Protection of Falling Conductors into Flammable Vegetation Faults

Vivek Adithya Jayaraman

Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Master of Science
in
Electrical Engineering

Virgilio Centeno, Chair
Vasillis Kekatos
Jaime De La Reelopez

December 14, 2020
Blacksburg, Virginia

Keywords: Protection, High Impedance Faults, Open Circuit Detection, Downed Conductor, Wildfires, Vegetation Faults
Copyright 2020, Vivek Adithya Jayaraman

Protection of Falling Conductors into Flammable Vegetation Faults

Vivek Adithya Jayaraman

(ABSTRACT)

Increasing modernization of the world have brought about a human component to natural disasters, which are exacerbated by the growing threat of climate change. Western United States and Australia have witnessed the some of the deadliest, costliest, and destructive wildfires in the recent past with downed electric power lines being a significant factor amongst the causes. The relationship between wildfires and power lines is not a newly discovered phenomenon, however, utilities across the globe are struggling to find an optimal solution to this problem. While existing regulations allow utilities to schedule power shutdowns, they are often accompanied by massive financial losses and discomfort to consumers. Utilities also need to factor in the climatic conditions in the region of their service and the flammability of the vegetation surrounding their lines while making decisions pertaining to system planning, load shedding and protection. This multi-faceted problem can be dealt in multiple ways: one such technique involves detection of a falling line into sensitive vegetation before it encounters the earth. This approach essentially boils down the problem into detecting a single line open circuit fault. The open circuit is momentary and hence, speed is of the essence in such a protection scheme. In this thesis, detection of an open circuit is carried out in two different ways, viz., with and without communication support between the various elements of the system, with the latter technique being an novel proposal with the aim of achieving a secure protection scheme with minimal additional infrastructural requirement.

Protection of Falling Conductors into Flammable Vegetation Faults

Vivek Adithya Jayaraman

(GENERAL AUDIENCE ABSTRACT)

The contact of a live wire with earth is a fault. While most faults can be cleared using traditional protection techniques, there is a higher risk associated with power lines that come in contact with dry surfaces, flammable plants and bushes, which cannot be detected that easily. These surfaces offer a very high resistance to the flow of current and are hence termed high impedance faults. These high impedance faults have the potential to spark and cause a fire, which can snowball into a wildfire depending on the geography and climactic conditions of the area. For years, this has been a major problem in places like Australia and California leading to loss of lives, power and money, but the optimal solution is evasive. While several techniques to combat this problem exist, the focus of this thesis is essentially what is known as the Open Circuit Fault. The technique revolves around detection of the fault while the falling conductor is midair. Given the short time frame, high speed detection is of the essence. This thesis will focus on achieving open circuit detection without the need for any communication support and is a novel contribution to this field.

Dedication

This work is dedicated in memory of my grandmother, N. Jayalakshmi.

Acknowledgments

Completing my Master's has been a very arduous task, fraught with unexpected personal and professional challenge I woudnť have imagined. First and foremost, I pay my sincerest gratitude to my advisor Dr. Virgilio Centeno.Your constant support, encouragement and guidance was invaluable. I really appreciate the freedom and flexibility you offer your students. I would like to thank my committee members Dr. Vassilis Kekatos and Dr. Jaime De La Ree whose courses on Distribution and Protection respectively instilled great interest and passion in this field for me. I enjoyed your classes immensely.

I would like to thank Minerva, Becky, JoAnna and Laura of the ECE Administrative staff for helping me out on many things. I am also very grateful for all the administrative support provided by Victoria, coordinator of PEC. I would also like to thank Roddy in ECE IT Support for his technical assistance. I would also like to thank the University Librarians - Larry, Edward, Ellen and Bruce for helping me find the right literature.

I am really grateful for some of the lovely friendships and connections I made with my fellow graduate students in the group - Sanij, Sagar, Pratigya, Yousef, Siddharth, Alok, Mana, Nitasha, Ruoxi, Carlos, Jenny, Genesis, Manish, Anaga and Sherin. To Tapas and Suchi, thank you very much for answering my million questions. To Ardavan, I am very grateful for your help with PSCAD. To Rounak, thank you very much for being a great mentor.

It would be remiss to not thank my roommates - Akshay, Arpit and Subhash for making me feel at home in Blacksburg. It would be impossible for me to be at this stage without the social and emotional support of my friends - so, thank you very much, Hariharan, Partha, Sowmya, Sahana, Manasi and Steph.

It goes without saying that my biggest thanks go to my parents, Jay and Kamala. You have been my strongest support system. I'd also like to thank my grandparents, aunts, uncles and cousins for their help and support and keeping me in their prayers.

A special shout-out to Coffee for powering me all my life. Every single word of this thesis was written under the influence of strong Madras filter kaapi.

Finally, to Sangeetha. Words cannot express our friendship and how much your support has meant to me in the last 2.5 years. Even during some of the darkest times, you ensured the sun never really set. Thank you for being the best possible friend one can ever ask for and being there for me in every step of the way.

Contents

List of Figures

List of Tables

List of Abbreviations

AEMO	Australian Energy Market Operator
CPUC	California Public Utilities Commission
DWT	Discrete Wavelet Transform
HIF	High Impedance Fault
MRA	Multi-Resolution Analysis
NEM	National Electricity Market
PBSP	Powerline Bushfire Safety Program
PG&E	Pacific Gas and Electric Co.
PMU	Phasor Measurement Unit
REFCL	Rapid Earth Fault Current Limiter
ROCOV	Rate of Change of Voltage
SDG&E	San Diego Gas and Electric Co.
SWER	Single Wire Earth Return

Chapter 1

Introduction

The year 2020, undeniably, will leave a lasting effect on humankind with a plethora of disasters. While the most notable, and global, was the Covid-19 pandemic, the year also witnessed the latter half of one of the worst bushfire seasons Australia has ever seen. The 2019-20 bushfire season in Australia resulted in a loss of at least one billion wild animals with some facing extinction, 34 human lives, 2600 homes resulting in a burnt area of approximately 46 million acres (72,000 square miles, 11 times the area burnt down by the 2020 California Wildfires) and is touted to be Australia's costliest natural disaster. [26]

These wildfires have catastrophic effects on the planet in a lot of way – human and animal lives, property damage, ecological destruction, abnormal weather patterns in the surrounding area, rising temperatures, etc. Aside from direct damage to natural resources, they can also result in depletion of water indirectly as well as cause destruction to electric power lines resulting in severe outage for millions of customers. Sydney, Australia's largest city, faced the possibility of a blackout after the fires burnt down the New South Wales – Victoria interconnect which resulted in electricity prices skyrocketing to A$ 14,700/MWh on the 4th of January 2020.[32]

In the United States, utilities operating in California, such as PG&E, Southern California Edison, San Diego G&E etc., regularly schedule power shutdowns to mitigate damage caused by wildfires. This practice is known as Public Safety Power Shutoff (PSPS) Events [5] and they resulted in a loss of power for about 3 million customers in the year 2019 [38]. Consequently, PG&E received a massive backlash from the public. In September 2020, PG&E had to cut off power to 172,000 customers as a pre-emptive measure[36]. Without new, innovative technology to tackle the challenges posed by wildfires to power systems, utilities have no other option but to opt for PSPS events to prevent further damage.

The relationship between wildfires and electric power lines is not one way. In the years 2011-15, Electric Power Lines were the third leading cause of wildfires in California, with the California Public Utilities Commission (CPUC) estimating that 10% of the state's wildfires are triggered by power lines [16]. Despite the seemingly low number, these fires are frequent and severe which prompted CPUC to consider the possibility of breaking up PG&E into smaller utilities[15]. Indeed, in the summer of 2018, the California Department of Forestry and Fire Protection report at least 17 major fires caused by power lines, with the

Camp Fire, caused by one of PG&E's downed lines, killing 86 people and destroying 14,000 homes.[23]

This situation is not vastly different in Australia as well. The deadliest bushfire in the country's history took place on February 7, 2009, mostly localized to the south-eastern state of Victoria. Known as the Black Saturday Bushfires, it originated in Kilmore East [20], a town just 65 kilometers north of Melbourne, due to the felling of a 2km section of an aging power line operated by SP AusNet, resulted in the death of 173 people. SP AusNet and Utility Services Group faced a legal class action settlement of 494 Million AUD, which was the highest amount settled in Australian legal history[17].

While wildfires are common in many parts of the world, the causes and the extent of devastation vary greatly. For example, fires in northwestern China and Canada are often caused due to lightning strikes. In Africa, Central America and other places with extensive rural populations and agricultural practices, the leading causes are animal husbandry and land conversion burning. As power engineers, our focus should be to improve our power system infrastructure and employ novel protection strategies to prevent power lines from inducing bushfires.

This thesis will attempt to understand how power lines cause fires, how existing regulations and technology affects the operation of power systems, the electrical characteristics of the faults that lead to fires and how current protection strategies operate upon them. These discussions will bloom into an analysis of a new, proposed protection technique that can prevent these fires that operate with and without a communication network. Further, the efficacy and pitfalls of this technique are discussed followed by concluding remarks and bibliography.

1.1 Existing Policies and Regulations on Fires

It is now well established that power lines are a repeat offender in inducing bushfire across the world, but especially in Australia and United States. Power utilities in these countries must ensure that their lines are well maintained and does not contribute to fires. On the other hand, they must also protect their own lines from falling prey to advancing fire fronts. Power utilities must also focus on ensuring that their customers do not face interruption, but they must do so safely with plenty of planning in advance. Utilities must perform this balancing act skillfully, and hence, follow regulations laid down by local, state, and federal/central agencies as well as the system operators. This section will examine the policies followed by utilities in Australia with special attention to the state of Victoria and California, United States.

1.1.1 Regulations in Australia

Fires are common throughout the country, and electric power lines are responsible for some of the most destructive ones in Australian history, regardless of the state. The focus of this section, however, be limited to the region covered by NEM, which accounts for about 80% electricity consumption in Australia and operates one of the world's longest interconnected power systems, stretching from North Queensland to South Australia.

Australia's geography and population distribution prevent the NEM from being heavily interconnected in comparison to the US Eastern Interconnection. Therefore, any large-scale power disruption caused in any of the states, can lead to power transfer cut off to other states, a blackout, or surging prices. For example, in 2020, the burning down of NSW-VIC interconnect resulted in extremely high prices in Sydney. In 2016, a storm caused a blackout[13] in South Australia, particularly affecting the city of Adelaide. The only two inter-connectors to Victoria were affected, thus, resulting in blackout after frequency collapse due to islanding.

The following subsections discuss the regulations adopted to fight against bushfires in terms of vegetation surrounding the power lines, new technology used to minimize fire risks and load management techniques on severe fire risk days.

Electricity (Principles of Vegetation Clearance) Regulations 2010

The Electricity (Principles of Vegetation Clearance) Regulations 2010 [8] define the legal requirements of vegetation clearance around power lines. This regulation is a development following the Electricity Act, 1996 and is applicable to the state of South Australia. This regulation includes requirements for clearing vegetation around high voltage transmission lines, low voltage distribution lines as well as legal safety limitations for planting trees near power lines and legal requirements for emergency clearance of vegetation on high fire risk days.

The regulation divides the responsibility of maintaining vegetation between two parties – the network operator (SA Power Networks, the sole distributor in the state) and the owner of the land depending on whether if the line services the occupant of the land. These regulations also vary from region to region within the state, depending on their fire risk classification. For example, in non-bushfire risk areas such as metropolitan Adelaide, the distributor may enter into agreements with local councils to conduct tree-pruning programs [30] around public lines.

For landowners and occupants who wish to plan trees, there are elaborate rules stating the types of vegetation allowed, safe distance from the power line that must be maintained, mature height of tree that must be maintained. These rules, again vary from region to region as well as the voltage level of the power line, the insulation status of those lines etc.

The regulations also expect distributors and occupants to observe a buffer zone in addition to the clearance zone prescribed.

Powerline Bushfire Safety Program

Following the devastating bushfires of Black Saturday in February 2009, the Victorian Government established the Victorian Bushfires Royal Commission to plan for, prevent and manage bushfires. The commission launched the Powerline Bushfire Safety Program [4] (PBSP) with an aim to reduce bushfires induced by powerlines. The PBSP supervises 6 projects, committing AUD 750 million for a series of measures for 10 years and they are summarized as follows:

- The Powerline Replacement Scheme aims to upgrade all basic infrastructure. This includes progressive replacement of all Single Wire Earth Return (SWER) lines and 22 kV with aerial bundled cables or insulated overhead lines or underground lines.

- The Network Assets Project aims to upgrade the devices installed in various parts of the network. It includes an upgrade to using remotely controlled Automatic Circuit Reclosers which will be subject to different styles of operation. During the six weeks of greatest fire risk, the reclose function will be disabled and during days of total fire ban, they will attempt to reclose only once. The project also encourages the use of Rapid Earth Fault Current Limiters, which will be discussed in detailed later.

- The Network Operations Project sets down rules for businesses to follow during days of total fire ban.

- The PBSP also focuses on Research and Development projects to better understand the threats posed by fires. These research fronts involve bushfire modelling and mapping, understanding the how powerlines can fail and create fires, developing new technology that can minimize faults and improve the overall safety.

- The PBSP also funds local assistance infrastructure projects encouraging rural users, especially in care facilities, to install back-up generators and rely on them in the event of a blackout.

Rapid Earth Fault Current Limiters

Rapid Earth Fault Current Limiters (REFCL) are devices employed in Victorian power systems to reduce the chances of downed power lines from arcing and inducing fires. REFCL is the result of the Powerline Bushfire Safety Program [6] and work on the principle of resonant coils. According to Victorian PBSP, they have the capability to reduce powerline fires by 50%. Theoretically, REFCLs are essentially a form of resonance grounding system where a coil, tuned to network capacitance is installed at the substation. REFCL has the capability to neutralize the fault current on the network within milliseconds, reduces the voltage of the faulted phase to very low values, and raises the voltage level of the non-faulted phases thereby re-routing power.

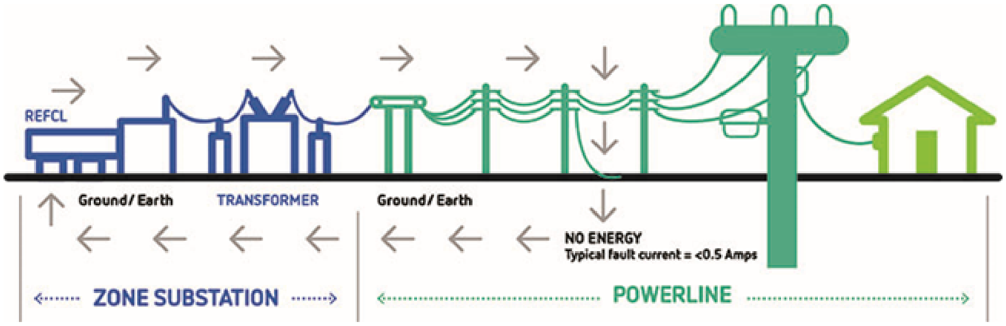


Figure 1.1: Implementation of Rapid Earth Fault Current Limiters. Source: [7]

The performance of an REFCL can be improved by supplementing it with an inverter and a controller. The operating terminology for REFCLs without an inverter is considered "passive" and is considered "passive + active" when it acts in tandem with an inverter.

Under passive operating conditions, the arc suppression coil reduces the Line-Neutral voltage at the substation transformer on the faulted phase and thereby suppresses the fault current. Therefore, the unfaulted phases have a line-earth voltage roughly equal to pre-fault line-line voltage.

Under "passive + active" operation, the residual current compensator injects phase-opposite current into the neutral to cancel out the residual current across the coil and further pushes the Line-Neutral voltage towards zero. In this case, the unfaulted phases have a line-earth voltage exactly equal to pre-fault line-line voltage.

REFCLs are designed to deal with single line to earth faults. Although, they are the most common types of faults, this technology may not work under double line to ground faults.

One of the key challenges that accompany the implementation of REFCL is the detection of fault circuit and location. REFCL is designed to protect multiple circuits, and therefore, identifying the faulted circuit becomes a challenge and power cannot be restored until it is manually cleared. REFCL work better when the reclosing functions are deactivated for all types of faults.

1.1.2 Regulations in the United States of America

Wildfires in the USA are extremely common in the state of California and other Pacific states. California is a part of the Western Electricity Coordinating Council and is served by many utilities such as Southern California Edison, San Diego Gas & Electric, Pacific Gas & Electric etc. They are all bound by regulations laid down by the California Public Utilities Commission (CPUC).

Managing power line induced wildfires in California are much for difficult when compared to Australia – the load centers are much more distributed and there are more utilities operating within the state, each with their own operating guidelines. However, CPUC has some common requirements in terms of vegetation clearance [9] and expects the utilities to opt into their Wildfire Funds programs and seek safety certifications.

The CPUC has Public Safety Power Shutoff (PSPS) programs[5]. However, it is not the CPUC that mandates the shutoffs – they are exercised at the discretion of the utility serving the area.

Utilities such as PG&E are following their own set of mechanisms to protect their service area from fires, such as by having vegetation clearance programs, routine infrastructure upgrades, better monitoring systems and of course, following PSPS.

As compared to the NEM in Australia, the CPUC guidelines are more vague and relaxed. There is lesser research and development breakthrough to minimize fire risk, although San Diego Gas and Electric have proposed a technique that will be explored in later chapters. As recently as 2018, power lines are still responsible for a significant number of fires and casualties in California. Utilities like PG&E are looking at the Victorian model of handling fire risks and are studying REFCLs.

1.2 Origins of Powerline Induced Wildfire

We have established that powerlines can cause wildfires. However, it is important to understand the exact cause of these fires. There are several factors that play in the escalation of a benign downed conductor fault into a raging wildfire. The voltage and current level of the conductor, nature of insulation, nature of surrounding vegetation, climactic conditions and the impedance of the fault all play a decisive role in sparking a fire. Additionally, fires are also caused due to other component failure, such as multiple automatic recloser attempts[24]. This section will attempt to dissect the various contributing factors of wildfires.

