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Wildfire Risk Mitigation: A Paradigm Shift in Power Systems Planning and Operation

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ABSTRACT Managing the risk of wildfires has been arguably the biggest recent challenge of electric utilities with infrastructure located in the wildland-urban interface. Utilities are deploying solutions for wildfire risk mitigation, such as public safety power shutoffs, which are counter-intuitive from a reliability-centric operation paradigm. This article presents an overview of the challenges, implications, and potential strategies for wildfire risk mitigation in power systems, and introduces the vision for a wildfire-resilient power system. The wildfire risk management strategies presented in this article range from fault prevention methods such as structural hardening, vegetation management and implementing advanced protection systems, to arc-suppression and ignition prevention methods. This article also identifies relevant research opportunities associated with implementing wildfire mitigation techniques on power systems.

INDEX TERMS Wildfire risk mitigation, power grid resilience, proactive operation, wildfire-resilient power grid.

I. INTRODUCTION

THOUSANDS of miles of power lines have been developed in arid wildland-urban interface to provide electricity service to rural and remote communities. Power infrastructure in these locations is often aged and at risk of igniting catastrophic wildfires —endangering utility infrastructure, the natural environment, and the lives and property of nearby communities. For decades, power systems have been designed and operated so as to limit the frequency and duration of disruptions to power service as assessed by metrics such as the System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI). However, recent catastrophic events have challenged this reliability-centric paradigm and have exposed the need for new metrics and operating principles in the power industry. The concept of resilience has been developed and explored in power grids with the objective of quantifying and ultimately enhancing the ability of the grid to prevent and respond to low probability catastrophic events that may have a high or long-lasting impact on power grids performance [1]–[3].

Power system resilience has been broadly defined as ‘‘the ability of the power grid to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions’’ [4]. Resilience differs from reliability in that it focuses on high impact low probability events rather than mitigating disruptions to electricity service during normal operating conditions. Notable resilience studies have encompassed impacts to the power grid due to severe weather [5], [6], cyber/physical attacks [7], [8], and cascading blackouts [9], [10].

A plethora of research literature explores methods to quantify power system resilience through performance evaluation approaches. The authors in [11] propose a method to quantify the resilience of an infrastructure system by measuring its ability to: 1) resist or prevent hazards, 2) absorb initial damage, and 3) recover to normal operation. This process has been expended in [12]–[14], and a series of resilience metrics have been developed based on measuring the power system's performance over time. The impacts of an extreme event to the power grid can be quantified by considering, for example, the number of customers without power, amount of

TABLE 1. Notable wildfires believed to have been ignited by power systems.

Fire Name	Location	Year	Power System Related Cause[1]	Fatalities[2]	Approximate Economic Impact ($M)[2,3,4]
Camp Fire [19]	California, USA	2018	Under Investigation	86	$16,500.00
Woolsey Fire [20]	California, USA	2017	Under Investigation	3	$6,000.00
Thomas Fire [21]	California, USA	2017	Conductor Slap	2	$2,200.00
Gatlinburg [22]	Tennessee, USA	2016	Arson/Fallen Tree	14	$1,000.00
Bastrop County [23]	Texas, USA	2011	Fallen Tree	2	$279.08
Las Conchas [24]	New Mexico, USA	2011	Fallen Tree	0	$44.73
Horsham [25]	Victoria, Australia	2009	Fastener Failure		
Kilmore East [25]	Victoria, Australia	2009	Conductor Failure + Recloser		
Weerite (Pomborneit) [25]	Victoria, Australia	2009	Conductor Slap	173	$3,559.43
Beechworth [25]	Victoria, Australia	2009	Fallen Tree		
Coleraine [25]	Victoria, Australia	2009	Tie Wire		
Witch Complex [26]	California, USA	2007	Conductor Slap & Tie Wire	2	$1,656.85
Rice [27], [28]	California, USA	2007	Vegetation Interference	0	$8.04
Malibu Canyon [29]	California, USA	2007	Pole Overloading (Termite Damage)	0	$70.15
Ash Wednesday [30]	Vic & SA, Australia	1983	Vegetation Interference	75	$1,350.89

[1] Power Systems may not have been the only cause of wildfire ignition. Please refer to cited sources for more information.
[2] Fatality and cost estimates are aggregated for complex fire event.
[3] Economic impact values converted to 2018 US Dollar. If dollar-year was not explicit, date of publication was assumed.

load curtailed, or number of power system components made unavailable over the course of a catastrophic event. Resilience metrics quantify different aspects of power grid performance during extreme events, including the rate at which the system reaches its most severely degraded state, the extent of impact caused by a catastrophic event, the duration of time at which the power grid remains at a degraded state, and the rate at which electricity service is restored, among other metrics.

