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How Trees Cause Outages

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Abstract

Ten tree species of operational significance to electric utilities were subjected to high voltage gradients in a controlled laboratory environment. Data from this project were combined with those from earlier work, resulting in a database covering 21 species. Differences in electrical conductivity were observed among species. This work confirms that the electrical impedance of live branches is variable, and supports the hypothesis that the risk trees pose to reliability of electric service varies by species. Test results suggest that the species of individual trees in close proximity to an overhead distribution line should be an important consideration in assessing risk to reliability. This work also suggests that the majority of tree-conductor contacts result in high impedance faults of low current, and are of relatively low risk to reliability. Only under some conditions do tree-initiated faults evolve to become low impedance/high current fault events, and cause interruptions. These findings can be applied in the development risk assessment criteria, and reliability driven preventive maintenance of trees posing a threat to overhead distribution lines. The work identified several important characteristics of the determinant variables of species, voltage gradient and branch diameter that are promising risk assessment criteria.

Key Words

High Impedance Faults, Interruption, Low Impedance Faults, Outage, Voltage Stress Gradient

Introduction

Trees continue to be a leading cause of service interruptions on electric distribution systems throughout North America. This in spite of the fact that electric utilities spend more than $2 billion annually on preventive maintenance of vegetation interacting with overhead distribution lines. While numerous refinements have been made in vegetation management practices over past decades, much of the change has been driven by financial and productivity considerations. Very little research has been completed on the fundamental question of how trees cause service interruptions.

The traditional approach to mitigating this risk involves uniform application of a fixed standard for clearance between trees and overhead conductors. Earlier work on a limited number of species led to development of a conceptual model of understanding tree-caused interruptions that provided a new understanding of the risk trees pose to reliability. This project further quantified the relative risk of operationally important tree species impacting overhead distribution electric lines in North America.

Project findings provide a means of assessing the relative risk of different tree species to electrical service reliability. Findings from the investigation also support modification to the tree-to-conductor clearance specifications, and the scheduling of preventive maintenance of trees in close association with overhead distribution lines. An improved understanding of the risk associated with individual tree species will support optimization of reliability-focused maintenance by allowing utility arborists to target more intensive levels of maintenance on those trees that pose the greatest risk of causing an interruption to electrical service.

METHODS

Experience suggests that the list of operationally significant "problem" species faced by utilities in each region tends to be relatively short. Further, the list for any physiographic region will have frequent overlap. A list of the most frequently occurring and operationally significant species in nine regions was developed. Table 1 identifies the important species posing a threat to overhead distribution system reliability in each region. The species that were the focus of this investigation are highlighted in the table and were selected for testing based on the interests of utility cooperators that provided support to the project.

