How Trees Cause Outages

Understanding Tree Caused Outages: The Research

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Abstract. Trees continue to be a leading cause of service interruption for most electric distribution utilities. Until recently, the "best practice" programs focused on establishing sound, cycle-based pruning schedules, while under funded programs sought to improve reliability performance through hot-spot pruning. In the early 1990's a series of field studies challenged conventional utility vegetation management wisdom. Additional research followed and new reliability centered strategies began to emerge. This paper is the first in a series of papers intended to review the research, relate the findings to reliability performance on the electric distributions system, and discuss how the conclusions affect distribution line clearance specifications. We will then explore how tree-caused interruption data can be used to better understand system performance, identify chronic poor performing circuits, and develop prescriptive vegetation management strategies that make lasting reliability improvements.

Key Words: Electric distribution system, tree-caused interruptions, electric mode, carbon path, outage risk.

Background

Trees cause interruption of the electric system in one of two ways, an electric short circuit (electric mode) or through physical damage to the system (mechanical mode).

Prior to the early 1990's, "conventional line clearance wisdom" held that trees growing into overhead distribution lines were a significant outage risk (electric mode) that provided a fault pathway to ground. Considerable line clearance dollars have been spent over the years to complete hot spot pruning of distribution lines, especially following the unexplained operation of substation breakers, or line reclosures affecting critical customers or large numbers of customers.

In 1994, arborists for Baltimore Gas & Electric challenged these perceptions by presenting the results of five years of field research[i]. Their work developed and presented several theories, including:

- Incidental tree contact does not pose a significant outage risk.
- An electric fault did not occur until a carbon path was formed between conductors (phase-to-phase or phase-to-neutral).
- A fault does not occur instantaneously when two conductors are bridged. Time seems to be necessary, and water and steam are expelled from the branch during the carbonization process.
- The impedance (resistance) of the tree must

Figure 1. Photo compliments of Chad Devine,BG&E

change before it will conduct enough current to fault.
- The distance between conductors seems to affect the time required to create the carbon path.

If correct, critical hot spot and cyclical pruning resources could be redirected to essential reliability improvement initiatives.

Objective

In this paper the author will summarize the research conducted by ECI to assist the reader in understanding and applying the results to field practice.

Testing the Concept

In 1996 Environmental Consultants, Incorporated, together with John Goodfellow, began to refine a conceptual model and develop the experimental protocols required to test the BG&E theories, and conduct preliminary high voltage experiments. They insisted that proof required rigid experimental design and structured analytical procedures. They envisioned testing large numbers of specimens in a controlled laboratory environment, with multiple replications and recorded time and current measurements.

The initial testing was made possible by funding from Allegheny Power Systems. The report presented in 1998 was entitled "Understanding the Way Trees Cause Power Outages."

A high voltage test bench was assembled, with insulators positioned a fixed distance apart. Specimens were placed within saddles formed of aluminum wire, allowing consistent positioning for each test sequence. A variable output AC high potential transformer allowed for uniform testing at predetermined voltage levels.[ii]

Figure 2. Laboratory test setup

Two hundred fifty six (256) living samples (4 species x 4 diameter classes x 2 origin conditions x 2 surface conditions x 4 voltage classes) and sixty four (64) dead branch samples (4 species x 2 diameter classes x 2 surface conditions x 4 voltage gradients) were tested.[2]

Protocols were further refined, and in 1999 a second report entitled "Understanding The Way Trees Cause Power Interruptions" was produced for Allegheny Power System, Niagara Mohawk Power Corp, and Portland General Electric. This round of testing examined eight species (seven additional species), studying up to eight different branch diameters and ten voltage gradients.

Combined, the two studies examined eleven species, testing more than eleven hundred specimens. The results of the studies are summarized below.

The Electric Mode of Failure

The ECI studies confirmed that *"the impedance (resistance) must change before it (the branch) will conduct enough current to fault,"* as suggested by BG&E.

Figure 3. Formation of the carbon pathway prior to flash over

When we take a moment to examine this, intuitively it makes sense. Wood has some higher level of resistance that must be overcome for a short circuit to occur. Most utility arborists have seen energized primaries on wooden cross arms and for years insulated line clearance tools were made of wood. The question was when do they become conductive? Quite simply the carbon path becomes the more conductive route for electricity across the wood.

