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A Practical Health Index for Overhead Conductors: Experience From Australian Distribution Networks

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ABSTRACT Quantifying the health condition of bare overhead conductors is an enabler for an effective condition-based risk management of the power distribution network. This paper presents a health index calculation methodology derived for the bare overhead conductors in the Australian power distribution networks. Proposed methodology is based on a customizable weighted sum algorithm and uses a set of input parameters, which are readily available for the asset managers. Industry experts' experience and conductor failure statistics are used for determining the most significant input parameters and corresponding numerical values. Finally, a methodology for correlating the conductor health index with the probability of failure is demonstrated on a set of copper and aluminum conductors. The methodologies developed in this paper could improve the accuracy and effectiveness of condition monitoring and asset management of bare overhead conductors in the power distribution networks.

INDEX TERMS Condition monitoring, distribution network, health index, overhead conductor.

I. INTRODUCTION

Overhead conductor is one of the most valuable assets in electricity networks. In Australia, Energy Networks Australia (ENA) members have almost 800,000 circuit-kilometres of overhead conductor in service and they are valued over several billion dollars. Many conductor assets in Australia are ageing with some already reaching 70+ years [1]. An unexpected conductor failure could lead to electricity supply disruptions and catastrophic disasters such as bush fires [2].

Though many advancements in technology have been achieved over the years, approaches to cost-effectively monitor condition of conductors in power distribution networks have not substantially changed. In the Australian context, existing conductor condition monitoring practices still rely on visual inspections and conductor replacement is usually driven by the frequency of conductor failures [3]. Reliable and cost-effective methods to assess the likelihood of a conductor failure have not yet been developed for

Australian distribution network service providers' (DNSPs) networks.

In this paper, we report a methodology developed for quantifying the health condition of bare overhead conductors in the Australian distribution networks. The proposed Health Index (HI) methodology uses set of input parameters, which are customizable and readily available or easily accessible to asset managers to calculate the health index. Thus, this methodology suits networks with very limited available condition and historical information. This research work is part of an industry funded and industry led project by the Australian network's peak body Energy Networks Australia (ENA). We conducted a comprehensive study on conductor failure modes, understanding their degradation mechanisms, and identifying important parameters, which are primarily responsible in influencing conductor degradation in Australia. We also surveyed current Australian industry practices in operation, inspection, and asset management of overhead distribution conductors. Based on these investigations, we have developed a practical health index method suitable for application to Australian distribution networks, which can be extended to any other networks as well.

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Health index has been widely applied to assess the condition of power system assets (e.g. transformers, circuit breakers, underground cables) and recently to overhead conductors for high voltage transmission networks [4]–[10]. In [4], a weighted sum-based health index was developed for conductors specifically for Canadian transmission networks. It used service records, conductor physical condition (number of repairs/splices/ remaining tensile strength etc.) and network operating conditions. In [7] a health index was calculated based on the information gathered through visual inspection. The health index method proposed in [7] used tensile strength and fault history of overhead conductors. Further, the overhead conductor health index methods proposed in [9] and [10] are heavily rely on visual inspections, zinc coating measurements of the steel strands, the electric resistance measurements, metallurgical examinations of the component strands, and chemical analysis for corrosion on strands. The effectiveness of aforementioned health index methodologies is dependent on both the quantity and quality of conductor data.

The application of health index for condition assessment of bare overhead conductors for distribution networks has not been well reported, nor extensively investigated due to the unavailability of data and complexity of diverse network operating conditions. In Australian distribution networks, like many other networks around the world, the overhead conductor circuits are normally not equipped with any online monitoring devices. Both the quantity and quality of the field conductor data available with the Australian DNSPs is limited. The above issues bring considerable difficulties in deriving a health index for bare overhead conductors in distribution networks.

Therefore, we explored a variety of parameters derived from conductor geographical locales, meteorological data, metallic measurements of conductor samples, network operating condition and industry experience. We dealt with several challenging issues: (1) what parameters are most informative to reflect the condition of the conductor and can be used as the inputs for the health index calculation; (2) to which extent these parameters can reflect the condition of conductors, and subsequently to determine the weighting factor of each parameter; (3) how to obtain these parameters from in-service conductor circuit; and (4) how to extract relevant information from various data and processing it into appropriate health indices. After completing a comprehensive study, we have developed a health index calculation methodology for Australian DNSPs. The computed health index values are also correlated with probability of conductor failure. The developed health index method is trialled on two types of distribution conductors and verified with field measurement data.

The paper is organized as follows. Section II presents survey results on conductor population in Australian DNSPs across four major Australian states. Section III starts with a brief overview of health index methodology proposed in this paper. The major conductor degradation mechanisms and the

TABLE 1. Definitions of the climate zones [11].

Climate zones	Definition
Coastal	Humid climate within 100 km from the coast.
Highlands	Mountainous areas with moderate rainfall.
Plains	Low to moderate rainfall area.
Arid	Barren, very low rainfall area.

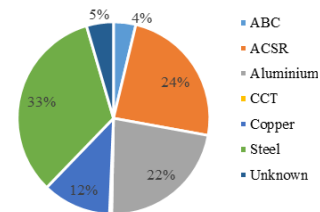


FIGURE 1. Conductor population statistics in Australian distribution networks in New South Wales, Queensland, Victoria and Western Australia [11].

parameters that affect each type of degradation mechanism are then detailed. Section IV provides the detailed information on the formulation and implementation of the proposed conductor health index methodology. In Section V, the results of a field trial of the proposed methodology is presented. The calculated health index values are correlated with the probability of conductor failure. The paper is concluded in Section VII.

