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Increasing the Resiliency of the Power Distribution Grid in the Face of Large Wildfires

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Abstract: 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.

Keywords: Power Grid, Resilience, Wildfires, Distribution Systems, MILP

I. INTRODUCTION

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].

Due to the growing demand to ensure higher quality electricity to end customers and particularly critical services, and intensified public focus and regulatory oversights, safe-guarding 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 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]. 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].

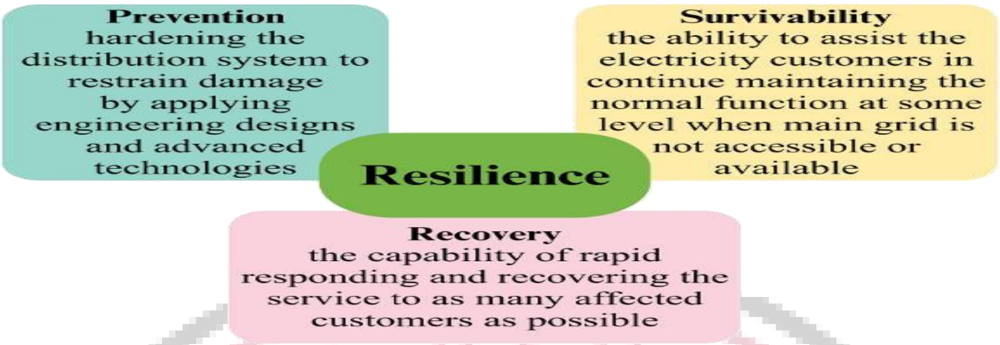


Figure 1.1: Elements of Resilience by Electric Power Research Institute (EPRI)

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.

The system cost analysis which has wind turbine generation, solar system, and storage battery system and diesel generator. The main aim of that paper is to find out the optimal cost of the hybrid plant in such a way to fulfill the load demand and minimized the cost [17]. It consists of various modules related to Solar PV technology, MPPT algorithms, DC/DC converters, and grid connected PV inverter topologies, power quality issues with grid connected PV systems have been studied, which form the back bone of the articles [18]. A comprehensive simulation and implementation of a three-phase grid-connected inverter is presented. The control structure of the grid-side inverter is firstly discussed [19].

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 1.1 [18].

Reliability	Resilience
High-probability, low-impact	Low-probability, high-impact
Static	Adaptive, ongoing, short- and long-term
Evaluates the power system states	Evaluates the power system states *and* transition times between states
Concerned with customer interruption time	Concerned with customer interruption time *and* the infrastructure recovery time

Table 1.1: The Conceptual Contrast Between Reliability and Resilience [18]

II. RELATED WORK

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.

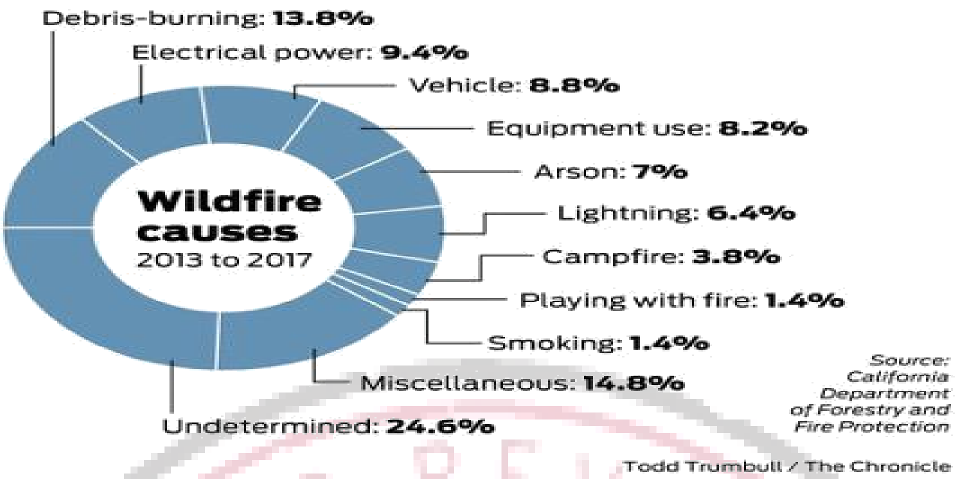
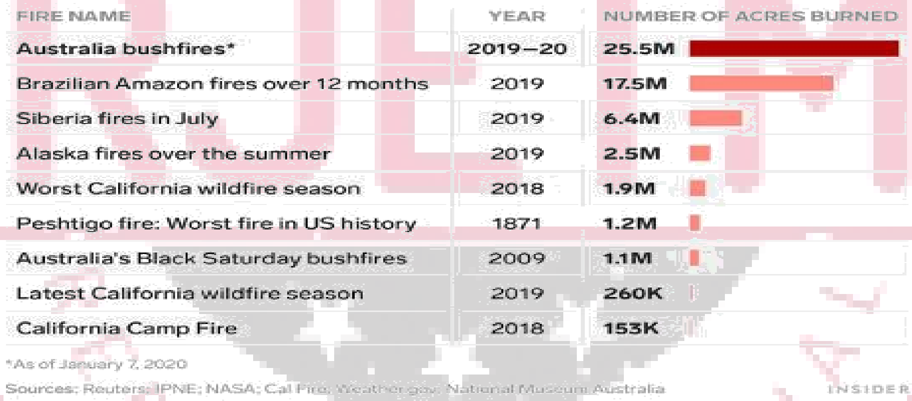


