IMPACT OF WILDFIRES ON POWER SYSTEMS

By

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Bachelor of Science in Electrical Engineering

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2018

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December 2021

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ACKNOWLEDGEMENTS

Prof. Nazaripouya has been a great teacher, mentor, and thesis supervisor, offering advice and encouragement. Although the topic I chose was unique with little support available, but with Professor's consistent guidance, I am able to successfully complete my thesis. I will remain thankful for his great support and guidance

Many thanks to all the teachers who helped me to learn and made me a positive addition to society.

Finally, immense gratitude to my parents and wife, who understood my commitment toward studies and supported me during this tenure

Name: QASIM ALSAEED

Date of Degree: DECEMBER 2021

Title of Study: IMPACT OF WILDFIRES ON POWER SYSTEMS

Major Field: ELECTRICAL ENGINEERING

Abstract:

Power systems, particularly those located near forests, are exposed to wildfires during summer seasons especially in regions with high temperatures. This issue may impact on operation of power grids and thus their reliability and resilience. However, the traditional reliability and resilience models may not be effective anymore as such events occurs more frequently and their impacts are broader than the ones were previously considered in system reliability assessments. In this study, the byproducts of wildfires are identified, and their impacts are modeled to provide a better picture for reliability and resilience assessments. These models will help analyze the effect of wildfires on different components in a power system, for instance, the impact of heat, smoke, or ash on the power lines and renewable energy resources. Studying the effects of wildfires on electrical power systems, analyzing and formulating these impacts, and determining their intensity on electrical components and energy production are contributions of this thesis. In particular, this work provides an overview of efforts in evaluating the impact of wildfires due to heat, smoke, and ash on different power grid components.

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CHAPTER I

INTRODUCTION

Multiple factors need to be accounted in design and operation of electric power systems as they need to provide rated power to consumers while experiencing a variety of stresses like transients and faults in their lifetime. Although many factors have been accounted, effect of wildfires which produce heat, smoke, and ash has not been fully considered in design and operation of power systems. Recent experiences show that wildfires are becoming one of the leading causes of power system failure.

In the power systems that dominate North America and some other places in the world, electrical power is typically produced in huge quantities away from population centers and sent by power lines cross the countries. Greater than 430,000 kilometers of transmission lines crisscross North America [1]. In this regard, these power lines are passing through the forests or coming near to them which make power lines vulnerable to wildfires that occur annually in those areas. For example, an active wildfire seasons that were happened in the Idaho in 2010 and 2011 burned over 160,000 acres of lands through which transmission lines pass, resulting in power outage, and unplanned replacement costs [2]. In 2017, Thomas wildfire which is the largest wildfire in California burnt 281,893 acres area in California, over a quarter-million Southern California, Edison customers lost power as a result of damage from the fire. Also, the power line that it runs from Ventura County to Goleta, to prevent further problems [3]. This enormous wildfire triggered a new round of evacuation in which its flames threatened power lines that supply Yosemite National Park [4]. In 2021 Oregon wildfire had burnt over 1,000,000 acres, and it has caused a power outage to the lines that feed electricity from the Pacific Northwest to California, leaving that area without a critical power source [5].

Figure 1: Power Lines Passing through Wildfire affected Area [68]

The wildfire in last four years have particularly proven catastrophic for California. Thomas wildfire destroyed more than 10,000 structures which resulted in more than 10 billion dollars of damage to electrical equipment [6]. 2020 was the worst year for California as record number of wildfires were reported with most area burning in a single year. It is recorded that an area of 4,420,301 acres was burnt just during 2020 [7]. In August 2021, The Pacific Gas and Electric company shuts off power for 48,000 customers as a planned safety measure due to worsening wildfire conditions [8]. The power remained off for up to 48 hours for most of the customers. 466,000 thousand customers in 38 counties were issued power outage warning in 2020 [9] .

Apart from the direct burning and damage to the infrastructure, other products of wildfire like smoke and ash create a noticeable effect on visibility as well as air quality, which impacts on solar power generation. Aerosols arise from wildfires absorb solar irradiation while also affecting cloud processes by functioning as cloud condensation nuclei [10]. During the hazy conditions caused by wildfire in Paso Robles, California, 685.708 kWh/day was produced in one of the solar energy sites [11]. The week before the hazy conditions, when the weather was sunny and clear, the same system produced 838.168 kWh/day. [11]. This extensive system had lost around 19% of its energy production or $30/day because of the wildfire's smoke. In terms of residential solar systems where 7kW is the average solar system size, a 1.60 kWh net loss per day is expected under the wildfire's smoke condition. In the summer of 2019 and 2020, Australian fires were damaging and burning more than 180,000 square kilometers of forest [12]. Due to the smoke from these fires, it has also been reported that in Sydney and Canberra, electricity production from rooftop solar PV has decreased by as much as 15-45% on some days [13].

In addition, in wildfire locations that experience heavy ash, the ash itself will settle on solar panels blocking sunlight, just like a heavy buildup of dust would undoubtedly do. The hefty ash debris is recognized to reduce power production by 30% or more if not cleaned off [11]. The writers in [14] and [15] had studied the impact of dust on the performance of solar panels. The study revealed the impact of atmospheric dust with a mean diameter of 80 mm at 250 g/m2 was found to reduce the short circuit current by 82%.

Wind power generation is another example that can be affected by wildfires. Wildfire ash and soot impact on surface roughness of wind turbine blades, which plays an important role on the aerodynamics and thus power production. Where the increasing advancements in wind turbine technology, along with the unpredictable operating environment, also present significant challenges with regard to wear issues on the leading edge of the blade [16]. Erosion of the leading edge of wind turbine blades because of particles (ash and soot) leads to reduced blade aerodynamic efficiency and power output [16].

The rest of this paper is organized as follows:

Chapter 2: Examines the existing literature on the impacts of wildfires on Power system operation.

Chapter 3: performs wildfire hazard modelling and formulations on the power line. The heat balance equation is considered to help measure the thermal heat delivered to the overhead lines in power systems.

Chapter 4: studies the effects of wildfire on the renewable energy. The attenuation of solar irradiance due to the smoke and dust. The impact of ash on the wind turbine blades roughness.

Chapter 5: studies the impacts that wildfire can have on widely used power equipment in the power system.

Conclusion: Presents the research conclusions and summarizes the main findings of this thesis.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

This chapter reviews studies published in academic papers and industrial reports focused on the impact of wildfires and their interactions with the power system. First, the causing factors of wildfires are listed. Then the damage and adverse effects that a wildfire can cause to the power systems are reviewed. Finally, economic losses incurred by electrical companies due to wildfires are discussed.

2.2 Wildfires Causes

When wildfires occur, the first step for first responders is to identify what triggered wildfires. Most wildfires do not occur naturally. According to the National Parks Services [17], human-caused wildfires account for around 60 to 80 percent of all reported wildfires. Figure 2 shows a thorough list of wildfire triggers from 2013 to 2017. Debris burning, electrical power arcing, vehicle fuel leakage, improper use of equipment, deliberate arson, campfires, playing with fire, smoking are some examples. Most of these fires start because of the reckless campers. According to the Frontline Wildfire Defense System [18], many wildfires begin due to the fact that campers have left their campfires unattended. Cooking around a campfire is appealing, yet even one stray spark on a dry and windy day can cause widespread damage. These fires can spread out very rapidly, sometimes reaching to residential areas.

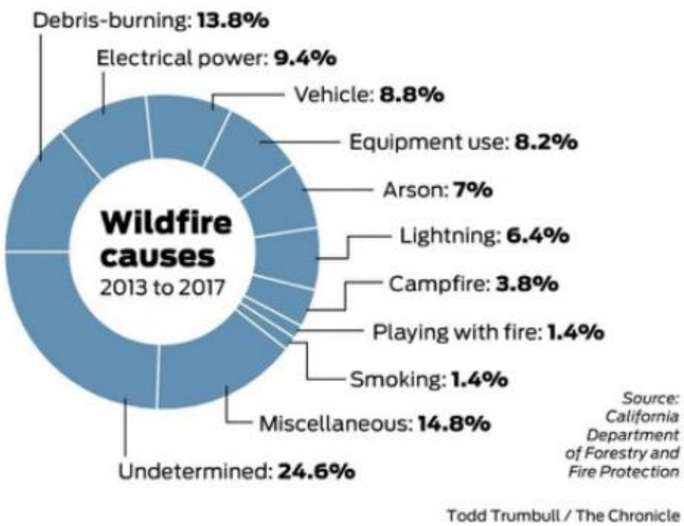

Figure 2: Wildfires causes

Apart from human caused wildfire, there are other natural reason which can cause wildfires. Lightning, particularly the lightning flash, is the major natural cause of random wildfires. Lightning does not constantly cause wildfires. However, conditions must be favorable for sparks to ignite as well as for the fire to spread. While the natural causes like lightning strikes are beyond our control, we can control the human caused wildfires by changing our habits especially in high-risk wildfire locations. In 2015, the state of Washington had 1,084 wildfires triggered by humans and 457 wildfires caused by lightning strikes [19].

According to meteorological data from various governmental agencies, human-induced global climate change is identified as a significant threat to cause wildfires in the near future. Research [20] shows that warmer and drier conditions are created because of the changes in climate. In the western U.S., projections show that a 1-degree centigrade temperature increase is an annual average which would increase the median burned area per year by up to 600 % in some forests [21]. Wildfires are also affected by low moisture availability, reduced snow accumulation in mountains, high temperature, reduced precipitation, and other environmental and meteorological parameters all of which are influenced by climate change drivers. Higher temperatures, diminished snowpack, altered rainfall and dry weather can make the conditions more suitable for fire due to increased availability of flammable dry vegetation for longer durations, thereby affecting the extent, frequency, and severity of wildfires in the future.