II. STATISTICS OF BARE OVERHEAD CONDUCTORS IN AUSTRALIAN DISTRIBUTION NETWORKS

This section presents an analysis of overhead conductor statistics of the studied distribution networks covering four major states, span about 6.2 million square kilometres and have almost 800,000 circuit kilometres of overhead conductors.

A. CONDUCTOR POPULATION IN AUSTRALIAN DNSP's NETWORKS

Historically, galvanized steel conductors were commonly used in Australian rural distribution networks, mainly in the Single Wire Earth Return (SWER) networks. Copper was the most commonly used conductor for overhead lines in the early days of distribution network growth until 1960s, when it was slowly overtaken by Aluminium Conductor Steel-Reinforced Cable (ACSR) and All Aluminium Conductors (AAC). This project is focused on overhead bare distribution conductor operating at voltages up to 33 kV.

Considering different climate zones and other possible factors, conductor population locations are classified into four climate zones as given in Table 1. The population of each conductor type are presented in Fig. 1 It can be seen that the steel conductor (33%) is the most common conductor type. ACSR and aluminium conductors are the second (24%) and third (22%) most common types.

Fig. 2 presents the average age of the bare overhead conductors installed in 10 Australian DNSPs' networks. It can be seen that the average age of the conductors in most of

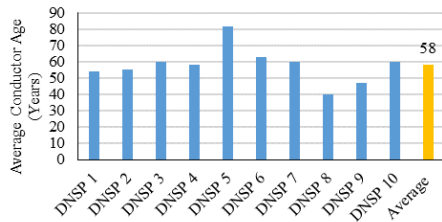


FIGURE 2. Average conductor ages in 10 Australian DNSPs' networks.

TABLE 2. Overhead conductor failure categories.

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

the DNSPs' networks are over 40 years. The overall average age of the conductors in the ten DNSPs is 58 years. These statistics show the necessities of developing a suitable methodology, which is essential for DNSPs' maintenance and replacement strategies.

B. CONDUCTOR FAILURE STATISTICS IN AUSTRALIAN DNSP'S NETWORKS

According to the conductor failure data received from the Australian DNSPs, two types of overhead conductor failure categories, "unassisted" and "assisted" were defined in Table 2. Conductor failure is considered to have occurred with a breakage of the conductor or a conductor drop. 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.

Fig. 3 (a) shows the percentage of unassisted conductor failures with respect to each geographic location (coastal, arid, highlands and plains) in the Australia distribution networks. It can be seen that the majority of the unassisted conductor failures were from conductors installed in the coastal areas.

The modes of the major unassisted conductor failure in Australian distribution networks are illustrated in Fig. 3(b). It can be seen that the most significant conductor failure mode is corrosion and it contributes to about 30% of failures. The other significant failure modes are Splice/Joint failure (19%) and fatigue (14%). It should also be noted that most of the above failure modes are sensitive to their environmental conditions.

C. IDENTIFICATION OF MAJOR CONDUCTOR FAILURE MODES IN AUSTRALIAN DNSP'S NETWORKS

By analysing conductor failure records and distribution network operating conditions, a number of root causes of conductor failure are identified as listed in Table 3.

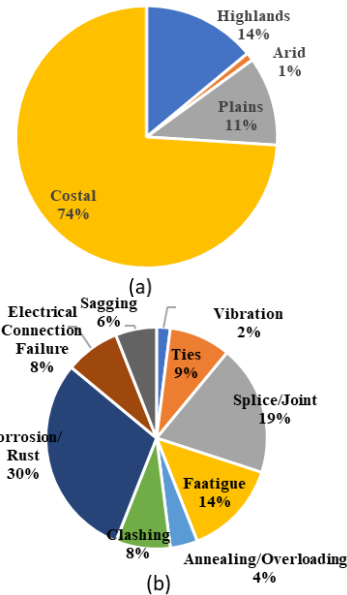


FIGURE 3. (a) Conductor failure statistics with respect to geographical location (b) Failure modes of unassisted failure in the Australian distribution networks [11].

TABLE 3. Conductor failure causes.

Causes	Impact on Conductor Condition
Corrosion	Affects overall condition of conductor, leading to pitting, loss of cross-sectional area and mechanical strength (Irreversible).
Annealing	Affects overall condition of conductor, leading to change in microstructure and loss of mechanical strength (Irreversible).
Fatigue	Generally, occurs at conductor fittings/points of support can be mitigated with armour rods and vibration dampers. Not representative of overall condition (reversible-can be repaired).
Accessory (Joint/Clamp etc.) degradation/failure	Generally, causes localized defects on conductor (reversible - can be repaired).
Arcing due to Clashing, lightning or interference	Causes localized defects on conductor (reversible - can be repaired).

The corrosion and annealing have long term effects on the overall condition of conductors. Eventually they can lead to conductor failures requiring the replacement of the whole circuit ("irreversible failure modes"). Other causes (fatigue, creep, arcing due to lightning and clashing, and failure due to accessory components) leading to localized failures but can be repaired or mitigated ("reversible failure modes"). Conductor is a distributed asset, the condition at a particular section of a conductor may not represent the overall condition of the line. The reversible and irreversible failure modes need to be treated separately. For the irreversible failure, conductor replacement may be the only solution. For the reversible failure, the remedial treatment can be performed by repairing or replacing the degraded segment of feeders or faulty accessories.