Policy and research literature has identified wildfires as a major natural disaster threat to the power system, and has also identified important challenges in mitigating the impacts caused by wildfires approaching power systems. The authors in [15] model the temperature increase of overhead conductors as a result of an approaching wildfire by use of heat transfer equations. The impacts of approaching wildfires on power systems operation have been formulated as an optimization problem for transmission systems and distribution systems in [16] and [17], respectively. Additionally, the authors in [18] demonstrate that, through proactive operation and selective power shutoffs through microgrid operations, wildfire risk could be effectively mitigated as a wildfire approaches a power distribution system.

Many of the studies in the literature consider wildfire risk to power systems to be a similar impact as other natural disasters —an externally caused, impending, and predictable phenomena from which power grid assets must be protected. However, recent wildfire events in Australia and California highlight the need for resilience-centric research literature to not only consider planning and operation strategies based on approaching wildfires, but also investigate mitigating catastrophic wildfire ignitions caused by power systems. In the last two decades, a number of notable wildfires have been ignited by power systems as shown in Table 1.

While power line ignition events occur relatively infrequently compared to other ignition sources (approximately 1% of wildfire ignitions in California are started by power systems), fires ignited by power lines tend to burn significantly more land area as compared to other ignition sources such as lightning or arson [30]. Power system infrastructure is often located among vulnerable communities who live in fire prone areas in the wildland-urban interface. As communities in the wildland-urban interface rapidly expand and grow, it is expected that power system wildfire ignitions will cause higher property damage and economic losses [31], [32].

The objective of this article is to provide a comprehensive review of planning and operation techniques that contribute to create a *wildfire-resilient* power system. In this article, a wildfire-resilient power system is visioned as one that not only possesses the qualities of a traditionally defined resilient grid, but also that mitigates catastrophic wildfire ignitions through a combination of planning, operation, and response strategies. This article focuses on mitigating strategies in power distribution systems, as a majority of faults, failures, and fires occur at the distribution level. This article identifies the myriad ways that wildfires and their subsequent impact can be mitigated, which are categorized as: 1) methods that prevent faults, 2) methods that prevent sustained ignitions of surrounding combustible fuel beds, and 3) methods that mitigate the impact of wildfires if an ignition caused by the power system occurs. This article also identifies a variety of planning and operation research opportunities in the area of wildfire mitigation that can be aligned with current utility grid modernization goals.

The remainder of this article is organized as follows: Section II provides a technical overview of wildfire ignition caused by power systems, and introduces a three pronged approach to wildfire mitigation covered in Sections III, IV, and V, which are described in detail subsequently. Section VI concludes the paper and provides an in-depth exploration for future research on wildfire-resilient power systems.

II. WILDFIRE IGNITION BY DISTRIBUTION SYSTEMS

Although faults, failures, and fires occur in nearly every subsystem within the power system, a vast majority of power system-related wildfires are caused by the distribution system. Distribution lines around the globe are scattered throughout arid wildland terrain that is susceptible to fire ignition [31]. In most known cases, wildfire ignition from power systems is initiated by an unintended fault or other form of catastrophic failure [33]. When power lines make contact with an external object, electricity flowing through that line may find an alternative path to ground causing a fault in the system. When this path to ground is realized, a high amount of current travels from the energized line to the ground through this path, inducing a high fault current in the line. Faulting causes an energy release along the path to ground, forming a high energy arc that can reach temperatures of up to 2240°C [34]. System protection devices such as circuit breakers and fuses are deliberately coordinated to detect fault current, and de-energize the faulted power line as quickly as possible.

Known wildfire ignition cases demonstrate a variety of ways whereby arcs can cause sustained ignition of a wildfire. Arcs can ignite surrounding fuels through direct contact, ignite a foreign object such as vegetation that makes contact with the energized line, and/or melt the metal conductor (typically made of aluminium and steel) causing molten metal particles or firebrands to be ejected from the power line onto the ground. These phenomena, as they relate to power system caused fire ignitions, have been studied in literature [34]–[36].

