AN INNOVATIVE APPROACH TO OVERHEAD CONDUCTOR MANAGEMENT

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Summary: Western Power, supported by Frazer-Nash Consultancy and Assetivity, embarked on an initiative to increase its understanding of the condition of its distribution overhead conductor fleet to better inform its strategy on renewal and maintenance. This comprised of a number of focussed innovative activities including a sampling program, metallurgical testing and a grassroots study (structured interviews with field staff at depots). This paper will outline how Western Power undertook sampling of the conductors, key findings and benefits of the program.

Western Power has an extensive distribution overhead network spanning more than 68,000 circuit kilometres over a large geographical area in Western Australia. Overhead conductors present a potential safety risk to the community and workforce. The condition of conductors is quite varied as the network consists of conductors of different ages and material types, which have been exposed to a variety of electrical and mechanical stresses depending on where it is located. Developing a more robust and consistent understanding of the condition is paramount to prudent management of the asset. The project successfully delivered a step change in asset knowledge through an approach that in terms of its scale, speed and robustness of the results has not previously been seen in electricity utilities’ asset management practice.

Keywords: Electricity Distribution, Asset Integrity, Human Factors, Asset Management, Design of Experiment, Bayesian Belief Networks, Expert Elicitation

WESTERN POWERS APPROACH TO ASSET MANAGEMENT

Introduction

Western Power adopts a risk-based approach to asset management, to fulfil its objective to connect people with electricity in a way that is safe, reliable and affordable. This risk-based approach is applied across all of Western Power’s asset types, including conductors, poles and sub-stations. The approach enables inspection, maintenance, repair and replacement decisions to be prioritised, so that sustaining capital is targeted most appropriately to reduce operational and safety risk and provide assurance that the business objectives are met.

Although the overarching risk-based approach is relatively mature, it relies on key inputs relating to asset condition, ageing and degradation mechanisms. For some of Western Power’s asset types, these inputs are clearly defined and well understood. However, for distribution overhead conductors it was recognised that improvements could be made to these inputs and their use.

Figure 1 illustrates the distribution overhead network scope (shown as distribution HV/LV). The distribution High Voltage (HV) network operates at 22kV and 33kV although some 6.6 and 11 kV network is in service. The distribution Low Voltage (LV) network operates at 240/415 V.
Western Power sought to improve the understanding of conductor ageing and degradation, so that more informed inputs could be generated and used in the risk-based asset management decision-making processes.

The functions conductors perform make them critical in maintaining required levels of network performance. The consequences of failure of a conductor or conductor accessory can be catastrophic, potentially resulting in fire, electric shock, or impact injury. Conductors are subject to an ongoing monitoring and condition / risk assessment regime to inform the need for remedial action. The objective of the distribution overhead conductor replacement program is to replace those overhead conductors that have reached the end of their service life and whose expected performance is now considered “unpredictable” and no longer meets the required level of safety and reliability outcomes.

Conductor failures occur when applied loads exceed the conductor strength causing a complete break in the conductor. Assuming no manufacturing or construction defects and loading within design limits, conductor failure occurs primarily as a result of:

- Reduction of the tensile strength of the metal, normally due to fatigue;
- Reduction of the ductility of the metal (i.e., brittleness), normally due to annealing;
- Reduction of the cross sectional area of the metal normally due to corrosion or mechanical damage (i.e., wear or clashing); or
- Stress concentrations due to mechanical damage (i.e., surface damage or over compression at a joint or point of connection).

As a learning organisation, Western Power applies the Plan-Do-Check-Act process. To check that the assumptions used when assessing risk were appropriate Western Power, in conjunction with Frazer-Nash Consultancy and Assetivity, undertook a focused data acquisition and analysis project aimed at:

1. Improving its knowledge and understanding of the condition, ageing characteristics and current remaining life of the conductor asset population; and
2. Improving its capability to identify and target those conductors that require remediation (replace, repair or refurbish).