2.3 Impact of Wildfires on Power System

A connected network of electrical equipment set up to generate, transmit, and consume electric power is called an electric power system. The electric grid, which delivers electricity to households and industries over a large area, is an example of a power system. The generators that produce the electricity, the power lines system that transports the power from the producing centers to the load centers, and the distribution system that distributes the power to surrounding households and enterprises make up the power grid.

The keystone of modern society is a resilient power grid that ensures an uninterrupted supply of electricity to citizens and interdependent lifeline infrastructure even during extreme events such as wildfires. However, legacy power systems have faced challenges to support their customers in the presence of recent low-probability, high-impact disasters similar to wildfires. Recent wildfires in California, Australia, and other parts of the world have shown this shortcoming and revealed that these events could lead to catastrophic blackouts and economic losses to the people and electric companies. According to the Department of Energy, there have been more than 2.7 million customers without power along California's coast due to 2019 wildfires and subsequent grid blackouts, indicating the lack of adequate resilience for a 21st-century power grid infrastructure [22].

2.3.1 Impact on Power Lines

Power lines help us in transmitting and distributing power over long ranges from the generating sources and are most vulnerable to wildfires. A widespread out wildfire can result in tripping dozens of transmission lines simultaneously, posing a severe threat to the safe operation of the power system. The effects of a wildfire on power lines depend on multiple factors. The transmission capacity of a power line can be affected by the heat, smoke, and ash from a wildfire, even if there appears to be no damage to the physical structure [23], [24]. For instance, the heat generated by wildfire can increase the surface temperature of the overhead conductors and its vicinity. Ash can also accumulate on the insulators that attach the lines to the towers, creating a conductive path and causing leakage currents that may force the line to be shut down. The insulation effect of air which is normally present between of phase-to-ground and phase-to-phase of power line can decrease significantly under wildfire smoke conditions, which can threaten the safe operation of power lines or even cause power line trips [25]. Ionized air in smoke can act as a conductor, causing arcing, either between lines or between lines and the ground, resulting in a line outage and further, faster propagation of the fire. Smoke, ash, and dust can also damage power poles. The high temperature can increase the conductor length and hence the sag of a power line. Annealing which can soften a metal and hence greatly reduce the tensile strength can also be caused by high temperatures present in wildfire. Reference [26] addressed the firing mechanism in wood poles of medium voltage distribution lines. Under certain conditions, the surface of one or more phase insulators collects smoke, ash or dust generated by wildfire, which conducts leakage current when lightly wetted. This leakage current can flow into and onto the wood of the structure and can, in certain cases, cause the wood to track, char, and ignite.

Figure 3: A firefighter trying to contain the fire which occurred in North Bay wildfire and burned 67,050 acres [67].

Besides the damages to the infrastructure such as poles and towers, or causing conductor sag, annealing, and loss of the tensile strength, this matter can decrease the ampacity of the power line due to the conductor's reduced thermal rating.

The fire, in its immediate vicinity, can increase the temperature of the overhead conductors, which can lead to permanent loss of tensile strength because of the annealing process. Accordingly, the thermal rating of lines may need to be dynamically adjusted to reduce the line's loading to counteract the heat addition from the fire. This may curtail the flow of power and dispatch of generation units.

Article [27] proposed a method for calculating tripping risk in overhead power lines caused by wildfires. The writer incorporated the risk of wildfire occurrence and comprehensively analyze the whole process to calculate the coefficient of power line trip. By doing so, he obtains the warning risk which can provide a guidance for early deployment of corrective measures to avoid widespread blackout due to wildfire.

2.3.2 Impact on PV Systems

The photovoltaic effect is used in solar cells to convert light energy into an electric current. Photovoltaics were first utilized only as a source of electricity for small and medium-sized applications. However, the number of grid-connected solar systems has greatly increased which resulted in in great amount of power being generated distributed across the power grid. Megawatts of photovoltaic power plants have been deployed as the cost of solar electricity has decreased. Solar PV is rapidly becoming a low-cost, low-carbon method for harvesting renewable solar energy. However, the power generated by solar cells are affected in fire-prone areas because of smoke and ash from wildfires. According to an article from *Microgrid Knowledge*, “AJ Perkins, president of Instant On, said that 25% of his microgrids in the Bay Area — which has been hit hard by wildfires — aren’t producing much solar power because smoke is blocking out the sun. Solar production has dropped by about 95% in some cases” [28]. Dust or ash deposited on solar panels, as well as smoke, lower the amount of light getting to the cells resulting in a loss in power production. In the summers, the majority of the Western United States especially California, Idaho, Colorado, and Utah have numerous wildfires raging. During these wildfires, the smoke and haze would have the same results as contamination on solar irradiance. In 2016 alone, there were about 67,743 reported wildfires impacting over 5.5 million acres of land, covering a large area in smoke [29].

2.3.3 Impact on Wind Power Generation

Wind power, often known as wind energy, is the utilization of wind turbines to generate mechanical power, which is then used to spin electric generators to produce power. Wind energy is a popular sustainable, renewable energy source with a lower environmental effect than burning fossil fuels. Wind turbines are often installed in groups to form a windfarm. This windfarm is then connected to the grid using a single power connection Setting up windfarm on the land is cheap and hence onshore wind is a low-cost energy source that is competitive with, and in many cases, more affordable than coal and gas facilities. Since onshore wind farms must be stretched out across more area than other power plants, they have a bigger aesthetic influence on the landscape than other power plants and must be developed in rural regions, perhaps leading to "countryside industrialization" and habitat degradation [30]. Offshore wind is more consistent and powerful than onshore wind, and offshore farms have a lower aesthetic effect, but repair and maintenance costs are much greater for these plants. Onshore wind power plants are set up to generates renewable energy to feed the generated power to the grid. These power plants produce fluctuating electrical energy due to fluctuations in wind flow. Usually, the wind flow is well predicted in advance and hence the power generated from a wind farm can be known in advance to facilitate its integration to the grid. Small onshore wind power plant can offer power to isolated off-grid sites or pump some energy into the grid. It produces variable power at the local level, which is constant year to year but fluctuates dramatically across shorter time scales. On the other hand, to establish a standalone wind power based grid, the grid must be combined with other energy resources or energy storage system to ensure a consistent supply of power.

Figure 4: Impact of wildfire particles.

Wildfire cause dusty and ashy environment. This type of environment may have adverse effect on wind power generation. It is important to suggest and verify some theoretical models to describe the result of blade surface roughness caused by harsh conditions to the wind turbine, which plays an essential role on the aerodynamics, power production, and the lifetime of a windmill. Heavy dust, ash, or smoke particles on the rotor's blades of wind turbines may lead to dirt accumulation on the blades which may lead to drastic reduction in wind power production.

Although the effect of wildfire particles (including ash and smoke) on the roughness and degradation of wind turbine blade's is not analyzed yet. But it is prudent to say that these particles will have similar or more adverse effects on the blades of wind turbine as the dust particles contamination will have. As the wildfire generated particles are much higher in concentration, they may strike blades at high temperatures and are more adhesive. Figure 4 shows picture of eroded blade of wind turbines.

In San Gorgonio, California, this article [31] studied the effect of wildfire on 120 kW wind turbine. Just in 15 days, the power reduction of around 20% was observed due to soiling. National renewable energy lab showed a decrease in 30% of annual energy production for a 65kW wind turbine due to dust accumulation [32]. Although multiple new designs were introduced to avoid decrease in power production, but no design could decrease the loss beyond 20%.

2.4 Overview – Experimental evaluation of Wildfire on Power System

2.4.1 Power Lines

Wildfires seriously affect the safe operation and load capacity of the high-voltage transmission lines. In the experiment in [33], the average tensile force of three kinds of aluminum cable steel reinforced (ACSR), were burned by wildfire and burned by simulated wildfire with firewood in tests. The results show that the safety value of the transmission lines load capacity is 15 kN. In the case where the horizontal span, height difference, and the maximum sag are known, the lowest point's horizontal tension arc sag on high-voltage transmission lines can be calculated. If it does not exceed 15 kN, even if the transmission lines have been subjected to wildfire, load capacity is greater than the tension of transmission lines. Thus, they can usually operate safely. If the lowest point's horizontal tension exceeds 15 kN, in the process of design and installation of the high-voltage transmission lines, by properly increasing maximum arc sag of transmission lines, the tension of the lowest point of arc sag is not more than 15 kN. However, increasing the maximum arc sag of transmission lines could lead to other problems, such as touching the ground or contact with bushes located under the transmission lines.

2.4.2 PV Systems

Smoke, ash, and dust are factors that considerably impact the efficiency of PV panels. El-Shobokshy and Hussein [34, 35] studied the impact of dust on the performance of PV cells. Their study includes investigations into the physical properties of the dust accumulation, deposition density, and their impact on degrading PV efficiency. The experiment was entirely emulated with artificial dust (including limestone, cement, and carbon particulates) and halogen lamps. While the solar (light) intensity was kept constant, with different densities of dust the test was repeated several times. Atmospheric dust with a mean diameter of 80 mm at 250 g/m2 was found to reduce the circuit current by 82%. Fine carbon particulates (5 mm) were found to have the most deteriorating effect on the PV efficiency. The study also found the impact of finer particles is greater than coarser particles on PV performance, for the same dust type as the smaller particles more evenly combine to hinder the light falling on the solar PV panel.

An article [36] studied the effect of airborne dust concentration on PV performance and observed a decrease in efficiency from 33.5% to 65.8% for an exposure of 1–6 months, respectively. It was evident from the study that the degradation progress occurs rapidly during the initial 30 days of exposure to dust.

2.4.3 Wind Turbines

The energy-generating cost of wind turbines directly depends on the wind turbine output, while the characteristics of the turbine blades and their surface roughness are influential factors in wind turbine output.

