



**TRIBHUVAN UNIVERSITY  
INSTITUTE OF ENGINEERING  
PULCHOWK CAMPUS**

**THESIS NO: 078/MSPSE/008**

**Analysis of Arc Flash and Mitigation Techniques in Substation  
Protection of Attariya Substation Nepal**

by

In Bahadur Rai

A THESIS

SUBMITTED TO THE DEPARTMENT OF ELECTRICAL ENGINEERING

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE

DEGREE OF MASTERS IN SCIENCE IN

POWER SYSTEM ENGINEERING

DEPARTMENT OF ELECTRICAL ENGINEERING

LALITPUR, NEPAL

JUNE, 2024

## **COPYRIGHT**

The author has agreed that the Library, Department of Electrical Engineering, Pulchowk Campus, and Institute of Engineering may make this report freely available for inspection. Moreover, the author has agreed that permission for extensive copying of this study report for scholarly purpose may be granted by the supervisors who supervised the project work recorded herein or, in their absence, by the Head of the Department wherein the project report was done. It is understood that the recognition will be given to the author of this report and to the Department of Electrical Engineering, Pulchowk Campus, and Institute of Engineering in any use of the material of this project report. Copying or publication or the other use of this report for financial gain without approval of to the Department of Electrical Engineering, Pulchowk Campus, Institute of Engineering and author's written permission is prohibited. Request for permission to copy or to make any other use of the material in this report in whole or in part should be addressed to:

Head

Department of Electrical Engineering

Pulchowk Campus, Institute of Engineering

Lalitpur, Nepal



Accredited by University Grants  
Commission (UGC) Nepal 2020

त्रिभुवन विश्वविद्यालय  
TRIBHUVAN UNIVERSITY  
इन्जिनियरिङ्ग अध्ययन संस्थान  
INSTITUTE OF ENGINEERING  
पुल्चोक क्याम्पस  
PULCHOWK CAMPUS

**DEPARTMENT OF ELECTRICAL ENGINEERING**  
Pulchowk, Lalitpur

The undersigned certify that they have read, and recommended to the Institute of Engineering for acceptance, a thesis entitled “**Analysis of Arc Flash and Mitigation Techniques in Substation Protection of Attariya Substation Nepal**” submitted by In Bahadur Rai in partial fulfillment of the requirements for the degree of Masters in Science in Power System Engineering.

Asst. Prof. Akhileshwar. Mishra

Supervisor

M.Sc. in Power System Engineering

Assoc. Prof. Jeetendra Chaudhary

Supervisor & Program Coordinator

M.Sc. in Power Electronics & Drive Eng.

Assoc. Prof. Dr. Basanta Kumar Gautam

Program Coordinator

M.Sc. in Power System Engineering

Yubraj Adhikari

Assistant Professor

Head of Department

Ranju Pandey

External Examiner

Director, Nepal Electricity Authority

..... 2024

## ABSTRACT

An arc flash refers to an electrical explosion that might happen when there is a sudden and intense flow of current, occurring either between a conductor and the ground or between two conductors. Arc flashes produce intense heat and light, and can release large amounts of energy. Arc flash analysis is required to quantify the associated risk and minimize the possible consequences with optimal protective measures. The electrical power system in Nepal is in a growing phase. There are a number of substations being upgraded, new substations being constructed. However, the consideration of arc flash analysis in substation protection systems are not found to the level it requires. The primary goal of this study is to quantify possible risks linked with arc-flash incidents in the Attariya Substation, and devise effective mitigation techniques. There were no official records of the number of incidents related to arc flash in Attariya substation such as fire in low voltage switchgear and arcing due to underground cable termination explosion. The transformers in Attariya substation have been upgraded with higher capacity, which might have resulted in a higher fault level in the substation. Thus, this study presents the result of a comprehensive analysis of arc flash and mitigation techniques in Attariya substation. The substation's electrical power system model is created and assessed through the utilization of ETAP 19.01. There are two 16.6 MVA 33/11 kV transformers, each connected to a respective incomer and a normally open 11 kV bus tie circuit breaker. While analyzing the substation with existing protection devices and circuit breaker settings, the fault clearing time and incident energy are observed to be at a higher level than the proposed alternative settings of protective devices and circuit breakers. With alternative settings of protective devices, the possible risk from arc flash incidents has been minimized significantly and the possible risk of equipment damage and injury to operating personnel is reduced. The significant decrease in injuries, damages, and their respective costs underscores the importance of conducting thorough arc flash analysis. Arc flash analysis results might be useful for selecting suitable arc-rated protective devices, electrical equipment, switchgear panels and accessories, enhancing the robust design and operation of the electrical substation. The study underscores the need for safety measures, connecting with broader power system studies. As Nepal's power system expands, implementing arc flash analysis becomes crucial for safety, operational efficiency and robust substation electrical infrastructure, aligning with global practices.

## **ACKNOWLEDGEMENT**

I would like to extend my sincere gratitude to my research supervisors, Assistant professor Akhileshwar Mishra and Associate Professor as well as M.Sc.in Power Electronics and Drive Engineering program coordinator Jeetendra Chaudhary, for their unwavering guidance, invaluable insights, and continuous support throughout the research process. Their expertise and encouragement have been pivotal in shaping this thesis. I also want to thank Assoc. Prof. Dr. Basanta Kumar Gautam for overseeing and coordinating the program, providing valuable feedback, and ensuring a conducive academic environment.

A special acknowledgment is extended to the Department of Electrical Engineering for providing the necessary resources, facilities, and academic support that significantly contributed to the successful completion of this research. I am sincerely thankful to the Nepal Electricity Authority Attariya Grid Branch for their generosity in providing access and essential information, which played a crucial role in the successful execution of the analysis.

Lastly, I would like to express my deepest appreciation to my parents and spouse for their unwavering support, understanding, and encouragement throughout this academic journey. Their love and belief in me have been my pillars of strength. I also would like to extend my gratitude to all the dedicated supporting personnel whose contributions were instrumental in the completion of this study. Your efforts, whether direct or indirect, have been invaluable, and I am truly thankful for your commitment and assistance.

## Table of Contents

COPYRIGHT.....	ii
ABSTRACT.....	iv
ACKNOWLEDGEMENT .....	v
Table of Contents.....	vi
List of Tables .....	viii
List of Figures .....	ix
List of acronyms and abbreviations .....	x
CHAPTER ONE: INTRODUCTION.....	1
1.1 Background.....	1
1.2 Problem Statement.....	2
1.3 Objectives .....	3
1.4 Scope and Limitations.....	4
1.4.1 Scope.....	4
1.4.2 Limitations .....	4
1.5 Report Organization.....	5
CHAPTER TWO: LITERATURE REVIEW .....	6
2.1 Introduction.....	6
2.2 Review of Journals and Articles .....	7
2.1 Research Gap .....	16
CHAPTER THREE: METHODOLOGY .....	19
3.1 Introduction.....	19
3.2 Equation for Arc Flash Calculations.....	19
3.3 Data Collection and System Modeling .....	21
3.4 Power System Analysis.....	26
3.4.1 Load Flow Analysis .....	26
3.4.2 Short Circuit Studies .....	26

3.4.3 Protection Coordination Studies .....	26
3.5 Overall Block Diagram of Arc Flash Analysis .....	28
CHAPTER FOUR: RESULTS AND DISCUSSION .....	33
CHAPTER FIVE: CONCLUSION AND RECOMMENDATION .....	56
5.1 Conclusion .....	56
5.1 Recommendation .....	57
REFERENCES .....	58
APPENDIX A: SLD and LFA simulation diagram of IEEE 4 node test feeder existing condition .....	60
APPENDIX B: SCS and AFA simulation diagram of IEEE 4 node test feeder existing condition .....	61
APPENDIX C: AFA simulation diagram of IEEE 4 node test feeder with alternative setting.....	62
APPENDIX D: Single line diagram of Attariya Substation .....	63
APPENDIX E: LFA simulation diagram of Attariya substation existing condition ...	64
APPENDIX F: SCS simulation diagram of Attariya substation existing condition....	65
APPENDIX G: AFA simulation diagram of Attariya substation existing condition ..	66
APPENDIX H: AFA simulation diagram of Attariya substation with alternative PD setting.....	67
APPENDIX I: PAPER ACCEPTANCE NOTIFICATION .....	68
APPENDIX J: CONFERENCE PAPER .....	69

## List of Tables

Table 2.1 Low Voltage arc flash incident frequency [1] .....	7
Table 2.2 Medium and High voltage arc flash incident frequency [1] .....	8
Table 2.3 Case-I Analysis Result [5] .....	10
Table 2.4 Case-II Analysis Result [5].....	10
Table 2.5 Case-II Mitigated Analysis Result with FG3225.....	11
Table 2.6 Case-II Mitigated Analysis Result with JG3225 .....	11
Table 2.7 Arc Flash Analysis Result [10].....	14
Table 2.8 Duration of PD clearance anticipated: .....	15
Relayed-CB: 2.4-13.8 kV [12].....	15
Table 2.9 Duration of PD clearance anticipated: .....	16
MCB, 600Volt, and lower [12] .....	16
Table 2.10 Duration of PD clearance anticipated: .....	16
PCB, 600V, and lower [12].....	16
Table 3.1 Two Winding Transformer Input Data of Attariya SS .....	23
Table 3.2 Line/Cable/Busway Input Data of Attariya SS .....	23
Table 3.3 Bus Input Data of Attariya SS .....	24
Table 3.4 Line Data of IEEE 4-Node Test-Feeder .....	25
Table 4.1 PD setting for IEEE 4-Node Test-Feeder Existing Condition.....	33
Table 4.2 LFA Result of IEEE 4-Node Test-Feeder Existing Condition .....	33
Table 4.3 SCS Result of IEEE 4-Node Test-Feeder Existing Condition.....	34
Table 4.4 AFA Result of IEEE 4-Node Test-Feeder Existing Condition.....	35
Table 4.5 Alternative PD setting for IEEE 4-Node Test-Feeder .....	35
Table 4.6 LFA Result of IEEE 4-Node Test-Feeder with PD alternative setting .....	36
Table 4.7 SCS Result of IEEE 4-Node Test-Feeder with PD alternative setting .....	36
Table 4.8 AFA Result of IEEE 4-Node Test-Feeder with alternative PD Setting.....	36
Table 4.9 LFA Result of Attariya substation Existing Condition.....	38
Table 4.10 SCS Result of Attariya substation Existing Condition .....	39
Table 4.11 PD setting for Attariya substation Existing Condition .....	39
Table 4.12 AFA Result of Attariya substation Existing Condition .....	43
Table 4.13 Alternative PD setting for Attariya substation.....	46
Table 4.14 AFA Result of Attariya substation with alternative PD setting.....	52
Table 4.15 AFA Result Comparison Existing vs Alternative setting .....	53

## List of Figures

Figure 2.1 Proportion of LV incidents [1] .....	7
Figure 2.2 Proportion of MV and HV incidents [1].....	8
Figure 2.3 IE versus FCT Plot [10].....	14
Figure 3.1 Single line diagram of Case Study Attariya Substation .....	21
Figure 3.2 Single line-diagram of IEEE Four-Node Test-Feeder [11] .....	25
Figure 3.3 Block diagram illustrating steps in arc flash analysis .....	28
Figure 4.1 TCC of PD for IEEE 4 Node Test Feeder Existing Condition.....	34
Figure 4.2 TCC of PD for IEEE 4 Node Test Feeder with alternative PD Setting.....	37
Figure 4.3 TCC of Relay1, 2, 3, 9 and 13 with existing setting .....	40
Figure 4.4 TCC of Relay 4, 5, 6, 10 and 13 with existing setting .....	41
Figure 4.5 TCC of LVCB, HV Fuse and Relay 13 with existing setting .....	42
Figure 4.6 11kV termination opening not concealed.....	44
Figure 4.7 33 kV UG cable termination damaged .....	44
Figure 4.8 TCC of Relay1, 2, 3, 9 and 13 with alternative setting .....	47
Figure 4.9 TCC of Relay1, 2, 3, 7, 8, 10 and 13 with alternative setting .....	48
Figure 4.10 TCC of Relay 4, 5, 6, 10 and 13 with alternative setting .....	49
Figure 4.11 TCC of Relay 4, 5, 6, 7, 8, 9 and 13 with alternative setting .....	50
Figure 4.12 TCC of LVCB, HV Fuse and Relay 13 with alternative setting .....	51
Figure A.1 Single line diagram of IEEE 4 node test feeder load flow analysis [11]...	60
Figure B.1 Simulation diagram of IEEE 4 node test feeder short circuit studies .....	61
Figure B.2 Simulation diagram of IEEE 4 node test feeder arc flash analysis .....	61
Figure C.1 Simulation diagram of IEEE 4 node test feeder arc flash analysis .....	62
Figure D.1 Single line diagram of Attariya substation .....	63
Figure E.1 Simulation diagram of Attariya substation load flow analysis .....	64
Figure F.1 Simulation diagram of Attariya substation short circuit studies .....	65
Figure G.1 AFA Simulation diagram of Attariya SS with existing PD setting .....	66
Figure H.1 AFA Simulation diagram of Attariya SS with existing PD setting .....	67

