Improving Situational Awareness to Reduce the Wild re Risks of Operating Power Distribution Infrastructure

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I would like to thank Professor Dutta for his guidance and mentorship throughout my academic pursuits at UC Berkeley. The opportunity to conduct research under him through Lab11 has been an experience I will always remember. I would like to give special thanks to Riley Lyman for helping me gather data during my experiments. Lastly I would like to thank my wife Rebecca for her unwavering support throughout the many hours I dedicated to my research.

Improving Situational Awareness to Reduce the Wildfire Risks of Operating Power Distribution Infrastructure

by

Timothy Jonathan Barat

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Professor Prabal Dutta, Chair
Professor Seth Sanders

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Improving Situational Awareness to Reduce the Wildfire Risks of Operating Power Distribution Infrastructure

by Timothy Jonathan Barat

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Abstract

Improving Situational Awareness to Reduce the Wildfire Risks of Operating Power Distribution Infrastructure

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Masters of Science in Electrical Engineering and Computer Sciences

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Electricity distribution infrastructure has caused some of the worst wildfires in California's history, including it's deadliest. During extreme weather, utilities do not have complete situational awareness of their equipment and the risks of operating power infrastructure often becomes too great. They are left with no choice but to de-energize their grids with preventative power shutoffs. This paper examines whether the ignition sources of wildfires caused by electricity distribution infrastructure emit mechanical signals during and prior to ignition. Preliminary experimental data is presented to suggest that mechanical signals caused by flashover arcing on conductors are detectable by pole-mounted accelerometers. Further experimental data is presented to suggest that a constant mechanical oscillation exists in power lines due to electromagnetic forces. The data also suggests that deviations in the structural integrity of poles may change this input oscillation as it travels through the pole and that these changes may be detectable by pole-mounted accelerometers. This knowledge highlights the importance of further research into the mechanical signals which occur on electricity distribution infrastructure and a promising opportunity to use accelerometers to decrease wildfire risk with real-time detection of failure modes and incipient faults.

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Chapter 1

Introduction

1.1 Motivation

Ever since Samuel Morse strung 40 miles of telegraph wires above the ground in 1844 to transmit the first telegraph, wooden utility poles have served as the back bone of our nation's power and telecommunications network. Utilities in the United States maintain over 150 million poles as support structures for almost 6 million miles of power lines that link power generation plants to factories, homes and businesses. The standard wooden utility pole is generally rated for a life-span of 50 years and the conductors it supports can last over 100 years. Although the poles, conductors, and various other pieces of overhead power distribution equipment have rated life-spans between 25 to 100 years, they are prone to multiple types of non-linear deterioration that can dramatically reduce their life expectancy and lead to failure. On the contrary, some equipment often lasts well beyond it's rated lifespan. To decide when equipment needs to be repaired or replaced, manual inspections are conducted on cyclic schedules, usually once every 10 years and are otherwise left unobserved. This means distribution equipment is either over-built or under-built, and may continue to be operable when it shouldn't be. Accelerated degradation, faults or failures often remain undetected until they are noticed by the general public, a fuse is tripped, or a fire is ignited.

During extreme weather, power distribution equipment can succumb to duress from elevated wind conditions. These elevated wind conditions can also cause vegetation to blow into contact with power lines. Power lines travel through grasslands and forests along the wildland-urban interface and the vegetation directly below or adjacent to the power lines can be dense and highly flammable. Regulations require utilities to ensure vegetation does not encroach within set boundaries around power lines but the large costs associated with continually removing vegetation growth make this difficult to enforce. Due to the high amounts of voltage travelling through power lines, faults or equipment failure can cause sparks or sustained arcing to occur. The combination of elevated wind conditions, equipment failure, sparks, dense vegetation, and the proximity of all these conditions to communities on the wildland-urban interface create a favorable environment for catastrophic wildfires.

