50% reduction in Young's modulus
1	231.59	243.08	319.85	163.76
2	232.01	244.58	324.52	164.05
3	463.2	490.21	641.9	327.53
4	470.8	495.69	653.04	332.91
5	693.84	727.23	959.59	490.62
6	696.37	730.52	978.08	492.41
7	928.05	977.42	1284.7	656.23
8	937.91	986.68	1314.9	663.2
9	1190.1	1246.8	1636.8	841.51
10	1206.3	1255.2	1669.7	852.97

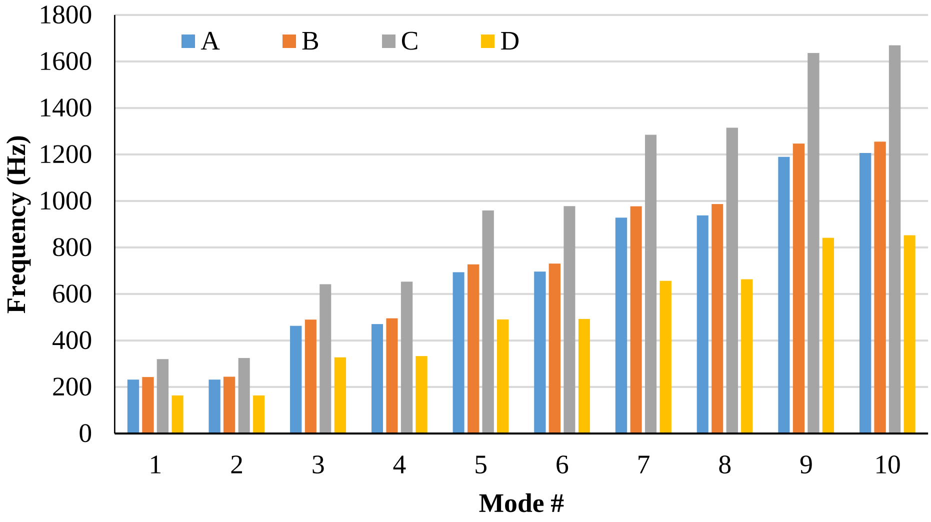


Figure 23 First 10 natural frequencies of 7/.064 copper overhead conductor and mechanical defects

5.2.3 Condition Assessment of Conductors (Step 3)

It is proposed to use vibration and temperature sensors mounted on overhead lines for condition assessment and conductor failure prediction. However, for a cost-effective and accurate condition assessment solution, selection of an optimum sensor location is essential. For the selection of sensor locations, geographical and environmental conditions such as high industrial pollution, coastal, bushfire and high wind has to be considered. For assessing Aeolian vibration effects, the sensors should be located close to particular line components, such as insulator and joints. There are a number of types of clamp or fitting arrangements to attaching the conductors to insulators. Thus, it is necessary to assess vibration performance for each type of connection arrangements.

The sensors suitable for conductor monitoring need to be lightweight and with data storage or wireless data transmitting capability. Further, they should have the capability of scavenging power from the magnetic field around the energised conductor and power itself. The temperature sensors that suits for this application are already commercially available. However, further investigations are required to identify the specifications of the suitable vibration sensor.

The measured temperature data can be used to validate the temperature estimation techniques used in step 2. The vibration data will be used to extract the modal parameters of the overhead lines. **Operational modal analysis** is a technique that can be utilised for this purpose. Finally, variations in model parameters of the lines will be used to assess the degradation of mechanical properties of the overhead lines.

5.2.4 Validation and Development of Guidelines (Steps 4 and 5)

The fourth step is the validation of the outcomes of first three steps. For that purpose, results from individual steps can be compared with each other. Further, experts' knowledge will also need to be utilised for validation of the research outcomes.

Finally, from the research outcomes, a set of guidelines will be proposed for Australian DNSPs. These include:

1. Collection of overhead conductor failure data
2. Assessment of the condition of the overhead conductors
3. Estimation of remaining life of a conductor

Acceding to the analysis of overhead conductor failure data presented in section 1, overhead conductor failure is a critical problem in the Australian distribution network. Hence, electric power utility companies worldwide are keen to know the probability of failure and remaining life of overhead conductors. Especially, in Australia, DNSPs are interested in developing a reliable model for estimating the probability of failure and end of life of aged overhead conductors. A comprehensive analysis of the overhead conductor failure data in Australian distribution network has not been conducted to this date. As a result, a failure probability/end of life model for overhead conductors in Australian distribution network has not yet been developed. In order to improve the condition assessment practices of overhead lines in Australian distribution networks, short-term and long-term research plans have been proposed.

6. Project Management

6.1 Project Progress

The main activities completed are summarized as below.