Thus, the overall likelihood that a wildfire will ignite on a section of distribution feeder has to do both with: 1) the likelihood that the line will experience a fault, and 2) that the resulting fault will ignite surrounding fuel beds, each of which is an unlikely event that depends on a variety of both controllable and uncontrollable factors [36], [37]. As such, the wildfire mitigation techniques explored in this article are categorized as follows, based on their role in mitigating wildfire occurrences in power systems:

1) **Fault Prevention** methods such as structural hardening, asset management and inspection, advanced protection systems and vegetation management are utilized to reduce the likelihood of faults or failures in distribution systems.
2) **Ignition Prevention** methods such as sensitive protection schemes, recloser disabling, and resonant grounding are implemented to reduce the likelihood of wildfire ignition in the case that a fault or failure does occur.
3) **Fire Response and Impact Mitigation** efforts such as maintaining situational awareness, and establishing communication with infrastructure partners, fire crews, and customers are employed in the unlikely case that a wildfire ignition occurs.

Wildfire mitigation techniques can perform one or more of the aforementioned roles. For example, burying a distribution line underground not only largely eliminates interference with vegetation (reducing fault probability), but in the case that a fault does occur, it is typically not at risk of igniting surrounding fuel beds (reducing ignition probability). A classification of most notable wildfire mitigation techniques is shown in Table 2. These three categories were selected to categorize the benefit of each wildfire mitigation technique and comprise the three-pronged approach to wildfire mitigation presented in this article, which are described in detail in Sections III, IV, and V, respectively.

TABLE 2. Classification of wildfire mitigation techniques.

	Fault or Failure Prevention	Arc-Ignition Prevention	Wildfire Impact Mitigation
Line Undergrounding	✓	✓	
Structural Hardening	✓		
Asset Inspections	✓		
Waveform Analytics	✓	✓	
Vegetation Mgmt	✓	✓	
Sensitive Protection		✓	
Disabled Reclosers		✓	
Proactive Operation		✓	
HD Weather Modeling		✓	✓
Fire Surveillance			✓
Emergency Planning			✓

III. FAULT PREVENTION

Wildfire mitigation begins with a precedent of high quality and well maintained power system infrastructure. Over time, load bearing elements on distribution systems can fatigue due to prolonged wind loading causing wire-downs, loose equipment, or conductor failure [38]. Thorough inspection, prognostics, and incremental replacements/upgrades of distribution system components, occurrence rates of catastrophic faults can be drastically reduced. Major fault prevention strategies include structural hardening, asset management and inspection, and utilizing advanced protection systems and vegetation management, which are discussed next.

A. STRUCTURAL HARDENING

Structural hardening includes methods of design and engineering implemented to prevent faults in distribution systems [2]. By assessing the structural needs of power lines in densely vegetated areas, utilities select upgraded materials and pole designs that effectively harden their power lines and reduce fault probability. A study by electric power research institute found that replacing wooden poles with steel or fiberglass may not be the most cost effective method to strengthen power line structures [39]. Rather, utilities can seek wooden poles with higher top circumference for greater mechanical strength [39]. Distribution line failure is often considered as a ‘‘weakest link’’ failure, so upgrading several consecutive poles (especially adjacent to those that carry automated switches and reclosers) is a commonplace hardening strategy [39], [40]. Additionally, spacer cables can help to reduce tree impact related outages [39].

Interference with trees cannot be altogether avoided on overhead distribution lines. Thus, some utilities choose to cover conductors with insulation to protect the conductor from vegetation interference. Covering conductors, however, can be costly as conductor insulation can drastically increase the weight of the conductor, requiring smaller tower spans. Aerial Bundled Conductors (ABCs) have been implemented in Australia since the Ash Wednesday bushfires of 1983. However, these conductors are not commonly used in the United States [41].

As a more permanent (albeit costly) solution, distribution lines can be strategically buried underground to eliminate interference with vegetation above ground. Since the Black Saturday Fires in 2009, the state of Victoria, Australia has allocated over A$200 million toward line undergrounding. However, burying distribution lines underground can be costly at a large scale, costing hundreds of thousands of dollars per mile of line, and increasing maintenance costs and fault response times for the lifetime of the line [2].