1.2.1 Downed Lines

A simple case of a line falling to the ground is a Line-Ground fault. However, this is not similar to a live wire accidentally coming in contact with a neutral wire or the transmission tower. The difference lies in the impedance offered in the path between the line and the ground. In the case of a live wire accidentally shorting with a ground wire, the impedance is very low, and consequentially, the fault current is very high and traditional over-current relays respond quickly. However, when a live wire falls to the ground, it offers a high surface contact resistance. Therefore, it draws very little current and may often not be sufficient enough to trip relays.

This results in a low magnitude, but dangerous amounts, of fault current seeping into the ground for a very long time. This has the potential to spark fires on the ground. These types of faults are known as high-impedance faults. The exact magnitude of this impedance is highly variable, which depends on the nature of the surface in question, length of the line that is in contact and the presence/absence of other obstacles such as a tree branch. High Impedance faults are tricky to detect and require the use of sophisticated signal processing techniques to analyze.

Downed conductors occur everywhere on the Earth, but not every one of them exacerbates into a fire. The other factors determine this transformation. However, a downed conductor is often the first in the sequence of events leading up to a fire.

Figure 1.2: Downed Conductor Induced Fire. Source: [1]

1.2.2 Effect of Vegetation and Surface Type

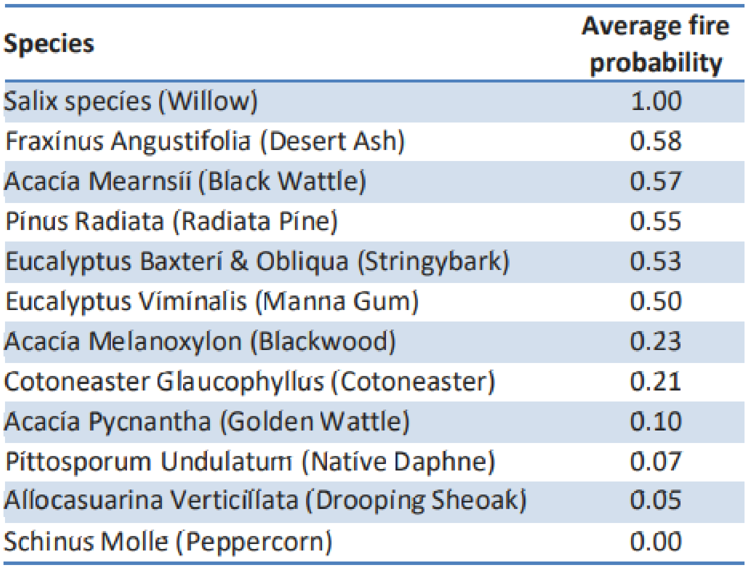
Vegetation around power lines are always a hindrance. They can unnecessarily encounter live wires in various ways causing faults. A live wire hanging dangerously close to a tree can give rise to a lot of momentary ground faults. These faults are momentary because the line is not broken and the contact with tree branches is for a very short time. Therefore, they are often cleared automatically and can easily be protected by recloser operations.

When a tree branch falls on a line, but does not cause it to break, it provides a high impedance path to ground and allows little current through it. However, since the line is unbroken, there are current contributions from both ends of the line and it is possible for directional relay elements to pick up this fault even if the current magnitude is below tripping settings for overcurrent relays.

Tree branches falling in between two lines create a line-line fault. However, since this fault does not involve any combustible material, other than the piece of wood in question, these do not materialize into fires often. The piece of wood may burn and disintegrate, but it also clears the fault in the process.

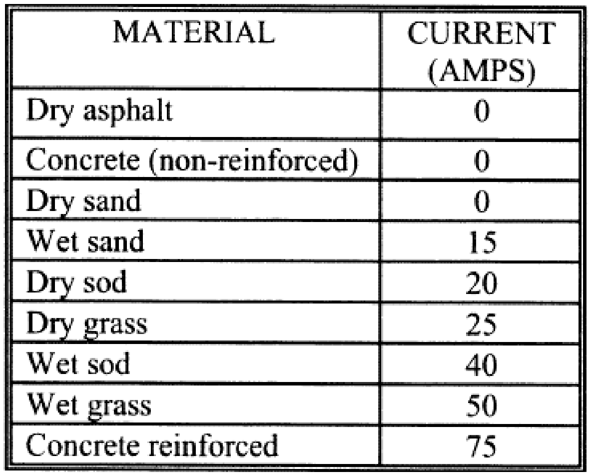
Therefore, the most significant effect of vegetation come into play when a line physically falls to the ground and is in contact with highly combustible plants. Therefore, there are elaborate regulations established by utilities to keep the right of way clear from combustible vegetation.

Not all types of vegetation can give rise to fires. The fire risk depends on the flammability of material, which is affected by moisture content, sap content, oil content, size of branches and leaves. The following table contains the fire risk surrounding various vegetation. This table is a part of the field tests conducted by the Victorian Powerline Bushfire Safety Program.[34]



Species	**Average fire probability**
Salix species (Willow)	1.00
Fraxinus Angustifolia (Desert Ash)	0.58
Acacia Mearnsii (Black Wattle)	0.57
Pinus Radiata (Radiata Pine)	0.55
Eucalyptus Baxteri & Obliqua (Stringybark)	0.53
Eucalyptus Viminalis (Manna Gum)	0.50
Acacia Melanoxylon (Blackwood)	0.23
Cotoneaster Glaucophyllus (Cotoneaster)	0.21
Acacia Pycnantha (Golden Wattle)	0.10
Pittosporum Undulatum (Native Daphne)	0.07
Allocasuarina Verticillata (Drooping Sheoak)	0.05
Schinus Molle (Peppercorn)	0.00

Figure 1.3: Average fire probability of various vegetation species. Source: [34]



MATERIAL	CURRENT (AMPS)
Dry asphalt	0
Concrete (non-reinforced)	0
Dry sand	0
Wet sand	15
Dry sod	20
Dry grass	25
Wet sod	40
Wet grass	50
Concrete reinforced	75

Figure 1.4: Fault Current through various surfaces at 12 kV. Source: [39]

1.2.3 Miscellaneous Factors

While the nature of the fault and vegetation play a particularly important role, there are several other factors and causes that can cause an electrical fire to escalate into a wildfire. Dry winds, pre-existing drought conditions, hot weather also play a crucial role, and are hence responsible for Wildfires being a seasonal event in Australia and the United States rather than an all-year-round occurrence.

Other causes of electrical fires include repeated attempts to reclose a faulted line. The multiple opening and closing can contribute to arcing between the recloser contacts. This is the reason why, in days of high fire risk, power utilities often do not attempt to reclose their lines as often. During Total Fire Ban Days in Victoria, especially with an REFCL in place, the automatic reclosers are allowed only one attempt to reclose and are completely disabled during the weeks of highest risk.

1.3 Contributions and Outline of Thesis

It is abundantly clear that preventing power line induced bushfires is a serious problem that needs to be dealt with. Utilities in Victoria have moved forward into developing new technology such as the REFCL because they believe frequent power shutdowns are not the solution. Utilities in California are yet to take bigger steps in that direction and are still relying on PSPS events as a reliable alternative, though not the most beneficial. Past work on this topic focuses primarily on detection of, and protection against High Impedance Faults. Recent work in Australia has dealt with the employment of a new device that has the potential to neutralize such fault currents. San Diego Gas & Electric are working on a protection strategy that detects a falling conductor before it hits the ground. The approach makes use of PMU measurements to capture voltage signal trends and decide to trip a broken line, which is an open circuit, before it becomes a ground fault. This technique, however, requires the use of sophisticated monitoring and communication infrastructure.

This thesis will combine the various aspects that have been explored in the past to devise a new protection strategy that can detect falling conductors without the need for a communication network. The signal processing tools employed to deal with high impedance faults will work in tandem with the observed characteristics of an open circuit to trip the line before it hits the ground. This technique will be analyzed for its reliability by considering imbalanced loads, load switching events, exposure to other fault types and will be implemented on an IEEE benchmark, viz, the WSCC 9 Bus System. This thesis will also attempt to establish some numerical settings that are required to ensure the protection is secure.

Chapter 1 introduces the problem, explores the origins of powerline induced fires and what various countries have done to minimize risk. Chapter 2 explores the technical literature behind these faults viz protection against high impedance faults, detection of open circuits, effect of vegetation, and some mathematical techniques typically employed. The literature review will also briefly study some fault classification techniques, as we will be importing the results to fix numerical settings for our relays to design a more secure protection scheme. Chapter 3 discusses high impedance faults and the signal characteristics; Chapter 4 discusses the theory behind open circuit detection and replicates the work by San-Diego G&E on tripping using PMUs. Chapter 5 introduces the new contribution and explores protection against falling conductors by tripping them without a communication network. Chapter 6 concludes the discussion and leaves room for future work, followed by bibliography.

Chapter 2

Review of Literature

This chapter discusses the literature pertaining to this thesis. The organization of this review follows the ideological flow of the thesis. The broad topics that this review cover include, but is not limited to, the link between power lines and wildfires, policies and regulations established to address the same, prior work done in this field, high impedance faults and open circuit faults.

2.1 Empirical Relationship Between Power Lines and Fires

Establishing the link between wildfires and electric power lines is the first challenge since it essentially defines the whole problem. [16] reports instances of power line induced wildfire disasters in the state of California.[23] [38] [36] highlights the statistics of human, financial and utilitarian losses faced by the citizens and power utilities in California. [24] probes into automatic reclosers as a potential source of California fires. [18] (authored by Congressional Research Service) provides a detailed report into California Wildfires and discusses options to improve the reliability of power systems.

[20] is a chapter from the official fire investigation report by 2009 Royal Victorian Bushfires commission that details the proceedings of the Kilmore East fire that later results in a costly and famous lawsuit discussed in [17]. [26] details the impact of the 2019-20 bushfire season in Australia while [32] highlights the disastrous consequences faced by consumers in the state of New South Wales when electricity prices went through the roof. Finally, [13] documents the events pertaining to a blackout in Adelaide caused by floods, which is essential to understanding the interconnections between Australian states.

Technical literature pertaining to this topic was scarce in journal and conference proceedings. Most of the existing literature is present as news articles, inquiry reports and investigations conducted by local, state, and federal/central agencies and power utilities. A more scientific approach is taken by [1] where the theory behind this relationship is solidified. [19] presents a detailed approach to arcing by fallen transmission lines.

2.2 Existing Policies and Regulations on Fire Risk Management and Vegetation Control

Following the catastrophic 2009 Black Saturday Fires in VIC, Australia, the Victorian Government instituted the Royal Victorian Bushfire commissions to investigate the issue. This resulted in the publication of a final report [11] and the eventual formation of the Powerline Bushfire Taskforce which has published a series of recommendations [12] to the state. One of the outcomes of the Taskforce was the Powerline Bushfire Safety Program which has instituted a series of schemes detailed in [4].

From the perspective of vegetation control, the rules, and regulations from the state of South Australia were obtained for review. [30], [8] provides details pertaining to planting, trimming vegetation near lines as described by the state's Electricity (Principles of Vegetation Clearance) Regulation 2010. The regulation offers guidance in terms of responsibility between public and private partnership in maintenance of vegetation and the type of vegetation that can be planted.

In the United States, especially California, the rules for vegetation management is set forth by California Public Utilities Commission in their official brochure [9]. [5] outlines the CPUC's recommendations behind frequent power shutdown events in California, while [15] reports some possible administrative options mulled by CPUC.

2.3 Prior Work

From the perspective of real-life implementation of new technology to combat the threat of wildfires, the Victorian government has taken several steps following the recommendations of the Powerline Bushfire Safety Program. One of the biggest outcomes of the safety program is the development of Rapid Earth Fault Current Limiters. [6] is the final report pertaining to the various trial and testing stages of the REFCL, which essentially works based on the principle of a Peterson coil. It is reported that the arcs can be prevented from developing into a fire, if the REFCL manages to bring the voltage level down within 85 milliseconds. While the REFCL is effective and is being studied extensively by Californian utilities, it is not without limitations. [35] highlights some of the problems associated with REFCLs including its inability to work with Double Line to Ground faults and its incompatibility with Single Wire Earth Return systems.

The Powerline Bushfire Safety Committee has also conducted a few ignition tests on live wires surrounding vegetation in a controlled atmosphere. [34] documents the results which contains valuable data pertaining to fire probabilities in vegetation which is essential in our discussions. Based on the publicly available dataset from these experiments, available at [3], some interesting research papers have been published that are directly relevant to this thesis in a more academic sense.

[28] uses the above dataset to detect High Impedance Faults occurring on sensitive vegetation. The paper extracts high frequency characteristics using Discrete Wavelet Transforms of the vegetation fault signatures. The resulting signal characteristic information is processed in many ways before it is used in a boosted tree classifier. While [28] is groundbreaking in its approach and results, it is hard to replicate the results in an American context because of the differences in vegetation growth, wind patterns and general differences in the power system. [28] also presents things from a more theoretical and analytical perspective, rather than provide options or techniques to prevent fires from happening. [27] is an extension of this research with sparse coding techniques for fault signature analysis.

2.4 High Impedance Faults

Conductor into earth faults that spark fire are essentially high impedance arcing faults. High Impedance faults are difficult to detect using traditional over-current or distance protection schemes due to the very low magnitude of fault current. [33] provides the most fundamental research pertaining to detection of High Impedance Faults using wavelets.

[29] provides a method to detect High Impedance Faults using Discrete Wavelet Transforms. The paper conducts an analysis on a 154 kV Korean Transmission line and extracts the first order detailed coefficients to detect faults and observe the variation of these coefficients with the distance of faults. [29] also discusses the choice of mother wavelet used for analysis. Likewise, [14] provides a similar analysis that is more useful from a fault classification perspective. [14] uses a different mother wavelet and sampling frequency for its discrete wavelet transform algorithm. The mother wavelet for this thesis is chosen based on discussions provided in both papers.

Similarly, [39] is another DWT based approach to identifying High Impedance Faults on distribution networks using microprocessor devices and contains information pertaining to fault current levels across different vegetation and surfaces.

The choice of using PSCAD for simulations in this thesis stems from similar research performed on the same platform. [42] provides a basis for carrying out the most basic HIF detection on PSCAD. The algorithm used follows the one proposed in [29]. Likewise, [41] discusses detection of downed conductors in distributions systems modelled as HIF and processed using DWT in PSCAD. However, the detection algorithm is far more complicated due to the use of Neural Networks.

One of the main drawbacks that could result in modelling a complex event such as line arc induced fire using PSCAD is its faithfulness to real world scenario. [25] addresses this conundrum about reliability of simulation methods and noise present in real world signals. Using the results provided by this paper, we can arrive at conclusions regarding detection speed, accuracy and sensitivity of our analysis when compared with the real world. Therefore, the results in this thesis stemming from simulation methods can be adjusted to real world scenarios in accordance with [25].

2.5 Open Circuit Faults and Detection

The idea of analyzing this event as an open circuit fault was first carried out in [37], which will be the crux of Chapters 4 and 5 in this thesis. [37], models this system using RTDS and employs PMUs to measure data. The theory of analyzing zero sequence voltages was discussed in [37], however it was not covered in detail. The exact algorithm is unclear since the paper devotes a lot of attention to the communication and RTDS setup of the system. [31] provides a stronger theoretical basis for the power system under a single open line. [31] analyzes the zero sequence voltages, currents and direction of power along with phasor diagrams in comparison with a healthy circuit in order to establish a stronger theory. [31] also proposes a rather convoluted protection algorithm to detect open circuits, however, this paper assumes the open circuit to last for an indefinitely long period of time and the protection does not pay enough attention to speed.

The speed of protection in this scenario is crucial, for that, an estimate of the time spent by the conductor midair important. On that front, [37], claims that a conductor takes 1s to drop to the earth on a 12 kV system. [22] presents a complicated power line carrier monitoring approach to estimate the sag of a line. Using the sag of the line, it is possible to estimate the tension and hence predict the time taken to fall. For the sake of simplicity, the method proposed in [22] has not been carried forward in this thesis, although this can possibly contribute towards another notable source of error.

The implementation of all algorithms proposed in this thesis was initially carried out in a classic 2 bus system. However, to test its efficacy in a more complicated power system, the IEEE 9 bus benchmark was used. The 9-bus system is essentially an approximation of the Western Electricity Coordinating Council's power system. The details of the model are available in [10] and its implementation in PSCAD was carried out with a previously tested and validated model available in [2]. [2] presents the transmission lines approximated using a Bergeron model, which is more suited for load flow and short circuit studies. Hence, this difference in the line model contributes for another deviation from the real-world settings.

Another popular mechanism used to detect open circuits are using travelling waves, detailed by [21]. This technique requires communication and is more suited to detect the location of the fault in a transmission line.

This literature review is not an exhaustive list of available literature on this field. There are multiple ways to improve this work. Reclosers can be included in this analysis since they are notorious for fires as well. [40] provides a similar discussion on this topic considering the impact of reclosers.

Chapter 3

High Impedance Faults into Flammable Vegetation

3.1 Problem Definition

One of the biggest contributors to electricity induced wildfires is the impact of downed conductors. At its simplest description, it is the physical contact of an energized power line with the earth, which is classified as a single line to ground fault. Single line to ground faults are universal and can often be easily picked up by traditional overcurrent relays or distance protection schemes. However, a downed conductor that has the potential to arc and cause flames is a very nuanced case of a single line to ground fault. There are several elements that distinguish a simple Line-to-Ground faults from these kinds of "special faults".

Firstly, a large number of single line to ground faults are short-lived and occur when an energized phase accidentally comes in contact with the neutral wire or the tower. However, these "special faults" develop into fires because they have a prolonged contact with the earth, extending into several minutes. This prolonged contact is due to a very high impedance in the path between the line in the ground due to dry leaves, bushes, tree branches etc.[1]

Secondly, the length of the conductor that is in contact with the earth plays a role in determining the overall fault current. A longer section of the line touching the ground means a bigger surface area for the current to seep through from the circumference of the conductor. Therefore, the current flowing from the tip of the conductor to the earth will be lower and increases the apparent fault impedance.

