Increased Risk of Electric Service Interruption Associated with Tree Branches Overhanging Conductors

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***Abstract*—Severe weather events such as ice and tropical storms routinely cause extensive damage to electrical distribution systems. Much of the damage and service loss can be attributed to trees. Events where service restoration spans days or weeks are generally closely examined through regulator directed hearings. Even when no specific actions are subsequently ordered, the common theme is that utilities should find ways of reducing the impact of future storms. However, utility pruning that achieves the greatest service reliability may substantially impact tree form. These alterations of tree form often elicit a negative reaction from property owners and communities. While utilities justify their pruning as an effort to improve service, they have not had a quantifiable means of determining the extent of that improvement. The methodology outlined for calculating the increased risk of service interruption attributable to branches overhanging conductors should prove useful in communicating the impacts of both utility pruning and community restrictions placed on that pruning.**

***Index Terms*-- Power distribution reliability, power distribution maintenance, storms, power system restoration, prediction methods, vegetation overhanging**

I. NOMENCLATURE

Hazard tree: a structurally unsound tree that could strike a target, such as utility lines, when it fails.

Bole: that part of the trunk of a tree beneath the point where branching commences.

II. INTRODUCTION

THIS paper presents a mathematical approach to determining the increased risk of electric distribution system service interruptions arising from maintenance that tolerates branches overhanging conductors. The next section provides a context by establishing that branches overhanging electrical conductors both pose a risk to the continuity of service and is a risk utilities wish to mitigate.

III. BACKGROUND

Electric utilities are faced with simultaneously assuring reliable service while appeasing public concern for tree preservation. When ice storms, hurricanes or other widespread high wind events occur, the electric system is often revealed to be vulnerable to extensive damage and extended service interruptions [1][2][3][4][5][6][7][8][9]. Six reporting utilities faced 44 major storms between 1989 and 2003, affecting more than 12 million customers and causing almost 250 days of power outages [10]. At a time when even momentary outages can cause substantial disruption to business [11][12], the average duration of these 1989 to 2003 power outages was 5.6 days [10]. A subsequent Edison Electric Institute survey of 14 electric utilities identified 81 major storms between 1994 and 2004 costing the utilities over $2.7 billion in damages [13]. While the cost to utilities may be catastrophic, exceeding all operating income, it is only a fraction of the regional economic losses associated with the loss of electric service [13].

In the aftermath of damaging weather events, the tone from politicians, regulators, media and public is often accusatory, laying blame for the service interruptions on the utilities [1][5][14][15][16][17][18][19][20]. For investor-owned utilities, which are not free to set their own electric rates but must apply to a regulator to have rates approved, including the recovery of storm remediation costs, the public relations aspects of service reliability must be managed [13][21][22]. A public frustrated and angered by enduring the cost and inconvenience of loss of electrical service makes a hostile political climate for the recovery of storm restoration costs. Public relations would be better served if the expected performance of the electric system based on regulator, community, and public imposed conditions such as limiting tree to conductor clearances, [4][23][24][25][26] could be clearly communicated in advance of any stress on the system.

The majority of storm damage is the result of tree-conductor conflicts [1][2][3][4][5][6][7][8][9][14][27][28] [29][30][31]. There has been very little quantitative work linking tree to conductor clearance, pruning types and total power line exposure to trees with electric system performance under storm stress loadings. While some work has been done to find the relationship between the frequency of maintenance activities and electric

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system performance, the work is focused on normal operating conditions [32][33][34][35][36]. Consequently, the utility industry has difficulty articulating how trees and the electric system will interact under storm stress.

Media articles in the aftermath of storms causing extensive electric system damage reveal a commonly held belief that much of the damage could have been averted through a more current or aggressive tree trimming program [1][25][37] [38][39]. This belief is erroneous. Electric system damage during major storms is predominantly a result of tree or branch failures [1][2][3][4][5][6][7][8][14][27][28][29][30] [31].