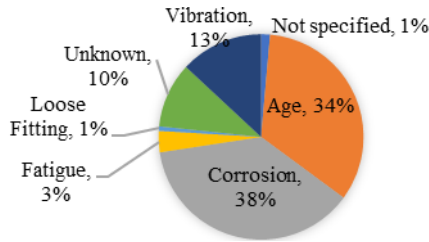


FIGURE 4. Causes of unassisted conductor failures.

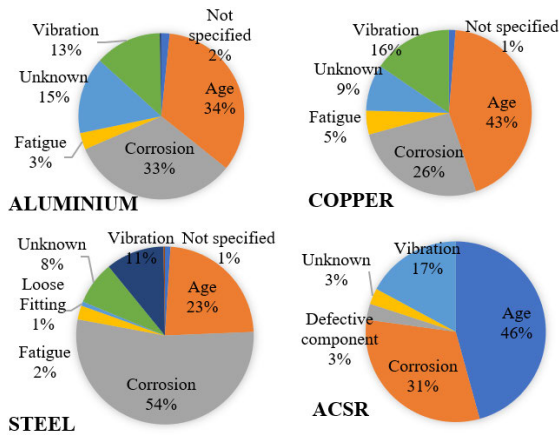


FIGURE 5. Unassisted failure by conductor type in the distribution network (2012-2018).

D. AN EXAMPLE OF CONDUCTOR FAILURES IN A TYPICAL AUSTRALIAN DISTRIBUTION NETWORK

Fig. 4 presents an example of conductor failure statistics of an Australian distribution network, which has about 200,000 circuit kilometres of overhead conductor *s* in service. In Fig. 4, the data was collected over a period of seven years (2012–2018).

From Fig. 4, it can be seen that age and corrosion are the main conductor failure causes in the above selected network. Age and corrosion have contributed to about 34% and 38% of conductor failures respectively. Further, vibration also contributed to 13% of overhead conductor failures.

Fig. 5 illustrates the causes of aluminium, copper, steel and ACSR conductor failures. These data was recorded from the studied distribution network over the period 2012 to 2018. It should be noted that in Fig. 5, the failure cause “Unknown” is used when the field officer has decided it does not fall under any of the other failure classifications. “Unspecified” is used when no input has been given by the field officer. Also, in Fig. 5 “Fatigue” is used to represent the failure influenced by Aeolian vibration in light winds and “vibration” is used to represent the failures caused by short term vibrations due to moderate to strong winds during severe weather events. From the data illustrated in Fig. 5, it can be seen that service age is the major cause of failures in aluminium, copper, and ACSR conductors. 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/splices, or cumulative fault and reclose operation.

III. METHODOLOGY OF INDUSTRY EXPERIENCE BASED HEALTH INDEX FOR BARE OVERHEAD CONDUCTORS

It is of great interest for Australian DNSPs to develop health index to assess the conductor condition and predict the likelihood of irreversible failure of conductors. Currently Australian DNSPs are not equipped with sensor-based condition monitoring systems for conductors. The availability of field test results is limited and some DNSPs do not have any field test data. Post-mortem studies are limited. Therefore, we decided that:

1. The HI should be calculated based upon the long-term failure modes that the conductor is likely to experience over its lifetime.
2. The HI should be calculated based upon parameters, which are readily available or easily accessible by the DNSPs’ asset managers.
3. The input parameter values and their weights should vary according to the conductor type, geographical location, and network service condition etc.
4. The HI formula should be generalized to account for different types of distribution overhead conductors.

Considering aforementioned requirements, a fully customizable weighted sum-based HI calculation methodology is proposed. Further, the most significant conductor degradation mechanisms which lead to conductor failures in the Australian distribution network were identified. Finally, considering the typical conductor information available for an asset manager, each degradation mechanism was further divided into a set of quantifiable input parameters. Detailed description is presented below.

A. WEIGHTED-SUM HEALTH INDEX

To calculate a health index of overhead conductors in the Australian distribution network, a weighted sum-based equation similar to that used in [4] is implemented. The proposed conductor health index calculation consists of two stages. At the first stage, each input parameter is represented by a set of sub-condition parameters. Then, a condition parameter score (CPS) corresponding to each condition parameter is computed as,

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

where,

- SCPS - sub-condition parameter score
- WSC - weight of sub-condition parameter
- SCPS_{n,max}- maximum Score for Sub-Condition Parameter
- β_n - data availability coefficient

At the second stage, the calculated CPSs of all input parameters are combined to obtain a health index as

$$HI = \frac{\sum_{m=1}^{\forall m} \beta_m (CPS_m \times WPC_m)}{\sum_{m=1}^{\forall m} \beta_m (CPS_{m, \max} \times WPC_m)} \times DRF \quad (2)$$

where,

CPS- condition parameter score

WCP - weight of condition parameter

CPS_{max} - maximum score for condition parameter

α_m - data availability coefficient

DRF - de-rating factor

Now the next task is to decide the types of input parameters, which can accurately represent the degradation mechanism that deteriorate the bare overhead conductors. A further task is to find out how to quantify each input parameter into sub-condition parameters.

As discussed in Section II, bare overhead conductors are subject to a number of reversible and irreversible degradation mechanisms. The irreversible failure modes usually affect the overall or a significant length of the conductor. The remedial treatment for the irreversible failure modes is the replacement of the conductor. Thus, in the current HI method, only two irreversible failure modes i.e. corrosion and annealing are included. However, it should be noted that both condition types (irreversible and reversible) can influence the probability of failure of the conductors.

