Enhancing Power Distribution Grid Resilience Against Massive Wildfires

by Fei Teng

B.S. in Automation, June 2018, North China Electric Power University

A Thesis submitted to

The Faculty of
The School of Engineering and Applied Science
of The George Washington University
in partial satisfaction of the requirements
for the degree of Master of Science

August 31, 2020

Thesis directed by

Payman Dehghanian
Assistant Professor of Electrical and Computer Engineering
Dedication

This MS Thesis is lovingly dedicated to my parents. They are the ones always nursing me with affections and love. Their support and encouragement have sustained me throughout my university life.
Acknowledgments

I would like to express my sincere gratitude to my advisor, Prof. Payman Dehghanian, for his guide, understanding, wisdom, patience, encouragements, and for supporting me reach this point. Thanks also to my committee members, for their time and patience.

Appreciation goes to my friends and the member of the Smart Grid Laboratory, specifically Mostafa Nazemi, Jinshun Su, Dingwei Wang, Yifu Li, Naihao Shi, Mohannad Alhazmi, Shiyuan Wang, and Bo Wang, for making my time at the George Washington University a wonderful experience.

Most of all, I am fully indebted to my parents for their support, without whom, the pursuit of this advanced degree would never have been started and accomplished.
Abstract

Enhancing Power Distribution Grid Resilience Against Massive Wildfires

In the past decades, wildfire hazards occurred more and more frequently. During summer seasons in regions with high temperature, power distribution systems especially those located near the forests are prone to wildfires. The temperature of conductor lines exposed to the fire increases rapidly, the shape and strength of which are, therefore, permanently reduced. The conventional reliability view is insufficient to cope with these challenges in modern power systems since such hazards cause prolonged and extensive outages, much more severe than those previously accounted for in system reliability assessments. Improving the resilience of the power grid, hence, becomes increasingly important and urgent. To enhance the resilience of the system against wildfires, the characteristics of wildfires need to be first studied so that effective mitigation strategies, e.g., dynamic line rating of the overhead power lines, can be proposed taking into account the impact of fires and the existence of uncertainties.

This thesis mainly focuses on designing an optimal operation strategy to minimize load shedding when distribution lines are affected by wildfires. Taking the uncertainties related to solar and wind – that influence the spread of wildfire and the renewable generators – into account, a stochastic mixed-integer nonlinear programming model is proposed and applied to a modified 33-bus power distribution system. The formulation aims to minimize the social cost which associates with the status of each wind turbine and the energy storage systems. By this means, the most effective operation strategy against wildfires is found, thereby enhancing the grid resilience and reducing the load outages during and following wildfire event. A sensitivity analysis is conducted on the overhead lines affected and the number of active components in the system to further investigate the best mitigation approach in the power distribution system when exposed to massive wildfires.
List of Figures

1.1 Elements of Resilience by Electric Power Research Institute (EPRI) . . . . . 7
1.2 The conceptual resilience curve related to a HILP event . . . . . . . . . . . . 8

2.1 Wildfire causes from 2013 to 2017 . . . . . . . . . . . . . . . . . . . . . . . 11
2.2 Number of arcs burned by wildfires in the world during 1871–2020 . . . . . 12
2.3 Flow of events, causes, and preventive solutions . . . . . . . . . . . . . . . . 17

3.1 Linear relationship for convection heat loss in case of non-zero wind speed \((T_a=273^\circ k)\) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 26
3.2 Piece-wise linearization of the radiation heat loss \((T_a=273^\circ k)\) . . . . . 27
3.3 Weibull distribution of the wind speed . . . . . . . . . . . . . . . . . . . . . 28
3.4 Wind speed mean value and stochastic values . . . . . . . . . . . . . . . . . 28
3.5 Wind direction mean value during a 24-hour period . . . . . . . . . . . . . . 29
3.6 Solar radiation mean value and stochastic values . . . . . . . . . . . . . . . . 29
3.7 Distance between the power line conductor and fire in different scenarios . . 30
3.8 Conductor heat gain rate from the fire in different scenarios . . . . . . . . . . 31

4.1 Single-line diagram of the modified 33-node power distribution system . . . 33
4.2 Relationship between the output power of a wind turbine and the wind speed 35
4.3 Relationship between the output power of a PV and the solar radiation . . . . 36
4.4 Expected Load Shedding for 10, 50 and 100 Generated Scenarios . . . . . . 41
4.5 Expected energy exchange with the upstream system . . . . . . . . . . . . . . 42
4.6 Power exchange price with the upstream system . . . . . . . . . . . . . . . . 43
4.7 Expected generated power and status of MTs . . . . . . . . . . . . . . . . . 43
4.8 Expected discharging power and SOC of ESS . . . . . . . . . . . . . . . . . 44

5.1 Objective function value: sensitivity analysis on every single line affected by wildfire . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 46
5.2 Expected load shedding cost: sensitivity analysis on every single line affected by wildfire . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 46
5.3 Expected load shedding when line 25 effected . . . . . . . . . . . . . . . . . 47
5.4 Objective function value when 2 lines are affected by wildfire . . . . . . . . 47
5.5 Expected load shedding when 2 lines are affected by wildfire . . . . . . . . 48
5.6 Expected power exchange when 2 lines are affected by wildfire . . . . . . . 48
5.7 Objective function value when 3 lines are affected by wildfire . . . . . . . . 49
5.8 Expected load shedding when 3 lines are affected by wildfire . . . . . . . . 50
5.9 Expected power exchange when 3 lines are affected by wildfire . . . . . . . 50
5.10 Objective function value when adding one distributed resource . . . . . . . 51
5.11 Expected load shedding when adding one distributed resource . . . . . . . 52
5.12 Expected power exchange when adding one distributed resource . . . . . . 52
## List of Tables

<table>
<thead>
<tr>
<th></th>
<th>Statistics of Outage Events in the U.S. Between 1984-2006</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>The Conceptual Contrast Between Reliability and Resilience</td>
<td>3</td>
</tr>
<tr>
<td>4.1</td>
<td>Location And Capacity of Distribution System Components</td>
<td>34</td>
</tr>
<tr>
<td>4.2</td>
<td>Location and Capacity of Distribution System Components</td>
<td>38</td>
</tr>
<tr>
<td>4.3</td>
<td>Simulation Results Concerning Different Number of scenarios</td>
<td>42</td>
</tr>
<tr>
<td>4.4</td>
<td>Revenues and costs</td>
<td>44</td>
</tr>
</tbody>
</table>
Nomenclature

A. Sets and Indices

\( i, j \in N_B \) Indices/set of nodes.
\( i, j \) Indices/set of distribution lines between nodes \( i \) and \( j \).
\( t \in N_T \) Indices/set of time periods.
\( (i, j) \in L \) Indices/set of branches.
\( N_B, N_T, N_L \) Number of all nodes, time periods, and branches.
\( \omega \) Indices/set of scenarios.
\( MT \in M \) Set of all Micro Turbines (MTs).
\( ESS \in M \) Set of all energy storage systems (ESSs).
\( S \in M \) Set of all photo-voltaic panels (PV).

B. Parameters and Constants

B.1. Fire Model

\( T^f \) Flame zone temperature (°k).
\( L^f \) Fire front length (m).
\( \alpha^f \) Fire tilt angle (rad).
\( \rho^b \) The bulk density of the fuel (kg/m³).
\( \varepsilon^f \) Flame zone emissivity

B.2. Environmental Conditions

\( \tau \) Dimensionless atmospheric transmissivity.
\( B \) Stefan-Boltzman constant (W/m²K⁴)
\( V^{\text{wind}} \) Wind speed (m/s).
\( \sigma^{\text{wind}} \) Angle between the fire and power line conductors (rad).
\( T^a \) Ambient temperature (°k).
\( k^a \) Thermal conductivity of air (W/mK).
\( \mu^\alpha \) Dynamic viscosity of air (kg/ms).
\( \rho^\alpha \) Density of air (kg/m³).

\( k^{\text{index}} \) Shape index of the Weibull distribution.

\( C \) Scale index of the Weibull distribution.

**B.3. Conductor Specifications**

\( mC_p \) Total heat capacity of conductor (J/mK).

\( D \) Conductor diameter (m).

\( K \) Solar absorptivity.

\( \phi^{\text{sun}} \) Solar radiation rate (W/m²).

\( R_{ij,a} \) Ambient line resistance.

\( T^{\text{max}} \) Conductor maximum temperature permitted (°K).

**B.4. Price and Costs**

\( V_{\text{oLL}} \) Value of lost load ($/MWh).

\( c^D \) Price for selling electricity ($/MWh).

\( c^{MT} \) Price for micro turbine generation ($/MW).

\( c^{\text{su/sd}} \) Micro turbine switching cost ($).

**B.5. Power Distribution System Components**

\( p_{\text{demand}}^{i,\omega, t} \) Real power demand at node \( i \) at time \( t \) (MW).

\( Q^{\text{demand}}_{i,\omega, t} \) Reactive power demand at node \( i \) at time \( t \) (MVar).

\( n^{ST} \) Conversion efficiency of energy storage systems.

\( E^{ST} \) Energy capacity of energy storage systems.

**C. Functions and Variables**

**C.1. Fire Model**

\( \theta^{f}_{ij,t} \) View angle between fire and conductor line \( ij \) at time \( t \) (rad).

\( d^{f}_{ij,t} \) Distance between wildfire and the conductor line \( ij \) at time \( t \) (m).

\( V^{f}_{t} \) Fire spread rate (m/s) at time \( t \).

\( T_{ij,t} \) Conductor temperature of overhead line \( ij \) at time \( t \) (°K).
$\phi^f_t$ Radiative heat flux at time $t$ (W/m$^2$).

### C.2. Heat Gain and Loss

$q^{\text{line}}_{ij,t}$ Resistance heat gain rate of line $ij$ at time $t$ (W/m).

$q^{\text{sun}}_{ij,t}$ Solar heat gain rate of line $ij$ at time $t$ (W/m).

$q^{\text{fire}}_{ij,t}$ Fire heat gain rate of line $ij$ at time $t$ (W/m).

$q^{\text{con}}_{ij,t}$ Convection heat loss rate of line $ij$ at time $t$ (W/m).

$q^{\text{rad}}_{ij,t}$ Radiation heat loss rate of line $ij$ at time $t$ (W/m).

### C.3. Power System Model

$pD_{i,t}, qD_{i,t}$ Real and reactive demand supplied at node $i$ at time $t$ (MW, MVar).

