Outside Right-of-Way Tree Risk Along Electrical Transmission Lines

Siegfried Guggenmoos and Thomas E. Sullivan

Abstract—**For power transmission systems compliant with safety codes and reliability standards there remains a risk of tree-caused interruptions from the in-fall of trees from outside the right-of-way. This paper reports on the quantification of tree exposure outside National Grid's transmission corridors and examines the variables impacting the risk of a line contact by trees. Correlations between the variables and National Grid's tree-caused interruption experience were tested. Regression analysis was applied to a calculated risk factor and the annual interruption frequency.**

Two mitigation approaches are compared for cost and efficacy in improving line security. One is based on a regulator suggested use of minimum right-of-way width, while the other is site specific, based on specific site risk versus the voltage class mean risk.

Index Terms-- **Power transmission lines, power transmission reliability, prediction methods, reliability management, reliability modeling, tree failure, tree risk, vegetation.**

I. NOMENCLATURE

Utility forest: the land base supporting tree growth, which could now or in the future interfere with the transmission or distribution of electricity.

Clear width: the distance from the outside conductor to the tree boles at the forest edge.

Danger tree: any tree which, on failure, is capable of interfering with the safe, reliable transmission of electricity.

Hazard tree: a danger tree that has both a target and a noticeable defect that increases the likelihood of failure.

II. INTRODUCTION

THE possibility of a cascading outage event impacting millions of people is a feature intrinsic to the transmission system. The risk of such an event has increased over the last 20 years for several reasons. Foremost among these are that the addition of new lines has all but ceased and transmission systems originally designed to optimize system security on a state or provincial level are now commonly deployed in regional transmission organizations and involved in inter-regional electricity flows. The effect is, there is little or no redundant capacity to tap when a line fails, and lines connecting to other systems, originally designed to protect local systems, are now heavily used for the import/export of electricity.

Trees are a major concern in transmission system reliability. This is powerfully illustrated by the fact that tree-conductor contact (flashover to a tree) was the root cause of these cascading outage events: July 2, 1996 on western grid, 2.2 million customers affected [1]; August 10, 1996 on western grid, 7.5 million customers affected [2]; August 14, 2003 on northeast grid, 50 million customers affected [3]; September 28, 2003 intertie-line between Switzerland and Italy, 60 million customers affected [4].

This history and the August 2003 northeast blackout specifically, have brought considerable scrutiny to utility vegetation management. While it was removed from the final report, one of the questions raised by regulators examining transmission company vegetation management programs following the 2003 blackout was whether there ought to be mandated right-of-way widths based on line voltage [5][6]. We demonstrate by work performed on the National Grid transmission system that while such a requirement may increase line security, it constitutes a very inefficient use of resources. Similar or greater gains in reliability can be achieved for substantially less cost with a program responsive to specific field conditions of above average tree risk.

III. BACKGROUND CONDITIONS

National Grid owns transmission facilities in New York, Massachusetts, Rhode Island, New Hampshire and Vermont. The lines are located on approximately 7,360 kilometers (4,600 miles) of rights-of-way; 2240 km (1,400 mi) in New England (NE) and 5120 km (3,200 mi) in New York (NY), respectively. Most of these rights-of-way are fully cleared. The rights-of-way contain from one to several circuits, with a voltage range from 69 kV to 345 kV AC and 450 kV DC.

National Grid's vegetation management program has been operated under the centralized control of the Transmission Forestry Department since 1993. The vegetation management program has focused on bringing order and control to vegetation within the rights-of-way (the floor) while removing hazard

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trees from the sides. Reliability of the system has been improved and by a concerted effort to push maintenance operations to the early stages of tree succession, cost efficiencies have been gained. Outage data indicates that tree-caused interruption incidents are due to the failure of trees outside the right-of-way. The incidence of tree-conductor conflicts arising from trees within the right-of-way is virtually non-existent at less than one per year with occurrence restricted to the lower transmission voltages (69 kV and 115 kV).

National Grid's experience is what would be expected for a transmission company compliant with the National Electric Safety Code (NESC) and good utility practice. The NESC requires transmission companies to consider line sag, line swing, flashover and tree growth to maintain adequate clearance between conductors and tree parts so as to avoid any phase-to-ground or phase-to-phase faults. A further focus on right-of-way floor vegetation offers National Grid minimal opportunity for further improvements in system reliability. If National Grid is to achieve a meaningful reduction in tree-caused service interruptions, it needs to better understand the variables affecting off right-of-way tree risk.

