Electrical Characterization of Vegetation Faults on Distribution Feeders

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***Abstract*-- Vegetation management is the single largest maintenance expense on distribution feeders. Vegetation intrusion causes a loss of reliability, reduction in power quality and safety issues. This paper describes the nature of vegetation-induced faults, including low-current events that do not trip protection devices and recurring high-current events that cause interruptions and outages. Actual field data and fault waveforms are included from staged vegetation faults at the Downed Conductor Test Facility at Texas A&M University.**

***Index Terms*-- Power system faults, Power system maintenance, Power system reliability, Vegetation intrusion**

I. Introduction

VEGETATION intrusion causes faults, outages, interruptions and other power quality problems on electric distribution feeders. These problems occur via a variety of mechanisms. Vegetation can cause direct or indirect short circuits between conductors, or it can mechanically tear down line sections. Tree limbs "can fall over onto conductors, can drop branches onto conductors, can push conductors together, and can serve as [a] gateway for animals" [1].

Broken or wind-blown limbs and other vegetation can cause sudden contacts. Continuous growth causes gradual encroachment. There is little documentation or understanding about how vegetation grows into conductors and causes faults. Literature postulates on the process as follows: "When a tree branch bridges two conductors, a fault does not occur immediately. This is because a moist tree branch has a substantial resistance. A small current begins to flow and starts to dry out the wood fibers. After several minutes, the cellulose will carbonize, resistance will be greatly reduced, and a short circuit will occur" [1]. A recloser may operate to clear the immediate short circuit from a vegetation contact, but the offending vegetation can remain in contact with or in close proximity to energized conductors and result in additional interruptions, outages, and other future problems.

Vegetation-induced faults, momentary interruptions and sustained outages contribute significantly to calculated reliability indices, such as SAIDI, SAIFI, and the like [2]. Many utilities are required to report these reliability indices to regulatory agencies, which use this information to assess the utility's performance [3]. In a published survey, one utility reported that tree contacts accounted for 10% of its outages [4]. Some regulatory agencies now require utilities to break down reliability indices by cause, including events caused by vegetation.

To prevent vegetation-related problems, utilities invest significant resources in vegetation management programs. One trade publication notes that vegetation management frequently is "the largest single cost element in an electric utility's operating budget," with tree trimming alone representing a US$7-$10 billion industry [5]. Many utilities employ fixed time-based cycles when scheduling tree trimming. Cycles generally are designed to eliminate tree contact for a certain number of years. However it is not generally considered possible to tailor management programs on a feeder-by-feeder basis. Applying a uniform trim interval to large groups of feeders results in some feeders being trimmed more frequently than necessary, wasting resources, while others are not trimmed often enough and suffer from degraded reliability.

The obvious reliability impact and extreme expense of vegetation management programs are causing utilities to explore ways to better optimize these programs. The goal is to achieve a desired level of reliability with minimum cost. Knowing when vegetation contacts occur, even if they are not yet causing outages, damage, or other detrimental effects to the system or to customers, would provide the basis for adjusting vegetation-management activities based on the real, quantified needs of each feeder.

II. Prior Work

Despite the need for better understanding and quantification of the problem, the literature describes very little fundamental work in the characterization of electrical behavior resulting from vegetation contacting energized conductors. Previous research efforts typically have been limited in scope and nature. One study developed a computer-based model of a tree contacting a medium-voltage conductor to determine the safety hazard of touch potentials developed on the surface of the tree [6]. An electrical model was proposed but not verified for accuracy, and no empirical data was presented. Furthermore, many simplifying assumptions were necessary because of the lack of fundamental research documenting actual measured effects.

Previous experimental work analyzed voltage gradients and currents produced when a single energized conductor contacted a tree [7]. For these experiments an energized phase conductor was brought into solid physical contact with a large

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limb in the main body of the tree. The feeder used for the experiments was of conventional construction and its neutral was solidly grounded at numerous points along its length. The return path for the fault current was through the tree's root system and the earth. The nearest pole grounds were approximately 50 feet from the tree. Local current measurements indicated that the current was limited to a few amperes by the resistance of the tree limb and trunk. Several of the experiments placed an energized conductor in solid contact with a branch for up to tens of minutes, but the resulting fault current never exceeded a few amperes. The experiments were limited to placing a single energized conductor in contact with vegetation and did not address vegetation spanning two phase conductors or a phase conductor and a neutral conductor. Researchers concluded that branches in contact with a single conductor are not likely to high-current events, unless of course they cause sufficient mechanical damage to weaken and break the conductor.

