Distribution Feeder Caused Wildfires: Mechanisms and Prevention

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Abstract
Drought conditions in the United States in recent years bring increased attention to the age-old issue of power line-caused fires. It has long been known that power line faults and failures can cause wildfires through multiple mechanisms. Failure mechanisms of various apparatus and operational conditions that result in wildfire ignition are reviewed. Case studies of faults and failures from operating utility systems are presented, along with a discussion of how these faults and failures represent competent sources of ignition for wildfires. Methods of preventing power line-caused wildfires are discussed.

Introduction
Under normal environmental conditions, various power line operational problems, apparatus failures, and fault conditions can cause fires. However, the drought conditions that have been experienced in the United States over the last several years have exacerbated the wildfire problem and focused attention on power line-related fire causation. In the last two years, some of the costliest fires in the United States have been caused by power lines with notable examples in Texas and California. This has resulted in hundreds of millions of dollars in losses and significant litigation.

Given the substantial costs of wildfires and the loss of human life, livestock, and wildlife, it is important that the power line-related causes of wildfires be understood. Certain power line faults and failures that cause fires can never be avoided, but it is possible that through better understanding, certain operating conditions and certain failures can be addressed and repaired before fires are caused.

The delivery of electric energy at typical distribution and transmission voltages clearly represents a competent ignition source for fires. Environmental damage to power lines is common from such causes as ice accumulation, high winds, tornadoes, and hurricanes. These forces damage power line structures, tear conductors from the air, drop poles and transformers, and otherwise create conditions that readily can start fires. However, many power line failures are not caused by extreme weather or environmental conditions, some of which may be detected and repaired before catastrophic failure causes fire ignition. It is these later mechanisms that are hereinafter described.

How Power Lines Cause Wildfires
There are multiple mechanisms for power line-caused wildfires. It is best to first understand the ignition mechanisms that are associated with power line failures.

For fire to occur, sufficient combustible material must be present with sufficiently low moisture content to create a combustible environment. A typical scenario is created by long periods of drought where grasslands and other vegetation with low moisture content are available under electric power lines and power equipment. When these conditions exist, various ignition mechanisms may result in wildfires.

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Fire ignition mechanisms loosely fall into the following categories:

1. High-current, high-energy arcing that may ignite combustibles directly
2. Molten or combusting metal particles expelled during faults
3. Burning embers from vegetation
4. Burning insulating fluids, such as found in transformers, reclosers, etc.

Any of the above ignition mechanisms represent sufficient heat and/or flaming conditions that will ignite dry grasslands or other dry vegetation. Several of these mechanisms may occur simultaneously, such as the arcing, melted metal, and heating that occurs when a power line contacts ground.

The ability of an arc to cause ignition of dry vegetative material is not in question. Electric arc temperatures are measured in thousands of degrees and arcs from high-impedance ground faults can persist for many minutes, readily providing sufficient energy and heating to cause combustion.

Ignition of ground level dry vegetation from metal particles is less understood. Fundamental work by Tse and Fernandez-Pello at the University of California Berkley has shown that relatively small aluminum particles (e.g. 1.5mm) can be expelled and can travel significant distances from power lines. These aluminum particles are frequently in combustion and are actually burning as they fall. Unless the particles are consumed before they hit the ground or are extinguished by some other means, they land while burning and represent a competent ignition source for vegetation. [1-2]

Power Line Failures and Faults

The failure of power line equipment and/or faults on the power lines that create ignition mechanisms can be grouped as follows.

1. Failing or faulted apparatus
2. Conductors contacting in the air (e.g. phase-to-phase or ground faults).
3. Downed conductors arcing to ground.
4. Vegetation-caused faults.

Failing or Faulted Apparatus

A distribution feeder consists of thousands of components which include switches, clamps, bushings, lightening arrestors, transformers, capacitors, etc. Any apparatus carrying electric current/voltage or connected to a power line may experience insulation failure resulting in overheating, burning, arcing, or explosion. These failures most often occur while the apparatus remains in the air.

Common examples of failing or faulted apparatus include bushing flashovers, which result in intermittent high-current fault events that may self-heal and possibly reoccur over time. Each flashover event represents an opportunity for catastrophic failure, emission of burning metal particles, or arcing, and therefore any such event can cause ignition.

Another failure mechanism is the relatively low current or "leakage" current failures of various insulators, switches, or clamps. Leakage currents on damaged, dirty, or broken insulators can ignite wooden crossarms. The arcing of a loose clamp or switch can result in emission of molten or burning metal that represents a competent ignition source.