Table 1. Frequently Occurring Tree Species by Region

NE	Midwest	Temp SE	Gulf Coast	Inter Mt.	Southwest	PNW	Pacific So	Sub Tropical
Northern red oak ***(Quercus rubra)***	**green ash** ***(Fraxinus pennsylvanica)***	**green ash** ***(Fraxinus pennsylvanica)***	black gum *(Nyssa sylvatica)*	**Siberian elm** ***(Ulmus pumila)***	**Siberian elm** ***(Ulmus pumila)***	black cottonwood ***(Populus trichocarpa)***	**sycamore** ***(Platanus occidentalis)***	live oak *(Quercus virginiana)*
red maple ***(Acer rubrum)***	*Siberian elm* (Ulmus pumila)	**sycamore** ***(Platanus occidentalis)***	live oak *(Quercus virginiana)*	Ponderosa pine ***(Pinus ponderosa)***	Ponderosa pine ***(Pinus ponderosa)***	*red alder* **(Alnus rubra)**	**Douglas fir** ***(Pseudotsuga menziesii)***	queen palm *(Syagrus romanzoffiana)*
black cherry ***(Prunus serotina)***	**silver maple** ***(Acer saccharinum)***	**black locust** ***(Robinia pseudoacacia)***	sweetgum *(Liquidambar styraciflua)*	quaking aspen ***(Populus tremuloides)***	black cottonwood ***(Populus trichocarpa)***	**Douglas fir** ***(Pseudotsuga menziesii)***	**bigleaf maple** ***(Acer macrophyllum)***	royal palm *(Roystonea spp.)*
paper birch ***(Betula papyrifera)***	**red maple** ***(Acer rubrum)***	weeping willow ***(Salix babylonica)***	boxelder *(Acer negundo)*	*red alder* (Alnus rubra)	pinyon pine *(Pinus edulis)*	**bigleaf maple** ***(Acer macrophyllum)***	Ponderosa pine ***(Pinus ponderosa)***	coconut palm *(Cocus nucifera)*
silver maple ***(Acer saccharinum)***	weeping willow ***(Salix babylonica)***	**honeylocust** ***(Gleditsia triacanthos)***	slash pine *(Pinus elliottii)*	**bigleaf maple** ***(Acer macrophyllum)***	mulberry *(Morus spp.)*	**quaking aspen** ***(Populus tremuloides)***	eucalyptus *(Eucalyptus spp.)*	ficus *(Ficus spp.)*
sugar maple ***(Acer saccharum)***	**black locust** ***(Robinia pseudoacacia)***	slash pine *(Pinus elliottii)*	loblolly pine *(Pinus taeda)*	*DOUGLAS FIR* (PSEUDOTSUGA MENZIESII)	Freemont cottonwood *(Populus fremontii)*	black locust *(Robinia pseudoacacia)*	blue oak *(Quercus douglasii)*	black olive *(Bucida buceras)*
quaking aspen ***(Populus tremuloides)***	sweetgum *(Liquidambar styraciflua)*	loblolly pine *(Pinus taeda)*	hackberry *(Celtis occidentalis)*	**paper birch** ***(Betula papyrifera)***	live oak *(Quercus virginiana)*	lodgepole pine *(Pinus contorta)*	English walnut *(Juglans regia)*	Norfolk Island pine *(Araucaria heterophylla)*
Eastern white pine ***(Pinus strobus)***	boxelder *(Acer negundo)*	pecan *(Carya illinoensis)*	water oak *(Quercus nigra)*	black cottonwood ***(Populus trichocarpa)***	Lombardy poplar *(Populus nigra 'Italica')*	Lombardy poplar *(Populus nigra 'Italica')*	redwood *(Sequoia sempervirens)*	melaleuca *(Melaleuca quinquenervia)*
weeping willow ***(Salix babylonica)***	black walnut *(Juglans nigra)*	water oak *(Quercus nigra)*	palm *(Sabal spp.)*	Western red cedar *(Thuja plicata)*	post oak *(Quercus stellata)*	Pacific willow *(Salix lasiandra)*	palm *(Sabal spp.)*	mahogany *(Swietinia mahagoni)*
boxelder *(Acer negundo)*	hackberry *(Celtis occidentalis)*	sweetgum *(Liquidambar styraciflua)*	bald cypress *(Taxodium distichum)*	boxelder *(Acer negundo)*	Southern red oak *(Quercus falcata)*	Western red cedar *(Thuja plicata)*	live oak *(Quercus virginiana)*	Australian pine *(Casuarina equisetifolia)*

Sample branches were collected from the residues generated by utility line clearance tree crews performing routine preventive maintenance pruning. Seventy-two (72) specimens in four diameter classes were collected. The diameter classes of interest were: 1.27, <2.54, <5.08, and <7.62 centimeters (<½", <1", <2", and <3"). All specimens tested were collected during the dormant season. This was a deliberate choice in the experimental design, as it allowed for ease of collecting, shipping, and preserving the fresh branch specimens from the time of collection in the field, to the time of testing in the laboratory. The samples were shipped to the high voltage testing laboratory in Redmond, Washington. Upon receipt, they were stored in a cool, moist environment until use. No sample was more than one week old when tested.

The diameter of each specimen was recorded. A small portion of each specimen was cut off and weighed. This small sample was then dried in a lab kiln at between 101 and 105 degrees Celsius (214 and 221 degrees Fahrenheit) until a constant weight was reached. Each dried portion was then re-weighed to determine the internal moisture content of each specimen being tested.

The project involved two related but different experimental efforts. Both protocols involved subjecting branch specimens to pre-established fixed high voltage stress gradients, typical of those found on energized overhead distribution circuits in the field.

