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Reducing Wildfire Risk through the Use of Advanced Electrical Waveform Monitoring and Analytics

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SUMMARY

Despite the excellent reliability of electric power distribution systems, lines and apparatus do fail, sometimes catastrophically. Common failure modes often create arcing and/or heating capable of igniting combustible material.

It is well known that powerlines start many brush fires and wildfires which cause substantial property damage and sometimes loss of life. Common ignition sources include arcing downed lines, vegetation contacting lines, sparks ejected from clashing lines, or failing apparatus arcing and/or dropping burning products to the ground. To the extent that such failures can be detected and repaired quickly, many wildfires can be prevented or minimized.

Smart grid efforts typically focus on hastening restoration following an outage. These systems provide value, but they do not detect incipient failures and temporary faults that not only cause customer interruptions and outages, but also more serious damage including wildfires.

Texas A&M University has developed sophisticated analytics that use waveforms from conventional CTs and PTs to detect feeder events, including faults and incipient feeder conditions that, if not addressed, may escalate and start wildfires. The basic concept underlying the application of these waveform analytics, which have become known as distribution fault anticipation (DFA) technology, is described. Case studies provide concrete examples of the ability to detect, locate, and repair failing devices before they create ignition sources capable of causing wildfires.

KEYWORDS

Power system analytics; wildfire prevention; smart grid; advanced monitoring; vegetation management; Distribution Fault Anticipation; DFA

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Introduction

In October 2007, multiple wildfires destroyed more than 1,000 homes and caused more than US$2 billion of property damage and as many as seven deaths in Southern California, USA. [1, 2] Many of these fires eventually were determined to be started by power lines. [1, 3] A series of wildfires in the Australian state of Victoria in February 2009, many of which the 2009 Victorian Brushfires Royal Commission determined to have been started by power lines, resulted in more than AU$4 billion in damages and 173 deaths. [4] In September 2011, the Texas Forest Service determined that power lines caused a wildfire near Bastrop, Texas, USA, resulting in more than US$300 million in insured losses and two deaths. [5] These high-profile incidents have focused significant attention on the role of power lines as ignition sources.

How Power Lines Ignite Wildfires

Power lines can ignite fires through a variety of mechanisms, including: direct ignition from high-current, high-energy power arcs; molten and/or burning particles expelled from faults; burning embers from vegetation; or the ignition and expulsion of the insulating fluid common in power system apparatus. [6] Such mechanisms can be caused by downed conductors, failing or faulted apparatus, vegetation-caused faults, conductors contacting each other in the air, to name a few.

Figure 1: Downed conductor ejecting molten particles

Downed conductors often remain energized for long periods of time (e.g., minutes, tens or minutes, or longer) and arc violently at points where the conductor contacts or comes very near the earth or a grounded surface. In Figure 1, for example, a downed conductor on concrete creates extreme temperatures and expels hot, sometimes burning, particles, readily capable of igniting proximate vegetation, building materials, or other combustibles. Such faults often arc violently but draw only a few amperes or tens of amperes of current, too little to operate conventional overcurrent protection reliably. The danger for ignition is obvious.

Figure 2: Vegetation-initiated arcing

Figure 2 shows another type of ignition source related to power lines. Here a tree branch spanning a line's phase and neutral conductors creates a conduction path and flashes over in a power arc. Vegetation-related faults on distribution feeders can be temporary but may recur multiple times, until either the vegetation burns clear, the line burns down, or protection trips and causes a permanent outage. Again this process clearly represents a competent ignition source.

As another example, failing apparatus, such as cracked bushings, can flash over in high-current power arcs multiple times, without discovery by the utility. Each episode creates arc products and causes progressive damage that eventually may result in catastrophic failure. As a final example, line conductors slapping together, even while still in the air, emit a shower of molten particles. When conductors are made of aluminum, the particles actually may be in combustion (i.e., burning) as they fall and contact proximate vegetation, building materials, or other combustibles.

