A Review of Operational Mitigation Measures for Wildfire Ignition by Power Lines

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***Abstract*—There are multiple mechanisms by which power lines can ignite wildfires. Because the conditions under which these mechanisms occur often coincide with factors that accelerate wildfire spread—particularly high winds—wildfires ignited by power-system equipment can rapidly become destructive and difficult to contain. In response, utilities implement a range of mitigation measures to manage this risk. This paper surveys the academic literature on mitigation strategies involving improved situational awareness, power shutoffs, and system hardening.**

***Index Terms*—wildfire risk, risk assessment, situational awareness, power shutoff, system hardening**

I. Introduction

There has been an increased focus on electric grid resilience against destructive events over the past several years [1]. These include wildfires, which have caused major disruption to power system operation and can require weeks for service to be restored. As power systems start approximately 10 percent of wildfires in the U.S., utilies have implemented measures to mitigate this risk [2]. Executive Order 14308, issued on June 12, 2025, directed federal agencies to consider rule-making that establishes the best of these practices for mitigating wildfire ignition risks from the power system [3]. The purpose of this paper is to provide an updated survey of the academic literature on operational measures that can reduce this risk.

Wildfires ignited by power systems can result in widespread devastation because conditions under which a power system may start a wildfire are likely to also be conducive to its spread. For example, Hawaiian Electric confirmed that high winds damaged its infrastructure and started a fire the morning of August 8, 2023, the day of the Maui wildfire [4]. These same winds, propelled by Hurricane Dora passing south of the island, fueled the spread of what became the deadliest wildfire in the U.S. in over a century [5], [6].

Power lines owned and operated by Pacific Gas & Electric (PG&E) were the official cause of the Camp Fire, California's most destructive [7]. The utility filed for bankruptcy protection in 2019 because of liabilities and pleaded guilty to involuntary manslaughter in 2020 [8], [9]. The cause of the state's second most destructive wildfire is still under investigation. However, the Justice Department has accused Southern California Edison of starting the Eaton Fire in January 2025, citing faulty equipment as the cause in lawsuits [10].

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In response to devastation from wildfires initiated by electric utility equipment, several states passed legislation that requires utilities to regularly submit Wildfire Mitigation Plans to Public Utility Commissions. As of July 2025, such legislation has been enacted in twelve states, including Texas and California. Some of these laws also include modified liability or damages provisions, under which utilities that maintain or receive approval for a plan may qualify for reduced legal exposure in the event of a wildfire [11].

The Pacific Northwest National Laboratory (PNNL) created an online database that compiles more than 400 Wildfire Mitigation Plans (WMPs) from 171 utilities across 19 states and one province. In addition, PNNL released interactive tools and a beta version of an AI assistant to support users in the analysis of these plans [12]. An extensive overview of the key topics addressed in WMPs is presented in [13]. These include system hardening, asset management, situational awareness, operational response, vegetation management, power shutoff, and risk-spend efficiency. This work also includes a comparison between power shutoff policies at multiple utilities.

There are several other literature surveys related to power systems and wildfires. A review of prediction, prevention, detection, monitoring, and suppression strategies are presented in [14]. The second part of this paper [15], covered mitigation measures of wildfire risk from power systems. In [16], a reference guide summarizing preparedness and mitigation practices of western utilities and recent research on pre- and post-wildfire analysis is provided. A summary of policy, industry procedure, and research related to power shutoff events is presented in [17] and a discussion of how wildfires, power systems, and climate change are connected in research literature and utility practice is presented in [18].

This paper complements these works by further surveying the academic literature related to the operational components of Wildfire Mitigation Plans. These are the electrical measures utilities can implement to modify power systems and mitigate wildfire risk, including: situational awareness, power shutoffs, and system hardening. The following section explains the mechanisms through which power systems can ignite wildfires,

Section III covers risk assessment of power lines, Section IV reviews operational mitigation measures, and Section V concludes the paper.

II. How Power Lines Ignite Wildfires

In [19], arcing faults, conductor heating, and ignition of nearby vegetation or insulation materials are identified as the primary mechanisms by which power systems can ignite wildfires. These typically occur when power lines are operating under specific system conditions, including (i) failed or faulted components (ii) downed conductors, (iii) conductor contact and vegetation-related faults. This section describes each of these mechanisms and the conditions under which they are likely to occur, as explained in [19].

1) Failed or Faulted Components: Failure of power line apparatus can result from degrading insulation that permits leakage current that initiates arcing capable of starting a wildfire. Such failures can occur in protection devices, switching equipment, transformers, and other energized components. Investigation of the Camp Fire in California concluded that the wildfire started when molten metal fell onto dry vegetation as a result of arcing between an energized transmission line and a steel tower. The arcing began after a C-hook failed and disconnected the insulator string that supported the transmission line from the tower's transposition arm [20].