**Monitoring & Assessing Risk**

The following activities are carried out to identify conductors that have a high likelihood of failure and may require remediation:

- Field inspections to validate conductor attributes and identify conductor defects. Defects are also identified during ad-hoc inspections which are carried out during planned or reactive maintenance.
- Office assessments which allocate bays, which are aggregated into network segments, for targeted field inspection (scoping) based on their risk. Likelihood of failure is assessed using the following attributes and influenced by environmental and operating factors as they are currently understood:
  - Copper < 6.1mm diameter and greater than 40 years age; then
  - Steel conductor greater than 40 years age; then
  - ACSR (Aluminium Conductor Steel Reinforced) conductors greater than 20 years age; then
  - Conductors greater than 40 years age.
  - Risk is then quantified by considering their potential to cause consequences, specifically in relation to their potential to impact public safety and service reliability.
- Scoping inspections of targeted bays identified in the office assessment. Following the scoping inspection bays are assigned a condition code ranging from 0-100, where 0-30 indicates a conductor that needs replacement, 30-60 indicates a conductor that is in a degraded state and 60-100 indicates a conductor that is as-new or in the early stages of degradation.
The Western Power Network Risk Management Tool (NRMT) conductors risk model, a Bayesian Belief Network based risk quantification model, considers each of the above factors as well as the environmental, design, construction and operational factors that contribute to conductor failure to identify Bays that require remediation.

Challenges
While the approach to asset management is relatively mature, there are a number of challenges that require effort to overcome:

- The basis for identifying conductor assets approaching their end of life was based on empirical failure data collected by Western Power. It was recognized this approach was good, but a relatively small sample data set given the numbers of conductors that fail;
- Conductor condition inspection has historically focused on visual inspection for defects – it is recognised within the industry that condition assessment methods beyond visual inspection are required to more confidently assess the health of conductor assets;
- As-constructed information was lacking for older parts of the network where original records are not readily available;
- The population of conductors believed to be approaching their end of life is large, and forecast renewal activities showed a bow-wave of investment required;
- The Western Power distribution network spans a vast geographic area and therefore there is significant variation in the operating conditions;
- Conductors form a part of long feeders and spurs; a 'weak point' in a small section can lead to a failure on a feeder that spans many kilometres, this presents practical challenges to inspection, restoration and management of conductor failure risk.

TARGETING THE INFLUENCING FACTORS
The asset management principle of Plan-Do-Check-Act is part of the Western Power asset management Strategy. To improve the outputs of the NRMT and Check the assumptions used in the NRMT it was recognised that better asset information was required. In particular, a better understanding of how the conductors degrade over time due to environmental conditions was required in order to develop an underlying physics based model.

Western Power captures a range of information on the conductors such as location, local pollutants, and distance to salt lakes. Working with Frazer-Nash Consultancy, the existing information was used to identify a number of factors that could be investigated. Following a series of workshops it was decided that a sampling program would be implemented in order to investigate:

- Establish a health index for the conductor population; and,
- Investigate the strength of conductors associated with each condition code.

Given the large geographical area the installed conductors cover (68,000 km) a well thought out strategy to select conductors for sampling was required. This strategy needed to target the conductors that were currently considered high risk as well as capture the effects of local operating environments on degradation rates. The environmental and operational factors that could affect degradation rates were identified and discussed during a series of workshops with Subject Matter Experts (SME's) as:

