Electrical phenomena associated with vegetation in contact with medium voltage conductors: summary of field experiments

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Abstract

Vegetation contact with medium voltage conductors is a major problem for many distribution network operators (DNOs) around the world. In addition to being a safety hazard and reliability concern, many DNOs are concerned about vegetation-induced teardowns of conductors igniting wildfires. Despite multiple controlled experiments performed at various laboratories around the world, many misconceptions persist about the electrical behaviour of vegetation contacting medium voltage conductors. This paper summarizes experiments performed by researchers at Texas A&M University and draws conclusions regarding the possibility of detecting vegetation contacts on active circuits.

1 Introduction

In the United States and much of the world, most high voltage electrical conductors have large, mandated, clearances along their right-of-way that prevent vegetation intrusion. The same is not true of medium voltage (MV) conductors. As a result, vegetation intrusion is a major cause of reliability and safety hazards, as well as, in some cases, wildfire ignitions. Unfortunately, many myths persist among researchers and practitioners regarding the electrical interaction of vegetation with medium voltage conductors.

1.1 Vegetation-caused faults

Broadly speaking, vegetation ingress causes faults in three ways. First, vegetation can mechanically tear down conductors, resulting either in a bolted poly-phase fault (or a single-phase fault in the United States on a four-wire multi-grounded system), or one or more energized conductors at earth level. Electrically, this is similar to any other mechanical teardown event. Second, vegetation can push two conductors together mechanically, resulting in a multi-phase or single-phase fault, depending on the configuration. Again, electrically this is similar to any other conductor slap condition. Third, vegetation can span multiple conductors, or a conductor and earthed object. This creates an electrical path across the vegetation itself. The third category of vegetation-caused faults is the subject of this paper.

It should be noted that often these three mechanisms are conflated with each other, particularly in outage reporting. Line crews are seldom concerned with differentiating between exactly *how* vegetation caused a fault, and frequently outage logs will simply note, "Tree." While this is understandable, it does require engineers and investigators to do additional work to understand what happened in any particular event.

2 Prior work

The authors have a long interest in the electrical characterization of faults and failures on medium voltage systems, including vegetation contact. Early work at Texas A&M dates back to the 1990's [1], with additional experiments performed in 2006 [2]. The 2006 experiments were performed at the Texas A&M Downed Conductor Test Facility. Originally conducted to study high-impedance faults caused by energized conductors on a variety of surfaces, the test facility allowed researchers to bring a 7.2kV conductor from an active distribution circuit to ground level. At the time of the tests, the facility had a maximum single-phase bolted fault current of approximately 2,200 amperes and was located approximately 3.2 electric kilometres from the substation. The subject circuit was a 12.47/7.2kV multi-grounded-wye distribution feeder serving approximately two megawatts of light residential and oil field load.

In the 2006 experiments, researchers used sawhorses with attached insulators to construct two parallel conductors, and laid branches of multiple types of trees across the conductors at varying lengths. The energized phase conductor was protected by a 2-ampere Type-T fuse, and the neutral conductor was grounded through a 500-ohm resistor board to limit fault current at the site and subsequent voltage drop seen by active customers on the circuit. The test setup can be seen in Figure 1, which shows an arc drawn between the two conductors following a flashover event.

Figure 1: Test setup in 2006 experiments, during flashover event.

Researchers observed that as the branch was energized charring and scintillation began immediately at both ends of the branch where the vegetation contacted the conductor. The charred path began to extend from both ends of the branch toward the centre. Eventually the two charred paths came close enough to each other to produce a high-current flashover. Due to the 500-ohm intentional resistance in the path, the fault current was limited to 14.4A and given the intermittent nature of the arcing the 2A fuse did not immediately clear. Instead, the fault current produced multiple, dramatic "Jacob's ladder" arcs, photos of which have been widely circulated online. The timeline from energization to flashover varied slightly depending on separation distance but generally lasted several minutes. While there was no formal measurement device at the fault point, a fluke meter hung on the conductor registered less than 0.3A during the duration of the tests before flashover.

While the 2006 experiments provided new insights to the progression of faults initiated by spanning vegetation, the artificial 500-ohm impedance was a key and valid criticism of the original test setup. Researchers believed the impedance had little-or-no impact on the pre-flashover behaviour but could not definitively prove that. Additionally, all electrical measurements in the 2006 experiments were taken at the substation. While this is more representative of the recordings a utility would likely have in practice, isolating the pre-flashover behaviour at the fault point might give insights about detection before flashover occurred.

3 Experimental setup

To address limitations of the 2006 experiments, researchers at Texas A&M University partnered with John Goodfellow of BioCompliance Consulting and Oncor Electric Delivery to perform a series of experiments on an active distribution circuit in the Dallas, Texas area [3]. With input from researchers, Oncor constructed a test setup served by an active distribution circuit at a water treatment plant. The test setup was served by a three-phase section of line with a nominal circuit voltage of 7.8/13.5kV. The test setup allowed for both phase-to-phase and phase-to-neutral connections, and energized conductors were protected with 100A fuses. In contrast to the Texas A&M Facility, the Oncor test facility had a substantially higher available fault current of approximately 4,000 amperes (line-to-neutral). A wide angle view of the test facility can be seen in Figure 2.

