Storm Hardening the Electric System Against Tree-caused Service Interruptions

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Abstract-- **In the aftermath of a windstorm that interrupted service on over 40% of Puget Sound Energy's transmission system, the regulator ordered an investigation, which was to evaluate options for hardening the electric system. This study quantified the extent of tree exposure along the transmission system and examined the correlation between various field measurable variables and tree-caused outage frequency. Based on the significant correlations, it is concluded that only mitigation, which reduces the extent of tree exposure holds the potential to significantly decrease tree-caused service interruptions during major storms.**

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

Puget Sound Energy (PSE) is a utility providing electric and natural gas service in western Washington. PSE has about 17,300 kilometers of electric distribution lines and about 3,360 kilometers of electric transmission. For the purposes of this study, transmission refers to lines energized at 55, 66, 115 and 230 kilovolts (kV).

In December of 2006, Puget Sound Energy experienced substantial electric system damage and service interruptions due to gale force winds. Soils were saturated from previous rains and tens of thousands of trees uprooted and fell into power lines and substations. The 115 kV system was particularly heavily impacted. In the aftermath of this storm, the Washington Utilities and Transportation Commission, or regulator, asked what could and would be done to avoid such extensive damage and prolonged outages in future storm events.

Other researchers have sought to make tree-related service interruptions predictable based on the frequency of maintenance [1][2][3]. Kuntz et al 2002 sought to optimize the maintenance cycle to achieve the best possible reliability for the maintenance dollar. Guikema et al 2006 using six variables in a model concluded that "tree trimming" does have a significant effect on distribution reliability during normal operating conditions. Of the six variables only two related to trees, permitting the calculation of the term of maintenance data available and the time since the last "trimming" operation. Radmer et al 2002 specifically focused on tree growth as did Kuntz et al 2002, though the latter acknowledged that it is generally agreed that trees do not cause line to ground faults on contact with single line distribution conductors [4][5]. No distinction was made by these researchers between "grow-in" and "fall-in" type outages. While the primary cause of the last three North American cascading outage events, including the Northeast blackout of August 14, 2003 [6] could be classified as grow-in events, generally, the majority of tree-related electric service interruptions are due to tree failure from outside the right of way [7].

In seeking to prevent future electric system damage it is necessary to understand what contributes to tree-related outages. Most tree-related outages arise from outside the right of way [7]. Operational data from PSE reveals from 2005 through 2007 more than 95% of tree-related service interruptions are due to tree failures rather than grow-ins and that 80% of all tree-related outages arise from outside the right of way. This study sought to establish what variables, if any, explain the experienced frequency of tree-related service interruptions. Past work established that the frequency of tree-related outages is strongly correlated to Risk Factor [8][9], a measure of outside right of way tree exposure. The Risk Factor (RF) is produced by a process called the Optimal Clear Width Calculator [7] and its validity, as a measure of tree-caused interruption risk has been established [9]. The Optimal Clear Width Calculator (OCWC) provides a measure of tree exposure risk, which is comprised of two factors: the number of trees capable of striking the line on failure; and, the arc of line exposure to a falling tree. The OCWC uses the field variables

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line height, tree height, clear width and tree density to calculate the RF. The RF value lies between 0 and 1, with 0 indicating no risk of trees falling into conductors and 1, which is the highest possible risk posed by trees adjacent to a power line.

Utilities make use of the variables line height and clear width to mitigate tree-conductor conflicts. This is particularly apparent on transmission line right of ways. As the loss of a transmission line holds the potential to interrupt service to thousands or even tens of thousands of electric customers, utilities typically increase the height of the conductor and the width of the right of way (greater clear width) with increasing voltage [10]. Adjustments to either one or both of these variables affects the amount of tree exposure. If these variables have been effectively used there should be a significant difference in the tree exposure risk between voltage classes, reflecting the seriousness of the loss of the lines. That is, in general, the loss of a 230 kV line has a far greater negative impact in terms of customers affected than the loss of a 115 kV line. Consequently, effective management of the electric system would be indicated by a significantly lower risk of experiencing tree-related outages on a 230 kV line versus lower voltage lines, such as 115 kV. One of the objectives of this study was to deliver an objective method of making such risk assessments.

Further objectives included the development of a quantitative method of comparing mitigation options seeking to reduce tree-related outages. Success with this objective would allow the development of predictive models, which would permit the establishment of a base case to which potential reliability improvement options could be compared [11].

III. Methods

The percent of treed edge along PSE transmission lines was derived from aerial photographs at 400 randomly selected points along the transmission system. Sample edges where 1609 m in length.