Electrical Waveform Monitoring and Advanced Analytics
Utilities across the United States are increasingly installing "smart-grid" technologies on distribution feeders. "Self-healing" systems aim to reduce the duration and extent of outages, by automating the processes of isolating faulty sections and switching to alternative sources and healthy feeder sections, to restore service to the maximum number of customers in the minimum amount of time. AMI (advanced metering infrastructure) systems also can enable improved fault finding. These and other "smart" technologies can improve overall reliability, as measured by standard indices such as SAIDI and SAIFI, but by their nature they are reactive and do not detect temporary, incipient or ongoing failure conditions – including those capable of igniting present or future wildfires. Stated differently, AMI and self-healing systems can improve reliability, but they do not detect many classes of problems and events that eventually may cause wildfires.

Over the past decade, researchers at Texas A&M University have conducted substantial research, funded primarily by EPRI and EPRI-member utilities, to detect and anticipate incipient failures on distribution feeders, using high-fidelity waveforms and sophisticated waveform analytics. This work, which has become known as Distribution Fault Anticipation (DFA) technology, has identified signatures produced by: failing equipment; external intrusions into power lines, such as vegetation; and improper or unexpected feeder events, including fault-induced conductor slaps. In many cases, this newfound "awareness" of feeder conditions and events has enabled utility companies to locate and correct incipient failures before they could escalate and produce catastrophic damage.

DFA devices currently monitor several dozen distribution feeders across the United States and Canada. DFA devices obtain high-fidelity waveforms from conventional feeder CTs and bus PTs at substations. DFA devices do not require communication with line devices (e.g. reclosers, capacitors). Rather analytics in the DFA devices infer, from CT and PT waveforms, the presence and detailed operation of line devices, as those devices operate. Analytics also detect failing line components, such as switches and connectors, based upon subtle electrical-waveform changes that occur as those devices begin to fail. In many cases, DFA reports provide the utility's only indication of a problem prior to a catastrophic failure and outage.

The following case studies are presented to demonstrate the potential for preventing or mitigating wildfires through the use of improved awareness of system events and conditions, as provided by waveform-based analytics.

Case Studies
Case Study 1: Failing transformer
During a rainstorm, a DFA-monitored feeder with over 125 circuit miles of overhead line experienced a fault. A mid-point recloser momentarily interrupted 103 customers, and then a downstream sectionalizer tripped, resulting in an outage for 82 customers. Utility crews investigated the outage, but ultimately were unable to find any cause. Four days later, during another rainstorm, a fault momentarily tripped the same mid-point recloser, but then reclosed and "healed" without any sustained outage.


Figure 3: Transformer with hole punched through lid

Utilities would know of the first fault, because it caused an outage. It is not uncommon, as was the case here, for crews to re-energize a circuit, find that the fault has "healed," and leave the scene with a diagnosis of "no cause found," "bad fuse," "lightning," "vegetation," or similar cause code. Few utilities would have any awareness of the second fault, unless a customer calls to report "blinking lights," and the DFA research program has documented that customers often do not call to provide such notification, even after repeated blinks.

In this case, the DFA system 1) reported each fault, 2) automatically identified that the two faults likely had the same

underlying cause, and 3) notified the utility of the presence of a recurrent fault on the circuit. Research has demonstrated that failing line apparatus can cause recurrent faults, which recur intermittently for weeks, until they eventually result in a sustained outage. After being informed of the recurrent fault, the utility compared DFA-reported fault parameters to their feeder model, and thereby was able to narrow the potential outage area to a small section of the circuit. By patrolling only that area, crews identified a transformer with arc marks on its jumper wire, and a hole through its lid, as shown in Figure 3. It is believed that adjacent vines, when weighed down by moisture, caused flashovers between the jumper wire and the lid, and that the resulting flashover arcs created the hole. [7]

It is worth pausing to consider the course of action of a typical utility in this situation. With only conventional sources of information, the utility likely would have no knowledge of the second fault. If the utility is unaware of the second occurrence, it obviously cannot determine that the second fault is related to the first, and therefore will take no action. The damaged transformer remains in service with a hole through its lid, enabling moisture ingress, with a high likelihood of faulting again during the next rainstorm.

