BUSHFIRE RISK MANAGEMENT OF ELECTRICITY TRANSMISSION LINES

Dan Tombleson, Linetech Consulting, Principal Engineer

Christian Nolden, ElectraNet, Senior Asset Strategies Engineer

Summary: On Saturday the 7th of February 2009 bushfires devastated Victoria, Australia, killing 173 and injuring 414. Black Saturday, as it has become known, combined extreme temperatures (46.4°C in Melbourne), high winds (over 100 km/h), and low atmospheric humidity levels (6%) at a time when Victoria was tinder dry. The subsequent Victorian Bushfires Royal Commission determined that many of these fires, including one of the most damaging, were caused by electrical infrastructure [1]. These fires were estimated to have an economic cost over AU$4.4B [2].

Societal and financial impacts of this magnitude are very significant in relation to the regulated asset base of the Australian Transmission and Distribution Network Service Providers. Understanding the risk associated with such high impact low probability events is critical, yet extremely challenging for large, geographically dispersed network assets. The Directors of these businesses require a transparent view of bushfire risk management practices and their effectiveness. ElectraNet are attempting to achieve this by developing a bushfire risk model which links the potential causes, pivotal events and consequences of electrical Flashovers.

An example of the value of this Asset Management tool is the highlighting of the significance of fauna as a fire start risk. This was an unexpected result. The bushfire risk model allows an entire transmission line asset base to be risk ranked using bushfire risk cost per annum. The bushfire risk model can be used to prioritise risk mitigation efforts.

Keywords: Risk, Electricity Transmission, Bushfire, Wildfire, Bow-tie diagram, Flashover

1 INTRODUCTION

ElectraNet are the Principal Transmission Network Service Provider (TNSP) of South Australia. ElectraNet own and operate approximately 5,600 circuit kilometres of high voltage electricity transmission lines, 89 substations and a significant network of telecommunications assets [3].

1.1 Project drivers

Prior to the development of the bushfire risk model described in this Paper, ElectraNet categorised their network into three regions: *high bushfire risk*, *bushfire risk* and *non-bushfire risk*. This approach was developed in the early 1980s following the South Australian Ash Wednesday fires. The aim of this review was to update practices for network and land-use changes and to improve decision making processes.

This review was sponsored by ElectraNet's corporate Risk Management and Insurance Officers, the updated approach is expected to deliver improvements in the following areas: public risk management (corporate social responsibility), Asset Management continuous improvement programs, and to ensure the safe operation of the network as required by the Australian National Electricity Rules. A number of hurdles were overcome in the process of risk model development. In large organisations it can be difficult to initiate projects which significantly rely on grey data. ElectraNet invested the time to analyse the data to reduce uncertainty in many areas. From the outset, it was clear that this model would guide high level decision making and not inform micro asset-based decisions. The latter would still require technical engineering input.

The bushfire risk model must be taken with a caveat, it has been developed in the context of the ElectraNet South Australian network, and any application outside this context would require careful consideration and most likely changes to the model.

1.2 History of bushfires in Australia

Bushfires have always been a part of the Australian landscape. Many native Australian plants have evolved to survive bushfires, particularly the Eucalyptus tree which is thought to encourage fire to eliminate competition from fire prone species [4]. However, with increasing population density, the frequency and economic impact of fires have increased.

1.3 Flashovers

The bushfire risk model is built around the premise that Flashover events have the potential to ignite bushfires. Flashovers are an expected function of air-insulated electricity transmission systems. Air-insulated means that the energised parts require a minimum air clearance distance to operate. If an electrically grounded object comes within near proximity to an energised component it has the potential to cause a Flashover. Flashovers are an uncontrolled release of energy in the form of a power arc (plasma) which travels through the air – e.g. a lightning strike. The arc inception points (e.g. Steel tower) release molten globules of metal and in the process create a shower of sparks.