1. Made a tentative project plan and submitted it to ENA and shared it with industry partners.
2. Reviewed ENA 2015-2016 conductor survey report.
3. Complied review report of the ENA 2015/2016 conductor survey report and submitted it to ENA and shared it with industry partners.
4. Reviewed existing literature published in IEEE, IET, CIGRE and other literatures on conductor failure mechanisms and conductor condition monitoring.
5. Discussed with industry experts (Colin Lee and Keith Callaghan) to identify the types of conductor, of which the current investigation needs to be focused.
6. Visited Energy Queensland to have discussion with Srinivansan on Energy Queensland practice on conductor asset management.
7. Prepared and sent a report to ENA and industry partners.
8. Conducted project team monthly meetings and identified the possible challenges and types of data available with industry partners.
9. The UQ team have done analysis on the following datasets
    - ENA conductor failure report raw data
    - Conductor failure data received from Energex
    - Reviewed existing publicly available literature on conductor annealing and fatigue.
10. Identified several areas, which need immediate attentions of research and development including sensor-based condition monitoring and dynamic conductor thermal rating.

6.2 Risks to the Project

1. Available conductor failure statistics provided by ENA and industry partners may not be complete and/or not directly relevant to the scope of the project.

2. UQ / ENA not being able to secure rights to use the Canadian health index system (or access to the level of detail required to make the system effective). Overcoming this risk may require ENA to consider funding the additional cost if subsequently approved by ENA AMC.

6.3 Project Financials

1. On the 30th July 2018, Dr. Lakshitha Naranpanawe was appointed as the Post-Doctoral Fellow for this project.
2. In November 2018, two fractional appointments were made to two industry experts Mr. Colin Lee and Keith Callaghan. Other than salaries for the above appointments, there were no other expenditures.

6.4 Next Step

The project is well on track. As per the following project timeline, the team has been contacting industry partners to collect conductor failure data. The team is currently conducting statistical modelling of conductor failure data. Based on the modelling results, the team will determine the feasibility of applying health index methodology to condition assessment of conductor. If the health index methodology is feasible, the team will demonstrate it for condition assessment of a representative type conductor in Australia DNSPs' lines.

Project Timeline

Task	Time (months)				
	1-6	7-9	10-12	13-15	16-18
Milestone 1					
Review, literature study, analysis and writing report	Completed				
Milestone 2					
Collecting conductor failure data	In-Progress	In-Progress			
Statistical modelling of conductor failure data		In-Progress			
Determining feasibility of developing condition assessment of conductor using health index methodology		In-Progress			
A demonstration of health index method for condition assessment of a representative type conductor in Australia DNSPs' lines			In-Progress		
Milestone 3					
Survey state-of-the-art conductor condition monitoring techniques				In-Progress	
Evaluating prospective emerging smart sensor-based conductor monitoring systems and provide some recommendations					In-Progress

[green] - Completed tasks [yellow] - In-Progress Tasks

7. Conclusions and Recommendations

7.1 Conclusions

This report presented a comprehensive investigation on conductor failure modes, degradation mechanisms and key parameters influencing conductor degradation in the context of Australian DNSP's networks. It also summarized Australian DNSPs experiences and practices to test, operate, inspect, and asset manage (maintain, replace and refurbish) overhead distribution conductors.

The analysis of overhead conductor failure data collected from a number of Australian DNSPs revealed that aluminium and steel are the most common conductor types in Australian LV (≤ 1 kV) and HV (> 1 kV) networks respectively. It has been found that the average age of the distribution conductors in Australia is about 50 - 60 years and average replacement age is about 54 years. Among unassisted failure modes, corrosion/rust is the major cause of conductor failure and most of the conductor failures have been recorded in the coastal areas. It has also been found that current overhead conductor asset management practices heavily rely on visual inspections. Currently the conductor replacement is mainly driven by reactive response to the volume of conductor failure incidents.

Annealing, corrosion and fretting fatigue were identified as main mechanisms that lead to ageing of overhead conductors. Among them, annealing can reduces the tensile strength of overhead conductors that operate at elevated temperature levels. Both environmental corrosion and galvanic corrosion can decrease the effective thickness of conductors and increase the risk of conductor failure. Fretting fatigue can occur when a conductor is subjected to mechanical forces and it can lead to failure of conductor strands, which close to insulators.

The comprehensive literature review revealed that electricity service providers around the world use various condition monitoring techniques to determine the condition of overhead conductors in their systems. However, almost all the techniques have been designed for overhead conductors in transmission network and condition of the conductors in distribution networks are rarely monitored.

At the next stage of the project, the research team will explore suitable modelling techniques for quantifying conductor condition and estimating its probability of failure. The team will also investigate the state-of-the-art commercially available conductor monitoring system and emerging smart sensor based system for Australian DNSPs' networks.

7.2 Recommendations

Two most important research areas, which can improve the condition assessment of the overhead conductors in Australian DNSPs' networks are recommended. The first one is the statistical modelling based conductor end-of-life failure model and calculating dynamic overhead line temperature. The second one is the smart sensor based technologies for real-time overhead conductor monitoring.

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