Figure 4: Case Study 1 transformer, on pole

This case has particular relevance to wildfire mitigation. The breached lid permits moisture ingress, which compromises the insulating quality of its oil, thus leading to an internal fault which may cause the transformer to explode and expel burning oil. This is a rare event, but one with potentially catastrophic consequences. Second, as long as the damaged transformer remained in service, it almost certainly would have continued to experience intermittent faults. Each temporary, self-healing fault poses a wildfire risk, particularly when vegetation is involved. Figure 4 shows the transformer before it was removed from the pole. It is not difficult to imagine a fault at this location igniting the proximate vines and causing a fire. Finally, this case illustrates the clear potential of advanced monitoring and analytics as tools for fire prevention. The transformer in question represented a fire risk of which the utility was unaware. DFA waveform analytics allowed the utility to know of and act on a potential liability, rather than allowing it to develop into an actual liability.

Case Study 2: Vegetation-caused burn down of line

This example began with a tree branch breaking, falling, and hanging across a single-phase section of rural line. The line was constructed with the phase conductor atop the pole and the neutral conductor several feet below. The broken branch hung on the phase conductor where the branch made a "Y." The branch was heavy enough and long enough to sag the phase conductor and span the distance to the neutral. The branch was in constant contact with the phase conductor and made intermittent contact with the neutral conductor.

The branch spanning from the phase to the neutral conductor caused a flashover fault, which was cleared by an unmonitored, three-phase line recloser momentarily interrupting 140 customers. Another flashover and momentary interruption happened an hour later. Then, after a 16-hour hiatus, more than a dozen additional flashover faults and momentary interruptions occurred. The final flashover, which occurred 24 hours after the very first, burned the line down.

Until the final burn-down, the utility company was unaware of the faults and momentary interruptions. No customers called, and the recloser was unmonitored. Each of the flashover faults in this sequence had the potential to ignite a fire. In the subject case, once the line burned down, the fault cleared, but in as many as 30% of cases, downed conductors remain energized, increasing the chance of a fire. [8]

Figure 5: Burned tree branch from Case Study 2

The subject event provided a good example of how faults and interruptions can occur, even repetitively, without the utility company having awareness that a problem exits. The subject event occurred before DFA analytics had advanced to the point of being able to detect and report this type of repetitive event automatically. Subsequent advances in the technology have resulted in analytics that detect individual faults and then determine when multiple individual faults likely have the same cause.

Since that time, the DFA system has been responsible for detecting and enabling correction of multiple similar problems. In one example, over a period of 26 hours, the DFA system detected a series of repetitive faults that resulted in four momentary interruptions for customers past a single-phase hydraulic recloser. As in the previous event, no customers reported the interruptions, and the utility had no conventional notification of the problem, including customer calls. The DFA system informed the utility of the repetitive faults and directed their search to a small portion of the affected feeder, where a crew found trees intruding into the overhead lines. The crew performed targeted trimming in the area, and the faults ceased. Based on actionable information provided by the DFA system, the utility was not only able to improve reliability for its customers, but also prevent the potential burn down of the line and associated fire risk, as happened in the earlier incident.

Case Study 3: Fault-induced conductor slap (FICS)

A phenomenon known as fault-induced conductor slap (FICS) occurs when an initial fault causes magnetic forces and movement in upstream conductors, sufficient to make the upstream conductors contact each other and cause a second fault, closer to the substation. Conductor slap from any cause, including FICS, typically expels molten particles and, in the case of aluminum conductors, even particles in combustion (i.e., burning) as they fall. [9]

The DFA system has detected FICS on multiple feeders at multiple utility companies. A span experiencing FICS often is found to have something unusual in its construction, such as extra length, extra sag, transition, etc. Left as it is, such a span is susceptible to repeat occurrences of FICS. The DFA research program has documented multiple recurrences of FICS in a given span, but because months often elapse between episodes, utility personnel often do not recognize the repetitive nature.