## List of acronyms and abbreviations

NFPA	National Fire Protection Association
OSHA	Occupational Safety and Health Administration.
ETAP	Electrical Transient Analyzer Program
PPE	Personnel Protective Equipment
IEEE	Institute of Electrical and Electronics Engineers
HVAF	High Voltage Arc Flash
NESC	National Electric Safety Code
AC	Alternating Current
DC	Direct Current
U.S.	United States of America
V	Volt
A	AMPERE
kV	Kilo Volt
Hz	Hertz
SSN	Silver Springs North
NEA	Nepal Electricity Authority
LPV	Liquid Propane Vapor
SLD	Single Line Diagram
LFA	Load Flow Analysis
AFA	Arc Flash Analysis
PCA	Protection Coordination Analysis
SCS	Short Circuit Studies
PD	Protective Device
PCB	Power Circuit Breaker
UG	Under Ground
LVCB	Low Voltage Circuit Breaker
HV	High Voltage
MV	Medium Voltage
LV	Low Voltage
CT	Current Transformer
OCR	Over Current Relay
OLR	Over load Relay

E	Incident Energy
SS	Substation
TCC	Time Characteristics Curve
CB	Circuit Breaker
MCB	Miniature Circuit Breaker
MCCB	Molded Case Circuit Breaker
MVA	Mega Volt-Ampere
MVAR	Mega Volt-Ampere Reactive
rms	Root mean square
CVB	Vertical Conductive Bus
HCB	Horizontal Conductive Bus
VCBB	Vertical Conductive Bus with an Insulating Barrier
HOA	Horizontal Opening in Air
VOA	Vertical Opening in Air
MHD	Magneto Hydrodynamics

## CHAPTER ONE: INTRODUCTION

### 1.1 Background

The analysis of arc flash hazards and implementation of effective mitigation techniques are of utmost importance in ensuring the safe operation of electrical system and preventing possible consequences. Understanding the hazards associated with arc flashes and implementing appropriate protection measures are critical for safeguarding personnel and infrastructure. Arc flash is a type of electrical explosion that can occur when there is a sudden and high current flow either between a conductor and ground or between two conductors. Arc flashes produces intense heat and light, and can release large amounts of energy. It can also create a shock wave that can travel through the air and cause damage to equipment and structures. The term "arc flash hazard" describes a potential source of harm or damage related to energy released from electric arc. The current flows through metallic object as it moves, creating incredibly hot arcs that vaporize conductors, ionize gasses, and create a ball of plasma. There's the sound of an explosion and a glaring brightness. Fast expanding gases have the potential to create metal oxide dust, liquid metal droplets, and doors to be blown open. A person standing a considerable distance away from the fault may get flesh burns and garments ignited by radiant and convective heat energy. There is a chance of death as well as temporary or permanent harm to the skin, eyes, hearing, and lungs. The arc flash could persist until a protective device located upstream detects and resolves the fault, typically taking anywhere from half a cycle to several seconds. Arc flash hazards pose a significant risk to personnel and equipment in electrical substations. These hazards can result in severe injuries, fatalities, and damage to the power distribution infrastructure, leading to disruption of electricity supply. Moreover, the resulting power outages and equipment damage can have significant economic and operational implications. It is essential to comprehensively analyze and implement effective mitigation techniques to ensure the safety and reliability of substation operations. In order to conduct arc flash analysis, the relevant power system needs to be modeled and analyzed so that, this study could be related to power system studies. This study focuses on conducting an arc flash hazards analysis, and exploring minimization techniques specifically in Attariya Substation located in Attariya, Kailali Nepal. The study will provide valuable insights into the factors contributing to arc flash incidents within the substation and identify appropriate measures to prevent or mitigate such events. Ultimately, the findings and

recommendations of this research will facilitate the development of enhanced safety protocols, operational guidelines, and protective measures, ensuring the secure and reliable operation of the Attariya Substation. It is imperative to understand the nature of these hazards and implement suitable mitigation measures to secure the safety and uninterrupted power system. Noticeable decrease in injury, damage and respective cost saving can show the significance of arc flash analysis. However, in Nepal the classification of electrical incidents have not started yet but with the increase in power system the classification and standard record is required to identify the specific cause and take possible action. Number of fire incident have been noticed in industries and commercial building due to electric faults and the failure to promptly clear in a safe manner. Comprehensive analysis of arc-flash hazard is required in electrical power system with the increase in its complexity as well as with increase in capacity, without proper analysis the coordination of protective devices could not be identified and the fault may not be cleared in safe timing which cause the arc flash with possible consequences. To the best of my knowledge and study there are not any practice of recording the incident of arc flash of the Attariya substation as well as in so many other substations in Nepal. This study shall be the beginning of Arc flash analysis in substation protection of Nepal. Arc flash analysis is an important consideration for design of a substation. Geographically, the Attariya substation is located in far western province, Kailali District, Godawari Municipality Nepal. This substation is connected to the Utility Grid. This is a major substation for supplying electricity in Kailali District. Since the commissioning of the initial Attariya substation, the number of changes recorded in the substation including transformer and circuit breakers upgrade. This study shows how much incident energy level can be minimized with alternative setting of the protective and fault clearing devices of the case study Attariya substation. With the obtained results possible risk of arc flash can be quantified and recommend the suitable action of minimizing the possible risk thus saving the cost of injury and damage to the electrical equipment and infrastructures.

## **1.2 Problem Statement**

Arc flashes are serious hazard in substations. It might cause serious injuries and fatalities to operators and can also damage equipment and infrastructure. If our substation infrastructure are not designed to withstand possible arc flash incidents that can disrupt power service, which can have a significant impact on business and

communities. Cable termination explosion and arcing have been noticed number of times in Attariya substation , as well as there was a unofficial record of fire in 11kV switchgear that might have resulted due to electrical fault and following arc flash consequences. There is no any official record of conducting Arc flash analysis of the Attariya substation after upgrading of measure equipment, which might have increased the fault level and possible arc flash risk. Therefore, there is a need to conduct a comprehensive study to identify the specific problems and fill the following gaps and challenges:

- a. **Lack of Arc Flash Analysis:** The Attariya Substation in Nepal lack a thorough arc flash analysis, which is essential for accurately assessing the potential hazards and risks associated with arc flash incidents.
- b. **Ineffective Mitigation Techniques:** The existing protection measures in the substation might not adequately address arc flash hazards.
- c. **Awareness and Training:** There might be a lack of awareness and training among personnel regarding arc flash hazards, their potential consequences, and the appropriate safety procedures to follow.
- d. **Regulatory Compliance:** The Attariya Substation needs to comply with national and international regulations and standards related to electrical safety, including arc flash protection. However, the substation might lack a comprehensive framework to ensure compliance with these regulations, which could lead to legal and safety risks.

### **1.3 Objectives**

The primary goal of this research is to assess and mitigate arc flash hazards in the Attariya substation and to enhance substation safety and reduce the risks associated with arc flash incidents. The specific goals of this research are:

- I. To conduct comprehensive arc flash analysis for the Attariya Substation by analyzing various factors, including fault currents, system configurations, and equipment characteristics.
- II. To identify the specific vulnerabilities and risk factors contributing to arc flash hazards in the substation.

III. To evaluate the existing mitigation techniques employed in substation protection systems, considering their effectiveness, practicality, and applicability to the local context.

IV. To develop and propose effective mitigation techniques tailored to the Attariya substation to minimize the likelihood and severity of arc flash incidents.

## **1.4 Scope and Limitations**

### 1.4.1 Scope

The goal of this research is to recognize possible arc flash risks, evaluate the operational protocols of the substation and propose effective mitigation measures. Conducting research to a specific substation can provide in-depth insights and recommendations that are directly applicable to the selected Attariya substation Nepal. This study is expected to bring about a multitude of positive impacts across various technical and non-technical domains. Some of the benefits includes quantification of risk associated with arc fault, improve working environment safety and economic benefits.

### 1.4.2 Limitations

IEEE Std. 1584 method has been considered for this arc flash analysis, this standard has limited applicability. The criteria under which the IEEE Std. 1584 calculation method remains applicable are as mentioned in methodology section 3.2 and some of the study limitations are:

- a. Considering average loading of the 11kV feeders
- b. This study may not extensively focus on these human factors such as human error, safety protocol and their impact on arc flash hazards.
- c. External factors beyond the substation's control, such as utility level protection system, interconnections may impact the overall arc flash hazards and mitigation effectiveness, these external factors are not fully accounted in the study.

Despite these limitations, the study aims to provide valuable insights and recommendations for arc flash hazards and mitigation techniques within the specific context of the Attariya Substation in Nepal. Awareness of these limitations will help in interpreting and applying the study's findings appropriately while considering the unique characteristics and constraints of the substation.

## **1.5 Report Organization**

The report organization section provides an overview of how the research will be organized to address the objectives effectively. The proposed organization section is as follows:

**Chapter 1. Introduction:** The initial section furnishes the study's contextual details, problem statement, study objectives, as well as its scope and limitations. Hence, this chapter offers an overview of the entire study.

**Chapter 2. Literature Review:** This section comprises an exploration of concepts, a review of past research, and an identification of gaps in present studies and methodologies.

**Chapter 3. Methodology:** This section presents the methodology utilized for conducting the study, detailing the research design and the tools and methods employed.

**Chapter 4. Results and Discussion:** This section will outline the results acquired from study and its possible consequences.

**Chapter 5. Conclusion and Recommendation:** In this section, overall findings of the study are summarized along with proposed recommendation based on the study.

## **CHAPTER TWO: LITERATURE REVIEW**

### **2.1 Introduction**

Ensuring the safe operation of electrical systems and averting potential repercussions highly depends on arc-flash hazards identification, and application of efficient alleviation strategies. Understanding the hazards associated with arc flashes and implementing appropriate protection measures are critical for safeguarding personnel and infrastructure. In recent years, there has been growing recognition of the need for comprehensive studies and strategies to address arc flash hazards in the field of electrical engineering. Extensive research and standardization efforts have been conducted on arc flash analysis in various countries, it is essential to focus on specific regional contexts to address unique challenges and regulatory frameworks. This study focus on providing insights into the arc flash hazards and mitigation strategies relevant to the country's electrical infrastructure. The literature review will cover a range of topics, including arc flash hazards, incident energy calculations, arc flash boundary determination, personal protective equipment requirements, and mitigation strategies. Through an analysis of the present understanding in these fields, this study seeks to identify gaps and contribute to the development of improved arc flash analysis and protection practices specific to the context of substation protection in Nepal. The literature review will draw upon a variety of sources, including peer reviewed research papers, industry reports, international standards such as NFPA 70E and IEEE 1584, and relevant case studies. It will provide an overview of the key concepts, methodologies, and tools employed in arc flash analysis, as well as the challenges and limitations associated with the existing approaches. Some articles have been published in reputable journals, concentrating on arc-flash analysis in LV, MV, and HV electrical systems using different tools and methodologies. There are some papers published in IEEE industry application transactions focused on analysis of arc-flash on IEEE standard test model utilizing computer simulation platform. In the realm of electrical engineering and substation protection, the phenomenon of arc flash poses significant challenges, especially in regions like Attariya, Nepal, where infrastructural development is rapidly advancing. This dissertation aims to contribute to the growing body of knowledge in this field by synthesizing existing research, identifying gaps, and proposing contextually relevant strategies for enhancing arc flash safety within the specific context of Attariya Substation.

## 2.2 Review of Journals and Articles

[1] This study analyzes the types and volume of arc flash injuries documented by OSHA reporters in the United States from April 1984 to June 2007. It considers various injury types and occurrences categorized by voltage class (ranging from 120 V to 240 kV), the frequency of events across different equipment classes and typical tools used, as well as the detailed descriptions of numerous incidents. OSHA, Occupational Health and Safety Administration, is part of the U.S. department of labor. The data can be summarized as following.