1.4 Exclusions

The following areas have not been considered in this Paper; future studies should independently consider their relevance:

- Costs associated with: temporary loss of electricity supply; transmission system repair; loss of human life; public relations / reputational impact; and, financial claims by disconnected generator and distribution companies.
- Science of fire and transmission line design practices to minimise the impacts of fires on operational assets

2 LITERATURE REVIEW

2.1 Bushfires

Bushfires are common in both Australia and North America (Wildfires). On average over 50,000 bushfires burn across Australia each year [5]. Data from the South Australian Country Fire Service (CFS) has been used to define the expected fire size distribution. While the records cover almost 100 years, the most recent 25-year dataset was used to calibrate the bushfire risk model [6].

The CFS also publish Fire Danger Ratings (FDR) and Total Fire Ban (TFB) information in South Australia. Since 2010 a common approach to FDRs has applied across Australia. In South Australia there is a direct link between FDR and TFB status [7]. The Australian fire agencies rely on the Australian Bureau of Meteorology (BOM) to provide daily FDR information based on the “McArthur Mk V Forest” and “modified CSIRO Mk IV grassland fire and danger meters” [8].

Records show that approximately 1.59% of all fires are accidentally caused by *Electrical failures* [9]; this category accounts for all the fire start causes addressed in this Paper. The most prevalent cause is *Deliberate human action* which accounts for 55.25%. This means, 35 fires are ignited by deliberate human action for every single fire due to electrical failures. In Australia, the common causes are [9]:

- Deliberate human action (55.25%)
- Accidental human action (29.81%)
- Cigarettes (12.65%)
- Re-kindled from a previous fire (5.09%)
- Matches or a lighter (3.86%)
- Escapes from planned burns (2.51%)
- Mechanical failure (2.42%)
- Electrical failure (1.59%)
- Undetermined (13.92%)
- Natural (1.03%)

2.2 Risk Models

Risk is simply defined as the “effect of uncertainty on objectives” [10]. The emphasis here is the inherent association with uncertainty. Mathematically risk is the product of likelihood and consequence. In the case of the bushfire risk model, the output is a financial risk cost per annum.

2.3 Bushfire Risk Management

In relation to TNSPs, bushfires are a High Impact Low Probability event. Consequences include; loss of life, environmental impact, and potential financial devastation. The Australian Distribution Network Service Providers (DNSPs) and TNSPs understand these risks and many have existing bushfire risk management plans.

Bushfire risk management is also of particular interest to the company’s Insurers, Executive Management and Board of Directors. In the case of the Board of Directors their concern is with the adequacy of corporate governance mechanisms. This requires taking all steps to reduce bushfire risk so far as is reasonably practicable. Those familiar with recent updates to Australian Work Health and Safety legislation will recognise similarities in wording here.

2.4 Australian Bushfire Risk Management Plans

A review of all publicly available bushfire risk management plans has been completed - these covered the majority of Australia at both Transmission and Distribution voltages. The primary purpose was to identify the key failure modes; these are outlined in Section 3.3.

3 DESCRIPTION OF WORK DONE

3.1 History - General

Figure 1 shows bushfires which have been ignited by electricity transmission and distribution lines assets in Australia. Where possible, those failure modes which are only applicable to lower voltage distribution network assets have been removed, e.g. failure of Expulsion Drop Out Fuses.