Field sampling was conducted along a subset of the 400 randomly selected points. Field sampling points consisted of single spans with 218 right of way edges being sampled during July and August 2008. The aerial photographs were used to guide the selection of points as the field sampling necessitated that there be an adjacent forest edge. The field variables measured were line height at the minimum ground clearance within the span sampled, the clear width (distance from outside conductor to the tree boles along the edge), wire zone, tree height of the adjacent trees, broken into two categories of co-dominant height for the visually assessed average canopy height and dominant height if there were trees emergent to the co-dominant canopy, and slope. Inside the forest edge of the sample span, timber cruising techniques were applied to determine the tree density. Three replicates of BAF10 samples were taken inside each forest edge [12]. All trees within the BAF10 sample were measured for diameter at breast height and if ≥ 10.18 cm (≥4"), identified by species and recorded. This involved 11,277 trees. The BAF10 samples were used to calculate the trees per hectare, or tree density.

Ten years (1998 through 2007) of electric outage statistics were obtained from PSE. These were entered into a database to facilitate queries. The outage statistics were filtered for tree-related events that occurred on the transmission system. Tree-related outage events were converted and expressed as the annual incident frequency (F_{AI}) per 1609 kilometers (1000 miles) to eliminate the influence of various line lengths between voltage classes. The very few 66 kV lines sampled were grouped with the 55 kV lines. A considerable amount of the 55 kV and 115 kV lines are not located in the center of the right of way, being located along roadways. Consequently, the extent of tree exposure is not the same for the two sides of the right of way. To address this variation, a separate F_{AI} was calculated for the roadside sections (designated by voltage followed by St) versus right of way side or line sections that did not have adjacent roadways (designated by voltage and ROW).

Statistical analysis sought to establish, which, if any, of the field measured variables or their derivatives could account for the outage frequency. For the variables or derivatives with a significant correlation to the outage frequency, regression analysis was performed to establish whether outage frequency could be predicted from field measurable variables.

The illustration of possible mitigation of future storm related tree-caused service interruptions was based on a found significant correlation and regression equation. A proposed scenario for mitigation suggested a potential for major improvements in electric system performance during storms. Using clear width as the adjustment variable, the new clear widths were derived from the target RF values and the resulting change in tree exposure was calculated to assess the feasibility of the proposed mitigation.

IV. Results & Discussion

The means for the variables of clear width, line height, tree height and tree density were calculated. From these, the total tree exposure or number of danger trees (trees that on failure could contact the electric line) and the number of trees per 1609 m (1 mile) of right of way edge were determined. The danger trees are adjacent to but outside of the maintained right of way. The Risk Factor (using the OCWC) rating was derived for each sampled edge using the found line height, tree height, clear width, tree density and slope. Risk Factor means for each voltage class or subdivisions there of, were calculated from the Risk Factor for each sampled edge. Having data on slope, line height, tree height, clear width and percent treed edge, it was possible to calculate the area supporting danger trees. The BAF10 samples within the forest yielded the average tree density or number of trees per hectare. The mean tree density is 675 trees/ha ± 32 at the

TABLE 1: KEY VARIABLES FOR PSE TRANSMISSION (AT FOUND SAG)

Voltage (kV)	Mean Clear Width (m)	Mean Line Height (m)	Mean Tree Height (m)	Mean Risk Factor	Total Tree Exposure	Trees per 1609 m Edge	F_{AI} 1609 km^{-1}
55 ROW	10.1 c	13.1 b	28.7 a	.3047 a	357,597	1,433	27.75
55 St	20.4 ab	13.1 b	30.5 a	.0786 b	23,671	664	0.30
115 ROW	11.3 c	13.7 ab	29.6 a	.2967 a	3,359,517	1,212	12.60
115 St	24.7 a	13.1ab	31.4 a	.0518 b	152,325	294	0.17
230 ROW	15.8 b	14.6 a	27.7 a	.1355 b	383,286	585	2.14

F_{AI} = annual incident frequency
ROW – line, right of way, treed edge
St – line, street, treed edge
Means within each column followed by uniquely different letters are significantly different

95% confidence level (272 trees/acre ± 13). Having determined the area supporting danger trees and the trees per hectare, multiplication provides the total tree exposure. The total PSE transmission tree exposure is 4,271,047 trees. The data is presented in Table 1.

It has been stated that utilities adjust line height and clear width in an effort to reduce the risk of tree-related outages [10]. The field measured variables were tested via a multiple means test to assess any significant differences between voltage classes (Student-Newman-Keuls, p=0.05) (Table 1). Clear widths between 55 kV and 115 kV lines were not significantly different (Table 1). For line height, there was no significant difference between 115 kV lines and 55 kV nor the 230 kV lines. There was no significant difference between tree heights found adjacent to the various voltage classes. The mean Risk Factor values did not vary significantly between the 55 and 115 kV ROW voltage classes but both of these varied significantly from the 230 kV ROW mean Risk Factor.