III. Vegetation-Related Faults

Vegetation related faults can be grouped into multiple generalized categories:

- Faults from "hazard trees" outside the utility's right-of-way
- Faults from trees contacting a single primary conductor
- Faults from trees pushing multiple primary conductors together
- Faults from trees spanning multiple primary conductors
- Secondary faults, including those in which a tree contacts a single bare secondary conductor and those in which a tree pushes multiple bare secondary conductors together

"Hazard tree" is a term used to describe a tree outside the utility's right-of-way but large enough to contact a line if it falls. Limbs and whole trees fall for a variety of reasons, including storms, car accidents, and improper actions by tree trimmers. These events cause sudden contacts and perhaps tear-downs, not gradual encroachment. Informal discussions with utilities suggest that hazard trees may cause a significant portion of vegetation-related outages, but because they are outside the right-of-way, the utility often can do little about them.

Trees contacting a single primary conductor can result from slow grow-in or from sudden contact, such as the breakage of a limb. If a single-conductor contact does not immediately break a conductor, the amount of ground-fault current drawn through the tree can be quite limited, as discussed in the previous section. It would be advantageous to detect the prolonged fault current produced by this situation, but the low level makes such detection challenging. The difficulty is compounded because measurement points generally will be at some remote point upstream, likely the substation, where load and fault currents are mixed. The few amperes of fault current must be discriminated from tens or hundreds of amperes of load current, a challenging task.

Vegetation contacts that cause direct physical contact between two or more primary conductors can reasonably be expected to cause sudden initiation of high-level fault current. This generally will cause operation of conventional protective devices. The fault will result in a permanent outage unless a reclosing device is involved and the conductors are able to mechanically separate before the circuit locks out. It seems reasonable to assume that there will be little difference in electrical behavior between this vegetation-induced fault and any other cause of the conductors coming into physical contact with each other.

Vegetation contacts also can affect secondary service conductors. A common fault scenario involves networked overhead secondary conductors being pushed together by a tree. If the conductors are not insulated or if the insulation is in poor condition, this causes a high-current secondary short circuit. The voltage involved is quite low (e.g., 120/240 volts), making it quite difficult to sustain a fault current if the conductors do not remain in intimate physical contact. Because trees generally cause more casual contact, these faults often clear themselves and do not cause an outage. Other work by the authors has documented numerous occurrences of this phenomenon. Some eventually lead to outages after multiple contact episodes occur, but these outages usually affect a fairly small number of customers.

The remaining category (fourth in the previous list) involves faults from trees spanning multiple primary conductors, without pushing them into direct contact with each other. Previous experiments showed that a branch contacting a single energized primary conductor causes available line voltage to be distributed over a relatively long distance between the contact point and the earth, which results in a relatively low voltage gradient [7],[8]. The significant path length between the contact with the phase conductor and the earth also results in relatively high fault-path resistance, so relatively little current flows.

By contrast, when a branch spans either two phase conductors or a phase conductor and the neutral conductor, the available voltage is distributed over a much shorter physical distance, resulting in increased voltage gradient. The hypothesis behind the experiments described herein is that this configuration is much more likely to cause a high-current fault, even though the branch initially might be a high-resistance path.

Field experiments were designed to gain a better understanding of this scenario. Researchers observed, recorded, and analyzed electrical activity during these experiments. They documented both the electrical behavior and the physical process and effects. Electrical measurements were made at the feeder substation, which serves significant load in addition to serving the site at which the experiments were conducted.

IV. Experimental Methodology

All experiments were performed at the Downed Conductor Test Facility at Texas A&M University. The facility is located approximately 3.2 electrical kilometers from the substation on a 12.47/7.2kV, multi-grounded-wye, overhead primary feeder that serves approximately two megawatts of residential, light commercial, and oil-field load. Available bolted single-phase fault current at the facility is approximately 2 200 amperes.