Between 2014 and 2017, electricity distribution and transmission equipment ignited 2009 fires in California. In 2017, 8 of the 12 fires during a deadly firestorm in Sonoma Country were ignited by vegetation contact and downed power lines. The firestorm claimed 46 lives and caused $9 Billion in damages. In 2018, the failure of a transmission cable hook on a structure in Butte County, California ignited the Camp Fire resulting in the state's deadliest and the world's costliest blaze. 85 lives were lost and damages exceeded $16.65 Billion. In 2019, a wildfire ignited by power lines ripped through Sonoma County causing $725 Million in losses and the evacuation of 190,000 people. In 2020, a tree coming into contact with power lines is suspected of causing the Zogg Fire in Shasta county which killed 4 people.

The locations where distribution equipment will ignite a fire are difficult to predict or even detect. To avoid ignitions during elevated wind conditions, utilities in California have been forced to de-energize large areas of the grid during planned Public Safety Power Shutoffs. These shutoffs can span multiple days and lead to economic impacts that exceed $2.6 Billion per occurrence. The societal and political coping costs of these shutoffs have only served to highlight the absence of real time situational awareness across distribution equipment. These factors point to a need for the accurate detection, prediction, and localization of ignition sources in real-time. This would enable grid operators to respond to ignitions rapidly, proactively perform repairs, and reduce the scale of shutoffs.

1.2 Thesis Statement

There are three main wildfire ignition sources which originate from power distribution equipment, high voltage arcing near dry grass, vegetation conducting high voltage current, and molten particles dropping into dry grass[9]. *We hypothesize that the failure modes which occur before, during, and/or after ignition from these sources emit mechanical signals which are detectable by accelerometers attached to wooden power poles.*

Chapter 2

Background and Related Work

Two of the most commonly reported metrics for the reliable delivery of power to ratepayers are the System Average Interruption Duration Index (SAIDI) and the System Average Interruption Frequency Index (SAIFI).[4] To increase reliability across these metrics, regular cyclic inspections are conducted across distribution and transmission equipment. These inspections are primarily carried out by visual patrols on foot, in vehicles, or from the air. When abnormalities are discovered, their severity is determined and repairs are accordingly prioritized. Some abnormalities. such as internal pole decay, transformer degradation or insulation breakdown are very difficult to detect visually. To detect internal pole degradation, inspectors conduct sounding tests, where the pole is struck with a hammer and the pole's integrity is determined by how it sounds. If deemed necessary, inspectors will proceed to conduct a bore test, where a hole is bored into the pole and it's integrity is determined by the wood's resistance to the drill.

Coupled with expanding evidence that electrically caused wildfires have severely greater consequences than from most other causes[9, 8], three major events are driving the adoption of technologies that mitigate electrically caused wildfires. Class action lawsuits were filed against SP Ausnet and Utility Services Group for the alleged ignition of fires during Australia's deadliest bushfire disasters, the Black Saturday bushfires in 2009. The Supreme Court of Australia approved the country's largest class action settlement of A$494 million. In a case that proceeded to the Supreme Court of the United States, San Diego Gas and Electric was held liable for $379 million of damages caused by the Witch, Guejito, and Rice fires in 2017. Previously, utilities in California had passed wildfire damages onto ratepayers. In response to the devastation of the Camp fire in 2018 which also led the Pacific Gas and Electric company to file for bankruptcy, California passed assembly bill 1054 to create a dedicated Wildfire Safety Division of the California Public Utilities Division and increase the regulatory scrutiny of wildfire mitigation efforts conducted by utilities. The bill also mandated utilities to invest $5 Billion in safety improvements, tie executive compensation to safety performance, and conduct new inspections of utility electrical equipment.

In this section we explore four technologies that have been developed to detect failure modes of power distribution and transmission equipment and prevent wildfire ignitions.