$p^{pf}_{ij,t}, q^{pf}_{ij,t}$ Real and reactive power flow on branch $(i, j)$ at time $t$ (MW, MVar).

$\text{SOC}^{ST}_{i,t}$ SOC of ESS at time $t$.

$p^{Ch}_{i,t}, p^{DC}_{i,t}$ Charging and discharging power of ESS at node $i$ at time $t$ (MW).

$p^{MT}_{i,t}, q^{MT}_{i,t}$ Real and reactive power output of MT at node $i$ (MW, MVar).

$p^{WT}_{i,t}, p^{S}_{i,t}$ Real power output of WT and PV at node $i$ at time $t$ (MW).

$V^{sqr}_{i,t}$ Squared voltage magnitude at node $i$ at time $t$ (kV$^2$).

$p^{\text{shed}}_{i,t}, q^{\text{shed}}_{i,t}$ Real and reactive load shedding at node $i$ at time $t$ (MW, MVar).

$p^{UP}_{i,t}$ Active power exchange with the upstream system at time $t$ (MW).

### D. Binary Variables

$\alpha_{i,j,t}$ Connection status of branch $(i, j)$ at time $t$
(1 if the branch is connected, 0 otherwise).

$u^{\text{soc}}_{i,t}$ Charging and discharging status of ESS at node $i$ at time $t$
(1 if charging, 0 otherwise).

$u_{i,t}$ Status of MT at node $i$ at time $t$
(1 if the MT is generating, 0 otherwise).

$\phi^U_{i,t}$ Buying or selling energy to the upstream network at time $t$
(1 if buying, 0 otherwise).
Chapter 1: Introduction

1.1 Problem Statement

Power grids, as the most complex man-made cyber-physical system to date, have been traditionally designed and planned to operate reliably under normal operating conditions and withstand potential credible outages. In the last decade, it has become more apparent that further considerations beyond the traditional system reliability view are needed for keeping the lights on at all times [1]. Table 1.1 shows the statistics of 933 power outage events, reported by the North American Electric Reliability Corporation (NERC), between 1984 to 2006 [2]. Extreme weather events and natural disasters have relatively low frequencies, but a greater impact on the electric power supply and a larger size of affected electricity customers, among these outage cause categories. According to the statistics provided in [3], a total of 178 weather disasters occurred from 1980’s to 2014 in the US alone with the overall damages exceeding the US $1 trillion.

Due to the growing demand to ensure higher quality electricity to end customers and particularly critical services, and intensified public focus and regulatory oversights, safeguarding the nation’s electric power grid resilience and ensuring a continuous, reliable, and affordable supply of energy in the face of the high-impact low-probability (HILP) events are among the top priorities for the electric power industry and has become more and more critical to people’s well-being and every aspect of our increasingly-electrified economy. The HILP events include two categories: (i) natural hazards, such as hurricanes, earthquakes, tornadoes, windstorms, wildfires, ice storms, etc.; (ii) man-made disasters, such as cyber or physical attacks on the power system infrastructure. Here in this thesis, the focus will be on the power grid resilience to wildfires [4].

Wildfire, similar to other natural disasters, is the one for which everyone pauses to listen each time it appears on the news. Sadly, for some families wildfires represent the loss of
<table>
<thead>
<tr>
<th></th>
<th>% of events</th>
<th>Mean size in MW</th>
<th>Mean size in customers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earthquake</td>
<td>0.8</td>
<td>1,408</td>
<td>375,900</td>
</tr>
<tr>
<td>Tornado</td>
<td>2.8</td>
<td>367</td>
<td>115,439</td>
</tr>
<tr>
<td>Hurricane/Tropical Storm</td>
<td>4.2</td>
<td>1309</td>
<td>782,695</td>
</tr>
<tr>
<td>Ice Storm</td>
<td>5</td>
<td>1,152</td>
<td>343,448</td>
</tr>
<tr>
<td>Lightning</td>
<td>11.3</td>
<td>270</td>
<td>70,944</td>
</tr>
<tr>
<td>Wind/Rain</td>
<td>14.8</td>
<td>793</td>
<td>185,199</td>
</tr>
<tr>
<td>Other cold weather</td>
<td>5.5</td>
<td>542</td>
<td>150,255</td>
</tr>
<tr>
<td>Fire</td>
<td>5.2</td>
<td>431</td>
<td>111,244</td>
</tr>
<tr>
<td>Intentional attack</td>
<td>1.6</td>
<td>340</td>
<td>24,572</td>
</tr>
<tr>
<td>Supply shortage</td>
<td>5.3</td>
<td>341</td>
<td>138,957</td>
</tr>
<tr>
<td>Other external cause</td>
<td>4.8</td>
<td>710</td>
<td>246,071</td>
</tr>
<tr>
<td>Equipment Failure</td>
<td>29.7</td>
<td>379</td>
<td>57,140</td>
</tr>
<tr>
<td>Operator Error</td>
<td>10.1</td>
<td>489</td>
<td>105,322</td>
</tr>
<tr>
<td>Voltage reduction</td>
<td>7.7</td>
<td>153</td>
<td>212,900</td>
</tr>
<tr>
<td>Volunteer reduction</td>
<td>5.9</td>
<td>190</td>
<td>134,543</td>
</tr>
</tbody>
</table>

Table 1.1: Statistics of Outage Events in the U.S. Between 1984-2006

their property, savings, and even life. Besides the excessive cost of physical damages from fires to different properties, there are many other consequences such as costs for evacuation, revenue loss for the businesses, costs for rehabilitation, etc. These are just some of the few example consequences of the thousands of wildfires that affect thousands of homes and burn millions of acres of land and business properties annually throughout the world [5]. In October 2007, 17 people lost their lives in a single Southern California wildfire; 10 were killed by the fire outright, 3 were killed while evacuating, 4 died from other fire related causes and more than $1.5 billion in property damages was reported [6]. In February 2009, a similar disaster happened in the state of Victoria, Australia. The Victorian Brush fires Royal Commission estimates the cost of this “mega-blaze” to be more than $4 billion and to have resulted in the death of 173 people [7]. On May 2016, a wildfire was initiated in Alberta, Canada. The direct financial loss to insurance providers from the great Alberta fire was estimated at about $3.7 billion [8]. In October 2017, a series of wildfires started to burn across the wine country of Northern California. These wildfires caused at least $9.4 billion in insured damages and the death of 44 people [9]. In fiscal year 2017, the cost
of battling blazes topped $2.4 billion \[10\]. For the first time in its 110-year history, the Forest Service is spending more than 50 percent of its budget fighting wildfires \[11\]. In November 2018, California experienced one of the most destructive and deadliest seasons in its wildfire history. Two major fires, Woolsey Fire near Los Angeles and Camp Fire at Northern California, killed at least 86 and 3 people, respectively. The Woolsey Fire cost about $4 billion while the Camp Fire destroyed more than 18,800 structures and caused more than $11 billion in damages \[12–14\]. During 2018, more than 8,500 fires burned across nearly 1.9 million acres in the state of California and resulted in more than $16.5 billion in the total damage. Cumulatively, the wildfires were the costliest natural disaster of 2018, as well as one of the deadliest. In Northern California’s Camp Fire alone, more than 85 people lost their lives \[15\]. Safeguarding the nation’s electric power grid resilience against wildfire and ensuring a continuous, reliable, and affordable supply of energy during such devastating events are among the top priorities for the electric power industry.

1.2 The Concept of Resilience

Unlike the widely adopted terminology "reliability" in many traditional principles, power system resilience is an emerging concept and its definition and quantification measures are unclear thus far; nonetheless, the definition has a common comprehension. "Resilience" and "Reliability" seem to have a similar but essentially distinct meanings \[16–17\]. The key characteristic difference between resilience and reliability is presented in Table 1.2 \[18\].

<table>
<thead>
<tr>
<th>Reliability</th>
<th>Resilience</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-probability, low-impact</td>
<td>Low-probability, high-impact</td>
</tr>
<tr>
<td>Static</td>
<td>Adaptive, ongoing, short- and long-term</td>
</tr>
<tr>
<td>Evaluates the power system states</td>
<td>Evaluates the power system states and transition times between states</td>
</tr>
<tr>
<td>Concerned with customer interruption time</td>
<td>Concerned with customer interruption time and the infrastructure recovery time</td>
</tr>
</tbody>
</table>
The existing reliability metrics do not concentrate on the consequences of individual HILP events. Beyond minimizing the probability of extensive and prolonged outages, resilience also takes the following into account: acknowledgment of the occurrence of such outages, smarter operations of the grid and harnessing its built-in flexibilities \[19\text{-}27\], preparation to cope with them, minimization of the outage effect, rapid restoration of the service, and learning from the experience to enhance the future performance \[28\text{-}32\].

National Academies of Sciences, Engineering, and Medicine \[28\] provides a definition in 2017 for resilience as follows: "Resilience is not just about lessening the likelihood that these outages will occur. It is also about limiting the scope and impact of outages when they do occur, restoring power rapidly afterwards, and learning from these experiences to better deal with events in the future." PJM Interconnection provides a definition in March 2017 as follows \[33\]: "Resilience, in the context of the bulk electric system, relates to preparing for, operating through and recovering from a high-impact, low-frequency event. Resilience is remaining reliable even during these events". This definition is more specific to the HILP events. In President Barack Obama’s Presidential Policy Directive \[34\], the term "resilience" refers to "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents". A definition of resilience for energy system is provided by the UK Energy Research Center \[35\] as follows:"Resilience is the capacity of an energy system to tolerate disturbance and to continue to deliver affordable energy services to consumers. A resilient energy system can speedily recover from shocks and can provide alternative means of satisfying energy service needs in the event of changed external circumstances."

Among the existing definitions of resilience, four aspects of the system resilience are summarized in \[27\text{-}36\text{-}37\] as follows:

- The state of electricity services in a power grid can be described by resilience when confronting an interruption or outage. The description of resilience contains the extent
of the service degradation, the rapidity of service recovery, and the recovery extent of
the service. As can be seen, resilience does not only reveal a discrete state of whether
a disturbance has happened, but also demonstrates and accounts for the level and
extent of the disturbance.

• The system resilience is determined by its design and its operation. These affect
the degradation degree during a disturbance, the swiftness of the recovery and the
completion of the restoration. For instance, a more redundant system that considers
recovery strategies and additional contingency operation modes might undergo fewer
and shorter interruptions. On the other hand, such a redundant system is more
strenuous to reconstruct.