Table 2.1 Low Voltage arc flash incident frequency [1]

Voltage[V]	Number of Incidents	Voltage[V]	Number of Incidents
120	1	600	5
208	3	640 DC	1
240	11	700	2
277	3	Unknown	87
480	216	Total	329

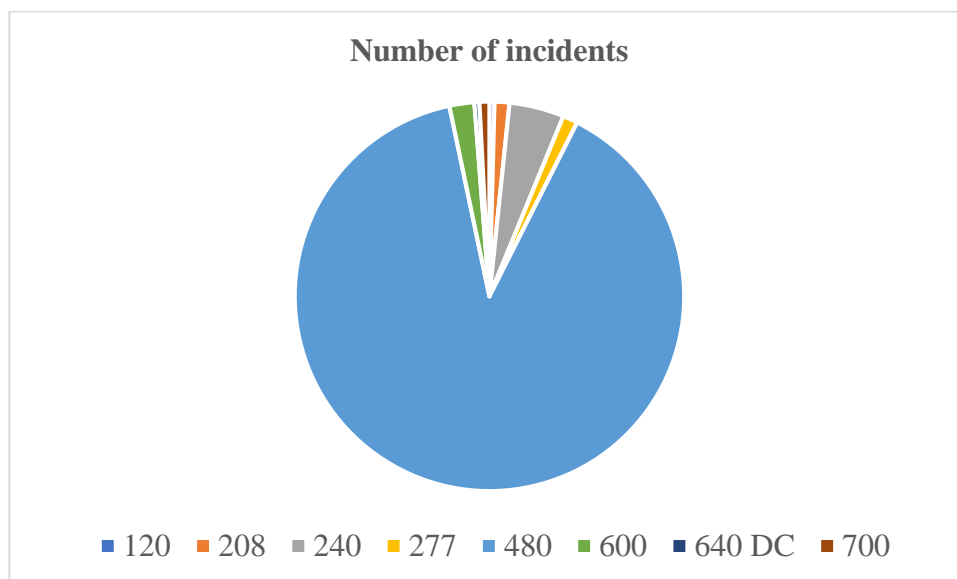


Figure 2.1 Proportion of LV incidents [1]

Table 2.1 and Figure 2.1 presents the numbers of arc incidents occurred at various low voltages documented by OSHA reporters in the United States from April 1984 to June 2007. Figure 2.1 indicates that, despite the significantly higher number of expose in lower voltage class, there were more accidents from 480 to 700 volts compared to a smaller number at 120 to 277 volts [1].

Table 2.2 Medium and High voltage arc flash incident frequency [1]

Voltage[V]	Number of Incidents	Voltage[V]	Number of Incidents
1k to 2.4k	8	33k to 34.5k	7
3k to 5k	37	46k to 72k	7
6.9k to 7.6k	24	115k to 240k	12
11k to 15k	51	Unknown	43
16k to 25k	14	Total	203

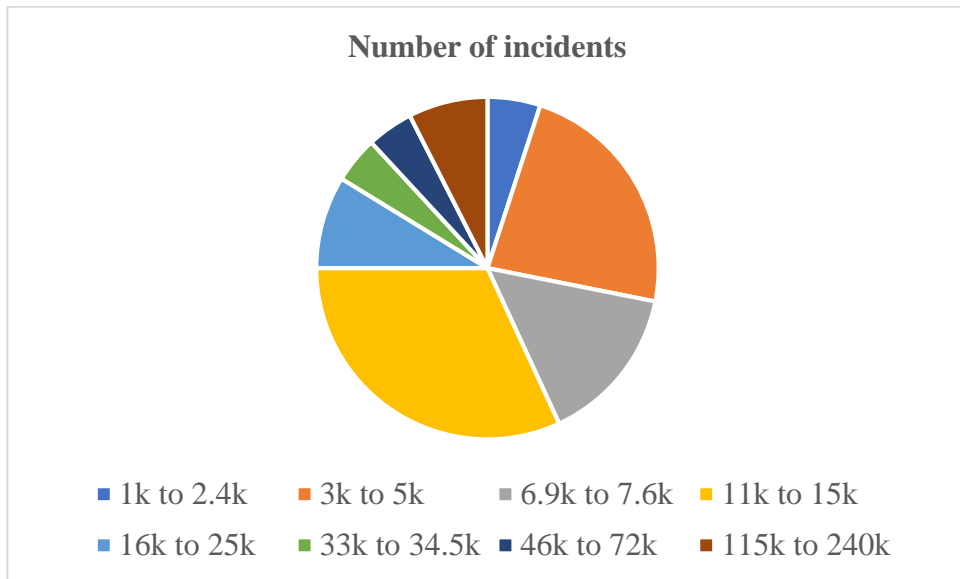


Figure 2.2 Proportion of MV and HV incidents [1]

Table 2.2 and Figure 2.2 presents the numbers of arc incidents occurred at various voltages reported by OSHA inspectors. The majority of accidents were observed within the voltage range of 11 to 15kV, surpassing the frequency at 7.2kV, where the most deaths have been recorded. Notably, a significant portion of injuries occurred within the voltage ranges of 3 to 5 kV and 11 to 15kV, which align with the typical power distribution voltages found in industrial and commercial facilities [1]. However, voltage levels for transmission, distribution and consumers supply are different in Nepal compared to U.S., there might be risk of arc flash incidents in Nepal. Number of electrical incidents have been noted but due to lack of proper data record incident related to arc flash could not be accessed.

[2] IEEE 1584-2018 provides a standardized procedure for carrying out arc flash analysis. Its range of application includes fault current from 500A to 106kA and three phase voltages between 208V and 15kV. It does not includes calculation guideline for

higher voltage ranges and beyond the range of current. For experts engaged in arc flash analysis, it offers a useful resource that offers a consistent method for evaluating risks, figuring out incident energy levels, and establishing the right safety precautions in place. This standard states that there is no maximum limit on the fault clearing time. The experiments were conducted with arc durations up to 30 cycles, but they were normalized to 6 and 12 cycles testing. It is deemed appropriate for time and incident energy to have a linear relationship. Unless specific test results for particular equipment have been mentioned, there is obviously a linear relationship between Incident energy and time beyond 30 cycles.

[3] The necessity of HV arc-flash examination has been discussed in this study, which also applied arc-flash analysis to a HV power system. This contrasts the many arc flash analysis methods that are available and examines the consistency of the findings. The optimum course of action, according to this study, is to use integrated analysis tools that are commercially accessible, such as those used for IEEE 1584-2018 and 2002 techniques.

[4] The IEEE1584-2018 standard employs a practical approach to interpolate intermediary values of mean arcing current, incident energy, and arc flash boundary, accounting for factors like enclosure dimensions and arc-current fluctuation. This research suggests a simplified approach for computing arcing-current, incident-energy, and arcing flash boundary, drawing upon the IEEE-1584 outcomes as a point of reference. At the beginning, the focus lies on analyzing normalized arcing fault-current within the context of maximum power transfer conditions. This unveils the pivotal influence of power factor on fault current dynamics and identifies an operational arc resistance. For low voltage AC power systems, for voltage less than 600 V, the article proposes provisional criteria for evaluating IE, AFB, and selecting appropriate PPE. This study validates the variables proposed by simpler version of model against the IEEE guide's arc-fault current calculation. Furthermore, numeral outcomes obtained from case-studies using proposed approach align closely with those obtained using the IEEE1584-2018 guide. By introducing a normalized model for arc-fault current analysis, emphasizing the influence of power factor, and identifying operational arc resistance, this study provides a comparative analysis against the IEEE 1584 standard method, demonstrating only minor deviations.

[5] A case study of Silver-Springs-North substation from North Florida has been presented in this paper. ETAP 14.1 is used to develop and assess the substation's electrical power system model. It carried the study taking various substation configurations into account. Arc flash analysis was mostly performed on two cases in this study. The first scenario involved the substation receiving its energy mostly from the utility grid, which is termed as Case-I, and the second involved the substation receiving its electricity primarily from emergency backup, liquid-propane-vapor generator, termed as Case-II. For the analysis, the IEEE 1584 technique was used. Primary goal of this research was to determine possible cause of a high incident energy level at one AC panel that was receiving emergency backup power. It was discovered that the cause of the high incident energy issue was from a linked PD's fixed trip setting, which made the PD operate slowly when clearing faults. Then, a solution that significantly lowers incidence energy was suggested to address the issues with excessive incident energy. The arc flash analysis result of this study are as mentioned following:

Table 2.3 Case-I Analysis Result [5]

Bus-ID	Voltage (kV)	IE (cal/cm <sup>2</sup> )	FCT (Sec)
PNL-1	00.2400	01.3200	00.21300
PNL-2	00.2400	01.3500	00.22700
PNL-3	00.2400	01.3100	00.20600
PNL-4	00.4800	00.4900	00.02300

Table 2.4 Case-II Analysis Result [5]

Bus-ID	Voltage (kV)	IE (cal/cm <sup>2</sup> )	FCT (Sec)
PNL-1	00.2400	0558.900	0170.800
PNL-2	00.2400	0574.300	0178.800
PNL-3	00.2400	0552.000	0167.400
PNL-4	00.4800	0075.430	0034.000

The Table2.3 presents arc flash analysis result of respective panels for normal configuration of substation and table 2.4 shows the arc flash analysis result of respective panels for LPV configuration. It identifies arc flash risk due to higher FCT in LPV configuration. Study analyzed number of possible mitigation method to resolve this problem and suggest the two possible solution of replacing the generator circuit breaker

with the mentioned model number. The arc flash analysis result for the recommendations are mentioned in the Table2.5, and Table2.6.

Table 2.5 Case-II Mitigated Analysis Result with FG3225

Bus-ID	Voltage (kV)	IE (cal/cm <sup>2</sup> )	FCT (Sec)
PNL-1	00.2400	0823.400	0251.700
PNL-2	00.2400	0847.400	0263.200
PNL-3	00.2400	0808.000	0245.100
PNL-4	00.4800	0099.720	0044.900

The Table2.5 Shows arch flash analysis result with recommendation1, however it does not reduce the incident energy and FCT, so that it could not be viable solution.

Table 2.6 Case-II Mitigated Analysis Result with JG3225

Bus-ID	Voltage (kV)	IE (cal/cm <sup>2</sup> )	FCT (Sec)
PNL-1	00.2400	00.1420	00.036
PNL-2	00.2400	00.1400	00.037
PNL-3	00.2400	00.1430	00.036
PNL-4	00.4800	00.0770	00.029

The Table2.6 Shows arch flash analysis result with recommendation 2 having breaker trip setting low 350A, this option has significantly reduced the IE and FCT so that this recommendation has been selected for resolving the arc flash problem.

[6] The OSHA has data of electrical incidents and classified their types and we can identify the incident due to arc flash. According to their record, In U.S, from 2021 to 2022 total 38 major electrical incidents were reported. Out of 38 reported incidents 20 incidents were due to arc flash with three fatality. However, In Nepal we do not have such organized data of arc flash incidents, there were many fire incidents reported at substation and industrial area and electrical workplace. I have collected some of the arch flash incident data by substation visit and reports from the substation Engineer. There was a CT burst incident and leading to arc flash in Siuchatar substation on June 17, 2023. There was smoke detected in the cable trench in Siuchatar Substation on July 03, 2023 as per NEA maintenance team reporter because of insulation failure and cable short circuit that was in low voltage control cable. Number of times cable burst incident were recorded in Attariya Substation leading to arcing and power system disruption.

According to substation engineer, unfortunately there was a serious Arc flash incident in Patan substation in 2053 B.S which was due to accidental burn in switchgear control panel which caused serious burns on hand and one fatality. As per the report from respective authority at Balaju, a fire broke out at the Nebico Biscuit Factory located in the vicinity, which was due to arc flash caused by short circuit. Which caused significant economic and technical loss. However these were some of the identified records and incident, there were not such practice of recording and classifying the electrical incident in Nepal. Recently, The Switchgear control panel in Attariya substation have been upgraded with the new digital relays, in that instance I find viable to do the arc flash analysis of the Attariya substation, because that might have resulted changes in the arc flash characteristics, and to ensure safety-reliability of the substation, which is a crucial element of the power system, is imperative, which is a key component of power system.