2.1 Automatic Circuit Reclosers (ACR)

Automatic Circuit Reclosers function similarly to standard circuit breakers or fuses except that they have the ability to automatically reclose. Often faults or circuit currents that are perceived to be faults occur that are transient and disappear after the circuit breaker has tripped. The issue with standard circuit breakers is that they must be reset manually. ACR's solve this issue by enabling the circuit breaker to trip and reclose multiple times before having to be reset manually. This allows fault current thresholds to be much lower and trip during High Impedance Faults. High Impedance Fault currents are very low and research has shown fault currents of 500mA can lead to ignition. [2]. The biggest weakness of ACR's is that if a sustained fault occurs such as a grounded power line, each time the ACR recloses, the fault current is re-introduced and can ignite a fire.

2.2 Rapid Earth Fault Current Limiters (REFCL)

In response to the Black Saturday disaster in Victoria, Australia, a research study was commissioned by the Victorian government to evaluate the performance of Rapid Earth Fault Current Limiters as a preventative solution to wildfire ignitions caused by power lines [5]. REFCL's are installed at the substation to monitor for currents between each phase to earth. They function by rapidly detecting phase to earth fault currents, usually within milliseconds and then limiting the voltage of the fault to below the point where ignition would occur. These phase to earth fault currents occur when grounded trees make contact with power lines or when power lines fall and make contact with the ground. When grounded trees or branches make contact with power lines, ignition occurs from resistive heating as current travels through the vegetation down to earth. The vegetation gets so hot that it ignites. When power lines fall and make contact with the ground, arcing occurs as the power line approaches the ground and as it bounces to rest. As the power line repeatedly approaches the ground, dry grass or vegetation that is present between the ground and the power line is ignited by the arcing. Although REFCL's have demonstrated their capability to dramatically reduce the risk of ignition from phase to ground faults such as grounded vegetation contact and fallen power lines, they have five weaknesses. Firstly, REFCL's cannot detect phase to phase faults such as a branch between two power lines. Secondly, after an REFCL has operated, further diagnostic tests must be conducted to determine if the fault is permanent or transient. Automatic diagnostic tests have been shown to result in ignition. Thirdly, if the fault is persistant, REFCL provides no insight into the location of the fault, leaving lineman to search across miles for the cause of the fault. Fourthly, REFCL's cannot detect incipient faults such as persistent micro-arcing caused by insulation breakdown. Fifthly, the deployment of REFCL's causes significant disruptions to the grid and most circuits require significant equipment upgrades to support it.

2.3 Distribution Fault Anticipation (DFA)

Distribution Fault Anticipation functions through real-time analysis of feeder electrical waveforms. Measurements are captured from Current (CT) and Potential (PT) transformers at the substation bus. These waveforms are analyzed using algorithms developed with historical labelled data to detect, characterize, and classify distribution equipment failure and pre-failure modes [10]. DFA has proven effective at detecting many different failure and pre-failure modes that result in detectable anomalies in the electrical signatures at the substation [1]. These modes include intermittent tree contact and the incipient failure of a power line clamp caused by series arcing which was detected and repaired before it failed. DFA has two main shortfalls. Firstly, the DFA system takes over two seconds to classify non-incipient faults and would not be a suitable candidate to de-energize power lines in time to avoid ignition. Secondly, the DFA system must be coupled with other systems to provide insights into the location of the faults it can detect.

2.4 Early Fault Detection (EFD)

Early Fault Detection uses directional antennas mounted on poles three miles apart to detect partial discharge (PD) signals generated by failing equipment. The EFD system processes the PD signals with FPGA's and then forwards filtered data to a secured cloud server. If a fault signal is detected, the system uses time of flight principles to compare timestamps from the two units which registered the signal first and locate the fault [13]. The system has been proven to detect multiple incipient faults before ignition could occur. These incipient faults included broken power line strands and internal equipment insulation breakdown in pole top transformers. EFD does not suffer from any of the weaknesses of REFCL and DFA technologies. EFD is designed to detect incipient faults early and available information does not provide enough information to determine if the system can detect un-expected faults such as trees blowing into power lines fast enough to de-energize the circuit before ignition can occur.

