THE RELATIONSHIPS BETWEEN WEATHER VARIABLES AND RELIABILITY INDICES FOR A DISTRIBUTION SYSTEM IN SOUTH-EAST QUEENSLAND

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ABSTRACT

This paper describes investigations into the statistical relationships between storm weather variables (lightning, wind, temperature, rainfall) and system outages (feeder lockouts, substation outages, distribution transformer outages) and interruptions (customers interrupted, SAIDI, SAIFI). A strong correlation between feeder lockouts and wind gusts prompted further investigations into the analysis of wind blown debris. From this analysis, a methodology is suggested to enable normalisation of the impacts of storm seasons with varying severity.

1. INTRODUCTION

In most electricity systems, the continuity of supply to customers is very dependent on the reliability of the medium and low-voltage networks. Many interruptions are due to faults and outages on overhead lines during storms. It is known that the main causes are lightning and wind effects, but it is difficult to assess the relative contributions.

In south-east Queensland, fast-growing trees are common near 11 kV and LV lines, and experience indicates that many faults are caused by wind-blown branches impacting on the lines. Clearly, faults are attributable to wind gusts and data are presented to support this assertion. However, lightning ground flashes to or near the lines can cause faults, and other factors are also tested for completeness.

After a description of the ENERGEX system, weather and vegetation environments, types and causes of faults, results are presented of research into statistical relationships between storm event variables and system outages and customer interruptions. A preliminary study of wind effects on trees and branches is made, leading to suggestions for optimizing management of vegetation near overhead lines. The strong correlation between outages and wind speeds leads to a possible methodology for normalization of varying storm seasons to enable better analysis of underlying network performance.

2. ENERGEX SYSTEM

ENERGEX supplies 4100 MW to 1.2M customers in a sub-tropical area of 25,000 km^2 in South-East Queensland which covers urban, coastal and hinterland areas. Seventy-four percent of the system is on overhead lines - about 3,000 km of 132/110/33 kV, 17,500 km of 11 kV and 15,000 km of LV (400/230V). The area has fast-growing trees, and many lines have trees near them; a vegetation program maintains air clearances of about 3 to 4 m. There are about 25 to 35 thunderstorm-days per year and these can have wind gusts up to 100 km hr^{-1}; the number of lightning ground flashes ranges between 500-5000 per storm. There are also 5-10 non-storm days each year when wind gust speeds can reach about 80 km hr^{-1}. Maximum temperatures vary between about 20 and 40℃ and the rainfall is about 1200 mm yr^{-1}.

Most faults during thunder-and wind-storms occur on the radial 11 kV and LV networks. In a severe storm, these can cause many outages and interruptions of supply; for example, up to about 120 feeder lockouts on the 11 kV network over a 2-3 hour period, and interruptions to about 100,000 customers. The reliability indices for the system in 2005/06 are – with exception events (2.5 Beta) excluded, SAIDI 160 minutes and SAIFI 1.8, and 210 minutes and 2.2 with all outage events included. The storm component of SAIDI varies considerably from year to year.

Vegetation management is a major component of the ENERGEX maintenance cost. Significant tree trimming is required in the area to keep pace with tree growth and there is a constant tension between reliability based tree reduction requirements and environmental considerations.

3. ANALYSIS OF WEATHER AND OUTAGES

Statistical correlation and regression techniques are used for bi-and multi-variate analyses between weather, outage and customer interruption data for all events that occurred during the years 2004/05 and 2005/06. The weather data for the storm event days were obtained from twelve Bureau of Meteorology (BOM) stations in the area, and include maximum wind gust 3-second speeds (WGSmax in km/hr), maximum temperatures (Tmax in ˚C) and rainfall (RainFall in mm), plus lightning ground flashes (LightningGF). For each event, these include feeder breaker tripouts (FdrTrip), feeder lockouts (FdrLock), substation outages (SubOut), wires down (WireDown), distribution transformer outages (DTsfOut), individual customer outages (IndCustOut), customer interruptions (CustInt), SAIDI (minutes), SAIFI, and repair jobs completed (RprJobs). There were 16 storm events in the relatively benign year of 2004/05 and 32 in the relatively severe year of 2005/06. Mean and maximum values of some of the noteworthy data are given in Table 1.

Parameter	2004/05	2005/06
LightningGF	306 – 972	1002 – 11037
Mean Tmax	30 – 32.9	30 – 35.4
RainFall	101 – 417	54 – 303
Mean WGSmax	48.2 – 59.9	48.3 – 75.5
SubOut	1.13 – 7	1.38 – 6
FdrLock	22.5 - 71	35 -126
WireDown	n/a	63 – 319
DTsfOut	37 - 98	52 - 202
RprJobs	311 - 1042	109 - 1580
CustInt	23463 – 89393	30815 - 116499

Table 1: Mean-Maxima for storm events 04/05 and 05/06

Initially, correlations within the weather data and the system data for each event are examined. Notable correlation coefficients (R) are between Lightning GF, and Mean Tmax and Mean WGSmax, being 0.31 and 0.24 respectively. The coefficients within the outage and customer interruption data are high, ranging from 0.75 between FdrLock and WireDown, to 0.96 for FdrLock and SAIFI.