Due to the low current level, these faults are not picked up by over-current relays easily. Inverse-Time characteristics ensure that the response time is very large (extending into minutes) even if the magnitude happens to be just above the trip settings. The resultant high impedance also places the operating point of the system well outside all three zones of a classic mho-relay controlled distance protection scheme.

Therefore, at its core, a downed conductor into earth fault is considered to be a High Impedance Fault (HIF). High Impedance Faults require special detection techniques that relies on a signal processing technique known as Discrete Wavelet Transforms (DWT) [33]. However, not all high impedance faults give rise to arcs. For example, a tree branch that forms a complete path between a taut line and the earth will not give rise to any fires because there is no avenue to form arcs.

Arc formation and combustibility are key factors that escalate a high impedance fault into fires. Electric arcs are formed whenever there is a small air gap in the path of the current. The voltage across the air gap must be significantly high and the length, very small for the arc to sustain. This is often the case with reclosers or circuit breakers, and these devices are designed with oil or air based arc quenching techniques. Arcs develop into fires in the presence of a fuel (in our case, easily combustible dry leaves) and a good supply of oxygen. Therefore, these conditions also dictate what kind of high impedance faults end up sparking a fire. For example, high impedance faults caused by a line hitting a concrete surface will not spark a fire.

Hence, combining the above aspects, we can call these kinds of special faults as “Flammable Vegetation High Impedance Faults”. At its core, they are High Impedance Faults. The vegetation is factored in to determine the trip settings of the protection mechanism. This chapter will attempt to outline ways to formalize this problem and discuss some techniques to detect such faults.

3.2 Detection of High Impedance Faults

As discussed above, High Impedance Faults are often difficult to detect because of their low fault current that’s below overcurrent settings and high impedance that is outside the zones of distance protection. A regular high impedance fault is detected by analyzing it in the frequency domain and looking out for high frequency components. Each of the different techniques possess different advantages and disadvantages, as discussed in Chapter 2.

In this section, we will look further into how High Impedance Faults are detected using Discrete Wavelet Transforms (DWT). DWTs possess time-domain information in addition to frequency-based analysis and is used to analyze non-stationary signals. The following section elaborates on the mathematical principles pertaining to DWT.

3.2.1 The Discrete Wavelet Transform

The Wavelet Transform is a mathematical transformation technique that is often used to represent a non-stationary, non-periodic and highly irregular signals into a series of daughter wavelets that are scaled and translated copies of a mother wavelet. The mother wavelet is basically a finite-length or a fast oscillating decaying waveform that is continuous and differentiable and is often, not expressible in closed form. The Discrete Wavelet Transform is, hence, the discrete representation of a continuous wavelet transform.

The Discrete Wavelet Transform holds several advantages as compared to a Fourier Transform, primarily, its ability to retain the time varying information in addition to frequency analysis. The Fourier transform is only localized in the frequency domain. The DWT works on the principle that it only allows change in the time extension, but not the shape. It is governed by the uncertainty principle:

$$\Delta t \times \Delta\omega \geq \frac{1}{2} \tag{3.1}$$

A larger time resolution results in a smaller frequency resolution, which is accompanied by a small frequency and large scaling factor. The Discrete Wavelet Transform of a signal x(t) is calculated by passing it through a series of high pass and low pass filters. The output from the low-pass filter is called as the approximate coefficient, while the output from the high-pass filter is known as the detailed coefficient. Depending on the frequency resolution of our interest and the initial sample frequency, sometimes, these filter banks are cascaded to achieve a series of high and low pass filters to achieve several orders of coefficients.

The Discrete Wavelet Transform of a signal is given by:

$$DWT(m,k) = \frac{1}{\sqrt{a_0^m}} \sum_n x(n) g(\frac{k - nb_0a_0^m}{a_0^m}) \tag{3.2}$$

Where g(n) is the mother wavelet, x(n) is the input signal and “a” and “b” are the scaling and translation parameters respectively and are functions of integer parameter m. Upon some manipulation, the expression can be generalized to a pair of low pass and high pass filters.

The low pass filter is given by:

$$y_{low}[n] = a_1[n] = (x * g)[n] = \sum_{-\infty}^{\infty} x[k]g[2n-k] \tag{3.3}$$

The high pass filter is given by:

$$y_{high}[n] = d_1[n] = (x * h)[n] = \sum_{-\infty}^{\infty} x[k]h[2n-k] \tag{3.4}$$

The resultant approximate and detailed coefficients each contain half of the total frequency information since they belong to different bands. Hence, the frequency resolution is doubled, which is accounted by using 2n in place of n. Schematically, the discrete wavelet transform, with its many levels, can be drawn as follows:

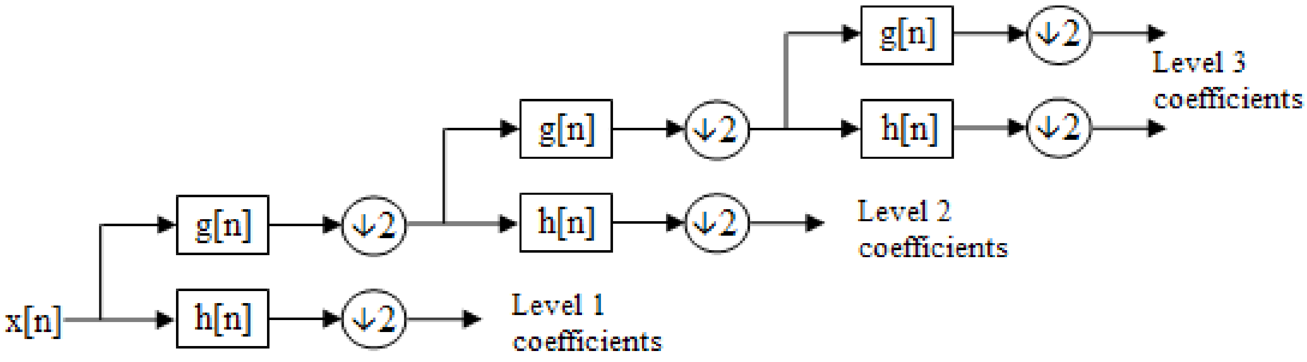


Figure 3.1: The Discrete Wavelet Transform modelled a series of cascading high-pass and low-pass filters

The DWT, as explained previously, works really well in analyzing High Impedance Faults because of its ability to retain miniscule time variations and also capture information across a wide frequency spectrum through the use of many levels of filtering. High Impedance Fault current exhibits a high frequency content, especially in the 2nd and 3rd harmonics of the power frequency [14]. The transient from pre-fault to fault condition does not show a significant peak due to the high impedance, but the DWT can pick up this transition.

One of the key aspects of using DWT for HIF detection is the choice of mother wavelet. Chapter 2 explores previous literature on HIF detection using DWT where elaborate discussions on the mother wavelet have been made.

The main factors that decide the choice of mother wavelet is the ability of that wavelet to deliver detailed coefficients that can clearly distinguish faulted phases from non-faulted phase as well as mark a distinction from pre-fault condition to faulted state. After reviewing four choices of mother wavelets, viz, db4, sym5, bior3.1 and coif4, the most appropriate choice for our study is db4. db4 has 4 vanishing moments and can, hence, encode a 4th degree polynomial signal.

3.2.2 Fault Detection using DWT based MRA for HIF

We now know that Discrete Wavelet Transforms can capture the signal characteristics pertaining to High Impedance Fault currents. The next step is to design an algorithm that makes of this information and tailor it different needs.

Some previous literature on this topic are keen on fault classification, estimation of fault distance from the substation, simple detection of fault of etc. The distance and the type of fault play a major role in the magnitude of the absolute values of detailed and approximate coefficients.

Once an acceptable threshold has been set for detection, the detailed and approximate coefficients are smoothed over by using a moving average filter with a window that captures one cycle of power frequency. This is to ensure that the coefficients display a consistent magnitude that is above the required threshold. Based on the techniques conducted by [29], the detailed and approximate coefficients must stay above the threshold for at least 2 cycles of power frequency for it to be determined as a High Impedance Fault. If it does, it will be deemed as a fault and the tripping sequence will be initiated.

The above logic has been summarized in this flowchart:

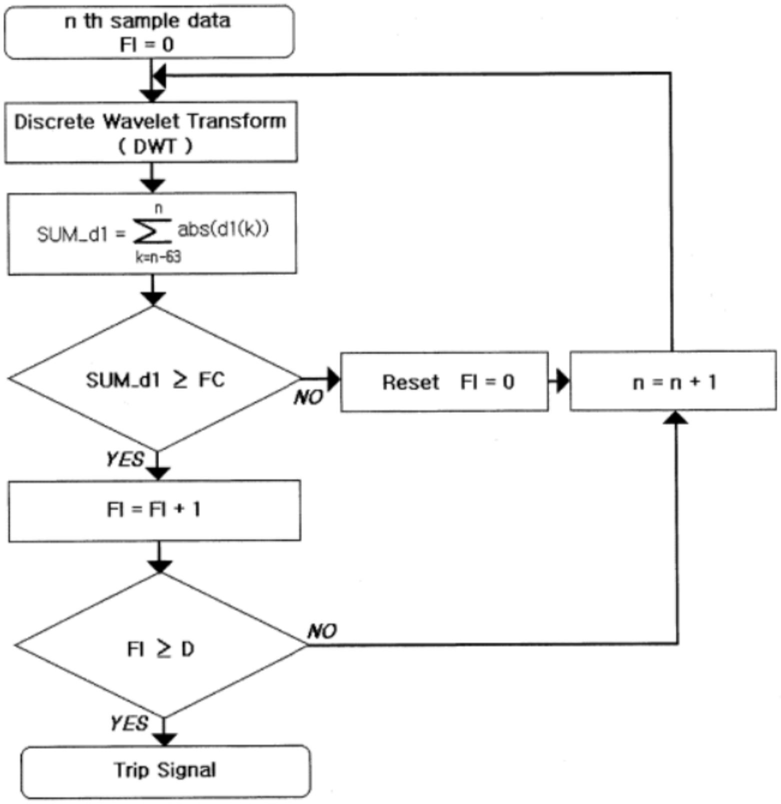


Figure 3.2: Flowchart of High Impedance Fault Detection using DWT. Source:[29]

3.3 Differences between HIF and Conductor into Vegetation Faults

The difference between a high impedance fault and conductor-into-vegetation faults lie in the nature of the vegetation surrounding the line. Conductor into Flammable Vegetation Faults occur in regions with very dry weather and surrounded by highly flammable leaves and bushes whose impedance and fault current levels are different from any generic high impedance fault.

The above detection technique has been developed for a generic high impedance faults for varying purposes. However, our purpose will be prevent power lines from inducing bushfires, and hence, will focus primarily on fault detection with an emphasis on speed. High Impedance Faults caused by lines falling on non-flammable surfaces like concrete will not be our concern, as are other kinds of HIF such as Line-Line faults.

Naturally, narrowing down the window of faults to detect comes with its own set of challenges in terms of signal characteristics that will be deemed useful and appropriate. In accordance with literature pertaining to high impedance fault classification, the magnitude thresholds will be altered. The impedance of the fault will be changed to reflect typical current levels through flammable vegetation.

3.4 Case Study - 154 kV Transmission Line

In this section, we will study the implementation of 154 kV, 60 Hz power system with two buses connected by a 26 km long transmission line. The buses are connected to a 240 MVA and a 180 MVA source respectively. This is essentially the Korean power system and is a review of the work done by [29]. High Impedance Fault is simulated in this line at varying distances and DWT technique is used for detection.

[29] uses a 3840 Hz sampling rate to obtain first order detailed coefficients, whose results are captured in Fig. 3.3. The below characteristic shows a distinct separation of Phase A from Phases B and C and thus, with a threshold magnitude = 0.085 and a time threshold of 2 cycles, which translates to a window length of 432 samples.

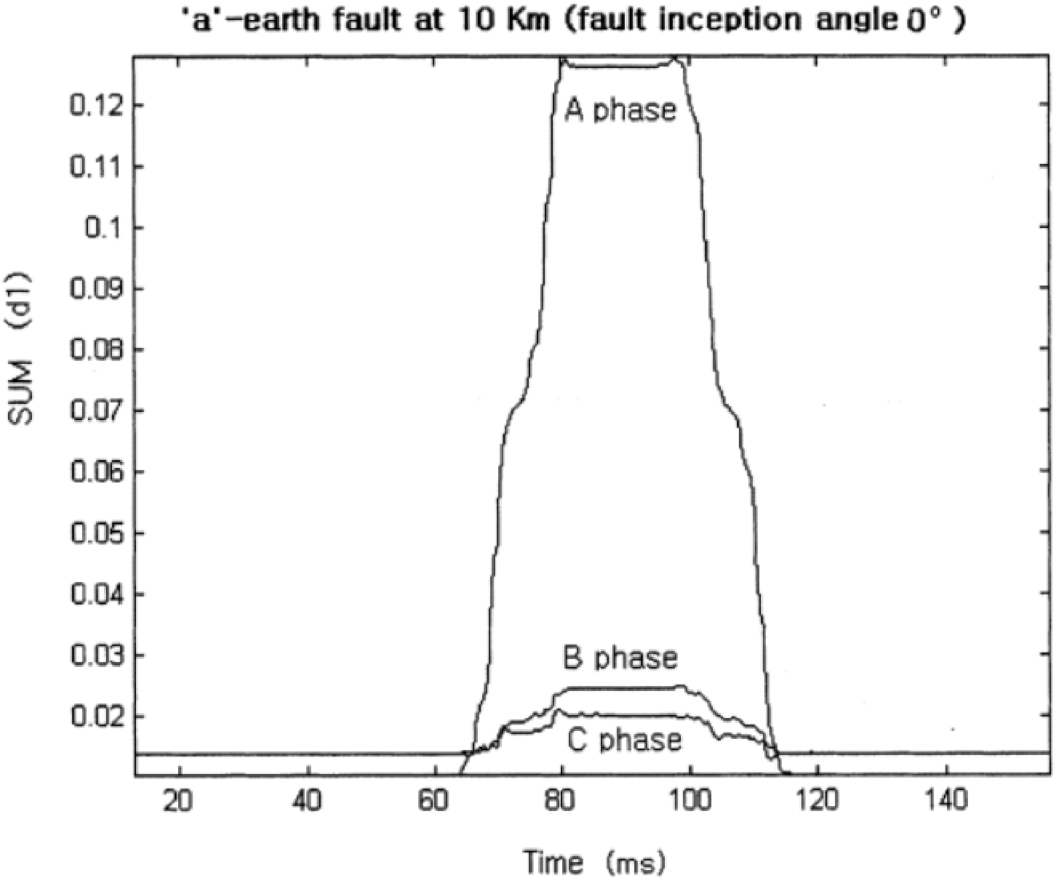


Figure 3.3: Sum of first level detailed coefficients of Fault current in a Phase A to ground fault. Source:[29]

3.5 Problem Development

Prior literature [29] [28] [39] [42] [14] has shown us that DWTs are a reliable method to tackle high impedance faults, and if tuned correctly, can detect faults into highly flammable vegetation. Since these methods have proven to be successful, it would be wise to utilize them as reliable backup protection techniques and hence, there was no attempt made to replicate results in this section.

The problem presented and addressed in this thesis, however, is slightly different. The High Impedance Fault comes into play once the fallen conductor touches the ground. There is a significant time difference between when the conductor snaps midair and when it touches the ground. We will exploit this time difference to trip the circuit before the conductor hits the ground. In such a scenario, we will be dealing with an unbalanced system with an open circuit on one of the phases that carries zero current. Therefore, our algorithm will have to be modified heavily to capture that state. This will be the focus of Chapter 4 and 5 where the problem is handled in two different ways, with Chapter 5 being a novel contribution to this field.

Chapter 4

Communication enabled Open Circuit Detection

Chapter 3 outlined the fundamentals behind high impedance fault detection and its purpose as a robust backup protection system against conductors falling into sensitive vegetation type faults.

This chapter will focuses on efforts to a falling line before it hits the ground. This implies the presence of a very momentary open circuit that lasts as long as the conductor is in the air. Due to the very short time frame in which these open circuit conditions exist, protection algorithms must work very fast to detect since the event will mutate into a high impedance fault very soon. [37] estimates that, for a system operating at typical distribution voltage levels (between 4 kV and 35 kV), the conductor may take about 1.0 seconds to fall to the ground. At the transmission level, this time is likely to be higher since the towers are taller and the conductors experience higher mechanical tension.

At power frequency, this corresponds to 60 cycles of open circuit conditions. However, the system conditions do not change continuously over the 60 cycles. The transition from pre-fault conditions to open circuit is achieved in about 2-3 cycles. After this period, the remaining cycles resemble an unbalanced steady state since the other two phases are healthy. The key will be differentiating this open circuit conditions from a healthy system imbalance. Hence, it is crucial to identify the transients and associated signal characteristics in the initial few cycles. The state of the system in the next 57 cycles would serve to validate if the system truly experienced the opening of a phase.

This avenue of protection was explored by researchers at San Diego Gas and Electric [37] for the same purpose as the thesis which is to prevent powerlines from causing wildfires. Researchers at SDG&E make use of measurements from Phasor Measurement Units (PMUs) to track deviations in voltage magnitudes and angles across buses to detect the open circuit. This monitoring system is also supported by a robust communication network. [37] explores three different methods of detecting open circuit using voltage phasor measurements. The first technique involves observing either the zero or the negative sequence voltage of the system to see if they rise above a certain threshold and exhibit a noticeable pattern. The voltage rise is sharper away from the source and is less pronounced closer to the source. The second technique involves observing the rate of change of voltage. This parameter has opposing polarities on either side of the break. The third technique observes deviations in the angle of zero and/or negative sequence voltage.