2.5 Summary

While these technologies can be greatly beneficial to mitigating electrically caused wildfire ignition events, they leave several problems unaddressed. The molten particles ejected from conductor slap during high winds or pole failure are unable to be stopped once midair. Conductor slap occurs as conductors swing in high winds or in freefall after a pole has failed. Both of these events remain undetected by the technologies outlined above until it is too late and conductors have made contact. Furthermore, the technologies all rely on electrical sensing and therefore require the grid to be energized. During planned or unplanned power outages, any damage or failure modes introduced while the equipment is de-energized remain undetected. Every mile must be comprehensively inspected before re-energization in a process that can take days.

Chapter 3

Common Faults and Their Mechanical Signatures

There are three main wildfire ignition sources which originate from power distribution equipment.

3.1 High voltage arcing near dry grass

When energized high voltage power lines fall and approach the ground, high energy arcs or flashover arcing occurs. If dry grass or vegetation is located near to the point of contact, it will almost certainly ignite. There are multiple reasons why power lines can fall and hit the ground. All of these failure modes emit mechanical signatures during ignition. The failure modes and their sources of mechanical signatures are described as follows:

- Trees falling onto and dragging conductors to the ground - The impulse from impact emits vibrations that travel through the conductors, attachments, and support structures.

- Failed clamps or power line attachments - The impulse from failure and conductor dislocation emits vibrations that travel through the conductors, attachments, and support structures.

- Failed support structures such as poles and cross arms - Vibrations are emitted as the structures fracture and acceleration occurs as the structures respond to gravity and fall to the ground.

- Failed conductors - Vibrations are emitted as the conductor snaps and falls to the ground. These vibrations travel through the conductors, attachments, and support structures.

- Arcing produced by conductors near the ground - The high energy arcing that occurs as power lines bounce on the ground produce acoustic emissions which travel through the conductor, attachments, and support structures.

3.2 Vegetation conducting high voltage current

Vegetation that makes conduct with power lines can either create a phase to phase fault path when a branch bridges two conductors or a phase to ground fault path when a grounded tree contacts a conductor. As the vegetation conducts the fault current, it experiences four stages of fault development [6].

- Sparking at contact points on the conductor - During this phase, small sparks occur as the vegetation begins to heat.
- Expulsion of moisture - This phenomenon occurs as moisture inside the vegetation is rapidly heated. The moisture expands, ruptures the exterior of the vegetation and whistling occurs as the steam escapes through small slits in the outermost layers of the vegetation.
- Ignition - Flames begin to slowly spread across the surface of the bark causing charring. Often pieces of flaming bark drop to the ground below.
- Flashover - When the flame extends and is unbroken across the fault path, large flashover arcing occurs.

Mechanical signals are emitted as the vegetation contacts the conductors, from acoustic whistling as moisture escapes, and when flashover occurs. These signals travel through the conductor, attachments, and support structures.

3.3 Molten particles dropping into dry grass

Some equipment failure modes produce molten particles which can drop to the ground below. If they come into contact with dry grass, ignition can occur. These failure modes include:

- Conductor slap - High winds can cause conductors to swing into each other resulting in a phase to phase fault current. Conductor slap can also occur when another phase to phase fault occurs downstream of the substation. The downstream fault causes conductors to dramatically repel from each other. When the downstream fault is cleared, the conductors relax and swing into each other. When the conductors clash, areas of metal at the point of contact melt and fall to the ground. The impact of the clash emits vibrations which travel through the conductors, attachments, and support structures.

- Switches, Fuses, Transformers, Capacitor Banks - Over time, the integrity of these pole top devices decreases and many failure modes can occur. These failure modes usually involve small partial discharges that progressively damage the equipment before a large flashover arc occurs. The vibrations emitted by the large flashover arc travel down into the support structures.

3.4 Mechanical signatures associated with incipient failures

All of the failure modes outlined above emit mechanical signals during the ignition event. However several modes begin to emit signals before the ignition.