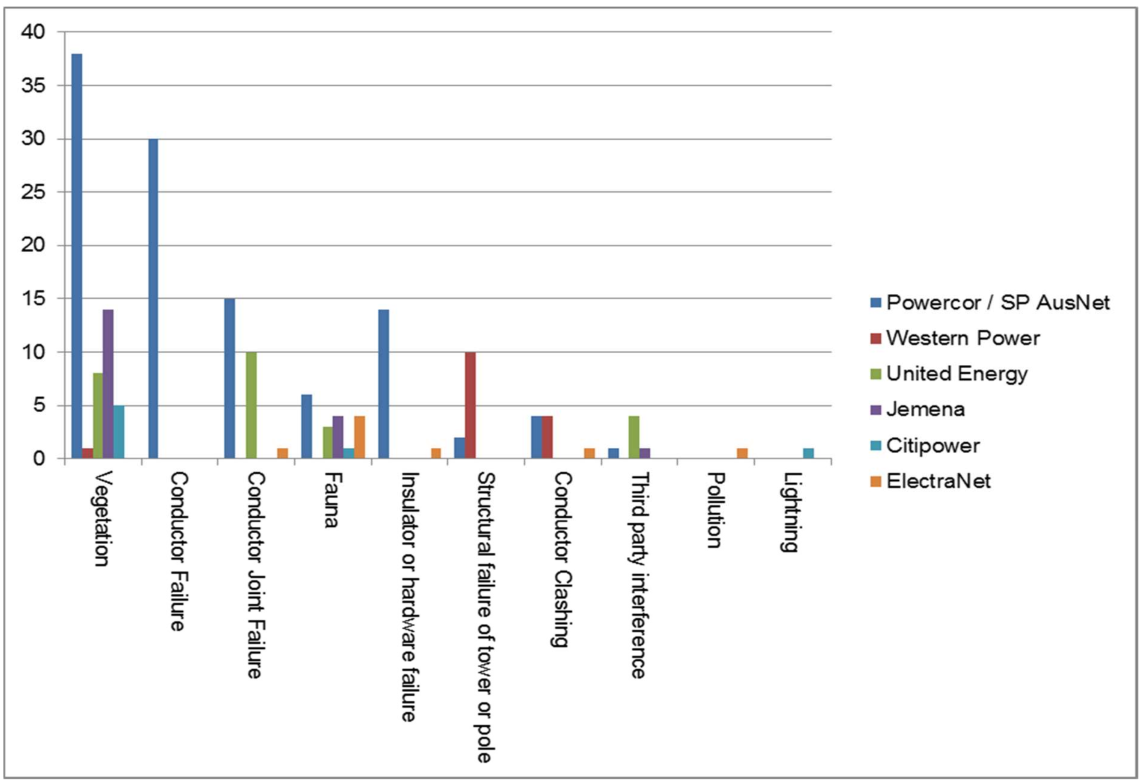

Figure 1: Australian DNSP and TNSP fire start data

3.2 History – South Australia

In South Australia there have been seven fire events over the past 15 years (between 60 m^2 and 10 hectares) which are relevant to the bushfire risk model. Four of these are thought to have been caused by fauna (birds).

3.3 Credible Events

The fire ignition history and primary causes in Figure 1 were used to develop a long-list of credible events. The long-listed fire ignition causes are:

- Conductor clashing
- Fuse failure
- Fauna
- Insulator Flashover including arcing horn operation
- Lightning
- Mechanical Failures
- Pole and/or cross arm fires
- Structure failures
- Third party interference
- Vegetation

The long-list was reduced to a short-list with consideration of ElectraNet's operating context. The short-listed fire ignition causes are:

- Fauna e.g. birds
- Mechanical failure including conductor failure, joint failure, insulator or hardware failure and structural failure
- Third party interference e.g. human interference, vehicle collision, etc.
- Insulation Flashover including lightning, pollution, and high wind deflection
- Vegetation including wind-blown debris and grow-in

3.4 Conceptual Model

Appendix A presents the conceptual Bow-tie diagram. It is considered "conceptual" because it is the structure that is important. The specific values in each branch are indicative only and vary according to the specific technical and non-technical details of each asset. The values on each branch of the model are for an example asset.

4 MODEL DEVELOPMENT

As with many reliability engineering projects, a significant effort was required to cleanse the datasets. This included millions of potential measurement points, over 1,000 forced outages and seven relevant fire starts. In some cases data confidence was improved by comparison with supplementary datasets [11]. The intent of the risk analysis tool is to reduce the level of uncertainty in the value for each parameter. If too much care is taken over every value the modelling process would not proceed. Once the model was fully developed a sensitivity analysis was used to refine the critical inputs.

The parameter values and descriptions discussed herein are generally applicable to the entire asset base. Where possible, an Asset Manager would develop asset specific likelihood values. For example, the likelihood of lightning may be calculated by the total number of lightning caused forced outages for the network over a nominal period divided by the total length of transmission lines. This may be considered appropriate where all assets are equally exposed, however, if this is not the case it would be necessary to determine lightning performance levels on an asset by asset basis.