In [37] an experimental investigation was performed on the effect of blade surface roughness resulted from dust accumulation on the performance of wind turbines. This study was conducted on Nordtank 300 kW wind turbine located at the Hurghada wind farm site. In the study, the amount of dust accumulated on the blade of Nordtank wind turbine was analyzed and the effect of dust accumulated on blades was investigated by simulating various dust conditions. The roughness area on blades was changed from 5 to 20% from the chord line towards the leading edge.

In another studies, the effect of dust on the performance of pitch-regulated 100 kW horizontal axis wind turbine was studied. The obtained results from pitch-regulated wind turbines were compared with 100 kW stall-regulated wind turbines.

The blade surface roughness depends on the amount of dust accumulated on the surface of the blade area. There is also a relationship between the amount of dust collected on the blade surface and wind turbine periods of operation.

2.5 Economic Impact of Wildfires

With the fast economic growth in the world, the demand for electrical energy has increased significantly, resulting in rapid progress in power infrastructure development. This rapid development of power infrastructure increases the requirements of land occupation. As many power lines are located inside forested land and grassland, which makes them vulnerable to the wildfires. That is, wildfires can damage this infrastructure and cause disruptions in power distribution.

2020 was California's worst wildfire season on record. Five of the 20 largest California wildfires occurred in 2020 as well as six of the 20 most destructive wildfires [38]. A combination of dry conditions, high temperatures and unfavorable weather conditions led to large areas of the state being scorched and many were left without power as companies tried to reduce the risk of creating more fires by power equipment. In an effort to reduce wildfire risk, utility companies also implemented preventative blackouts, cutting power to millions of customers. This case will lead to losing a massive amount of money by the electric companies.

Also, wildfires raise electricity cost by forcing users to draw electricity from relatively expensive sources that do not use threatened transmission lines. The amount increase of utility costs depends on several variables, including the price of the electricity source, the duration of the outage, and the load.

Wildfires present a unique financial threat to American power and utility companies because they do not only cause faults in the system but rather they often wipe out the whole system present on the ground and left the burnt structure. In most states (with California as a notable exception), if a utility company is found to have operated its system prudently, any resulting property damage and other costs are typically borne by private insurance companies and property owners rather than the utility itself. However, if a utility is found to have operated its system imprudently, the company could be held liable for such damages, which are likely to be in the billions of dollars. Damages of this magnitude can bankrupt a utility company, as we've seen with PG&E. In either case, the wildfire will increase costs to utility-sector stakeholders, including investor-owned utilities, state and local governments, ratepayers, and taxpayers. These increased costs will, in turn, place financial stress on utility companies and crowd out essential investment in renewable energy and grid upgrades [39].

Apart from fault related outages, power often needs to be shutoff when the chances of occurrence of wildfire is high. The average public safety power outage duration in the periods between 2013-2020 and 2018-2020 was 41 hours (1.7 days) [40]. The longest recorded public safety power outage duration reported was 162.8 hours (6.75 days) [40]. According to Michael Wara of the Stanford Woods Institute for the Environment, the economic cost of these shut offs in just one month of October during 2019 approached $2.5 billion [41]. That indicates that the total cost of reported public safety power outages from 2013-2020 could be $5.3 billion, or approximately $0.58 per customer outage minute [40].

Pacific Gas & Electric plans to bury 10,000 miles of its power lines to protect them from wildfire damage. The daunting project aims to bury about 10% of PG&E's distribution and transmission lines at a projected cost of $15 billion to as much as $30 billion, based on how much the process will cost. The company believes it will find ways to keep the final bill at the lower end of those estimates. Most of the costs will likely be shouldered by PG&E customers, whose electricity rates are already among the highest in the U.S. [42].

CHAPTER III

IMPACT OF WILDFIRE ON POWER LINE

3.1 Introduction

This chapter aims to develop a model to study the impact of heat from various sources including wildfire flames on power lines. Heat and high temperature can damage the electrical components of power lines, including poles, cables, insulators, and pole grounding cables.

The current carrying capacity of a power line can be reduced by heat, smoke, and particles generated by fire, even if there is no apparent damage to the physical structure [43]. The insulating material in power lines can melt due to intense heat which can lead to short circuit. Moreover, wooden poles which are widely used in distribution system may get burned up.

In addition to the heat that can induce damage, the byproducts of wildfire also have adverse effect on the power system. For example, insulators that attach the lines to the towers can collect ash. This ash development can develop conductive path which may cause short circuit. Furthermore, ionized air in smoke can function as a conductor, causing arcing either in between lines or between line and ground, which may lead to a line outage.

Finally, even if the cables are well protected from fire, fire prevention procedures can cause damage to the power line. Dropping fire retardants through aircraft could cause short-circuit if the retardant used is not a good insulator.

While the physical effects of fire on power lines are easily apparent, it is difficult to approximate for how long those effect will remain. For example, it is difficult to predict the length of time that a line will be down in these instances [44]. Moreover, these outages are also often intentionally done. The repeated occurrence of wildfire in near history and prevalent fire causing conditions require the line outages to be predicted. For example, the year 2020 was California's worst wildfire period on record. A mix of arid conditions, high temperatures, and unfavorable weather led to large areas of the state being uncomfortably hot as many homes were left without power while firms tried to reduce the danger of power lines overheating, potentially causing more fires. Five of the 20 largest California wildfires took place in 2020, in addition to 6 of the 20 most destructive wildfires [45].

3.2 Impact of Wildfires Heat

A wildfire includes a chemical reaction between a combustion source and oxygen. In other words, fire is an oxidation reaction that launches thermal energy into its surroundings. Heat transfer is a process that concerns the exchange of thermal energy between physical systems, which is classified into three fundamental mechanisms: thermal conduction, thermal convection, and thermal radiation.

Conductive heat transfer is the process of energy transfer from one molecule/electron to other through vibratory interaction between the molecule's electrons in the conducting medium. [46]. Heat convection deals with the movement of molecules where a high energy molecule transfers the energy from one point to other by moving to

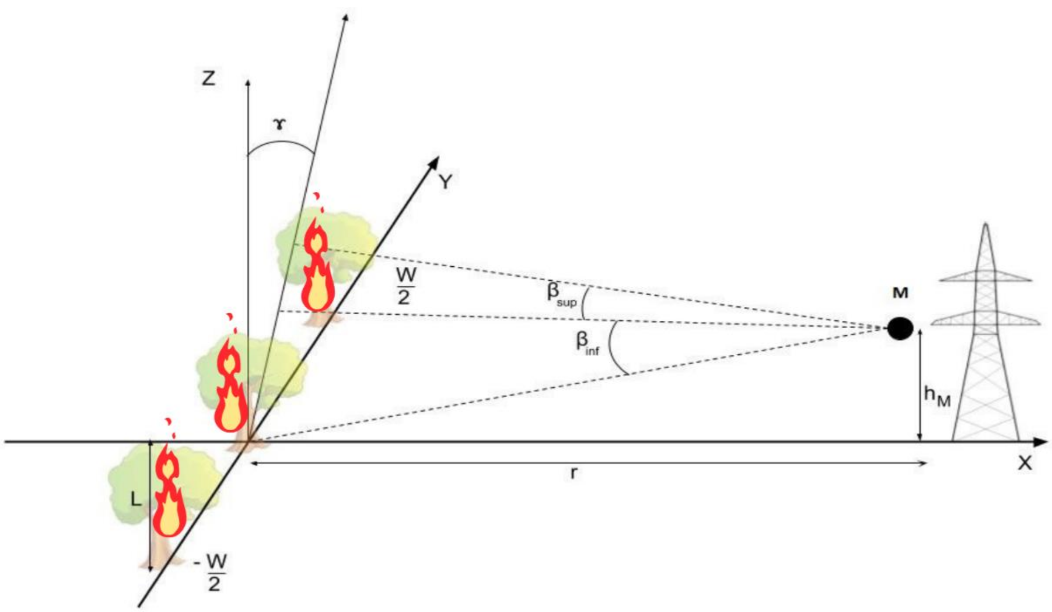

Figure 5: Schematic diagram of fire geometry

the next point of integration. So, in convective heat transfer, the molecules itself move to transfer the energy [47]. Radiative heat transfer is the transfer of heat energy through emitting radiation and does not involve movement of ions, molecule, or electrons. All matter with a temperature greater than absolute zero emits thermal radiation.

The wildfire's heat is mostly transferred through radiation and convection [48].

The article [49] discussed an equation to calculate the effect of heat on conductor ampacity. The heat from wildfire can drastically change the resistance of the overhead power lines. The resistance of conductors tends to increase as the temperature increases where it led to change the ampacity. In this case, even one power line's reduced ampacity may affect the power generation system and its economical operating point [49]. Also, the change in resistance is mainly due to a transformation within the material's resistivity and is caused by the rapid movement of the molecules that the material is made from.

IEEE Standard 738-1993 [50] proposed a thermal balance design for Dynamic Thermal Rating (DTR) of bare-conductor power lines. This standard is first order differential equation that balances the heat created by conductor's resistance, the heat from solar irradiance, the heat stored in the conductor, and the heat dissipated with convection and radiation [49]:

$$RI^2 + Q_s = mc_c \frac{dT_c}{dt} + Q_r + Q_c \tag{3.1}$$

Where R is the conductor resistance (Ω/m), I is the current flow through the conductor (A), Q_s is the solar irradiance heat transfer rate per unit length of conductor (W/m), c_c is the specific heat of the conductor (J/K), T_c is the conductor's temperature ($°C$), Q_r is the radiative heat loss rate per unit length of conductor (W/m), and Q_c is convection heat loss rate per unit length of conductor (W/m).