- High voltage arcing from fallen power lines - The failure modes involving conductors falling to the ground all begin with an impact or impulse at the time the power line begins to fall and travel to the ground. This impact or impulse emits vibrations which travel through to the support structures. Overhead power lines are subject to strict guidelines set by Table 232-1 of the National Electric Safety Code (NESC) for minimum height clearances above the ground. At minimum power lines must have 12ft of clearance but they usually have around 30ft [12]. The shortest amount of time taken for the conductor to reach the ground is governed by the well known equation $d = \frac{1}{2}gt^2 \rightarrow t = \sqrt{\frac{2d}{g}}$. At 12ft, the conductor will take 0.86 seconds to reach the ground and at 30ft, the conductor will take 1.37 seconds. During this time, the mechanical signal will travel through the conductor at the speed of sound (6320 $^{m}/_{s}$ through aluminum) and down into the support structure. Assuming a maximum conductor span between two support structures of 100m, it will take at most 7.9ms for the signal to reach the closest structure. This leaves almost 0.8 seconds for de-energization of the conductor before it hits the ground.

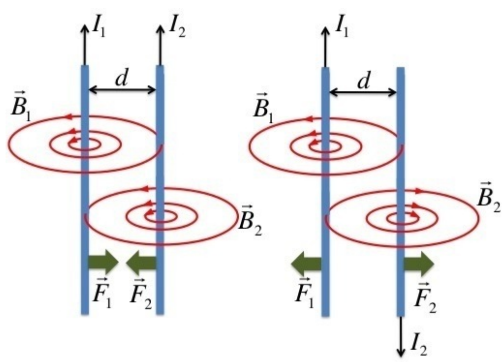
- Failure of support structures such as poles and cross arms - The deterioration of poles and cross arms can be detected through standard manual inspections. However, these inspections often only occur every 10 years and the methods currently employed do not always detect internal damage. During this time, non-linear degradation can occur, leaving the support structures prone to failure during a high wind event. The mechanical forces on parallel current carrying AC power lines include a periodic repulsive force between them [7] (Equations 3.1). These forces induce a steady 120Hz oscillation in the conductors [3] (Figure 3.1), which travel into the support structure at the point of attachment. As these oscillations travel through the support structures they are transformed by the medium they are travelling through. If degradation is present in the structure, it transforms the signature in proportion to the level of internal damage.

$$\hat{F}_1(i,d,l,t) = \frac{1.26 \cdot 10^{-6} \cdot i^2 \cdot l \left[\sin\left(120\pi t\right) \cdot \left(2 \cdot \sin\left(120\pi t + \frac{2\pi}{3}\right) + \sin\left(120\pi t + \frac{4\pi}{3}\right)\right)\right]}{4\pi d}$$

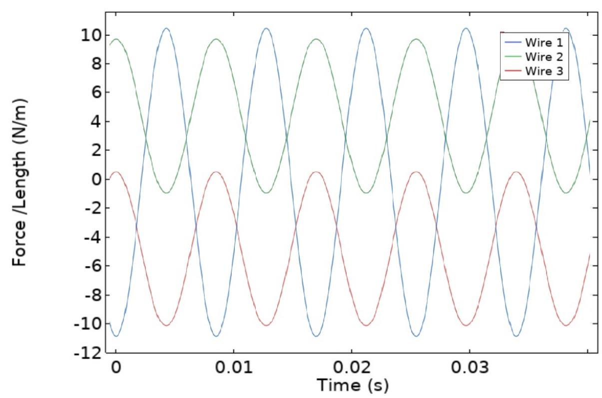
$$\hat{F}_2(i,d,l,t) = \frac{1.26 \cdot 10^{-6} \cdot i^2 \cdot l \left[\sin\left(120\pi t + \frac{4\pi}{3}\right) \cdot \sin\left(120\pi t + \frac{2\pi}{3}\right) - \sin\left(120\pi t\right) \cdot \sin\left(120\pi t + \frac{4\pi}{3}\right)\right]}{2\pi d}$$

$$\hat{F}_3(i,d,l,t) = -\frac{1.26 \cdot 10^{-6} \cdot i^2 \cdot l \left[\sin\left(120\pi t\right) \cdot \sin\left(120\pi t + \frac{4\pi}{3}\right) + 2 \cdot \sin\left(120\pi t + \frac{2\pi}{3}\right) \cdot \sin\left(120\pi t + \frac{4\pi}{3}\right)\right]}{4\pi d}$$