[7]NFPA70E-2018, it has introduced regulations and guidelines aimed at ensuring electrical safety within work environments, particularly emphasizing the dangers associated with electrical systems and arc-flash incidents. This standard's primary goal is to safeguard workers from electrical hazards, thereby minimizing the occurrence of injuries and fatalities. It outlines a detailed approach, for evaluating electrical risks, implementing safety measures, and selecting proper PPE for electrical work. This standard includes provisions for assessing incident energy levels and determining necessary PPE. Furthermore, it addresses key aspects of electrical safety such as risk assessment, safety programs, arc flash analysis, lockout / tagout procedures, training, equipment maintenance, and inspection. By integrating NFPA 70E-2018 into workplace safety protocols, organizations can significantly reduce the likelihood of electrical accidents and improve worker safety. Its comprehensive guidelines offer a structured framework for risk assessment, safety protocols, and PPE choices. Adhering to this standard in both research and practical applications contributes to enhancing worker safety and preventing electrical accidents and injuries. In addition to its focus on electrical safety protocols, NFPA 70E-2018 also emphasizes the importance of regular training and qualifications for workers involved in electrical tasks, ensuring they are equipped with the necessary knowledge and skills to perform their duties safely. Furthermore, the standard underscores the significance of ongoing equipment maintenance and inspection to identify and address potential hazards before they

escalate into accidents or injuries. Implementation of NFPA 70E-2018 not only reduces the risk of electrical accidents but also fosters a culture of safety awareness and accountability within organizations, ultimately promoting a safer work environment for all personnel.

[8] The main aim of this research was for presenting a mathematical approach for modeling arcing-voltage, then to examine the voltage properties of arc faults in short – gaps, within medium-low-voltage systems. The simulation method of magneto hydrodynamics has been investigated as a mathematical model amendment to obtain the dependable model parameters. In order to simplify application on-site, a substantially different model has been devised to compute arc voltage gradient, which has proven to be effective in predicting voltage-gradient of medium-voltage, and low-voltage shorts arcs with reasonable accuracy based on fitting results. Additionally, this research systematically delved into the mathematical approach for thoroughly analyzing the dynamic behaviors of arc voltage in medium-low arc flash incidents. As an enhancement to the existing mathematical method, the study suggests the utilization of the MHD-simulation-based arc-modeling technique, which has been derived from a rest configuration. By conducting comparisons between models, the study concludes that the newly proposed model exhibits a strong fitting ability, accurately capturing the voltage-gradient of medium-voltage, and low-voltage short-arcs. Consequently, the model serves as a practical and user-friendly resource for improving measures aimed at protecting against medium-low arc faults.

[9] In this research, arc flash analysis tests were conducted at EPRI's testing facility located in Lenox, Massachusetts. The study encompassed tests involving both bushings and dead-ends. Notably, the test outcomes unveiled higher incident energy levels than initially anticipated for both overhead arc-flash instances, and arc-flash incidents occurring at pad-mounted switches. The meticulous analysis was undertaken in case of overhead arc-flash instances, taking into account extended arc-lengths. Additionally, for pad-mounted switches, an equation was formulated to aid in aligning protective-clothing-requirements, incorporating minimal distances for approaching and protection relaying positioned at the upstream. Ultimately, the study underscores the significance of assessing specific equipment and arc flash scenarios to enhance the precision of arc flash analysis methodologies.

[10] This study conducted an analysis of arc flash on the IEEE 8-bus test model through DIgSILENT software. The incident energy calculation is based on IEEE 1584 and NFPA 70E standard method and using DigSILENT. Study Modeled the IEEE 8 bus test system then performed Load flow analysis, Short circuit analysis, Relay co-ordination analysis and finally performed arc flash incident-energy calculation. The result of arc-flash-analysis, and FCT variation with respect to incident energy have been mentioned in the study. Nevertheless, the occurrence of an arc fault poses a considerable risk, potentially resulting in substantial damage to equipment and severe injury to workers. This study performed study on the basis of data collected for IEEE 8 bus test system considering various arrangements of electrodes including: CVB; VCBB; HCB; VOA; and-HOA. The determination of incident-energy (IE) involved applying the methodology outlined in the IEEE 1584 and NFPA 70E standards.

Table 2.7 Arc Flash Analysis Result [10]

Bus-ID	Voltage (kV)	IE (cal/cm <sup>2</sup> )	Ia (kA)	AFB (m)
Bus1	148	45.27	36.4	34.34
Bus2	139	50.12	40.5	48.65
Bus3	145	22.77	27.3	24.61
Bus4	148	50.90	38.2	41.45
Bus5	146	46.87	23.9	39.92
Bus6	149	63.67	37.9	50.41
Bus7	145	25.34	23.2	26.92
Bus8	139	64.43	30.6	45.78

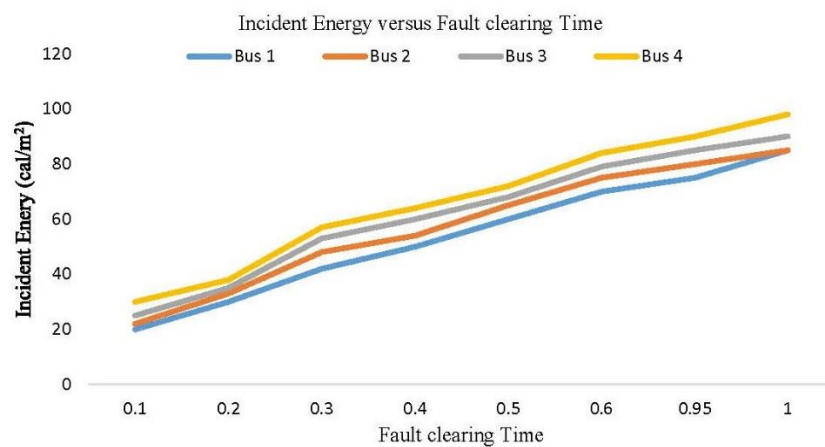


Figure 2.3 IE versus FCT Plot [10]

The table 2.7 shows the arc flash analysis result including incident energy (cal/cm<sup>2</sup>), short circuit current (kA), nominal bus voltage (kV) and arc flash boundary (meter). On the other hand, the figure 2.3 shows the variation of FCT with respect to the incident energy (IE). From the above figure it could be observed that, with increase in fault clearing time (FCT), the incident energy (IE) of all the buses including Bus1, Bus2, Bus3 and Bus4 have been increased.

[11] This provides an IEEE four node Test feeder with the data mentioned in Annex A, This provides a simple test feeder to examine our method of arc analysis. It explains all the necessary data and parameters required to model the test system using selected tool.

[12] This presents standardized guidelines for conducting protection coordination studies in power systems, commonly referred to as IEEE Buff Book or IEEE Std. 242-2001. It offers standardized guidelines for conducting protection-coordination studies in power systems. This guide delineates key principles for ensuring the protection and efficient coordination of industrial, and commercial power-systems, aimed at safeguarding them against potential anomalies expected during operation. The information is systematically organized, facilitating easy comprehension and making it an invaluable resource for both initial system design and the optimization of existing operations for enhanced protection. According to this standard, the total clearing time of protective devices is contingent upon factors such as the relay type and the choice of circuit breaker or fuse. Tables 2.8 through 2.10 within the standard provide estimated clearing times for various protective devices, aiding in efficient system planning and maintenance.

Table 2.8 Duration of PD clearance anticipated:

Relayed-CB: 2.4-13.8 kV [12]

	Rapid action- piston- Instantaneous	Induction-type- Instantaneous- relay	Induction-type Inverse-time
Relay-times In-cycles	00.25-1.00	00.50-2.00	6.00-6000.00
Circuit-breaker clearing-time In-cycles	03.00-08.00	03.00-08.00	03.00-08.00
Total-time in-cycles	03.25-09.00	03.50-10.00	09.00-6000.00

Table 2.9 Duration of PD clearance anticipated:

MCB, 600Volt, and lower [12]

	Frame Size	
	0225.00-0600.00	1600-4000A
Instantaneous-in-cycles	02.00-03.00	02.00-03.00
Short-time in-Cycles	010.00-030.00	010.00-030.00
Long-time in-Seconds	Above 100.00	
Ground-fault-in-cycles	010.00-030.00	010.00-030.00

Table 2.10 Duration of PD clearance anticipated:

PCB, 600V, and lower [12]

	Frame Size	
	00.50-01.00	1600-4000A
Instantaneous-in-Cycles	00.50-01.00	1600-4000A
Short-time-in-Cycles	010.00-030.00	010.00-030.00

[12] The standard outlines fault clearing time into three categories, those are:

- a. Relayed Circuit-Breaker: The overall duration required for fault-clearance comprises the operation time of the overcurrent-relay (OCR), in addition to any time taken by auxiliary-relays (if employed), along with the circuit breaker's interruption time.
- b. Direct-tripping Circuit-Breaker. The complete fault clearance-time (FCT) is equivalent to the operating time of the circuit-breaker.
- c. Fuses: The total-fault clearance -time (FCT) encompasses both the melting-time and the arcing-time.

Thus the reference standard provides guidelines and standard platform for coordination studies and also defined the standard estimated fault clearing time.

## 2.1 Research Gap

Despite significant advancements in the field of arc flash analysis and mitigation, there are still several research gaps that need to be addressed, particularly in the context of substation protection in Nepal. These research gaps include:

**I. Limited studies in specific regional contexts:** While arc flash analysis has been extensively studied in various countries, there is a need for more research focused on specific regional contexts such as Nepal. Regional factors, including infrastructure,

equipment, climate and regulatory frameworks, may exert a considerable influence on arc-flash hazards and mitigation strategies. Therefore, there is a gap in the literature regarding the specific challenges and requirements for substation protection in Nepal.

**II. Lack of comprehensive studies on substation-specific hazards:** Substations present unique challenges in terms of arc flash hazards due to the presence of high-voltage equipment, complex interconnections, and multiple power sources. However, there is a scarcity of comprehensive studies that specifically address the arc-flash hazards, and mitigation-techniques of substation environments. Existing research often focuses on broader electrical systems and does not provide sufficient guidance for substation protection.

**III. Limited focus on practical implementation and effectiveness of mitigation techniques:** While there are several mitigation techniques available for arc flash hazards, the practical implementation and effectiveness of these techniques in substation protection require further investigation. The literature lacks comprehensive studies that evaluate the real-world application of mitigation strategies, their impact on reducing arc flash hazards, and their cost-effectiveness in substation settings.

**IV. Limited consideration of human factors and safety culture:** Although the technical aspects of arc-flash analysis and mitigation-technique are crucial, it's essential not to underestimate the importance of human factors and safety culture. There is a need for research that examines the influence of human behavior, training programs, and organizational safety culture on the effectiveness of arc flash mitigation strategies in substation environments. Understanding the human factors involved can lead to the development of more comprehensive and effective safety protocols.

Addressing these research gaps is necessary to enhance the understanding and implementation of arc flash analysis in substation protection. However these research gap exists, this study aim is to conduct the arc flash analysis in Attariya substation Nepal due to following reasons and research requirements. One significant research gap is the limited studies on arc flash analysis and mitigation techniques specific to the Nepalese substation context. While extensive research has been conducted on arc flash hazards and mitigation globally, there is a lack of comprehensive studies that focus specifically on the unique challenges and requirements of substation protection in Nepal. There is a need for research that examines the effectiveness of mitigation

techniques in reducing arc flash hazards in Nepalese substations. While various mitigation measures are available, their practical implementation, effectiveness, and cost-efficiency in the Nepalese context remain largely unexplored. This research will bridge the gap by evaluating the real-world application of mitigation strategies, analyzing their effectiveness in reducing arc flash incidents, and assessing their economic feasibility in the Attariya Substation. By addressing these research gaps, this study will contribute to the body of knowledge on arc flash analysis and mitigation techniques in substation protection specifically in the Nepalese context. The findings will enhance the understanding of arc flash hazards in Nepalese substations, provide practical recommendations for improving substation protection, and contribute to the development of guidelines and standards that are tailored to the unique needs of Nepal's electrical infrastructure. In the realm of electrical engineering and substation protection, the phenomenon of arc flash poses significant challenges, especially in regions like Attariya, Nepal, where infrastructural development is rapidly advancing. As we delve into the literature surrounding arc flash analysis and mitigation strategies, it becomes apparent that while considerable strides have been made in understanding and addressing this hazard, there remains a critical need for tailored solutions that accommodate the unique environmental and operational characteristics of Attariya Substation. This dissertation aims to contribute to the growing body of knowledge in this field by synthesizing existing research, identifying gaps, and proposing contextually relevant strategies for enhancing arc flash safety within the specific context of Attariya Substation. By doing so, we endeavor not only to mitigate the risks associated with arc flash incidents but also to foster safer working environments for personnel and ensure the reliability and sustainability of Nepal's power infrastructure.

## CHAPTER THREE: METHODOLOGY

### 3.1 Introduction

This methodology section of the study outlines the method and steps that will be followed to achieve the research objectives. This study has been started with a comprehensive literature review to gather relevant studies, articles, and industry standards related to arc flash hazards and mitigation techniques. A feasible and suitable Attariya substation has been selected based on its past arc flash incident record and new equipment upgrades. IEEE Std. 1584 [2] is the main reference of arc flash analysis of this study and IEEE Std 242-2001 [12] is the reference for protection coordination study.