B. ASSET INSPECTIONS AND TRACKING

Many distribution systems in the United States were built over 30 years ago and continue to fatigue today. It is notable that the expected life of distribution infrastructure is approximately 40-50 years [42]. Thus, many of these assets have seen adverse conditions during their lifetime, which influence the rate of deterioration, and consequently the likelihood of a catastrophic fault. When distribution systems equipment fail, low cost solutions such as line splices are implemented to fix the problem. By accumulating detailed knowledge of power distribution assets, utilities can optimize maintenance, and reduce catastrophic fault probability. Namely, mechanical elements such as clamps and line splices are commonly carefully tracked, and plans are developed in advance to replace worn, stressed, or fatiguing infrastructure. Although structural requirements for distribution poles and conductors are rated by the National Electrical Safety Code [43], and are designed to withstand storm level wind speeds, a vast majority of failures occur at wind speeds much lower than this critical wind speed [40]. This relationship implies that, while failure probability is inextricably related to wind speed, distribution system faults can occur independent of high wind speeds, and that deterioration of structural elements may contribute to failure rates of power lines even at low wind speeds.

To abate deterioration of distribution components, asset owners have traditionally scheduled routine inspection schedules for visual inspections. By patrolling distribution circuits, inspectors search for visible deterioration along the line. Intrusive inspections are also carried out whereby wooden distribution poles are inspected for decay, termite damage, or structural fatigue, and soil samples around the pole may be taken. Although line inspections can be carried out concurrently with other business, feeder patrols still represent a major ongoing cost to utility companies. In many cases, distribution feeders are inspected subannually, with detailed inspections occurring every 3 to 5 years. However, in California, as regulated by the California Public Utilities Commission (CPUC), feeder patrols should occur annually in Extreme or Very High Threat Fire Districts (HTFDs) [44].

C. ADVANCED WAVEFORM ANALYTICS AND PROTECTION SYSTEMS

While visual inspections of distribution feeders may allow line patrols to identify visibly obvious issues (e.g., broken elements, vegetation interference), many issues may not be visible to the naked eye, or may not be occurring at the time of inspection. For example, arcs may be so small that they are not visible to patrol crews, temporary arcs may only last for a few milliseconds, and/or arcing may occur very infrequently —making these events nearly impossible to detect via visual inspection. While small events may not result in catastrophic failure or wildfire ignition, over time, they degrade the equipment and increase the probability that a catastrophic failure may occur in the future.

The improbability of these events highlights the need for advanced protection systems for detecting faults in distribution systems. Advanced waveform analytics, such as ones presented in [45], [46], use advanced modeling techniques to detect abnormal behavior in distribution systems. More recent prognostics systems are able to not only detect but discriminate between fault causes, and instruct the system operator on corrective actions [47]. By use of advanced waveform analytics, asset owners and operators can identify small problems in distribution systems and repair them before they result in a catastrophic failure. Similar technologies can be used to recognize high impedance faults resulting from vegetation interference or a downed conductor.

High impedance faults are similarly difficult to detect. High impedance faults occur when a conductor comes into contact with an external object that does not conduct electricity well (i.e., the path to ground has a high impedance) and may only partially or intermittently disrupt power flow through the line. High impedance faults are troublesome because resulting fault current may not be sufficient to trip the line via time overcurrent protection methods. Therefore, specialized high impedance fault detection methods are commonly introduced in distribution circuits with dense vegetation, high impedance soil types, and areas with high fire danger. A review of high impedance detection methods can be found in [48], [49].

D. VEGETATION MANAGEMENT

Vegetation management represents one of the costliest and most challenging tasks to wildfire mitigation [50]. Historically, vegetation management has been carried out on fixed schedules to areas that may or may not need trimming. However, advances in aerial imaging (e.g., drones, LIDAR) enable utilities to recognize areas that need trimming, efficiently model tree locations, heights, and approximate proximity to distribution conductors to enhance situational awareness and conduct more efficient condition based trimming. As a result, utilities are able to more efficiently dispatch vegetation management crews along their distribution corridors to target high-risk areas.

Although common practice in the US allows utility companies to trim up to 12 feet (or more) of clearance from distribution lines [51], [52], case studies show that trees from up to 100 feet away from energized conductors can cause damage via airborne debris [53]. Grasses, nearby trees, underbrush, and other ignitable material surrounding power lines may not only interfere with power lines via vegetation growth or as airborne debris, but also could ignite as a result of ejected material from an arc. Therefore, distribution corridors can also be maintained and controlled for long-term vegetation growth to not only prevent faults, but also reduce the likelihood of ignition if a fault does occur by clearing dead and dry debris in proximity to power lines. Herbicides are commonly applied underneath the poles to limit vegetation growth [52].