A normal component of a utility vegetation management program is the identification and removal of hazard trees. However, an Eastern Utilities study found only 44% of trees that failed under normal operating conditions (winds of 72 to 96 km per hour) had an indicator of structural weakness [32]. The Eastern Utilities study reveals that as winds approach 96 km per hour the number of apparently fault-free trees that fail already exceeds the number of structurally weak trees that fail. Therefore, under severe storm stress loadings the majority of failed trees will have had no indicator of structural weakness. As apparently healthy trees or limbs that meet the tree to conductor clearance specifications are not removed during a maintenance event, a more current vegetation management program holds little potential to decrease storm damage.

To assess whether any type of pruning holds the potential to avert major storm related tree-caused outages it is necessary to consider the specific electric system vulnerabilities associated with different types of risk exposure.

IV. TREE AND STRESS LOAD INTERACTIONS

There are two types of stress loading trees experience that lead to tree-caused outages: wet snow or ice loading and wind loading. Wind loading causes branch or whole tree failures, resulting in tree parts falling into, across or through conductors. Tree windthrow has been found to increase with tree age and height, with softwoods being more susceptible to windthrow than hardwoods [40][41][42][43]. Wet snow or ice loading leads to two modes of service interruption: trees or branches bending to lie on or across conductors and, branch or trunk failures with tree parts falling into, across or through conductors. The northeast ice storm in 1998 revealed damage was more extensive to hardwoods than softwoods; larger trees suffered more crown damage while smaller diameter trees (12.7 cm – 25.4 cm) were more susceptible to leaning (greater than 45° angle)[44].

Tree and branch failures can cause electrical faults by bridging phases, pushing conductors into each other or by physical damage to equipment that disrupts the circuit. When branches bend or trees lean to lie on conductors, without pushing phases into such close proximity so as to cause a direct fault, whether a fault occurs is dependent on a number of variables including the voltage gradient, branch or tree diameter and tree species [45][46].

It emerges that there are a few pruning practices that will lead to reductions in tree-caused outages during severe storms and also, that there are conditions which can only be mitigated by managing the total tree exposure of power lines [47][48]. Crown reduction pruning of the 12.7 cm – 25.4 cm diameter trees so that they cannot contact a conductor when they bend under load and the removal of overhanging branches that could either bend to lay on conductors or break and fall into or through conductors will reduce storm-caused interruptions. While pruning to remove overhangs does not preclude the possibility of windthrown branches from the crown causing service interruptions, it removes the most direct threat: that of a downward fall of a tree branch. The investigation of the December 2002 ice storm in the Carolinas found that the municipalities with the most restrictive tree-trimming ordinances and greatest amount of overhanging branches suffered the most electric system damage and customer outages [4][9].

A. Branches Overhanging Electrical Conductors

Comparing the risks associated with the condition of overhanging branches versus no overhanging branches two different failure types need be considered. Where the failure is a limb failure, the tree with an overhanging branch represents a risk versus a zero risk for no overhanging branch. The extent of the risk varies with the specific tree species' susceptibility to branch failure under load. The second failure type, where risk to the electrical system is impacted by overhanging branches, is tree failure by uprooting or trunk failure. It is for this second failure type that the increased risk of service interruptions is calculated. This work does not attempt to establish the probability of a trunk failure. Rather, it compares the risk for conductor contact when a tree fails for the conditions of overhanging branches versus no overhanging branches.

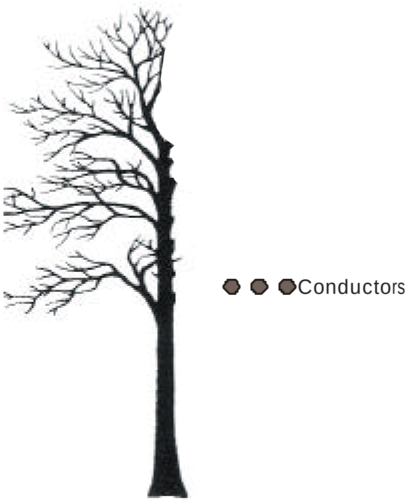

Fig. 1. Ground-to-Sky Utility Pruning

Branches overhanging conductors is a condition not uncommon to distribution lines but is not a risk faced by higher voltage transmission lines where the condition is precluded by meeting safety code. Electrical distribution conductors and associated hardware must co-exist with the public's valued shady, tree-lined closed-canopy streets. While utilities attempt to limit overhangs by practices like V-pruning, often based on the location of the tree relative to the conductors, this is not an option.