### 3.2 Equation for Arc Flash Calculations

The mathematical expression based on IEEE Std. 1584 [2] for determining the incident-energy, and arcing current can be briefly presented. The criteria under which the IEEE Std. 1584 calculation method remains applicable are as follows [2].

- i) Range of Voltage: 208 V-15 kV, three-phase (line-to line)
- ii) Frequency Sixty Hertz or Fifty Hertz
- iii) Current in bolted fault condition
  - i) For voltage-208V to 600V: 500A to 106kA
  - ii) For voltage-601V to 15kV: 200A to 65kA
- iv) Gaps between conductors:
  - i) For voltage-208V to 600V: 06.35mm to 076.2mm
  - ii) For voltage- 601V to 15kV: 019.05mm to 0254mm
- v) Working distances of 305 millimeters or more
- vi) Electrode configuration: VCB, VCBB, HCB, VOA & HOA

The Incident Energy (E), Arcing fault current (I<sub>a</sub>), and Arc-Flash-Boundary (AFB) are calculated applying the following formulae of computation [2]:

$$\begin{aligned} \text{Log}(I_a) = & a + 0.662 * \log(I_{bf}) + 0.000526 G + 0.0966 V \\ & - 0.00304 G * \log(I_{bf}) + 0.5588 V * \log(I_{bf}) \end{aligned} \quad \text{Eq. 3.1}$$

Where, fault current in kA is represented by I<sub>a</sub>, The constant “a” value is -0.097 and 0.153 for box configurations and open configurations respectively. The fault-current in bolted-fault condition, in the range of kA, is represented by I<sub>bf</sub>. V is the system voltage

in kV. G denotes gap between conductors in millimeters. The common spacing between-conductors, on panels within voltage range of 0.208 kV to 1 kV is usually 25 mm.

$$\text{Log}(E_n) = a_1 + a_2 + 0.0011 * G + 1.081 * \log(I_a) \quad \text{Eq. 3.2}$$

Where,

a1 equals 0.792 and -0.555 for open-configurations and box-configurations respectively. a2 is 0.00 and -0.113 in case of ungrounded (high-resistance grounded) and grounded system respectively.  $E_n$  signifies normalized incident energy in cal/cm<sup>2</sup>.  $I_a$  is arcing-fault current, measured in kA.

$$E = E_n C_f (t/0.2) * (610^x / D^x) \quad \text{Eq. 3.3}$$

Here,

In case of voltages exceeding 1 kV, the value of  $C_f$  is set to 1, while for voltages below 1 kV, it is adjusted to 1.5. The parameter D and t represents working distance in millimeters and arcing time respectively. Distance exponent, denoted by x, is determined according to IEEE Std.-1584.

$$D_B = [E_n * C_f (t/0.2) * (610^x / E_B)]^{1/x} \quad \text{Eq. 3.4}$$

Here,

$E_B$  denotes the incident-energy value at the boundary, measured in cal/cm<sup>2</sup>, while  $D_B$  represents the boundary distance in millimeters.

It is obvious that IEEE 1584 standard method provides the calculation only up to 15 kV. In cases where the voltage surpasses 15kV or the gap extends beyond the model's specified range, the Lee method might be implemented to determine the incident energy, employing the following equation Eq. 3.5 [10].

$$E = 2.142 * 10^6 * I_{bf} * (t/D^2) \quad \text{Eq. 3.5}$$

Here,

“E” refers to incident-energy measured in cal/cm<sup>2</sup>, system-voltage measured in kV is represented by “V”, and the variable “t” refers to arcing-time in seconds. The Variable “D” represents distance from potential arcing location point, measured in millimeters.

According to the Lee method, Boundary Distance is given by the following equation [10]:

$$D_B = [2.142 \cdot 10^6 \cdot V \cdot I_{bf} \cdot (t/E_B)]^{1/2} \quad \text{Eq. 3.6}$$

Where,  $D_B$  denotes the distance from the arc point measured in millimeters, "V" refers to the system-voltage expressed in kilovolts, and "t" stands for the duration of arcing measured in seconds and  $E_B$  refers to incident energy  $\text{cal/cm}^2$  at the boundary distance.

### 3.3 Data Collection and System Modeling

The site visit to Attariya substation has been completed and all the necessary data have been collected. The gathered information encompasses equipment specifications, including voltage rating, MVA rating, impedance, system fault level, X/R ratio, and protection settings of the substation. The panel's electrode configuration was validated and documented following the guidelines specified in Std. 1584-2018 [2]. According to the collected data and information, the substation from 33 kV towards the load, has been modeled in ETAP 19.01 [2]. Based on the collected data and information the substation from 33 kV towards the load has been model in ETAP 19.01.

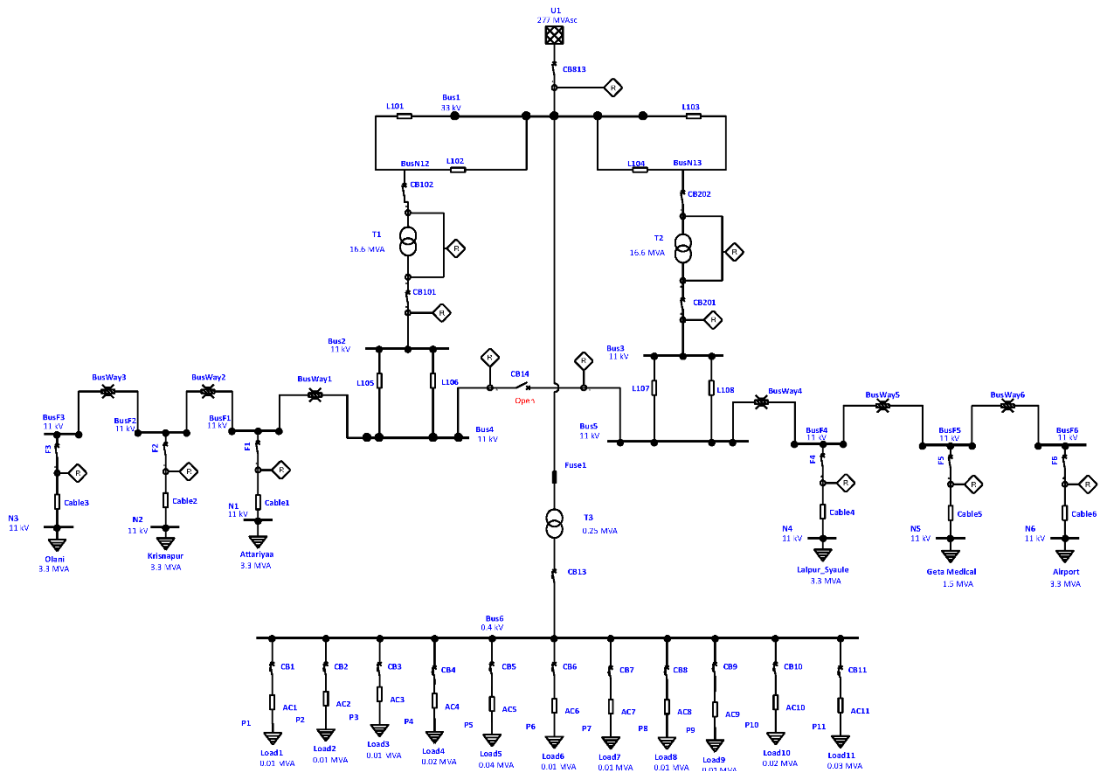


Figure 3.1 Single line diagram of Case Study Attariya Substation

The Figure 3.1 shows the single line diagram of Attariya Substation. The enlarged drawing presented in appendix D. It contains two 16.6 MVA, 33/11 kV power transformer, One 0.250 MVA, 33/0.400 kV station service transformer, five 3.3 MVA feeders and one 1.5 MVA feeders. There are two incomers in 11 kV switchgear with a bus tie CB in normally open configuration. The main 33 kV incomer has been protected by OCR, two power transformer have been protected by differential relays separately, 11 kV incomers are protected by multifunction relay with OCR and EF enabled, six outgoing feeders are also protected by multifunction relay with OCR and EF enabled. The Station service transformer HV side protected by fuse element and LV side protected by MCCB. Original setting of PD and CB have been recorded and implemented in the substation model prepared for the analysis. There are 11 outgoing circuits from station service distribution panel, each circuit protected with 4 pole MCB. The loading of the outgoing feeders are considered with respect to the average loading of the feeders, normally feeders loading found to be 50% of the total MVA rating. The OCR of five feeders have been set to trip at 195 A, one 1.5 MVA feeder OCR has been set to trip at 60 A. All the outgoing feeder circuit breakers are rated 1250 A, with breaking Capacity 25 kA and making capacity of 63 kA. While two incomers CB rated 2000 A, with braking capacity of 25 kA, and making capacity of 63 kA. The Bus bars and Bus ways are rated 2500A, with 25kA Peak and electrode configuration in Panel are HCB with reference to Std.1584 Guideline [2]. General Spacing line-line are 152 mm while line-ground spacing noted 52mm. The UG cables connected from the indoor switchgear panel to the outdoor distribution pole termination in open air horizontal that means HOA configuration. Power transformer breaker are rated 2000A, with breaking capacity 25kA and making capacity 65 kA. The Bus 1 is considered as swing bus which will be connected to 132 kV bus bar through grid transformer. The six 630 mm<sup>2</sup> UG cable connects 33 kV Bus bar to Transformer 1, that means two 630 mm<sup>2</sup> cable in each phase and similar applies to Transformer 2. The 11kV output from 16.6 MVA transformer has been connected to indoor switchgear Incomer 1 by six 400 mm<sup>2</sup> UG cable, that means two cable in each phase, and similar applies connection between transformers to Incomer 2. The 11kV switchgear to outdoor distribution pole has been connected by 300 mm<sup>2</sup> UG cable. For one 1.5 MVA feeder 95 mm<sup>2</sup> cable has been installed.

Table 3.1 Two Winding Transformer Input Data of Attariya SS

Transformer ID	Phase	MVA	Prim . kV	Sec. kV	%Z	X1/ R1	% Tap Prim.	Type	Shift Angle
T1	3P	16.6	33	11	11.93	15	-2.5%	Dyn	0
T2	3P	16.6	33	11	11.93	15	-2.5%	Dyn	0
T3	3P	0.250	33	0.4	4.5	1.5	0	Dyn	0

Table 3.1 Show the transformer parameters based on collected data from the field visit and with reference to their nameplate available. Two transformer T1 and T2 are Power transformer, while Transformer T3 is station service transformer. The vector group of all transformer is Dyn without any phase shift.

Table 3.2 includes all the cable, line and bus way input data used in the modeling of the existing Attariya substation, the resistance, impedance and admittance values are for the specified temperature. AC1, AC2, AC3, AC4, AC5, AC6, AC7, AC8, AC9, AC10 & AC11 are 4 mm<sup>2</sup> cable installed for station service circuits. Six Cable from Cable 1 to Cable 6 are installed from indoor 11 kV switchgear to outdoor distribution feeder pole starting terminal. Line from L101 to L108 are cables connecting from 33 kV Bus up to transformer primary terminals. Busway 1 to Busway 6 included to represent the intermediate bus bar connection in between each feeder bus bar.