IV. ARC SUPPRESSION AND IGNITION PREVENTION

Although many of the preceding techniques can be taken to reduce the number of faults on overhead power distribution systems, faults are not completely preventable. Therefore, it is necessary to investigate methods that reduce ignition likelihood in the case that a fault does occur in the system. Two methods are investigated in this section: 1) Arc-Fault Suppression, and 2) Proactive Operation Strategies.

A. ARC-FAULT SUPPRESSION

Arc duration has a high correlation with probability of sustained ignition from power lines [36]. The probability of sustained ignition of surrounding fuel beds increases drastically over the course of milliseconds if an arc persists. Thus, any method to reduce the duration of (or eliminate) arcing in lines represents a key factor in wildfire-resilient grid operation.

1) SENSITIVE RELAY PROTECTION

One straightforward method of reducing arc duration is to trip faults more quickly with existing time overcurrent protection. Tripping on distribution systems occurs by circuit breakers and fuses, that can be located throughout a distribution circuit. Circuit breakers and fuses are coordinated to detect and trip downstream faults while leaving the upstream grid energized. Where applicable and reasonable, more sensitive circuit breaker settings or fuse ratings can be set to trip faults in less time —resulting in less arc contact with vegetation and/or less molten material ejected into combustible fuel beds. Additionally, some fuse types can emit sparks when blown, so careful consideration should be taken to replace these fuses with non-sparking alternatives in high threat fire districts [54].

2) DISABLED RECLOSERS

According to many industry statistics, 60-70% of faults on distribution systems are self-clearing. If and when the external path to ground is cleared, lines can be re-energized with automated reclosers. However, in cases under which faults do not self-clear, attempting to re-energize distribution lines can cause a second arc event that is equally or more likely to result in sustained ignition compared to the initial fault. In many cases, re-energization attempts result in higher fault current than the initial fault event if the fault is not cleared. Additionally, recloser restrikes that occur within 5 seconds after the initial fault event are more likely to ignite surrounding combustible materials. Time delays in reclosing attempts of 30 seconds or more can reduce ignition probability in cases in which the fault has not cleared. However, it remains unclear if reclosers on the market today have the ability to reclose on a time delay [36]. In California, reclosing is commonly completely discontinued in HTFDs during fire season. However, this action requires manual inspection of power lines before re-energization can occur, negatively impacting reliability metrics.

3) RESONANT GROUNDING

System neutral grounding practice differs around the world, and can have a significant impact on fault current levels. On isolated neutral systems, resonant grounding systems (such as Peterson Coils) shift voltages on the faulted phase during a fault such that arcs are extinguished within milliseconds [55]. However, there are two issues with this method. First, these systems can cause transient over-voltage, which can cause dangerous fault states that can damage equipment along the distribution circuit. Secondly, taps on Petersen Coils must be constantly adjusted to match distribution circuit capacitance, requiring changes to Petersen Coil taps any time distribution topology changes. The cost and regulatory barriers for implementing resonant grounding in the United States make it uncommon in distribution systems. However, resonant grounding systems have been widely implemented in Victoria Australia's power system as a response to the 2009 Victoria bushfires [25].

B. PROACTIVE OPERATION

While utility companies work to ensure safe operation of their power lines, their efforts would likely not eliminate the chances of wildfire ignition for the foreseeable future. Thus, there is a need for operational solutions that can be carried out on systems as they exist today. Proactive operation strategies, such as proactive de-energization and network reconfiguration, prevent ignition on power lines by de-energizing lines before a catastrophic fault, failure, or fire occurs.

1) PROACTIVE DE-ENERGIZATION

Proactive de-energization (also known as Public Safety Power Shutoff) has been suggested as a wildfire mitigation strategy in many of the California Public Utility Wildfire

Mitigation Plans, and has been utilized in multiple high-risk fire weather scenarios in Australia [54], [56]. Since permitted by CPUC, only a handful of de-energization events have been reported [57]. Proactive de-energization is permitted when high-risk fire weather conditions present themselves in areas where power infrastructure is located, and keeping lines energized presents a significant safety threat to surrounding communities. When considering de-energization as a fire mitigation technique, utilities consider several factors, including: the current state of power infrastructure, the state of surrounding vegetation, seasonal weather and precipitation levels, and the impact that de-energization will have on the surrounding communities. At time of writing, the decision to de-energize has not been automated based on quantitative criteria alone. De-energization decisions largely relies on decisions by experienced professionals who clearly understand the risks and trade-offs associated with de-energization [54].