Recognizing the role overhanging branches play in storm damage, some utilities have begun to prioritize important three phase feeder lines for remedial "ground-to-sky"[1] (Fig.1) or other "storm-proof" pruning as a system hardening measure [4][49][50][51]. A common characteristic of storm proofing strategies is the removal of overhanging branches [49][50][51]. The public, however, is very resistant to pruning practices that radically alter the form of trees (Fig. 1) and utilities face considerable difficulty gaining acceptance of such practices as they have no process to quantitatively forecast the impact of them on system reliability. Generally, it is only in the aftermath of a major storm impacting millions of customers that there is sufficient political will to give utilities the leeway to try measures such as "ground-to-sky" pruning. Utilities can subsequently gather performance data on circuits having received storm-proofing treatments and this data may serve to guide future practices.

V. ANALYSIS

A. *Defining the Condition*

Fig. 2 shows a tree with branches overhanging a three phase electric line. The clear width (CW) is the distance from the conductor to the adjacent tree trunk. To determine the increased risk of a service interruption arising from the overhanging branch, is a multi-step process, the first of which is to establish a baseline. The baseline condition will be branches equal in length to CW but with no overhanging branches. The baseline condition will be compared to the overhanging branch condition to establish the difference in risk to the power line. The length of the overhanging branch is the CW plus the extent of the overhang (OH) (see Fig. 2).

B. *Establishing a Baseline*

In Fig. 3, the branches have been pruned back just enough that none overhang the conductors. Should load stress cause the tree to fail, it could fall anywhere within the 360° of a circle. In this case, any fall towards the line would result in a hard contact. Hence, the probability of contact on tree failure is 180°/360° or 0.5. The arc of a safe fall that does not contact the conductors is also 180°. This informs us that when there is a branch overhanging the conductor (as in Fig. 2) the probability of a line contact on tree failure is necessarily greater than 0.5. This is illustrated in Fig. 4, which shows that for overhanging branches to clear the conductor on tree failure the arc of safe fall is decreased while the arc of possible contact is increased. The pie wedge formed (Fig.4) between the power line and the angle of tree fall direction (11 o'clock) represents the increased risk. This is, however, only one half of the increased risk, as the illustration shows the tree falling away from the viewer but the same potential exists should the tree fall towards the viewer (creating a mirror image wedge at 7 o'clock).

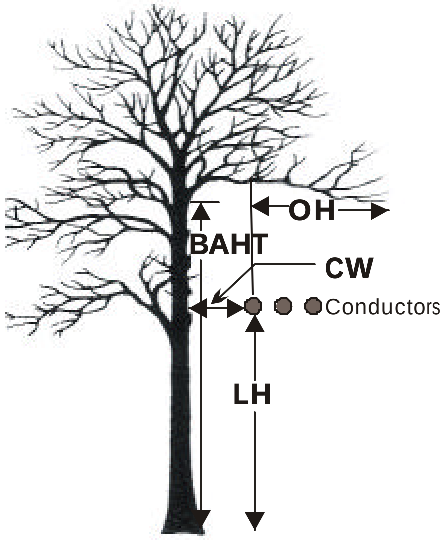

Fig. 2. Branches Overhanging Conductors
BAHT = branch attachment height
CW = clear width
LH = line height
OH = overhang