The model assumes steady-state thermal equilibrium in the conductor, meaning that conductor's temperature variation is equal to zero. In this manner, the differential formula turns into an algebraic formula from which the thermal line rating can be calculated as proposed in [51]:

$$RI^2 + Q_s = Q_r + Q_c \tag{3.2}$$

However, for knowing the effect of wildfires on thermal rating of power lines, it is essential to consolidate the heat transferred from the fire to the conductor into the DTR of the line. Therefore, radiation (Q_{rc}) and convection (Q_{cc}) heat that transfers from the wildfire flames must be added in equation (3.2) as follows [49]:

$$RI^2 + Q_s + Q_{rc} + Q_{cc} = Q_r + Q_c \tag{3.3}$$

The radiation heat transfer can be calculated according to the solid flame model proposed in [48] as shown in **Error! Reference source not found.**. In this model, a flame is considered a geometrical body that consistently radiates heat from its entire surface. In **Error! Reference source not found.**, L is the flame length, W is the flame width, γ is the tilt angle, and v_f is the rate of spread that moves toward target M, r is the distance from the fire front to the object of interest (M), $\propto_{vf}$ is the solar absorptivity, ε_{FZ} is the flame zone emissivity, σ is the Stefan-Boltzman constant (W/m^2K^2), and τ is the atmospheric transmissivity, we can write equation for the radiative heat flux received by the target located at height h_m as [52]:

$$\Phi_r = \tau\varepsilon_{FZ}\sigma T_f^4\left[\propto_{vf}\left(\mathrm{r}_{inf},\beta_{inf}\right)+\propto_{vf}\left(\mathrm{r}_{sup},\beta_{sup}\right)\ \right] \tag{3.4}$$

where,

$$\beta_{inf} = \tan^{-1}\left(\frac{h_m}{r_{inf}}\right) \tag{3.5}$$

$$\beta_{sup} = \tan^{-1}\left(\frac{L\ \cos(\gamma)-h_M}{\mathrm{r}_{sup}-(L\sin(\gamma))}\right) \tag{3.6}$$

$$\mathrm{r}_{inf} = r \tag{3.7}$$

$$\mathrm{r}_{sup} = r + h_M tan\,\gamma \tag{3.8}$$

$$Q_{rc} = D_c\Phi_r \tag{3.9}$$

where D_c is the conductor diameter (m).

The convective heat transfer highly depends on the direction of movement of high energy molecules which depends on prevailing surrounding conditions. The convection heat transfer Φ_c can be calculated by (10) [52].

$$\Phi_c = 22h_c\left(\frac{I_{FL}^{2/3}}{h_M^{5/3}}\right) \tag{3.10}$$

$$Q_{cc} = D_c\Phi_r \tag{3.11}$$

where h_c is transfer coefficient of the convective heat (W/m^2), and I_{FL} is the Newman for fire intensity.

The Q_s, Q_r and Q_c in (3.3) are calculated as following equation [53] :

$$Q_s = \alpha Q_{se}\sin(\theta_s)\cdot A \tag{3.12}$$

$$Q_r = 0.0178\cdot\ D_c\varepsilon_c\left[\left(\frac{T_c-273}{100}\right)^4-\left(\frac{T_a+273}{100}\right)^4\right] \tag{3.13}$$

$$Q_{c1} = \left[1.01 + 0.0372 \left(\frac{D_c \rho_a V_w}{\mu_a}\right)^{0.52}\right] k_a k_{angle} (T_c - T_a) \quad (3.14)$$

$$Q_{c2} = \left[0.0119 \left(\frac{D_c \rho_a V_w}{\mu_a}\right)^{0.6}\right] k_a k_{angle} (T_c - T_a) \quad (3.15)$$

$$R = R_{ref}[1 + \alpha(T_c - T_{sa})] \quad (3.16)$$

$$Q_{cn} = 0.0205 \rho_a^{0.5} D_c^{0.75} (T_c - T_a)^{1.25} \quad (3.17)$$

$$Q_c = \max(Q_{c1}, Q_{c2}, Q_{cn}) \quad (3.18)$$

$$K_{angle} = 1.194 - \cos(\theta_w) + 0.194 \cos(2\theta_w) + 0.368 \sin(2\theta_w) \quad (3.19)$$

Where Q_{c1} is the forced convection heat loss rate for low wind speed, Q_{c2} is the forced convection heat loss rate for high wind speed, Q_{cn} is the natural convection heat loss rate, respectively. Q_{se} is the total solar and sky radiated heat flux rate (W/m^2), A is the projected area of conductor per unit length (m^2/m), ε_c is the conductor emissivity and T_{sa} is the standard ambient temperature ($°C$), T_c is the conductor's temperature ($°C$), ρ_a is the density of air (kg/m^3), V_w is the wind speed (m/s), μ_a is the dynamic viscosity of air (Pa-s), $k_a$is the wind direction, and θ_w is the angle of wind direction with respect to conductor axis.

The resistance of conductors is also a function of temperature described in equation (3.16) tends to increase as the temperature increases where wildfires led to change the ampacity of the power line. When the ampacity is reduced power generation system and its economical operating point will be affected. So, we must figure the ampacity I from equation (3.3) to know the impact of wildfire heat in power lines. So, first, we must collect the data of ambient temperature and solar irradiance. Second, calculate the heat flux received by the power line from equation (3.1) or convection heat when the fire underneath the power line from equation (3.10). Finally, calculating the Q_s, Q_r and Q_c from equations (3.12), (3.13), and (3.18).

3.4 Mechanical Impact of High Temperatures on Power Lines

As the temperature of the conductor increases, multiple physical parameters are impacted. Excessive exposure to heat due to wildfire may cause the conductor to past a conductor cable's highest working temperature which can result in sag or damage.

The admissible clearance between a line and the objects underneath will depend on the operating voltage of line. Greater the operating voltage of line, larger the clearance is required to enable safe operation of power line. The sag permissible will depend on the length of the span between towers and the height of the conductor connection point at the tower.

The sag in power lines is normally caused by the weight of a conductor, where the final conductor length at the standard ambient temperature due to weight ($L_{f,w}$) can be calculated as [54]:

$$L_{f,w} = L_i\left(1 + \frac{Li^2 w^2}{24H^2}\right) \tag{3.20}$$

where w is the weight per length, H is the tension of the conductor, and L_i is the initial length of the line (m) at the standard ambient temperature.

Temperature can also change the length of a line. The linear thermal increase of the line length can be expressed as [54]:

$$dL = L_{f,w}\, \beta\, (T_c - T_{sa}) \tag{3.21}$$

where dL is the change in the line length (m), β is the linear expansion coefficient $(m/m°C)$, and T_{sa} is the standard ambient temperature. The final length of the conductor then can be calculated as:

$$L_f = L_{f,w} + dL \tag{3.22}$$

So, the total sag caused by the weight and thermal expansion can be calculated by (3.23).

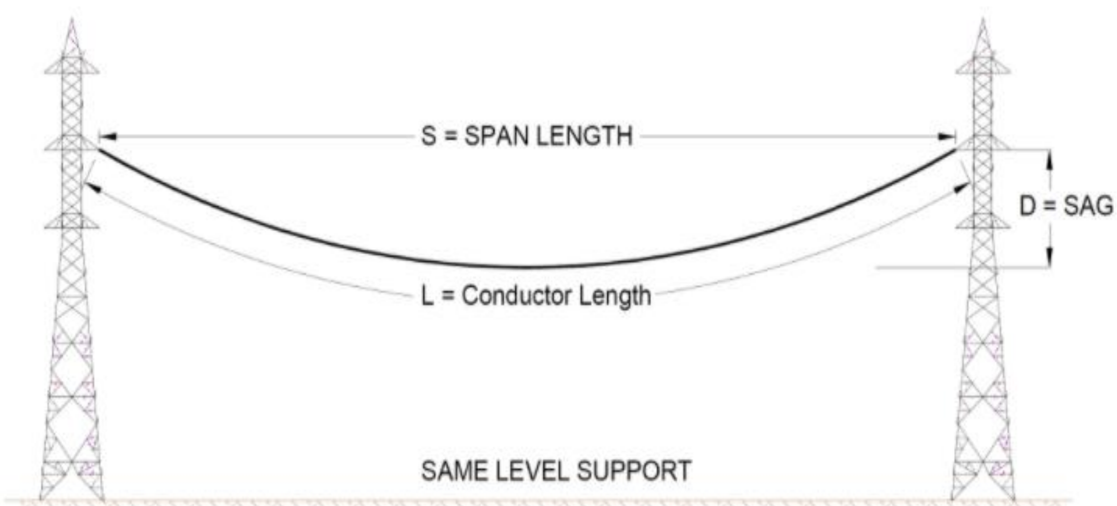

Figure 6: High temperature low sag [69].

$$D = \sqrt{\frac{3L_i(L_f - L_i)}{8}} \tag{3.23}$$

Conductors used in power lines will expand or contract with changes in the temperature. The rate of expansion or contraction is dependent on the conductor materials and the degree of temperature change. From the equation above we can tell that as temperature increases, the conductor expands in length and therefore its tension decreases, while the sag increases. With the reduction in tension, there is also a reduction in strain in the conductor. Thus, the transmission lines that are located near to the wildfires are susceptible to be exposed to a high temperature which lead them to damage. Given the hanging height of the tower, and calculated Sag, one can easily conclude how much clearance between ground or tree is available for the safe operation of a line.

CHAPTER IV

IMPACT OF WILDFIRES ON THE RENEWABLE ENERGY

4.1 Introduction

This chapter deals with the degradation analysis of power output from PV panels and wind turbines due to wildfire. First, this chapter mentioned how the solar irradiance absorbed by PV panels and how wildfires impact that irradiance. Then it covers the impact of wildfire's heat, ash, and smoke which affect the power output of PV panels. Finally, how could the wildfire's smoke, ash and dust reduce the wind turbines power output is discussed in this chapter.

4.2 Overview

Renewable power sources are becoming more popular worldwide as power demand rises, prices of fossil and other non-renewable fuels increase, and concerns related to climate change and air quality which is playing a role for attenuating the solar irradiance.