A. Experimental Setup

Researchers designed experiments to simulate vegetation spanning two conductors. They recorded high-resolution current waveforms at the serving substation for an extended duration of time (e.g., tens of minutes at a time). The goal was to record the evolution of electrical activity for subsequent analysis.

Researchers selected branches of varying diameters and lengths from local vegetation, consisting primarily of hackberry, chinaberry, and crape myrtle trees. These branches were then placed across the conductors to simulate prolonged contact with trees.

Researchers mounted two pin-type insulators in a sawhorse, one at each end. Using conventional ties, they attached a section of 2/0 ACSR conductor to the insulators, parallel to the top of the sawhorse. They then attached one end of the conductor to a longer section of conductor brought down from one of the overhead primary phase conductors. They used a similar arrangement to separately attach a second conductor to insulators on another sawhorse. The second conductor was connected to a section of conductor solidly tied to the system neutral through the ground conductor on a proximate pole. The connection to the neutral was made through a 500-ohm resistor. As long as fault current is in the range of an ampere or so, the effect of this resistance should be minimal, but the fault current was limited to 14.4 amperes in case a bolted fault occurred. The primary conductor was fused with a 2A, type T fuse to protect the 500-ohm resistor in case of a bolted fault.

Researchers placed the two sawhorses approximately 1.3m (4ft) apart, a typical separation distance for overhead distribution. For each experiment, a selected branch was placed spanning the phase and neutral conductors, but without any firm attachment. A lineman then energized the phase conductor to begin the experiment. Researchers documented the progression of each experiment with video and still photographs.

Electrical measurements were recorded at the substation. Measurements were acquired on a laptop-based National Instruments data acquisition system sampling at 15 360 Hz, or 256 points per cycle.

RMS current measurements were available at the test site, from a clamp-on ammeter placed on the primary phase conductor before it was energized. This measurement did not include any load current and it provided researchers with a general sense of the level of fault current.

The experiments were performed at the end of April 2006.

B. Procedure

Researchers performed numerous experiments. Two examples are documented here and illustrate the primary observations made during the larger set of experiments. The experiments are labeled Experiment 1 and Experiment 3 because these were their original designations during testing.

1) Experiment 1: The branch used for Experiment 1 was from a crape myrtle tree. It was approximately 2cm (0.75in) in diameter at its thickest point and 1.25cm (0.5in) at the smaller contact point. Crape myrtle has hard wood and thin bark.

2) Experiment 3: Experiment 3 used a branch from a hackberry tree. It was approximately 2.5cm (1in) at its thickest point. The smaller end of the branch contacted the conductor in two points. One contact point was approximately 1.25cm (0.5in) in diameter and the other was approximately 1cm (0.375”) in diameter.

V. Results

A. Experiment 1

When the conductor was energized, visible scintillation immediately began to occur at both contact points and carbonization, or charring, began to form on the exterior of the branch. Over time a carbonized path began to grow from each contact point, generally in the direction of the other contact point. There was audible sizzling. Smoke and steam emanated from points along the branch, generally following the carbonized path. Arcing and burning were clearly visible along this path as well. Smoke and burning appeared along the exterior from both ends of the branch as well. Researchers observed the path lengthen more quickly along the end of the branch with the smaller diameter. This observation was confirmed in subsequent experiments. Local current readings from the clamp-on ammeter showed that the current generally remained around one ampere during the early portion of this and all other experiments.

The branch continued to carbonize and burn in a high-resistance state for four minutes, 38 seconds as the two carbonized paths continued to grow toward each other. When the two paths met near the middle of the span, there was an abrupt transition into a low-resistance state. Current immediately increased to near its maximum available level of 14.4 amperes. A continuous power arc formed between the now-continuous carbonized path between the two contact points.

As soon as the power arc formed, it began to rise away from the branch in a well-known Jacob's Ladder effect. As the arc rose, its erratic path elongated and finally extinguished. Another arc then soon formed along the carbonized surface of the branch and the process repeated. A series of violent power arcs lasted approximately 27 seconds and eventually blew the 2T fuse. During this time, an arc formed and extinguished nineteen times, with the final burst lasting approximately 172 cycles (2.86 seconds).