Table 3.2 Line/Cable/Busway Input Data of Attariya SS

Line/ Cable ID	Size mm <sup>2</sup>	Length (m)	# Phase	T °C	R Ohm/ km	X Ohm/km	Y Simens / km
AC1	4	150	1	75	6.019744	0.130000	0.0000013
AC2	4	150	1	75	6.019744	0.130000	0.0000013
AC3	4	150	1	75	6.019744	0.130000	
AC4	4	150	1	75	6.019744	0.130000	
AC5	4	600	1	75	6.019744	0.130000	
AC6	4	150	1	75	6.019744	0.130000	
AC7	4	150	1	75	6.019744	0.130000	
AC8	4	150	1	75	6.019744	0.130000	
AC9	4	150	1	75	6.019744	0.130000	
AC10	4	150	1	75	6.019744	0.130000	
AC11	4	150	1	75	6.019744	0.130000	
Cable 1	300	50	1	75	0.076302	0.105000	0.0001590
Cable 2	300	50	1	75	0.076302	0.105000	0.0001590
Cable 3	300	60	1	75	0.076302	0.105000	0.0001590
Cable 4	300	70	1	75	0.076302	0.105000	0.0001590
Cable 5	95	50	1	75	0.236536	0.123000	0.0001015

Cable 6	300	50	1	75	0.076302	0.105000	0.0001590
L101	630	40	1	75	0.040059	0.108000	0.0001027
L102	630	40	1	75	0.040059	0.108000	0.0001027
L103	630	40	1	75	0.040059	0.108000	0.0001027
L104	630	40	1	75	0.040059	0.108000	0.0001027
L105	400	35	1	75	0.040059	0.108000	0.0001027
L106	400	35	1	75	0.040059	0.108000	0.0001027
L107	400	40	1	75	0.040059	0.108000	0.0001027
L108	400	40	1	75	0.040059	0.108000	0.0001027
BusWay1		0.8	1	25	0.015652	0.008858	0.0001762
BusWay2		0.8	1	25	0.015652	0.008858	0.0001762
BusWay3		0.8	1	25	0.015652	0.008858	0.0001762
BusWay4		0.8	1	25	0.015652	0.008858	0.0001762
BusWay5		0.8	1	25	0.015652	0.008858	0.0001762
BusWay6		0.8	1	25	0.015652	0.008858	0.0001762

Table 3.3 Bus Input Data of Attariya SS

Bus ID	Nominal voltage kV	Initial Voltage		Load Constant Z	
		% Mag	Angle	MW	Mvar
Bus1	33	100	0.0		
Bus2	11	100	0.0		
Bus3	11	100	0.0		
Bus4	11	100	0.0		
Bus5	11	100	0.0		
Bus6	0.40	100	0.0		
BusF1	11	100	0.0		
BusF2	11	100	0.0		
BusF3	11	100	0.0		
BusF4	11	100	0.0		
BusF5	11	100	0.0		
N1	11	100	0.0	1.485	0.719
N2	11	100	0.0	1.485	0.719
N3	11	100	0.0	1.485	0.719
N4	11	100	0.0	1.485	0.719
N5	11	100	0.0	1.485	0.719
N6	11	100	0.0	1.485	0.719

The table 3.3 shows the Bus input data of Attariya substation, where Bus 1 is Swing Bus and rest of other buses are load bus. From BusF1 to BusF6 represents 11kV feeder bus bar, from N1 to N6 represents outdoor termination at the feeder. Thus all the necessary data has been collected and entered into the circuit model. The load constant Z defined for modeling of load as constant impedance load. The modeling of existing

Attariya substation has been completed using ETAP 19.01 and make the model ready for power system analysis including: The Load-Flow analysis, Short-circuit Analysis, Protection-coordination and Arc flash analysis.

On the other hand, before proceeding to our case study arc flash analysis, the IEEE four node test-feeder system has been modeled based on standard data available in reference [11] in order to perform comprehensive arc flash analysis using ETAP19.01.

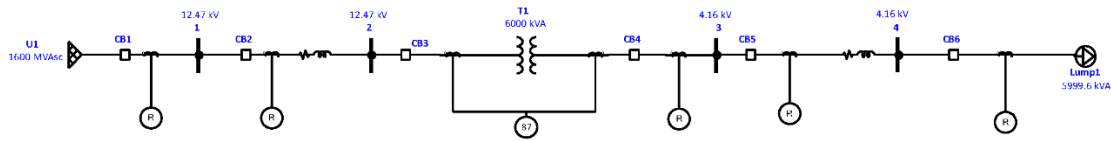


Figure 3.2 Single line-diagram of IEEE Four-Node Test-Feeder [11]

Figure 3.2 presents IEEE four-node test-feeder model. Enlarged drawing of the single line diagram is shown in appendix A. It includes a two winding transformer rated 6000 kVA, 3 Phase, 12.47 / 4.16 kV, %Z1=6.08%, X1/R1=6, YNyn. Model contains four buses: Bus 1 as swing Bus 12.47 kv, Bus2 is 12.47 kV Bus3 is 4.16 kV and Bus4 is 4.16 kV with Initial voltage magnitude of 100%, the Bus 4 is load bus with 5.5 Mw and 2.615 Mvar loading.

Table 3.4 Line Data of IEEE 4-Node Test-Feeder

Line ID	Size mm <sup>2</sup>	Length ft	# Phase	T °C	R Ω / 1000 ft	X Ω /1000 ft	Y Simens /1000 ft
Line 1	336	2000	1	50	0.057968	0.118739	0.0000013
Line 2	336	2500	1	75	0.057968	0.118739	0.0000013

The table 3.4 shows the line data of IEEE 4 node test feeder used for arc flash analysis in our study. The resistance, impedance or admittance shown are at specified temperature.

Thus with all the system data and relevant information, the study could be proceeded in sequential manner of load-flow analysis, short-circuit current calculation, protection-coordination studies, and final arc flash analysis. All of the preceding studies shall be conducted before arc flash studies in order to determine the system loading status, for

verifying protective device coordination status, and to find out the fault clearance time. Without knowing the exact fault clearing-time, the incident energy and arcing current could not be calculated accurately based on IEEE 1584-2018 Std. Thus this arc flash analysis could be related to the power system studies and this study could be a part of dissertation for master in power system engineering.

### **3.4 Power System Analysis**

Once the study model has been finalized with reference to the collected verified data and relevant standards, the arc flash analysis includes the series of power system studies as mentioned earlier, such as load-flow-analysis, short-circuit studies, and protection-coordination studies. The Attariya Substation serves as a critical node within the power distribution network, necessitating thorough analysis to enhance its operational efficiency and reliability. This section introduces the methodologies adopted for load-flow analysis, short-circuit studies, and protection-coordination studies using ETAP 19.01, the brief method of those analysis could be explained as mentioned following using the ETAP 19.01.

#### **3.4.1 Load Flow Analysis**

Load-flow analysis is fundamental in understanding the steady-state behavior of the power-system, aiding in voltage regulation and network optimization. Utilizing ETAP 19.01, this study involves comprehensive modeling of the substation's network topology, incorporation of load characteristics, and simulation of various operating scenarios. Analysis of voltage profiles, active and reactive power flows, and line loading is conducted to ensure optimal system performance.

#### **3.4.2 Short Circuit Studies**

Short-circuit studies are crucial in assessing the system's response to fault conditions and determining fault currents. Using ETAP 19.01, fault scenarios are simulated at critical points within the Attariya Substation. The analysis includes calculation of fault currents, fault levels, and voltage dips to ensure equipment withstand capability and personnel safety.

#### **3.4.3 Protection Coordination Studies**

Protection coordination is essential to optimize protective device settings for selective fault isolation. ETAP 19.01 facilitates the creation of coordination curves, allowing

analysis of relay operating times and coordination intervals. This ensures reliable and efficient protection schemes, minimizing disruption to system operation. The protection coordination studies has been conducted with reference to the IEEE Std.242-2001, which explains all the necessary steps and methods for protection coordination study of the power system considering all the relevant scenarios and protective device characteristics.

Protection coordination is important to ensure the right device will be operated for the fault within the designated time such that the fault will be cleared with minimum pressure to the power system network, in this case the substation equipment and devices. Practical implementation involves data acquisition, model development, simulation setup, analysis execution, and result interpretation within the ETAP 19.01 environment. This phase ensures seamless integration of theoretical concepts into practical applications, providing actionable insights for system enhancement. The results obtained from load-flow analysis, short-circuit studies, and protection coordination are presented and critically discussed. System vulnerabilities are identified, protection settings are optimized, and operational enhancements are recommended to improve the overall performance of the Attariya Substation. In conclusion, the methodology outlined for load-flow analysis, short-circuit studies, and protection-coordination using ETAP 19.01 demonstrates its effectiveness in enhancing the operational reliability and safety of the Attariya Substation. These insights contribute to informed decision-making and sustainable management of the power distribution network. If there are any scenario noticed which contribute to the arc flash beyond the designated level, the necessary action could be taken and possible risk of arc flash could be minimized without any unplanned outage thus saving cost of outage as well as possible risk of injury or damage to equipment and electrical infrastructures.

### 3.5 Overall Block Diagram of Arc Flash Analysis

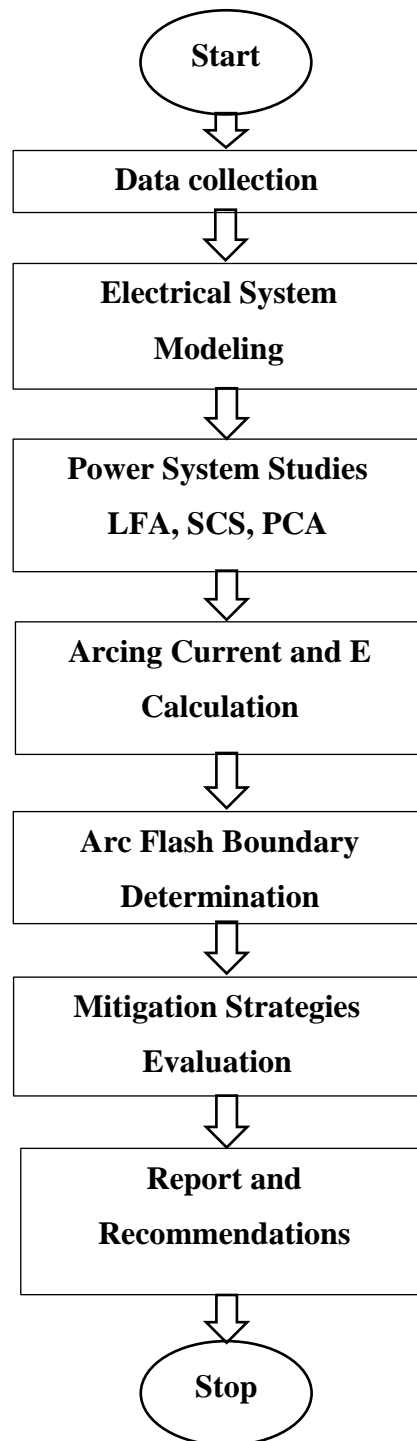


Figure 3.3 Block diagram illustrating steps in arc flash analysis

The Figure 3.3 presents the overall steps to perform this arc flash analysis in power system studies. The study begins with relevant data collection, system configuration

review and the modeling of the system has to be completed and verified. Then the power system studies begins with load flow analysis, short circuit studies and protection coordination analysis, with all these preceding analysis completed ,the arc flash analysis of the system could be completed . IEEE 1584-2018 Std. Method has been implemented in Arc flash analysis using ETAP 19.01 that means all the calculation form ETAP 19.01 software are based on above equations Eq. 3.1, Eq. 3.2, Eq. 3.3 and Eq. 3.4. For the bus voltage above 15 kV Lee method has been implemented in ETAP 19.01 using Eq. 3.5 and Eq. 3.6.

The overall block diagram could be explained as mentioned flowing

#### **Data Collection:**

The study begins with comprehensive data collection about the electrical system, including equipment ratings, configurations, conductor lengths, and operating conditions. Relevant IEEE standards for data collection include IEEE 1584-2018 and NFPA 70E. The electrode configurations and enclosures are defined with reference to the standards mentioned and all the necessary ratings and information for system modeling are collected.

#### **Electrical System Modeling:**

With reference to the collected data and relevant IEEE standards detailed model of the electrical system has been completed using specialized software ETAP 19.01 tools. This model should accurately represent the layout and characteristics of the substation. For the system modeling the device and other interconnecting cables and accessories are be selected to match the actual site conditions and verified with reference to relevant standards.

#### **Power System Studies:**

Various power system studies has been conducted to analyze the behavior and status of the electrical system under different conditions. This includes: load flow analysis, short circuit studies and protection coordination studies with ETAP 19.01. The Std.242-2001 provides detail guidelines to conduct the protection coordination studies.

#### **Arcing Current & Incident Energy Calculation:**

The arcing current and incident energy levels have been determined in the event of an arc flash. This involves using IEEE 1584-2018 for calculating arc flash parameters. The

Analysis has been conducted according to the relevant standard guidelines using ETAP 19.01

**Arc Flash Boundary Determination:**

Establish the arc flash boundary, which is the safe distance from the equipment where the incident energy is below a certain level. IEEE 1584-2018 provides guidelines for determining the arc flash boundary.

**Mitigation Strategies Evaluation:**

Identify and evaluate various mitigation strategies to reduce the risk of arc flash incidents. This may include equipment modifications, protective gear, and administrative controls. IEEE 1584-2018 and NFPA 70E (Standard for Electrical Safety in the Workplace) offer recommendations for mitigation measures.