Equations 3.1: Forces on 3 parallel AC current carrying conductors



(a) Electromechanical Forces



(b) Forces on 3 AC Current Carrying Conductors

Figure 3.1: Forces on 3 phase AC conductors

- Vegetation conducting high voltage current - When the vegetation first comes into contact with a conductor, and through out the first sparking phase, mechanical signals are being emitted which travel through the conductor to the support structure. This phase can last as long as a minute or as little as a few seconds [6]. Governed by the same principles as the previous item, this time can be used to de-energize the conductor before the vegetation ignites.

- Molten particles from conductor slap - During high winds, conductors experience three types of wind induced oscillations; Aeolian vibration, galloping, and subspan oscillation [11]. As the magnitude of these oscillations increase, the conductors approach each other and can eventually clash. These oscillations result in large mechanical forces on the point of attachment which propogate throughout the support structure. The magnitudes of these forces can be used to detect when conductors may clash and de-energize them before they can drop molten particles.

3.5 Summary

All of the failure modes on power distribution equipment which can lead to wildfire ignition emit mechanical signals as they occur. These signals are all present on the support structure and if efficiently detectable could be used to alert grid operators for rapid response after ignition. Additionally, some failure modes emit mechanical signals which are present on the support structure during the incipient stage and if detectable could be used to avoid ignition altogether by preventative shutoff.

Chapter 4

Evaluation

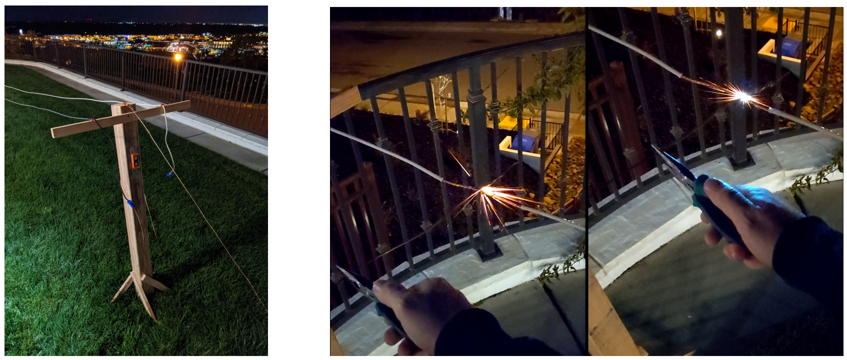
A simulation and an experiment was designed to explore the following questions:

1. Are acoustic emissions from flashover arcing on a conductor detectable by an accelerometer attached to the wooden pole supporting the conductor?
2. Are acoustic emissions from vegetation contact on a conductor detectable by an accelerometer attached to the wooden pole supporting the conductor?
3. Do the forces experienced by parallel current carrying conductors result in a steady oscillation at the points of attachments to the wooden pole supporting the conductors?
4. Does the integrity of a wooden pole transform the steady oscillation from the conductors enough to be detectable by an accelerometer attached to the pole?