• Different resilience levels of the system can be resulted from different response at
different costs. For instance, the system rebuilt with additional resources and a more
efficient set of equipment can provide higher quality of service when exposed to
extremes than the original configuration.

• The system state of resilience changes over time. The quality and continuity of service
in a system could be enhanced with regular maintenance and upgrades but at a cost.
On the other hand, the service in a system without regular maintenance and upgrades
has a lower operating cost but it can be anticipated that the quality and reliability of
service will lessen in the future [38–44].

The National Infrastructure Advisory Council (NIAC), USA provided four main features
of resilience in [45]:

• Robustness: The capability to maintain operation or withstand disturbances when
disaster occurs, especially HILP events. Besides the system structure or design, it
also relates to the system redundancy in case of some important components damages,
along with the investment and maintenance of the critical infrastructure.
• **Resourcefulness**: The capability to expertly handle the occurred disaster. It incorporates determining the strategies and priority of the actions that should be taken to both control and diminish the hazardous emergency, and convey the decisions to the crews to execute. This feature mainly relates to the human, and not the adopted technology.

• **Rapid Recovery**: The capability to restore the system to its normal operating condition as soon as possible following the extremes. It relates to elaborately prepared contingency plans, capable emergency operations and strategic resources distribution and crews dispatch.

• **Adaptability**: The ability to learn from a hazard. It relates to the enhancement of the robustness, resourcefulness and recovery abilities of the system for the future hazards via new tools and technologies.

The Cabinet Office, U.K. also provides four main characteristics of infrastructure resilience in [46] as follows:

• **Resistance**: provides the strength or protection to withstand the disaster and its main effects to further mitigate the damage or disturbance.

• **Reliability**: the infrastructure components are ensured to be inherently designed to maintain operation under certain conditions.

• **Redundancy**: the availability of the backup equipment or spare capacity to allow the operation to be switched or redirected to alternative routes.

• **Response and Recovery**: rapid and effective response to and recovery from the hazards.

Additionally, Electric Power Research Institute (EPRI) in the U.S. also determines the three elements of resilience which are prevention, survivability, recovery for power distribution systems in [47] as demonstrated in Figure 1.1.
Notice that these elements and aspects of the system resilience can also lead to its measurement (or metrics). Most of the existing definitions of resilience refer to the capability of the system to withstand and rapidly recover from HILP events. A conceptual resilience curve is proposed in [18] to describe the variations in the system resilience level over time with regard to a HILP event, as illustrated in Figure 1.2, where $R$ represents the resilience level of the system. With respect to a HILP event, the power system experiences the following operating states [18, 48]:

- **Resilient State** $t_0 \sim t_e$: before the HILP event happens at $t_e$, the power system should be robust and resistant to withstand the first strike of the HILP event by sufficiently predicting the time and location of the external disturbance and preventive actions (e.g. preventive generation rescheduling) taken by the system operator, aiming to enhance the disturbance resilience of the infrastructure.

- **Event Progress** $t_e \sim t_{pe}$: during the HILP event progress, the system is degraded to post-event degradation state, where the system resilience decrease to $R_{pe}$. Emergency or corrective actions (e.g. generation re-dispatch alone or generation re-dispatch...
Figure 1.2: The conceptual resilience curve related to a HILP event [18]

coordinating with dynamic-boundary microgrid operation) can be taken to reduce the effect of the external disturbance.

- **Post-Event Degraded State** $t_{pe} \sim t_r$: after the event strike, the system enters the post-event degraded state. At this stage, the key resilience features are the *resourcefulness, redundancy, adaptive self-organization*, where they offer the necessary *corrective operational flexibility* to accommodate and cope with the changing situation. This assists in minimizing the consequence of the event and the degradation in the system resilience level (e.g. $R_0 - R_{pe}$) while appropriate and effective coordination and preparation enable rapid start of the restoration state.

- **Restorative State** $t_r \sim t_{pr}$: the system should manifest fast *response* and *recovery* ability to recover the system resilience level from $R_{pe}$ to $R_{pr}$. $R_{pr}$ may be the pre-event resilience level $R_0$ or a desired resilience level that is not as high as $R_0$.

- **Post-Restoration State** $t_{pr} \sim t_{ir}$ and **Infrastructure Recovery** $t_{ir} \sim t_{pir}$: Following the restorative state, the event consequence on the system resilience and its perfor-
mance during the event need to be evaluated and analyzed to enhance the infrastructure resilience for future similar or unpredictable events. Depending on the severity of the event, the system may need longer time to recover the infrastructure in $t_{ir} \sim t_{pir}$.

1.3 Thesis Outline

The rest of this thesis is organized as follows:

Chapter 2 provides a background and reviews the existing literature on cause factors of fires, their impacts on the power system operation, and several strategies to enhance the power grid resilience to wildfires.

Chapter 3 explores the implements wildfire hazard modelling and formulations. The heat balance equation is taken into account to help measure the thermal heat delivered to the overhead lines in power distribution systems. The Dynamic Line Rating is proposed to model and correlate this heat to the temperature increase of the power conductors. Then the uncertainties of the surroundings is estimated and several sets of scenarios are generated using the proper probability distribution functions.

Chapter 4 proposes a mixed-integer nonlinear programming (MINLP) optimization model on a 33-bus power distribution system exposed to wildfires. The same scenarios and models for wildfires developed in Chapter 3 are employed serving as the inputs to the optimization engine. The formulation is further linearized, hence reducing the computational complexity. A base case is studied to find the best number of scenarios taken, and the efficacy of the resilience measures and mitigation actions on the system operation.

In Chapter 5, the numbers and positions of lines out of service due to the progressive wildfires is changed and additional power sources are added. The same test system and damage scenarios are applied in the case studies with different components affected to explore the sensitivity of each element when facing the wildfire extremes.

Chapter 6 presents the research conclusions and summarizes the main findings of this thesis. Future work is also provided in this chapter.
Chapter 2: Literature Review

2.1 Introduction

This chapter reviews research in different fields of science and industrial projects that attempt to address wildfire issues and their interactions with the power system. First, the causing factors of wildfires are listed and the various scenarios of faulty electrical networks that may lead to progressive wildfires are highlighted. Then the damages and negative effects that a wildfire can cause to the electric grid are summarized. Finally, prediction and prevention means and measures are discussed.

2.2 Root Causes of Wildfires

Wildfires are typically initiated from natural events such as lightning, spontaneous combustion, or volcanic eruptions or as a result of day-to-day human activities or the operation of indispensable equipment. A detailed list of wildfire triggers from 2013 to 2017 is illustrated in Figure 2.1.

**Wildfires and Climate Change.** Meteorological data from many national agencies have shown that one prime factor for recent wildfires is global climate change. In the western parts of the North America, during the wet periods, generous rain creates substantial fuel sources that can create a suitable condition for fire throughout the drought and warming periods. During these seasons, the land is flammable due to its carbon-rich vegetation, and oxygen-rich atmosphere [49, 50]. Weather-related effects on a fire consist of many aspects such as behavior (e.g., wind speed and conditions), fuels (e.g., combustible material created), and ignitions (e.g., lightning). Wildfires are also influenced by moisture availability, snow-pack, temperature, precipitation, and other meteorological factors of the environment that are all affected by climate change drivers. Further climate change would only exacerbate
the problem, as increased temperatures, a reduced snow-pack, and altered precipitation would lead to increased flammability of fuel for longer periods, which could affect the size, frequency, and severity of wildfires in the future. These changing conditions may pose an increasing threat to the energy infrastructure along the coast, including power plants, transmission and distribution lines, gas storage facilities, and pipelines \[51\]. The 2012 and 2013 studies by Sathaye et al. \[51\] assessed the possible impacts that the increased air temperature may have on the thermal performance of natural gas fired generation and substations. Several studies have shown that climate change is likely to increase the size and frequency of wildfires in California, a state that already leads U.S. wildfire-related economic losses. Of the ten largest wildfires in California’s history, eight have occurred since 2001. This is evidenced by an increase in the number of arcs burned by wildfires in the world as shown in Figure 2.2

**Wildfires and Human Activities/Interventions.** Wildfires can also start from day-to-day human activities and the operation of essential equipment. According to official
reports, about 85-90% of wildfires are caused by human mistakes to deal with materials and malfunction of equipment. The fire sources include equipment uses and faults, campfires out of control, negligently discarded cigarettes, burning of debris, and intentional acts of arson [52]. Some specific ignition sources are preventable, such as arson, discarded cigarettes, electrical faults in power lines, failure of aged electrical equipment, oil-filled transformers explosion, and sparks from vehicles and mechanical equipment.

**Wildfire-Triggering Events in Power System.** The chances of fire initiation by electrical infrastructure are low (normally about 1.5% of all ignitions [?]), but in periods of drought and when the heat tide comes, the percentage of fires linked to electrical assets rises dramatically up to 30% of total ignitions [?]. For instance, the deadliest of the October 2017 wildfires in California’s wine country and the 2018 Camp Fire were started by electrical equipment owned by Pacific Gas and Electric Company (PG&E) or by equipment that was owned, installed and maintained by a third party [53]. Power system faults could be
caused by many different reasons and one prior one is the tree/vegetation/bush-related faults (non-metallic short-circuit faults). It has been estimated that 80% of all vegetation-related problems with power systems are the result of falling trees or branches, often from trees that are off the electric utility’s right-of-way [54]. This may lead to the falling and breakage of the line conductor. Therefore, current may flow for a long duration with high-energy, causing the vegetation to dry, leading to high-temperature arcing and eventually start a fire.

This is one of the most common and critical cases for wildfires studies.

Power lines have caused more than 4,000 wildfires in Texas in the past 3 to 4 years, where 30% of cases are reported to be downed-line faults [55]. Vegetation can also cause wildfires through non-mechanical mechanisms. For example, a branch could simultaneously contact a phase conductor and neutral. As a result, a very low current flow can occur (e.g. tens of milliamps) for a long period of time. This can result in charring of the vegetation, with the end result of an arcing fault [56]. The phenomenon could also happen on a phase-to-phase or phase-to-phase-to-ground basis. Non-mechanical vegetation faults are relatively uncommon on single-phase basis and more common for phase-to-phase fault conditions, because of higher voltage gradients. Line failure is another reason for power-system-related wildfires. Short circuits in the power system lead to electromagnetic forces between conductors carrying current. The conductors, even at non-faulted locations, begin to swing as the result. The higher the fault current, the larger the physical motion. This movement could lead to conductor clash and create a consequent fault with the possibility of arcing [57]. The wire slap may also happen under windy conditions. This phenomenon can ignite combustibles directly if close to vegetation. Also, the ejection of hot metal particles can ignite dried vegetation on the ground or any combustible such as transformers’ oil.