1. Electrical load – this affects the temperature in the conductor and therefore has an influence on conductor creep and annealing. However, electrical load across the network is considered reasonably stable. This factor would be randomised during the experiment design, but considered in any subsequent analysis, for example to help explain degradation mechanisms.
2. Mechanical load – this affects the mechanical stress in the conductor and includes static loads from tension in the line or dynamic loads from external factors such as wind. While data on wind speeds and direction could be derived from Bureau of Meteorology (BOM) or Agricultural Weather Station data, the actual mechanical load in each conductor is not readily available. Data on sag would be captured during the sampling program so that mechanical load can be evaluated during any analysis.
3. Conductor Diameter – a number of different diameter conductors exist in the network and the smaller diameters are considered more likely to fail in service. This is primarily due to smaller diameters having a lower load bearing capacity and therefore being more sensitive to metal loss from degradation mechanisms such as corrosion. The corrosion process itself is independent of diameter. Any analysis would need to assess corrosion rates in conjunction with the load bearing capacity of the conductor.
4. Age – any failures that occur within 10 years of installation are most likely due to infant mortality, and not due to ageing and degradation. Ageing was also not considered a hugely significant factor in the failure of conductors less than 20 years old. Therefore conductors < 20 years old were excluded from the program. Age data for the conductor population is not 100% reliable, particularly for older conductors.
5. Materials – the number of different materials in the population, combined with the environmental factors, is large. Therefore newer materials were excluded and focus put on those conductors that are aged.
6. Environment and Stress Factors – the current database has drawn upon BOM and Agricultural Weather Station data to better understand the environments in which conductors are located. There are a large number of factors available to investigate at both a high level and detailed level. All of the factors are of interest, but the level to which they are investigated depends on the experiment objective.

7. Condition codes – 2,500km of conductors have undergone scoping inspections and had condition codes assigned to them. These conductors were selected for inspection, based on the outputs of the NRMT. However, not every condition code for each material could necessarily be captured due to a lack of accurate information on condition across the network.

As outlined, each conductor on the network is subject to a range of factors that affect degradation and an important requirement of developing a physics based model is understanding the relationship between factors. An innovative approach to selecting conductors for samples was required.

Design of experiments (DOE) is a systematic method most frequently used in manufacturing industries to determine the relationship between factors affecting a process and the output of that process. In other words, it is used to find cause-and-effect relationships. This information is used to manage process inputs in order to optimize the output. In this innovative case, DOE principles were used to identify the optimum number of samples required to investigate a combination of influencing factors. The factors for the health index are shown in Table 1 and the factors for the condition code objective are shown in Table 2. Following the application of the DOE principles it was determined that 100 combinations of factors with five repeats would be investigated for the health index objective, for a total of 500 samples. For the condition code objective there were 55 combinations of factors with a target of four repeats for investigation.

**Table 1 Factors investigated for the health index objective**

<table>
<thead>
<tr>
<th>Conductor Type</th>
<th>Age Bracket</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu HV</td>
<td>20 - 30</td>
<td>Metro</td>
</tr>
<tr>
<td>Cu LV</td>
<td>30 - 40</td>
<td>Non-Metro</td>
</tr>
<tr>
<td>SCGZ HV</td>
<td>40 - 50</td>
<td>Coastal</td>
</tr>
<tr>
<td>AAC Random</td>
<td>50+</td>
<td>Salt Lake</td>
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<tr>
<td>ACSR HV</td>
<td></td>
<td>Pollution Zone</td>
</tr>
</tbody>
</table>

**Table 2 Factors investigated for the condition code objective**

<table>
<thead>
<tr>
<th>Conductor Type</th>
<th>Condition Code</th>
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</thead>
<tbody>
<tr>
<td>Cu HV</td>
<td>100</td>
</tr>
<tr>
<td>Cu LV</td>
<td>90</td>
</tr>
<tr>
<td>SCGZ HV</td>
<td>80</td>
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<tr>
<td>AAC Random</td>
<td>70</td>
</tr>
<tr>
<td>ACSR HV</td>
<td>60</td>
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<td></td>
<td>50</td>
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<td>10</td>
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<td>0</td>
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</tbody>
</table>
SAMPLING AND TESTING

Sampling Strategy

Once the combinations of factors were determined, Bays which fit the profile were selected according to Western Power’s database. One of the program challenges was the timeframe available to take samples and undertake testing – approximately four months. Therefore a well thought out logistics plan and innovation in sampling was required.