B. DETERMINING INPUT PARAMETERS BASED ON SIGNIFICANT FAILURE MODES OF AUSTRALIAN DISTRIBUTION CONDUCTORS

As conductors degrade, they lose their mechanical strength and consequently lose the ability to perform their intended functions. Australia is a country where most of its population reside near the coastline. Hence, a significant portion of the Australian distribution network is situated in close proximity to the coastline. As illustrated in Fig. 3 and Fig. 4, close proximity to the coastline has made corrosion one of the most significant conductor failure modes.

On the other hand, Australian distribution network comprises of significant number of long feeders in rural areas that are prone to short term temperature overloading from high or long duration current faults and multiple reclosing. These faults are caused by lightning and vegetation impact and wildlife activities. Taking the above into consideration, annealing was selected as the second major conductor failure mode in the Australian power distribution network.

1) CONDUCTOR CORROSION

Conductor corrosion can result in the loss of metal material, which leads to the loss of mechanical strength. Overhead conductors are subjected to two main types of corrosion, namely atmospheric and galvanic corrosion [12].

Atmospheric corrosion occurs when conductors are exposed to oxygen, carbon dioxide, water vapour, salt, and sulphur and chlorine compounds. On the other hand, some physical characteristics of conductors such as how easily the conductor captures and holds the moisture and other pollutants also contribute to corrosion.

Galvanic corrosion occurs when metals with different electric potentials are in contact in the presence of moisture. The metal which can easily release electrons becomes the anode and the other acts as the cathode [12]–[14]. 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 vanishes over time and the aluminium is in contact with the steel, its aluminium becomes the sacrificial anode and corrodes at a high rate. The galvanic corrosion can produce a white powder residue, which may be visible on the conductor surface.

The field inspection data and industry experience indicate that overhead conductors in a close proximity to the coast (less than 5 km) deteriorate at a much higher rate due to corrosion. It becomes evident in the loss of cross section area of a conductor and its tensile strength. It is found that the galvanized steel conductors may wear out to a critical level (where the loss in strength is 10% or more) as early as at the age of 20 years.

Copper and aluminium conductors are more corrosion resistant than galvanized steel. The average wear out occurs in the range of 30 years for the copper conductor and about 45 years for the aluminium conductor. However, the presence of salt can accelerate conductor corrosion, hence, extra precautions are required. For example, when copper and aluminium conductors have to be joined together, the aluminium conductor should be located above the copper and the bi-metallic clamps need to use.

After a detailed investigation of conductor corrosion in the Australian distribution network, the parameter set (in Table 4) is defined to estimate the extent of conductor degradation caused by corrosion. The sub-condition parameters in Table 4 are chosen in such a way that no sophisticated tests will need to be conducted to determine the parameter values.

2) CONDUCTOR ANNEALING

Overhead conductors anneal when they operate at elevated temperature levels. Overload conditions, high resistance conductor joints, environment temperature rising and multiple reclose operations are some of the common causes leading to conductor overheating. Annealing is a process that can decrease the tensile strength of the hard-drawn bare overhead conductors [13], [14]. Different types of metals anneal at different rate. It is 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 [15]. By comparison, copper and aluminium conductors can lose strength at temperatures less than 100 °C [16].

The loss of tensile strength due to annealing is dependent on temperature, time exposed to that temperature,

TABLE 4. Selected sub-condition parameters input parameters for calculating the condition parameter scores of corrosion and annealing.

Sub-Condition Parameter	
Corrosion	Annealing
Material type	Material type
Proximity to coast	Electrical loading (% of CCC)
Proximity to other pollution sources (e.g. industrial, agricultural, salt lakes)	History of faults within the conductor’s protection zone
Moisture levels (e.g. rainfall)	Fault energy at conductor location
Age	Age
Corrosion related defects	Protection scheme employed within the conductor’s protection zone
Strand configuration and strand diameter	Strand configuration and strand diameter
Surface visual appearance	

diameters of the wire and draw rod [16]. Therefore, the set of sub-condition parameters, which are listed in Table 4 are defined to estimate the extent of conductor degradation caused by annealing. The selected annealing related sub-condition parameters represent the possibility of conductor overheating and the time a conductor may operate at an elevated temperature level. Considering the factors that could influence conductor annealing, the parameter set (in Table 4) are defined to estimate the extent of conductor degradation caused by annealing.

IV. IMPLEMENTATION OF HEALTH INDEX FOR CONDUCTORS IN AUSTRALIAN DISTRIBUTION NETWORKS

As discussed in previous sections, both corrosion and annealing are the primary condition parameters and they are influenced by sub-condition parameters in Table 4. Each sub-condition parameter is further divided to a set of quantifiable parameters as listed in Table 5.

In Table 5, each parameter is assigned a value in the range of 1–10 considering their influence to the corrosion and annealing. The value of 10 represents the least influence on the primary condition parameters. Each parameter has a different influence on the overall asset health. Hence, it is required to rank the parameters and assign weights in the range 1–10. The parameters that have greater contribution to asset degradation and failure are given higher weights. The range of values for each parameter may vary between utilities because of different geographical and environmental exposures and are best determined by experienced industry or utility members.

In the implementation process, the values of the set of parameters are defined based on the DNSPs’ practice and asset manager’s experience on their network. After that, the initial input parameter values are tuned using field expertise or measurements. Availability and quality of each of the input parameters are not uniform. To take this into account, the parameter β in (1) is used and it is defined in Table 6. If users have high quality data, they would use a higher β

TABLE 5. Quantifiable components of each sub condition parameters.