The Transmission Forestry Department at National Grid undertook a risk assessment study focused on quantifying the size and characteristics of the utility forest outside the electric utility right-of-way. The goal of the Transmission Forestry Department is to minimize tree-caused interruptions, balanced against financial resources, to improve overall system reliability as measured by number of tree caused incidents and loss of supply to customers. Within this goal, there is a particular focus on higher voltage transmission lines (230 & 345 kV) where National Grid seeks a management plan that results in no tree-caused outages due to the major impact the loss of such a line could have and the associated risk of system instability. This goal is consistent with the reliability standards emerging in response to the 2003 northeast blackout. The project was designed to provide the Transmission Forestry Department the data required to quantify the current level of tree risk and thereafter to develop and assess the cost of a range of mitigation options.

IV. METHODS

The project involved a number of phases. The key aspects can be summarized as the random selection of 400 right-of-way points where the percent of treed edge, right-of-way characteristics such as line height, tree height, clear width and adjacent forest characteristics were collected. The percent of forested edge was derived from aerial photographs within National Grid's GIS. Aerial photographs were available for 377 of the 400 random sample points. Literature on major storm damage to trees was researched to assess tree failure modes and identify what species represent the largest risk to transmission service in the US northeast. Weather events from 1950 through 2003 were compiled by county, to determine the frequency of tree damaging events. The frequency of tree damaging weather events and the specifics of tree species vulnerabilities are not presented in this article.

The fieldwork collected data on 131 sample points in New England (NE) and 178 points in New York (NY). Some of the 400 random sampling points could not be used, as there was no adjacent forest. There was no 69 kV sampled in NY. For the forest data, which identified the tree species, measured the diameter at breast height (dbh) of trees falling within a BAF10 prism sample and identified the cover type, over 22,000 records were generated.

Field data collection occurred from January 2004 through mid-July. Due to the timing of data collection and that National Grid experiences peak loads in response to air conditioning demand, the vast majority of the measured line heights do not reflect a maximum sag condition.

Analysis involved the use of the Optimal Clear Width Calculator [7] (OCWC), which through triangulation determined whether off right-of-way trees were capable of interfering (danger trees) with the transmission system, and provided a measure of the extent of the risk. In this way distinctions could be made between the total tree exposure and the tree exposure comprised of trees tall enough to strike a conductor on failure, thereby constituting a current risk to the transmission system. Also assessed and analyzed were forest cover types, species composition, and the incidence of emergent (dominant) trees. Data on forest cover types and species composition are not presented in this article with one exception relevant to emergent (dominant) trees. The measured variables of line height, tree height, clear width and the derived tree risk are examined in relation to the history of tree-caused outage incidents.

The quantification of a particular vulnerability, that of forest stands where a tree species is emergent (dominant) above the general tree canopy (co-dominant), was an identified focus of the study. Trees emergent to the canopy are more susceptible to lightning strikes; wind; wet snow and ice stress loadings and, therefore, are more susceptible to failure.

V. RESULTS

In both NE and NY White Pine was the predominant current emergent species, occurring along 12.4% and 8.5% respectively, of the right-of-way edge. The risk posed by emergent trees has the potential to expand substantially over the next 30 years, especially in the NY service area, as the amount of the utility forest containing White Pine is 20.4% in NE and 27.2% in NY.

A. Utility Forest Beyond the Right-of-Way

Total current tree exposure was determined from the size of the utility forest times the tree density. One of the variables necessary to estimate the size of the utility forest is a measure of length or the extent of treed (forested) edge. The other, the measure of depth was derived by triangulation using mean tree height, line height and clear width.

The percent of treed right-of-way edge is 77.46 ± 3.1 in NE and 61.83 ± 2.93 in NY. The total treed right-of-way edge is 3456 ± 138 km (2160 ± 86 mi) in NE and 6336 ± 300 km (3960 ± 188 mi) in NY. The land base for the utility forest beyond the right-of-way is 1390 ha (3447 acres) in NE and 2108 ha (5227 acres) in NY. Not all of the treed edge is a current liability. The utility forest component with current potential for tree-conductor conflicts is 1931 km of right-of-way edge of 4621 km (1,207 miles of 2,888) in NE and 2488 km of right-of-way edge of 10,246 km (1,555 miles of 6,404) in NY.