Other faults include back-fed faults which are ‘wire down’ faults caused by a fallen conductor (on a radial system) that remains connected to electrical source from the ‘downstream’ side where the line is broken; pole-related failures such as corrosion of structures, bare conductors, insulated/covered conductors, conductor swing and uplift into the structure, live
down-wire and a host of pole components, such as long rod insulator, spindle, post insulator, cross arm, jumper, lug and crimp, conductor joint, pole twist, stay, pole-top fire and pole foundation and soil mechanics failures; electrical apparatus failures which means the failure of power system equipment such as transmission and distribution lines, an explosion of transformers, failure of breakers, switches, clamps, bushings, surge arrestors or capacitors might be a reason for initiation of a wildfire [58, 59].

2.3 Wildfire Impacts on Power Systems

Increases in the size and frequency of wildfires in California would affect the state’s major electricity transmission lines. Interestingly, these transmission line-related impacts resulted from wildfires are not limited to the actual destruction of the structures. In the case of an intensive wildfire, in a forest for example, the wooden poles would likely catch fire and the conductors would melt. So, the line will fall in ruins and must be reconstructed. Nevertheless, there are many small or moderate wildfires having an extensive front length, in places with combustibles of low height that cause thermal stress to the power lines. In these situations, the transmission capacity of a line can be indirectly affected by the heat, smoke, and particulate matter from a fire, even if there is no actual damage to the physical structure [5]. For example, the combined impacts of temperature and ash will significantly reduce the gap’s insulation strength, and the breakdown of the air gap results in outages of the electrical transmission line. Soot can 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 shut down. Ionized air in smoke can act as a conductor, causing arcing, either between lines or between lines and the ground, that results in a power line fault and potential outages in the power grid [60].

Additionally, the surface temperature increase of the conductor can affect the conductor’s rate of annealing and reduce its tensile strength. It is well known that the degradation in strength of the conductor exposed to high temperatures is cumulative. This loss of strength
of the conductor is a result of cumulative annealing during its lifetime. When the wires of a conductor are heated, two processes take place: recovery and re-crystallization. During recovery, some of the non-mechanical properties of the metal may change \cite{61}. All these effects finally lead to the violation of safety clearance between the conductor and the ground due to excess conductor sag. Finally, even if the power lines are protected from fires, the effects of firefighting can also negatively affect transmission operation either by aircraft dumping loads of fire retardant that can damage the lines or through preventive shutdowns for safety measures.

2.4 Wildfire Mitigation Strategies

**Vegetation Management.** One useful approach to stop the spread of the wildfire is to build an isolation zone. The principle of this approach is to isolate combustibles from the source of the fire. Since no combustibles are available in the area, the fire will automatically extinguish. Fire isolation belts are mainly used to prevent a fire from spreading and expanding when a fire occurs in a piece of building or a large area of forest with a further fire resistance level because the fire cannot be extinguished quickly. Power distribution company Southern California Edison (SCE) inspects approximately 900,000 trees annually and prunes nearly 700,000 of them per year, including 400,000 trees in high fire risk areas. The company also frequently monitors trees outside SCE’s designated pruning zones that could potentially fall into lines to determine whether they are dead, dying, diseased or hazardous \cite{62}.

**Sensors and Situational Awareness Technologies.** Usually, the wildfires start from a small region and spread quickly with certain wind conditions. Many accidents can be prevented if the information about the fire can be collected timely before the situation gets serious. In \cite{63}, the authors proposed a distributed control framework designed for a team of unmanned aerial vehicles to help closely monitor a wildfire in open space, and precisely predict its development. This method is promising because the vehicles can replace humans in hazardous fire tracking and significantly reduce operation costs. In 2013, SCE completed
a system-wide meteorological study and used the updated wind speed data to implement new pole designs and construction standards appropriate for expected conditions. SCE then launched a comprehensive pole replacement program in 2014, concentrating first on poles located in areas that posed both high wind and high fire risks, and assessing those poles against the updated wind standards. When extreme weather conditions are forecasted, the company restricts certain types of work and does not automatically re-energize distribution power lines in high fire risk areas after a circuit interruption. Under normal conditions, the grid automatically tests the circuit and, if the fault condition no longer exists, the circuit is quickly re-energized. During extreme fire conditions, affected circuits are not automatically re-energized and SCE crews physically inspect the lines before they are re-energized.

**Public Safety Power Shutoff.** Another operational practice that can reduce fire risk is Public Safety Power Shutoff (PSPS). When there is a high probability that an extreme wildfire would happen, electrical companies might shut down power preemptively in limited, high fire risk areas. While this method is planned only as a “last resort,” millions of customers experienced blank-out in practice.

**Resilience Zone and Microgrids.** To mitigate the effects of PSPS, the electric utilities, particularly the ones in California, have laid out a raft of proposals, from sectionalism portions of the grid to reducing the scope of outages during PSPS events, to building “resilience zones” which could extend emergency backup power to services such as grocery stores and gas stations in areas suffering from a PSPS. The preparation work includes re-configuring segments of the distribution system that can be quickly isolated from the broader grid, and reinstalled interconnection hubs (a transformer and associated interconnection equipment, ground grid, and grid isolation and protection devices) where Pacific Gas and Electric Company (PG&E) can connect the “temporary mobile generation” to energize the area. Some novel concepts, like working with non-utility partners to install or utilize on-site generation or distributed energy resources for continuous power during safety outages and exploring the potential for true microgrid systems to play a role are also proposed and under
investigation. The ability to island (to disconnect completely from the centralized grid) at key times can allow for the sustained backup generation to critical facilities in communities working to respond and recover from wildfires and other natural disasters.

**Hardening Power Lines.** The design of the infrastructure can be strengthened by increasing the use of fire-resistant poles, composite cross arms, and covered conductors in select high fire risk areas.

The following Figure 2.3 illustrates a general overview of the wildfire morphology, highlighting its causes, and preventive solutions at each stage.

![Figure 2.3: Flow of events, causes, and preventive solutions](image)

**2.5 Pathways to Enhanced Resilience**

**2.5.1 Resilience in Modern Power Grids**

The road to a resilient power grid is cluttered with a myriad of formidable challenges. Resilience, as defined by the Cabinet office of the government of the United Kingdom, is “the ability of assets, grids, and systems to anticipate, absorb, adapt to, and/or rapidly recover from a disruptive event.” This definition identifies four components of a resilient electricity grid: fault-tolerance, fast response, maintenance and recovery, and reliability. These aspects should be tailored into the power grid operation and planning paradigms to ensure its resilience to natural disasters. Note that large and centralized power plants, bulk transmission lines, substations, and transformers are potential points of vulnerability in power systems since an uncontrollable minor incident could lead to the interruption of
megawatt flows [64, 65].

Both long-term and short-term strategies for enhancing grid resilience against extreme conditions have been addressed in the literature. In the former, enhancing the grid structural resilience is primarily the focus of concern, and suggestions are made toward “grid hardening” plans through reinforcement, preventive maintenance of critical infrastructure [66–80], vegetation management, and efficient allocation of flexible energy resources (e.g., storage units). In the latter, improving the operational resilience is targeted through fast emergency response and remedial actions, defensive islanding and micro-grids. Power system resilience is quite a complicated concept with many driving factors. A number of past research has identified that the high variability and intermittency of renewable energy have limited their integration and storage largely to day-to-day normal operating conditions [81–100], where some solutions in response are proposed. To efficiently deal with weather-driven HILP incidents in a timely and effective manner, today’s operational planning tools should smartly account for high levels of unpredictability. They should take advantage of environmentally-friendly renewable as possible grid-support resources equipped with both analytical and human insights in deriving resilience plans and emergency response strategies [64]. The GW Laboratory researchers have studied the resilience challenges that the power grid faces to a wide range of threats and have proposed solutions for detection, verification, and mitigation in response [16, 17, 27, 29, 32, 37, 101–117].

2.5.2 Techniques to Enhance Resilience against Wildfires

Several papers have done some research on enhancing the resilience of the power system to extreme fire conditions. In [118], the thermal rating of the at-risk lines was dynamically adjusted to reduce the loading of the line counteract the heat gained from the fire. S. Dian et al. [60] have proposed a line outage model (LOM), based on wildfire prediction and breakdown mechanisms of the air gap, to predict the breakdown probability varying with time and the most vulnerable poles at the holistic line scale. Reference [119] proposed
a dynamic line rating of the overhead lines in order to model the impact of wildfires on conductor temperature and flowing current. Transmission faults caused by recent wildfires in California have induced the disconnection of utility-scale converters in power plants. Postmortem investigations reported that tripping commands were caused by phase-locked loops and dc-side dynamics, which are typically unmodified in classical transient stability studies. To address this shortcoming, [120] set forth a positive-sequence model for PV power plants that are derived from physics’s and control’s first principles. Instances of the developed model are integrated into illustrative power systems containing conventional generators. Numerical simulations of the obtained multi-machine multi-converter power systems were assessed via a suitable set of stability and performance metrics. Reference [121] proposed a method for enhancing the resilience of distribution systems that are exposed frequently to disastrous conditions. In case of a fault, the distribution system is sectionalized into self-sufficient microgrids to prevent a possible spread of the fault with the minimum load shedding of the islanded portion of the distribution system. A new ultra-fast circuit breaker technology is introduced that enables a new approach to the optimal protection of rural lateral lines. A novel protection scheme is presented and is shown to represent the optimal solution for both reliability performance and prevention of electrical faults causing wildfire ignition on extreme weather days. For fault levels typical on rural lateral lines, when switched off in less than a half cycle, there is inadequate energy in the arc to cause fire ignition. This alternate protection mode can be remotely commanded over SCADA to allow rapid network response to extreme weather. Recent research efforts on wildfires and the technological developments can be found in [122–129].
Chapter 3: Wildfire Hazard Model and Formulations

3.1 Introduction

In this chapter, a model for the fire flame is formulated to present its impacts on the power distribution system in the later research. The rest of this chapter is organized as follows. First, the propagation mode of the flame will be discussed, where the equations corresponding to each model are presented and explained. Afterward, the dynamic line rating constraints will be addressed to demonstrate the influences of wildfires on the power system in detail. At last, some uncertain factors related to the fire will be stressed to make it a general model.