Irradiance: Solar irradiance is the power per unit area obtained from the sun at a wavelength of the light. It is measured in watt per square meter in SI units (W/m^2). Principal spectral irradiance variants are seen in many wavelengths, starting from the visible and IR, through the UV, to EUV and X-ray. [55].

4.2.1 Solar Power

The perfect emitter of radiation is the sun, which has a temperature close to 5800 K. Any receiver located outside the Earth's atmosphere will receive extraterrestrial radiation from the sun that consists of direct radiation only. Since medium space is virtually devoid of material that might scatter or reflect light, it appears nearly black [56].

Solar radiation is altered by interaction with components present when it passes through the earth's atmosphere. Some of these, such as clouds, reflect radiation. Others, for example, ozone, oxygen, carbon dioxide, and water vapor, have significant absorption at several specific spectral bands. Smoke, ash, and dust from the wildfires also scatter solar radiation. The breakdown of the solar radiation incident on PV panels at the earth's surface into clearly differentiated components results from these processes. Direct radiation, made up of beams of light that are not reflected or scattered, reaches the surface straight from the sun. Diffuse radiation, coming from the sky apart from the sun's disc, is the radiation scattered towards the receiver. The reflected radiation is radiation reflected from the ground. The total radiation falling on a surface is the sum of direct, diffuse, and reflected and is termed global radiation. [56].

As wildfires produce smoke, ash, and dust particles that hinder the solar radiation and cause aerosol absorption and scattering. This causes the irradiance level to attenuate which reach PV panels for producing power. The aerosol absorption and the aerosol scattering term need to be known to determine the exact value of diffused radiation received in case of wildfire.

4.3 Impact of Wildfires on Solar Power

Solar Panels are designed to produce maximum power at the rated irradiance and ambient temperatures. Any deviation in these two parameters will sharply decrease the power output (P_{PV}) of the solar system. The output power of a solar system at the maximum power point (MPP) is obtained from the following equation [57].

$$P_{PV} = [P_{PV,STC} \times \frac{G_T}{1000} \times [1 - \gamma \times (T_j - 25)]] \times N_{PVs} \times N_{PVp} \quad (4.1)$$

where the $P_{PV,STC}$ is the rated PV power at the MPP and standard test condition (STC), the T_j is the cell temperature at the standard test temperature which is 25 degrees Celsius, the γ is the power temperature coefficient at the MPP, G_T is the irradiance at (STC) which is 1000 W/m^2, N_{PVs} and N_{PVp} are the number of modules in series and in parallel that composed the generator.

The cell temperature T_j can be obtained from the following equation.

$$T_j = T_a + \frac{G_T}{1000} \times (NOCT - 20) \quad (4.2)$$

Where the T_a is the ambient air temperature, and the *NOCT* is a nominal operating cell temperature. So, from equation (4.2) the cell temperature will be increased when the G_T increase.

4.3.1 Impact of Heat on Solar Power

The equation (4.2) shows that temperature is one of the main sources that can change the output power of the PV panels. So as the ambient temperature and the G_T increases, the output power is decreases.

$$P_{PV} = [P_{PV,STC} \times \frac{G_T}{1000} \times [1 - \gamma \times ((T_a + \frac{G_T}{1000} \times (NOCT - 20)) - 25)]] \times N_{PVs} \times N_{PVp} \quad (4.3)$$

Wildfire as a source of heat reduces the power output of solar panels by increasing the T_a. The relationship between heat that is transferred from wildfires to solar panels and temperature change contains all the following factors [58]:

$$Q = mc\Delta T_j \quad (4.4)$$

where the Q is the heat transferred to the cells, *m* is the mass of the cells, *c* is the specific heat of the cells, and ΔT_j is the cell temperature change.

So, from equation (4.4), we need to calculate the T_j for getting how much power does the solar reduces by applying T_j in equation (4.3) when the heat Q increases.

4.3.2 Impact of Smoke on Solar Power

Wildfire smoke is another influential factor on the output power of the PV panels. Smoke is an assortment of strong molecules, fluid, and gas particles. It can contain many various synthetics materials and vapor. Most of noticeable smoke are, carbon, tar, oils, and dust or ash. There are two kinds of smoke, one of them happens when there is inadequate ignition, and the other occurs with flame. These tiny particles stay in the atmosphere for a significant time, and even remain there for weeks. Particulate matter in the smoke result in visibility reduction. When the visibility is reduced, the irradiance that comes from the sun throughout the atmosphere will reduces. Thus, according to the equation (4.1), when the Irradiance, G_T, decreases, the output power will decrease. This section will study how to calculate the amount of light that the smoke absorbs and then calculate the transmitted light that reaches PV panels to generate power.

4.3.3 Absorption Calculation

For calculating the absorption of light, the Beer-Lambert law is utilized. Lambert's law states that the absorbance of light in a medium is directly proportional to the length of the sample in which the light passes where it calculated as follow [59].

$$A_b = log(\frac{G_T{}'}{G_T})\alpha l \tag{4.5}$$

where,

A_b : the amount of light absorbed by the sample as per beer’s law
l : The length of the light path
$G_T{}'$: The intensity of light after passing through the path of length
G_T : The intensity of light at incidence

As the absorbance of light is directly proportional to the length the light has to travel through, the absorbance can be expressed as below, where ϵ is the molar absorptivity of the sample.

$$A_b = \epsilon l \tag{4.6}$$

Beer's law states that the absorbance of light in a sample is directly proportional to the concentration of the sample in which light travels.

$$A_L = log(\frac{G_T{}'}{G_T})\alpha C \tag{4.7}$$

where,

A_L : the amount of light absorbed by the sample as per Lambert’s law
C : The concentration of sample

$$A_L = \epsilon C \tag{4.8}$$

When we combine the Beer and Lambert laws, the relationship between the light's attenuation through a medium (e.g., smoke) can be obtained as a function of several properties of that medium, which is as follow:

$$A_{bL} = \epsilon C l \tag{4.9}$$

where A_{bL} is the absorbance, which in this application is the amount of light absorbed by the smoke, ϵ is molar absorptivity, C is the concentration, and l is the length of the light path.

The absorbance and hence the transmitted light from the smoke can be calculated as

$$A_{bL} = log(\frac{G_T{}'}{G_T}) \tag{4.10}$$

where $G_T{}'$ is the intensity of light received on solar panel after passing through the smoke. Since in this application, we are interested in evaluating the impact of wildfire smoke on power generated by solar cells, the smoke concentration, length of the light path through the smoke, and the molar absorptivity of the smoke through the light should be calculated.

For an open system, the smoke concentration C_s, which is the amount of combustion products found in the specified volume of air, typically calculated as grams of emission per cubic meter of air (g/m^3) can be expressed as [60]:

$$C_s = Y_s \, \dot{G}_f \, A/\dot{V}_T \tag{4.11}$$

where Y_s is the yield of smoke (g/g), $\dot{G}_f$ is the rate of burning material per unit surface area of the material ($g/m^2 s$), A is the surface area of the material (m^2), and $\dot{V}_T$ is the volumetric rate of gases byproducts due to fire and air mixture given in (m^3/s) . The yield of smoke can be expressed as [60],

$$Y_s = f_s\, k_s \tag{4.12}$$

where f_s is the efficiency of smoke production due to fire, and k_s is the maximum possible yield of the smoke.

The generation rate of material per unit surface area of the material for fires, can be expressed as:

$$\dot{G}_{f,fl} = [q_e + q_{fl} - q_{rr}]/L \tag{4.13}$$

where q_e is the external heat flux per unit surface area of the material (kw/m^2), q_{fl} is the flame heat flux per unit surface area of the material (kw/m^2), q_{rr} is the surface radiation loss per unit surface area of the material (kw/m^2), and L is the heat gasification of the material. Knowing how to calculate all parameters of the smoke concentration now, one can substitute the smoke concentration from equation (4.11) into equation (4.9). But we still need to figure the molar absorptivity, which is expressed as (4.21) for well ventilated flaming fire [60],

$$\epsilon = 3.213/\lambda\, p_s \tag{4.14}$$

Where λ is the wavelength of the light source and p_s is the density of the smoke (g/m^3).

Here the smoke density p_s need to be measured as this highly depends on the spatial location where this value is required and cannot be calculated. Given the intensity of light $G_T$from the source, the value of the transmitted light $G_T{}'$ can be calculated by putting the value of ϵ in equation (4.14). However, our goals are to calculate the transmitted light, $G_T{}'$, in this case, we have the standard measurement of the source light, G_T or the optical density, which will be the smoke density, p_s. So, to get that, we must measure the smoke density because it is so hard to calculate it.

4.3.4 Impact of ash on Solar Power

The soot and ash particles on solar panels also reduce the amount of light that absorbed by PV panels. According to the equation (4.1), when the solar irradiance (which is considered the amount of light that is reached to the PV panels (G_{To})) decreases, the output power reduces. So, to calculate the amount of light blocked by the dust, we must calculate the amount of soot and ash on the PV panels surface. In [61], authors mathematically investigated the impact of dust on the transmittance of the light on PV panels. The study [61] formulated equations with normal and different incidence angles that is received by PV panels.

So, we have to calculate the transmittance light which is G_{To} in equation (4.1) in order to calculate the attenuation of power generated by PV panels. To do so, we have to know the particle size of accumulation in the PV panels because of wildfire's ash.

First, the ratio of the particle size to the wavelength of the incident radiation must be calculated (λ). The scattering of light incident because of particle is dictated by the ratio between particle size and wavelength of the incident radiation. This ratio is called size parameter α, which is given by:

$$\alpha = \frac{\pi D}{\lambda} \tag{4.15}$$

Where D is the particle diameter.

The attenuation of light intensity due to scattering and absorption by particles is called extinction. The extinction of light produced by a particle is a function of the particle extinction efficiency Q_e.