This chapter will attempt to replicate the results of [37] for a 2 bus system connected by a transmission line, which will then be extended onto an IEEE benchmark, viz, the IEEE 9 bus system. Prior to simulating these case studies, basic theory on an open circuit system will be discussed.

4.1 The Open Circuit Scenario

One of the most defining characteristics of an open circuit is the lack of current flow in the line. However, measuring zero current is unrealistic and leaves little room for error margins. The significant aspect, however, is the presence of the zero-sequence component (voltage and current). Another noticeable metric is the voltage phasors on both ends of the broken line: the node that is closer to source experiences a rise and the node further away experiences a drop. These deviating phasors can be exploited to observe open circuits.

Another interesting feature of open lines are the travelling waves that run back and forth between the broken end of the line and the taut end. These travelling waves are of high frequency content and are useful in detecting the location of the fault. [33] discusses a novel algorithm using wavelet analysis to detect and locate faults. This will be discussed further in Chapter 5 where a confluence of wavelet analysis techniques and open circuit detection techniques are employed.

Another key metric that shows an interesting pattern is the zero sequence power flow in the lines. [31] conducts a mathematical study of the zero sequence power, direction of zero sequence currents and shifting of the neutral point on grounded and ungrounded systems under open circuit conditions. [31] concludes that the zero-sequence current and power are numerical factors of the nominal load current and power in the system. The factors depend on the positive, negative and zero sequence impedance of the transmission lines. For typical ratios of these parameters in transmission lines, the total positive sequence real and reactive power in the system can drop to about 60% of the nominal load, which has been verified using EMTDC simulations.

From [31] , the zero sequence current of the system with a single open line (Phase A) and two healthy phases (B and C) can be written as:

$$I_0 = \frac{-I_{LA}\sum X_1}{\sum X_1 + 2\sum X_0} \tag{4.1}$$

Where I_{LA} is the load current through Phase A with the assumption that $\sum X_1 = \sum X_2$ which is reasonable in transmission lines.

The zero sequence voltage phasors across the line with sending end S connected to bus M and receiving end R connected to bus N is shown in Fig. 4.1

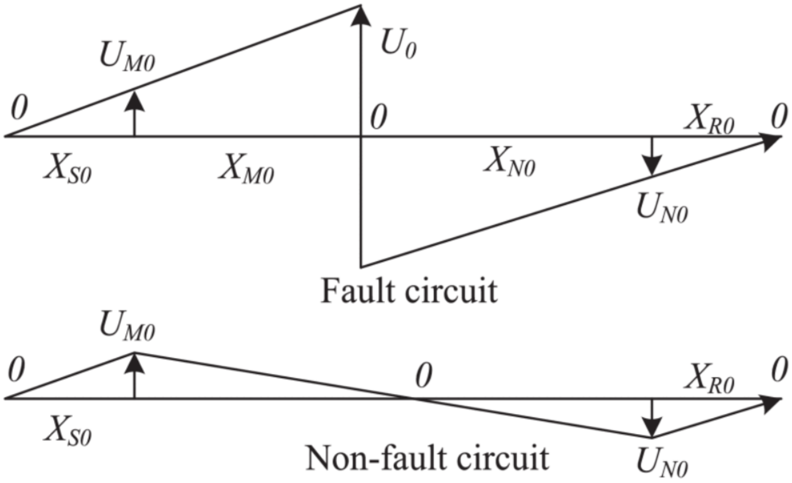


Figure 4.1: Phasor Diagram of Zero Sequence Voltages. Source:[31]

This phasor diagram clearly establishes the trend of deviating zero sequence voltage across both ends of a broken line. Although [37] does not explicitly discuss the above theory, it is utilized to detect open lines. [31] focuses more on the theoretical aspect behind such events, and provides a protection algorithm to detect them, it assumes the open circuit to long for an indefinitely long period of time, which is not true in our case. Consequently, [31] does not discuss the speed of protection which is very critical in our analysis.

Combining the theory proposed in [31] and the methods used in [37] on the standard IEEE 9 bus system will be a major focal point in this chapter. It is important to note that the zero-sequence voltage (or any zero-sequence component) is virtually absent in Line-Line faults. Therefore, employing this technique will ensure security of the protection algorithm.

4.2 The Two Bus System

To explore the characteristics of an open circuit line, a two-bus system connected by a transmission line with distributed loads was simulated on PSCAD. The system operates at 12 kV, 47 MVA at 60 Hz connected by a 42 km long transmission line with two distributed loads of 12.4 MVA and 30 MVA. The single-phase open circuit is simulated using a circuit breaker located at 10 km from the sending end S. Multimeters are located at the sending and receiving end buses. Additionally, meters are placed at the point of a load tapping just for observational purposes of this study. In a real system, a PMU in the middle of a transmission line may or may not be placed depending on if the line contains a regulator or a recloser. Therefore, this system can also be considered as a 3 bus radial system where the PMU corresponding to the middle location can be assumed to be connected to a fictitious bus from where a feeder is tapped or a spot load is present. The purpose of this section is to validate and verify the logic proposed in [37] and [31] .

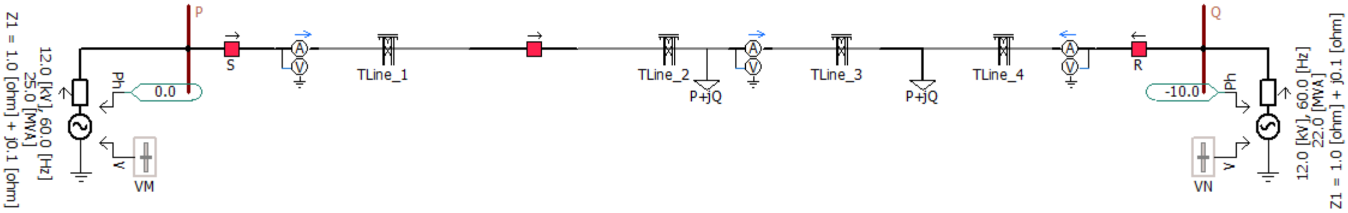


Figure 4.2: Two Bus System Implemented in PSCAD

This system has been simulated for an open circuit at Phase A at 0.5 seconds and lasts for 1 second.

4.2.1 Initial Results

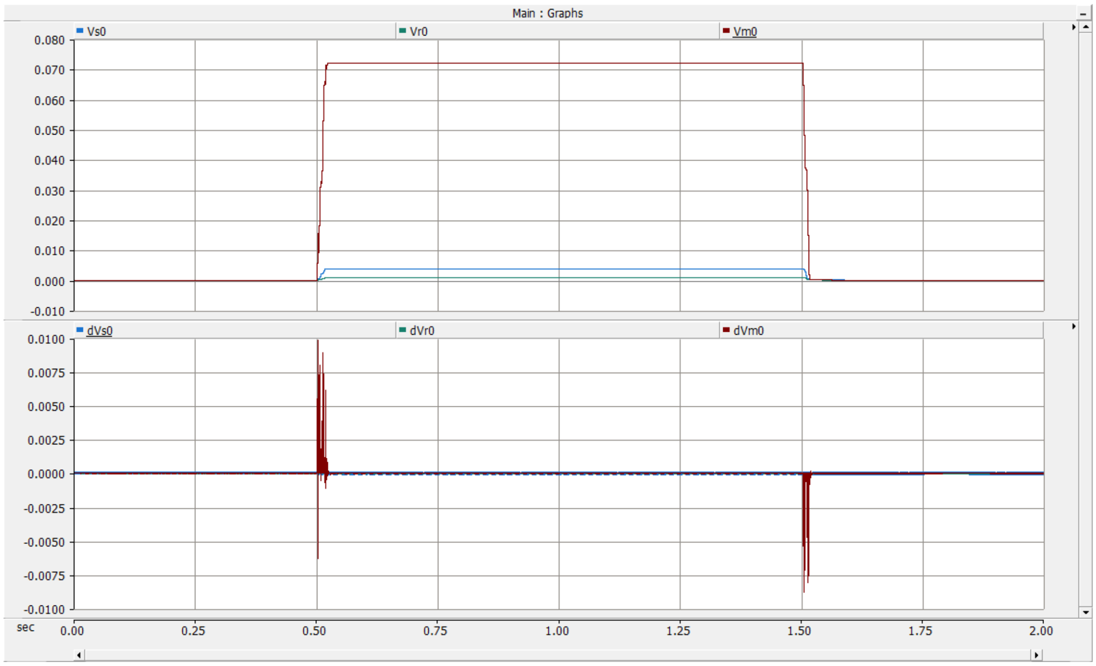


Figure 4.3: Zero Sequence Voltages and ROCOV measured by meters

The initial observation shows a marked deviation of the zero-sequence voltage magnitude of the midpoint during the open circuit as compared to the sending and receiving end buses. A major reason is that the sending end and receiving end buses have a controlled, grounded voltage source. Hence, the bus voltages are nearly in line with the substation voltage. However, the zero sequence quantities of these buses clearly show a rise in magnitude in comparison to their operation during a healthy state, i.e., they are definitively non-zero.

This is a big reason for the need of another multimeter at the midpoint. The protection algorithm will not involve the measurements from the fictitious bus "M", but its worth noticing the change in zero sequence voltage along the line for an analytical discussion. Observing the rate of change of zero sequence voltage, again, bus M shows the highest magnitudes. Bus M is also the closest to the open circuit, hence the massive spike.

It must be noted that the direction of power (and zero sequence power) plays a big role in determining the magnitudes of rate of change of voltage. It is observed that the receiving end of the resultant power flow experiences a bigger surge than the sending end. In this context, due to M being on the receiving side with respect to the open circuit fault, records the surge.

Further conclusions on this will be drawn by simulation on an extended radial system with around 5 buses.

4.2.2 The Five Bus System

The five-bus system is not an IEEE benchmark, but is merely an extension of the two-bus system into having longer lines, more loads and stretch out the radiality. The primary intention with the five-bus system to observe the changes in zero sequence quantities without the influence of the voltage source that tries to hold the system at nominal levels.

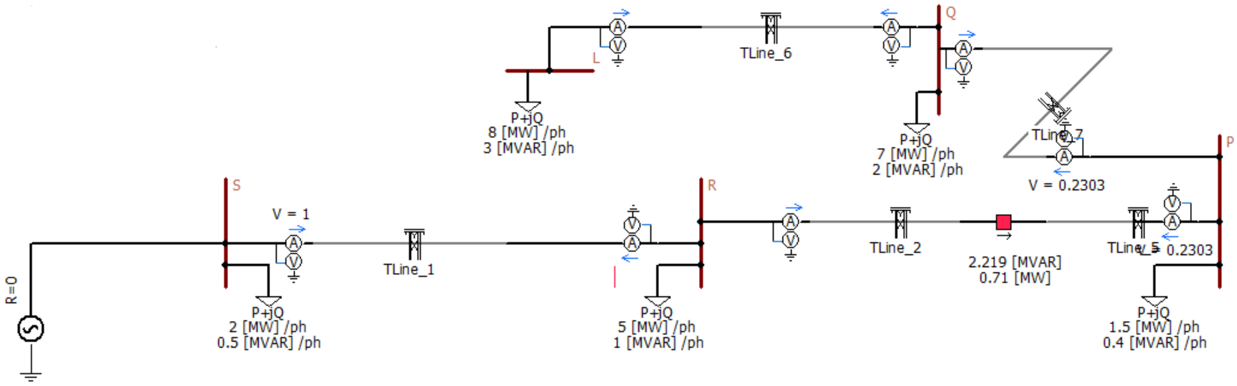


Figure 4.4: Five Bus System with Open Circuit between Buses R and P

When the open circuit is simulated between buses R and P, we observe the following zero sequence voltage magnitudes:

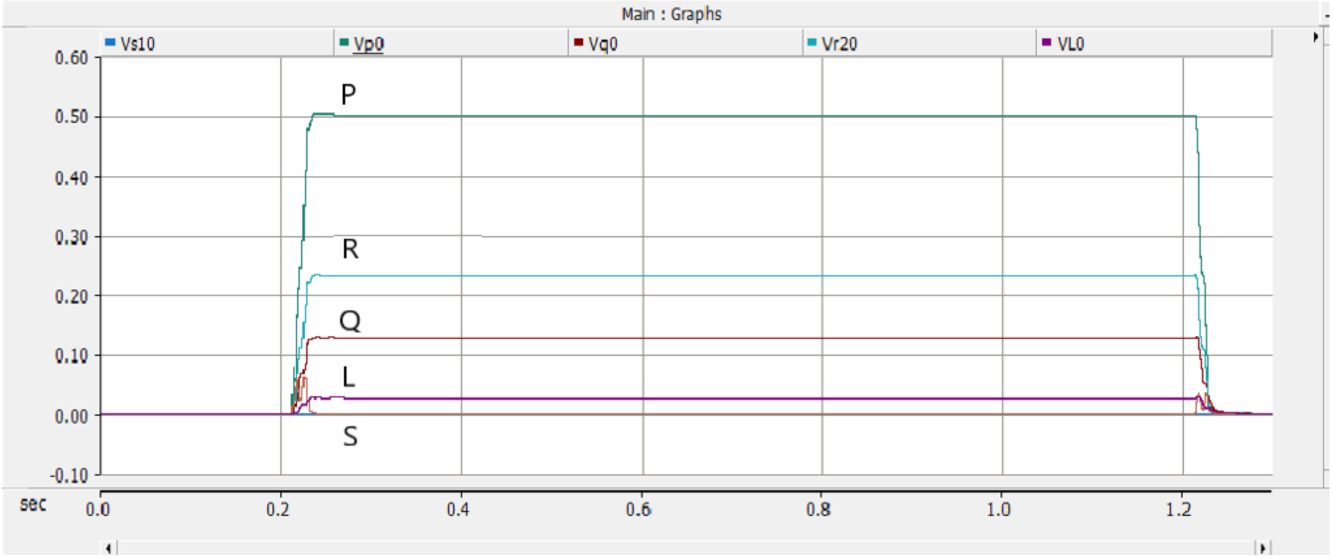


Figure 4.5: Zero Sequence Voltages across the five buses in pu.

Here, we can see rather clearly that buses P and R report the highest magnitude of zero sequence voltages. Bus R shows a lower magnitude than P because P is at the receiving end of the power flow in the system. This is evident in [37] where it was established that the zero sequence magnitude change is steeper when the bus is further away from the source. Buses Q and L are even further away, but they do not show a significant rise in magnitude. This proves that the theory works on the simulation – the open circuit characteristics have the maximum impact on the buses connected to either end of the lines.

Therefore, the protection algorithm's first task will be to identify the two buses which show the highest zero sequence voltage magnitude. Then, this will be cross-checked with the rate of change of zero sequence voltage to see if either of the identified two buses show the highest spike. If they do, then it can be concluded that the open circuit fault is most likely between the two buses.

Following this, the zero-sequence voltage magnitude on the two buses will be monitored to see if they remain above the threshold for at least two cycles. If they do, a trip is initiated on both ends of the line.

This gets trickier if the open line is between the substation (Bus S) and the adjacent bus (R). Therefore, if the bus with the highest value of zero sequence voltage happens to be bus R, then we can conclude that the fault lies between R and substation. This can be drawn from the fact that the receiving end bus shows the highest magnitude deviations and every other bus, no matter the distance from source, will show a progressively decreasing magnitude of zero sequence voltage.

4.3 Implementation on the IEEE 9 Bus System

The IEEE 9 bus benchmark, described by [10], is a simple approximation of the Western Electricity Coordinating Council into an equivalent system with 9 buses, 3 generators connected by 6 lines. This model, due to the nature of its approximation, has a small length for its transmission lines with a very high bus impedance matrix per unit mile. [2] documents PSCAD's official modelling of the 9-bus system where the line lengths are as small as 1m. For this study, the line lengths have been increased to 10km while keeping the total line impedance constant by scaling down the bus impedance matrix by a factor of 10,000. The 9-bus system has been picked because it is the simplest available benchmark that is well balanced. Other benchmarks such as the 13 bus system have a high degree of inherent imbalance with many single or double phase lines, which makes computation of zero sequence quantities hard. The system is also too radial to the point that any attempt at clearing the open circuit will result in islanding a large part of the feeder. Other distribution models such as the 34 bus system are vastly complicated and difficult to implement. The below diagram shows the 9-bus system with an open circuit simulated at 5km from Bus 4 on the line connecting Buses 4 and 6. The model has 6 PMUs that measure the line voltages and currents across the 6 lines that form a loop around Buses 3-9, which operate at 230 kV.