Figure 2: Oncor test facility (2020 tests)

4 Results

The Oncor test facility provided two notable benefits over previous test facilities used for experiments of similar types. First, the lack of sensitive customers on the circuit meant the tests could be conducted on an active power system with no intentional impedance limiting. This eliminated the somewhat artificial constraint of previous tests. Second, while the Texas A&M facility only allowed for phase-to-neutral tests, the Oncor facility enabled phase-to-phase tests, which in turn allowed for substantially higher voltage gradients.

Findings from the high current tests in 2020 broadly mirrored results from earlier experiments. As soon as the branch was energized, charring and scintillation was observed at both ends, and progressed toward the middle of the branch. This continued for some time, with the charred path moving toward the centre of the branches. Ultimately the charred paths connected, resulting in a high-current flashover.

Unlike previous events where impedance limiting resulted in dramatic power arcs, the high available fault current combined with relatively small 100 ampere fuses resulted in immediate fuse operation and clearing of the high current fault. Figure 3 shows the end of one such test as the high-current arc is extinguished.

One substantial technological change from 2006 to 2020 was the availability of compact and high-speed cameras that available at a modest price point. Researchers used commercial GoPro cameras recording at 240 frames per second (effectively 4 frames per cycle on North American 60Hz systems) to record video of the experiments close to the contact points.

Figure 3: Extinguishing of high-current arc from 2020 tests.

The high-speed video shed new light on the behaviour of arcing, particularly in the early stages of fault formation. Figure 4 and Figure 5 show images captured from high-speed video during one test.

Figure 4: Arcing visible at sub-ampere current levels

Figure 5: Flames and arcing just before flashover

One particularly important finding from the video recordings combined with electrical measurements taken at the fault point is that substantial arcing activity can exist even at relatively low current levels. In particular, the image in Figure 4, which is not cherry-picked, shows arcing occurring below the 500mA limit that is often cited as an important level for reducing the probability of ignition. Figure 4 and Figure 5, along with images obtained from other tests, suggest that branches in a similar configuration could represent a competent ignition mechanism given an appropriate fuel load.

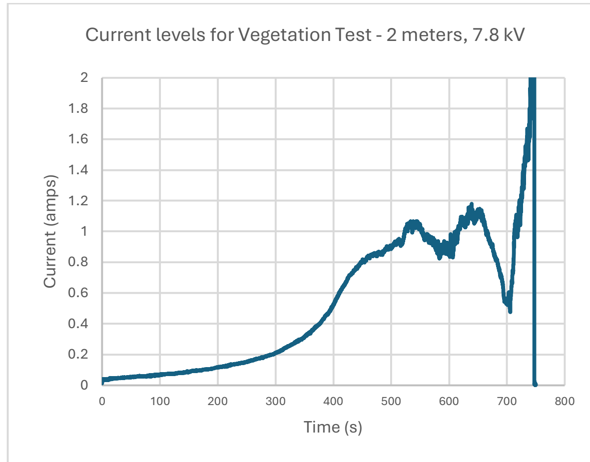

Figure 6: Current levels for exemplar vegetation test

Figure 6 shows current levels during one exemplar test. Current measurements were taken at the site using AEMC data loggers which recorded current values 8 times per second. The graph in Figure 6 shows the current readings for Test 5, shown in Table 1 below. The test lasted approximately twelve and a half minutes, and for the vast majority of that time – over eleven minutes – the current never exceeded 1.2 amperes. Three seconds before the flashover which operated the 100 ampere fuse, the current at the fault point was only 3 amperes.

This finding, which is broadly corroborated by other research groups [4-6], highlights the challenges of detecting and acting on vegetation intrusion into lines before flashover, which will be discussed in more detail later.

Table 1 shows a list of the high-current tests performed during the 2020 tests. In total, researchers performed seven tests with different branch separations and voltage gradients.

As with previous tests, these results suggest a loose relationship between voltage gradient across a branch and the time to flashover. For the two events where the branches burned clear, researchers are confident the branch would have eventually flashed over if it had remained in contact with the line. The only difference in those tests were that the structural integrity of the branch failed before the carbonized path could reach the centre of the branch and cause a flashover.

Several of the tests are notable because the voltage gradient across the branch falls below the 2kV/ft (6.5kV/m) limit that is often cited as required for vegetation flashover. Test 6 involved a 3m (10ft) branch across 13.5kV – a voltage gradient of under 1.5kV/ft (4.5kV/m), yet video evidence strongly suggests that the branch was close to flashover when it structurally failed. It is also worth noting that the distance in Test 6 – 3m / 10ft – is substantially longer than any typical medium voltage conductor spacing, at least in North America.

Table 1: Summary of experiments

Test Number	Separation	Voltage	Time of Test	Result of Test
Test 1	0.63m	13.5kV	0:42	Flashover
Test 2	0.63m	13.5kV	0:20	Flashover
Test 3	1.82m	7.2kV	7:58	Burned Clear
Test 4	1.82m	7.2kV	9:30	Flashover
Test 5	1.82m	7.2kV	12:27	Flashover
Test 6	3.0m	13.5kV	26:04	Burned Clear
Test 7	1.82m	13.5kV	2:33	Flashover

5 Discussion

The results of the 2020 tests raise multiple questions about the nature of vegetation contacts with medium voltage conductors, both operational and academic.