In their discussion of the "Conceptual Model of the Electrical Mode of Failure" in the 1998 report ECI states; "The electrical stress at the point(s) of contact are due to unequal potential across the conductor surface, branch surface (outer bark), inner bark (cambium), and xylem (wood). The electrical stress causes arcing; a high energy point discharge. Heat energy generated from the arc is sufficient to cause breakdown of organic compounds (cellulose and lignin) into elemental carbon and charcoal. The carbon generated is relatively conductive as compared to branch tissue." [iii]

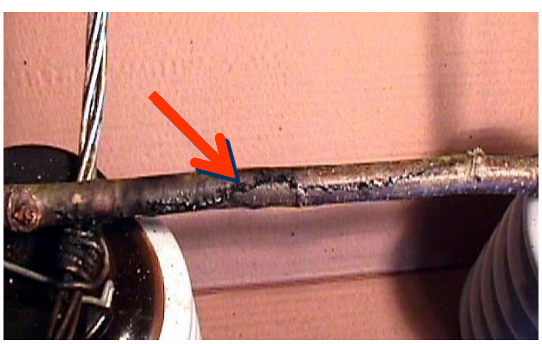

Figure 4. A completed carbon path, fault occurred

The pathway is largely evident as a "blackened area of charcoal" across the branch surface, between the two points of contact. When the pathway was not evident on the surface, branch dissection often revealed internal tracking. Once the pathway was complete, a fault was instantaneous each time the branch was re-energized.[iv]

Role of Voltage Gradient

The studies also confirmed that voltage gradient is the variable with the greatest effect on outage risk. Figure 5 shows the time in seconds for a carbon path to form and the fault to develop, decreases rapidly as voltage gradient increases. While BG&E suggested the fault is not instantaneous when two conductors are bridged, the time and current measurements showed it can be nearly instantaneous at higher gradients. At the same time, the steepness of the curve at lower voltage gradients clearly suggests a threshold exists below which a carbon path will not form.[v]

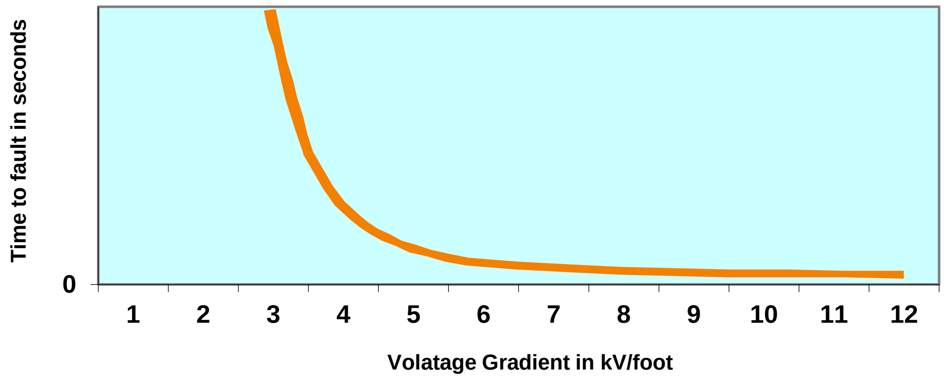

Figure 5. Influence of Voltage Gradient on Time to Fault

Figure 6 confirms the threshold theory. It examines the results from the first (1998) study, in which more than 300 specimens were tested at four pre-determined voltage gradients. There were no outages at the 1.2 kV/foot gradient, and 100 percent failure at 11.5 kV/foot. Variability in outage risk exists at the 3.32 and 5.16 kV/foot gradients, indicating there may be differences among species and related to other wood characteristics.[vi]