Corrosion	Annealing
Material Type	
SCGZ	
SCAC	
CU	
ACSR	
AAC	
AAAC	
Proximity to coast (Pc)	Electrical Loading (Pel)
0km < Pc <= 1km	100% Current Carrying Capability (CCC) < Pel <= CCC
1km < Pc <= 5km	71% CCC < Pel <= 100% CCC
5km < Pc <= 10km	51% CCC < Pel <= 70% CCC
10km < Pc <= 20km	31% CCC < Pel <= 50% CCC
20km < Pc	Pel <= 30% CCC
Number of corrosion related defects/km (Defcor)	History of Faults (Pf) on Feeder/ annum
0 = Defcor	5 < Pf
1 < Defcor <= 5	3 < Pf <= 5
5 < Defcor	1 < Pf <= 3
Proximity to pollution sources (Pps)	0 = Pf
0km < Pc <= 1km	History of Faults (Pf) on Feeder/ annum
1km < Pc <= 3km	No history of faults
3km < Pc <= 5km	Moderate history of faults
5km < Pps	High history of faults
Moisture levels	Fault Energy (may be feeder based)
Heavy rainfall	High fault energy
Moderate rainfall	Moderate fault energy
Light rainfall	Low fault energy
No rainfall	Very low fault energy
Surface visual appearance	Protection scheme employed on Feeder
As new- bright shiny appearance	Recloser with two shot reclose
Dull appearance – some surface roughening	Recloser with one shot reclose
First signs of corrosion	Recloser with no reclose
Widespread corrosion	Fuse Protection
Surface pitted and severely roughened	LV relying on HV fuse protection?
Observable loss of cross-sectional area due to corrosion	
Age of conductor (Age in years)	
0 < Age <= 20	
20 < Age <= 40	
40 < Age <= 60	
60 < Age	
Strand configuration and strand diameter combination	
3 strand conductor with overall conductor diameter <= 6mm	
7 strand conductor with overall conductor diameter <=6mm	
7 strand conductor with overall conductor diameter <=9mm	
19 strand conductor with overall conductor diameter <= 9mm	
7 strand conductor with overall conductor diameter <=15mm	
19 strand conductor with overall conductor diameter <= 15mm	
Any strand conductor with overall conductor diameter > 15mm	

value. However, if the data quality is low, a smaller β value needs to be used.

V. CASE STUDIES AND DISCUSSIONS
A. HEALTH INDEX OF CONDUCTORS IN AUSTRALIAN DISTRIBUTION NETWORKS

In this section, two case studies are presented to exemplify the HI methodology for the bare overhead conductors. The

TABLE 6. Data availability and quality (B).

Data availability and quality	β
No data available	0
Limited data available and low quality	0.2
Moderate data available and moderate quality	0.5
Good data available and good quality	1.0

first case study illustrates the key steps of calculating HI of a single distribution line. In the second case study, the HI methodology algorithm is trialled on a range of conductors from distribution lines of an Australian DNSP.

1) CASE STUDY 1

A distribution line of 55 years old 7/1.60 Steel Core Galvanized Zinc (SCGZ) conductor is located in an industrial area, 4 km from the coast in a subtropical climate zone with moderate rainfall. According to maintenance records, this line had 15 previous corrosion related defects. Onsite inspections revealed a widespread corrosion on the conductor with visible pitting on the surface. The line is on a HV rural feeder loaded at 40% of its Current Carrying Capability (CCC) and subjected to an average of one low energy fault per annum. The line is protected by master drop out fuses.

To calculate the health index for the above conductor, the first step is extracting input parameters from available field data and information. These data and information comprise all the input parameters listed in Table 5. The corresponding input parameter values and weighting factors are listed in Appendix A, Table 7.

The second step is to assign a weight to each input parameter. These weights are determined based on the network operating conditions, experts' knowledge and failure statistics. Then, the values of the parameters and their weightages are used to calculate condition parameter scores (CPSs) as below (3) and (4) as shown at the bottom of the page.

The computed CPS values corresponding to corrosion and annealing are 53% and 75% respectively. Finally, the above two CPS values are used to calculate the health index of the above conductor as

$$HI = \frac{(1 \times 0.5333 \times 1) + (1 \times 0.7515 \times 1)}{(1 \times 1 \times 1) + (1 \times 1 \times 1)} \times 1 = 64\% \quad (5)$$

In (5), it is assumed that corrosion and annealing have equal weights on the conductor health index and thus a weighting factor of one is adopted for both.

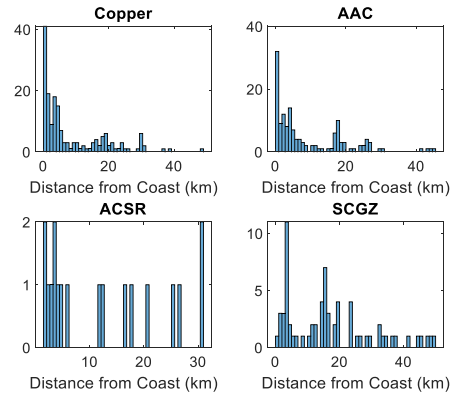


FIGURE 6. Histogram of the distance from coast to the conductor location.

Since the above distribution line is located just 4 km from the coast, it is likely that the conductor is more susceptible to corrosion. Thus, the weighting factors may be adjusted, e.g. a higher weight is assigned to corrosion while a lower weight is assigned to annealing. Hence, the above conductor has a health index in the range of 53% to 64% and can be considered in fair condition (health index value of 100% can be regarded as a brand-new conductor). The HI calculation is dependent on the input parameters as well as the data availability and quality. It is suggested that each utility use a trial and error approach by changing the values and weightings so that calculation matches what is observed in the field with the ageing conductor assets.