Fig. 1 shows one of the power arcs from Experiment 1 in progress. The arc had just formed and was still quite close to the branch. Hot arc plasma rose by convection and caused the arc to rise away from the branch. Arcs typically lengthened substantially before extinguishing. Researchers visually estimated the length of many of the elongated arc paths to be two to three meters (six to nine feet) in a generally semicircular shape terminating at the contact points between the branch and the conductors. Most of the arcs persisted for approximately fifteen cycles, but the final burst was significantly longer. Researchers believe this burst was of extended length primarily due to a large gust of coincident wind. Rapid dispersion of the plasma prevented longer arcs from forming, resulting in more continuous arcing closer to the surface of the limb. This extended burst caused the fuse to operate, de-energizing the conductor.

Fig. 1. Arcing crape myrtle

Researchers then replaced the fuse and re-energized the conductor without disturbing the branch. This resulted in the immediate recreation of the arc, which, due to another gust of wind, continued for approximately five seconds until the fuse again operated and de-energized the conductor. The fuse was replaced one additional time and re-energized, resulting in a sustained four-second arc burst which operated the fuse for a third time.

Researchers posited that because of the physical resilience of the crape myrtle, a hardwood tree, the branch seemed likely to remain in contact with the conductors for an indefinite amount of time until the branch was removed or burned itself in half. Additionally, each time the conductor was re-energized, the presence of the carbonized path allowed the fault to immediately draw its maximum fault current.

While the branches in these experiments maintained sustained contact with the conductors, it is hypothesized that long-term intermittent contact between branches and conductors could lead to similar formations of carbonized paths over an extended period of time, which would allow subsequent contacts to proceed to an immediate bolted fault state.

Following the experiment, researchers inspected the conductors and the branch for physical damage. Not surprisingly, the branch suffered significant physical damage. Fig. 2 shows a picture of the branch contact point with the phase conductor. As can be seen in the photograph, there was significant damage to the conductor as well as the heavy damage to the branch. While it is likely that a small tree branch will fail sooner than the conductor, the high-current arcs clearly damaged the conductors, potentially impacting their mechanical integrity.

Fig. 2. Damage to branch and phase conductor after Experiment 1.

Fig. 3 shows the branch contact point with the neutral conductor. Again there is clear and significant damage to both the branch and conductors. Fig. 4 shows clear damage along the branch mid-section, particularly near the point where the carbonized paths met. Bark can clearly be seen peeled back from the wood in the photograph.

Fig. 3. Damage to branch and neutral conductor after Experiment 1.

Fig. 4. Damage to branch, mid-branch after Experiment 1.

Finally Fig. 5 shows damage to one of the insulators supporting one of the conductors. Photographs prior to the experiment show a small stem from the branch making incidental contact with the insulator. The insulator was not new, but had only minor damage from previous use. During the experiment, arcing through the branch cracked the porcelain, further damaging the insulator and ultimately causing a large porcelain chip to separate.

Fig. 5. Damage to insulator after Experiment 1.

Fig. 6 shows recorded data from a 27-second period during the fault recorded in Experiment 1. The figure shows RMS neutral current calculated at two points per cycle. Each peak on the graph corresponds to one burst of the higher current. The final extended burst can also be seen. As observed from the graph, load levels for the recorded period are nominally 30 amperes, with bursts up to approximately 35 amperes. Because of normal imbalances between phases of the feeder, this does not mean that the fault current was five amperes. Observations from the clamp-on ammeter were erratic and difficult to judge, but it is believed that actual fault current during these bursts was closer to its maximum available value of 14.4 amperes.