Voltage gradients found on the overhead distribution systems of the utilities participating in this project were determined by reviewing overhead line construction standards. This review provided phase-phase and phase-neutral spacing (d), and nominal operating voltage (v) information for each line type. Because conductor tension and sag can vary, the distance measurement was taken at the structure between insulators. The voltage gradient for each line type was determined by the following calculation:

Voltage Gradient = v/d

Two factors create higher gradients on multi-phase lines than on single-phase lines. First, the voltage differential between two energized phases is higher than the corresponding phase to neutral voltage. Second, phase-to-phase spacing is usually less than the distance between phase and neutral. The result is that much higher voltage gradients are found on multi-phase (phase-to-phase) lines than those typically seen on single-phase (phase-to-neutral) lines. Voltage gradients present on the cooperating utility's distribution systems were found to vary by an order of magnitude, ranging from <1kV/ft to >10kV/ft.

Both experimental procedures were conducted in a controlled high voltage laboratory setting. Individual test specimens were placed between two conductor segments positioned a fixed distance apart. This configuration permitted the branch specimens to be consistently positioned for each testing sequence. This design allowed a predetermined test voltage level to be impressed uniformly across a fixed distance, achieving the desired voltage stress gradient.

Figure 1. Specimen under high voltage testing.

The voltage gradient impressed on each specimen was controlled and varied for different sample lots by varying the voltage input. A variable output AC high potential test transformer provided a means of voltage control. A 60:1 power transformer with a maximum rated output of 15 kilovolts was used as a high voltage source. An instantaneous current-sensing trip coil of a protective relay protected the test circuit. The relay was set to interrupt at fault current level of 275 mA. Test set instrumentation provided for a continuous record of time and current, as well as real-time observations of current, time and voltage. When the voltage stress gradient was applied to each test specimen, a timer was automatically actuated. Each test was concluded when the current level flowing through the test specimen exceeded the test set output, tripping the protective circuit breaker. In each case, the time to fault (defined as current flow sufficient to cause the instantaneous current sensing trip coil of a protective relay to operate) was recorded. Tests were also declared complete for those specimens that failed to flash over when the fault current levels being measured dropped to a steady level well below that observed on initial energization. A third variant occurred when the specimen failed by either burning through or falling clear.

FINDINGS

- Electrical conductivity Varies by Species. Figure 2 summarizes the variability in measured conductivity observed in 18 of the species tested. Rho is a standard measure of the resistivity of a material.

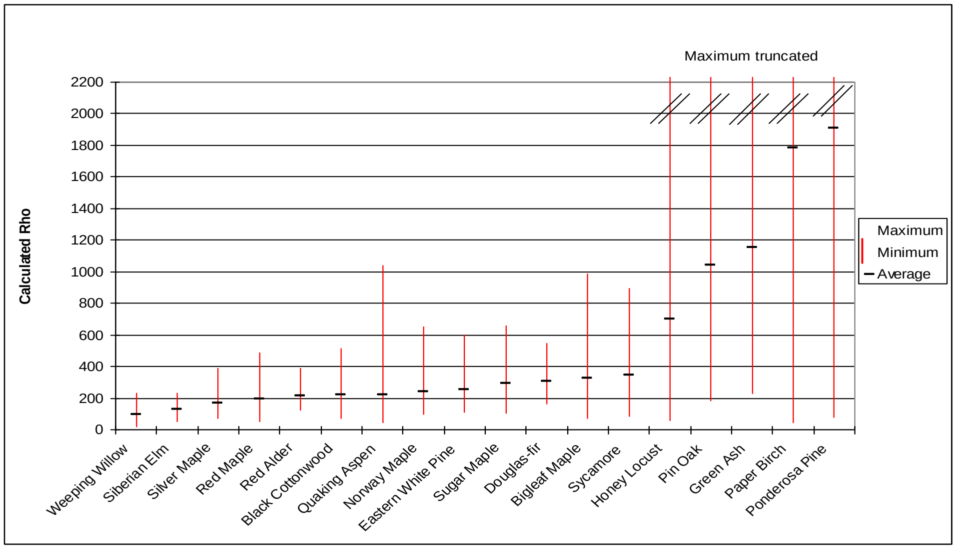

Figure 2. Chart of calculated Rho by species tested.

- Electrical Conductivity Varies by Branch Diameter. Time-to-fault decreases as diameter increases at a given voltage stress gradient as illustrated in Figure 3.