Correlation analyses of maximum demand, Tmax and Rainfall show little association with FdrLock, IndCustOut, SAIDI or SAIFI, with R values between ± 0.05. The only weather data that show significant positive correlation with system outage and interruption data are maximum wind gust speeds and lightning ground flashes. The results of the 2-variate correlations are given in Table 2 for the storm events in both years**.** The correlations between the maximum WGSmax and system outages are lower than for mean WGSmax (shown in Table 2). Data points for one of the correlations are shown with its regression line in Figure 1.

Parameter 1 - 2	2004/05	2005/06
Mean WGSmax - FdrLock	0.62	0.74
Mean WGSmax - FdrTrip	0.46	0.70
Mean WGSmax - all outages	0.74	0.78
Mean WGSmax - WireDown	n/a	0.77
Mean WGSmax - RprJobs	0.73	0.80
Mean WGSmax - CustInt	0.51	0.77
Mean WGSmax - SAIDI	0.59	0.72
Mean WGSmax - SAIFI	0.57	0.76
Mean WGSmax - IndCustInt	0.73	0.70
LightningGF - FdrLock	0.36	0.59
LightningGF – all outages	0.51	0.57
LightningGF – CustInt	0.16	0.58
LightningGF – SAIDI	0.08	0.46
LightningGF – SAIFI	0.26	0.58

Table 2: Correlation coefficients (R)

The 2005/06 correlation results are generally better than 2004/05. This is most likely because of the greater number of storm events in the 2005/06 season.

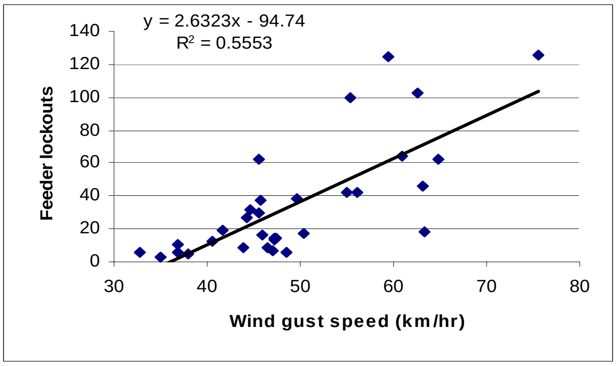

Figure 1: 2005/06 lockouts vs mean max. wind gust speeds

The 2-variate regression analyses provide the following correlations between the weather data and the outage and interruption data for 2004/05 and 2005/06, and include the coefficient of determination (R^2), the correlation coefficient (R) and the standard error (SE) of the dependent variable.

2004/05 FdrLock = 1.85 MeanGWSmax – 66.7
$R^2 = 0.39$ R = 0.63 SE = 30.3
CustInt = 1852 MeanGWSmax – 65703
$R^2 = 0.25$ R = 0.5 SE = 20667
2005/06 FdrLock = 2.63 MeanGWSmax – 94.7
$R^2 = 0.56$ R = 0.75 SE = 23.8
CustInt = 2249 MeanWGSmax – 80055
$R^2 = 0.57$ R = 0.76 SE = 19706

Because both gust wind speeds and lightning ground flashes display significant positive correlation with system outage and interruption data, 3-variate regression analyses were carried out for the 2005/06 data, with the following results.

FdrLock = 2.268 MeanGVSmax + 0.0073 LGF – 84.1
$R^2 = 0.73$ R = 0.86 SE = 18.8
CustInt = 1949 MeanGWSmax + 5.995 LGF – 71260
$R^2 = 0.74$ R = 0.86 SE = 15630

The 3-variate analyses produced better correlation statistics than the 2-variate ones. The relative sensitivities of system outages and interruptions to variations in wind gusts and lightning ground flashes are also examined. This is done for typical base values of MeanWGSmax (50 km hr^{-1}) and Lightning GF (1000), and 20 % increase in each, giving

MeanWGSmax = 50 Lightning GF = 1000
FdrLock = 36.6 CustInt = 32185
MeanWGSmax = 60 Lightning GF = 1000
FdrLock = 59.3 (+54%) CustInt = 51675 (+60.5%)
MeanWGSmax = 50 LightningGF = 1200
FdrLock = 38.1 (+4%) CustInt =33304 (+3.7%).

It is clear that system outages are much more dependent on wind gust speeds than on lightning ground flashes.