When the particles are tiny compared with the incident wavelength, $\alpha < 0.3$, the particle extinction efficiency will be as follow,

$$Q_e = \frac{8\alpha^4}{3}[\frac{m^2-1}{m^2+2}]^2 \quad (4.16)$$

where m is the particle refractive index. For larger particles, when $\alpha > 0.3$ or when the particle diameter is larger than 0.05 um at $\lambda = 0.5\, um$, calculating the Q_e is more complicated. When particles become larger and larger ($\alpha > 12$ or diameter larger than 2 um at $\lambda = 0.52\, um$), Q_e approaches its limiting value of 2.0 with oscillations. In this case, all the geometrically incident power (light) is scattered by reflection and refraction or partially absorbed within the particle. Therefore, when the particle is very large compared with the wavelength, the particle scattering efficiency will not be affected by the change in the wavelength, or it is no longer sensitive to the wavelength.

If number of particles dust (N) settle beside each other on the glass surface, they would cover an area equal to $N\pi r^2$. The particles will be assumed to be spherical with mean diameter D (cm), mean radius r (cm), density $\rho = 2.65\ g/cm^3$.

The mathematical model here will be based on the assumptions of equally sized spherical particles uniformly distributed. A whole layer of dust particles is assumed to be formed before the second layer formation. The difference of the results from the real scenario will be depicted in the mathematical analysis for the measured data. When the particles settle beside each other until they cover the whole area of 1 cm^2, they tend to be distributed. In this case, to find the total number of particles, the study [61] described a procedure according to which the total number of particles that occupy an area of 1 cm^2 (N_T), forming one whole layer, is given by:

$$N_T = \frac{1.155}{D} \times \frac{1}{D} = \frac{1.155}{D^2}\ particles \quad (4.17)$$

Where these particles will cover a total area of:

$$A_T = \frac{1.155}{D^2} \times \pi (\frac{D}{2})^2 = 0.91\ cm^2 \quad (4.18)$$

To find the mass of these particles, the number of particles is multiplied by the mass for a single particle. Thus, the mass of particles (M_T) per square centimeter that form one full layer over the glass surface is given by:

$$M_T = \frac{1.155}{D^2} \times \frac{4}{3}\pi\rho(\frac{D}{2})^3 = 0.605\rho D\ g \quad (4.19)$$

where ρ is the density of sand particles Also, in this study [61] we can learn in detail how the author formulate these equations.

Therefore, the maximum particles' number that can occupy an area of 1 cm^2 forming one full layer of particles for D = 6 um is $1.155/D^2 \approx 3 \times 10^3$ particles having the mass (M_T) of $0.605\rho D \approx 1\ mg$, covering an area equal to 0.91 cm^2.

For a given mass (*M*) of particles per unit area (cm^2), the total number of particles (*N*) can be found from:

$$N = \frac{M}{\frac{4}{3}\pi\rho\left(\frac{D}{2}\right)^3}\ paricles \quad (4.20)$$

Which covers an area (A_c):

$$A_c = \frac{M}{\frac{4}{3}\pi\rho\left(\frac{D}{2}\right)^3} \times \pi\left(\frac{D}{2}\right)^2 = \frac{1.5M}{\rho D}\ cm^2 \quad (4.21)$$

From (4.21), it is clear that for a given mass (M) of particles, smaller particles cover more total area (A_c) than larger ones. In contrast, for a given number of particles (N), larger particles cover more total area $N\pi r^2$ than smaller ones.

Therefore, at the normal incidence angle, the cross-sectional area of light which is no more available to the PV panel due to presence of dust particles is equal to the particle-projected area times its extinction efficiency ($Q_e \pi r^2$).

For a number of sand particles (N) per unit area (cm^2), the area covered is $NQ_e\pi r^2$. Therefore, the light transmittance (G_T) is:

$$G_T = \frac{1 - NQ_e\pi r^2}{1} = 1 - NQ_e\pi r^2 \qquad (4.22)$$

So, according to the equation (4.30) when G_T, which is considered as the transmitted light, decreases, the output power of the PV panel will reduce.

When the incidence light angle is not zero, the area covered by particle is different from that at the normal incidence light angle. The article [61] has provided a way to find the area that particle is covering given the incident light angle θ.

$$A_c = \frac{M}{\frac{4}{3}\pi\rho r^2}\,\pi\frac{r^2}{2} \times \left[\frac{1}{\tan\left(\frac{90-\theta}{2}\right)} + tan\left(\frac{90-\theta}{2}\right)\right] \qquad (4.23)$$

Hence the light received at an angle θ by the PV panel which is covered by particles can be combined with equation (4.23), where the irradiance (G_T) is:

$$G_T = 1 - Q_e A_{c(\theta)} \qquad (4.24)$$

So, from this equation (4.24), we can say when the area covered by particles is large, the irradiance that can be absorbed by the PV panel is low, which means the total output power decreases according to the equation (4.1).

4.3 Impact of Wildfires on Wind Turbine

The revenue generated by a wind turbine is directly proportional to the wind turbine power output, which can be affected by the qualities of the turbine blades and their surface area roughness. The soot or ash from wildfires has potential to weaken the smoothness of the wind turbine's blade which may drastically decrease the power output of the wind turbine. Therefore, the soot/ash build-up on the blade surface can be listed as one the main impacts of wildfire on performance of wind turbine. To this end, it is essential to study some theoretical models to describe the effect of roughness on wind turbine performance, as the blade surface roughness plays a critical role in the aerodynamics, power production, and lifetime of the windmill. Soot or ash on the wind turbine's blades may also lead to a halt in power production as heavy accumulation of these particles may not allow stable operation of the wind turbine.

According to the experiment done by M. Khalfallah [62], throughout the rotor blades' rotation in dusty weather conditions, the leading edge of rotor blades collects more and more dust around the stagnation points of aero foils over the radius of blade. Then, because of increased air rate along the radius of the blade, the dust grains build up at the outer part of the blade. The blade surface roughness depends on the quantity of dust collected externally on the blade area.

Since we are concerned about the effect of soot and ash particles on wind turbine power generation due to wildfire, we can reasonably assume that the impact of soot and ash particles due to wildfire are very much similar to the normal dust particles present in the air. Moreover, due to wildfire, the total quantity of soot or ash particles in air would increase by many folds which would otherwise take up from three to six months for the normal quantity of dust particles to add up to that level. Hence, one can explain the effect of soot/ash particles produced by wildfires on turbine blades based on the study conducted in [62] on the particle accumulation effect over long term. Fig. 8, shows the effect of dust on the power curve of Nordtank 300 kW wind generator for different operating durations, one day, one week, one month, three months, six months, and nine months. There was no cleansing of blades during each of these tests, the dust gathered on the blade surface area was only eliminated at the beginning of each test. Since the accumulation of particles is also related to wind speed which is out of the human control so the effect of wind speed on particle accumulation was ignored. The same assumption can also be applied in our case as the wind speed during wildfires can have different values.

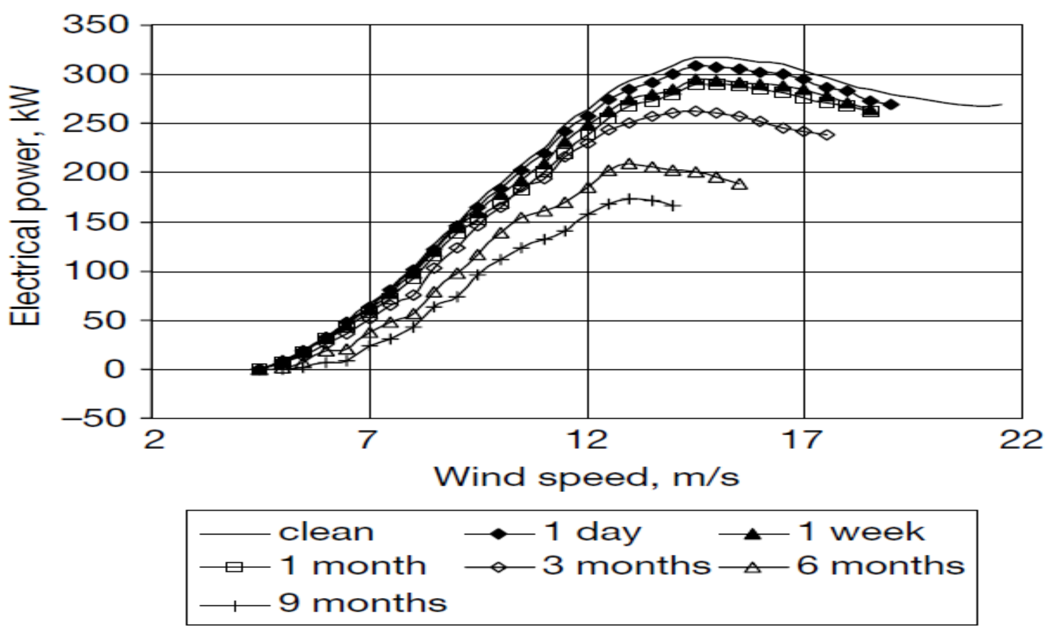

Figure 7. Effect of dust for various operation periods on the power curve of turbine [62] .

The result of the long time operation duration of the wind generator without getting rid of dust on its size was displayed in Fig. 8. From the curve on the Fig. 7, it can be concluded that the power output is reduced from wind turbines when the rotor blades are not cleaned for a long period of time. We are interested in studies for duration greater than 3 months which resembles wildfire particle accumulation scenario. Therefore, we can conclude that wildfire can drastically reduce the power production of wind turbines by up to 70 percent of its normal power capacity (concluded from the graph plotted for 6 month).

The measured data in Fig. 8 is fitted linearly as following:

$$D_d = 0.08T + 0.02 \tag{4.25}$$

where D_d is the dust size (size in mm), and T is the size of the operation period in months

The blade dust area is specified as the area of the blade which is covered by dust. This area is measured from the leading-edge as a proportion of the overall length of the blade.