The correlation between the mean field measured variables, their derivatives and the outage frequency was tested across all voltage classes. Results are presented in Table 2.

TABLE 2: VARIABLE RELATION TO TOTAL TRANSMISSION INTERRUPTION EXPERIENCE (F_{AI} 1609 KM^{-1})

Variable (means)	Correlation Coefficient (r)	P(r=0)
Clear Width	-0.8238	0 .0864 ns
Line Height	-0.2760	0.6530 ns
Tree Height	-0.4114	0.4914 ns
Total Tree Exposure	0.2446	0.6917 ns
Trees per 1609 m Edge	0.9201	0 .0268 *
Risk Factor	0.8878	0.0443 *

* significant - 95% level
** highly significant - 99% level
ns not significant

Only two variables, trees per 1609 m (1 mile) edge and Risk Factor, were found to be significantly correlated to outage experience. Both of these derived variables are measures of tree exposure. The correlation coefficients are very strong for both variables, being in the 0.9 range. Regression of each of these variables on F_{AI} was performed.

Various forms of regression were tested for trees per 1609 m of right of way edge and $F_{AI.}$ Several regression forms were found to provide significant regression equations. However, the smallest residuals were found with the exponential regression form. The algorithm

F_{AI} 1609 km^{-1} = 0.0509058888*e^(0.00442152631* Trees 1609m^{-1} edge) has an r^2 = 0.8634 and P(0) = 0.0224.

Previous work [9] found a significant correlation between outage frequency and Risk Factor (RF) and via regression a highly significant exponential algorithm. The nature of that relationship is confirmed in this work. Various forms of regression were also tested for Risk Factor and $F_{AI.}$ Several regression forms were found to provide significant regression equations but the smallest residuals were found with the exponential regression form. The algorithm

F_{AI} 1609 km^{-1} = 0.08765294536*e^(18.2203153259*RF) has an r^2 = 0.9559 and P(0) = 0.0040.

Having established by the coefficient of multiple determination of the regression equation that Risk Factor explains over 95% of the difference in annual outage incident frequency between voltage classes, we can conclude that targeted reductions in Risk Factor value will mitigate against tree-caused outage incidents. As reductions in Risk Factor are reductions in electric system tree exposure, all else equal, mitigation is effected under both normal operating conditions and during major storms. Consider 1609 m of forested edge along a power line with 500 danger trees. If the right of way is widened and the number of residual danger trees is thereby reduced to 400, and if the same storm could strike the before and after right of way edges, the widened right of way would experience 20% less interruptions.

TABLE 3: TREE-CAUSED OUTAGE MODELING USING THE OCWC RISK FACTOR ON THE SYSTEM LEVEL

	Tree Risk		**Tree Risk for Records with RF=<Mean RF**		**Tree Risk for Records with RF>Mean RF**			**Tree Risk After Mitigation**	
	No. of Records	**Ave. Risk Factor**	**No. of Records**	**Ave. Risk Factor**	**No. of Records**	**Ave. Risk Factor**	**Risk Factor After Mitigation**	**Ave. Risk Factor**	**Improvement (Weighted Average)**
55 kV	48	0.2764	25	0.0970	23	0.4714	0.2764	0.1830	33.80%
115 kV	108	0.2581	60	0.0884	48	0.4702	0.2581	0.1639	36.52%
230 kV	62	0.1355	38	0.0377	24	0.2902	0.1355	0.0755	44.23%
System	218	0.2273						0.1429	37.10%

While reducing the Risk Factor has been revealed as a viable and certain outage mitigation strategy, there is no precedent for what would constitute a reasonable target Risk Factor. To explore the extent of tree-caused outage mitigation a 'what if' scenario was run. The scenario assumed that target Risk Factor for any site would be less than or equal to the current voltage class mean Risk Factor. Table 3 shows the number of records for each voltage class and the average Risk Factor. The records were then parsed into records where the Risk Factor ≤ the voltage class mean Risk Factor and records where RF > the voltage class mean RF. It was assumed that the latter group would see intervention so as to reduce the RF to the voltage class mean RF. A new weighted average RF, resulting from the hypothetical mitigation, was calculated for each voltage class. Providing other variables that influence reliability are kept constant, this approach would yield a 37% improvement in the transmission system RF. This reduction would apply even during major storms, as reductions in RF are reductions in electric system tree exposure. There are a number of mitigation strategies that could be used to lower the RF, including increasing clear width, increasing line height and decreasing tree height.