3.2 Wildfire Model

As a process, a wildfire can take many forms, all of which involve a chemical reaction between combustible species and oxygen. In other words, fire is an oxidation reaction releasing thermal energy to the surroundings. Heat transfer is a process that concerns the exchange of thermal energy between physical systems. Heat transfer is classified into three basic mechanisms, such as thermal conduction, thermal convection, and thermal radiation. While these mechanisms have distinct characteristics, they often occur simultaneously in the same system.

**Thermal Conduction** is the transfer of internal energy by microscopic collisions of particles and the movement of electrons within a body. The colliding particles, which include molecules, atoms, and electrons, transfer disorganized microscopic kinetic and potential energy, jointly known as internal energy. Conduction takes place in all phases: solid, liquid, and gas. The rate at which energy is conducted as the heat between two bodies depends on the temperature difference (and hence temperature gradient) between the two bodies and the properties of the conductive interface through which the heat is...
transferred [130].

*Heat Convection* occurs when the bulk flow of a fluid (gas or liquid) carries heat along with the flow of matter in the fluid. The flow of fluid may be forced by external processes, or sometimes (in gravitational fields) by buoyancy forces caused when thermal energy expands the fluid (for example in a fire plume), thus influencing its transfer. The latter process is often called "natural convection". All convective processes move heat partly by diffusion, as well. Another form of convection is forced convection. In this case, the fluid is forced to flow by use of a pump, fan, or other mechanical means.

*Thermal Radiation* is the electromagnetic radiation generated by the thermal motion of particles in matter. All matter with a temperature greater than absolute zero emits thermal radiation. Particle motion results in charge-acceleration or dipole oscillation which produces electromagnetic radiation.

In our case, the heat from wildfire is transferred through radiation and convection. But since convection affects the conductors’ temperature in a short distance—i.e., nearly under the power line, it is most likely that a power line will already be out of order when the convection happens. So in this Section, only radiation transfer is considered. For a large fire incident, the flame model is based on the radiant surface approach shown in [131]. This approach does not account for the flow and the fire dynamics and only represents the flame as a radiant surface (solid-flame assumption). The model relates to the flame front width and the estimation of the flame front. The radiative heat flux \( \phi^f \) from the whole flame emitted to a conductor is then determined considering the geometry of the flame and the properties of the fire front according to:

\[
\phi^f_{i,j,\omega,t} = \frac{\tau \cdot \varepsilon^f \cdot B \cdot T^f}{2} \cdot sin(\theta^f_{i,j,\omega,t}) \tag{3.1}
\]

where \( \tau \), \( \varepsilon^f \) and \( B \) are all parameters related to the environment. \( T^f \) is the temperature of the wire front set as 1200\(^\circ\)k [132], and \( \theta^f \) is the view angle between the threatened line and...
and the fire front expressed in the following:

$$\theta_{ij,\omega,t}^f = \tan^{-1}\left(\frac{L^f \cdot \cos(\alpha^f)}{d_{ij,\omega,t}^f - (L^f \cdot \sin(\alpha^f))}\right)$$  \hspace{1cm} (3.2)

In the equation above, $L^f$ is the length of the fire front. $d^f$ represents the distance between wildfire and the conductor line affected and is computed in Equation (3.3).

$$d_{ij,\omega,t}^f = d_{ij,\omega,t}^f - 1 \cdot V_{\alpha,t}^f \cdot \Delta t \cdot \cos(\sigma_{ij,\omega,t}^{\text{wind}})$$  \hspace{1cm} (3.3)

$$V_{\alpha,t}^f = \frac{k \cdot (1 + V_{\omega,t}^{\text{wind}})}{\rho^b}$$  \hspace{1cm} (3.4)

$V^f$ (m/s) is the specific rate of flame spread in wildland on a flat ground that depends on the wind speed $V^{\text{wind}}$ (m/s). $\rho^b$ is the bulk density of the fuel equal to 40 kg/m$^3$ in the forest. $k$ is equal to 0.07 for wildland fire and 0.05 for wood crib [118].

### 3.3 Dynamic Line Rating (DLR): Heat Balance Equation

In practice, power line thermal ratings are calculated seasonally assuming the given or forecasted weather conditions. It is worth mentioning before giving basic aspects of the DLR that the current-temperature relationship of power line conductors can be computed by the guidelines presented in the IEEE Std. 738 and the CIGRE SC.B2 WG 22.12. According to the comparison in [133], one can demonstrate that they provide essentially the same results. It is assumed that the conductor cross-sections are circular.

The power line conductor’s total heat is the multiplication of coefficients and heat loss rates, which include the convective heat loss rate $q^{\text{con}}$ and the radiative heat loss rate $q^{\text{rad}}$, and heat gain rates, which include ohmic losses resistant of the power line $q^{\text{line}}$, radiative heat flux from fire $q^{\text{fire}}$ and solar heat gain rate $q^{\text{sun}}$. Therefore, any changes in the temperature for any time interval is calculated using the following non-steady-state heat equation which
is a first-order nonlinear differential constraint:

\[
(T_{ij,\omega,t+1} - T_{ij,\omega,t}) = \frac{\Delta t}{mC_p} \cdot \left( q_{line}^{ij,\omega,t} + q_{sun}^{ij,\omega,t} + q_{fire}^{ij,\omega,t} - q_{con}^{ij,\omega,t} - q_{rad}^{ij,\omega,t} \right)
\] (3.5)

Each of the terms in the introduced equation is explained in the following sections

### 3.3.1 Heat Gain

The heating terms in the given equation are the solar heat energy that can be absorbed by the conductor, the resistive thermal energy generated due to currents flowing through the power line conductor and the fire radiation heat calculated as follows:

\[
q_{sun}^{ij,\omega,t} = D_{ij} \cdot K_{ij} \cdot \phi_{ij,\omega,t}^{sun}
\] (3.6)

\[
q_{line}^{ij,\omega,t} = R_{line}^{ij,\omega,t} \cdot (I_{ij,\omega,t})^2
\] (3.7)

\[
q_{fire}^{ij,\omega,t} = D_{ij} \cdot \phi_{ij,\omega,t}^{fire}
\] (3.8)

In Equation (3.6), \(D_{ij}\) is the diameter of the conduction lines and \(\phi_{ij,\omega,t}^{sun}\) is the sun radiation rate. \(K_{ij}\) is the solar absorptivity that varies between 0.27 for the bright stranded aluminum conductor and 0.95 for the weathered conductor in an industrial environment. It is equal to the ratio of the solar heat absorbed by the conductor to the solar heat absorbed by a perfectly black body of the same shape orientation and increases with age for the overhead power lines. This value for a brand new power line is 0.2 to 0.3. A typical value for a conductor that has been in use for more than 5 (in industrial environments) to 20 years (in rural clean environment) is 0.9. A value of 0.5 is often used if nothing is known about the conductor absorptivity [134].
In Equation (3.7), $R^{\text{line}}(T_{ij},\omega,t)$ is a function that describes the relationship between the resistance of the power line conductor and its temperature. $R_{ij,a}$ is the resistance of the line at ambient temperature $T_{ij,a}$ ($298^\circ k$). $d_{ij}$ is the conductor thermal resistant coefficient.

$$R^{\text{line}}(T_{ij},\omega,t) = R_{ij,a} \cdot (1 + d_{ij} \cdot (T_{ij},\omega,t - T_{ij,a})) \quad (3.9)$$

### 3.3.2 Heat Loss

The last two terms in Equation (3.5) accounts for the cooling down of the power line conductor. The convection loss in this paper is forced convection meaning the conductor is cooled down via a cylinder of moving air around the conductor. The convection heat loss is the largest value between high-speed wind $q_{ij,\omega,t,(\text{high})}^{\text{con}}$ and low-speed wind $q_{ij,\omega,t,(\text{low})}^{\text{con}}$ according to the IEEE standard [135]. Equation (3.10) and Equation (3.11) represent the calculation of the convection loss.

$$q_{ij,\omega,t,(\text{high})}^{\text{con}} = K_{\text{angle}} \cdot 0.754 \cdot N_{\text{Re}}^{0.6} \cdot k^a \cdot (T - T^a) \quad (3.10)$$

$$q_{ij,\omega,t,(\text{low})}^{\text{con}} = K_{\text{angle}} \cdot [1.01 + 1.35 \cdot N_{\text{Re}}^{0.52}] \cdot k^a \cdot (T - T^a) \quad (3.11)$$

The magnitude of the equation depends on $N_{\text{Re}}$, the Reynolds number and wind direction factor $K_{\text{angle}}$ given by:

$$N_{\text{Re}} = \frac{D_{ij} \cdot \rho^\alpha \cdot V_{\text{wind}}^{\omega,t}}{\mu^\alpha} \quad (3.12)$$

$$K_{\text{angle}} = 1.194 - \cos(\sigma_{ij,\omega,t}^{\text{wind}}) + 0.194\cos(2\sigma_{ij,\omega,t}^{\text{wind}}) + 0.368\sin(2\sigma_{ij,\omega,t}^{\text{wind}}) \quad (3.13)$$
Next, the cable radiated heat rate can be described by the following equation:

\[ q_{ij,ω,τ}^{rad} = 17.8D^ij \cdot ε \cdot \left[ \left( \frac{T_{ij,ω,τ}}{100} \right)^4 - \left( \frac{T_{ij,a}}{100} \right)^4 \right] \]  

(3.14)

Equation (3.7), Equation (3.10), Equation (3.11) and Equation (3.14) make the heat balance equation non-linear, non-convex and, consequently, hard to solve. In the following section, we propose a methodology to effectively solve this problem.

### 3.3.3 Convexification of the Nonlinear Terms

The heat gain results from the ohmic losses, presented in Equation (3.7), is proportional to the multiplication of the square of the current flow and conductor resistance. For an ohmic conductor, as shown in Equation (3.9), the resistance can be calculated by a function of conductor temperature. In order to convexify the heat produced by the current, we considered that the resistance of the conductor is a constant value equal to its maximum at the highest temperature \( T_{ij,(max)} \). Also, the voltage is considered close to 1 p.u.. Applying this method, the current flow is equal to the apparent power flow and the equality constraint Equation (3.7) is relaxed to an inequality one given by:

\[ q_{ij,ω,τ}^{line} \geq R^{line}(T_{ij,(max)} \cdot (|P_{ij,ω,τ}^{flow}|^2 + |Q_{ij,ω,τ}^{flow}|^2) \]  

(3.15)

This relaxation is accurate concerning the considered approximations when the temperature is less than the maximum permissible one and this inequality constraint above will be identical to the equality one. The error introduced by such an approach is progressively reduced when the conductor line temperature comes closer to its maximum limit. Since we are interested to better exploit the lines during the wildfire conditions when they reach their maximum operating temperatures, the error in this approximation is acceptable.