Conductor Slap

The phase-to-phase faults caused by contact of conductors in the air can result in ignition of ground-level vegetation. Heavy winds can result in the contact of two phase conductors or a phase to neutral, particularly where there is excess sag or other structural conditions that allow conductors to move into close proximity. Other conductor-to-conductor faults that cause fires are caused by fault-induced conductor slap (FICS). [3] A case study to follow explains FICS more fully. Current research suggests FICS is a more common occurrence than previously thought. Other phase-to-phase fault conditions can occur when conductors are pushed together by trees or falling vegetation or by leaning poles which have altered the conductor separation distance.

Downed Conductors

The most commonly understood fire cause is a downed, arcing conductor. Broken conductors may result from a wide variety of conditions, including accidents involving poles (e.g. car hits pole) or the failure of an insulator or cross arm dropping a conductor to the ground. In these cases, arcing may continue for minutes if a high-impedance fault occurs, limiting fault current below protection device settings. Fire danger is high. As shown in the following photograph (Figure 1), arcing to earth, asphalt, or concrete creates extreme temperatures and also ejects molten particles capable of starting a fire. [4-5]

Figure 1

Vegetation-Induced Faults

Faults due to vegetation on power lines that result in fires are uncommon, but do occur. The mechanisms for vegetation-caused faults must be understood clearly as we attempt to limit power line-caused wildfires. Definitive research to better understand faults due to vegetation intrusion has been conducted by researchers of the Power System Automation Laboratory at Texas A&M University. A detailed discussion of the various ignition mechanisms is included in a technical report entitled “Reliability Based Vegetation Management Through Intelligent System Monitoring.” [6]

Vegetation-caused faults have multiple mechanisms. Falling trees or large limbs may result in mechanical tear down of conductors and result in arcing that causes fires. This is the most common form of fires caused by vegetation intrusion. It has been estimated that 80% of all vegetation-related problems with power systems are the result of falling trees or branches, often from trees that are off the electric utility's right-of-way.

Vegetation also can cause fires through non-mechanical mechanisms. One mechanism that can occur is for a branch to simultaneously contact a phase conductor and neutral. When the separation distance of these two conductors is sufficiently short, very low current flow can occur (e.g. tens of milliamps) for a long period of time. This can result in a charring of the vegetation, with the end result of an arcing fault. An example of such a condition is shown in the following photograph (Figure 2). Here a branch is in contact with a 7,200-volt phase conductor and a neutral conductor. Initial currents were low, and only scintillation was observed during that initial period, but after four minutes of charring and burning, a higher-current flashover fault occurred.

Figure 2

Non-mechanical vegetation faults are relatively uncommon on single-phase taps of 15kV-class feeders (e.g. 7,200 volts to ground). Vegetation from a growing tree contacting a single-phase conductor at 7,200 volts creates insufficient voltage gradient to cause a high-current fault. Work by Texas A&M University and independently by Dr. John Goodfellow have shown that a voltage gradient exceeding 2kV per foot generally is necessary for development of a vegetation-induced fault. [7] At 7,200 volts to ground, a conductor-to-conductor separation distance of less than four feet typically would be required for a branch or other vegetative material to cause a short circuit. Vegetation spanning two phase conductors is more likely to cause burning and flashover, because the higher phase-to-phase voltage and the relatively close conductor separation result in a higher voltage gradient, often exceeding 2kV per foot.

Case Studies

This section provides case studies involving power line faults and failures that constitute potential sources of wildfire ignition. These case studies represent real examples, documented as a part of ongoing research at Texas A&M University.

Case 1: Multiple Flashovers and Eventual Burn-Down Resulting from Tree Branch

A branch broke free from a tree and fell across a single-phase line. The line was constructed with the phase conductor atop the pole and the neutral conductor attached several feet below. An offshoot of the broken branch hooked over the phase conductor, causing the branch to hang on the phase conductor. The branch was heavy enough to sag the phase conductor and also long enough to contact the neutral conductor below. As a result, the branch made good contact with the phase conductor and at least intermittent contact with the neutral conductor.

A previous section discussed the process that occurs when a branch spans two conductors at different potentials. This example demonstrates some of the implications of that process. Following a presumed period of low-current scintillation, the spanning branch caused an 800-amp flashover. A three-phase line recloser tripped to clear the fault, momentarily interrupting 140 customers. It reclosed successfully two seconds later. An hour later (11/02/2004 07:58:33 in the table below), the branch caused another flashover. The line recloser tripped and reclosed. Fault current resumed, so it tripped and reclosed again. The second reclose was successful, and no further activity of note occurred immediately. Sixteen hours later, the branch caused another fault, accompanied by another single-momentary operation of the recloser. As shown in the table below, multiple additional flashovers and recloser operations occurred in the six hours that followed. At the end of this period, approximately 24 hours after the first flashover, cumulative damage from the repeated high-current flashover arcs resulted in the phase conductor breaking and falling to the ground, at which point the recloser tripped three times and locked out.