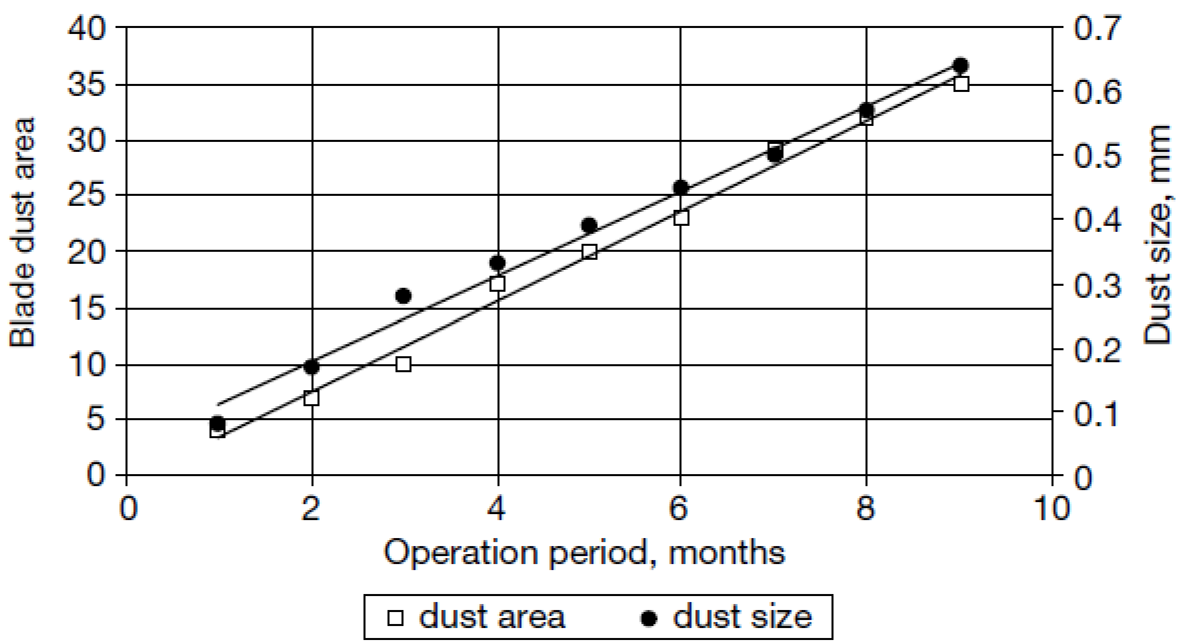

Figure 8. Blade dust specification with operation period of turbine [62] .

The blade dust area increases linearly with the generator's length of operation given that the blades are not cleaned.

The measured data as shown in Fig. 9 can be fitted mathematically as:

$$D_A = T/25 \tag{4.26}$$

where DA is the dust area in percentage. So, when the wildfire happens near the wind turbines, the ash and soot from a fire will be increased accumulating in the blades of the turbines during the operation time, which will affect the generating of power.

The mean power loss due to dirt collected on the blade surface was determined at various operation periods using the actual blade roughness during the measurements. Fig. 9 shows the impact of dust particles (dust size) on the mean power generated from the wind generator. In these measurements, 10% of the blade area is covered by different sizes of dust.

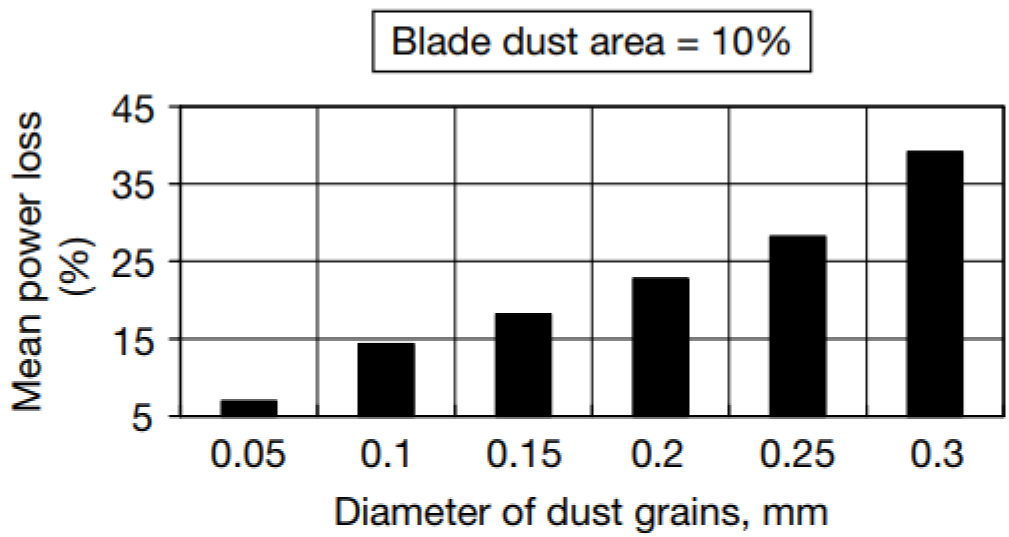

Figure 9. Effect of various dust thickness on the mean power loss (%) of turbine [62] .

When the dimension of dust fragments increases, the mean power loss is raised because of the increase in blade surface roughness. In the case of 0.3 mm dirt particles, the mean power loss reached 38% roughly. However, it reached 6.5% in the case of 0.05 mm diameter dust grains. From these results, it is clear that the performance of straight axis wind generators depends upon the blade surface roughness. Likewise, there is high loss in annual mean power generated by wind turbines with a high blade roughness index (dust size), especially in a high wind location. The mathematical relationship between the mean power loss (MPL) and dimension of dust particles can be expressed linearly as:

$$MPL(\%) = 125 * d \tag{4.35}$$

where d is the size of dirt fragments in (mm) for a dust area of 10%. Fig. 9 shows the result of the basic roughness index in the Hurghada site, where the diameter of dust particle was 0.28 mm. In these measurements, the blade dust area was altered to 5%, 10%, 15%, and 20% from the overall surface area of the blade. As shown in Fig. 10, the mean power loss increased as the blade dust area is increased

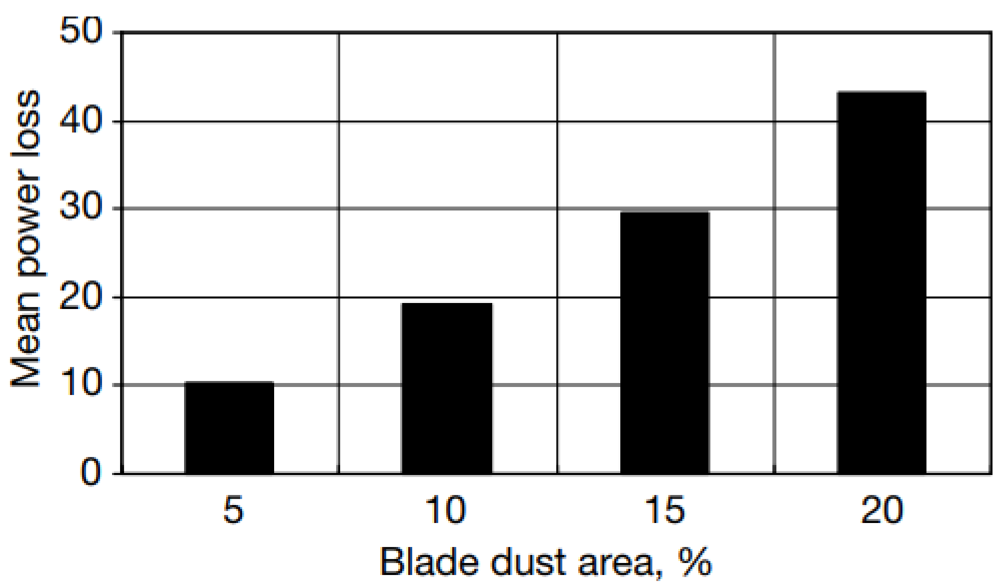

Figure 10: Effect of standard dust thickness (0.28 mm) with various blade dust area on the turbine power loss [62].

For the case of standard roughness index (thickness, d = 0.28 mm), the mathematical relationship between the blade dust area and mean power loss is formulated linearly as following:

$$MPL(\%) = 2A_d - 1 \tag{4.27}$$

where A_d is the blade dust area in (%). This linear formula was expressed from dust simulators and checked with the actual results. The maximum numerical error was found to be within ±5% [62].

CHAPTER V

IMPACT OF WILDFIRE ON POWER EQUIPMENTS

5.1 INTRODUCTION

Aging facilities, load growth, and an increase in a sustainable generation has raised the need to develop more electric transmission and distribution system.

Meanwhile, severe weather conditions are repeatedly causing wildfires, which ultimately require the power system to be developed more robust to keep themselves safe from the wildfire-induced damages.

The power system should execute the command and isolate the faulty/overload portion when an anomaly is detected. The consequences of not doing so lead to consumer blackouts and damage to the costly equipment, which can substantially impact the utility.

Wildfire impacts the equipment that catches fire and other nearby facilities because of heat, smoke, and toxic fumes. The heat from wildfire is particularly of immediate concern (as are the smoke and fumes), but the smoke may also have long-term consequences on electrical contacts. They may coat insulators, cause high resistance between connections, and decrease insulation properties due to chemical changes in plastic insulations [63]. Fires and the associated heat soften plastic insulation and fracture ceramic insulators, which reduce the insulation strength of the insulators. Further, suppose there are transformers (which often use oil as a cooling medium) [63]. In that

Figure11: Duke Energy Substation located in California ***Invalid source specified.***

case, the containment oil tank rupture may spread burning insulating oil, usually containing polychlorinated biphenyl (PCB), over floors and into the drain systems, which is dangerous for the living organisms [63]. Usually, Substations are equipped with automatic fire-suppression systems to deal with fire, which automatically act as soon as the fire is observed. These systems may help keep the substation operational for a critical control period and perform necessary control operations and fire suppressing before shutting down the substation. Some substations are not equipped with automatic fire suppression systems and depend on an alarm for manually controlling the fire. In these situations, the availability of portable fire extinguishment equipment and accurate evaluation of the case is essential. Training of emergency response personnel and procedures should be a part of fire extinguishing procedures, especially those depending on manual suppression of fire [63].