The convection heat loss can be considered as a function of wind speed, the difference between ambient temperature and internal conductor temperature, and altitude. As shown in
Figure 3.1 the relations between the convection heat at each generic wind speed and the difference of the conductor temperature with the ambient temperate are linear. However, since the equation is different for high and low wind speeds, as discussed before, the one producing the largest heat losses should be used. In this study, we can use the maximum of the slope calculated for high and low wind speeds as inputs to the optimization problem.

The radiation heat loss rate can be piece-wise linearized. The radiation heat loss depends on the fourth power of the conductor temperature as shown in Equation (3.14). To piece-wise linearize this term, it is written as a function of the conductor temperature with a domain between the maximum conductor temperature and the ambient temperature. This approximation is shown in Figure 3.2 where the term is evenly divided into three pieces.

The proposed piece-wise linearization approximations can be replaced with a linear approximation to avoid binary variables and this simpler approximation brings a very small error but effectively decreases the computational time. The radiation heat rate is finalized as:
Figure 3.2: Piece-wise linearization of the radiation heat loss ($T^a=273\,^\circ k$)

\[
q_{ij,\omega,t}^{rad} = a \cdot T_{ij,\omega,t} + b
\] (3.16)

3.4 Uncertainties

The parameters related to the environment such as wind speed, wind direction and solar radiation are considered uncorrelated but with uncertainties.

3.4.1 Environment Parameters

A large number of experiments have summarized that the stochastic wind speed approximately follows the Weibull and von Mises distributions. Suppose that the stochastic wind speed $V^{\text{wind}}$ is a stochastic quantity with the following probability density function:

\[
f(V^{\text{wind}}) = \frac{k^{\text{index}}}{C^k} \cdot V^{k^{\text{index}}-1} \cdot e^{(-V/C)^{k^{\text{index}}}}
\] (3.17)

where $k^{\text{index}}$ and $C$ are the shape index and the scale index of the Weibull distribution.
Equation (3.17) could be depicted as Figure 3.3.

Figure 3.3: Weibull distribution of the wind speed

In this thesis, a k-factor of 2 is assumed. The standard deviation is considered equal to 15% of the mean value. With the above probability distribution, the wind speed and direction can be used as inputs to the optimization engine. The mean value and the standard deviation of the wind speed is shown below.

Figure 3.4: Wind speed mean value and stochastic values

10, 50, and 100 series of values are generated and considered in the test cases. All these
stochastic numbers representing uncertainties are generated in Matlab.

Figure 3.5: Wind direction mean value during a 24-hour period

The illumination intensity is considered the main factor affecting the output power of the photovoltaic panels. Suppose that the stochastic illumination intensity also follows the Weibull distribution. The mean value and normal distribution value of the solar radiation data is exploited below in Figure 3.6.

Figure 3.6: Solar radiation mean value and stochastic values
3.4.2 Fire Parameters

The stochastic parameters of wind are substituted into the constraints in Section 3.2 and Section 3.3. We can get the distance between the wildfire and the threatened conductor line in Figure 3.7.

It can be concluded that the fire reaches the conductor line in the last hours of the simulation. And the slopes of the lines are similar with different scenarios.

Figure 3.8 presents the fire radiation rate. Comparing the two figures, it is observed that the heat is greater than zero when the distance between the fire and the threatened line is less than 400m and increases sharply after the fire comes to a close distance. Also, one can observe that the time when the heat flux reaches the peak point is different but is, in this case, later than 18 hours.

3.5 Conclusion

Wildfire affects the power line conductors in different ways, but the most evident is the heat exchange with the line. In this chapter, the thermal energy exchange between the wildfire
and overhead lines is quantified using the heat balance equation. After the convexification of the nonlinear terms in the equation, the optimization problem is transformed into a mixed-integer problem that has quadratic constraints and needs to be solved using a CPLEX solver. Due to the uncertain nature of the environmental factors, the typical distributions for the stochastic parameters are used to generate different series of scenarios and account for such uncertainties. In this way, the heat flux from the fire, the wind speed, the solar radiation, and the parameters of convection loss is computed and will be used as the inputs to the optimization engine developed in the following chapters.

Figure 3.8: Conductor heat gain rate from the fire in different scenarios
Chapter 4: Power Distribution System Optimization Model for Enhanced Wildfire Resilience

4.1 Introduction

This chapter investigates the optimization model for resilient operation of the distribution system (DS) when the wildfire approaches the system. The chapter is organized as follows: first, a mixed-integer linear programming (MILP) optimization model is developed for the DS considering the wildfire model presented in Chapter 3. Afterward, the parameter uncertainties are accounted for through 10, 50, and 100 scenarios generated using Beta Distribution and Weibull Distribution and integrated into the optimization model for testing and evaluations.

4.2 Formulation

In this thesis, we consider a 33-bus distribution system (DS) that consists of the energy storage system (ESSs) and distributed generators (DGs). The wind turbines (WTs) and solar photo-voltaic (PVs) are modeled as stochastic resources while micro turbines (MTs) are considered fully controllable. In this section, we discuss only a base case condition meaning that the wildfire affects only one power line (line 1-2) which connects the DS with the upstream network as shown in Figure 4.1.

A stochastic optimization model is used for enhancing resilience when a wildfire approaches the DS. Although resilience relates directly with load shedding according to [136], operating costs should also be considered to further provide the most economic solution. Accordingly, the DS operates in the most efficient way at a minimum load shedding cost during the emergency operating conditions. Thus, the objective function is designed to
Figure 4.1: Single-line diagram of the modified 33-node power distribution system
minimize the expected social cost as expressed below:

\[
\min \left( \sum_{t=1}^{N_T} \sum_{\omega=1}^{N_\Omega} \pi_{\omega} \cdot \sum_{i=1}^{N_R} \left( (VoLL \cdot p_{i,\omega,t}^{\text{shed}} - c^D \cdot p_{i,\omega,t}^{D}) \right) + \sum_{t=1}^{N_T} \sum_{\omega=1}^{N_\Omega} \pi_{\omega} \cdot \sum_{i=1}^{N_B} (c^{MT} \cdot p_{i,\omega,t}^{MT}) \right) \\
+ \sum_{t=1}^{N_T} \sum_{\omega=1}^{N_\Omega} \pi_{\omega} \cdot \sum_{i=1}^{N_B} \left( (su_{i,t}^{MT} + sd_{i,t}^{MT}) \right) + \sum_{t=1}^{N_T} \sum_{\omega=1}^{N_\Omega} \pi_{\omega} \cdot c^U \cdot (p_{U,t}^{p_B} - p_{U,t}^{p_S}) \right) \\
\right)
\]

(4.1)

In the first line, \(VoLL \cdot p_{i,\omega,t}^{\text{shed}}\) represents the load shedding cost and \(c^D \cdot p_{i,\omega,t}^{D}\) represents the revenue from providing energy to the end customers. The second and third terms represent the generation, start-up, and shut down costs of MT. And the last term represents the power exchange cost with the upstream network. To represent the operation of a DS, multiple constraints should be considered. The optimization model includes components constraints, power balance constraints, and linearization constraints.

### 4.2.1 Renewable Generation Constraints

In this thesis, multiple distributed generators are connected to the system as shown in Table 4.1. In this section, the output power of renewable generators will be discussed.

<table>
<thead>
<tr>
<th>Type</th>
<th>Bus</th>
<th>Capacity (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WTs</td>
<td>14/16/31</td>
<td>0.8/0.8/0.8</td>
</tr>
<tr>
<td>PV</td>
<td>11</td>
<td>0.5</td>
</tr>
<tr>
<td>MTs</td>
<td>8/13/16/25</td>
<td>3/2/2/3</td>
</tr>
<tr>
<td>ESSs</td>
<td>19/26</td>
<td>0.5/0.5</td>
</tr>
</tbody>
</table>

Table 4.1: Location And Capacity of Renewable Resources

Based on the known probability distribution function of the wind speed expressed in Chapter 3, the relationship between the output power of a wind generating unit and the wind
speed can be formulated as follows:

\[
P_{i,t}^{WT} = \begin{cases} 0, & 0 \leq v \leq v_{ci} \text{ or } v_{co} \leq v \\ P_{i,t}^{w} \left( \frac{v - v_{ci}}{v_{r} - v_{ci}} \right), & v_{ci} \leq v \leq v_{r} \\ P_{i,t}^{w} \text{ rated}, & v_{r} \leq v \leq v_{co} \end{cases}
\]  

(4.2)

Where \( v \) is the wind speed at the hub height of the wind unit; \( v_{ci} \), \( v_{co} \), and \( v_{r} \) are, respectively, the cut-in wind speed, the cut-out wind speed, and the rated wind speed; and \( P_{w}^{\text{rated}} \) is the rated output power of the wind unit \([137]\). In this thesis, the cut-in, cut-out, and rated wind speeds are assumed 4, 20, and 12 m/s, respectively. Thus, the relationship between the output power of a wind turbine and the wind speed at the given height could be shown as Figure 4.2.

![Figure 4.2: Relationship between the output power of a wind turbine and the wind speed](image)

As for the solar power, the illumination intensity is usually considered the dominant factor affecting the output power of the solar panel. The relationship between the illumination
intensity and the output power of a solar generating source can be described as follows:

\[
P_{i,t}^S = P_{\text{rated}}^S \cdot \left( \frac{S}{S_r} \right), \quad 0 \leq S \leq S_r
\]

\[
P_{i,t}^S = P_{\text{rated}}^S, \quad S_r \leq S
\]

In the equations above, we have \( S \) as the illumination intensity, \( S_r \) the rated value, and \( P_{\text{rated}}^S \) the rated output power of the solar cells.

The relationship between the output power of a PV unit and the illumination intensity could be shown as in Figure 4.3.

![Figure 4.3: Relationship between the output power of a PV and the solar radiation](image)

The rated illumination intensity of the PVs is set at 1000 \( W/m^2 \). The solar and wind data and the corresponding uncertainties are tackled through the scenario approach described earlier in Chapter 3.