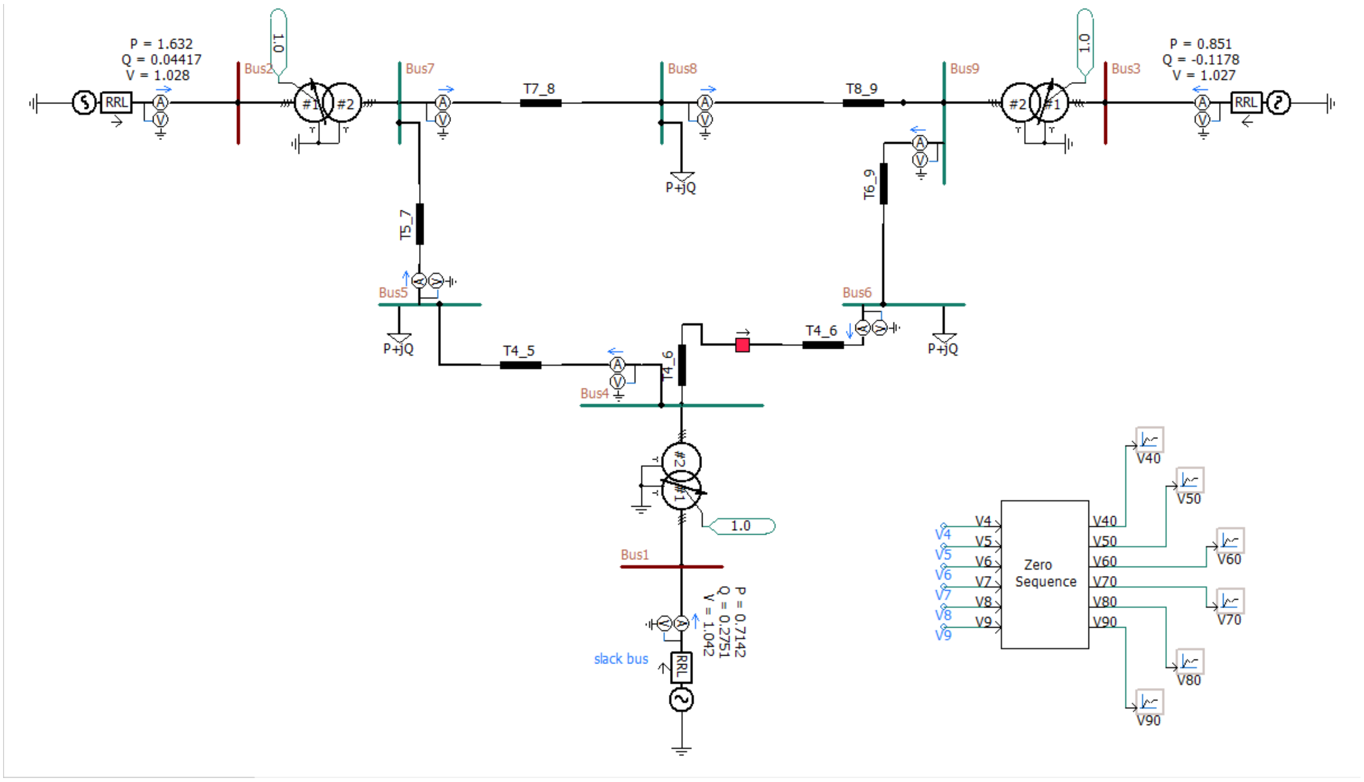


Figure 4.6: IEEE 9 Bus system implementation on PSCAD

4.3.1 Results

Upon simulation of the system under described conditions, we observe the following patterns in zero sequence voltages:

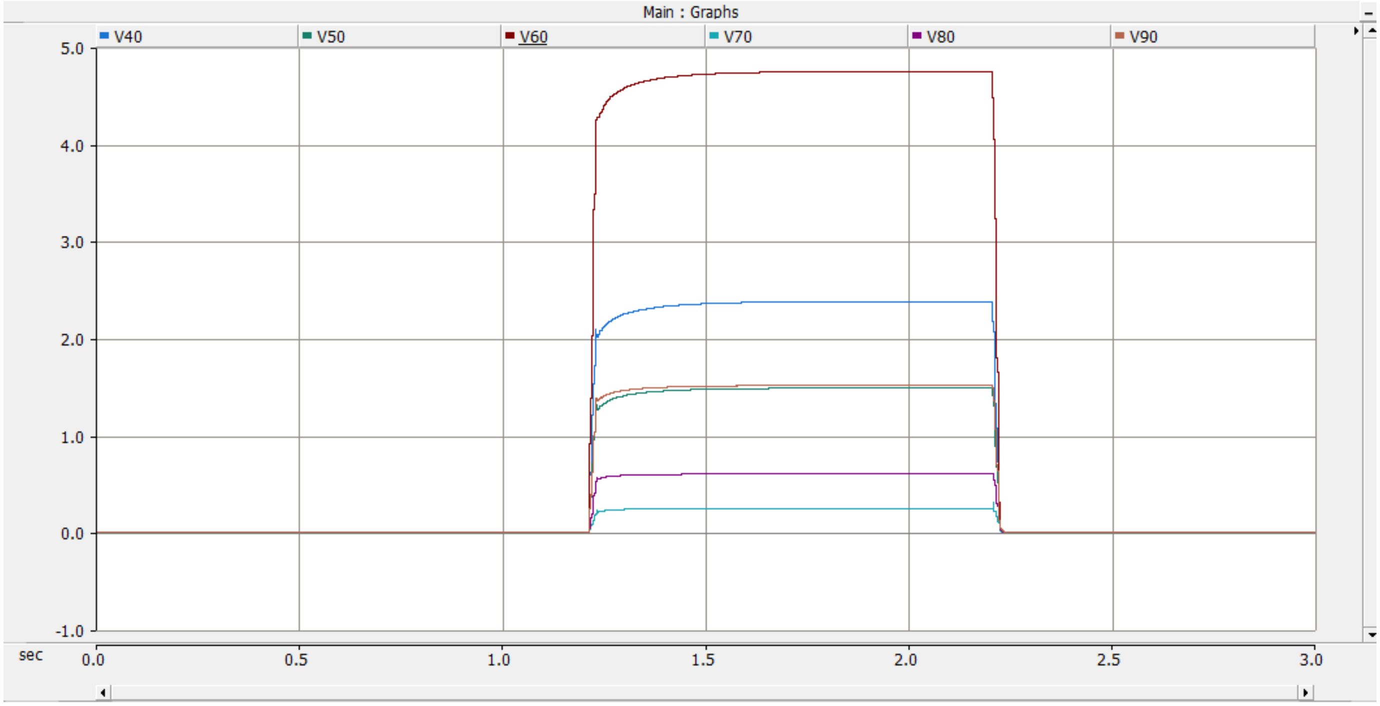


Figure 4.7: Zero Sequence Voltage Magnitudes across Buses 4-9

The curves show once again that the buses that face the maximum change in zero sequence voltages are the ones that lie on either on of the open circuit, viz, buses 6 and 4. It is also observed that Bus 6 has a higher magnitude than Bus 4 because it is on the receiving end of the power flow through the line connecting them. This can be deduced from the results of the Load Flow Analysis, whose graphics are displayed alongside in Fig 4.7.

From the above and below curves, we can see that the bus that shows the highest spike in ROCOV is Bus 6, followed by 4. This is consistent in our findings with the previous section. The results are also consistent for all locations of the open circuit fault across the system – the only difference is the actual magnitude of the zero sequence voltages, which depend on the nominal line currents and impedances described in section 4.2. Therefore, protection settings must take this variation into account while setting thresholds.

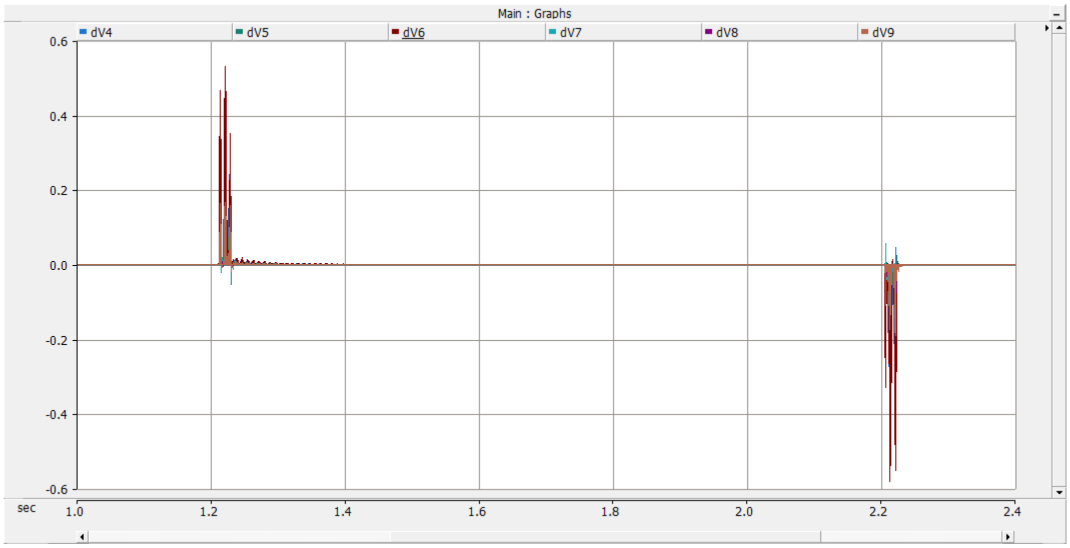


Figure 4.8: Rate of Change of Zero Sequence Voltage Magnitudes across Buses 4-9

4.3.2 Detection and Tripping

Based on the earlier results, we can now strengthen the logic proposed in Section 4.3.2. The absolute value of rate of change of voltage curve is examined first and smoothed using a moving average filter of window size equal to one cycle. If the curve is non-zero for at least one bus throughout one cycle, we can say that there is a transition in the state of the system.

Then, that shows the highest peak in this time frame is identified. This bus is most likely to have either the first or the second highest magnitude of zero sequence voltage. If this happens to be true, we can be more certain about the event. Following the validity of this condition, the zero sequence magnitude of the buses showing the two highest voltages are tracked, and if they remain above the threshold for at least two cycles, then we can issue a trip signal.

4.4 Limitations

One of the biggest limitations with an approach like this is the need for a strong communication network with minimal delays and information loss. We have assumed that we have access to all PMU data which is processed centrally to determine the buses that show the maximum deviation. This also comes with meeting other basic PMU standards including the need for a synchronization in time-tagging across all devices.

The functionality of a precise metering with time tagged data is realized through a multimeter, which cannot measure the actual phase angle. Multimeters in PSCAD only compute the phase angle difference between voltage and current phasors. Additionally, modelling the communication network in PSCAD is not possible. This technique also does not fully exploit the high frequency content associated with the transition to open circuit. If the settings are improper, it will become difficult to differentiate an unbalanced load switching from an open circuit.

The high frequency content is also not very pronounced in the current IEEE 9 bus model due to the nature of its transmission lines that are modelled in PSCAD. The entry of bus impedance matrix directly onto PSCAD's transmission line interface creates a Bergeron model, which works well for short circuit and load flow studies. For transient and dynamic studies, the Frequency Dependent (Phase) Model works best, but that requires the geometry of the conductors and towers.

These problems are mostly resolved in Chapter 5 where this discussion is combined with Discrete Wavelet Transform to improve the reliability of detection.

Chapter 5

Local Detection of Falling Conductors

5.1 Introduction

Chapter 4 outlined the theory behind the open circuit problem, with special emphasis to the behavior of zero sequence voltages. The protection strategy discussed in Chapter 4 involves a robust communication network since it requires measurements from all buses at one central location in order to determine the buses with the highest swings in zero sequence voltage magnitude.

In this chapter, the focus will be on detecting the open circuits without the need for a centralized communication support. Therefore, the detection will be based on local measurements and local settings. Communication maybe added to enhance security through the means of permissive transfer tripping. The technological requirements for achieving that are minimal, when compared to the requirement of PMUs and PDCs.

During an open circuit, there are high frequency travelling waves of voltage and current between the broken end and the bus. The frequency of these waves depends on the characteristic impedance of the line, which is usually much higher than power frequency. Therefore, there is a lot of high frequency content during an open line.

An important distinction must be made with respect to the presence of high frequency content vs the presence of zero sequence components. The zero sequence is present whenever there is an imbalance in the system, either due to pre-existing load conditions or due to a fault. It is not present when the line is completely open, i.e., all 3 phases are open. The high frequency travelling waves are present whenever one end of a line is open, and the other end is tied to a bus at a certain voltage. Therefore, they are not necessarily present whenever there is an imbalance, and they are also absent when both ends of the line have been opened by a circuit breaker.

Secondly, the high frequency content present during a High Impedance Arcing Fault is different from travelling waves. In that case, the high frequency is due to the presence of an arc between line and ground. Therefore, the frequencies lie in different bands.

In the case of conductor into vegetation faults, we assume one of the three phases to be broken and is falling to the ground. Therefore, this event contains both zero sequence voltage and high frequency components. Extracting them would prove to be beneficial in fault detection.

Hence, in this technique, the Discrete Wavelet Transform will be used on the Zero Sequence Voltage computed across buses. Based on the exact signal characteristics, a combination of previously discussed techniques will be employed to clear the fault.

The initial study will focus on the two-bus system, which will then be subject to some modifications before we move on to testing it on the IEEE 9 Bus system.

5.2 The Two Bus System

An open circuit fault on Phase A is simulated on a balanced 60 Hz, 22 kV, 750 kW 150 kVAR system with two buses S and R (sending end and receiving end respectively). The buses are connected by a 100 km long line, with the open circuit occurring at 80 km from the sending end. The fault is simulated to last for one second (between 0.51s and 1.51s). Meters are present at both buses to record instantaneous voltage, which will then be processed to calculate the zero-sequence voltage and subsequently, the detailed coefficients of the Discrete Wavelet Transform.

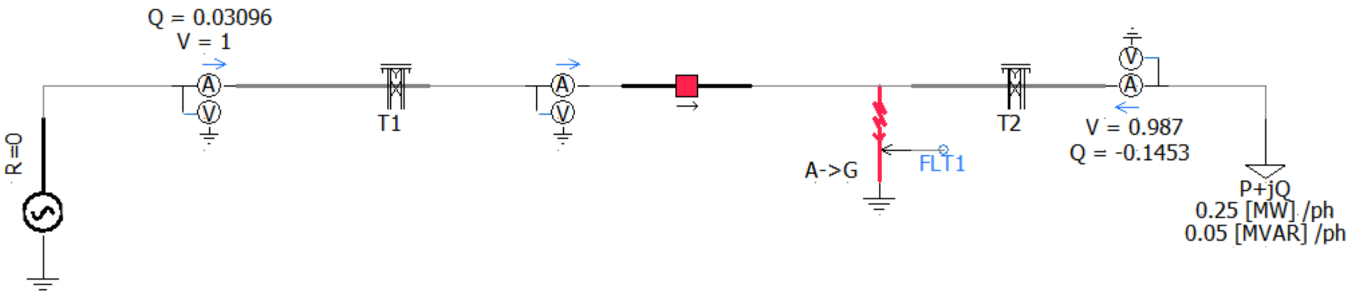


Figure 5.1: PSCAD Implementation of Two Bus system with open circuit & high impedance fault on Phase A

5.2.1 Discrete Wavelet Transform Settings

As discussed in Chapter 3, the choice of mother wavelet, initial sampling frequency and the level of filtering make a huge difference in the performance of the DWT in extracting the most useful features of the signal. [14] employs a 10 kHz sampling rate for a 50 Hz system with db4 as the mother wavelet to extract the 6th detailed coefficient for High Impedance Faults. In this case, for a 60 Hz system, a sampling rate of 12.96 kHz has been used.

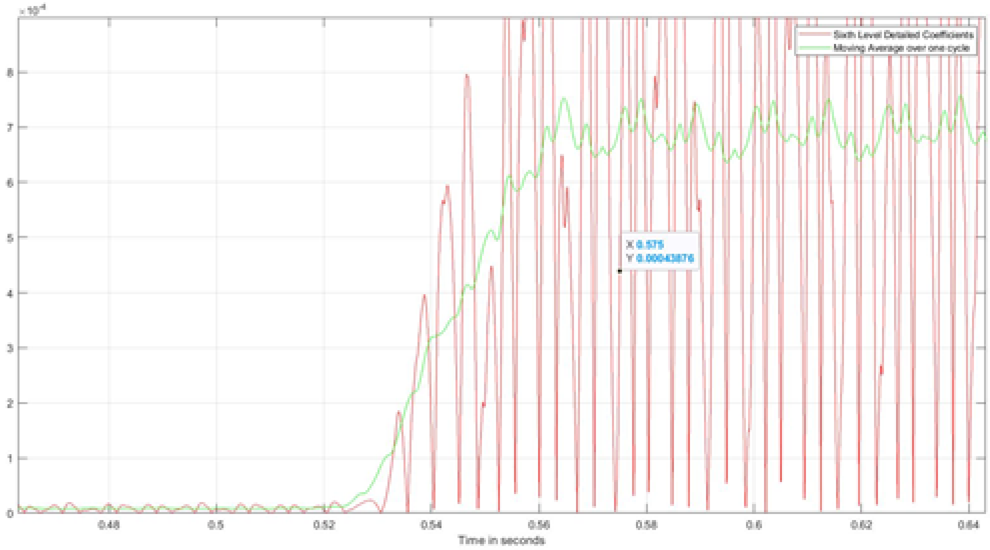


Figure 5.2: 6th Level Detailed Coefficients of Zero-Sequence Voltages and its moving average over one cycle of power frequency.

Fig 5.2 shows a clean transition from a healthy state to an unbalanced state of the system around 0.52s. The moving average filter is essentially the average of the coefficients where the width of the window is equal to number of samples per cycle (64 in this case) and the window moves by 1 sample with every iteration. This results in a curve with reduced noise and outliers, aside from being directly useful for further computation. We see that the coefficients are of extremely low magnitude, but the two states are clearly discernible.

However, 12.96 kHz is an exceedingly high sampling rate that may not be possible to achieve in local detection and measurement system, especially if the lines connect geographically remote areas. [29] uses 3840 Hz for observing first order detailed coefficients. We shall use 4000 Hz for the 4th order detailed coefficients.

Additionally, the time-threshold has been set to 3 cycles. This is due to spikes in the DWT waveform that tends to last just less than a cycle prior to stabilization. To prevent false tripping, this threshold has been extended.

5.2.2 Unbalanced Two Bus System

The system in Fig 5.1 was modified to introduce an imbalance by virtue of doubling the load on Phase A. In traditional over-current relays, the trip settings are placed in between double the load and one-third of the minimum fault current, and hence, this protection mechanism must also be resilient against double the load.