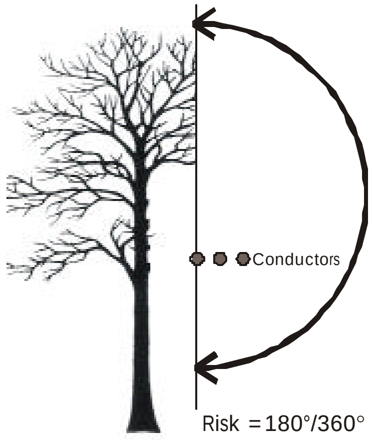

Fig. 3. Risk Exposure Arc No Overhanging Branches

To quantify the risk associated with a branch overhanging a conductor, first the baseline condition of a tree with branches to but not overhanging the conductor (length=CW), falling parallel to the conductor (Fig. 5) is considered. Drawing a line to form a right angle at the point of the branch attachment, the length of the line from the tree trunk to the conductor is equal to CW. A triangle is formed by drawing another line (H) from where the first intersects the conductor to the base of the tree, forming the angle θ, which is to be determined (Fig. 5).

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[1] Ground-to-sky is intended to convey the extension of the right of way in the vertical plane. No intrusion of branches from the side into the right of way is tolerated and thereby, no overhangs can exist.

It has already been stated that the probability of a contact is 0.5 for a fall towards the line. The angle θ will be referred to as θ_1 for the baseline condition, a fall, of a tree with branch length of CW, parallel to the power line. This fall would result in the tree branch just touching the conductor (but not causing an interruption).

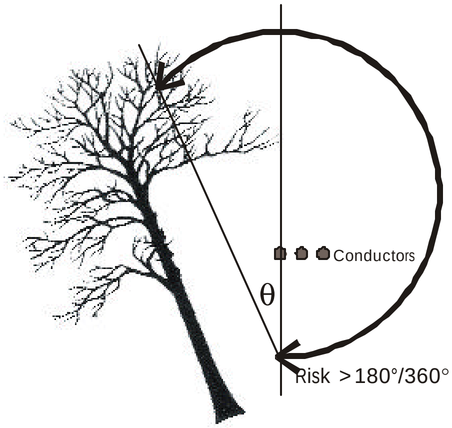

Fig. 4. Risk Exposure Arc With Overhanging Branches

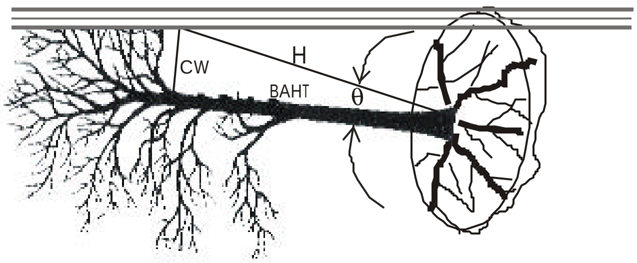

Fig. 5. Tree Fall Parallel to Line
H = hypotenuse

Replicating such a fall to just touch the conductor when there is an overhanging branch, would necessitate a tree fall not parallel to but somewhat away from the conductor. That is, the angle θ will increase as the amount of overhang increases (Fig. 4). Thus, comparing θ for the overhanging branch condition (θ_2) with that of the baseline condition (θ_1) provides the basis for quantifying the change in interruption risk.

C. *Branches Overhanging Conductor*

In the next step, a tree fall of such an angle that the overhanging branch just touches the conductor is explored in more detail (Fig. 6). Again, a line at a right angle to the bole is drawn from the tree to the closest conductor. In this case, the length of this line is CW plus the length of OH. The distance from the point of branch attachment to the ground line remains the same (BAHT). The angle between the hypotenuse (H) and the tree trunk will be referred to as θ_2.

The change in θ is used to compare the risk between the conditions of an overhang versus no overhang. This difference is θ_2 - θ_1. Any fall toward the line for the base condition would likely result in an interruption and the associated probability is 0.5. The risk associated with the overhanging branch then is,

$$\frac{2(q_2 - q_1)}{180^\circ} \times (0.5) + 0.5 \qquad (1)$$

Equation 1 uses two times the difference between the angles θ because a replication of the potential exists in falls to the right side (Fig. 5 and Fig. 6 show the tree falling only to the left side).