### 4.2.2 Micro Turbine Constraints

As shown in Table 4.1, several MTs are connected to the DS. In this optimization model, the active and reactive output power of MTs and their start-up and shut-down costs need to be
considered as follows to guarantee the power balance in the system at a minimum cost.

\[ p_{i,(\min)}^{MT} \cdot u_{i,t}^{MT} \leq P_{i,\omega,t}^{MT} \leq p_{i,(\max)}^{MT} \cdot u_{i,t}^{MT} \]  

(4.4)

\[ q_{i,(\min)}^{MT} \cdot u_{i,t}^{MT} \leq q_{i,\omega,t}^{MT} \leq q_{i,(\max)}^{MT} \cdot u_{i,t}^{MT} \]  

(4.5)

\[ su_{i,t}^{MT} \geq 0, su_{i,t}^{MT} \geq c_{i}^{SU} \cdot (u_{i,t}^{MT} - u_{i,t-1}^{MT}) \]  

(4.6)

\[ sd_{i,t}^{MT} \geq 0, sd_{i,t}^{MT} \geq c_{i}^{SD} \cdot (u_{i,t}^{MT} - u_{i,t-1}^{MT}) \]  

(4.7)

where Equation (4.4) and Equation (4.5) set the limits for MTs; \( p_{i,(\max)}^{MT} \) is the maximum output power of the turbine as shown in Table 4.1, while \( p_{i,(\min)}^{MT} \) is set as 10 percent of the capacity of the unit. Equation (4.6) and Equation (4.7) reflect the start up and shut down costs of the turbines. The binary variable \( u_{i,t} \) is used to determine the status of MTs, 1 for start up and 0 for shut down. The corresponding prices \( c_{i}^{SU} \) and \( c_{i}^{SD} \) are considered the same and set to $300.

4.2.3 Energy Storage System (ESS) Constraints

The system also consists of two ESSs as shown in Figure 4.1, the operations and limits of which can be expressed using the following constraints:

\[ soc_{i,\omega,t}^{ST} = soc_{i,\omega,t-1}^{ST} + \left( \frac{n_{i}^{ST} \cdot p_{i,\omega,t}^{Ch} \cdot (\Delta t \cdot 3600)}{E_{i}^{ST}} \right) - \left( \frac{p_{i,\omega,t}^{DC} \cdot (\Delta t \cdot 3600)}{n_{i}^{ST} \cdot E_{i}^{ST}} \right) \]  

(4.8)

\[ soc_{i,(\min)}^{ST} \leq soc_{i,\omega,t}^{ST} \leq soc_{i,(\max)}^{ST} \]  

(4.9)
\[ 0 \leq p_{Ch}^{i,\omega,t} \leq p_{Ch}^{i,\omega,t,(max)} \cdot u_{i,\omega,t}^{soc} \]  
(4.10)

\[ 0 \leq p_{DC}^{i,\omega,t} \leq n_{i}^{ST} \cdot p_{DC}^{i,\omega,t,(max)} \cdot (1 - u_{i,\omega,t}^{soc}) \]  
(4.11)

\[ q_{ESS}^{i,(min)} \leq q_{i,\omega,t}^{ESS} \leq q_{ESS}^{i,(max)} \]  
(4.12)

\[ soc_{i,\omega,t end} \geq soc_{thres} \]  
(4.13)

In the equations above, Equation (4.8) calculates the state of charge (SoC) of ESSs. The limitation on the SoC of ESSs is set by Equation (4.9). Equation (4.10) and Equation (4.11) guarantee that the active power charged or discharged by ESSs is within the limits considering their operation mode. Equation (4.12) represents the reactive power limits of ESSs. Equation (4.13) is to ensure that the SOC of ESSs is above a certain threshold \( soc_{thres} \) at the end of the simulation. \( n_{i}^{ST} \) is the conversion efficiency of the ESSs, \( E_{i}^{ST} \) represents the energy capacity, \( p_{Ch}^{i,\omega,t} \) and \( p_{DC}^{i,\omega,t} \) are respectively the charging and discharging active power of the ESS, and \( \Delta t \) is the duration of time intervals. The parameters related and the node connected to the ESSs are shown in Table 4.2. The boundary \( soc_{thres} \) is set to 30 percent. A time step of 30 minutes is chosen since it is a suitable time step for DLR models [138].

<table>
<thead>
<tr>
<th>Energy Storage System</th>
<th>( E^{ST} ) (MWh)</th>
<th>( p_{Ch/DC}^{i,\omega,t,(max)} ) (MW)</th>
<th>( q_{max}^{ESS} ) (MVAr)</th>
<th>( q_{min}^{ESS} ) (MVAr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESS(node 19)</td>
<td>1.5</td>
<td>0.5</td>
<td>0.3</td>
<td>-0.3</td>
</tr>
<tr>
<td>ESS(node 26)</td>
<td>1.5</td>
<td>0.5</td>
<td>0.3</td>
<td>-0.3</td>
</tr>
</tbody>
</table>
4.2.4 Power Balance Constraints

Each bus should maintain a real and reactive power balance between the generated power and demanded loads. With constraints listed in subsections above, the power balance constraints of the system will be as in Equation (4.14) and Equation (4.15).

\[
\sum_{i=1}^{N_B} P_{\text{flow}}^{i,\omega,t} = P_{i,\omega,t}^{MT} + P_{i,\omega,t}^{WT} + P_{i,\omega,t}^{UP} + P_{i,\omega,t}^{Ch} - P_{i,\omega,t}^{DC} - P_{i,\omega,t}^{D} \tag{4.14}
\]

\[
\sum_{i=1}^{N_B} Q_{\text{flow}}^{i,\omega,t} = q_{i,\omega,t}^{MT} + q_{i,\omega,t}^{Ch} - q_{i,\omega,t}^{D} \tag{4.15}
\]

\[
-M_1 * u_{i,\omega,t}^l \leq p f_{i,\omega,t}^P \leq M_1 * u_{i,j,\omega,t}^l \tag{4.16}
\]

\[
-M_1 * u_{i,\omega,t}^l \leq p f_{i,\omega,t}^Q \leq M_1 * u_{i,j,\omega,t}^l \tag{4.17}
\]

Equation (4.16) and Equation (4.17) allow the power flow through each line only when \(u_{i,j,\omega,t}^l\) is equal to 1 meaning that the line is functional and online. The large enough positive number \(M_1\) value is a relaxation parameter. The variables \(p_{i,\omega,t}^D\) and \(q_{i,\omega,t}^D\) are the demanded active and reactive power served to the customer. They are calculated by the load shedding \(p_{i,\omega,t}^{\text{shed}}\) and the original demand of each node \(P_{i,\omega,t}^{\text{Demand}}\) in Equation (4.18) and Equation (4.19).

\[
p_{i,\omega,t}^D = P_{i,\omega,t}^{\text{demand}} - P_{i,\omega,t}^{\text{shed}} \tag{4.18}
\]
\[ q_{\omega,t}^D = Q_{\omega,t}^{demand} - q_{\omega,t}^{shed} \]  

(4.19)

\[ 0 \leq p_i^{shed} \leq P_{i,\omega,t}^{Demand} \]  

(4.20)

\[ \begin{align*}
q_{i,\omega,t}^{shed} &= p_i^{shed} \cdot \frac{Q_{i,\omega,t}^{Demand}}{P_{i,\omega,t}^{Demand}} \\
&= p_i^{shed} \cdot \frac{Q_{i,\omega,t}^{Demand}}{P_{i,\omega,t}^{Demand}}
\end{align*} \]  

(4.21)

In Equation (4.14), the active power \( p_{\omega,t}^{UP} \) represents the power exchange with upstream system during the optimization. It depends on the energy buying from or selling to the main grid and needs to be limited as shown in Equation (4.22), Equation (4.23), and Equation (4.24). The binary variable \( \phi_{\omega,t}^{UP} \) is used to determine buying (1) or selling (0) energy during the studied time horizon. The maximum energy import from and export to the main grid are set 12MWh and 4MWh.

\[ p_{\omega,t}^{UP} = p_{\omega,t}^{buy} - p_{\omega,t}^{sell} \]  

(4.22)

\[ 0 \leq p_{\omega,t}^{buy} \leq P_{\omega,t}^{buy} \cdot \phi_{\omega,t}^{UP} \]  

(4.23)

\[ 0 \leq p_{\omega,t}^{sell} \leq P_{\omega,t}^{sell} \cdot (1 - \phi_{\omega,t}^{UP}) \]  

(4.24)

### 4.2.5 Linearization Constraints

Based on the DistFlow branch equations in [139], constraint (4.25) and (4.26) represent the power flow equation. The large enough positive number \( M_2 \) value is a relaxation parameter to relax these two constraints for open branches. Constraint (4.27) states the boundary for
the nodal voltage magnitudes across the network.

\[
V_{sqr_{i,t}} - V_{sqr_{j,t}} \leq (1 - \alpha_{i,j},t) \cdot M_2 + 2 \cdot (r_{ij} \cdot p_{f_{ij,t}} + x_{ij} \cdot q_{f_{ij,t}}), \quad \forall (i,j) \in L, \forall t \in T
\]  

(4.25)

\[
V_{sqr_{i,t}} - V_{sqr_{j,t}} \geq (\alpha_{i,j},t - 1) \cdot M_2 + 2 \cdot (r_{ij} \cdot p_{f_{ij,t}} + x_{ij} \cdot q_{f_{ij,t}}), \quad \forall (i,j) \in L, \forall t \in T
\]  

(4.26)

\[
V_{sqr_{i}} \leq V_{sqr_{i,t}} \leq \sqrt{V_{sqr_{i}}}, \forall i \in B, \forall t \in T
\]  

(4.27)

### 4.3 Case Study

The wild model proposed in Chapter 3 is applied in order to optimize the DS operation during an approaching wildfire in the next 24 hours. In this case, only line 1-2 which connects the DS with the main grid is affected by the wildfire. The proposed model was solved using GAMS and CPLeX solver considering different numbers of scenarios on wind speed, wind direction, and solar radiation.

The results on the expected load shedding for each case are presented in Figure 4.4. Between hours 19 and 24, the demand is not met due to the disconnection of line 1-2 and the low output power of DGs and ESSs. After hour 22, the wind is increasing so the load shedding is not recorded for some cases. According to the uncertainty analysis, the line

![Figure 4.4: Expected Load Shedding for 10, 50 and 100 Generated Scenarios](image-url)
affected is most likely to be out of service after 18 hours, and the load shedding is increasing with more scenarios being considered. This is reasonable since the uncertainty makes it harder for the system to go back to normal.

Table 4.3 shows the value of the objective function, the load shedding, and the total Cplex time.