Tree density was found to be 491 ± 15 trees per ha (198 ± 6 trees per acre) (Table I). Using this finding, the total danger tree exposure was calculated to be 642,874 trees in NE and 795,770 in NY at the estimated maximum conductor sag position. At the maximum conductor sag position the number of danger trees per kilometer of right-of-way edge is 148 (236 mi^{-1}) in NE and 77 (123 mi^{-1}) in NY. Annual mortality was derived using stand data for the closest permanent sample plots (Allegheny Forest in Pennsylvania) used in the Forest Vegetation Simulator (FVS) [8] in a mortality modeling algorithm [7]. Hazard tree development based on the derived annual mortality rate is 1.9 (3 mi^{-1}) trees in NE and 1.3 (2 mi^{-1}) trees in NY per kilometer of right-of-way edge. If the average number of hazard trees identified and removed on an annual basis falls below the expected mortality, then it is likely that there is an increasing but as yet unrecognized population of hazard trees. Over time, this unrecognized hazard will become susceptible to failure under progressively less stress loading [9].

TABLE I
TREE DENSITY BY OPERATING AREA (TREES/HECTARE)

	Trees Per hectare	**Trees Per hectare (>10 cm dbh)**
NE	1218 ± 149	491 ± 25
NY	1074 ± 92	489 ± 20
All	1131 ± 82	491 ± 15

Fig. 1 provides the size of National Grid's off right-of-way utility forest in both hectares and trees per km. The hectares of utility forest are derived from the number of hectares per km times the number of km for the voltage class. The data in Fig. 1 provides National Grid with measures of the scale of the undertaking if the risk associated with trees beyond the right-of-way is to be managed.

Variable means were compared by voltage class within each operating area (Student-Newman-Keuls, p=0.05). Fig. 2 shows the mean clear width, with the associated confidence interval. Letters above the bars provide the results of significance tests. Means for NE are tested independent of NY means. The data for NE shows an overlap in the clear width for 115 kV, 230 kV and 345 kV lines and there is no significant difference. The data indicates that while right-of-way widths and thereby, clear widths are greater for higher voltage lines, significant differences in mean clear widths occur only relative to the lowest voltage class.