2) CASE STUDY 2

In this case study, the HI methodology is trialled on a range of conductors from distribution lines of a typical Australian DNSP. The conductor data comprises of material test results (tensile strength), geographical (distance to coast) and other information (proximity to pollution sources). The material test was performed on 500 conductor samples of these distribution lines. Fig. 6 presents a histogram of the distance from these conductors to the coast.

The conductor data does not contain information relevant to the annealing condition parameter such as electrical loading, fault history, fault energy level and protection scheme etc. However, as illustrated in FIGURE 6, most of the conductor samples were collected from the locations close to the coast. Thus, it was assumed that the most significant failure mode for the above conductor section is corrosion. Therefore, the HI for this case study was calculated solely based on corrosion, i.e. using $m = 1$ and $HI = CPS_{Corrosion}$ in (2) and (3) in the calculation as in (6). The corresponding input parameter values and weighting factors are listed in

$$CPS_{Corrosion} = \frac{\{(\beta_1 \times SCPS1 \times WSCP1) + \dots + (\beta_8 \times SCPS8 \times WSCP8)\}}{\{(\beta_1 \times SCPS1_m \times WSCP1) + \dots + (\beta_8 \times SCPS8 \times WSCP8)\}} \quad (3)$$

$$CPS_{Annealing} = \frac{\{(\beta_1 \times SCPS1 \times WSCP1) + \dots + (\beta_7 \times SCPS7 \times WSCP7)\}}{\{(\beta_1 \times SCPS1_m \times WSCP1) + \dots + (\beta_7 \times SCPS7 \times WSCP7)\}} \quad (4)$$

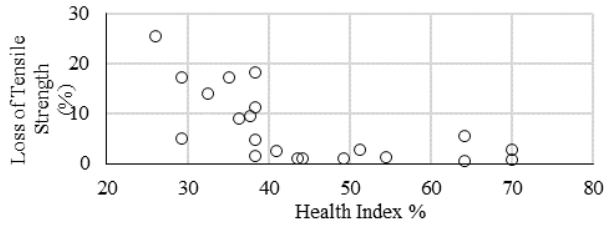


FIGURE 7. HI vs. percentage loss of tensile strength of copper conductors.

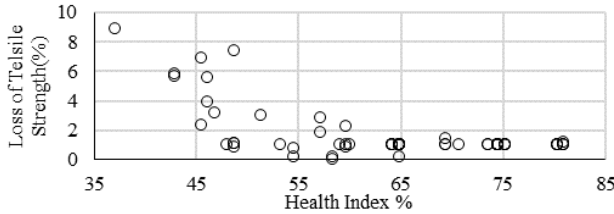


FIGURE 8. HI vs percentage loss of tensile strength of AAC conductors.

Appendix A, Table 8 and Table 9.

$$HI = CPS_{Corrosion} = \frac{\sum_{n=1}^{\forall n} \beta_n(SCPS_n \times WSCP_n)}{\sum_{n=1}^{\forall n} \beta_n(SCPS_{n,max} \times WSCP_n)} \quad (6)$$

The remaining tensile strength of a conductor is considered a good indicator of the conductor’s condition. Thus, the calculated HI was compared with the measured tensile strength. Note that the tensile strength was not taken as an input to the HI algorithm. A comparison between the calculated HI values of copper and AAC conductors from the above distribution lines are illustrated in Fig. 7 and Fig. 8 respectively.

From Fig. 7 and Fig. 8, it can be seen that the conductors’ HI values for both conductor types decrease with the increase of the percentage loss of the conductor’s tensile strength. This verifies that the HI values calculated using the proposed methodology can represent the health condition of the conductor. In both figures, there are several anomalous or outlier data points. Given that the health index of the conductor types calculated are only based on corrosion related data, the reason could be that the corresponding conductors could lose their tensile strength due to other failure modes such as annealing. Further, it is important to be able to correlate HI with the loss of tensile strength and the probability of failure for an improved interpretation of HI values.

B. CONDUCTOR HEALTH INDEX AND ITS PROBABILITY OF FAILURE

The conductor’s end-of-life failure (ageing failure) is a type of non-repairable failure. This type of failure occurs at the wear-out-stage of the conductor’s life cycle curve. The life curve of an overhead conductor usually does not consist of an infant stage [4], [17], and typically has two stages, namely a normal operating stage and a wear-out stage.

To calculate the probability of failure of a conductor, the process illustrated in Fig. 9 was adopted. Information

TABLE 7. Input parameter values and weighting factors used for HI calculation in case study 1.