Table 4.3: Simulation Results Concerning Different Numbers of scenarios

<table>
<thead>
<tr>
<th># of Scenarios</th>
<th>OF ($ \times 10^3$)</th>
<th>Load Shedding (MW)</th>
<th>Computation Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>-52.31</td>
<td>2.52</td>
<td>21.5</td>
</tr>
<tr>
<td>50</td>
<td>-52.32</td>
<td>2.67</td>
<td>791.56</td>
</tr>
<tr>
<td>100</td>
<td>-52.95</td>
<td>2.96</td>
<td>3802.5</td>
</tr>
</tbody>
</table>

10 scenarios seem to be the best choice since the computation time is the least while the results are similar to other cases. In the following sections, we will consider only 10 scenarios.

The expected energy exchange with the upstream network is presented in Figure 4.5.

Figure 4.5: Expected energy exchange with the upstream system

It is observed that until time 16, the power is only bought from the upstream system. Considering the power exchange price in Figure 4.6, the reason is that the price of MT
Figure 4.6: Power exchange price with the upstream system

generation (80$/MWh) is greater than the buying price from the upstream network before time 16, and the system cannot balance with only renewable generators and ESSs. After 16 hours, the power exchange has a higher price; accordingly, to make most revenue the power is generated by MTs and sold to the main grid as in Figure 4.7. At time 20, the energy exchange cost is still higher than the cost of MTs, but the power is bought from the upstream network to charge the ESSs to prepare for the outage of line 1-2.

Figure 4.7: Expected generated power and status of MTs

As shown in Figure 4.8 at the beginning of the day, ESSs are charging until time 16 to maximize the revenue from selling energy to the customers and the upstream network. After time 18, the discharging power is lower to save for later use when line 1-2 is in outage due
to the progressive wildfire.

![Figure 4.8: Expected discharging power and SOC of ESS](image)

Table 4.4 presents the load shedding cost, the revenue from selling energy to customers, the cost of DGs and the cost of exchanging power with the upstream network.

<table>
<thead>
<tr>
<th>Load shedding cost</th>
<th>Revenue from customers</th>
<th>Generation cost</th>
<th>Power exchange cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.56</td>
<td>69.16</td>
<td>8.04</td>
<td>4.30</td>
</tr>
<tr>
<td>2.547</td>
<td>67.505</td>
<td>8.099</td>
<td>4.54</td>
</tr>
</tbody>
</table>

### 4.4 Conclusion

In this chapter, a stochastic mixed-integer linear programming model is developed considering the wildfire model with different series of scenarios. The proposed model is applied to an IEEE 33-bus system and the social cost was set as the objective function. The results show that the 10 scenario model is the proper one for further analysis considering the computational complexity. The proposed optimization model provides the mitigation strategies of a resilient operation of the power distribution system when facing an approaching wildfire.
Chapter 5: Sensitivity Analysis

5.1 Introduction

In this chapter, the proposed model and analysis data in Chapter 4 will be further studied to investigate the sensitivity of the solutions to changes in each element in the system. Four cases are studied to get a better understanding of the impact of wildfires on the system operation and how to minimize the wildfire consequences considering possible uncertainties in the system elements and how the fire progresses.

5.2 Case Study: Wildfire Affecting Different Overhead Power Lines

5.2.1 Case 1: Wildfire Affecting Different Single Lines

In Chapter 4, we assume that only line 1 (from node 1 to node 2) was threatened by the approaching fire. In order to show how a wildfire affects different power line and to quantify the impacts accordingly, in this section all 32 lines are set as possible targets affected separately by a wildfire. The objective function value and the load shedding cost are shown below in Figure 5.1. The results demonstrate that when power line 25 (connecting node 6 to node 26) is out of service, the consequence load shedding is the maximum. This is because the branch isolated from the system comprises only one ESS and one WT, the capacity of which can not satisfy the total demand in the system.

This observation can be further supported by the detailed load shedding chart at each node when line 25 is affected by wildfire in Figure 5.3.

5.2.2 Case 2: Wildfire Affecting Different Double Lines

In this case, the same model in Chapter 4 is applied to cases where the wildfire is considered to affect two lines at the same time. These two lines need to be connected lines (adjacent).
Figure 5.1: Objective function value: sensitivity analysis on every single line affected by wildfire

Figure 5.2: Expected load shedding cost: sensitivity analysis on every single line affected by wildfire
Based on the results observed in Case 1, lines 1&2, lines 8&9 and line 22&23 are chosen as three pairs of lines being affected by the studied wildfire.

When the wildfire affects line 1&2, the social cost is the maximum value; this is mostly due to the load shedding cost depicted in Figure 5.5. When lines 1&2 are affected, the branch from node 2 to node 22 is separated from the system, and the only ESS left cannot meet
the demand, while in other cases, only the node between these two lines is affected. When line 1 and line 2 are affected simultaneously by the fire, since line 1 is the line connecting the system to the main grid, there is no energy exchange when it is out of service. In other situations, the generators and storage systems connected with the separated (isolated) parts cannot meet their demand, so the energy is always imported from the main grid as can be seen in Figure 5.6.
5.2.3 Case 3: Wildfire affecting different three lines

Case 3 focuses on the situation when 3 lines are disconnected when wildfire approaches the system. As discussed in case 2, these 3 lines are also connected (adjacent) lines. Line 1&2&3 and line 4&6&25 are the two scenarios selected here for analysis. Figure 5.7 depicts the social cost in each situation.

![Figure 5.7: Objective function value when 3 lines are affected by wildfire](image)

In the first case, node 2 is isolated, while the rest of the DS is divided into two parts: the individual distribution system, and a single branch from node 19 to node 22 supplied by the ESS connected to node 19. Since the main grid is unavailable for the system, DGs and ESSs are critical for maintaining the demand-supply balance. At node 11, only a PV is connected, and its capacity is not large enough compared with the demand; also, the ESS in the isolated branch is not able to satisfy the demand. So the load has to be shed in nodes 2, 11, 19, 21, 27, and 30 (see in Figure 5.8). In the second case, node 6 is isolated, while the rest part is separated into 3 parts: the upper part of node 5 which connects with the upstream system, a microgrid system consisting of six generators from node 7 to node 18, 3 and a branch from node 26 to node 33. The first 2 parts are able to supply the load demand while
the third part has only one ESS and one MT, so the nodes of this branch had load shedding in this situation.

![Figure 5.8: Expected load shedding when 3 lines are affected by wildfire](image.png)

When line 1 is affected by the wildfire, there is no energy exchange with the upstream network since it is the only transfer line. When other lines are affected, part 1 of the divided system which connects with the main grid buys the energy from it continuously since it cannot supply its demand by itself.

![Figure 5.9: Expected power exchange when 3 lines are affected by wildfire](image.png)
5.3 Case Study: Modified IEEE 33-Node Distribution System with Different Numbers of DGs and ESSs

In this section, one more distributed resource is connected to the system. The capacity of each element is the same as that in Chapter 4. The results are shown below compared with those in the base case condition studied earlier. Only one element is added at each time, and they are all connected to node 30.

![Objective function value when adding one distributed resource](image)

**Figure 5.10: Objective function value when adding one distributed resource**

Considering the difference in the results obtained in each case, it is observed that much less load shedding would be recorded in the system if a MT was connected. And the generators and storage systems can decrease the load shedding in general.

The power exchange profile in each case is also shown in Figure 5.12.

When renewable generators are added, they can supply some demand so less power is bought from the main grid before MT start up at hour 16 and more sold afterward. When MT is added, it is not working until time 16 when the price of selling the electricity to the upstream network is greater than the generation cost. After 16 hours, more energy is sold making more revenue. When ESS is added to the system, more energy is bought at the
Figure 5.11: Expected load shedding when adding one distributed resource

Figure 5.12: Expected power exchange when adding one distributed resource
beginning for charging purposes while ESS discharging to the grid happens more toward the end of the studied time horizon.

5.4 Conclusion

In this chapter, different numbers of lines are set out of service as a result of the progressive wildfire, and DGs are added to the network to analyze their sensitivity and performance when facing a wildfire. It is recognized that the spatial load shedding depends on the lines affected by wildfire as well as the position, number, and type of generators and storage systems in the network. The analysis of this chapter will help distribution system planners and decision makers better decide on sizing and siting of distributed energy resources across the network aiming to achieve an enhanced grid-support and resilience against wildfires should they happen in the future. Future research could include the analysis of the system in response to wildfires in the presence of different energy storage technologies and grid-support resources [140–149].
Chapter 6: Conclusion

6.1 Conclusion

With the recent increase in the frequency and intensity of wildfires around the world, and the projection for a higher trend in the years to come, maintaining and enhancing the ability of the power system to be resilient against such disruptions is a challenge. When the wildfire approaches the power system, the thermal burden and stress is added and the affected lines could allow less current flowing through them or even become out of service. It is significantly important to efficiently and smartly exploit the available resources to minimize the consequences of a wildfire, e.g., load shedding in the system. Dynamic Line Rating is considered to model the thermal impacts of wildfires on power lines and a stochastic mixed-integer linear program (MILP) optimization model is established aiming to minimize the social cost of the system when exposed to a wildfire.

In Chapter 3 the wildfire hazard model and the associated uncertainties were presented. Different numbers of scenarios were generated employing the normal distribution approach to account for the extreme event uncertainty. The non-steady state heat balance constraint was used to model the impact of wildfires on the temperature of power line conductors. The results were considered as inputs in the following chapters.

In Chapter 4 the optimization model aiming to mitigate the impacts of a progressive wildfire on the power distribution system was presented and studied. To explore the effectiveness of the suggested model, a base case was considered with fire progression. It is observed that the resilient operation of the system can be achieved with reduced load shedding and a lower social cost.

In Chapter 5 the impact of various factors in the optimization model was studied. The same test system with the same wildfire model was optimized with different lines being affected and different availability of distributed energy resources across the network. The
results revealed that the load shedding depends on the combinations of the position (spatial factor) of the resources and lines being affected as the wildfire progresses (temporal factor).

6.2 Future Research

Future work may include investigating the combination of the thermal and physical influences of wildfires on the shape of overhead lines since the high temperature can cause sag to the conductors. Future research may also include the contribution of flexible loads and the interdependent services in the resilience evaluation of the system [150] and the repair strategies in facilitating the power system restoration during the post-disaster outage scenarios. Also, the role of intelligent electronic devices (IEDs) [151–156] as well as the existing and next-generation sensors [157–167] on detecting and preventing the wildfire-triggering events in power systems should be studied.
Bibliography


[54] N. Fuhrmann, “Disposal of trees affected by the pine beetle: The dilemma and why air curtain burners should be used,” 2009.