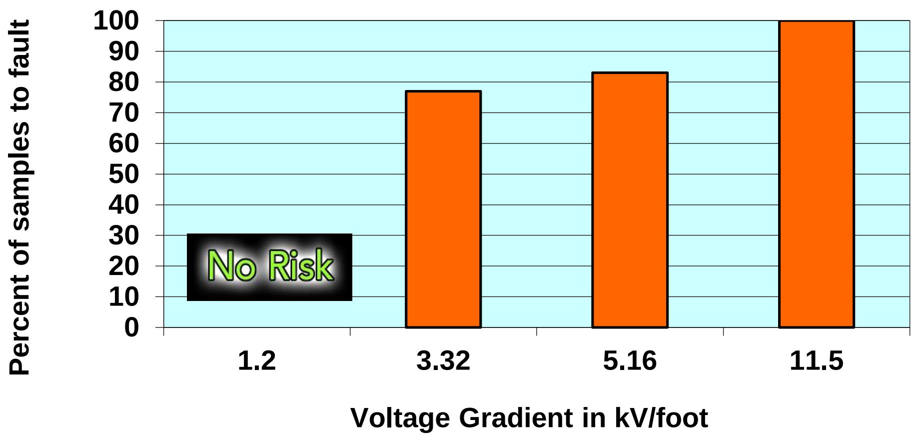

Figure 6. Influence of Voltage Gradient on Likelihood to Fault

While the 1998 study tested the samples at specific voltages and no outages occurred below 1.2 kV/ft., the 1999 study tested specimens at gradually declining voltage gradients until a no fault threshold was determined for each species. Significant variability was found between species.[vii] The studies also looked beyond voltage gradient to determine if differences existed between species, as well as several physiological factors such as branch diameter, branch origin, dead wood vs. live wood, and internal and surface moisture condition.

The studies were followed by two additional studies. In 2001 ECI completed "Assessing the Seasonal Variation in the Electrical Characteristics of Trees" for Allegheny Power. This was followed by "Species Specific Variation in Impedance as Related to Electrical Fault Potential" in 2004. The results of these studies are summarized as follows.

Species Variation

In the 2004 study, ten new species were investigated, and the results combined with the findings from previous work to bring the total number of species tested to twenty-one. Testing protocols were further refined to explore questions posed in the earlier testing. The combined results expanded our knowledge and identified key risk factors.

Voltage gradient remains the most significant risk factor. Voltage gradients above 5.5 kV/ft. are a high risk for fault, while gradients below 1.3 kV/ft. are low risk to no risk. Voltages gradients from 1.4 kV/ft. to 5.2 kV/ft. exhibited a moderate failure risk, with significant variability based on species and branch diameter. [viii]

Variation in species resistively, as measured by the average "Rho" for all specimens within a species, ranged from a low of 89 for weeping willow (most conductive), to a highs of 1,782 for paper birch and 1,903 for Ponderosa Pine (least conductive). The average "Rho" for all species was 614.[ix]

All three studies (1998, 1999 and 2004) found that large diameter branches are usually more conductive (higher risk) than small branches, and the carbon path developed more rapidly. Their findings are consistent with previous research which believes branch conductivity is related to cross sectional area. They also reported branches less than 0.5 inches in diameter were significantly lower risk than those in the 0.5 – 1 inch, 1 – 2 inch, or the 2 to 3 inch classes. [x]

Seasonal Variation

Seasonal variations in conductivity were examined in 2001. Red maple samples were tested during seven dormancy stages. The results were consistent with earlier research into seasonal changes in electrical resistance, finding that the samples taken during the active growing season (June, July) were significantly more conductive than samples taken during the dormant season (March, October). [xi]

Other Physiological Differences

The original studies found no significant difference in carbon path formation based on branch origin, e.g. from either normal growth or sprout growth. [xii]

They also found wetting the branch surface caused a "slight and non-significant difference in time to fault between wet and dry samples." It speculated that wetting may initially reduce resistance at the two points of contact. However, after overcoming the contact resistance the current must then overcome the resistance of the limb itself. As a result, the average time to fault for branches that were either surface wet or dry, were so similar that their failure curves overlay each other when plotted.[xiii]

Internal stem moisture content was not a significant variable between live branches, but it does play a role in fault development. In the 2004 report, ECI explains that most water within the plant is stored in the sapwood (xylem), and that the internal moisture levels of these tissues are consistently above fiber saturation. "Fully moistened fibers are at their most conductive" levels. Since all living tissue is well past fiber saturation, there is little variability between species. However, they suggest a strong indication that the xylem is a significant conductive pathway, since most moisture in the tree is stored in the sapwood. This would help explain the presence of steam and water coming from the samples when an electrical stress is applied. Below fiber saturation conductivity in the branch is limited by moisture. [xiv] The theory remains consistent with the "branch surface phenomenon" discussed earlier in this paper regarding carbon path formation. While the sapwood tissue just beneath the cambium may be the most conductive, the heat energy created by the electricity readily burns through the cambium and bark tissues, becoming evident on the surface.