Below, we discuss the impact of wildfires on some of the critical components in power systems.

5.2 Transformer

Transformers are one of the main components of power transmission and distribution system. They are some of the most vulnerable to the wildfire as they are usually installed in the open yard. Oil is the most common insulator and cooling medium used in the power transformers. Although oil possess some positive features like good insulation properties, it is inherently flammable. In case of high temperatures due to wildfire, if the oil catches fire, it is extremely difficult to control the fire and prevent the damage to the nearby equipment.

The most common cause of transformer failure is insulation failure. Common factors which impact the insulation quality of insulators are temperature induced strain, moisture, degradation in the oil quality due to chemical decomposition and extreme temperature levels. These are all adverse factors that can be created by wildfires and lead to the negative effect on the insulation of the transformer. Transformers are designed to perform for a minimum of 20-30 years if effectively sized, mounted, and preserved. However, temperature level is one of the main factors that affect a transformer's life. Transformers exposed to excessive heat due to wildfire for an extended amount of time may have reduced life expectancy [64]. Heat-dissipating radiator tubes on the outside of a transformer provide a convective oil flow to remove heat from the transformer's core (Fig.13). The oil inside the radiator tube of a transformer can ignite at approximately 150 °C (300 °F). A typical wildfire may reach temperatures of 800 °C (1,472 °F) which is far beyond the ignition temperature of oil. Under severe conditions, a wildfire can produce more than 10,000 kilowatts per meter of fire front. This would mean fire heights of 50 meters or more and flame temperatures surpassing 1200 °C (2,192 °F) [65].

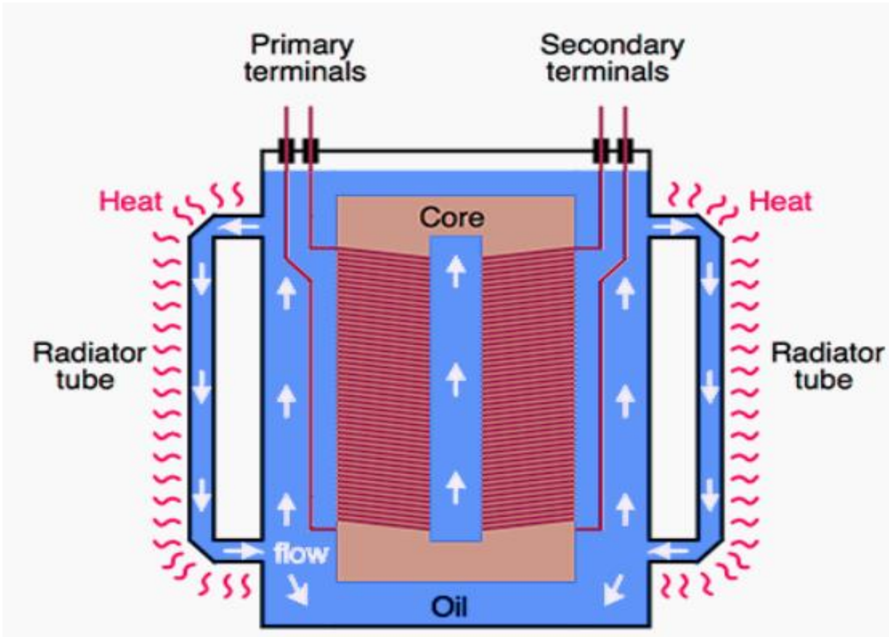

Figure 12: Big power transformers with heat dissipating

Also, the thermal aging of transformer insulating materials is related to the chemical reactions happening within the materials which can be attributed to the aging of insulators. These chemical reactions are brought on by pyrolysis oxidation and hydrolysis, which can be sped up by enhanced levels of temperatures caused by the wildfire [66]. Transformers can also become covered in wildfire ash which may lead for arcing and loss of cooling capacity.

5.3 Switchgear

*Figure 13 An open yard high voltage switch gear**Invalid source specified.***

Unlike transformers that are quiescent elements, switchgear is an active element that can fail structurally by not separating or closing the circuits when commanded or acting spuriously upon command due to the burning of some control signal cables. The heat from the wildfire can damage the control wiring and lead to an inappropriate control signal. These appropriate control signals can create problems in the connected circuits by opening and closing the circuits which are not intended to be closed or open. Suppose a breaker fails to clear upon signal or becomes overloaded because of wildfire's heat, smoke, or ash. In that case, the circuit will be subjected to further damage until an upstream breaker (usually larger and set for a higher current rating) can sense and clear the fault/overload [63].

On the other hand, if a breaker fails to close, this normally means that all circuits that receive power from this feed point cannot perform their expected functions. Moreover, the ash and fumes from a wildfire can damage the contacts of circuit breakers in the open substation yard. This may lead to mechanical, operational failure even if the control wiring is intact in the substation [63].

Interruption of any significant electrical circuit, which wildfire's high temperature can cause, can create unbalance in the supply circuits, which can cause cascading load rejection and bring down the entire system. Spurious switchgear operation, either opening or closing, can easily be responsible for creating unsafe conditions [63]. For instance, an unscheduled introduction may disconnect a load vital to some operation phase, or a breaker closing could subject the system to unneeded load surges.

5.4 Lightning Arrestors

Lightning arrestors are important safety equipment in the power system and must function when called on. Otherwise, damage to other elements will be excessive. The purpose of lightning (surge) arrestors is to limit the excessive currents and voltage spikes during lightning or switching-induced surges [63]. High temperatures resulting from wildfire may damage the lightning arrestors [63]. Although lightning (surge) arrestor failures are often characterized by physical failure of the ceramic insulator and containment, it is very difficult to judge the health of surge arrestors. Thus, it may cause damage to costly equipment after the wildfire is over. Especially the equipment that is located near to the wildfire, such as transformers, which are essentially protected on both the high- and low-voltage sides, to protect not only the insulation of the transformer but to keep sensitive electronic monitoring and control equipment in the plant from being subjected to damaging voltages and currents.

5.4 Cables and Connectors

Power and control cables are really at risk of being damaged by wildfire. Because of the large radius turns required, power cables are generally not located indoors. Usually, power delivery cables, often run in a standard cable tray, are vulnerable to cascading fire. A fire on a single line may spread to adjacent cables and cable trays. Once a cable tray fire has started, not only does its extinguishment become difficult, but damage potential can extend significantly beyond the limits of the fire. Almost all present-day power cables use polyethylene, and PVC insulation, which, when heated sufficiently by internal or external means, will evolve flammable gas, char, and burn [63]. Even when protected by coatings and/or in covered trays, cabling rapidly becomes unusable for electrical circuitry when subjected to fire or extreme heat. There is even some evidence that depending on the type of coating, and if they catch fire, it will increase the difficulty of quick and complete extinguishing such a cable tray fire once it is started [63]. For this reason, extra care and attention must be given to the prevention and early detection of wildfire and other possible ignition in any area where cables exist.

5.5 Control Board

Control panels usually consist of low-power and low-voltage systems. They often work as master and slave units where they collaborate to control the operation/s of single or multiple equipment. Due to low power handling capability, these boards are also susceptible to being heat or smoke damage [63]. Failure in the control or communication system in the power system can create havoc as it may prevent the controller/operator from taking necessary action or can generate inappropriate signals in the control wiring [63]. This can generate fake commands to the switchgear unit, which can cause a short circuit in the power system, which may lead to a further severe fire in the substation. Due to electric short circuits, the temperature can reach up to thousands of degrees and are even more severe than the wildfires. As often, the control boards are usually clustered into the trays so the fire can also spread into the regions designed to be well protected from external effects.

CONCLSION

Maintaining and enhancing the power system's resilience against wildfires and their byproducts is a challenge because of the increase in the frequency and intensity of wildfires worldwide in recent years.

Power systems that are approached by the wildfires will be out of service due to the thermal rating limits, stress of heat, smoke, and ash. It is essential to efficiently exploit the available knowledge and analyze the impact of wildfires' smoke, heat, flame, and ash on power system infrastructure.

From Chapter 3, it can be concluded that during a wildfire situation the use of a static monitoring system, which cannot incorporate the effect of high temperatures, may lead to a damage to the power lines. It is essential to use a dynamic system that can monitor the temperature of the conductor so it can automatically adjust the power rating in the power line. Any time that power lines pass through fire-prone areas it is essential to calculate the variation of conductivity on the conductor caused by temperature. Soot particles and ash can also affect the power lines, which should be considered.

In Chapter 4, it is shown that solar irradiance can also be impacted by the wildfire's smoke, which can attenuate the sun light and the solar energy from reaching to the PV panels. This reduces the power output of solar PV panels. The chapter also evaluates the solar radiation received by PV panels impacted by the ash or soot particles. Using the equations obtained in this thesis, one can analyze the impact of wildfires on renewal energy. In the future, this would help PV designers to estimate this radiation more accurately and improve the predictive ability for solar energy simulation models. It also, showing how could the ash and soot from wildfire could impact the wind turbine blades and reduces the power out.

In Chapter 5, The effect of wildfire heat and byproducts on widely used power system's equipment are highlighted. These effects should be taken into consideration while designing power systems. Especially the systems which are located in fire-prone area should be designed to endure high temperatures and resist wildfire impacts. This can help us to reduce the wildfire caused power outages and save costly equipment from being damaged by wildfire.

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