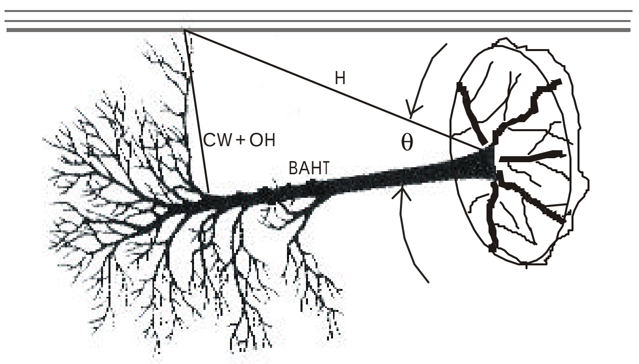

Fig. 6. Tree Fall With Overhanging Branches (Just Touching Line)

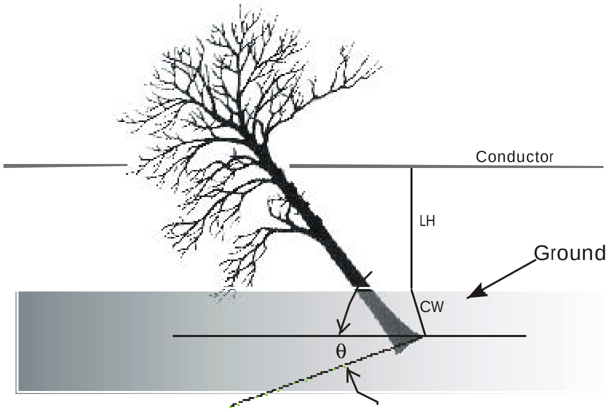

Fig. 7. Fall Angle

D. *Calculating the Risk Associated With Overhangs*

To this point the role of the power line height on the angle θ has not been considered. This may have created the impression that the angle θ is determined at ground level as in Fig. 7. However, as the distance between the conductor line height (LH) and the overhanging branch (BAHT-LH) decreases, the length of the arc of a safe fall also decreases, ultimately, to the point where the only possible safe fall is one perpendicular to and away from the power line. The distance between the conductors and the overhanging branch is a variable important to interruption risk. To incorporate the influence of this variable, the triangle from which the angle θ is derived must be pictured on a horizontal plane at line height (Fig. 8).

First, picture the fall of the tree in Fig. 6 arrested at the point that the branch makes contact with the conductor. This yields a triangle comprised of the branch CW+OH horizontal at line height; another side being the tree trunk (BAHT) sloping from line height to the ground and the hypotenuse (H) from the point of branch and conductor contact sloping to where the trunk intercepts the ground (Fig. 8).