One of the key challenges was to source sufficient quality performance data and also to determine how much detail was necessary to support the overall aim. The component failure rates are derived per component per year. The bushfire risk model uses the number of components per asset (or in the entire network) to determine the effective rate per unit length. In the process of passing through the bushfire risk model, all units are converted to the unit *per circuit kilometre per year*. In all cases, the event rates described are residual risks after significant control barrier intervention (e.g. inspections and maintenance).

4.1 Fault tree

The fault tree method was created in 1962 and quickly became popular in the nuclear and aviation industries. Fault trees use Boolean logic gates to model causal relationships between events [12]. The high level contributing events are:

- Insulation Flashover, including lightning, pollution, and high wind deflection (95.4% of events)
- Mechanical failure, including conductor failure, joint failure, insulator or hardware failure and structural failure (2.0% of events)
- Fauna, e.g. birds (1.5% of events)
- Vegetation, including wind-blown debris and grow-in (0.6% of events)
- Third party interference, e.g. human interference, vehicle collision, etc. (0.5% of events)

Across the fault tree, each failure rate was calculated by the number of relevant failures, divided by the number of years of data, divided by the average number of components in-service over the period.

4.1.1 Insulation Flashover

Insulation Flashovers occur regularly on the ElectraNet network and have resulted in one fire start, most likely caused by pollution. Insulation Flashover includes the following failure modes: Lightning, Pollution, High Wind Deflection, and Unknown causes.

A specific note on high wind deflection is required, this event includes: conductor clashing and conductor to structure Flashover under high winds. The ElectraNet records provided no evidence of phase to phase conductor clash events. It is a common misconception that this failure mode is prevalent at voltages 132 kV and above.

4.1.2 Mechanical Failure

Mechanical failures have caused fires on the ElectraNet network. The credible events in the area of mechanical failures are: Insulator and/or hardware failure, Conductor failure, Joint failures, Tower/pole structural failure by asset type an individual asset where justified.

Unfortunately no information is available on “Immediate Response” corrective maintenance to prevent mechanical failures. These suspended data points would significantly improve data confidence.

4.1.3 Fauna

Fauna includes all bird interactions and in some areas can be influenced by snakes, possums and other animals. In the ElectraNet system, twelve events over the past 14 years are attributed to fauna. Interestingly, four of these have resulted in fire ignition – many due to a smouldering bird falling to the ground. Additional investigations are recommended in this area.

4.1.4 Vegetation

Vegetation management is an integral part of transmission line asset management. All DNSPs and TNSPs have active programs to manage vegetation risks. Vegetation Flashovers normally start with vegetation in close proximity or in contact with a conductor. This is followed by leakage current through a branch, as current flows the branch heats up, moisture levels in the branch reduce and the electrical resistance reduces. Eventually the leakage current increases until the protection system operates. By this time the branch is at a temperature likely to ignite a fire if it fell to the ground.

The vegetation part of the fault tree includes both grow-in and wind-blown (e.g. airborne canola stalks) causes. The grow-in vegetation parameter is calculated by combining the defect rate per annum for the particular asset and the maintenance inaction factor. The maintenance inaction factor illustrates the concept that a very small percentage of recorded vegetation defects will eventually cause a Flashover. The link between vegetation defect rates and vegetation Flashover rates will ensure that heavily forested parts of the network represent a higher risk.

Vegetation events include both Wind-blown and Grow-in.

4.1.5 Third Party Interference

Third party interference includes events such as vehicle collision, vandalism and terrorism. These are very remote likelihood events which contribute negligibly to the overall risk and have been included for illustrative purposes.

4.2 Central Event – Flashover Occurs

“Flashover occurs” is the “*loss of control event*” in the middle of the Bow-tie diagram. Because Flashovers result in a loss of service they are considered an objective service quality measure and are often reported to industry regulators. One of the most comprehensive datasets is provided by the Canadian Electricity Association [11].

One of the many quality checks applied to the bushfire risk model was to confirm that the sum of the short-listed credible events aligns with ElectraNet’s overall forced outage rate. The bushfire risk model considers each switching event as a single entity whether it includes multiple or no auto-reclose attempts. The bushfire risk model aligns with the ElectraNet data, which also aligns well with [11].