Live limbs were found to be significantly *higher risk* of failure than dead limbs. This is believed to be related to the lack of internal moisture within the dead limb tissue. Small dead limbs (1-2 inch) were a much lower risk than larger limbs (3-4 inch), but even larger dead limbs were significantly lower risk than living limbs of the same size. [xv]

Bark texture, tissue morphology and biochemical composition of the branch tissues and the sap may also be conductivity and outage risk factors. For example, smooth bark appears to be more conductive than cork like, plated or rough bark, and differences in vascular tissues between coniferous and deciduous species may affect conductivity. [xvi]

Conclusions

This research is providing utilities with a better understanding of the electrical failure mode of failure, as well as the risk of outage when trees grow into energized overhead lines or fall onto them from above or beside the lines. The relationship between electric distribution systems and the natural environment surrounding them are far more complex than accepted ten years ago.

The design, construction and operation of the distribution system are a critical factor in tree outage performance and overall system reliability that is often overlooked. At the same time, effective vegetation management strategies are being re-written into dynamic, prescriptive applications that make long-term reliability improvements. Successful strategies go beyond a one size fits all model, requiring support from arborists, engineers, field operations personnel, reliability personnel, senior management, regulators, the public, etc. Opportunities exist for utilities to apply this knowledge on their systems, to refine historic vegetation management practices, identify areas of cost savings and those needing additional funding, and effectively focus their expenditures on cost effective system improvements.

About the Author: Mr. Kenneth Finch has over 40 years of vegetation management experience, including 28 years' experience managing vegetation management operations for a large New York utility. Mr. Finch has actively managed ECI Total Management Services operations at several electric cooperatives in the southern U.S. He has also developed management plans for various large and small utilities. Mr. Finch has been involved in various research projects related to how trees cause outages and managed a highly successful program to improve reliability through intensive risk tree identification and mitigation. Mr. Finch has a BS degree in Forestry and has served on boards and committees of professional associations.

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[i] W. R. Rees, T.C Birx, et al, Baltimore Gas & Electric, "Controlled Phase to Phase Tree Fault Test", Dec 3, 1992, and Exhibit F, "Commentary for Tree Fault Test Tape."

[ii] Environmental Consultants, Inc. for Allegheny Power Systems, 1998, "Understanding the Way Trees Cause Power Outages", pgs 3, 5.

[iii] Environmental Consultants, Inc. for Allegheny Power Systems, 1998, "Understanding the Way Trees Cause Power Outages", pg 10.

[iv] Environmental Consultants, Inc. for Allegheny Power Systems, Niagara Mohawk Power Corp, Portland General Electric, 1999, "Understanding the Way Trees Cause Power Interruptions," pg 12

[v] Environmental Consultants, Inc. for Allegheny Power Systems, 1998, "Understanding the Way Trees Cause Power Outages," pg 7.

[vi] Environmental Consultants, Inc. for Allegheny Power Systems, 1998, "Understanding the Way Trees Cause Power Outages," pg 6.

[vii] Environmental Consultants, Inc. for Allegheny Power Systems, Niagara Mohawk Power Corp, Portland General Electric, 1999, "Understanding the Way Trees Cause Power Interruptions," pg 12, 13.

[viii] Environmental Consultants, Inc., "Species-Specific Variation in Impedance as Related to Electrical Fault Potential", 2004, pg 6.

[ix] Environmental Consultants, Inc., "Species-Specific Variation in Impedance as Related to Electrical Fault Potential", 2004, pg 12, 67, 77, 111.

[x] Environmental Consultants, Inc., "Species-Specific Variation in Impedance as Related to Electrical Fault Potential", 2004, pg 12, 15.

[xi] Environmental Consultants, Inc. for Allegheny Power Systems, "Assessing the Seasonal Variation in Electrical Characteristics of Trees", Executive Summary, pg 1, 11.

[xii] Environmental Consultants, Inc. for Allegheny Power Systems, Niagara Mohawk Power Corp, Portland General Electric, 1999, "Understanding the Way Trees Cause Power Interruptions," pg 8.

[xiii] Environmental Consultants, Inc. for Allegheny Power Systems, Niagara Mohawk Power Corp, Portland General Electric, 1999, "Understanding the Way Trees Cause Power Interruptions," pg 10.

[xiv] Environmental Consultants, Inc., "Species-Specific Variation in Impedance as Related to Electrical Fault Potential", 2004, pg 18.

[xv] Environmental Consultants, Inc. for Allegheny Power Systems, Niagara Mohawk Power Corp, Portland General Electric, 1999, "Understanding the Way Trees Cause Power Interruptions," pg 9.

[xvi] Environmental Consultants, Inc., "Species-Specific Variation in Impedance as Related to Electrical Fault Potential", 2004, pg 19.