Due to uncertainty around the accuracy of the database, a number of alternative Bays were identified. All the conductors were first scoped in order to confirm that the database information was accurate and the bay satisfied the required combination of influencing factors. The procedure for sampling was as follows:

1. Carry out a scoping inspection of the carrier length in accordance with Western Power’s ‘Conductor Replacement Scoping and Assessment Guideline’ and assign a condition code;
2. If not as expected, move on to the alternative conductors as required and repeat the scoping inspection;
3. Additional local environmental factors such as farmland, bush, sheltered vs. open areas along the length of the carrier should be recorded so that any effects can be identified during the analysis phase;
4. From the carrier length, select the Bay in the worst condition for sampling. This ensures that test results are conservative, while comparison with the scoping inspection along the length of the conductor will inform how representative these results may be of the carrier;
5. Prior to sampling, use an appropriate method to measure the tension in the line, so that mechanical loading may be calculated during the analysis phase;
6. Perform sampling in accordance with the task specification.

Samples were taken under live line conditions to avoid any interruption to supply and a new procedure was developed to allow this. A 3m length of conductor was removed from the mid-span, marked and packaged in a reticulation pipe to protect the sample, delivered to the Western Power Evidence Retention Centre before being sent for metallurgical testing. The use of the reticulation pipe, which could be coiled and reduce the footprint of each sample, was innovative as it allowed samples to be transported quickly and negated the need for large shipping packaging which would have dramatically increased the cost of the program.

Metallurgical Testing

The aim from metallurgical examination was to determine the strength of each conductor and relate it to visual condition and remaining life. The tests undertaken were:

- A visual examination prior to testing allowing links to be drawn between visual examinations and the results of all other tests, thereby supporting the further development of the condition codes;
- Diameter measurements of the whole conductor followed by individual strands from the surface to the core in order to identify differences in the rate of corrosion;
- Metallography of a cross section of the outer, inner and core wires which show the greatest level of degradation to examine the corrosion morphology and any signs of annealing;
- Hardness tests to identify any evidence of annealing or softening;
- Chemical analysis of the conductor to confirm the grade of material and chemical analysis of the corrosion products to identify any pollutants;
- Tensile testing to determine the Ultimate Tensile Strength (UTS) of the conductors and how it has changed with time in service and the operating environment;
- Torsional ductility tests to determine how fatigue strength has changed with time in service and the operating environment;
- A wrapping test to see if the results of the other tests can be linked to this relatively simple test, thereby allowing a simple and inexpensive method for determining the condition of samples in the future.

Figure 3 shows examples of steel conductors with varying condition scores. It can be seen that the appearance of corrosion is different and although the conductor shown in (c) has the highest condition score, its torsional ductility is lower than (b).
Figure 2 Samples been taken from a live line (a), marked for transport (b) and stored within a reticulation pipe for transport (c).

Figure 3 Examples of steel conductors with varying condition scores and Torsional Ductility, (a) was given a condition score of 20 and experienced ~1 turn to failure, (b) was given a condition score of 50 and experienced ~16 turns to failure while (c) was given a condition score of 90 and experienced ~14 turns to failure.
Analysis of Results

Multiple data points for all samples were consolidated into the Western Power corporate data warehouse and combined with other data sets including electrical, geographical and locational to perform statistical analysis and derive key patterns/trends. The following are just some of the trends identified:

- **For Cu conductors:**
  - Tensile tests were a good indicator of condition;
  - There was a good correlation with the distance to the coast, i.e. the closer to the coast the worse the condition;
  - Poorer condition conductors could be correlated with wind direction;
  - All annealed conductors were found in metro areas which would never have been detected by visual inspections;
  - Some of the findings validated what was already assumed in the NRMT;
  - However some findings were new, such as age not being a strong predictor of condition and visual assessment with the current guidelines being a coarse indicator; a condition code of 0-70 can be good to poor but above 70 the results have more confidence.

- **For Steel conductors:**
  - Torsional ductility is a better indication of steel performance than tensile strength;
  - The current visual assessment is a coarse indicator of condition;
  - Age is not a key indicator – under the attribute based system all steel over 40 years would have been considered in poor condition but analysis found that this was not a strong correlation;
  - ACSR cables over 20 years old with a history of failures were considered bad but tests showed the conductors were actually in good condition – this pointed to localised conditions at the pole top being a root cause of past failures.