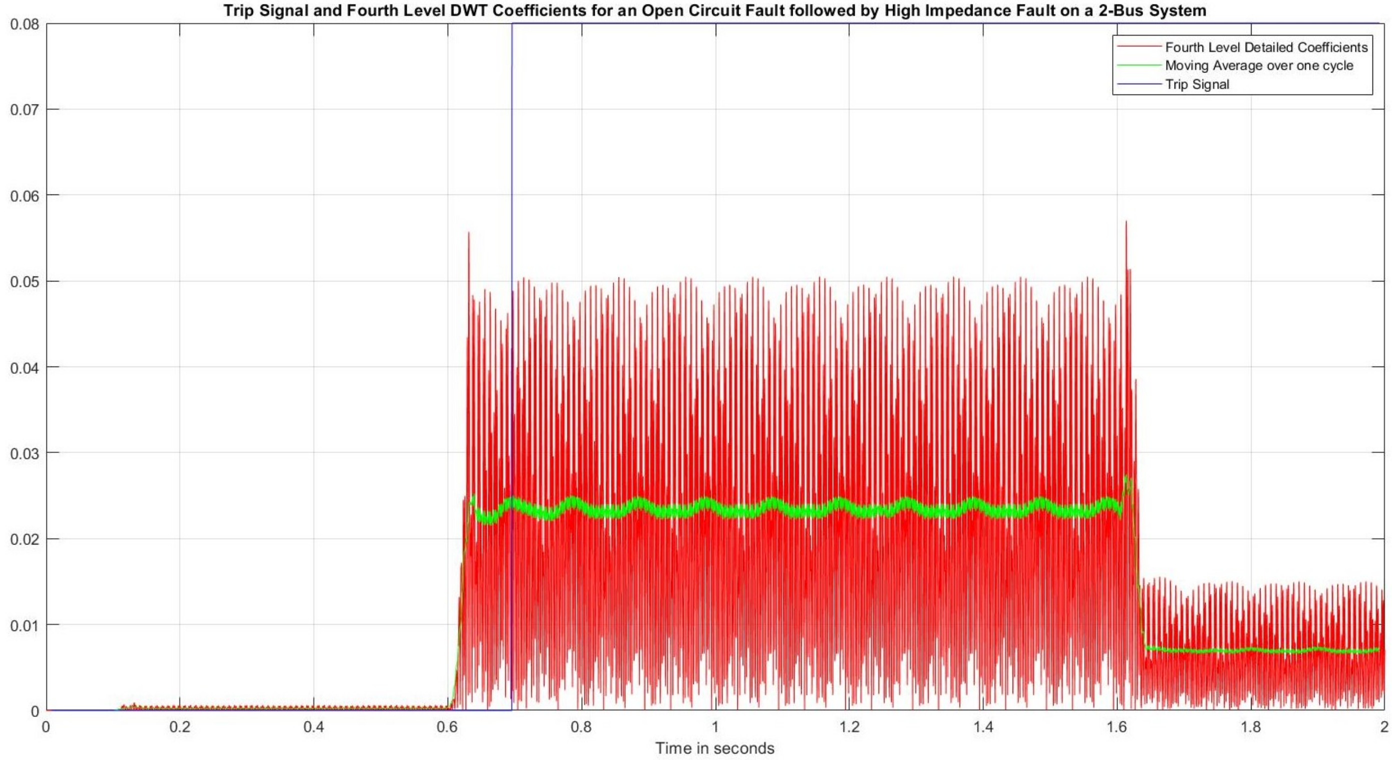


Figure 5.3: Trip Signal issued for an unbalanced system by analyzing the d4 coefficients.

From the above figure, it is seen that a trip signal is generated about 100 milliseconds after an open circuit begins to develop on Phase A. The fourth order coefficients have varying magnitude and sign but smoothening them out using a moving average filter on the absolute values provide a rather robust parameter to detect.

It can be seen that the magnitude of these coefficients drops to a lower value once the system moves on from a state of Open Circuit to a state of High Impedance Fault. The change in magnitude is also accompanied by a lower degree of periodicity. Both factors indicate that the DWT filters have been tuned to detect the open circuit more effectively than the HIF.

A noticeable characteristic of these signals during the open circuit state is that it is periodic, and it builds an envelope. An envelope detector can be used to characterize this section. Manual observation of this envelope suggests that there is a superposition of two phase-shifted envelopes of the same frequency.

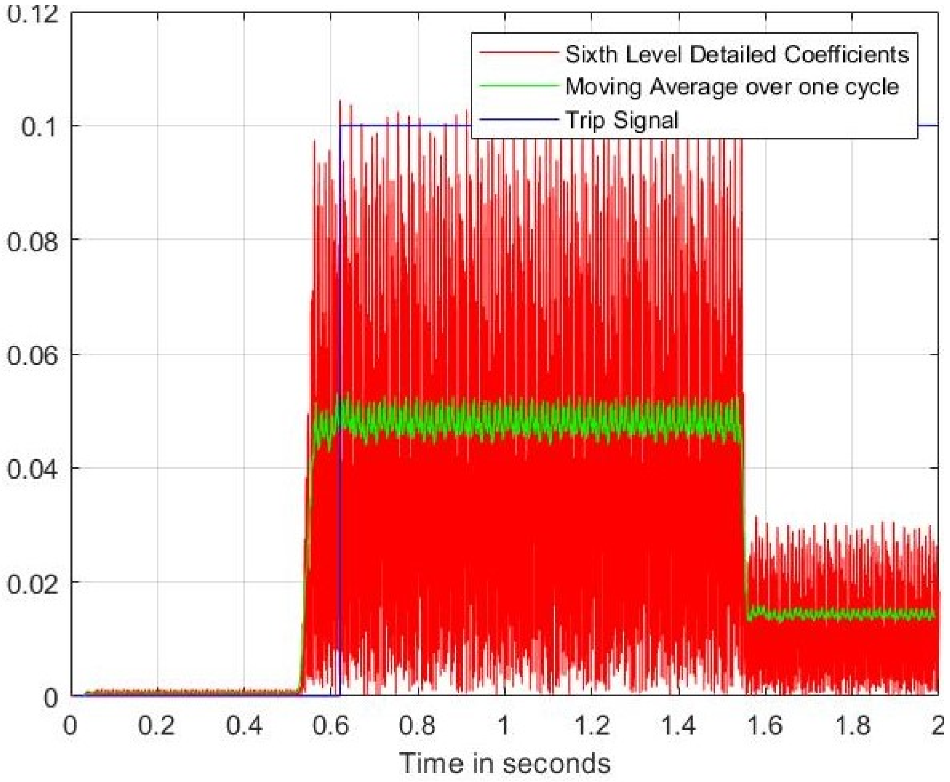


Figure 5.4: Trip Signal and moving average d6 coefficients of a 2-bus system with open circuit and high impedance fault on Phase A at 12.96 kHz .

The same procedure was repeated at a higher frequency, i.e., 12.96 kHz and using the 6th order detailed coefficients instead. The envelopes appear to be at a higher frequency. It is possible that, due to the nature of wavelet transforms, that certain frequency components are completely captured at this stage for the case of 4 kHz as sampling frequency as opposed to 12.96 kHz.

From the perspective of a practical implementation, a lower sampling frequency such as 4 kHz is more achievable and requires less memory for storing these coefficients and subsequent computation of the moving average. Therefore, the envelopes are not a significant factor in decision making from a protection standpoint.

Fine-tuning the filter to obtain the most decisive set of characteristics, followed by effective manipulations of the envelope detection require more work and is out of scope for this thesis. This opens possibilities of a future extension.

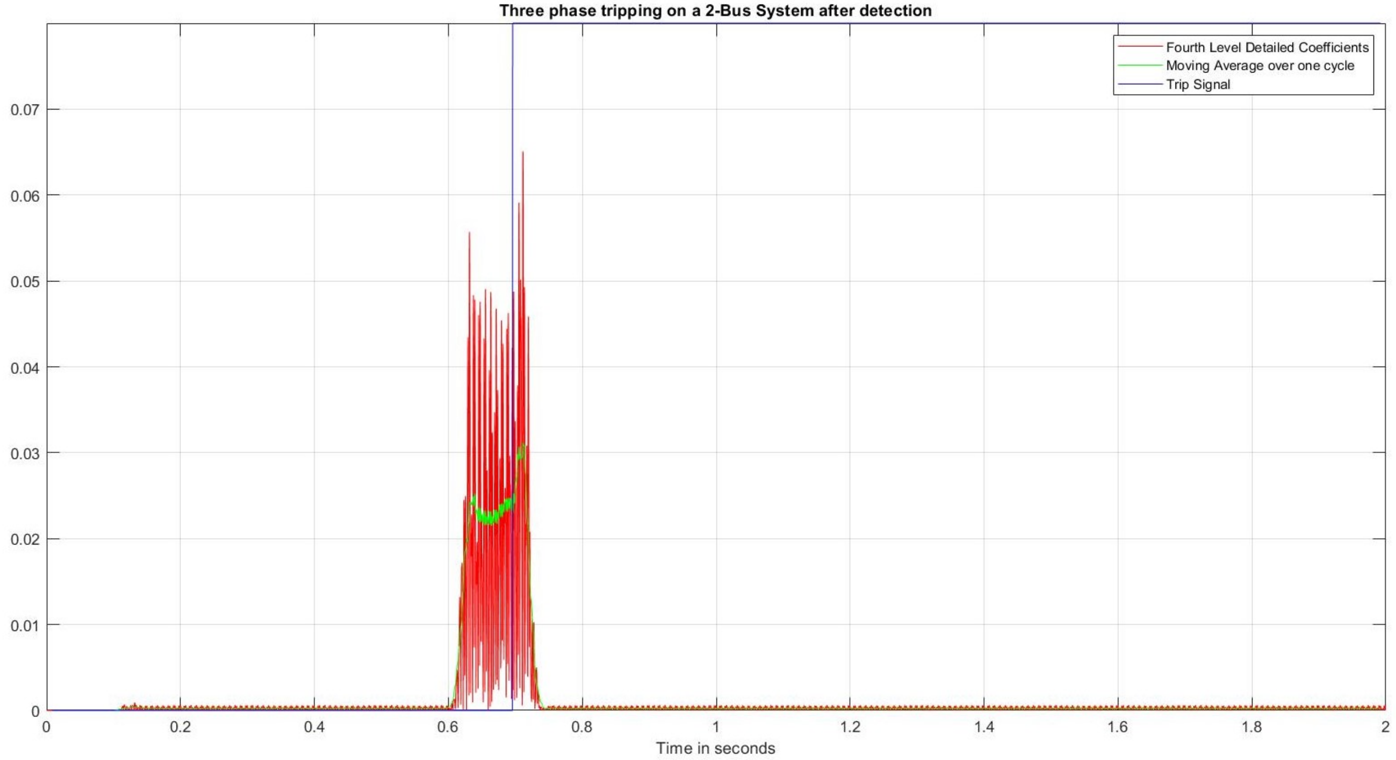


Figure 5.5: d4 coefficients after trip signal clears the open circuit fault.

The above result considers a two-fold load imbalance. The system performance is also not affected by sudden load switching, i.e., if suddenly the load were to be switched onto the circuit at 0.3s, the algorithm will not generate a false trip. This is because the magnitude of d4 coefficients during a load switching event are lower than the predetermined threshold. Intuitively, this can be explained with the fact that a load imbalance introduces zero sequence component, but not any high frequency components.

In the subsequent section, we shall see the implementation of this logic onto the IEEE 9 bus system.

5.3 The IEEE 9 Bus System

The IEEE 9 Bus system (modelled as an approximation of the WSCC power system) is used again to validate the above discussed protection algorithm. The system's transmission lines in PSCAD have been modified in a similar way to Section 4.4. An open circuit in Phase A is simulated between two buses at 1s after start time and lasts for 1s. A custom module is defined in order to process zero sequence components and subsequently extract the 4th order detailed coefficients corresponding to a sampling frequency of 4000 Hz.

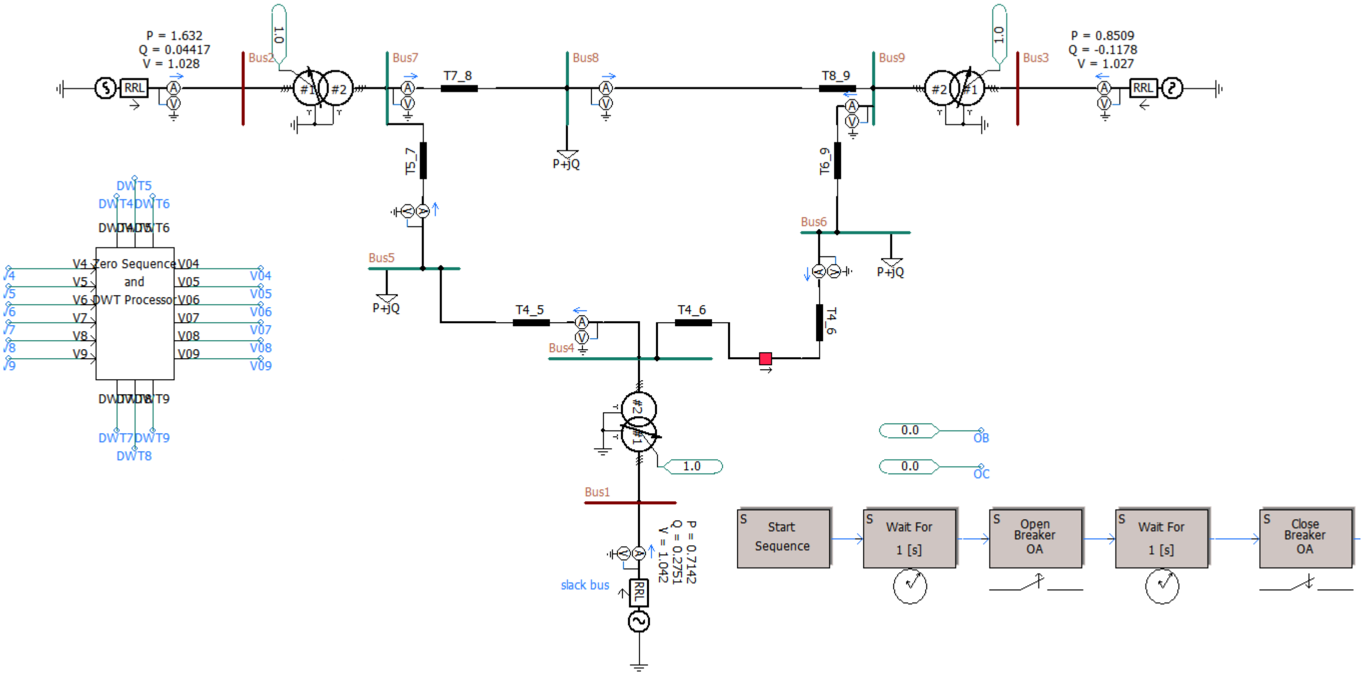


Figure 5.6: PSCAD Implementation of 9-Bus system with custom designed DWT processing module.

5.3.1 Initial Results

Before outlining the protection strategy and settings, it is important to notice the efficacy of this technique by observing the numerical values of the d4 coefficients. To enable this, the open circuit fault has been simulated in all possible lines to observe zero sequence voltages and their 4th order detailed coefficients.

After recording the fault signatures for all cases, the coefficients have been smoothed out using a moving average filter which is scaled by a factor equal to the number of samples per cycle. Hence, the resulting curves are essentially the sum of d4 coefficients over one cycle.

The first impression is that Bus 5 and Bus 7 show the highest coefficients compared to other buses. Hence, theoretically, it follows the logic proposed in Chapter 4. However, because the aim is to identify faults without communication, it is essential to devise settings that do not rely on any comparisons.

In simpler words, it does not technically matter if Bus 5 or Bus 7 have the highest d4 coefficients. As long as these buses display a different behavior when they are healthy and as long as their signatures are just distinct enough from those observed at other buses, it will be possible to detect and trip the fault.

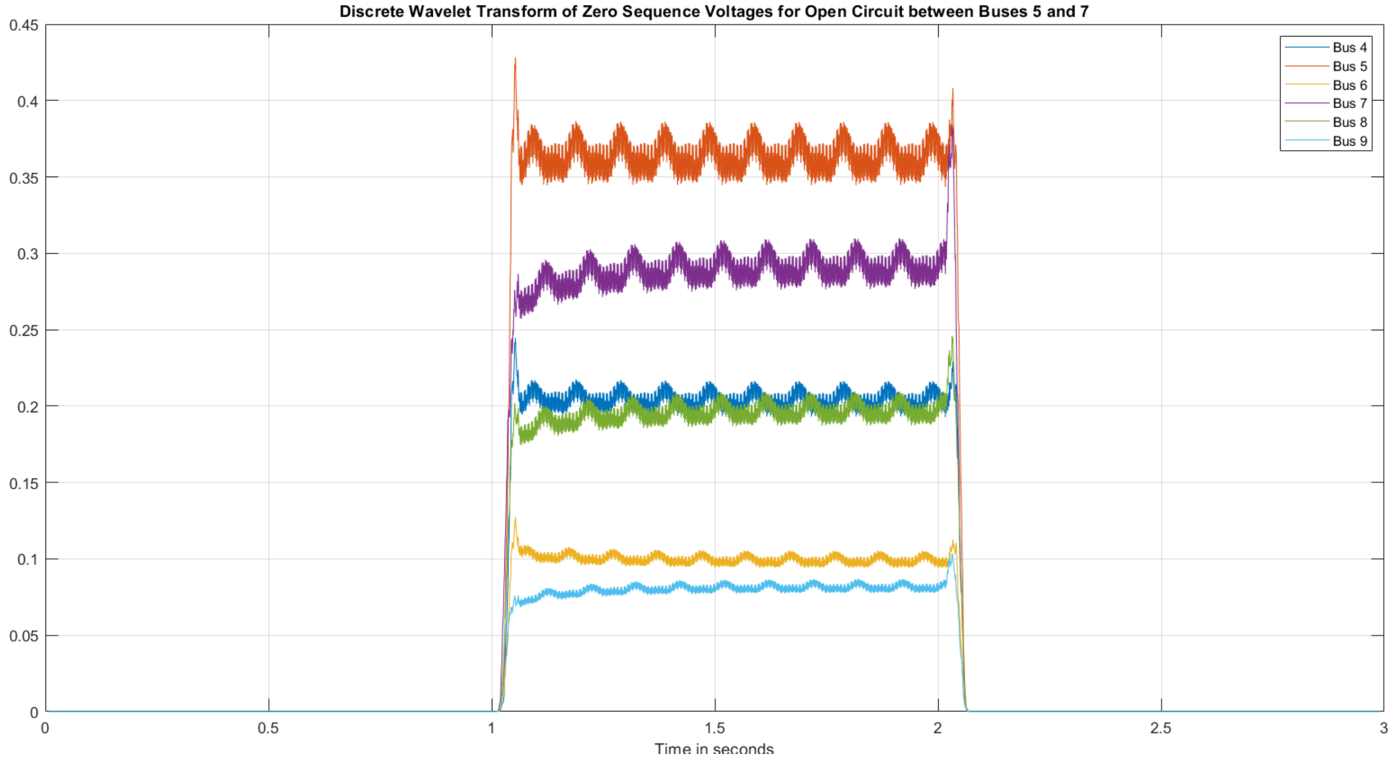


Figure 5.7: Sum of d4 coefficients of zero sequence voltages across all buses for an open circuit between buses 5 and 7.