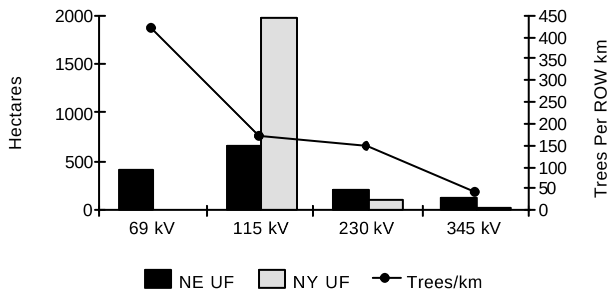

Fig. 1. Utility Forest Beyond ROW

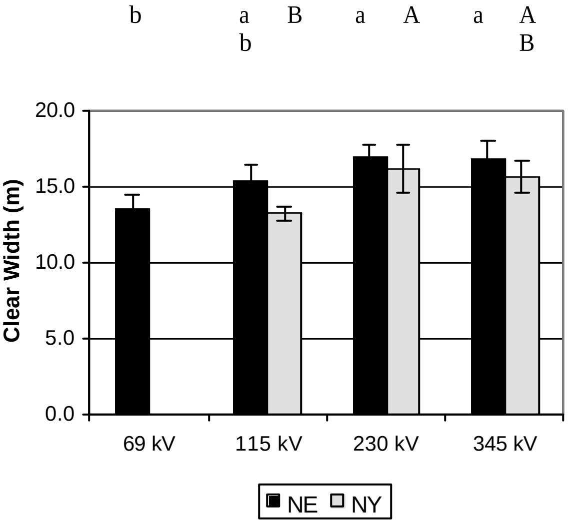

Fig. 2. National Grid Transmission Clear Width

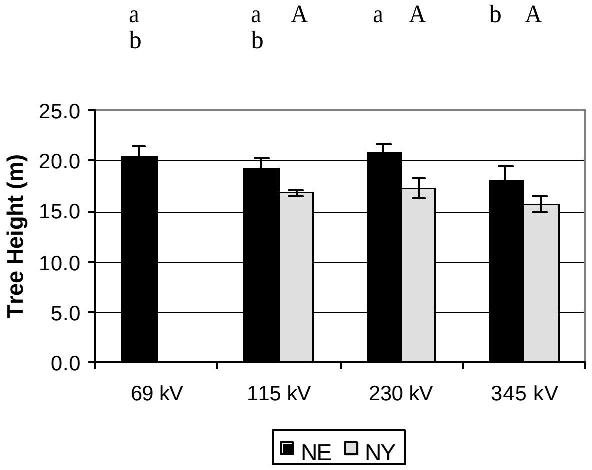

Fig. 3. Mean Tree Height

One would not expect significant differences in mean tree height between voltage classes as the choice of line voltage installed is based on needs independent of tree height along the route (Fig. 3).

There is a clear trend of increasing line height for higher voltages in NE and the 345 kV lines in NY were found to have a significantly greater ground clearance (Fig. 4).

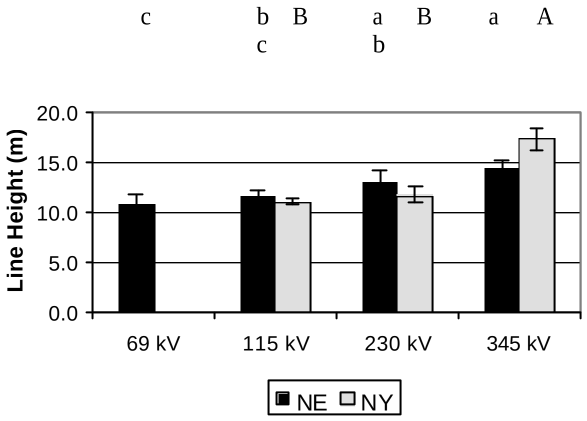

Fig. 4. Mean Line Height

Examining where significant differences between means for line height, tree height and clear width occur, it is difficult to assess the extent of difference in risk exposure and whether such differences would yield significantly different interruption incidents between voltage classes.

TABLE 2
AVERAGE TREE RISK FACTOR (%) AT FOUND SAG

	NE	NY
All voltages	5.99	4.98
69 kV	10.28 a	-
115 kV	6.02 b	6.19 A
230 kV	3.78 bc	2.30 B
345 kV	2.12 c	0.19 B

The use of the Risk Factor (RF) generated by the OCWC reduces these three variables plus tree density to one value. The RF (Table 2, Fig. 5) shows a very orderly decrease in tree risk with increasing voltage. These differences, however, are not large enough to provide a distinct risk profile for each voltage class (Table 2).

The correlation between variables and voltage class was determined. The correlation between voltage class and the variables of clear width (r=0.1669), line height (r=0.2705) and Risk Factor (r=0.2934) (Fig. 5) were significant. There was no significance found for the correlation of voltage class to tree height (-0.0592) and trees per acre (-0.0048). The correlations confirm expectations. Higher voltage lines are constructed with greater ground clearance within wider right-of-ways. The magnitude and need for electrical load arises independent of forest characteristics such as tree height and density.

Tree-caused interruption experience was examined. In NE nine years of data was available while NY had only 4 years of data. Of the 72 incidents recorded, 97% occurred on the 69 kV and 115 kV circuits. The remaining 3% occurred on 230 kV in NE. There were no tree incidents on NE 345 kV, NY 230 kV and NY 345 kV lines.

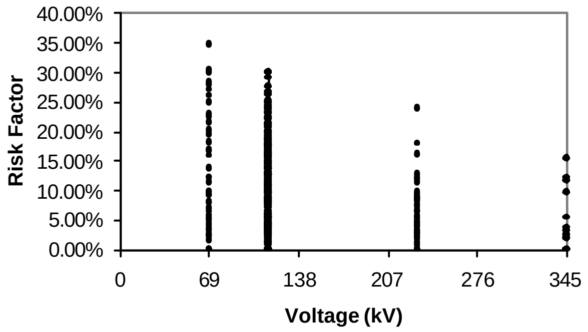

Fig. 5. Scatter Diagram Risk Factor vs. Voltage

VI. DISCUSSION

A. Variable Correlation to Outage Experience

National Grid's objective for this study was to gain insight into mitigating tree-caused service interruptions arising from tree failures outside the right-of-way. This requires both a means to rate the current vulnerability of a specific line or location to tree-caused interruptions and to reasonably predict interruption frequency after treatment. National Grid has used the OCWC to assess current and future tree risk. Tree risk after treatment had not been correlated to interruption frequency.