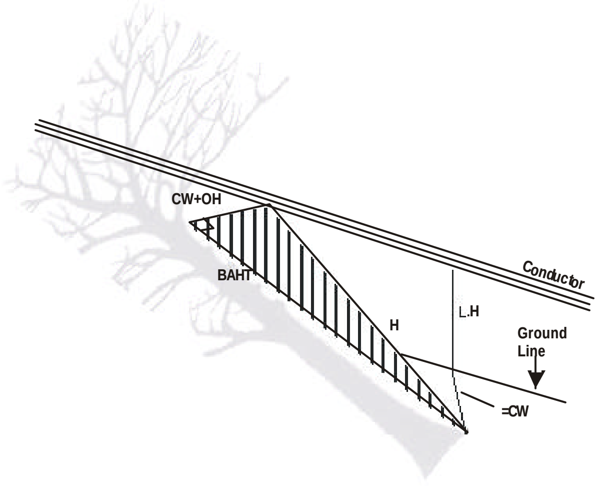

Fig. 8. Derivation of Fall Angle at Line Height – first stage

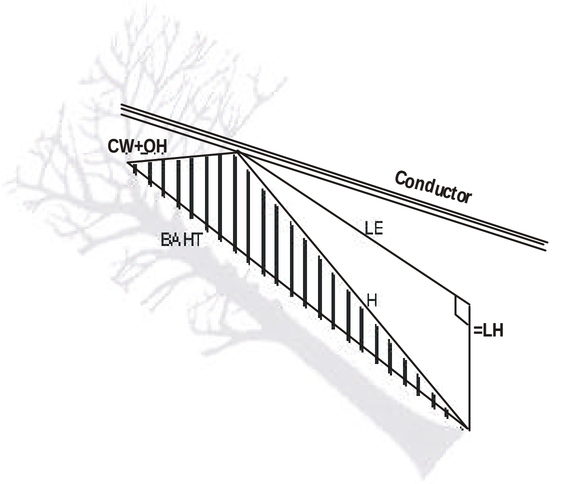

Fig. 9. Derivation of Fall Angle at Line Height – second stage

Then a vertical triangle sitting directly over H is created; a vertical rising from the intersection of BAHT and H of a length equal to the line height (LH). From the point at line height above BAHT-H a line is drawn back to the point where the branch intersects the conductor (Fig. 9). This new line, which is labeled LE in Fig. 9, becomes the hypotenuse of a third triangle, horizontal and at line height (Fig. 10). The length of this line is calculated using the Pythagorean theorem (2)(3). The side opposite angle θ has the length (CW + OH). The third line runs directly over BAHT at conductor height. Using the sine function, the angle θ can be calculated (4).

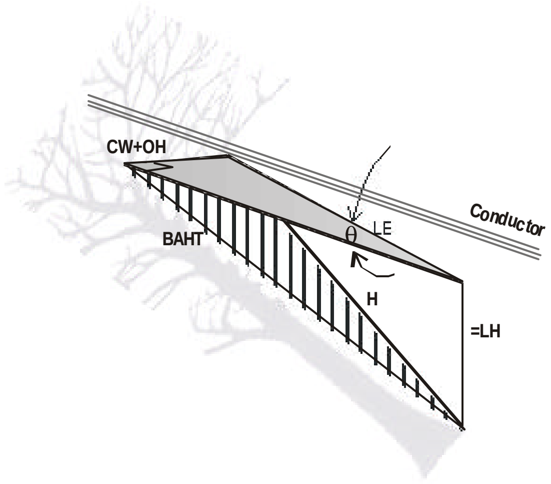

Fig. 10. Derivation of Fall Angle at Line Height – third stage

The following calculations are used in determining the angle θ in Fig 8.

$$H = \sqrt{(CW + OH)^2 + BAHT^2} \qquad (2)$$

$$LE = \sqrt{H^2 - LH^2} \qquad (3)$$

$$Sine\ q = (CW + OH) \div LE \qquad (4)$$

$$\text{degrees}\quad q = \sin q \times \frac{180}{p} \qquad (5)$$

To illustrate the calculation of the risk (R) associated with an overhanging branch using measurable variables, an example is provided. Assume the following are the found variables.

- Line height (LH) is 8.5 m (28 feet)
- Point of overhanging branch attachment (BAHT) is 13 m (43 feet)
- Clear width (CW) is 3.3 m (11 feet)
- Branch overhang (OH) is 4.5 m (15 feet)

The fall parallel to the line with total branch length equal to the CW, is expressed as:

θ_1=

$$\sin^{-1}\left(CW \div \sqrt{\left(\left(\sqrt{BAHT^2 + CW^2}\right)^2 - LH^2\right)}\right) \times \frac{180}{p} \qquad (6)$$

=18.55°

The situation with an overhanging branch and a tree fall such that the branch just contacts the conductor, is expressed as:

θ_2=

$$\sin^{-1}\left((CW + OH) \div \sqrt{\left(\left(\sqrt{BAHT^2 + (CW + OH)^2}\right)^2 - LH^2\right)}\right) \times \frac{180}{p} \qquad (7)$$

= 38.41°

The degrees of increased risk exposure resulting from the branch overhang are calculated.

$$\theta_2 - \theta_1 = 19.87^\circ \qquad (8)$$

The risk of a conductor contact on tree failure for the overhang condition is calculated.

$$R = \left(\frac{2(q_2 - q_1)}{180^\circ} \times 0.5 \right) + 0.5 \qquad (9)$$
$$= 0.61$$

For the example conditions, the overhanging branch has increased the risk of a conductor contact on tree failure by 22.1% ((0.61-0.5)/0.5). This is the difference between conditions as represented in Fig 2 and Fig. 3.