Material type: SCGZ (WSCPcorrosion = 1 , WSCPannealing = 5)			
SCPS1	Actual	5	(Between 1-10)
β1	Data confidence	1	(Between 0-1)
Distance from Coast: 4 km (WSCPcorrosion = 1)			
SCPS2	Actual	6	(Between 1-10)
β2	Data confidence	1	(Between 0-1)
Other pollution source: Industrial (WSCPcorrosion = 2)			
SCPS3	Actual	3	(Between 1-10)
β3	Data confidence	1	(Between 0-1)
Moisture levels: Moderate rainfall (WSCPcorrosion = 8)			
SCPS4	Actual	7	(Between 1-10)
β4	Data confidence	1	(Between 0-1)
Age: 40 years (WSCPcorrosion = 5)			
SCPS5	Actual	6	(Between 1-10)
β5	Data confidence	5 ⁰	(Between 0-1)
Corrosion related defects: 12 defects in the 3 km section (WSCPcorrosion = 4)			
SCPS6	Actual	3	(Between 1-10)
β6	Data confidence	1	(Between 0-1)
Surface visual appearance: widespread corrosion on the conductor with visible pitting (WSCPcorrosion = 5)			
SCPS7	Actual	5	(Between 1-10)
β7	Data confidence	5 ⁰	(Between 0-1)
Strand configuration and diameter: 7 strands and diameter <=6mm (WSCPcorrosion = 4 , WSCPannealing = 2)			
SCPS8	Actual	5	(Between 1-10)
β8	Data confidence	1	(Between 0-1)
Electrical Loading: 40% CCC (WSCPannealing = 5)			
SCPS2	Actual	7	(Between 1-10)
β2	Data confidence	1	(Between 0-1)
Fault history: 1 per annum (WSCPannealing = 2)			
SCPS3	Actual	8	(Between 1-10)
β3	Data confidence	1	(Between 0-1)
Fault energy: Low (WSCPannealing = 2)			
SCPS4	Actual	8	(Between 1-10)
β4	Data confidence	1	(Between 0-1)
Age: 55 years (WSCPcorrosion = 4 , WSCPannealing = 5)			
SCPS5	Actual	6	(Between 1-10)
β5	Data confidence	1	(Between 0-1)
Protection scheme: MDO fuses (WSCPannealing = 2)			
SCPS6	Actual	1 ⁰	(Between 1-10)
β6	Data confidence	1	(Between 0-1)

such as measured tensile strength and service age are used to develop the relationship between conductor probability of failure and its age. Tensile strength measurements have been

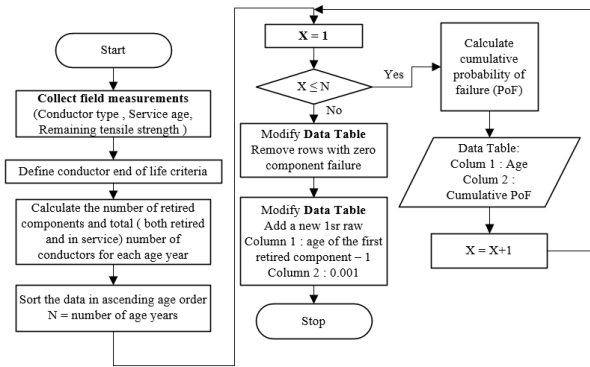


FIGURE 9. Process of computing the probability of failure of conductors.

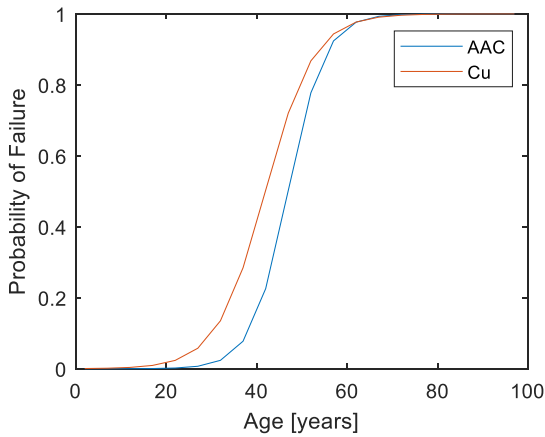


FIGURE 10. Probability of failure vs Age of bare overhead conductors.

performed on samples collected from both in-service and retired bare overhead conductors.

Fig. 10 presents the probability of failure with respect to age curves of copper and aluminium conductors which have reached end of life in an Australian DNSP. The probability of failure curves in Fig. 10 have been calculated from field measurements using the methodology presented in Fig. 9. Considering the Australian network operating conditions, current industry practices and failure statistics, 10% loss of tensile strength was used as the conductor end-of-life criteria. Then, the cumulative probability of failure value (P_n) corresponding to each age are calculated using (7). In (7), $n = 1, 2 \dots N$ where, N is the number of elements in the “age” column of the data set which has been sorted in ascending order (see Fig. 9). $X_{retired}$ and $X_{in-service}$ are the retired (failed) and in-service (survived) conductor numbers correspond to each age respectively.

$$P_n = \sum_{i=1}^n \frac{X_{retired_i}}{X_{retired_i} + X_{in-service_i}} \quad (7)$$

It can be seen that the curves (probability of failure vs age) for both overhead conductors have two regions i.e. a normal operating and a wear-out stage. The failure probability of the copper conductor starts increasing at around 20 years of age. From about 25 years to about 60 years, the copper conductor’s probability of failure steeply increases (e.g. the

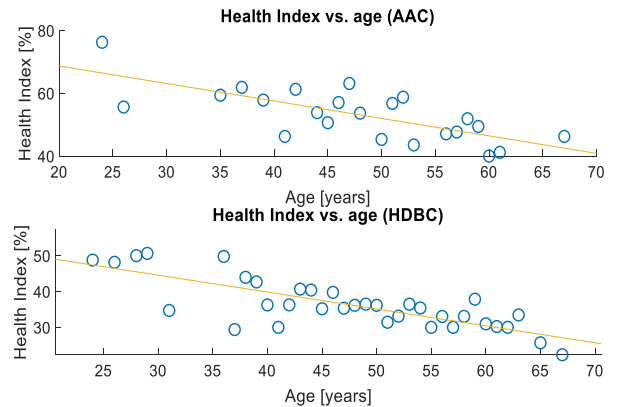


FIGURE 11. Correlation between the health index and service age of bare overhead conductors (AAC - All aluminium conductors, HDBC - Hard Drawn Copper Conductors).

wear out stage). In contrast, the aluminium conductor enters the wear out stage at around 35 years of age. Both copper and aluminium conductors in the studied Australian DNSP’s network reached end of life at an age around 60.