The magnitude of the voltage class RF means in Table 2 are aligned with National Grid's tree-caused outage experience. To further test the viability of a number of variables as predictors of future transmission system performance the correlation between their means and National Grid's tree-caused interruption experience was tested. Different time frames of outage history between operating areas, necessitated the tree-caused outage data to be expressed as an annual interruption frequency. The results are presented in Table 3.

TABLE 3
VARIABLE RELATION TO INTERRUPTION EXPERIENCE

Variable (means)	Correlation Coefficient (r)	P(r=0)
Tree Height	0.0833 ns	0.8591
Line Height	-0.6003 ns	0.1541
Clear Width	-0.9128 **	0.0041
Total Tree Exposure	0.8441 *	0.0169
Trees/km ROW Edge	0.5770 ns	0.1750
Risk Factor	0.8124 *	0.0264

ns not significant

Generally, the correlation coefficients in Table 3 meet expectations. Line height and clear width are negatively correlated as increases in these variables reduce the line exposure to trees. The weak and non-significant correlation of mean tree height to interruption experience is unexpected. However, no data on tree height for actual the outage incidents was provided. It is not known if mean tree heights used in this analysis accurately represent the height of failed trees giving rise to outage incidents.

Measures of the tree exposure, such as total exposure and tree per km of ROW edge, serve to bring some clarity to the magnitude of the danger tree risk and the operational challenges. Of these two variables, only total tree exposure was found to be significantly correlated to the total number of tree-caused incidents (Table 3).

Comparing trees per km of ROW edge to tree-caused interruption frequency, however, fails to consider the length of line per voltage class. To put both the trees and tree incidents on a unit length basis it was necessary to transform the data to yield the number of tree-caused outage incidents per unit line length. In this case the chosen unit is per 1,000 kms. A significant correlation between annual outage incidents per 1000 kms and trees per km of ROW edge exists, with r =0.8691 and P(r=0)=0.0111. The implications are that the number of tree-caused interruptions is directly related to the amount of tree exposure.

RF, which incorporates the variables of line height, tree height, clear width and tree density, was found to have a significant correlation to tree-caused interruptions, with an r-value of 0.8124 (Table 3). Due to regional differences in the extent of tree cover the data was segregated by operating area prior to regression of the RF for annual outage incidents per 1000 kms. Various regression equations were tested, with the Exponential regression form yielding the lowest P in ANOVA (P=0.0035) and the smallest residuals. Regression analysis was undertaken only for the more comprehensive outage data set of NE, yielding (1).

$$F_{AI} = 0.13424751\ 967 \times e^{(40.2108865\ 236 \times \mathrm{RF})} \qquad (1)$$

where F_{AI} is annual interruption frequency and RF is Risk Factor as produced by the Optimal Clear Width Calculator [7].

The annual interruption frequency for 230 kV is $0.22\mathrm{yr}^{-1}$. An interruption is expected to occur once in 4 to 5 years. No tree-caused outages have been experienced on the 345 kV lines. The 345 kV lines are not devoid of tree risks as indicated by the found RF of 0.0212. If the RF 0.0321 based on maximum conductor sag of the NE 345 kV lines is used, the expectation for tree-caused outages is F_{AI}=0.136659 or 1 incident in 8 years.

B. Mitigation

Although, the RF ratings (Table 2) indicate an operational responsiveness to the adjacent forest conditions, one of the main observations of this work is the wide range of variability in the RF within any given voltage class. An examination of the data for 345 kV lines illustrates the variability in tree risk. There are 83 sample records. Of these, 72 records have a tree RF of 0%. There are 8 records where the RF exceeds 2.5% (Table 4). This led to an examination of the potential impact on line security of addressing only the areas of high tree risk with comparisons of efficacy and costs to a suggested regulatory approach of a specified minimum right-of-way width based on voltage. The strong correlation found between National Grid's interruption experience and mean clear width segregated by voltage class (Table 3), indicates the suggested regulatory approach of specifying a minimum right-of-way width to manage tree-caused outages is supported, on National Grid's transmission system.