The table below illustrates the timeline of flashover faults and momentary interruptions leading to the burn-down. Of note, until the conductor broke and the sustained outage ensued, the utility received no complaints from any of the 140 customers downstream of the recloser, despite the numerous momentary interruptions in the 24-hours period. The photograph shows the offending tree branch, whose surface shows significant, visible charring and burning.

Date/Time		Operations	
11/02/2004	06:57:47	1	
	07:58:33	2	
11/03/2004	00:09:06	1	
	00:16:48	1	
	00:40:38	1	
	00:40:53	1	
	01:10:51	1	
	01:12:37	1	
	01:15:30	1	
	03:24:47	1	
	04:19:39	1	
	04:30:36	1	
	05:51:01	1	
	06:19:45	3	(burn down)
Total Recloser Operations		**17**	

In addition to obvious reliability impairment and safety implications, this case illustrates multiple fire hazards associated with vegetation-induced flashovers and line burn-down:

1. Each flashover event involved a high-temperature flashover arc, generating concentrated energy sufficient to ignite proximate vegetation or other items. Had environmental conditions been more conducive to fire, each flashover event had the potential to cause ignition.
2. Each flashover event likely ejected hot particles. Particularly in situations involving aluminum conductors, whose particles not only melt but can combust, these particles represent competent ignition sources for underlying vegetation or other matter.
3. Both scintillation and flashover faults could ignite the branch itself. In such a case, even if the branch eventually falls free without burning down the line, the burning branch represents a competent ignition source.
4. Cumulative damage from the repeated flashover events eventually weakened and broke the conductor. Broken conductors may remain energized for extended periods of time before tripping conventional protection. During such a time, the downed conductor typically produces violent, high-temperature arcing capable of igniting proximate vegetation or other objects.

Case 2: Fault-Induced Conductor Slap

In a 2003 IEEE paper, Dominion Virginia Power's Daniel Ward documents and mathematically analyzes the phenomenon of fault-induced conductor motion, with particular emphasis on how such motion can cause conductors to slap together, causing additional faults and outages. [2] Fault-induced conductor slap (FICS) typically occurs when a fault trips a sectionalizing protection device, isolating that fault, but pre-trip fault current created sufficient magnetic forces to cause conductors upstream to swing together. This contact causes a second fault, which occurs upstream of the sectionalizing protection device, and which has higher fault current than the initial fault. Because the second fault occurs upstream of the sectionalizing device, upstream protection must trip to clear the second fault. FICS has multiple practical ramifications, including feeder-wide outages for faults that line reclosers otherwise should have sectionalized.

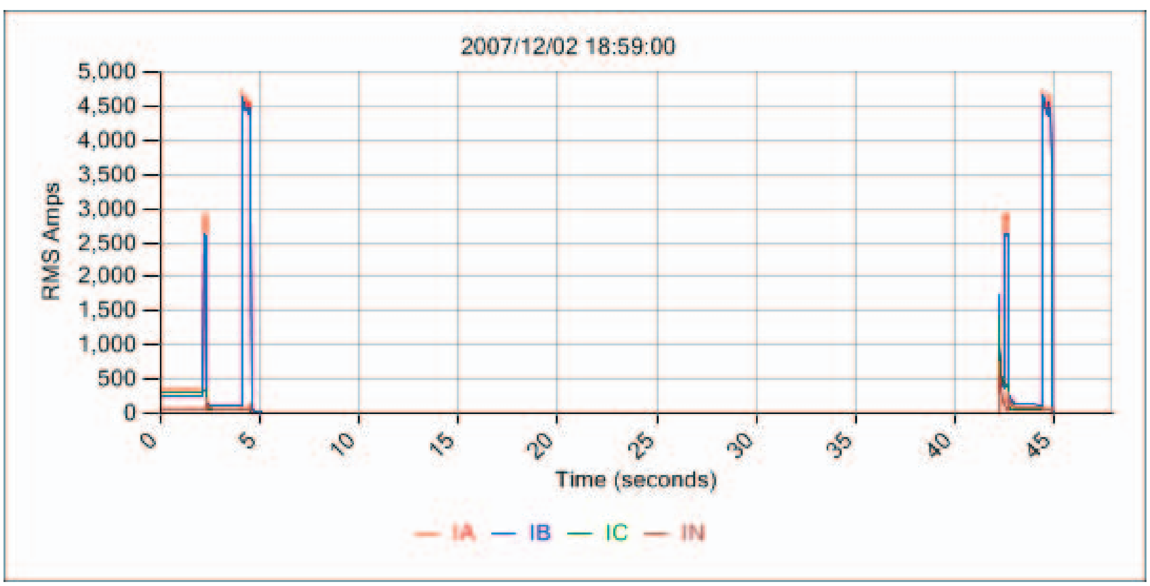
The plot near the end of this case study uses a measured example to illustrate the sequence. Here an initial fault of approximately 2,800 amps occurred and was tripped by a sectionalizing recloser. Two seconds later, however, FICS from that initial fault created a second fault, this one of 4,500 amps, necessitating a trip by the substation breaker. The breaker reclosed 38 seconds later, but the entire fault sequence immediately reoccurred, resulting in a second operation of the substation breaker, which locked out the whole feeder of 4,000 customers.