In October 2018, a California utility company made the decision to enact its first proactive de-energization based on forecasted high-risk fire weather [57]. After the event, the utility company highlighted the extensive wind related damage to the de-energized system, including: 18 damaged spans of conductor, 5 damaged cross-arms, 3 damaged insulators, 2 damaged fuses, 1 damaged transformer, and 1 damaged pole. While the decision to de-energize caused loss of power to approximately 60,000 customers, this event stands as a prime example wherein weather forecasts and proactive de-energization were utilized to mitigate wildfire risk. Customer outage data were collected from a post-event report and are plotted in Fig. 1. Customers were forewarned up to 48 hours in advance, and feeders were repaired and restored in sections for two days following the de-energization event.

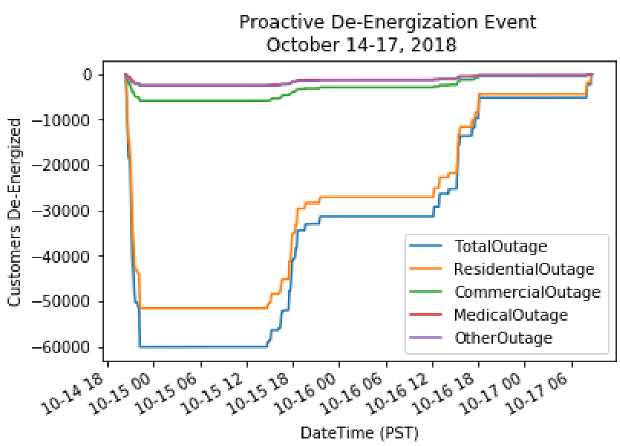

FIGURE 1. Proactive de-energization event in October 2018.

2) NETWORK RECONFIGURATION AND DISTRIBUTED ENERGY RESOURCES

Following disruptions in power service caused by proactive de-energizations, the distribution grid can be automatically sectionalized using fault location, isolation, and service restoration (FLISR) systems [58]. Rural distribution grids are typically radial in nature, but isolating the fault allows downstream sections of the grid to become energized if so designed. Power can be partially restored to meet critical loads by either grid network reconfiguration or islanded operation [59]–[62]. During network reconfiguration, an alternate or backup network topology is utilized to provide an alternate path to grid sourced power for the islanded section of the grid. If distributed energy resources (DER) such as backup dispatchable generators, renewable energy sources, or energy storage systems exist in isolated sections of the grid, they can be utilized to provide the capability to temporarily or intermittently restore power to downstream customers. A study focused in Victoria, Australia found that solar PV and lithium-ion battery energy storage used in conjunction with power line de-energization could reduce comparable levels of fire risk for approximately 10% of the cost of burying rural distribution lines underground [56].

V. FIRE RESPONSE AND IMPACT MITIGATION

Utilities with infrastructure located in high threat fire districts are expected to allocate more resources and efforts into fire response and impact mitigation. While electric utilities are not necessarily directly involved in fire suppression, strategies such as maintaining situational awareness, and developing protocols for mutual assistance and communication with customers have proven to be vital in cases in which catastrophic wildfire ignition occurs. This is also emphasized by the regulatory agencies; for instance, the CPUC recently highlighted that utility activities in California should "be focused on preventing catastrophic wildfires, not simply ignitions" [63].

A. WILDIRE RISK MODELING

Maintaining situational awareness is a major priority for utility companies as highlighted in recent Wildfire Mitigation Plans [54]. Wildfire situational awareness is defined as a distribution system operator's ability to monitor and understand the wildfire environment in their service territory [52].

1) ADVANCED WEATHER MODELING

Weather plays a vital role in wildfire situational awareness. Historical weather trends can be characterized via cumulative distribution functions allowing meteorologists to recognize atypical weather patterns in utility service territory. Likewise, detailed high resolution weather forecasts can be performed up to 48 hours in advance, although these forecasts become uncertain beyond 6 to 12 hours in the future. Weather forecasts are one of the most important inputs to the proactive de-energization decision making process, and add value to the system operators in a variety of other ways. In addition to installing remote automated weather stations, advanced weather modeling techniques are also being widely used by California utilities, and are quickly becoming more computationally efficient and accurate [64].