During the study, initially we shall perform the arc flash analysis in IEEE 4 Node Test feeder form [11]. It contains two models one is original existing model with one set of protective device settings and second model with alternative protective settings and characteristics. The relevant result obtained will be analyzed. Then the case study of Attariya substation shall be performed sequentially as mentioned in the Figure 3.3. The case study also has two models, one with existing protective device settings and characteristics, and second with alternative protective device setting and characteristics. The bolted fault current ( $I_{bf}$ ), Arcing current ( $I_a$ ), Fault Clearing Time, Incident Energy and Arc flash boundary shall be evaluated then based on the result obtained we shall recommend the safe working distances and alternative mitigation in order to make substation more safer so that electrical infrastructure and equipment could be prevented from possible damage and the operating personnel shall be secured from possible consequences.

**Understanding about Cascading Arc Flash:**

All these methods evaluates for the individual arc flash event, there might be cascading arc flash, which means one arc flash event can trigger another arc flash event and can lead to devastating destructive condition. However this is very rare in place. Although the cascading arc flash analysis is not part of this study, understanding about cascading arc flash analysis is important. In the realm of electrical safety, the term "arc flash" often invokes images of isolated incidents - sudden, intense releases of energy that pose serious risks to personnel and equipment. However, in complex electrical systems, a

single arc flash can trigger a chain reaction known as a cascading arc flash event, amplifying the danger manifold. Consider a bustling substation, its intricate network of transformers, switches, and conductors humming with energy. In such environments, a fault in one component can cascade through the system like a ripple in a pond, setting off a series of successive arc flashes with devastating consequences.

The analysis of cascading arc flash events demands meticulous attention to detail. It begins with a thorough examination of the electrical system, mapping out its pathways and vulnerabilities. Data collection is paramount - every circuit, every connection must be scrutinized to identify potential weak points. Power system studies play a pivotal role in understanding the dynamics of cascading faults. Load flow analysis reveals how electrical currents propagate through the network, while short circuit studies pinpoint areas of high stress. Protection coordination studies ensure that safeguards are in place to isolate faults before they escalate. Calculating the potential incident energy of cascading arc flash events requires specialized tools and methodologies. Models like IEEE 1584 provide valuable insights into arc flash parameters, guiding engineers in estimating the magnitude of the hazard at various points in the system. Mitigation strategies must be robust and adaptive, capable of halting the progression of cascading faults before they spiral out of control. Enhanced protective relays, redundant systems, and proactive maintenance regimes all play crucial roles in minimizing risk. In the end, the analysis of cascading arc flash events is not merely an exercise in theoretical speculation - it's a vital safeguard against catastrophic failure. By understanding the intricacies of electrical systems and anticipating potential hazards, engineers and safety professionals can ensure the resilience and reliability of critical infrastructure, protecting both lives and livelihoods.

### **Introduction to Arc Flash Analysis in Overhead Distribution Feeders:**

In addition to the primary focus on arc flash analysis within substations, understanding arc flash incidents in overhead distribution feeders is imperative due to their critical role in the electrical network. This section introduces the arc flash analysis in these feeders, encompassing considerations such as network topology, load characteristics, fault current calculation, and equipment rating and protection coordination. Following established standards and guidelines from organizations like IEEE and NFPA, past analyses and references provide valuable insights into real-world scenarios and best practices for arc flash analysis. While such analyses offer advantages like enhancing

personnel safety and minimizing equipment damage, challenges include the complexity of feeder configurations and variations in load profiles. Incorporating arc flash analysis in overhead distribution feeders alongside substation analysis broadens the dissertation's scope, providing a comprehensive understanding of arc flash hazards and mitigation techniques across the entire electrical network.

However, this research mainly focus on analysis of arc flash in specific Attariya substation Nepal. The arc flash analysis till the starting point of feeder, which means substation outgoing termination point has been considered in this study, but the analysis at various location or point of distribution feeder, has not been included in the scope of this analysis, that could be further extension of this study and might need all the relevant information about the line spacing, load characteristics, information about distributed generations full information if any connected to the distribution line etc. However, the arc-flash analysis guidelines, methodologies could be similar to the analysis of arc flash analysis in substation environments.

## CHAPTER FOUR: RESULTS AND DISCUSSION

The results obtained can be presented in two parts since two models have been considered for analysis. First we shall discuss about the result of IEEE 4 Node Test feeder analysis result and then, we shall discuss about the result of case study Attariya Substation analysis.

IEEE four node test feeder input data are as mentioned earlier in methodology section and Table 3.4. For this standard test feeder the system was analyzed with first set of PD settings.

Table 4.1 PD setting for IEEE 4-Node Test-Feeder Existing Condition

Relay ID	CT Ratio	PSM	TDS
Relay 1	300:1	0.95	0.95
Relay 2	300:1	0.95	0.6
Relay 4	1200:1	0.65	0.35
Relay 5	1200:1	0.65	0.35
Relay 6	1200:1	0.65	0.25

The table 4.1 shows the OCR setting of relays for existing condition of IEEE four-node test-feeder standard model system. Relay 3 is differential relay set to operate at 0.02 seconds.

Table 4.2 LFA Result of IEEE 4-Node Test-Feeder Existing Condition

BUS ID	Nominal voltage kV	Voltage %	Current Flow Ampere	% PF
Bus1	12.47	100	335.8	82.3
Bus2	12.47	98.93	335.8	82.6
Bus3	4.16	93.99	1006.7	85.7
Bus4	4.16	82.712	1006.7	90.0

Table 4.2 represents the load flow of IEEE 4-node test-feeder, where Bus 1 is voltage regulated swing bus, Bus1 Supplies 5.967 Mw of active power and 4.124 Mvar reactive power to load connected to Bus4, which with draws 5.4 Mw active power and 2.615 reactive power rest of power dissipated among lines and cables. The load flow simulation diagram is shown in appendix A.

Table 4.3 SCS Result of IEEE 4-Node Test-Feeder Existing Condition

BUS ID	Nominal voltage kV	Symm. kA rms	Asymm. kA rms
Bus1	12.47	74.891	117.382
Bus2	12.47	21.089	23.259
Bus3	4.16	14.337	17.740
Bus4	4.16	9.750	12.978

The table 4.3 shows the summary of result obtained from short circuit studies of IEEE 4 node test feeder. It includes current flow during a short circuit under symmetrical (balanced) conditions and asymmetrical (unbalanced) condition. The Short circuit simulation diagram is shown in appendix B.

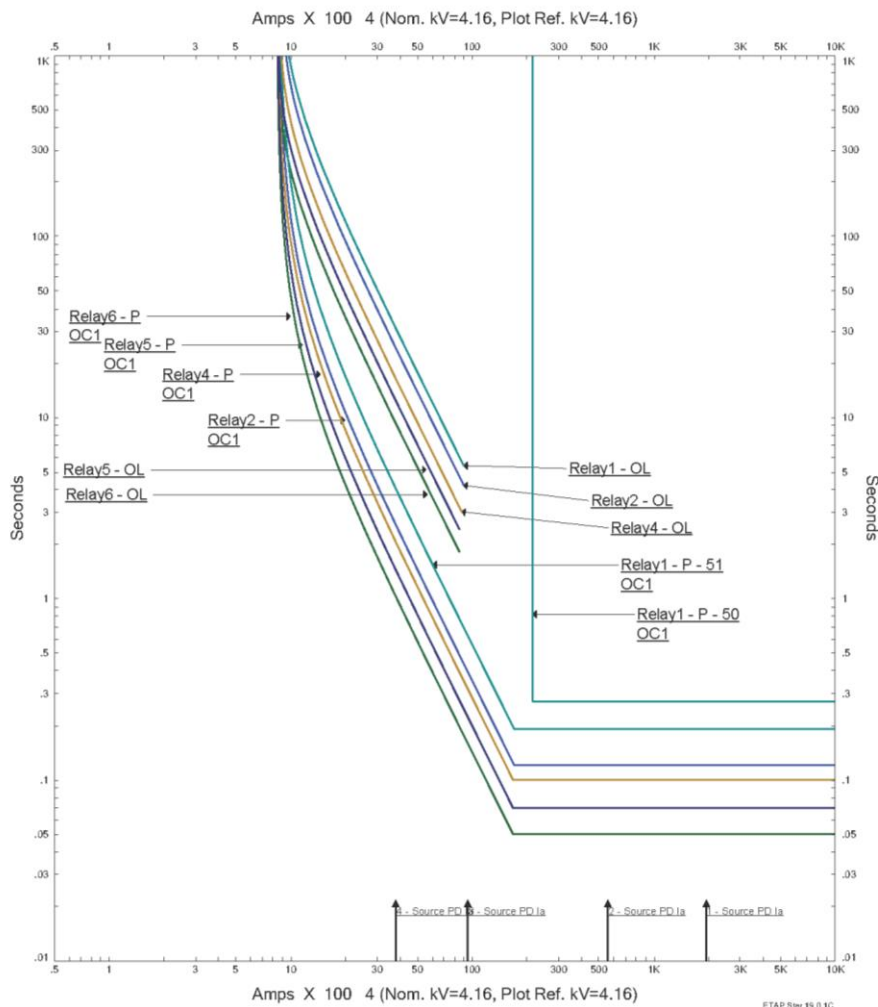


Figure 4.1 TCC of PD for IEEE 4 Node Test Feeder Existing Condition

Figure 4.1 shows the TCC of protective devices for IEEE 4 node test feeder system. TCC curve can be used for calculation of operating time of protective devices for the given fault current magnitude, and there is no any intersection points, which signifies

that only one PD operates at one time for a given fault, resulting proper coordination of the protective devices. This TCC curve has been generated from ETAP 19.01 based on the characteristics of PD considered.

Table 4.4 AFA Result of IEEE 4-Node Test-Feeder Existing Condition

BUS ID	Nominal voltage kV	I <sub>bf</sub> (kA)	I <sub>a</sub> (kA)	Incident Energy (cal/cm <sup>2</sup> )	FCT (sec)	AFB (ft)
Bus1	12.47	74.891	65.714	41.69	0.490	28.8
Bus2	12.47	21.089	19.401	9.79	0.370	11.4
Bus3	4.16	14.337	12.126	8.27	0.467	10.3
Bus4	4.16	9.750	8.308	18.98	1.55	17.4

The above table 4.4 shows the result of arc flash analysis of IEEE 4 node test feeder with VCB electrode configuration and relevant setting of protective devices and circuit breakers as mentioned in Table 4.1. This result shows that incident energy is extremely high for the fault at Bus1 and Bus 4, while incident energy are comparatively lower for fault in Bus2 and Bus3. Now, our analysis have proposed alternative PD settings in order to reduce the incident energy and make the system less vulnerable to arc flash hazards. There might me recommendation to replace the CB with lower operating time in order to clear the fault which might significantly reduce the incident energy , but that recommendation might be more costlier than changing PD setting with almost negligible cost. Changing setting of PD only involves protection coordination study cost and technical manpower cost for changing the setting. Now the result of analysis of IEEE 4 node test system with alternative settings could be presented and discussed as mentioned following. Simulation diagram has been shown in appendix B.

Table 4.5 Alternative PD setting for IEEE 4-Node Test-Feeder

Relay ID	CT Ratio	PSM	TDS
Relay 1	300:1	0.95	0.5
Relay 2	300:1	0.95	0.35
Relay 4	1200:1	0.65	0.25
Relay 5	1200:1	0.65	0.20
Relay 6	1200:1	0.65	0.10

The table 4.5 shows the OCR setting of relays for existing condition of IEEE 4 Node test feeder system. Relay 3 setting remains unchanged.

Table 4.6 LFA Result of IEEE 4-Node Test-Feeder with PD alternative setting

BUS ID	Nominal voltage kV	Voltage %	Current Flow Ampere	% PF
Bus1	12.47	100.00	319.3	84.2
Bus2	12.47	99.00	319.3	84.5
Bus3	4.16	109.897	826.6	87.0
Bus4	4.16	100.730	826.6	90.0

Table 4.6 is the result of LFA of IEEE 4 node test feeder with alternative PD setting. Along with the alternative setting of PDs the transformer tap has been changed adjusted to 5% in primary and 10% in secondary in order to overcome the under voltage problem in Bus3 and Bus4.

Table 4.7 SCS Result of IEEE 4-Node Test-Feeder with PD alternative setting

BUS ID	Nominal voltage kV	Symm. kA rms	Asymm. kA rms
Bus1	12.47	75.119	117.710
Bus2	12.47	21.335	23.559
Bus3	4.16	12.215	15.044
Bus4	4.16	9.386	12.575

The table 4.7 shows the summary of result obtained from short circuit studies of IEEE 4 node test feeder with adjusted tapping of transformer.