An interesting aspect of FICS faults is that they tend to reoccur, in exactly the same span, although there may be long intervening periods. Over a period of 50 months, the aforementioned research at Texas A&M documented FICS five times at exactly the same location on the same feeder. The five dates of occurrence appear in the table below the plot, and a photograph of the offending span appears next to the table. Reoccurrence in a given span occurs because line conditions, in this case line separation, make certain spans susceptible to FICS. Inset in the photograph is a close-up view of the arc-pitted conductors found in the offending span.

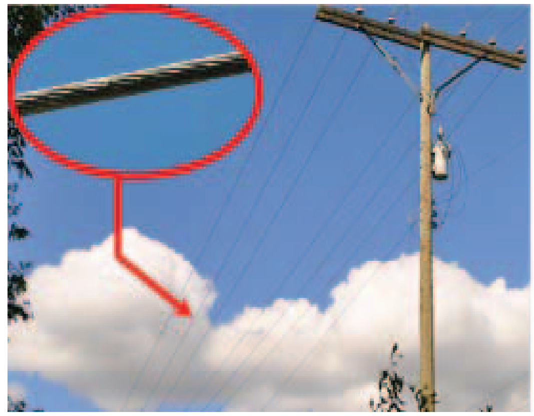
Lest the reader think this case an anomaly, it should be noted that the aforementioned research program has documented FICS on multiple feeders at multiple utilities, and reoccurrence in a given span is not unique to the specific case detailed above.

In addition to obvious reliability impairment, this case illustrates multiple fire hazards associated with FICS:

1. Each FICS-induced fault causes conductors to clash together, generally resulting in a high-current arc and the ejection of hot metallic particles. As previously noted, in cases involving aluminum conductors, these particles may combust during their descent, rather than cooling.
2. Each FICS-induced fault creates arc damage to conductors. A conductor, particularly a large conductor, may withstand multiple such events, but conductor damage accumulates, weakening the conductors and eventually creating the possibility of a conductor breaking and falling to the ground energized.



Date	# Breaker Operations	Result
11/12/2007	2	Momentary Interruptions
12/02/2007	2	43-Minute Lockout
11/13/2009	2	36-Minute Lockout
11/18/2009	1	Momentary Interruption
12/25/2011	2	13-Minute Lockout



Preventing Wildfires
As previously stated, many power line fires can never be prevented because they occur for reasons outside the control of the electric utility. Accidents that bring down lines or adverse conditions that cause power line failure when distribution feeders are stressed beyond design limits can never be prevented. However, the detection, identification, and repair of failing apparatus or improper operating conditions should be a high priority for electric utilities. Failing devices may exhibit multiple reoccurring high-current faults over weeks or months prior to catastrophic failure. As shown in the case studies above, the operation of protective devices over many hours, days, or weeks can be a definitive indication of an adverse operating condition or a failing piece of apparatus. Prompt attention and repair or correction of such failures or conditions can reduce the statistical probability of fire causation.

Improved intelligent monitoring of distribution feeders to find and correct incipient failures not only will result in increased customer reliability and improved service continuity, but also will reduce the probability of fire causation and reduce the possibility of conditions that may create public safety hazards.

In the future, the operation of distribution feeders should emphasize improved monitoring, intelligent and autonomous analysis of data to create actionable information, and diligent response and correction of failures as they are identified.

Summary
Power line failures are a common cause of wildfires. Although some conditions can never be corrected, certain incipient failure mechanisms on power lines and in apparatus can be identified and corrected before catastrophic failure results in fires. Ignition mechanisms include arcing conditions, ground faults, phase-to-phase faults from a wide variety of causes including broken devices, vegetation-caused short circuits, and overheating and burning conditions. Better knowledge of fire causation events can help electric utilities prevent some wildfires from occurring.

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