TABLE 4

VARIABILITY IN TREE RISK FACTOR FOR 345 KV

Operating Area	Sample Pt. No.	Line No.	Risk Factor (%)
NE	2	303	3.80
NE	8	394	15.46
NE	44	343	12.16
NE	64	394	11.64
NE	99	394	11.81
NE	131	394	3.23
NE	139	315	5.69
NY	37	4	9.69

TABLE 5

TREE FREE CLEAR WIDTH FOR MEAN CONDITIONS

Voltage	Mean Risk Factor (%) At Maximum Sag	Current Mean Clear Width (m)[1]	Tree Free Clear Width (m)[2]	Tree Free Based On Tallest Tree Found Clear Width (m)[3]
69 kV	11.95	13.3	25.5	34.8
115 kV	7.39	14.2	20.3	32.4
230 kV	4.34	16.3	23.6	29.7
345 kV	1.71	15.8	20.3	31.5

[1] For right-of-way width double the clear width and add the distance between outside conductors i.e., for 69 kV = 13.3 X2 + 3.7 = 30.3m

[2] This is the clear width required to achieve tree free on the average line. Lines facing above average tree exposure will not be tree free.

[3] The clear width that would actually achieve a tree free condition based on data of tallest trees found within the samples.

In undertaking this comparison it is necessary to assume what the minimum regulator specified right-of-way width might be. This assumption is made using the data from the National Grid system (Table 5). Using 345 kV lines to explore the merits of the approaches to managing tree risk, a clear width of 20.3 m (67 ft) (Table 5) would make the average 345 kV line tree free. Setting the clear width based on the average condition found for 345 kV lines does not reduce the risk of tree incidents to zero. Based on tallest tree encountered in the sampling a zero tree risk is only achieved at a 31.5 m (104 ft) clear width (Table 5), which equals a right-of-way width of 63 m (208 ft) plus the distance between outside conductors. Any new tree growth will serve to increase the required clear width. It was assumed that regulators might require all the 345 kV lines to have a minimum clear width of 21.2 m (70 ft). On this basis of this assumption, 89% of National Grid's 345 kV transmission system requires widening. However, 69% of the samples with a clear width of less than 21.2 m, currently have a RF rating of 0%. While the overall improvement in line security of increasing the clear width to 21.2 m from the current 15.8 m (52 ft) (Table 5) is 78%, the majority of this widening (i.e. 69%) will yield no improvement.

Using the RF ratings, a site-specific treatment approach was developed. It is comprised of reducing the tree risk of all spans to the voltage class average RF, which is 1.71% (NE & NY) at estimated maximum sag for 345 kV lines. Only 20% of the samples had a RF above the average. However, the average RF for these anomalous sites is 8.27%, with F_{AI}.=3.7336. Increasing clear width, line height or reducing tree height to bring the RF at these sites down to the average will improve overall line security 79% and in so doing, reduce the voltage class average RF to 0.36%. The F_{AI} is shifted to 0.1552 (under normal operating conditions) or an expected tree-caused incident frequency of 1 in 23 years.

Similar analysis of the other voltage classes leads to the same conclusion. On National Grid's transmission system, managing tree risk through the use of minimum clear widths based on voltage class constitutes an inefficient use of resources, costing 30-70% more than using site-specific prescriptions, which reduce the RF to at least the voltage class average.

The use of a tree RF provides a quantifiable approach to managing tree risk. One of the key findings of the work to assess the beyond right of way tree exposure of National Grid's transmission system is that there are areas of anomalous tree risk, substantially higher than the average for the voltage class. This observation is a product of having produced a RF rating for each sample point edge. Because the RF is responsive to the actual field conditions, it identifies where a dedication of resources will yield the greatest return in avoided tree-caused interruptions.

Aspects of this work may be extended to other utilities. For example, given the range of possible variability in tree height and density and, to a lesser extent in clear width and line height, the finding that the economics of a site-specific approach to managing tree risk proves superior to the use of standardized clear widths based on voltage, will hold true. The RF is a measure of tree exposure, while the outage experience provides the information on vegetation failure rates. This work has demonstrated a strong correlation between the RF produced by the OCWC and tree-caused interruptions. The methodology is transferable to other utilities. However, due to differences in tree species and their associated failure rates and modes of failure, the regression equation (1) cannot be expected to be applicable to other utilities, unless they are located in the same geographic area as the National Grid transmission system. For other utilities the relationship between a measure of the tree risk, which reflects local tree conditions, and the tree-caused interruption experience will need to be established.

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VIII. BIOGRAPHIES

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