The example provided applies to trees that break or tip at ground level. Does the value of R change if the tree failure occurs above ground level? To make this determination the height of the break is subtracted from both LH and BAHT prior to solving for θ. If the trunk failure occurred at 3 m above the ground R=0.62; at 6 m above the ground R=0.63. As trunk failures above ground level increase the interruption risk, using the assumption of a failure at the ground line will yield a conservative estimate of the increased risk associated with an overhanging branch.

VI. UTILITY PRUNING TO MINIMIZE INTERRUPTION RISK

There is another risk comparison that can be made. In the pursuit of reliable service, utilities sometimes remove all branches on the line side back to the bole (Fig. 1). This type of line clearance has been variously dubbed as ground-to-sky, wall-trimming and right of way reclamation by utility foresters.

The public tends to resist pruning that dramatically changes the appearance of trees as in Fig. 1. The most negative public reaction occurs when a utility intent on restoring reliability of service [24] shifts trees as they appear in Fig. 2 to Fig. 1 in one pruning. The public, shocked by the drastic change in the appearance of the tree [52][53], object to the destruction of the tree form. It is difficult to appease the public’s concern if it is not possible to quantify the benefit of such pruning in terms of improved electric service.

Hence, it is desirable to compare the risk of service interruption on tree failure under ground-to-sky clearance versus the condition of overhanging branches. Adding another variable to the example, that the tree is 21.2 m (70 feet) tall allows a comparison of risk between overhanging branches (Fig. 2) and the case of branches on the line side being pruned back to the bole (Fig. 1). By a process of triangulation using the variables of tree height, line height and clear width the risk of a line strike on tree failure, for the conditions illustrated in Fig. 1, is determined to be 0.31 [48]. Thus, not only removing overhang but also pruning the branches back to the bole (Fig. 1) results in a 49% ((0.61-0.31)/0.61) improvement in line security (over Fig. 2).

VII. CONCLUSIONS

It has been shown that the acceptance of branches overhanging conductors will result in more system damage when storm stress loadings cause trees to fail. It has also been shown that there are pruning practices that hold the potential to substantially reduce the extent of storm damage.

In areas that have encountered severe electrical system damage during storms, such that people have been left without electric service for multiple days, a means of reducing the system damage and thereby restoration times by almost one half in future bad weather events would be tremendously appealing. At the present time such extended loss of service results in demands for under-grounding the distribution system [9][19][54]. While under-grounding would indeed resolve the problem, it is so prohibitively expensive [54][55] that regulators and politicians hesitate to commit to broad scale conversion, which would obligate the ratepayer to bear the costs.

While the condition of tree branches overhanging conductors applies only to an unknown fraction of North America’s electrical distribution system, such areas are particularly susceptible to storm damage [4][54]. The opportunity to roughly halve storm damage in areas with overhanging branches would appear to provide a compelling reason for cooperation between the community and the local utility on initiatives such as tree replacement or to tolerate the alterations of tree form necessary to achieve this substantial increase in electric service continuity. When the removal of overhanging branches is selectively applied to lines or line segments based on the number of customers impacted, the potential reliability benefit is greater than the percent avoided infrastructure damage [50].

As a minimum, quantifying the risk of service interruptions associated with branches overhanging conductors will facilitate communication of the consequences of customer and community choices and, thereby, establish realistic expectations for electric system performance under storm stress.

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IX. BIOGRAPHIES

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