It should be noted in this case study the end of life of the conductor is based on a conservative value for the loss in mechanical strength of 10%. Further work by the project team suggests a more appropriate value for end of life for a distribution conductor is from 20% to 30% loss in mechanical strength. The implications for the probability of failure vs age curve is that the curve will move to the right, with a higher age when wear out begins.

Correlating a conductor’s health index with its probability of failure can assist decision-making of conductor operation and maintenance. To do so, both probability of failure and HI of conductors were mathematically represented as functions of service age. The relationship between the conductor’s probability of failure and its service age as shown in Fig. 10 is modelled using a modified logistic function as below. Parameter a and b in (8) can be calculated by using a curve fitting method.

$$PoF = \frac{1}{a e^{-bt} + 1} \quad (8)$$

Fig. 11 presents the conductor HI with respect to its service age. From VI, it can be seen that a relationship exists between the HI and the service age and this can be approximated using a linear function. By combining (8) and the linear function in Fig. 11, the probability of failure vs. health index curves of bare overhead conductors can be obtained, which is shown in Fig. 12.

As illustrated in Fig. 12, the probability of failure of a copper conductor in the studied part of the Australian distribution network remains almost zero until its health index reaches about 40%. However, in the case of an aluminium conductor in the same distribution network, its probability of failure starts increasing at around HI of 60%. The end of life HI values of copper and aluminium conductors are around 25% and 45% respectively.

TABLE 8. Input parameter values used for HI calculation in case study 2.

	SCPS
Material Type	
SCGZ	1
SCAC	7
CU	5
ACSR	7
AAC	9
AAAC	9
Proximity to coast (Pc)	
0km < Pc <= 1km	1
1km < Pc <= 5km	5
5km < Pc <= 10km	7
10km < Pc <= 20km	9
20km < Pc	10
Proximity to pollution sources (Pps)	
0km < Pc <= 1km	1
1km < Pc <= 3km	9
3km < Pc <= 5km	10
5km < Pps	10
Moisture levels	
Heavy rainfall	10
Moderate rainfall	8
Light rainfall	6
No rainfall	4
Age of conductor	
0 yrs < Age <= 20 yrs	10
20 yrs < Age <= 40 yrs	7
40 yrs < Age <= 60 yrs	5
60 yrs < Age	1
Number of corrosion related defects/km (Defcor)	
0 = Defcor	10
1 < Defcor <= 5	3
5 < Defcor	1
Surface visual appearance	
As new- bright shiny appearance	10
Dull appearance – some surface roughening	8
First signs of corrosion (loss of galvanising, isolated patches of corrosion, signs of white oxides on Al conductors)	5
Widespread corrosion	3
Surface pitted and severely roughened	2
Observable loss of cross-sectional area due to corrosion	1
Strand configuration and strand diameter combination	
3 strand conductor with overall conductor diameter <= 6mm	1
7 strand conductor with overall conductor diameter <=6mm	3
7 strand conductor with overall conductor diameter <=9mm	4
19 strand conductor with overall conductor diameter <= 9mm	5
7 strand conductor with overall conductor diameter <=15mm	6
19 strand conductor with overall conductor diameter <= 15mm	7
Any strand conductor with overall conductor diameter > 15mm	10

In Fig. 12, the probability of failure is calculated based on an end of life criteria where the conductor has loss 10% of

TABLE 9. Weighting factors used for HI calculation in case study 2.

SCPS	SCPS
Material type	1
Proximity to coast	1
Proximity to other pollution sources	4
Moisture levels	8
Corrosion related defects	4
Surface visual appearance	5
Age	5
Strand configuration and strand diameter combination	4

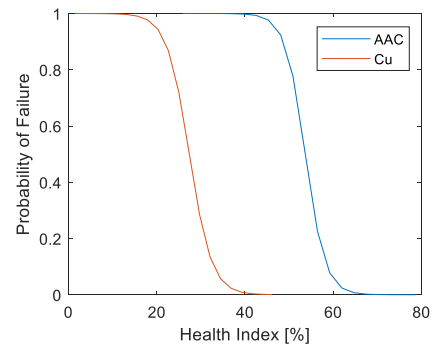


FIGURE 12. Probability of failure vs HI of bare overhead conductors.

its initial strength. However, it is more likely that distribution network service providers accept an end of life criteria where from 20% to 30% loss in initial strength has occurred. If such end of life criteria is used, the curves in Fig. 12 move to the right indicating increasing age until a failure is deemed to have occurred.

VI. CONCLUSION

This paper presents results from an industry led research project to improve the condition assessment of bare overhead conductors in the Australian distribution networks. Through comprehensive investigations of network operating conditions and failure statistics, corrosion and annealing were identified as the most significant conductor failure modes. A weighted sum health index methodology, which is based upon sub parameters that are readily available or easily accessible to asset managers is proposed. The proposed health index methodology was tested on a set of aged copper and aluminium conductors. Results revealed that health index values calculated are in a good agreement with or can be a good predictor of the true health state of the conductor. Using the available field test data, a mathematical model that can be used to correlate the probability of conductor failure to the calculated health index is developed.

It should be noted that present work has been conducted using a limited number of failure statistics and field measurements. Thus, further investigations and validations are needed for improving the accuracy of the health index and probability of failure calculation methods, which are planned for a continuing project.

APPENDIX

The Input parameter values and weighting factors provided by an Australian distribution network service provider considering, maintenance records, fault history, network operating conditions and asset manager's expert knowledge are listed in Table 7 to 9.

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