4.3 Event tree

Event tree analysis is a bottom-up logical modelling technique which is used to identify the consequences of an initiating event (i.e. Flashover occurs) [13]. The derivation of the likelihood values applied in the bushfire risk model are described in this Section. In general, an attempt has been made to align the consequences (fire size distribution) with the CFS data. The parameter values described in this Section should be considered indicative only; some will vary by location and/or with the technical asset characteristics. These are simplistic interpretations, further work is required to improve confidence in the specific values.

4.3.1 Ignited object falls to the ground

The presence of this pivot event acknowledges that Flashover events caused by Vegetation and Fauna have a significantly higher likelihood of causing fire ignition than other Flashover causes. The likelihood value for *Ignited objects falls to the ground* is derived from the proportion of total Flashovers caused by Vegetation and Fauna (calculated from the fault tree). The likelihood is in the order of 0.02.

4.3.2 Fire starts

Statistically, very few Flashovers actually start fires (approximately 0.1%). The resulting fires can effectively self-extinguish with an insignificant impact (e.g. 1 m^2 of land damage) or in extreme cases take weeks of intense human intervention to control and raze over 10,000 km^2 of land. Consequence analysis is a very complex task which is strongly dependent on weather, topography, and the nature of the initial ignited object. The bushfire risk model described herein has taken a simplified top-down approach. A complementary study is underway at the CSIRO where researchers are currently developing advanced computer models of fire starts in specific geographic locations (bottom-up) from Victorian DNSP assets [9].

The likelihood of an initial fire start is:

- Fauna or Vegetation causes: 0.33
- Other than fauna or vegetation: $3x10^{-3}$

4.3.3 Total Fire Ban (TFB) status

The bushfire risk model assumes that any fire started on non-TFB days will not result in significant fires. This assumption is made to ensure the resulting fire size distributions align with historical experience, not because it is impossible for bushfires to burn on non-TFB days. TFB status incorporates fuel dryness (based on rainfall and evaporation), wind speed, temperature and humidity. Further technical information on the TFB and FDR systems are provided in Section 2.1.

The regional TFB data from 2004 to 2015 was analysed to determine the likelihood of TFB days in each Fire Region. The results show that it is essential to class assets geographically as the highest risk region about has about 10 times more TFB days as the lowest risk region.

4.3.4 Fuel load

Fuel includes both live and dead vegetation which accumulates over time (leaves, twigs, bark, grass, shrubs, trees, etc.). Scientists classify fuel by type, size, quantity, arrangement and moisture content. The fuel load is essentially the density of these fuels per unit area of land (typically in tonnes per hectare). A common method of reducing the fuel load is to undertake controlled burn-offs during low fire risk seasons.

There is a strong positive correlation between fuel load and fire intensity. The higher the fire intensity the more difficult it will be to control the fire [14]. The bushfire risk model assumes that fires started on TFB days with high fuel loads will end up being considered medium (50 km^2) or large (500 km^2). When the fuel load is not high, the resultant fire is assumed to be small (1 km^2). The presence of High fuel load is 0.5 – this has been determined by analysis of historic fire size distributions. It is not a reflection of the actual fuel loads measured at any particular location or time.

4.3.5 Ability to detect and supress fire based on location

This pivotal event considers two factors that affect the resultant size of each fire. For a fire event to arrive at this branch we know that: the fire has started, it is a TFB day and there is a high fuel load. This combined with a site that is considered difficult for early detection and suppression will result in a large fire (500 km^2). The alternative branch results in a medium fire (50 km^2).

4.4 Consequences

The intent of the bushfire risk model is to provide reasonable guidelines which enable effective management decision making. The bushfire risk model is seen as a mechanism to reduce uncertainty rather than predict the exact outcomes of any individual Flashover or fire events. The inputs to the financial consequences calculations are the fire size per branch and land damage cost per km^2.

To apply this, the attributes of each transmission line must include details of each Land Use Category in near proximity to the line. ElectraNet have this information available in the standardised ALUM format (Australian Land Use and Management Classification).