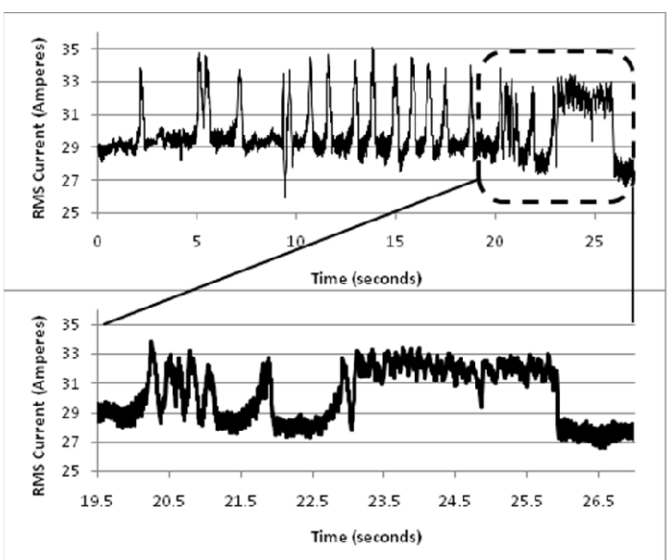

Fig. 6. RMS neutral current, Experiment 1.

B. *Experiment 3*

Visible, audible, and electrical observations at the beginning of the experiment were quite similar to those in Experiment 1 and most other experiments. Scintillation began almost immediately and carbonized paths began to form and grow toward each other. This continued for four minutes, 55 seconds, at which time the two carbonized paths met, resulting in a low-resistance arc. Jacob's Ladder arcs repeatedly formed and extinguished for eighteen seconds. There were thirteen individual short bursts followed by a final burst of extended duration. As in Experiment 1, short bursts typically persisted for approximately fifteen cycles. The final extended burst was again coincident with a gust of wind, and persisted for approximately 6.5 seconds.

RMS neutral current for a 20-second period is shown in Fig. 7. As with Experiment 1, arc bursts during Experiment 3 increase the substation-measured neutral current by approximately five amperes.

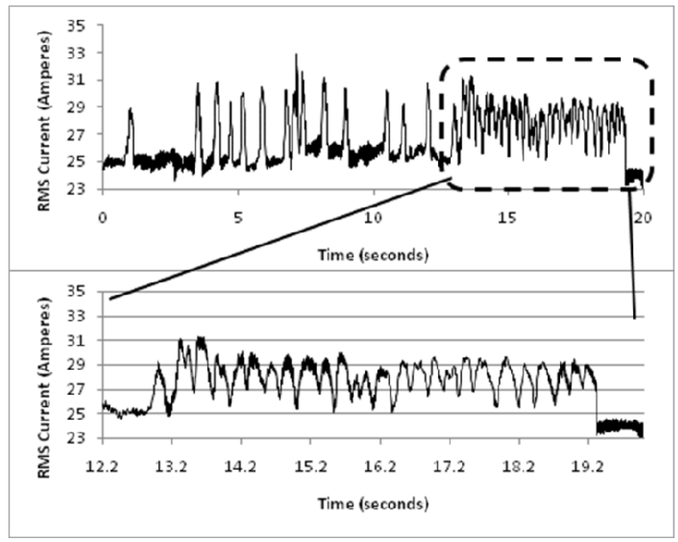

Fig. 7. RMS neutral current, Experiment 3

The final 6.5-second arc burst did not blow the 2T fuse. Rather the contact point at the neutral conductor burned through so that the carbonized path was not physically present to reestablish another arc. The branch did not fall clear of the conductors, but its mechanical configuration was altered such that there were new points of contact between the conductors and the branch. The branch remained in contact with the conductors for an additional one minute, 45 seconds, and a new carbonized path began to form along the branch. At this time, the new contact point burned through, causing the branch to fall clear of the neutral conductor and come to rest on the concrete slab on which the tests were performed. Researchers allowed the branch to remain in contact with the concrete and energized primary phase conductor for approximately one minute, but no additional activity resulted.

Fig. 8 - Fig. 11 are photographs taken during and after Experiment 3. Fig. 8 shows the branch during the eighteen-second interval of power arcs before the branch first moved. Fig. 9 shows the branch immediately after the final arc burst in that period. It can be seen from the photograph that it has dropped from its original position and is no longer arcing.

Fig. 8. Arcing branch, Experiment 3.

Fig. 9. Burned-through branch immediately after final arc burst, Experiment 3

Fig. 10 shows the end of the branch contacting the phase conductor, which remained attached by means of a small offshoot branch, visible in the photograph. Fig. 11 shows a larger portion of the same section of conductor with the branch moved to show the damage. As with Experiment 1, the conductor remains intact, but it has sustained damage which may adversely affect its mechanical strength and structural properties.