2) Downed Conductors: A downed conductor can remain energized and continue to carry current through the ground. This can result in arcing that may ignite nearby vegetation. Because the ground has high impedance, the fault current can be smaller than relay pickup levels, which makes these high-impedance faults (HIFs) difficult to detect. In many cases, utilities only become aware of HIF faults when customers report them. As a result, arcing can persist for an extended period of time. Fig. 1 shows intense arcing from a downed conductor [21].

Fig. 1. Arcing from a downed conductor. Fig. 1 from [21].

3) Conductor Contact and Vegetation-related Faults: Contact between bare conductors can lead to phase-to-phase faults that generate high-temperature arcs and melted conductor fragments. Direct contact may occur as a result of high winds, excessive sag of power lines, and changes to structural components such as crossarms and poles. Vegetation can also initiate faults by bringing conductors together when a tree or large branch falls across power lines. Phase-to-ground faults can occur whenever vegetation is in contact with power lines and the ground.

Faults can also be triggered when vegetation comes into contact with more than one phase at the same time. If the separation distance between conductors is sufficiently small, current on the order of tens of milliamps can flow through the vegetation. Sustained current over time can lead to charring of vegetation and ultimately, an arcing fault. This is illustrated in Fig. 2 where arcing across a branch in contact with two conductors is depicted [22].

Fig. 2. Arcing caused by vegetation contacting two energized conductors. Fig. 2 from [22].

III. Risk Assessment of Power Lines

Assessment of risk associated with individual power lines allows for more effective, risk-informed measures to be implemented and lines with the highest risks to be prioritized. The wildfire risk of a power line depends on the physical condition of the line itself and the power-system components it is connected to. Environmental factors such as vegetation, terrain, elevation, and other topographic features determine whether an ignition can lead to wildfire spread and therefore contribute to this risk. Weather variables—particularly temperature, humidity, and wind speed—further influence the progression of a wildfire. Utilities therefore consider each of these factors in their assessment of a line's wildfire risk [23].

The variability of weather and limited availability of weather datasets with sufficient spatial and temporal resolutions for power system planning studies make this assessment challenging [24]. The installation of environmental sensors to obtain localized data on weather conditions and the surroundings of power lines has therefore been recommended [25].

A survey of the literature shows that few studies quantify the wildfire risk associated with individual power lines. In [26], a framework is presented for modeling weather and other environmental inputs, including events such as wildfires, into power-flow and transmission-planning tools. The wildfire risk associated with each transmission line was quantified in [27] by combining weather and topographic data to simulate the spread of a wildfire and estimate the burned area as well as the resulting damage to both civilian and power-system infrastructure.

A machine-learning surrogate model that estimates the wildfire-ignition risk from conductor clashing in real time is developed in [28]. The model is trained on physics-based simulations of power-line motion under varying wind and structural parameters and assigns a score, between 0 and 1, that quantifies the portion of a line in contact with a neighboring conductor or vegetation. These risk scores are included in a risk aware operation planning problem that identifies power lines of highest wildfire risk for de-energization.

In addition to topographic and weather data, [29] incorporated grid topology information to generate wildfire ignition scenarios and simulate wildfire progression under varying weather conditions. Post-wildfire grid conditions in each scenarios are evaluated by AC optimal power flow analysis. The wildfire risk of a line is quantified by the power outages expected when it ignites a fire.

IV. Operational Mitigation Measures

This section surveys the academic literature on mitigation strategies focused on improving situational awareness, implementing power shutoffs, and hardening power-system infrastructure.

A. Situational Awareness

Many studies improve situational awareness by analyzing PMU and waveform data to identify signature events that could start a wildfire. Other works further analyzes these data to develop better fault-detection methods.

The use of Distribution Fault Anticipation (DFA) technology for prompt detection, localization, and corrective action of conditions that increase wildfire risk in waveform data is described in [30], [31]. The practical application of DFA to real-world distribution system voltage and current waveforms was demonstrated in [32].

A DFA system consists of data collection devices installed at substations and a centralized master station that aggregates information from these devices in real time and informs utility operators of abnormal conditions. Each device monitors voltage and current waveforms and uses a classification engine that combines signal processing and pattern-classification techniques within a fuzzy expert-system framework to identify electrical event signatures associated with potential wildfire ignition mechanisms [33], [34].

Other works presented improved fault-detection methods. In [35], a real-time deep-learning framework that extracts features from distribution-level voltage and current measurements of a single device is presented to classify fault types using CNN Model-T and localize them using CNN Model-L. The wildfire risk associated with a fault is quantified by its incident energy. Features from time- and frequency-domain analyses of voltage and current fault data are extracted in [36] to develop a method for early detection and prediction of wildfire ignition risk caused by vegetation-related high-impedance faults.