4.1 Methodology

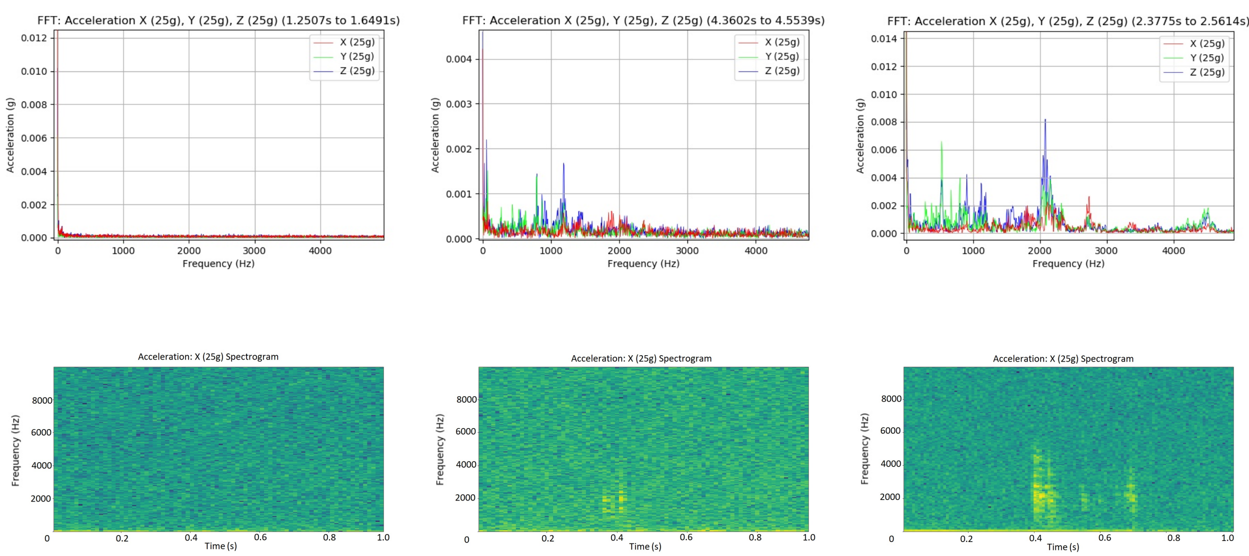
Flashover Arcing Experiment

To explore Questions 1 and 2, a physical experimental setup was constructed to simulate the occurrence of flashover arcing and vegetation on a span of conductors. 50 feet of parallel 0 gauge insulated copper conductors was supported by two 6 inch by 6 inch pine timber posts and two pine cross arms. An over-current protection device was installed in an enclosure mounted on one of the posts to connect a 110V mains lead to the 0 gauge conductors. The conductors were unsheathed at 10ft intervals to facilitate phase to phase fault currents. A 12 gauge copper conductor was used to intermittently bridge the live and neutral conductors and cause flashover arcing. An Endaq S3-E25D40 Piezoelectric accelerometer was attached to the other post and 126 measurements were obtained across multiple conditions. Vibration measurements across 3 axes were captured at a sampling rate of 20kHz during 10 flashover arc events, 55 vegetation contact with no arcing events, and 60 time intervals during serene conditions. The measurements were truncated to ± 0.5 seconds around the event, then downsampled before a FFT was performed to transform the data into 512 frequency amplitude buckets. A K-neighbors classifier was trained using these measurements with a 25% training split. The classifier performed with 91% accuracy on the test data set. The preliminary



(a) Setup (b) Flashover Arcing

Figure 4.1: Flashover Arcing Experiment



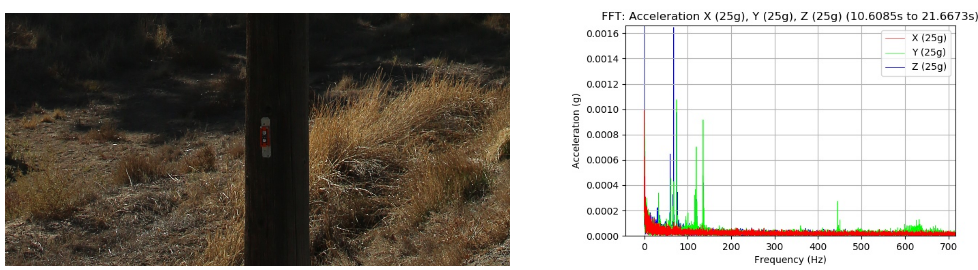
Serene Conditions Vegetation Contact Flashover Arcing

Figure 4.2: Frequencies detected on post during Flashover Arcing Experiment

data suggest that acoustic emissions from flashover arcing and vegetation on a conductor is likely to be detectable by an accelerometer attached to the wooden pole compared with serene conditions. Future work may explore richer features, deeper analysis of false positive and false negative rates, and characterization of the background environment.