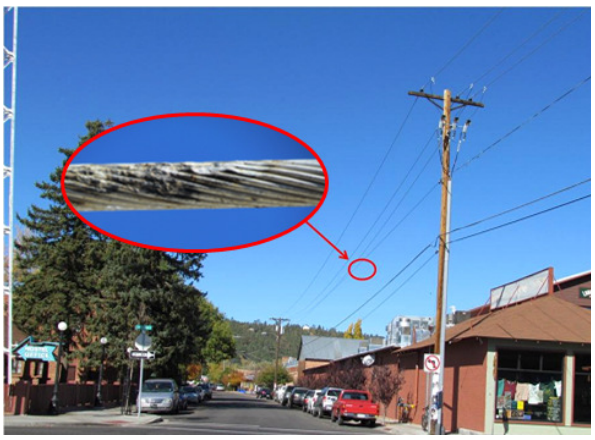

Figure 6: Conductor damage from FICS

As one example, DFA analytics detected FICS that resulted in utility personnel locating the arc pitting shown in Figure 6, thus confirming the FICS diagnosis. The FICS in this case had caused the substation feeder breaker to operate twice and lock out. The utility company recognized that the initiating fault had occurred past a mid-point recloser, which should have sectionalized the fault without operating the substation breaker, but they were unaware that FICS was the cause of this apparent misoperation. Interestingly a local police officer reported a “poletop fire” to the utility company, apparently after observing the shower of sparks typical of conductor slap. This report roughly coincided in time with the breaker operation, but the utility originally found no sign of

a “poletop fire” and therefore closed the report ticket. The initial fault occurred relatively far away from the location at which the officer reported the “poletop fire,” so it did not occur to utility personnel that the two incidents might be related.

The shower of sparks typically produced by slapping conductors, including FICS, represents a competent source of ignition. Alerting the utility to FICS enables them to make alterations and therefore prevent future FICS in the offending span. Waveform analytics, as embodied in the DFA system can provide such notifications, based solely on waveforms from conventional substation-based CTs and PTs.

Conclusion

Power lines are known to cause wildfires in spite of the best efforts of utility companies, who can never prevent all faults or fires. Wildfires are costly to utility companies and to the public, in terms of property loss, interruption of commerce, and even loss of life. The past decade has seen multiple high-profile cases of wildfires determined to have been started by power lines. These power line-ignited fires collectively have caused over 100 deaths, and resulted in billions of dollars of damage. The public nature of these events has led to heightened awareness of the role power lines play in wildfire ignition, as well as creating interest in practices and technologies that might mitigate or prevent power line-caused fires in the future.

Particularly in drought prone areas, the geographically dispersed nature of distribution feeders, coupled with the thousands or tens of thousands of components on a utility’s system which may result in a fire, constitutes a significant challenge for fire prevention. Many failures of power line components create arcing and/or burning materials that represent competent sources of ignition. Utilities do not have the manpower to manually inspect every component on their systems. Neither conventional monitoring and protection systems nor more modern “smart grid” technologies are designed to detect the incipient failures that create arcing and lead to more catastrophic failures over time. Likewise, recording waveforms (e.g. with a PQ meter) for offline analysis does not provide any real-time situational awareness benefits, which are critical for the mitigation of wildfires.

Electrical waveforms, as can be measured from conventional CTs and PTs, represent feeder activity, including normal events, faults, and other anomalies. Intelligent, waveform-based analytics can detect many of these events and conditions, providing the utility company a heightened level of awareness and actionable information. Benefits to be derived include improved reliability, power quality, and customer satisfaction. Benefits also include the ability to reduce the number of potential fire-ignition events that occur because of failing equipment, slapping conductors, and the like.

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