A real-time multi-head CNN–LSTM method to identify patterns in measurement data and detect vegetation-related HIFs is presented in [37]. This work is the first to distinguish between vegetation contact with power lines that poses a wildfire ignition risk and requires immediate action and that with low risk. Machine learning techniques were implemented in [38] to identify numerical patterns of vegetation-related faults in current measurement data and develop a real-time detection system that also differentiates between problematic and safe contact of vegetation with power lines.

Deep neural networks (DNNs) in [39] were trained on wavelet-transformed voltage and current signals from simulated faults to classify and locate open-conductor events. The method detects and clears faults within the conductor's falling time, before it contacts the ground and can ignite a fire. Two high-impedance fault (HIF) detection algorithms were presented in [40] to mitigate wildfire risk. The first is based on the non-harmonic components of fault current and the second on its odd-harmonic content. Evaluation of these algorithms included modeling of different ground surfaces that a downed conductor may come in contact with.

B. Power Shutoffs

When a power system component is de-energized, the associated wildfire risk is almost entirely eliminated. It is therefore common practice for electric utilities to restrict recloser operation to *one-shot*, blocking repeated action when wildfire risk is elevated. More recently, utilities are increasing the sensitivity of protection settings for faster fault isolation. When wildfire risk is very high, portions of the grid may be de-energized in what is referred to in California as a Public Safety Power Shutoff (PSPS) [41].

Given the effectiveness of PSPS as a mitigation measure and the inconveniences it brings to customers, Public Utility Commissions often regulate how utilities implement PSPS events and permit this practice only as a measure of last resort [42]. Following complaints from customers and state officials, the California Public Utilities Commission issued a warning to Southern California Edison on October 3, 2025, regarding its PSPS program over the previous 18 months [43]. The utility had lowered the wind speed threshold for initiating PSPS events after the Eaton Fires in January 2025, which it is being accused of starting, and cut power to over half a million customers in 2025, compared to 137,000 in 2024 [44].

The Optimal Power Shutoff problem (OPS), the first optimization framework to minimize wildfire risk and maximize load delivery was introduced in [45]. Wildfire risk was quantified using risk values assigned to individual components. A mixed-integer linear program (MILP) based on DC power flow was then formulated, in which a risk-weighting parameter balances the trade-off between de-energizing components and maintaining electricity supply.

In an extension of the OPS problem, [46] presented the Security Constrained Optimal Power Shutoff formulation, which incorporates post-contingency security constraints to balance wildfire risk against pre- and post-contingency load shedding. The OPS problem was also extended in [47] to co-optimize preemptive shutoffs and post-event restoration in a multi-period MILP. The model enforces restoration constraints and

is solved on a rolling horizon as wildfire-risk forecasts are updated.

In [48], wildfire spread was modeled by stochastic disruption scenarios of random timing and magnitude and a two-stage stochastic MILP that optimizes de-energization and power flow decisions under uncertainty was formulated. A decomposition algorithm based on enhanced Lagrangian cuts to solve the problem was also presented. An extension of this work in [49] incorporates dynamic multi-stage wildfire scenarios and includes restoration constraints as well as fairness constraints so that outages are shared among customers.

Machine learning models in [50] were trained on the spatial and temporal patterns shared across similar OPS instances to guide the solution of OPS problems and address computation challenges of MILPs. This allows for higher-quality solutions to be obtained in significantly less time than traditional optimization solvers. In a related effort, [51] developed a data-driven framework for real-time decision making during wildfire events. The work first formulated an optimal power flow–based management strategy that uses wildfire risk maps and cascading-failure constraints to identify high-risk transmission lines for de-energization under varying operating conditions and network topologies. The resulting optimal shutoff and load-shedding decisions were then used to train a machine-learning model that approximates these actions in real time.

A wildfire-risk-aware operation planning framework presented in [28] uses real-time wildfire-ignition risk scores from a machine-learning surrogate model developed in the same work to identify lines for de-energization during PSPS events and balance wildfire risk and load shedding. A two-stage mean–CVaR stochastic unit commitment formulation in [52] treats wildfire risk as a constraint and optimizes day-ahead commitments and line de-energizations under demand uncertainty. The model identifies all Pareto-optimal cost–risk tradeoffs and allows operators to avoid high-cost demand scenarios.

A multi-period scheduling formulation in [53] balances wildfire risk and load delivery by de-energizing components, redispatching power across the network, and temporally shifting load using energy storage as wildfire risk conditions change over time. A rolling mixed-integer linear optimization framework in [54] uses past load-shedding outcomes and next-day wildfire-risk and demand forecasts to select which power lines to de-energize, while incorporating fairness metrics designed to prevent the repeated concentration of outages in the same communities. An equality- and equity-based Optimal Power Shutoff framework in [55] optimizes the de-energization of transmission lines, generators, and loads under wildfire conditions. The model balances equality in load shedding across all customers and equity in prioritizing critical loads while observing a wildfire-risk threshold.