2) WILDFIRE DETECTION AND SPREAD MODELING

High-Definition cameras installed in utility service territory allow for early spotting and triangulation of wildfires. By installing high-definition cameras at strategic vantage points, utility companies are granted visual observation capability to remote distribution feeders. To automate the process of wildfire detection, machine learning techniques are being developed to recognize fires in camera footage by identifying visible features of fires such as bright spots and grey smoke plumes [65]–[68]. If a wildfire is detected or reported, understanding likely spread scenarios is vital to protecting power infrastructure and conducting emergency response. Fire spread is predominately determined by a combination of land use type, slope, wind speed, and wind direction. A broad spectrum of fire spread modeling tools exist in forestry research. The most complex models require the use of high performance computing to model a dynamic fire boundary [69]–[71]. Other theoretical fire spread models such as the minimum travel time method have been presented as computationally efficient and sufficient for research uses [72].

B. UTILITY EMERGENCY PLANNING

Utilities play an increasingly critical role in emergency management during wildfire incidents. Emergency management is generically comprised of pre-event planning, real-time response, and long-term infrastructure restoration.

If high-risk fire weather is forecasted to occur, observation crews may be dispatched to remote feeders to provide additional situational awareness and report potential hazards. Utilities strive to warn customers of weather related impacts to electrical service in advance. Utilities reach out to customers via phone, email, and social media (among other methods), and take special care to make contact with medical baseline customers. Utility companies coordinate with other key stakeholders such as municipalities, state government, and operators of natural gas, transportation, and water networks if an impact to electrical service is expected [73]. Planning within the utility company also occurs during this time to ensure staffing needs are met during the anticipated service interruption.

If a fire incident occurs, system operators and decision makers convene with other key stakeholders in local operation centers to coordinate fire response. Fire suppression ground and aerial crews are dispatched once ignition occurs and the wildfire location is confirmed. Power lines, although unaffected by the wildfire incident, may need to be de-energized to allow fire crews to operate in their vicinity safely. Fire boundaries and anticipated weather changes are closely monitored to ensure response crew safety. Some utilities provide backup generation to hospitals and community centers during prolonged service interruptions [54]. Depending on the severity of the fire, communities and utility service personnel may be evacuated from the area until the fire is contained. Once utility personnel obtain permission to enter a fire zone, a thorough damage assessment of the power system is conducted, and repairs are coordinated so as to restore power to as many customers as possible within the shortest time – depending on the extent of damage and complexity of the repair work.

Each wildfire event occurs for different reasons, and impacts communities differently. Ultimately, each wildfire event teaches the power system community a lesson that serves to inform utility practice for future catastrophic wildfire events.

VI. CONCLUSION AND WILDFIRE MITIGATION RESEARCH DIRECTION

This article provided a comprehensive overview of wildfire risk mitigation techniques for power systems. The risk mitigation techniques are categorized according to their function in mitigating wildfires as: 1) Fault Prevention, 2) Arc-Ignition Prevention, and 3) Fire Response and Impact Mitigation. For each solution, relevant literature and use cases are presented. The concept of mitigating catastrophic wildfires presents a promising area of future research, and offers many problems that can spark innovation in research and practice communities. Three major directions for future wildfire mitigation research are summarized next.

A. CHARACTERIZING A WILDFIRE-RESILIENT POWER SYSTEM

The definition of resilience should be clarified as it relates to catastrophic wildfires. Existing resilience literature treats wildfires similarly to other natural disasters: an external and predictable event. However, recent cases show that decisions made by power system planners and operators affect power system fire risk. The concept of wildfire-resilience power system should be expanded to encompass the unique relationship between power systems and catastrophic wildfires. Namely, that the grid should be designed and operated in such a way that power system assets are not only protected from external wildfire threats, but also that catastrophic wildfires are not ignited by power system infrastructure.