Figure 2.1: Wildfire causes from 2013 to 2017

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 [20]. The 2012 and 2013 studies by Sathaye et al. [21] 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



FIRE NAME	YEAR	NUMBER OF ACRES BURNED
Australia bushfires*	2019–20	25.5M
Brazilian Amazon fires over 12 months	2019	17.5M
Siberia fires in July	2019	6.4M
Alaska fires over the summer	2019	2.5M
Worst California wildfire season	2018	1.9M
Peshtigo fire: Worst fire in US history	1871	1.2M
Australia's Black Saturday bushfires	2009	1.1M
Latest California wildfire season	2019	260K
California Camp Fire	2018	153K

*As of January 7, 2020

Sources: Reuters; IPNE; NASA; Cal Fire; Weather.gov; National Museum Australia

INSIDER

Figure 2.2: Number of arcs burned by wildfires in the world during 1871–2020

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 [25]. 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 [23]. 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 [24]. 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.

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 [20].

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 [24, 25].

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 [18], 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. [20] 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 [19] proposed a dynamic line rating of the overhead lines in order to model the impact of wildfires on conductor temperature and flowing current.

III. PROPOSED EXPERIMENTAL SETUP

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.

Case Study: Wildfire Affecting Different Overhead Power Lines

Case 1: Wildfire Affecting Different Single Lines

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 3.1

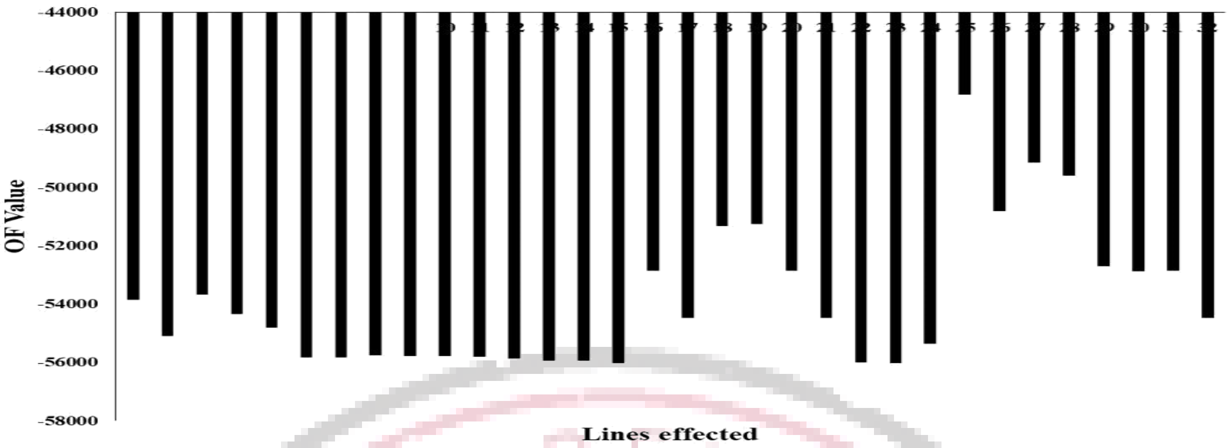


Figure 3.1: Objective function value: sensitivity analysis on every single line affected by wildfire

Case 2: Wildfire Affecting Different Double Lines

In this case, the same model in this chapter 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). 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 a the studied wildfire The objective function values of the base case 1 and case 2 are shown in Figure 5.4. When the wildfire affect 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 effected.