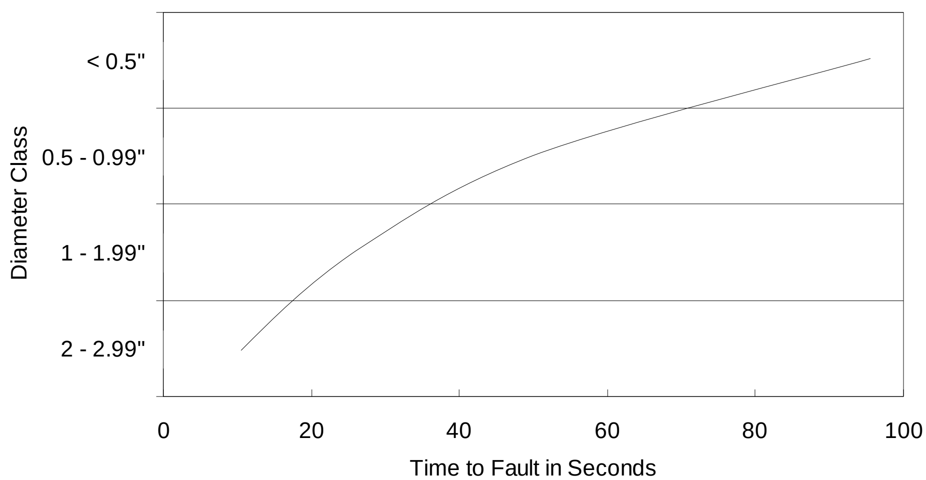

Figure 3. An example of mean variability in measured conductivity observed over the range of diameter classes for a single species (red alder) at 3kV per foot voltage stress gradient.

- Voltage gradient is the most important factor in determining the risk of tree-initiated, low impedance, high current faults. Figure 4 clearly demonstrates the importance of voltage gradient as a factor in determining the risk of a tree contact providing a low impedance pathway and resultant high current fault.

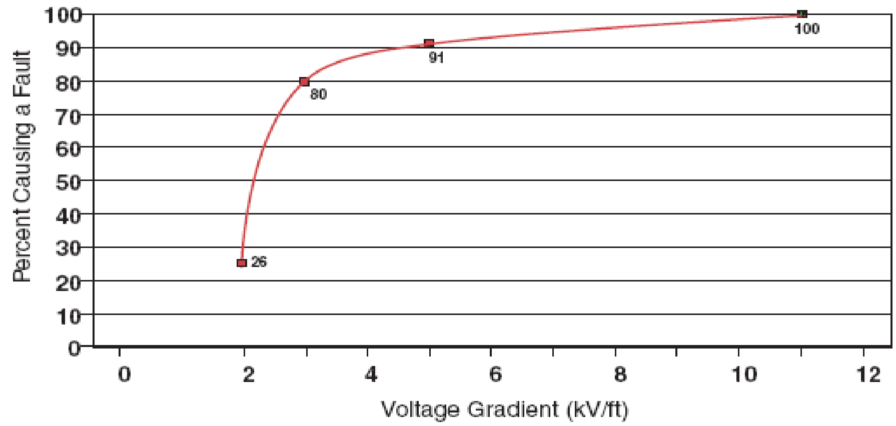

Figure 4. The percent of samples that resulted in a fault increased with voltage gradient

- There appears to be a voltage gradient threshold below which a tree branch will not provide a low impedance fault pathway. Figure 5 suggests that tree initiated fault pathways subject to voltage gradients less than 2kV/ft are much less likely to result in high current faults.

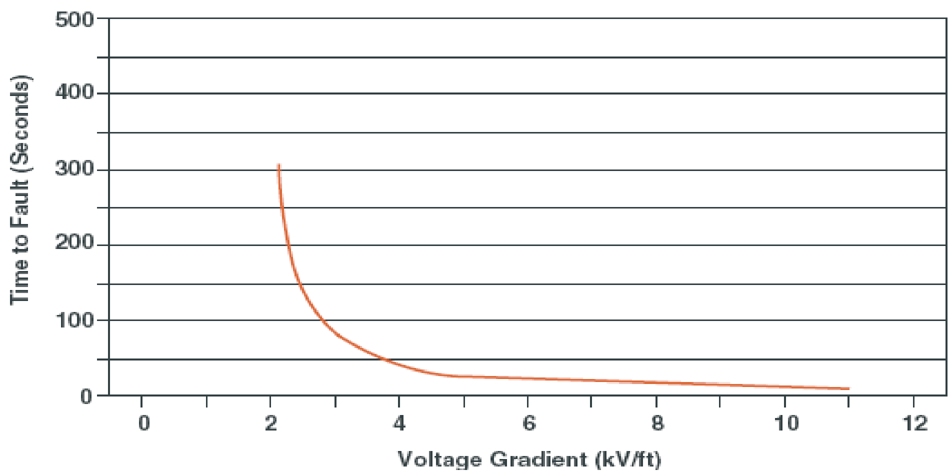

Figure 5. Time-to-fault decreases as voltage stress gradient increases.