This finding suggests that not only is storm hardening possible but potential storm damage could be substantially reduced. To determine whether such an improvement was in fact feasible, the change in clear width required to achieve the target RFs were derived from the OCWC. The reduction in total transmission system tree exposure was also calculated. The changes in mean clear width necessary to achieve the target RFs were not great, ranging from 0.6 m (2 feet) to 1.8 m (6 feet). Total tree exposure would be reduced from 4,276,395 to 3,905,052 trees, an 8.7% reduction.

Other approaches to mitigation are also possible. All of them are based on reductions in electric system tree exposure. A spreadsheet model was developed which incorporated the data on the found tree exposure and regression equation for outage frequency based on changes in trees $1609m^{-1}$ edge. This model allows PSE to explore the reliability impact of changes to the variables impacting system tree exposure. These variables include line height, tree height and clear width. The model does not provide a direct probability of tree-related outage events occurring. Rather, as the variables that may change are restricted to those affecting tree exposure, the model is useful only on a comparative basis. The models uses the current found conditions as a base case against which conditions resulting from potential reliability improvement projects can be measured. An illustration of the calculations in the spreadsheet is presented in the following example.

PSE's 115 kV system suffered particularly heavy damage in the December 2006 storm. It comprises about 78% of the total transmission miles. The mean clear width for the 115 kV right of way side is 11.3 m (Table 1). What would be the impact of increasing this clear width to achieve a mean of 14.3 m, an increase of 3 m (10 feet)? The current trees per 1609 m (1 mile) of edge is 1212 and the F_{AI} per 1609 km is calculated to be 10.83. Increasing the mean clear width by 3 m results in less area supporting danger trees. This reduced area times the mean tree density of 675 trees/ha results in 965 trees per 1609 m of edge. Using the algorithm F_{AI} 1609 km^{-1} = 0.0509058888*e^(0.00442152631* Trees $1609m^{-1}$ edge) produces 3.63. Assuming, conditions similar to those over the 10-year data period used, tree-related outages would be reduced by 66.5% on the 115 kV lines. Achieving this projected reduction in tree-related outages involves reducing the danger tree exposure by about 20%.

Increasing line height, another mitigation option, reduces tree exposure. By calculating the F_{AI} from the trees per 1609 m (1 mile) of edge both before and after mitigation, the associated change in reliability can be determined.

V. CONCLUSION

While PSE has installed greater line height and clear width with increasing voltage class, the differences between voltage classes are not sufficient to result in distinct, significantly different tree risk for each voltage class, as the risk for 55 kV lines is not significantly different from the risk along 115 kV lines.

Two variables, Risk Factor and trees per 1609 m of edge, were strongly and significantly correlated to tree-related outage frequency. Regression analysis not only provided algorithms to make outage frequency predictable from Risk Factor and trees per 1609 m of edge but the strength of the coefficient of multiple determination being 0.96 and 0.86 respectively, indicates that reducing storm related tree-caused outages will necessitate reductions in tree exposure. This answers both whether it is possible to reduce electric system storm damage and how. Redundancy and other forms of system protection can be engineered to reduce storm impacts. These methods may reduce the duration of an interruption but with the exception of undergrounding, do not eliminate the interruption event itself. Reductions in transmission system tree exposure will actually avoid some of the outage events.

The methods for reducing tree exposure consist of increasing clear width, increasing line height, reducing adjacent tree height and undergrounding. The feasibility of undergrounding has been studied many times, predominantly on distribution systems. The costs are considered prohibitive for distribution systems [13] [14]. Undergrounding transmission lines costs far more due to the need for cooling and consequently it is not generally a feasible option [15]. Due to the height of the trees found adjacent to the right of way in the PSE service territory averaging about 30 m, reducing tree height so that the trees on failure could not contact a power line (mean height of 14 m) is not an option. To achieve meaningful reductions in tree exposure would necessitate height reductions of about one half of the adjacent tree. This would constitute severe tree topping, with trees being cut to below any branches, resulting in the death of many trees. Both remaining options, increasing clear width and increasing line height are generally objectionable to the public. Tall structures are considered unsightly, having a negative impact on property values. People cherish their trees. This work has shown that based on a 10-year history of tree-related outages that tree-caused outages, even during major storm events, could have been reduced by over 37% through the targeted removal of 8.7 % of the current transmission system tree exposure. While it will be necessary for PSE, the regulator and their public to determine the balance between tree preservation, electric system performance and reliability, this study has found that substantial gains in system performance during storms, that is storm hardening, is possible.

VI. References

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VII. Biographies

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