The second observation is the presence of massive spikes for all buses immediately following the opening of a circuit, which last for less than a cycle. Without any averaging filter, these spikes would be higher. Therefore, to prevent these spikes from falsely tripping, the sample threshold should be long enough such that they do not affect the decision making. For this analysis, a length of 3 cycles have been chosen.

5.3.2 Trip Settings

The trip settings of the protection algorithm outline the various magnitude thresholds for various buses and scenarios. The prime feature of the trip settings of this setup is the need for multiple thresholds.

The meters installed at every bus measure the voltage at that bus. Based on just the voltage characteristics, it would be hard to identify the exact line that has experienced an open circuit. Due to lack of communication, buses cannot issue any signals to the neighboring buses to identify the correct line to trip.

Therefore, each bus will have two trip thresholds – a lower threshold value (T_{low}) and an upper threshold value (T_{high}). These thresholds correspond to the d4 coefficients evaluated at that bus when either of the two lines connected to that bus breaks.

Designing a two-fold threshold setting allows the bus to decide which line to trip. For example, if Bus 7 exceeds the lower threshold, it can trip Line 5-7. If it exceeds the higher threshold, it can trip Line 7-8 and prevent tripping of 5-7.

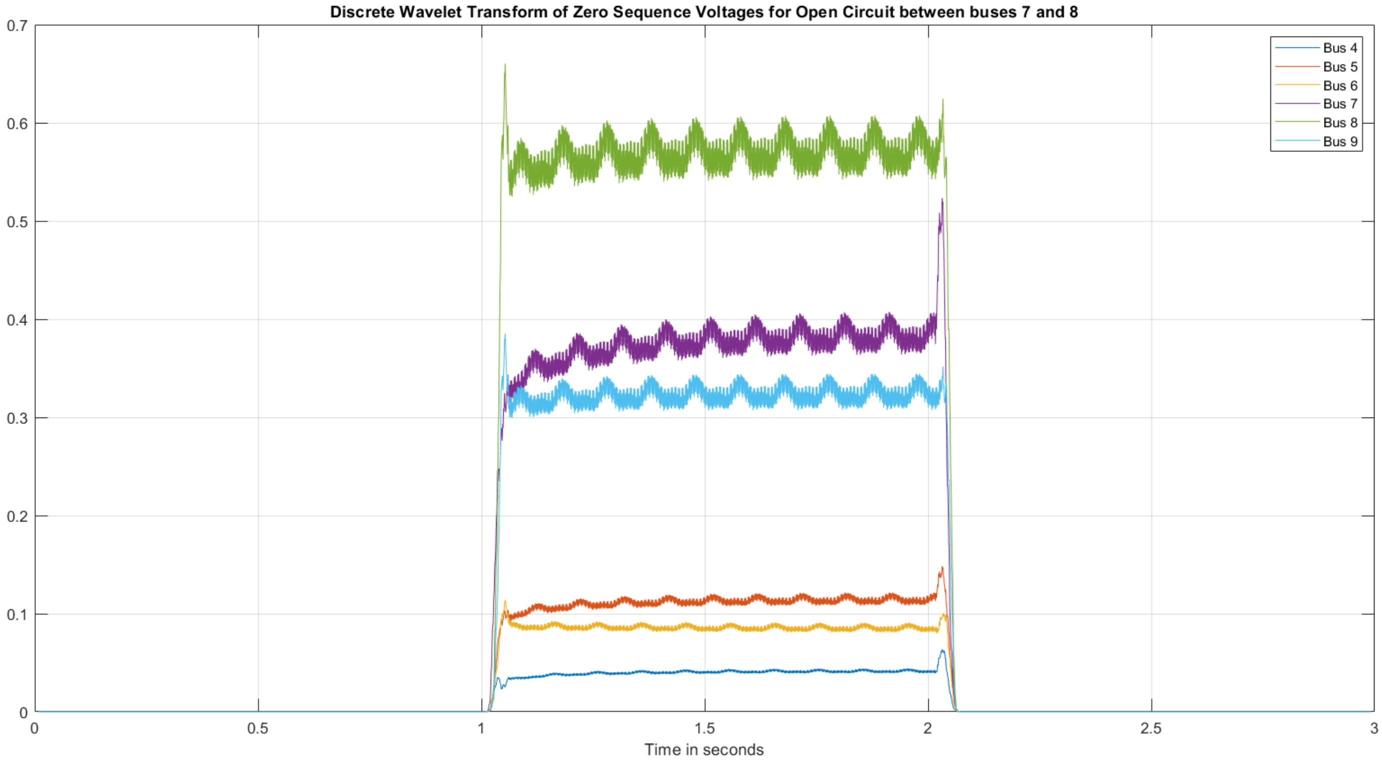


Figure 5.8: Sum of d4 coefficients of zero sequence voltages across all buses for an open circuit between buses 7 and 8.

Comparing figures 5.5 and 5.6, both of which have bus 7 as a common factor, we can design the lower threshold to be 0.26 and the higher threshold to be 0.32. These thresholds are also cross verified with the other 4 scenarios to ensure Bus 7 does not exceed these values. For Bus 7, this holds true.

However, it has been deemed necessary to impose two upper bounds; T_{bound_1} and T_{bound_2} respectively. for some buses. In these cases, although the lower and upper threshold work perfectly to trip, they also display higher d4 coefficients for faults located elsewhere. For example, Bus 9 has lower and upper thresholds of 0.14 and 0.24, respectively. However, for an open circuit between 7 and 8, Bus 9 has d4 coefficients much higher than 0.24. Therefore, an upper bound has been set around 0.3 to prevent Bus 9 from initiating a trip. For Bus 8, this boundary exists between its lower and upper threshold. Hence, this concept has been generalized to encompass two sets of inequalities.

Combining the results from all the six different fault scenarios we have:

Table 5.1: Trip Thresholds and Bounds for Different Buses

Bus	T_{low}	Line Tripped	T_{bound_1}	T_{high}	Line Tripped	T_{bound_2}
4	0.12	4-6	N/A	0.26	4-5	N/A
5	0.34	5-7	N/A	0.375	4-5	N/A
6	0.24	4-6	N/A	0.3	6-9	N/A
7	0.26	5-7	N/A	0.32	7-8	N/A
8	0.115	8-9	0.17	0.53	7-8	N/A
9	0.14	8-9	N/A	0.24	6-9	0.3

5.3.3 Protection Algorithm

With information from Table 5.1, the protection algorithm can be designed, and it is visualized in Fig. 5.7. Essentially, each bus monitors its own voltage and computes the coefficients. The coefficients are averaged before processing. The sum of the coefficients is computed over one cycle. This sum is compared against the defined thresholds and bounds.

If this sum is above the lower threshold and below the upper threshold, then the line corresponding to that value is tripped.

If this sum is above both the thresholds, then the line corresponding to the upper threshold is tripped.

If any boundary conditions are violated, no line connected to that bus is tripped.

During the comparison, the sum must satisfy the above conditions consistently for four cycles. If they are violated midway for even a single sample, then the count is reset is to 0.

Since the buses do not communicate with each other, the buses at the two ends of the broken line do not necessarily trip synchronously.

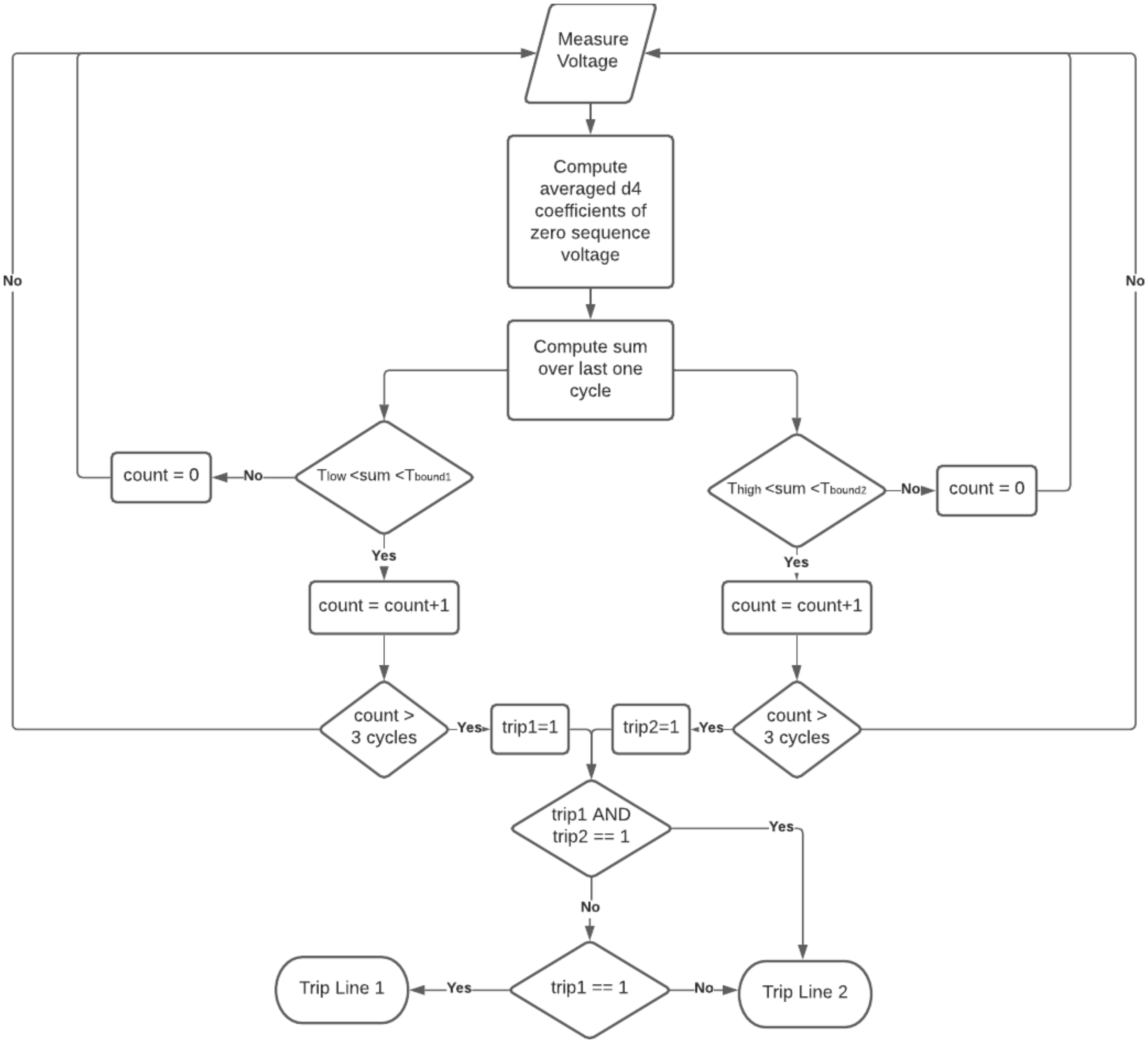


Figure 5.9: Flowchart of Protection Algorithm

5.3.4 Detection and Tripping

Based on the flowchart described by Fig 5.8 and the simulation settings described in the introductory segment of this section, an open circuit fault was simulated between buses 5 and 7.

The algorithm was able to correctly generate trip signals at buses 5 and 7 corresponding to Line 5-7 around 100 milliseconds after the open circuit fault. The trip signals control 3 phase breakers on either end of the line. None of the other buses responded, and hence, this protection scheme is secure for this fault.

This algorithm was found to be successful for all the 6 different lines in its ability to break the circuit and open the line prior to falling of the conductor, thus preventing a potential fire.

The time taken to detect, in this case, is an underestimate when compared to the real world, since processing times and delays, time taken by circuit breakers to respond and other miscellaneous factors have not been incorporated.

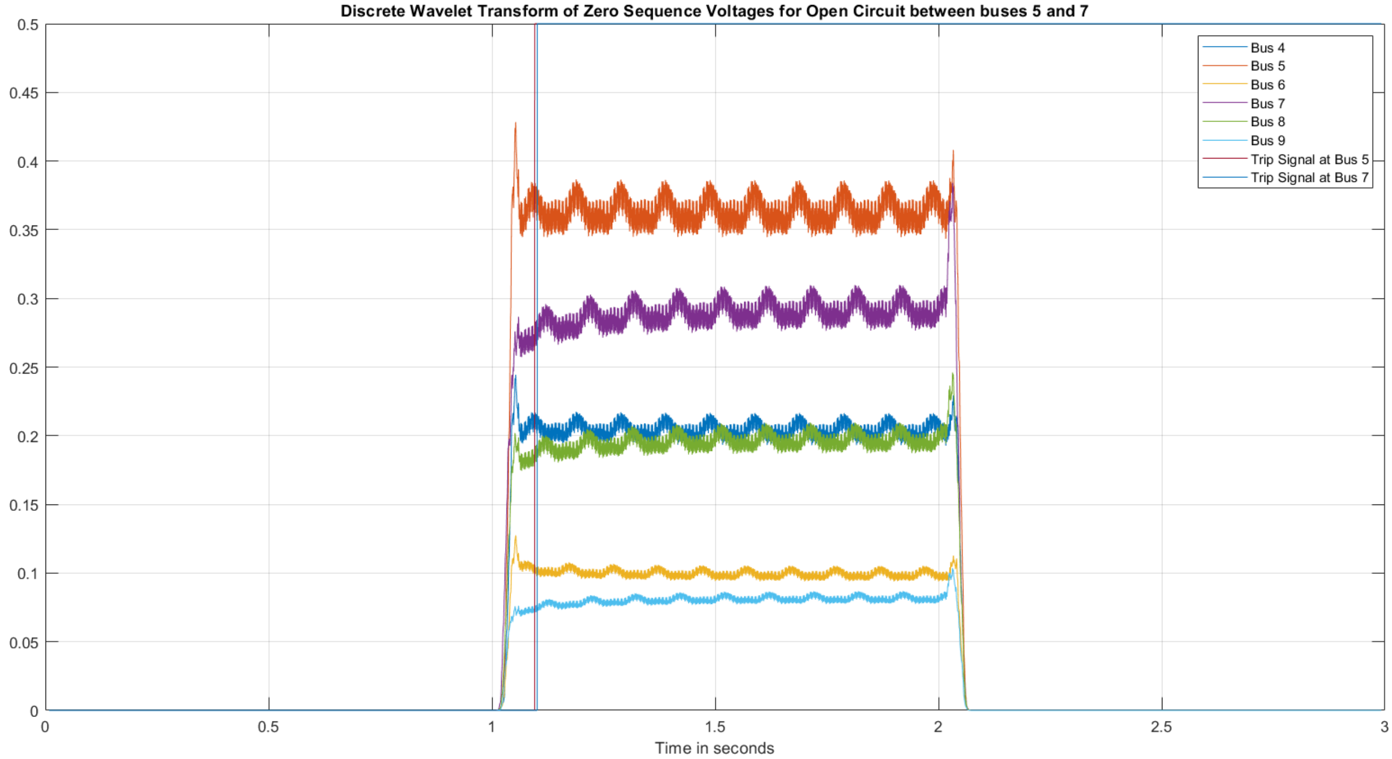


Figure 5.10: Trip Signal generated at Buses 5 and 7 for an open circuit fault in Line 5-7

The above figure also illustrates the need for different bounds that need to be placed. For example, Bus 8 registers d4 coefficients around 0.2 during the faulted interval. With only a lower threshold of 0.115 as described by Table 1, Bus 8 will falsely trip Line 8-9, but not Bus 9.

The protection scheme guarantees dependability, since for 5 of the 6 different cases, the right buses were identified and the correct lines were tripped.

However, in the case of a fault happening between lines 6 and 9, two lines open instead of one. From a security perspective, this is not ideal, but it ensures dependability.