The fire size assumptions are closely linked with the fire size distribution and pivotal event effectiveness rates discussed in Section 4.3. Table 1 outlines the fire size distribution and the nominated fire sizes used in the bushfire risk model; these are based on 1882 fires recorded over the past 25 years in South Australia [6].

Table 1: Expected fire size distribution based on CFS records

Item	Small ($<1km^2$)	Medium ($1-100km^2$)	Large ($>100km^2$)
Fires size distribution – CFS records - All	49%	43%	8%
Nominal fire size (km^2)	1	50	500

The land damage density values in Table 2 have been provided by ElectraNet based on prior investigations. The Upper and Lower bound values allow for regional variances. All dollar figures in this report are in 2015 Australian dollars and do not consider the time value of money.

The derived consequences are the sum product of the likelihood of fire, size of fire, and land damage density. Where land damage density is the product of the actual proportions of each Land Use Category for that asset and the relevant damage density value. A note of caution is required in this area as consequence assumptions are subjective and can result in significant inconsistencies. In particular – a review of values in Table 2 is recommended to refine the model.

Table 2: South Australian Land Damage Density ($/$km^2$)

Land Use Category	Lower bound	Upper bound	Recommended
Natural	$34	$1,412	$1,412
Plantation	$1,361,111	$1,361,111	$1,361,111
Crops	$46,809	$91,157	$91,157
Livestock	$9,839,714	$48,389,112	$48,389,112
Industry	$12,732	$58,050,209	$58,050,209
Residential	$12,732	$58,050,209	$58,050,209

5 ANALYSIS OF RESULTS

This Section presents a sample of results from the bushfire risk model. It is considered a sample because the output of this research is an interactive and adaptable risk model – not a static set of values. The bushfire risk model is currently being used in two ways:

- For analysis of individual asset scenarios (a transmission line in a specific geographic location)
- For batch analysis of an entire network (e.g. ElectraNet's 5,600 circuit kilometres of transmission lines)

5.1 Risk model

Analysis of the Bow-tie diagram shows:

- The most prevalent mode of Flashover is *Insulation Flashover* which contributes 95.4%, mostly due to *Lightning* (66%) and *Unknown causes* (31%)
- Approximately 0.9% of Flashovers will result in a fire
- Approximately 1% of fires will be of a significant size
- Approximately 69% of fires result from ignited objects (Fauna or Vegetation)
- The remaining 31% of fires result from molten globules of metal ejected from the arc inception points

Table 3 provides sample bushfire risk model outputs for five (of total 202) transmission lines assets.

Table 3: Sample Risk Model Output

Asset ID	Circuit length (km)	Predominant structure type	Number of structures	Voltage (kV)	Total Risk Cost /year (000s)	Rank by total risk cost	Total Risk Cost /km/year (000s)	Rank by risk cost /km/year
A	12.5	Tower	36	132	$889	21	$71	5
B	12.9	Pole	65	132	$445	35	$35	25
C	121.0	Tower	292	132	$1,867	12	$15	55
D	616.7	Tower	710	275	$7,192	3	$12	73
E	6.8	Pole	22	275	$3	117	$4	125

5.2 Risk ranking

The financial risk analysis shown in Table 3 supports the view that it would be misleading to rank assets solely on total risk cost. Total risk cost is inherently correlated (positively) with the total transmission line length. For this reason the outputs are also normalised on a per km risk cost. This is an important distinction because many of the risk reduction measures are likely to have implementation costs proportional to the line length, e.g. modifications to the structures. The final risk ranking method will include consideration of both factors.

5.2.1 Total risk cost results

The total risk cost varies from approximately $1,000/year to $8,910,000/year with a mean of $445,000 /year.

5.2.2 Risk cost density results

The risk cost density varies from $1,000/km/year to $128,000/km/year with a mean of $32,000/km/year.