B. QUANTIFYING WILDFIRE RISK AND EFFECTIVENESS OF MITIGATION TECHNIQUES

Modeling and quantifying the wildfire risk is crucial to utility companies' ability to understand wildfire risk and strategically harden the power grid. An example of wildfire risk modeling techniques is an approach that was used to strategically harden Victoria's power grid as a result of the Victoria Royal Commission following the 2009 Black Saturday Bushfires [74]. In this analysis, wildfire ignition likelihood was calculated as a function of historical fault data, and consequence was determined using a Monte Carlo-based spread model that took into account historical wind directions. Several fires were simulated along every node in the system, and damage was quantified by the number of buildings destroyed. By combining ignition likelihood with consequence of spread, a risk value was generated for nodes across Victoria's power grid, allowing the system planners to identify areas in the regional power grid at which infrastructure upgrades would result in the most wildfire risk reduction.

Further, quantifying the effectiveness of wildfire risk mitigation techniques represents one of the foremost challenges in wildfire mitigation planning. Currently, there is no unified method of quantifying the complex nature of wildfire risk in power systems. However, by categorizing wildfire mitigation methods by their function (e.g., preventing faults, reduce arcing probability, etc.), the benefits of these various techniques can ultimately be quantified. As faults, failures and fires on power distribution systems are all rare events, probabilistic methods will likely need to be utilized. Once the benefit of various wildfire mitigation techniques is successfully quantified, these measures can be used in cost-benefit analysis and selected for utilities based on their specific needs.

C. PLANNING AND OPERATION OF WILDFIRE-RESILIENT POWER SYSTEMS

From a power system planning standpoint, there are major trade-offs between the various wildfire mitigation solutions that have been highlighted in this article. Wide ranging factors such as utility history and location, customer needs, previous design choices and standards all affect the decision on how to mitigate wildfires. Understanding the potential costs of taking no mitigation action may aid decision makers in allocating the necessary funding for wildfire mitigation improvements.

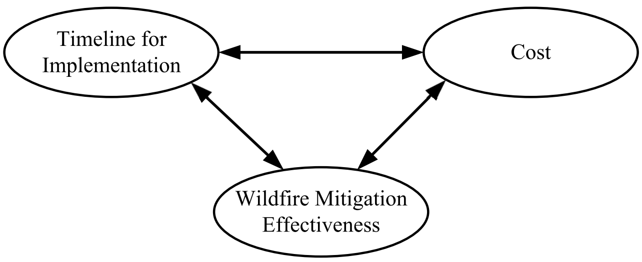

FIGURE 2. Trade-off between wildfire mitigation solutions.

The trade-off between cost, timeline for implementation, and wildfire mitigation effectiveness that are central to the wildfire mitigation asset planning problem is shown in Fig. 2. For example, proactive de-energization is effective at preventing arc-ignitions, and can be carried out on power grids as it exists today (i.e., short implementation timeline), but consequently carries a high cost to customers. However, hardening measures such as burying lines underground also effectively prevent arc-ignitions, but burying lines comes at a high cost and may take years to implement across utility service territories. In addition to these three trade-offs, efforts to reduce wildfire risk should consider the changing nature of the grid, and be aligned with other long-term grid modernization goals.

A variety of opportunities exist for deploying advanced optimization techniques to solve power system planning problems based on wildfire mitigation effectiveness, timeline for technology implementation, and budgetary constraints. The authors in [58] utilized mixed integer linear programming to determine where to implement sectionalizing switches in distribution feeders with a constrained budget. Similar approaches can be taken to consider the various other technologies available to mitigate wildfire ignition probability such as waveform prognostics sensors, high impedance fault detection technologies, and the underlying infrastructure required to enable these technologies on rural distribution systems. A prerequisite to these analyses, however, is a clear understanding of the relative benefits of each technology to mitigate wildfire.

Understanding and modeling of high-risk fire weather presents several opportunities to make decisions based on trade-offs both on and off power systems. Optimal power flow objectives such as minimizing load curtailment in public safety power shutoff scenarios through use of distributed energy resources (DER) has already been studied, though not in the context of wildfire risk mitigation (see e.g., [60], [62]). As DER become more cost-effective, a variety of operational optimization techniques could be used to guide operational practices, which would lead to a lower likelihood of wildfire ignition caused by power systems. In known fire weather scenarios, there has often been a 24-48 hour lead time during which precarious fire weather was forecasted. During this time, DER, mobile generators, and other resilience-enhancing technologies can be coordinated and dispatched as a comprehensive utility response strategy. Other operational challenges such as condition-based line inspection and maintenance may also inform utility practices in the area of mitigating catastrophic wildfires.

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