Fig. 10. Main branch remains on conductor, Experiment 3.

Fig. 11. Damage to Conductor, Experiment 3.

VI. Discussion of Results

The experiments produced both expected and unexpected results for a branch spanning two primary conductors.

- Initial current levels are quite low, on the order of an ampere or so. This can persist for quite some time, on the order of minutes. This level of current is of the same general order of magnitude seen in previous experiments involving a single primary conductor in contact with a tree.
- Progressive carbonization is key to establishing a low-current path.
- Fault current increases as carbonization increases, but not uniformly. The transition from a few amperes to a "bolted," high-current condition occurs suddenly when the carbonized path is complete.
- Concentrated heating can cause significant damage to conductors, even at relatively small current levels.
- Scintillation, burning, and repetitive power arcs may be cause for concern about fire in arid regions.
- When a vegetation-induced power arc is interrupted by a reclosing device, the presence or lack of continued physical contact between both conductors and the carbonized path is a key determinant of whether a lockout and outage will occur.

Experimental observations suggest a model for the phenomenon of vegetation spanning two conductors on a medium-voltage circuit. The branch initially can be thought of as a continuous high-resistance path between the contact points, as shown in Fig. 12. Shortly after contact occurs, current concentration at the point of contact causes significant localized heating. Scintillation begins and causes the organic wood products to carbonize, or char. The resistance of char is quite low, so it acts as an effective short circuit across the much higher resistance of the underlying wood. Resistance of the overall path therefore decreases. The area immediately adjacent to the char then becomes the point of current concentration and scintillation and burning begin at this point. This extends the charred path and further reduces the overall resistance. The process continues and the charred path progresses preferentially in the direction of the other contact point. As the charred paths lengthen, the overall branch resistance decreases, as more of the "high-resistance" wood is short-circuited by the much lower-resistance carbonized path. This continues until the two paths meet and form a continuous, charred, low-resistance path, enabling a high-current event.

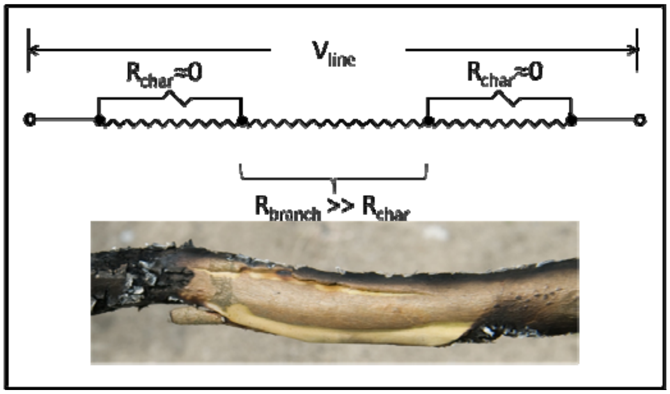

Fig. 12. First-order electrical model of tree branch spanning two conductors

VII. CONCLUSIONS

Vegetation intrusion causes significant power quality, reliability, and safety problems on distribution feeders. Experimental results provide insight into the evolution of vegetation-related faults.

Vegetation contacts can produce electrical signals which are measurable from a remote substation. These contacts need not result in momentary interruptions or sustained outages in order to be detectable. Individual contacts may or may not be self clearing, depending on factors including vegetation size and type, physical movement of trees and/or conductors, wind, moisture, etc. The period of time over which casual, intermittent contacts occur before producing a noticeable high-current event may be hours, days, or even weeks.

Vegetation contacts that are self-clearing and do not result in immediate catastrophic conductor damage may still physically damage conductors and other power system equipment, potentially resulting in future outages and other types of degraded system performance.

These data substantially enhance understanding of the electrical and physical progression of vegetation-related events, and continue to suggest the use of measured electrical signals for detection of incipient vegetation-related problems.

VIII. ACKNOWLEDGMENT

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X. BIOGRAPHIES

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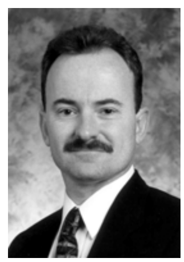

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