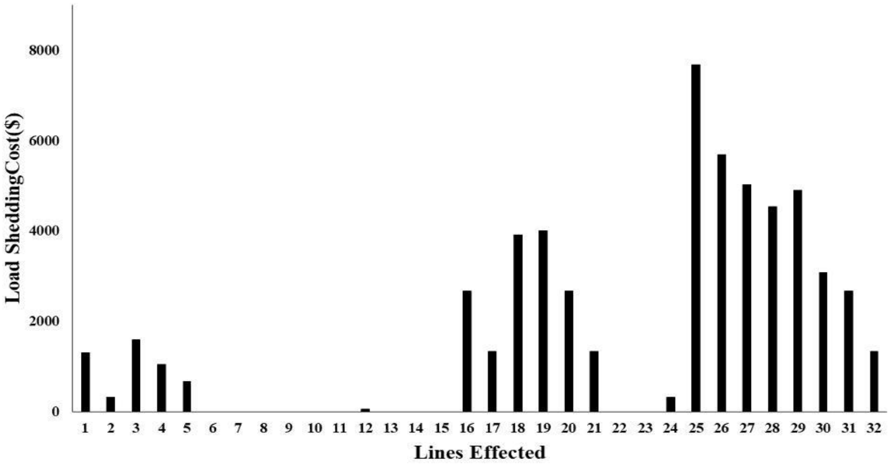


Figure 3.2: Expected load shedding cost: sensitivity analysis on every single line affected by wildfire