Three PSPS-scheduling models were formulated in [56]. Each is expressed as a dynamic program that determines optimal shutoff policies under the following conditions: (i) penalties for exceeding a PSPS budget, (ii) cost recovery when events are below budget, and (iii) minimizing the number of PSPS events subject to a total-cost constraint. Optimal closed-form policies are derived for the first two scenarios, while the third is solved using value iteration for constrained Markov decision processes. In addition, the first model is applied to critical-peak-pricing scheduling and an optimal policy for reducing peak demand as it varies with weather is presented.

C. System Hardening

Rather than de-energizing a line to eliminate wildfire risk, a line can be isolated from the conditions that initiate wildfires. Hardening measures such as conductor insulation or covering significantly reduce the likelihood of phase-to-phase faults and vegetation contact. Undergrounding provides even greater protection by completely isolating a line from environmental risk factors and eliminating the need for wildfire-related management [57]. In addition, installing batteries and distributed generation can support the system with local power sources and maintain service when wildfire risk is high.

Wildfire risk of individual power lines is assessed in [58] by the likelihood of a fault occurring and the potential for a fire to spread. These risk metrics are then used in an optimization model that selects which lines to underground in order to minimize wildfire risk across multiple scenarios under a predefined budget. A mixed-integer robust optimization model in [59] identifies which lines to underground so that wildfire risk and load shed are minimized across scenarios with varying wildfire conditions, wind and solar availability, and demand. To handle a large number of scenarios efficiently, a delayed constraint generation algorithm is introduced where scenarios are added iteratively until an optimal solution is found.

A multi-period MILP in [60] selects lines for de-energization during PSPS events and optimally locates and sizes infrastructure investments—including batteries, solar PV, and power line hardening measures—to minimize wildfire risk and load shedding. A planning framework in [61] minimizes wildfire risk across scenarios with spatial and temporal variation in demand, renewable generation, and wildfire ignition risk. Using Benders decomposition, the framework is separated into two stages: a master MILP that determines battery siting and sizing and selects transmission lines for undergrounding, and a subproblem that applies a DC optimal power flow model to evaluate the operational performance of these investment decisions.

A long-term planning framework in [62] is developed to optimally size, site, and operate long-duration batteries during both normal conditions and PSPS events. The model evaluates hourly operations within multi-day scenarios across an entire year to consider seasonal and wildfire-risk variations. To solve this large multi-scenario optimization problem, traditional progressive hedging techniques are extended to make battery placement decisions and state-of-charge values consistent across adjacent time periods. A quasi second-order stochastic dominance optimization model in [63] determines PSPS-related actions and the dispatch of mobile power sources (MPSs) to balance wildfire risk and load shedding. The formulation is a stochastic MINLP that is reformulated as

an MILP and incorporates wildfire-cost scenarios driven by weather uncertainty.

A two-stage stochastic planning framework in [64] balances load shedding during PSPS events with expansion decisions for power lines and the siting and sizing of energy storage systems in unbalanced distribution systems. Wildfire and PSPS line de-energizations are modeled by scenarios that are created from historical data of an area. The model is formulated as an MILP in which the first stage selects investment decisions, and the second stage minimizes operation costs. In another work [65], an MILP model for transmission system expansion planning determines the optimal number of new lines to be added while considering wildfire risk and line de-energizations caused by PSPS events.

A two-stage, three-level distributionally robust planning framework for distribution systems under wildfire risk is presented in [66]. The first stage determines topology configuration and investment decisions—including switching actions, construction of new lines, and line-hardening options. The second stage evaluates the worst-case expected operational cost under decision-dependent uncertainty (DDU), where line-failure probabilities depend on first-stage power-flow levels and hardening decisions. A two-stage robust expansion-planning model in [67] selects new lines, hardens existing ones, and installs DERs to maximize long-term load delivery and manage wildfire risk. The first stage minimizes expansion and operational costs, while the second stage identifies worst-case uncertainty in demand, DER availability, and wildfire-ignition risk.

V. Conclusion

Wildfires ignited by power system components are among the most destructive in the U.S., and electric utilities have implemented multiple measures to mitigate this risk. This paper explains the mechanisms through which power systems can start wildfires and reviews operational mitigation measures to reduce wildfire risk. These measures include improving situational awareness, optimization-based power shutoffs, and hardening power-system infrastructure. Modeling of the risk associated with power lines is also discussed, although the existing literature in this area remains limited.

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