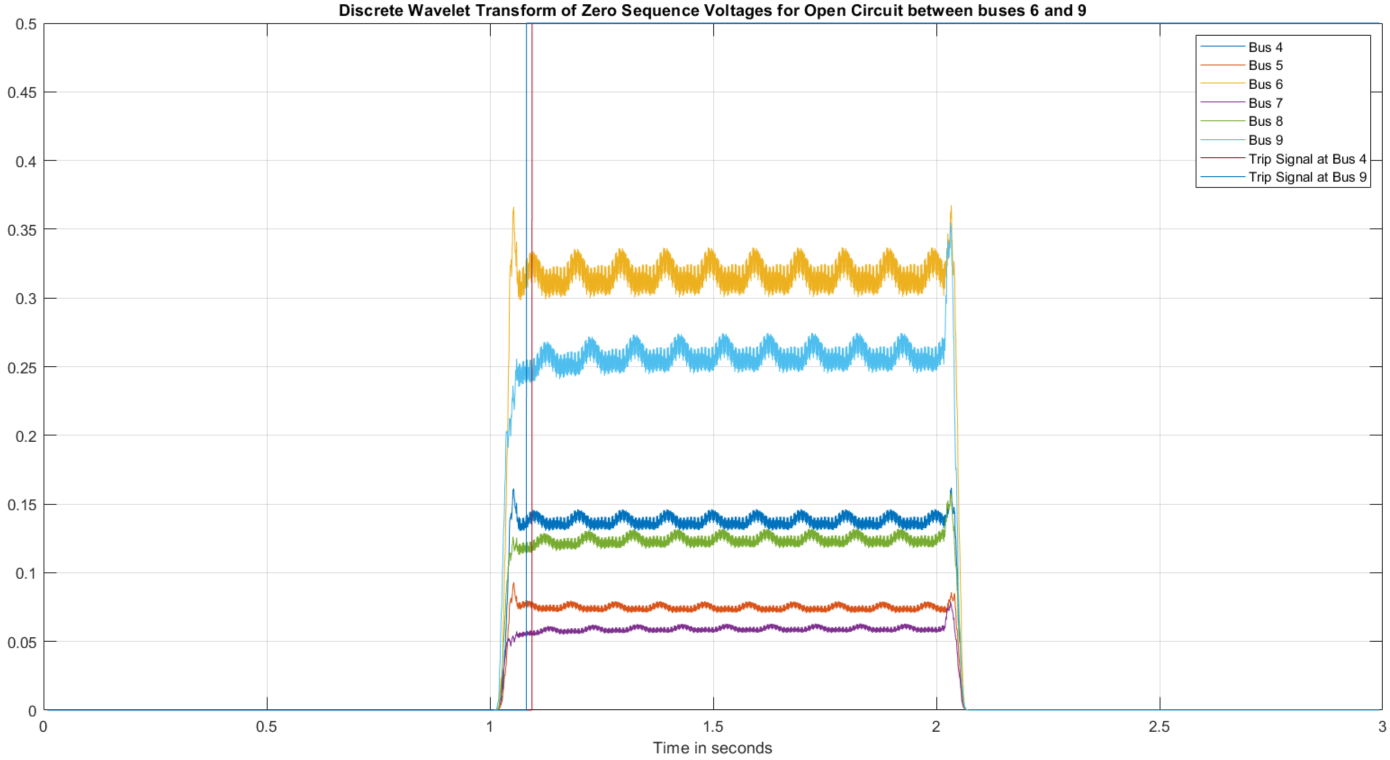


Figure 5.11: Trip Signal generated at Buses 4 and 9 for an open circuit fault in Line 6-9

The reason for this anomaly lies in the voltage profile of Bus 4. Bus 4 produces similar signal characteristics for open-line faults at Lines 4-6 and 6-9. It was not possible to designate a threshold that can effectively differentiate the two cases at Bus 4. Additionally, Bus 4 responds faster to the fault at 6-9 than Bus 6. Pausing the algorithm at various instances reveal that Bus 6 is roughly a cycle away from successfully detecting the fault by the time Bus 4 reacts.

Ideally, Bus 6 would also respond to the fault since no two buses communicate and detection depends purely on local settings. However, the breakers on 9-6 and 4-6 react faster, leading to Bus 6 being islanded and de-energized.

This anomaly is acceptable from the point of view of the bigger picture. We can successfully prevent a fire from being induced, but at the cost of an additional line opened. Bus 6 loses connections to both of its neighboring buses, and hence, the loads serviced at Bus 6 will experience a shutdown. The power at loads connected to Bus 6 can be restored very quickly once the operator realizes that Line 4-6 has been incorrectly tripped.

One possible solution to overcome this security problem is by strengthening this protection scheme using minimal communication such as permissive transfer tripping/blocking. However, this is beyond the scope of the current thesis since our focus to solve the problem without the need for communication. Additionally, transfer trip schemes will have to be generalized for the whole system and should not be limited to just one bus. Transfer trip schemes can also ensure that both ends of a line are tripped synchronously.

Asynchronous tripping of lines has not affected the overall efficacy of the protection because the time difference between the two trip signals is miniscule. By the time, the contacts of the breaker corresponding to the first signal part ways, the second trip would have already been initiated. Thus, this scheme works well for the purpose of this thesis.

Chapter 6

Conclusion and Future Work

This thesis presents a present-day environmental disaster through the lens of a power engineer. While wildfires are natural; unmaintained, and ill-equipped power lines run the risk of exacerbating the problem as well as run the risk of getting burnt down themselves. In this thesis, the former aspect is focused upon. In a complex and interdisciplinary topic such as this, it is important to define the problem clearly and differentiate how this situation from the more common abnormal conditions in a power system.

Vegetation and weather play a major role in inducing wildfires. Dry weather, high temperatures, drought-like conditions, and high wind are favorable flammable conditions. Unfortunately, these factors lie largely outside the control of an electrical engineer. Hence, controlling the amount and nature of vegetation surrounding a line is crucial. Policies and regulations pertaining to vegetation trimming implemented in California and Australia have been reviewed in this thesis, as well as a peek into the typical fault current levels for various kinds of vegetation.

This thesis looks at more than one way to prevent fires initiated by faulted power lines. Some of the techniques employed involve fault current limiters, some take a classic high-impedance fault detection approach. We conclude that, while both methods are highly effective, they do come with their own set of challenges. Therefore, they can always be used as reliable backup techniques.

The later chapters were dedicated to viewing the problem from an open circuit perspective with protection speed being the top priority. The first of the two approaches resorted to high-end metering requirements and the need for a robust communication network, the second approach attempted to solve the problem locally, without the need for communication.

The second method, i.e., local detection of open circuit without communication, is hopefully a novel contribution to this field. This technique involves a combination of the theory related to open circuit faults and the signal processing techniques relating to high impedance faults. This was also implemented in the standard IEEE 9-Bus benchmark with reasonable success in detection as well as timing.

In this method, meters were placed on all lines and buses strategically to constantly monitor voltages, which are processed to find zero sequence voltages and the resultant coefficients arising out of DWT. For each of these buses, predetermined thresholds and bounds are set. Buses that violate these conditions will trip the appropriate line. This method was very dependable and gave promising results in terms of accuracy and speed.

All of the open circuits were detected and the correct lines were tripped in about 100 milliseconds, without accounting for any delays. In one particular case, protection could only be achieved by tripping an additional line. From the perspective of preventing fires, this is an acceptable result that comes with a compromise.

By no means is this thesis an exhaustive approach to the problem of wildfires. There are plenty of avenues that can be explored and developed upon, as follows:

- Explore options to prevent wildfires from damaging powerlines and operations. Analysis pertaining to scheduling load shedding, altering the system operating conditions on high fire risk days, predicting the advances of the fire front can minimize the impact that consumers face.
- Improve the novel method proposed by introducing permissive transfer tripping and blocking techniques to prevent any additional lines from being tripped.
- Analyze the impact of reclosers on fires and coordinating the protection scheme to include recloser operations.
- Extend the algorithm to more asymmetrical systems, single phase systems and include more fault varieties such as Line-Line-Ground faults. The system can also be complicated further with the addition of regulators and solar PV panels to bring about a more realistic picture.
- Employing more robust signal processing techniques to better characterize the various coefficients of the discrete wavelet transform is a significant step to understanding the nature of various transients. Using an envelope detector, the variations in the d4 coefficients can be better understood and its periodic nature can provide more insight into the different frequency components present during an open circuit. Additionally, the choice of mother wavelet, sampling frequency and the level of filtering can be modified to achieve the same goals.
- The analysis and protection scheme can be extended to systems with unequal line impedance across various buses. The presence of short lines immediately following a very long line affects the various bus voltages differently than systems with similar levels of impedance and line lengths. This is especially true in California, and therefore, the protection design will have to accommodate this in the future.

With plenty of options to explore, this thesis is merely an introduction to a complicated real-world problem that needs to be given utmost attention to.

Bibliography

[1] How Do Power Lines Cause Wildfires? | Texas Wildfire Mitigation Project. URL https://wildfiremitigation.tees.tamus.edu/faqs/how-power-lines-cause-wildfires.

[2] Knowledge Base | PSCAD. URL https://www.pscad.com/knowledge-base/article/25.

[3] Powerline Bushfire Safety Program - Vegetation Conduction Ignition Test Report and Data - Datasets - Victorian Government Data Directory, . URL https://discover.data.vic.gov.au/dataset/powerline-bushfire-safety-program-vegetation-conduction-ignition-test-report.

[4] Powerline Bushfire Safety Program, . URL https://www.energy.vic.gov.au/safety-and-emergencies/powerline-bushfire-safety-program.

[5] Public Safety Power Shutoff (PSPS) / De-Energization. URL https://www.cpuc.ca.gov/deenergization/.

[6] Rapid Earth Fault Current Limiter, . URL https://www.energy.vic.gov.au/safety-and-emergencies/powerline-bushfire-safety-program/network-assets-program/rapid-earth-fault-current-limiter-refcl.

[7] Rapid Earth Fault Current Limiters, . URL https://www.ausnetservices.com.au/en/Community/Powerline-Bushfire-Safety-Program/Rapid-Earth-Fault-Current-Limiters.

[8] South Australian Legislation. URL https://www.legislation.sa.gov.au/LZ/C/R/Electricity(PrinciplesofVegetationClearance)Regulations2010.aspx.

[9] Tree Trimming and Vegetation Management Information. URL https://www.cpuc.ca.gov/general.aspx?id=1974.

[10] WSCC 9-Bus System - Illinois Center for a Smarter Electric Grid (ICSEG). URL https://icseg.iti.illinois.edu/wscc-9-bus-system/.

[11] 2009 VBRC - Final Report. Technical report, 2009 Victorian Bushfires Royal Commission, 2009. URL http://royalcommission.vic.gov.au/Commission-Reports/Final-Report.html.

[12] Powerline Bushfire Safety Taskforce: Final Report. Technical report, Victorian Government, Melbourne, Victoria, 2011. URL http://www.esv.vic.gov.au/Portals/0/AboutESV/Files/RoyalCommission/PBSTfinalreport.pdf.

[13] *Integrated Final Report SA Black System 28 September 2016*. AEMO, 3 2017. URL http://www.aemo.com.au/-/media/Files/Electricity/NEM/Market_Notices_and_Events/Power_System_Incident_Reports/2017/Integrated-Final-Report-SA-Black-System-28-September-2016.pdf.

[14] Sundaravaradan Navalpakkam Ananthan, Rajaraman Padmanabhan, Rounak Meyur, Balimidi Mallikarjuna, Maddikara Jaya Bharata Reddy, and Dusmanta Kumar Mohanta. Real-time fault analysis of transmission lines using wavelet multi-resolution analysis based frequency-domain approach. *IET Science, Measurement and Technology*, 10(7):693–703, 2016. ISSN 17518822. doi: 10.1049/iet-smt.2016.0038.

[15] Associated Press. State regulators consider breaking up PG&E over safety concerns - Los Angeles Times, 12 2018. URL https://www.latimes.com/local/lanow/la-me-ln-utility-breakup-possible-20181221-story.html.

[16] William Atkinson. The Link Between Power Lines and Wildfires | Electrical Contractor Magazine. *Electrical Contractor*, 11 2018. URL https://www.ecmag.com/section/systems/link-between-power-lines-and-wildfires.

[17] Rachel Brown. Power company faces class action over Black Saturday. *Australian Broadcasting Corporation*, 4 2009. URL https://www.abc.net.au/news/2009-04-23/power-company-faces-class-action-over-black/1660796.

[18] Richard J. Campbell. California Wildfires and Bulk Electric System Reliability. Technical report, Congressional Research Service, 2019. URL https://www.everycrsreport.com/reports/IN11189.html.

[19] Krystian Leonard Chrzan and Zbigniew Wróblewski. The threat caused by fires under high voltage lines. *Scientific Papers of the Institute of Electrical Engineering Fundamentals of Wroclaw Technical University Conferences*, (40):208–211, 2004. ISSN 03249441.

[20] Commission B. The Kilmore East Fire. *The Fires and the Fire- Related Deaths*, 1. URL http://www.royalcommission.vic.gov.au/Finaldocuments/volume-1/PF/VBRC_Vol1_Chapter05_PF.pdf.

[21] P. A. Crossley and P. G. McLaren. Distance protection based on travelling waves. *IEEE Transactions on Power Apparatus and Systems*, PAS-102(9):2971–2983, 1983. ISSN 00189510. doi: 10.1109/TPAS.1983.318102.

[22] Wernich de Villiers, Johannes Hendrik Cloete, L. Martin Wedepohl, and Arthur Burger. Real-time sag monitoring system for high-voltage overhead transmission lines based on power-line carrier signal behavior. *IEEE Transactions on Power Delivery*, 23(1):389–395, 2008. ISSN 08858977. doi: 10.1109/TPWRD.2007.905550.

[23] Peter Eavis and Ivan Penn. California Says PG&E Power Lines Caused Camp Fire That Killed 85 - The New York Times, 5 2019. URL https://www.nytimes.com/2019/05/15/business/pge-fire.html.

[24] Peter Fairley. Automatic Circuit Reclosers Probed as Potential Cause of California Fires - IEEE Spectrum. *IEEE Spectrum*, 12 2017. URL https://spectrum.ieee.org/energywise/energy/the-smarter-grid/utilities-probed-as-potential-cause-of-california-fires.

[25] Amin Ghaderi, Hossein Ali Mohammadpour, and Herbert Ginn. High impedance fault detection method efficiency: Simulation vs. real-world data acquisition. *2015 IEEE Power and Energy Conference at Illinois, PECI 2015*, pages 1–5, 2015. doi: 10.1109/PECI.2015.7064882.

[26] Global Fire Emissions Database. 2019-20 Australian bushfire season. (March), 2020. URL https://globalfiredata.org/pages/2020/01/03/2019-20-australian-bushfires/.

[27] D P S Gomes, C Ozansoy, and A Ulhaq. Vegetation High-Impedance Faults' High-Frequency Signatures via Sparse Coding [arXiv]. *arXiv*, page 8 pp., 6 2019. URL http://arxiv.org/abs/1906.00594.

[28] Douglas P S Gomes and Cagil Ozansoy. High-Sensitivity Vegetation High-Impedance Fault Detection Based on Signal ' s High-Frequency Contents. 33(3):1398–1407, 2018.

[29] Chul-hwan Kim, Hyun Kim, Young-hun Ko, Sung-hyun Byun, Raj K Aggarwal, Senior Member, Allan T Johns, and Senior Member. A Novel Fault-Detection Technique of High-Impedance Arcing Faults in Transmission Lines Using the Wavelet Transform. 17 (4):921–929, 2002.

[30] A Lewis. Networks Protocol for Vegetation Management Near Powerlines 2016-2018. page 53, 2018. URL https://www.sapowernetworks.com.au/public/download.jsp?id=54955.

[31] Yadong Liu, Jiwei Sun, Guangshun Gong, and Xiaoli Zhang. Open-Circuit Fault in EHV / UHV Transmission System and New Zero Sequence Over-current Protection Scheme. 3093(1):3093–3098.

[32] Angela Macdonald-Smith. Fires cut power link between NSW and Vic, 1 2020. URL https://www.afr.com/companies/energy/nsw-at-risk-of-blackouts-as-fires-cut-power-link-with-vic-20200104-p53ov4.

[33] F H Magnago and A Abur. Fault location using wavelets. *IEEE Transactions on Power Delivery*, 13(4):1475–1480, 1998. ISSN 1937-4208 VO - 13. doi: 10.1109/61.714808.

[34] Tony Marxsen. Powerline Bushfire Vegetation Conduction Ignition Test Report. Technical report, Centre of Excellence - Electricity Bushfire Safety, Melbourne, Victoria, 2015. URL https://www.energy.vic.gov.au/__data/assets/pdf_file/0022/41719/R_D_Report_-__Marxsen_Consulting_-_Vegetation_conduction_ignition_tests_final_report_15_July_2015_DOC_15_183075_-_external_.PDF.

[35] Joseph W Mitchell. Power line failures and catastrophic wildfires under extreme weather conditions. *Engineering Failure Analysis*, 35:726–735, 2013. ISSN 1350-6307. doi: https://doi.org/10.1016/j.engfailanal.2013.07.006. URL http://www.sciencedirect.com/science/article/pii/S1350630713002343.

[36] Emma Newburger. Wildfires: PG&E to shut off power to over 2 million people in California, 10 2019. URL https://www.cnbc.com/2019/10/26/pge-will-shut-off-power-to-940000-customers-in-northern-california-to-reduce-wildfi
html.

[37] William O'Brien, Eric Udren, Kamal Garg, Dennis Haes, and Bala Sridharan. Catching falling conductors in midair - Detecting and tripping broken distribution circuit conductors at protection speeds. *69th Annual Conference for Protective Relay Engineers, CPRE 2016*, 2017. doi: 10.1109/CPRE.2016.7914881.

[38] J.R. Stone and Alix Martichoux. PG&E PSPS map: These California counties were impacted by PG&E's Public Safety Power Shutoffs - ABC7 San Francisco, 9 2020. URL https://abc7news.com/public-safety-power-shutoff-bay-area-psps-pge-blackouts-outage-map/6413174/.

[39] Fabian M. Uriarte and Virgilio Centeno. High-impedance fault detection and localization in distribution feeders with microprocessor based devices. *Proceedings of the 37th Annual North American Power Symposium, 2005*, 2005:219–224, 2005. doi: 10.1109/NAPS.2005.1560528.

[40] Martin Van Der Linde. Fire risk mitigation in the overhead electricity distribution network. In *2019 29th Australasian Universities Power Engineering Conference, AUPEC 2019*. Institute of Electrical and Electronics Engineers Inc., 11 2019. ISBN 9781728150437. doi: 10.1109/AUPEC48547.2019.211806.

[41] Ming Ta Yang, Jhy Cherng Gu, and Jin Lung Guan. Detection of downed conductor in distribution system. *2005 IEEE Power Engineering Society General Meeting*, 2: 1107–1114, 2005. doi: 10.1109/pes.2005.1489429.

[42] H Yong, C Minyou, and Z Jinqian. High impedance fault identification method of the distribution network based on discrete wavelet transformation. In *2011 International Conference on Electrical and Control Engineering*, pages 2262–2265, 2011. ISBN VO -. doi: 10.1109/ICECENG.2011.6057329.