Pole Degradation Experiment

To explore Questions 3 and 4, measurements were obtained from 103 in service wooden utility poles located in Grand Junction, Colorado. The poles were professionally inspected with sound and bore tests 7 days prior to taking the measurements and 13 poles were determined to contain internal heart rot or decay. An Endaq S3-E25D40 Piezoelectric accelerometer was temporarily attached to each pole at heights of 10cm and 110cm with 2 screws torqued to 21Nm. The accelerometer was positioned so that the z-axis was always parallel with the conductors supported by the pole. 30 second measurements were captured at a 20kHz sampling rate, then downsampled before a FFT was used to transform the signals into 7000 frequency buckets. A K-Neighbors classifier was trained using these measurements with a 25% training split. The classifier performed with 83% accuracy on the test data set correctly identifying 3 of 3 sensors as having heart rot/decay and misclassifying 3 of 15 sensors as having rot where none existed. The amplitude of the 120Hz frequency bucket was elevated



(a) Setup

(b) Spectral content of ambient vibrations

Figure 4.3: Accelerometer on in service pole

in the measurements however there was no obvious correlation between the spectral content and the presence of heart rot or decay in the poles. This suggests that although the preliminary study shows promise, further analysis is required to show the phenomenology in a human interpretable manner.

Experiment Code and Data is located at:
https://drive.google.com/drive/folders/1ZzJWGaHXrXNDu7YXVZzMQKgMu0ztOkKP?usp=sharing

Chapter 5

Discussion

The objective of this paper is to demonstrate the potential for pole-mounted accelerometers to detect and prevent power distribution equipment ignition sources. Further research is needed to solidify the claims outlined, however the findings show that some signals are present. In this study, a high performance sensor sampling at 20kHz was used, however low-power, low-cost accelerometers which can also sample at 20kHz and are sufficient to detect the mechanical signals described in this paper are readily available. A compelling opportunity exists for the development of a platform containing a low power accelerometer, a low powered mcu, a long range communications radio, and battery backed energy harvesting that is permanently attached to poles. These platforms would be deployed in a swarm fashion to provide robustness and redundancy.

The sparsity and variance in the signals associated with failure modes pose a challenge to the realization of pole-mounted accelerometers. There is still a large burden of proof required that failure modes can be reliably detected with a pole-mounted accelerometer. Without a wide scale deployment of sensors on in service poles, the probability of capturing actual data during these failure modes is low. An interesting question exists between the costs associated with increasing the number of sensors and the degree of evidence that would be obtained. Another option would be to perform deeper physics based, modelling and analysis on this data. Physics engines, modelling, and further lab experiments appear to be the most promising direction towards the realization of this technology.

Chapter 6

Conclusion

The analysis presented in this paper supports the hypothesis that ignition sources from power distribution infrastructure failure modes and incipient faults produce mechanical signals which may be present on wooden power poles. Results from two experiments suggests that mechanical signals from both flashover arcing on conductors and internal pole damage may be detectable with pole-mounted accelerometers. The motivation of the paper is to provide preliminary evidence that further research into mechanical signals on power distribution infrastructure will be useful towards decreasing electrical wildfire risk.

Further analytical and emperical research may explore the mechanical signals associated with each individual ignition source to better understand which features are best suited for resource constrained classification as well as the characterization of their ambient environments. Additional research may also explore system level design challenges associated with expedient data ex filtration, data management algorithms, energy harvesting methods, and attachment methods.

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