CONCLUSIONS AND RECOMMENDATIONS

Species Considerations

This project clearly establishes that electrical impedance varies by species. The variability between species appears great enough to warrant consideration in evaluating risk to reliability posed by trees on overhead electric distribution circuits.

Overhead Circuit Considerations

This study emphasizes the point that multi-phase lines, which typically have substantially higher voltage gradients than do single phase lines, have greater risk exposure to tree-related interruptions than do single phase lateral taps. This increased risk is due to the higher voltage gradients created by the close proximity of areas of unequal electrical potential. These elevated voltage stress gradients are impressed across a branch when it provides a phase-to-phase fault pathway. Voltage gradients may vary by nearly an order of magnitude on an overhead distribution circuit, and should be considered in developing vegetation maintenance prescriptions.

Construction Framing Considerations

The findings of this study demonstrate that the relative risk of tree-related interruptions varies by construction framing standards. Changes may be possible in standard structure design which could reduce the voltage gradient, or change the orientation of energized equipment to reduce or eliminate the likelihood that a broken or deflected branch would make contact with two or more areas of unequal electrical potential.

Diameter Considerations

Branch diameter was shown to play a major role in conductivity, with the largest branches being much more conductive than small shoots. This factor should be considered in developing risk assessment criteria. In terms of tree morphology, larger branch diameters occur closer to the main stem. By definition then, conductor contact with larger diameter branches will more often occur with trees in very close proximity to overhead lines. These high-risk contacts will also develop over a long period of time. Branches of only a few growing seasons in age represent relatively lower risk. The implication is that periodic assessment should allow identification of higher risk tree-conductor contacts before they are manifest as an interruption.

Growth Considerations

This project adds to an understanding of the high impedance pathway provided by small diameter new growth, and provides an important piece of information useful in scheduling periodic preventive maintenance. Basically, the incidental branch-conductor contacts that develop as a circuit "ages" and trees grow back into the cleared area is of low risk to reliability. Simply stated, it is unlikely that trees cause interruptions on 15kV class distribution lines merely by growing into contact with a conductor. The brown foliage that has traditionally been described as "burning" is more probably leaf wilt. This is due to the effect of resistance heating, desiccation and subsequent death of the living tissues of new shoots and leaves. Wilted foliage is a poor indicator of a tree's threat to reliability. Since these new contacts do not appreciable affect the risk of an interruption, some level of contact can be tolerated. The preventive maintenance cycle period can be based on an economically optimal period, rather than strictly on the basis of maintaining line clearance.

Overcurrent Protection Considerations

The project also confirmed that once formed, the low impedance/high-current fault pathway provided by a tree branch is persistent. This confirmation presents a potential opportunity in re-thinking tree caused faults in the context of system overcurrent protection. If the fault pathway provided by a branch remains, subsequent faults will occur when the circuit is reenergized. The decision to make application of "fuse sacrifice" or "feeder selective relaying" overcurrent protection coordination philosophies on distribution circuits with elevated risk exposure to tree-caused interruptions needs to be made with this in mind. Furthermore, the overcurrent protection scheme in place at many utilities today is designed to protect against faults that occur within a cycle or cycles (60 Hz). This study suggests that tree-related faults often develop over extended periods. This reality may require changes in the design of system protection schemes.

APPLYING THE RESULTS

Based on the enhanced understandings of how trees cause interruptions and documented differences in impedance between tree species, there are considerable situational differences in risk of interruption due to tree contact with energized conductors. Factors such as species, diameter, and voltage gradient discussed in this paper are readily observable in the field. Consequently, this information can be incorporated into risk assessment criteria, maintenance specifications, maintenance planning and scheduling strategies, and site-specific vegetation maintenance prescriptions.

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