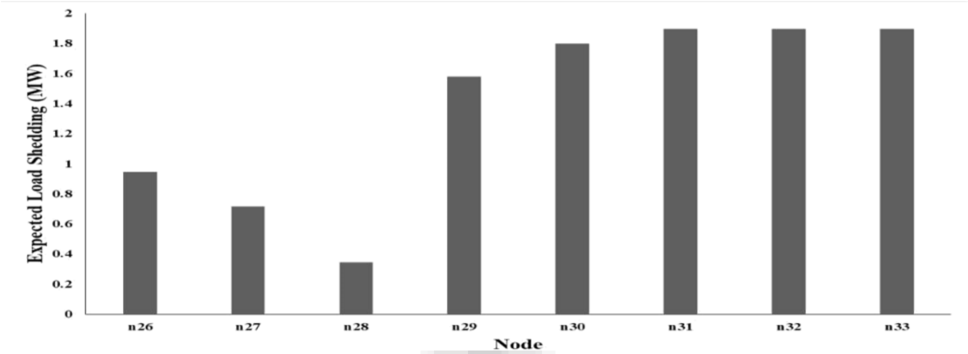


Figure 3.3: Expected load shedding when line 25 effected

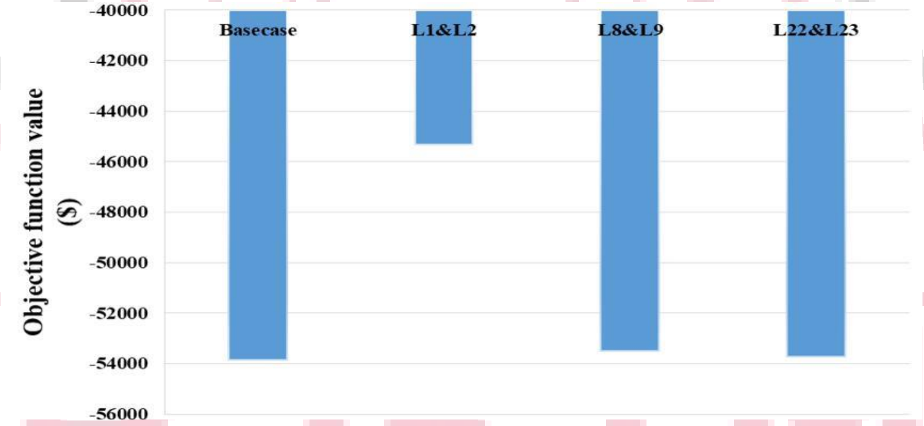


Figure 3.4: Objective function value when 2 lines are affected by wildfire

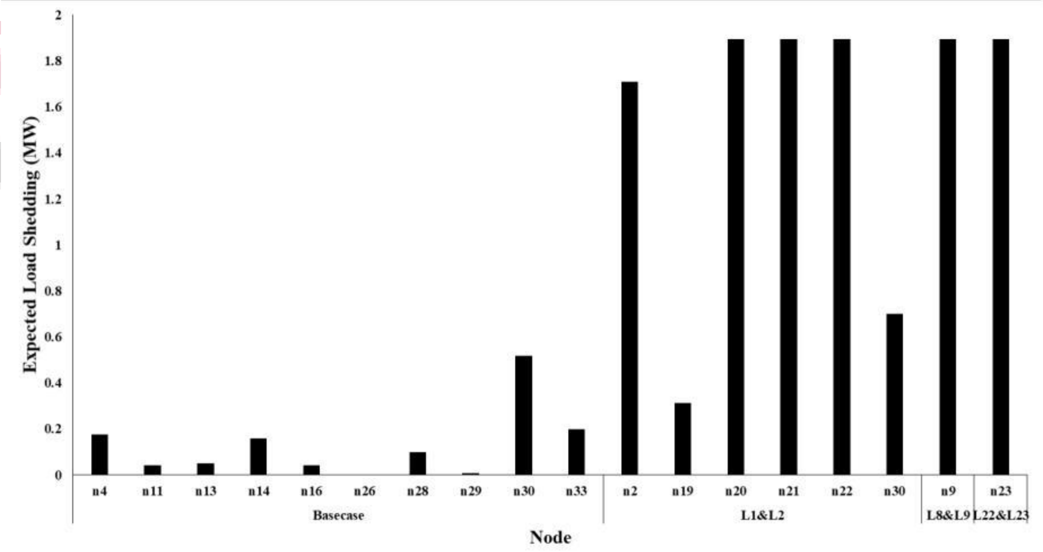


Figure 3.5: Expected load shedding when 2 lines are affected by wildfire

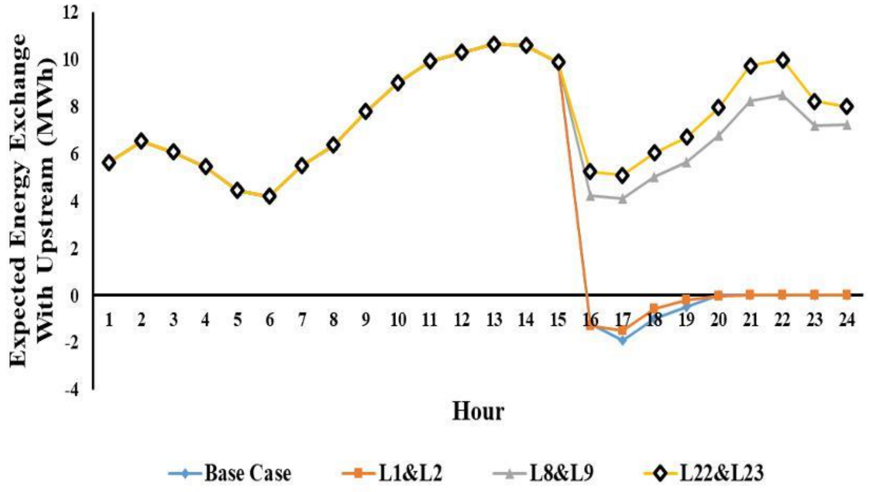


Figure 3.6: Expected power exchange when 2 lines are affected by wildfire

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.

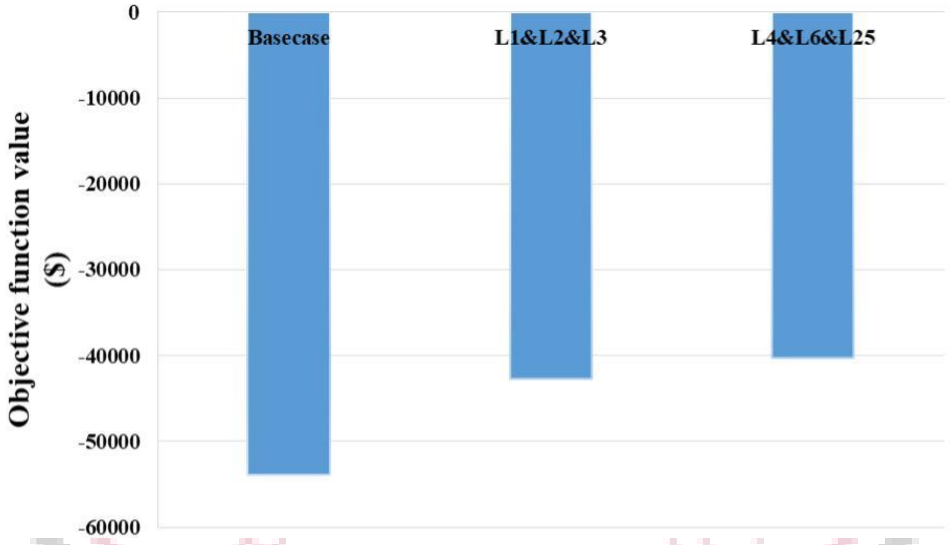


Figure 3.7: Objective function value when 3 lines are affected by wildfire

IV 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.

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