4. REFINED WIND GUST ANALYSIS

Wind speed data for six exception event storms in 2005/06 were analysed. For each outage, the wind gust velocity for the preceding half hour was assigned from the nearest BOM weather station. The mean of the gust wind speed was then calculated and plotted against the system outages for each of the six events. This refinement was used to test for localized effects to see if a different result was obtained compared to the more general wind speed versus outages analysis in section 3 above. The results shown in Figure 2 suggest a better correlation ($R^2 = 0.74$). The extrapolated threshold of wind related outages is around 35 km hr^{-1}. While the correlation is better than the more general result, it supports the analysis conducted across a much broader range of storms using average weather data.

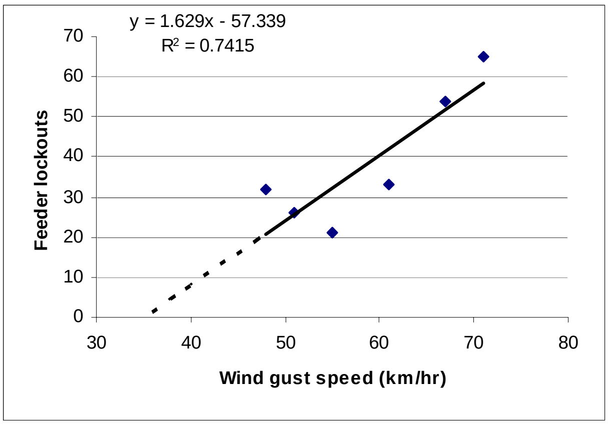

Figure 2: Wind gust analysis of 2005/06 exception events

5. VEGETATION PROFILE ANALYSIS

A simple model was constructed to explore the relationship between vegetation proximity and line outage performance. The objective was to determine the potential distances that wind blown vegetation debris could travel as a function of wind speed and horizontal and vertical distance from the line. This information could assist in understanding the relationship between weather events, vegetation clearance distance and line performance.

The model estimates the trajectory of a representative stick by developing equations of motion in horizontal and vertical directions. Vertical movement is governed by acceleration due to gravity, with the horizontal motion governed by the effect of wind providing an accelerating force due to drag.

For the purpose of modelling, a representative stick of 12.5mm diameter and 1m length was chosen as these dimensions approximate typical wind borne debris from Australian eucalypt species. Figure 3 illustrates the basis of the model which predicts the horizontal distance (h) that vegetation may be blown as a function of wind speed and initial height above the overhead wires (x).

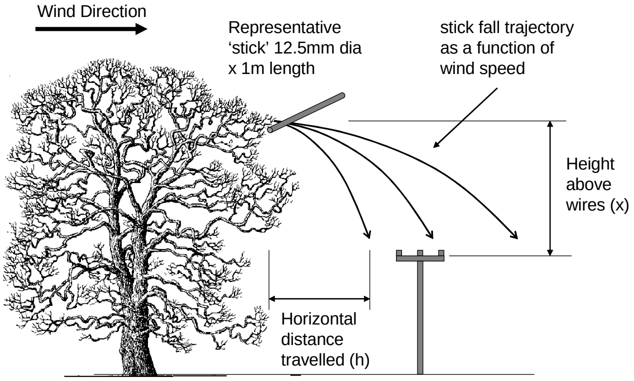

Figure 3: Basis of the wind debris trajectory model

A summary of results obtained for a range of initial debris heights is presented in Figure 4.

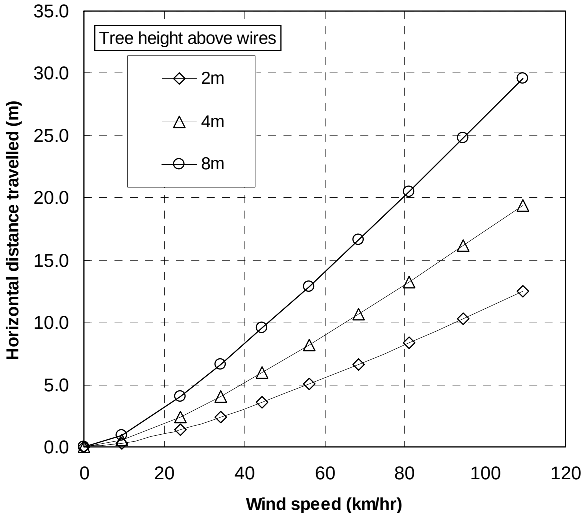

Figure 4: Distance vs wind speed and initial height

It can be seen from Figure 4 that vegetation located 4m above the overhead line can potentially travel up to 5m horizontally in a 40 km hr^{-1} wind. This can explain why vegetation related outages can continue to occur on lines in relatively normal weather conditions following clearing to the typical vegetation clearance profile.