5.1 Operational Challenges

Operationally, the tests highlight the challenges of detecting and acting on vegetation intrusion before it causes a flashover event. There are at least three major challenges. The first is detection. Currents produced in the initial fault stages are too low for reliable detection. All tests conducted at the Oncor facility had currents generally under 1200mA until just before the flashover. This finding has been broadly confirmed. Especially on four-wire multi-grounded circuits which are common in North America and where loads are connected between a single-phase and neutral, the long-term variability of the neutral current is substantially higher than the current produced by the early stages of vegetation contact. Said differently, the “signal” of the low-current vegetation fault would be overwhelmed by the “noise” of normal loads operating on the circuit. One might think a transition to a three-wire compensated or uni-grounded neutral system would overcome this problem due to the lack of phase-to-neutral connected loads. While this certainly makes the detection problem easier, many US and UK three-wire uni-grounded systems have standing $3I_0$ levels of several amperes. While this is one or two orders of magnitude lower than on four-wire multi-grounded systems, it is still often three to five times the signal of interest. Additionally, standing $3I_0$ waveshapes are generally harmonic rich and highly distorted, causing additional issues when trying to isolate the signal of interest. More problematic, however, is that most spanning vegetation configurations would not be phase-to-neutral (because there is no neutral conductor), but phase to phase. Detecting phase-to-phase events is more difficult than phase-to-earth or phase-to-neutral events, whether on a three-wire or four-wire system.

Even if one could develop a reliable detection method, the second practical challenge is location. Because the early stage fault currents produced by vegetation ingress are both variable and have a large impedance, conventional impedance-based fault location techniques are not suitable. Most fault analysis software packages (CYME, Aspen, Windmill) assume a fault with zero or near-zero impedance, which is not the case until flashover. Consequently, even if a utility knew with high confidence that an early-stage vegetation fault was in process on a circuit, they would have no way to meaningfully locate it. Again, this is a particular challenge in North America where medium voltage circuits tend to be much longer than in other parts of the world. North American circuits generally range from tens to hundreds of kilometres in length, and few if any utilities would send a patrol to investigate a condition without at least some idea of where the problem might lie.

The final practical obstacle is time. Vegetation in contact with medium voltage conductors is likely to produce a flashover event in minutes to tens of minutes. For most circuits, this means that even if the utility could detect the fault and could pinpoint its location to within a few hundred meters, it would still be impossible to dispatch a crew to the area and clear the fault before flashover occurred. There are some scenarios – namely circuits located in fire-prone areas on high-risk days – where a utility *might* deenergize a circuit if they had high confidence of an in-process vegetation fault. But many, perhaps even most, would not.

5.2 Theoretical concerns

In addition to the practical considerations discussed in 5.1, the 2020 Oncor tests raise several academic curiosities about the relationship between voltage gradient and flashover time, and the underlying electrical mechanisms involved.

The commonly held belief is that higher voltage gradients lead to shorter flashover times, and that is generally supported by the tests. At the same time, Test 4 and Test 5 had identical voltage gradients, yet Test 5 lasted almost 30% longer than Test 4. Additionally, Tests 4, 5 featured similar voltage gradients to Test 6, but a shorter separation distance. Test 6, however, lasted over twice as long as Test 5 before eventually burning clear. This suggests that while voltage gradient does play a factor in time-to-flashover, the relationship is not as simple as saying “X volts/meter will result in a flashover time of Y minutes.”

Additionally, current measurements taken at the fault point suggest that the simplistic electrical model proposed in [2] is at best incomplete. In that work, the authors propose that the branch acts more or less like an infinite series of resistors, and the charring and scintillation produced over the course of the fault progressively “short circuit” those resistors, since carbon is a relatively good conductor of electricity. Curiously, however, current levels measured at the fault point remain relatively consistent between tests before the time of flashover even at different separation lengths and voltage gradients, suggesting that other factors are contributing to fault current levels.

6 Conclusion

Vegetation intrusion represents a major challenge for distribution system operators, impacting reliability and creating safety hazards. Experimental work described in this paper, and other sources, broadly confirms that initial current levels drawn by branches in contact with medium voltage conductors remains low, often below one ampere, until just before a high-current flashover occurs. These findings suggest that detecting early-stage vegetation faults will be difficult, even on three-wire systems where no loads are connected line-to-neutral. Additionally, the time from initial contact to final flashover suggests that even if a utility were able to detect and reliably locate an in-process vegetation fault, it would be difficult to dispatch a crew to the location before flashover occurs.

Despite this, additional questions remain about the precise micro-level electric mechanisms that occur when vegetation contacts medium voltage conductors. Additional research on operational distribution circuits using high-fidelity monitoring at the fault location combined with improved high-speed video analysis could prove useful in determining the uniqueness of vegetation related fault signatures which might enable future detection efforts.

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