ACQUIRING GRASS ROOTS KNOWLEDGE

An additional aim of the Western Power strategy to improve the understanding of risks to distribution conductors was to better capture ‘grass roots’ information. In particular, the experience and knowledge of personnel involved in the inspection and maintenance of conductors. The Western Power network is divided into a number of maintenance zones (MTZN) that contain a variety of conductors in different environments, although it was considered unlikely that the maintenance zones contained examples of conductors that would fall into all the factor combinations for the health index and condition code experiments.

Working with Assetivity, a series of interviews were conducted with maintenance staff across the network using a structured interview process. This process elicited the opinion of the MTZN staff to better understand the condition of conductors and the causes of failures. The interviews took place over five weeks and workshops were held at 22 field depots. They involved:

- Developing a process to facilitate discussions with field personnel on conductor condition and observed failure modes.
- Developing databases to record and report findings, including:
  - Comparing field personnel observations of conductor condition with samples taken from the conductor sampling program;
  - Capturing various factors (including conductor type, material, age and local environmental conditions) and associated conductor condition for specific sections of conductor; and
  - Mapping results for those specific sections of conductor using detailed network maps.

The design of the location specific data gathering exercise was based around the population of A1 sized printed network maps, covering the distribution network of each region. The maps were used for reference and discussion generation, allowing the field personnel to capture relevant information against specific sections of the network that they were familiar with. Using this method data was collected on 285 specific locations, covering 4600km (6.7%) of the total distribution network. This gave a confidence interval of 1.4, against a confidence level of 95%. The sample size was thus considered well over the size needed to be statistically significant.

The discussion on each of the 285 specific locations was captured on a questionnaire, prompting discussion on conductor location, details, type, condition, age, common failure modes and a projection of remaining life. The answers were selected from a list of pre-developed options, which allowed the information to be digitised and added to the electronic network mapping system. The questionnaire evolved over the first few sessions, gaining more detail in certain areas and refining the way some questioned were asked.

A general discussion was held with the larger groups on the trends of conductor condition within their specific regions. This discussion proved difficult in the first two sessions, prompting the generation of a pre-developed table, showing the percentage of each conductor type within their specific region. This was then used successfully to develop an understanding of the general condition of certain conductor types within each region.
A discussion was also facilitated with the group on general trends and patterns observed by field personnel in each region, including other topics beyond conductor condition.

Following the workshops the interview results were collated and assessed. The outcomes were:

- Insights into conductor failure modes, informing a number of refinements to the current conductor management strategy;
- A database comparing observed conductor condition with samples taken from the conductor sampling program;
- Improved awareness of regional and type specific conductor failure modes and conditions;
- Improved understanding of how well the current conductor sampling program represented the general conductor condition in the field.

CONCLUSIONS

This program of work applied the asset management principle of Plan-Do-Check-Act by undertaking a detailed program of activities to improve the understanding of the physical condition of assets, thereby checking the assumptions used in the NRMT.

A number of innovations were developed as part of this program:

- The use of DOE principles to identify the influencing factors and develop a sampling program;
- A number of logistical innovations to allow the program to be completed in a short timeframe;
- A structured program of interviews with maintenance personnel across the network to acquire ‘grass roots’ information on the network condition;
- The incorporation of various sources of knowledge into a Bayesian Belief Network based risk quantification model.

The knowledge gained from these activities have allowed a refinement of the data used to undertake asset management at Western Power. By feeding this back into the NRMT, Western Power was able to improve targeting of those conductors that presented the greatest risk to meeting business objectives, significantly optimising ongoing asset management expenditure and maintaining safe operation of the network through an increased understanding of risk. This work demonstrates that within the field of Asset Management there is significant value to be gained by applying the principle of Plan-Do-Check-Act to improve strategy, and in particular checking and understanding Asset Integrity and how physical assets degrade over time.

The need for better data on the physical condition of assets is applicable to many other utilities. Working collaboratively with supporting organisations can enable innovative approaches to be developed. It also demonstrates that, while been a challenging task to undertake, the benefits of programs like this can be great and add significant value to an organisation.