5.3 Decision making

Numerous stakeholders are concerned with the adequacy of TNSP bushfire risk management. The most exposed group is the landowners/occupiers who live in near proximity to transmission line assets in bushfire prone regions. While they do not have direct access to critique the bushfire risk model, their views are considered by the following parties:

- ElectraNet's Insurer
- ElectraNet's Board of Directors
- AER in relation to regulatory control period determinations
- ElectraNet's Executive management (obligations under the Work Health and Safety Legislation [15])

The aim of this study is to provide a high level tool to support decision making at all levels throughout an organisation. This will ensure Senior Management and above can be confident, in advance of any incidents, that they are doing all that they reasonably can to prevent the consequences of significant bushfires. It also provides a more quantified view of the factors contributing to bushfire risk.

5.4 Risk Mitigation

The bushfire risk model supports "what-if" analysis, this enables consideration of discretionary bushfire risk management improvements (i.e. those which are both technically feasible and worth-doing) in addition to mandatory safety requirements (i.e. considered reasonably practicable under Work Health and Safety legislation) [16].

To illustrate an example of risk mitigation, the risks associated with Fauna have been investigated further. Fauna was chosen because it is ElectraNet's largest single contributor to actual fire starts and it impacts both the left and right hand sides of the Bow-tie diagram. Detailed analysis of the available fault history highlighted that all the previous Fauna faults had occurred on one particular design of structure, the 132 kV Stobie Pole fitted with Wishbone cross-arms. This structure configuration is shown in Figure 2. All faults involved the top phase on the side with two phase conductors (top left conductor in Figure 2). It is hypothesised that this is due to large birds perching in the red highlighted area in Figure 2.

Large birds (e.g. wedge-tailed eagles with wing spans up to 2.3 m) can easily breach minimum phase to ground clearance distances to the cross-arm. At 132 kV, electricity can puncture air if the phase to ground distance is reduced to approximately 400 mm, this is the effective electrical insulation breakdown strength of air. Following an encroachment a plasma arc will travel from the conductor to the bird, through the bird and to the cross-arm. The protection system will detect the fault and switch the line off within 0.2 s but not before molten metal drops and the bird catches fire.

Figure 2: Example Stobie Pole Structure with Wishbone Cross-arm Arrangement

Other drivers to reduce bird / transmission line interactions include: environmental responsibility (reduce bird fatalities), pollution performance (i.e. faecal matter and streamers), to avoid potential health issues for workers, bird nests can cause Flashovers, and to reduce the likelihood of birds chewing silicone rubber insulators.

Conceptual options for reducing bird related bushfire risks include: retrofit of a modified cross-arm arrangement to improve clearances, retrofit bird deterrents (e.g. spikes across the cross-arm), ultrasonic bird deterrents, regular nest relocation, and insulator washing.

6 CONCLUSIONS

An adaptable and interactive probabilistic bushfire risk model for use on electricity transmission lines assets has been developed. The inputs are based on a comprehensive review of all available transmission lines failure data and historic bushfire records. The bushfire risk model estimates risk in dollars, either by individual transmission line asset or for an entire network. It is recommended that analysis of the outputs considers ranking of assets by total risk cost and risk cost per km. Analysis of the results show that there is a factor of 36 between the highest and lowest bushfire risk costs per km per year. This result highlights the value of the risk model as a tool to guide sensible targeted investments.

Bushfire risk reduction can be achieved by: modifications directly to the transmission lines, or by operational changes effecting bushfire propagation characteristics. An example was explored which investigated the interactions between large birds and a typical structure used in South Australia.

Further research and development is recommended in the following areas:

1. Seek independent review of the bushfire risk model from Insurers
2. Review the land damage density values
3. Development of a similar bushfire risk model tailored for DNSP assets (below 132 kV)
4. Identify the applicable control barriers for each branch of the fault tree
5. Integrate detailed technical knowledge by asset (e.g. expected performance rates for: lightning, pollution, fauna, vegetation, etc.)
6. Investigate, in conjunction with the CFS, targeted fault patrols on TFB days
7. Australian electricity industry to pursue the VBRC recommendation to strengthen the State frameworks regarding prevention and mitigation of electrically caused bushfires [17]

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9 APPENDIX A – BOW-TIE DIAGRAM FOR AN EXAMPLE ASSET