Considering extreme weather with gusts of 100 km hr^{-1}, it can be seen from Figure 4 that vegetation debris can potentially travel large horizontal distances, for example 17m for vegetation with a starting height of 4m and 27m for large trees with a starting height of 8m above the line. The potential large distances highlight an inherent performance limitation for medium voltage overhead lines in vegetated areas as it is generally not practicable to obtain sufficient clearance to prevent vegetation contact in storm conditions.

6. DISCUSSION AND CONCLUSIONS

It is clear from the information presented in Sections 3 and 4 that wind gust speed is the parameter that dominates the occurrence of outages and interruptions during storms. Faults begin to occur whenever wind gust speeds exceed about 40 km hr^{-1}. It is known from weather records in south-east Queensland, that this speed is exceeded during about 100 days each year. Most thunderstorms only cover part of the ENERGEX area, and so the bi-variate correlations between the means of wind gust speed maxima recorded at 12 weather stations and outage data for the whole system only produce correlation coefficients of about 0.7 to 0.8. Better correlations are obtained if data localized to the thunderstorm are used. There is a smaller but still positive correlation between lightning ground flashes and outage and interruption data, with correlation coefficients of about 0.4 to 0.55. The use of tri-variate analyses involving both wind gust speeds and lightning ground flashes as the weather variables and system outage or interruption data result in relatively high correlation coefficients of about 0.86. Sensitivity analyses demonstrate that the effect of wind gust speed is far greater than the effect of lightning.

Theoretically calculated trajectories of wind-borne debris support the correlation found between wind gust speed and outages. The observation that outage rates increase as wind speed exceeds 40 km hr^{-1} is supported by the theory that shows that, at such speeds, wind blown debris can begin to bridge a typical 3-4m vegetation clearance.

The theory suggests that improving performance in extreme storm conditions will be problematic, as debris can travel large distances (above 20m), requiring removal of substantial vegetation if performance is to be improved. Despite this, significant improvement for moderate winds may be obtained by tailoring the vegetation trimming profile based on the research, targeting removal of vegetation based upon it's likelihood (i) to shed wind-borne debris (eg species), and (ii) for its debris to reach the overhead line. In this way it may be possible in future to better manage the tree clearing program to enable an increase in the 40 km hr^{-1} threshold for the commencement of significant network outages due to wind. A relatively small increase in this threshold will significantly reduce the number of days that the network is vulnerable to outages due to wind. The ability to better target vegetation clearing will enhance relationships between ENERGEX and key environmental stakeholders. An alternative approach for new lines is to utilize designs that avoid the debris eg. lines constructed at sufficient height to be above the vegetation.

One of the motivations for the work reported in this paper was to find an objective method for assessing the severity of a storm year, thus permitting objective comparisons between years. The method suggested is the concept of wind blowing days (akin to the heating or cooling days used to assess the dependence of system maximum demand on the temperatures encountered during a year). It is suggested that the severity of a storm year can be described by a wind blowing characteristic determined by summing the daily means of the maximum wind gust speeds (WGS) that exceed 40 km hr^{-1}, that is $\sum (\mathrm{WGS} - 40)$. The values of the wind blowing characteristic for the storm events in 2004/05 and 2005/06 are 136 and 328, giving a ratio of severity of about 1 to 2.4, which corresponds reasonably well to the actual ratios of outages and interruptions for the two years.

The intent in future is to carry out comparisons of the under-lying performance of the network by removing or normalizing the effects of the severity of the storm season. In this way, a better assessment can be made of the results being achieved from the various asset management programs. ENERGEX is carrying out a range of initiatives aimed at reliability performance improvement eg. remote control switches, covered conductor and additional substations. While the impact of these can be modeled in advance to provide expected performance improvements, efforts to date to assess actual improvements have been made difficult by the variability in seasonal impacts.

The methodology developed also potentially allows more objective reporting of the performance of the network. To date, standards for reliability (SAIDI, SAIFI) have been set by regulators on the basis of improvements compared to historical results. While some normalization has been attempted, such as the correction for exclusion events, it is believed that the standards do not yet provide a fully objective assessment of the under-lying performance due to the variability of storm seasons in the ENERGEX area.

Future work is proposed to examine other normalization techniques to obtain clearer assessment of the under-lying network performance.

There are two additional considerations that prompted the authors to write this paper. We would be interested to find out if other distribution companies have carried out statistical analyses of the effects of wind gust speeds and lightning ground flashes on system outages and interruptions. Likewise, we would be interested to learn of other quantitative studies of the impact on distribution lines of trees, branches and other debris caused by wind gusts, and how the vegetation cutting profiles might be optimized to reduce the occurrence of such faults to tolerable levels.

7. ACKNOWLEDGEMENTS

The work reported in this paper is intended to contribute to the ENERGEX programs to improve the reliability of the network. The provision of weather data from the Bureau of Meteorology is acknowledged.