Table 4.8 AFA Result of IEEE 4-Node Test-Feeder with alternative PD Setting

BUS ID	Nominal voltage kV	I <sub>bf</sub> (kA)	I <sub>a</sub> (kA)	Incident Energy (cal/cm <sup>2</sup> )	FCT (sec)	AFB (ft)
Bus1	12.47	75.047	65.834	34.1	0.400	25.33
Bus2	12.47	21.258	19.555	8.56	0.320	10.47
Bus3	4.16	13.100	11.100	5.94	0.391	8.08
Bus4	4.16	9.549	8.139	12.95	1.096	13.14

After changing the setting of PDs the protection coordination have been verified and table 4.8 presents arc flash analysis result with alternative setting of protective devices. The AFA simulation diagram shown in Appendix C.

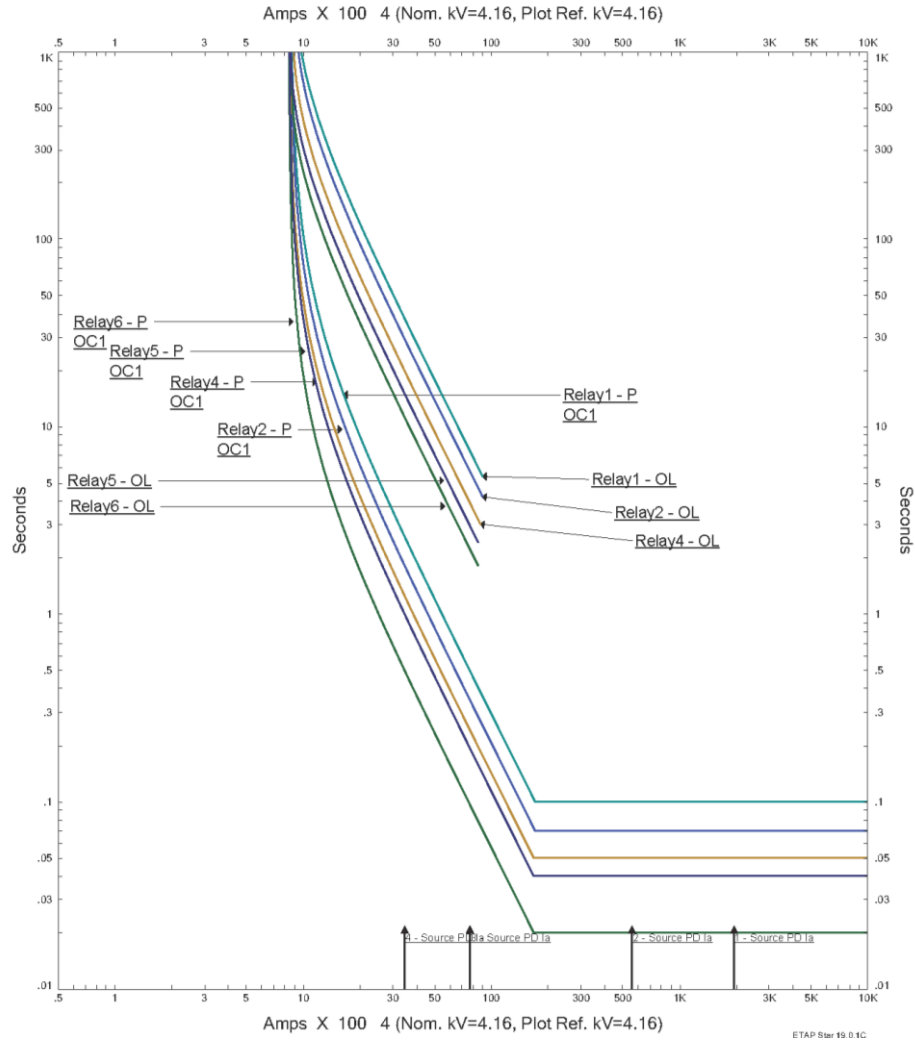


Figure 4.2 TCC of PD for IEEE 4 Node Test Feeder with alternative PD Setting

Figure 4.2 shows that all the protective devices are properly coordinated as there is not any intersection point indicating that only one device will be operated at once. On the other hand, Table 4.8 is the result of the arc flash analysis of IEEE four node test-feeder standard system. Simulation diagram is shown in Appendix A. With reference to the comparison of arc flash analysis result shown in table 4.4 and table 4.8, this signifies that incident energy at Bus 1 reduced by 18.12%, incident energy at Bus 2 reduced by 12.56%, incident energy at Bus 3 reduced by 28.17% and incident energy at Bus4 reduced by 31.77 %. The Fault clearing time have been reduced significantly. Also, the arc flash boundary has been reduced because of the lower incident energy level and lower fault clearing time. Overall, with technical calculation and adjustments the possible fault clearing time could be reduce there by reducing incident energy level

hence reducing the risk of possible consequence after arc flash incident in an electrical system. There are other methods of reducing incident energy like increasing panel enclosure size, changing electrode configuration, implementing no or very minimum time delay in breaker operation, use of high speed ground switch devices etc. Despite other mitigation, for the IEEE 4 node feeder, we have just analyzed with alternative protective device setting, because protective device setting could be altered without physical equipment replacement and it's faster, easier and could be implemented immediately.

With this analysis of IEEE four-node test-feeder, the analysis shall be elaborated using the similar method for the case study Attariya substation arc flash analysis.

Table 4.9 LFA Result of Attariya substation Existing Condition

BUS ID	Nominal voltage kV	Voltage %	Current Flow Ampere	% PF
Bus1	33.00	100.00	163.9	88.5
Bus2	11.00	100.746	261.6	90
Bus3	11.00	101.033	214.4	89.2
Bus4	11.00	100.739	261.6	90
Bus5	11.00	101.026	214.5	89.2
Bus6	0.400	98.703	110.1	91.4
BusF1	11.00	100.739	261.6	90.0
BusF2	11.00	100.739	174.4	90.0
BusF3	11.00	100.739	87.2	90.0
BusF4	11.00	101.026	214.5	89.2
BusF5	11.00	101.026	127.1	88.6
BusF6	11.00	100.026	87.5	90.0
N1	11.00	100.731	87.2	90.0
N2	11.00	100.731	87.2	90.0
N3	11.00	101.729	87.2	90.0
N4	11.00	101.015	87.2	90.0
N5	11.00	101.018	39.8	85.0
N6	11.00	101.018	87.5	90.0

The table 4.9 shows the load flow result of Attariya substation considering normal operation configuration, where Bus tie breaker CB13 have been in normally open condition. The loading of all the buses are normal, there are not any constraints violations. The load flow analysis simulation diagram is shown in Appendix E.

Table 4.10 SCS Result of Attariya substation Existing Condition

BUS ID	Nominal voltage kV	Symm. kA rms	Asymm. kA rms
Bus1	33.00	4.846	7.375
Bus2	11.00	4.777	7.269
Bus3	11.00	4.777	7.269
Bus4	11.00	4.771	7.250
Bus5	11.00	4.770	7.247
Bus6	0.400	7.881	8.011
BusF1	11.00	4.771	7.250
BusF2	11.00	4.771	7.249
BusF3	11.00	4.771	7.249
BusF4	11.00	4.770	7.247
BusF5	11.00	4.770	7.247
BusF6	11.00	4.770	7.247
N1	11.00	4.751	7.817
N2	11.00	4.751	7.816
N3	11.00	4.747	7.174
N4	11.00	4.742	7.519
N5	11.00	4.745	7.101
N6	11.00	4.750	7.184

The table 4.10 shows the short circuit study result of Attariya substation for the fault at the given Bus ID location. Symmetrical kA represent 3-phase balanced fault current and on the other hand asymmetrical current signifies fault during unbalanced fault condition. The short circuit studies simulation diagram is shown in Appendix F.

Table 4.11 PD setting for Attariya substation Existing Condition

Relay ID	CT Ratio	PSM	TDS
Relay 1	300:1	0.65	0.25
Relay 2	300:1	0.65	0.25
Relay 4	300:1	0.65	0.25
Relay 5	300:1	0.20	0.25
Relay 6	300:1	0.65	0.25
Relay 7	900:1	0.69	0.5
Relay 8	900:1	0.69	0.5
Relay 9	900:1	0.69	0.75
Relay 10	900:1	0.69	0.75
Relay 13	900:1	0.5	0.85

Table 4.11 shows the setting of OCR existing in Attariya substation. Relay 11 and Relay 12 are differential relay. CB13 is MCCB with rating of 350 Ampere and thermal magnetic trip device. Based on these existing protective device setting the coordination

study of protection completed, and time characteristics curve of the various relay coordination can be presented as following.

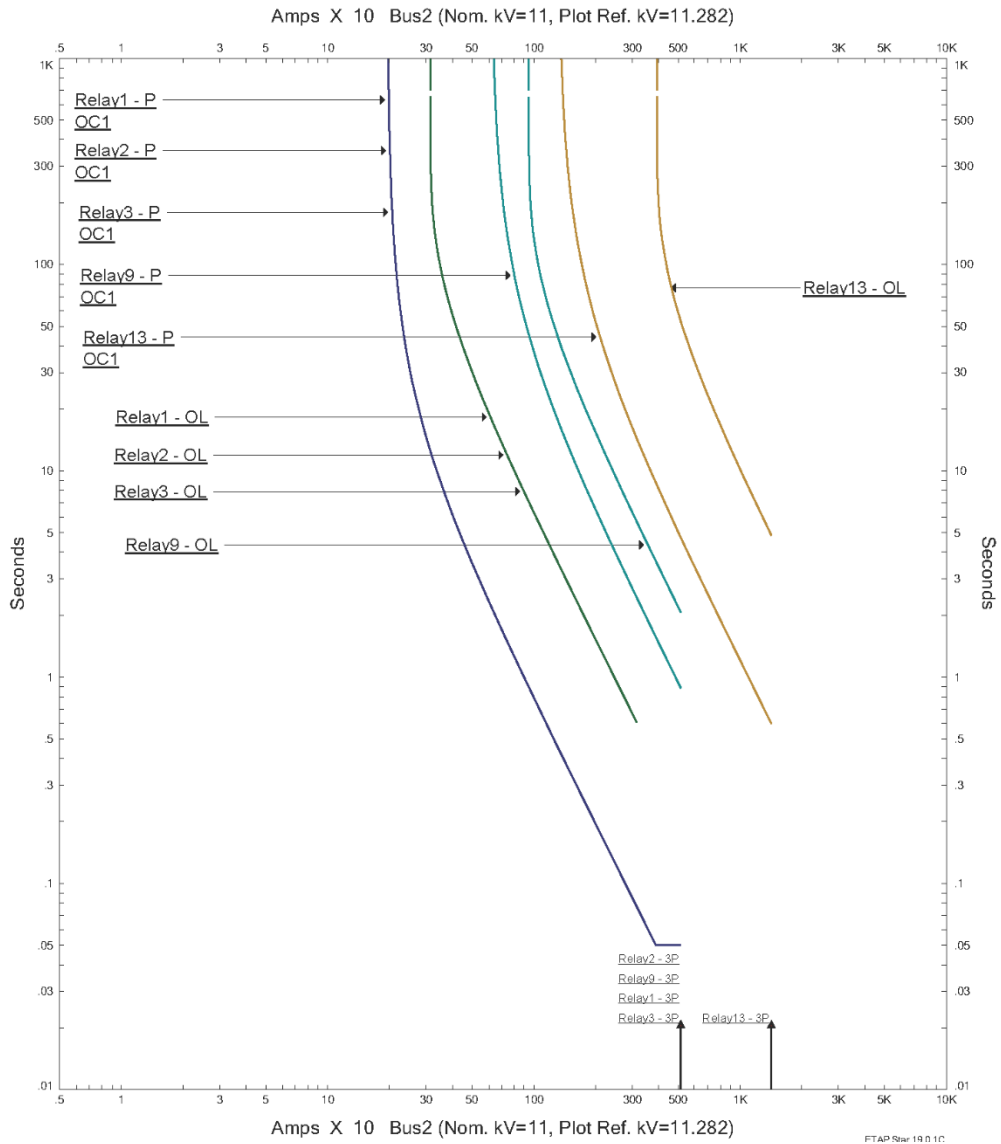


Figure 4.3 TCC of Relay1, 2, 3, 9 and 13 with existing setting

Figure 4.3 presents time characteristics curve of Relay1, Relay2, Relay3, Relay9 and Relay 13. From this time characteristics curve the coordination could be verified as per IEEE Std. 242-2001 and it is obvious from the curve that only one protective device operates at once to clear the fault starting from load terminal towards the source.

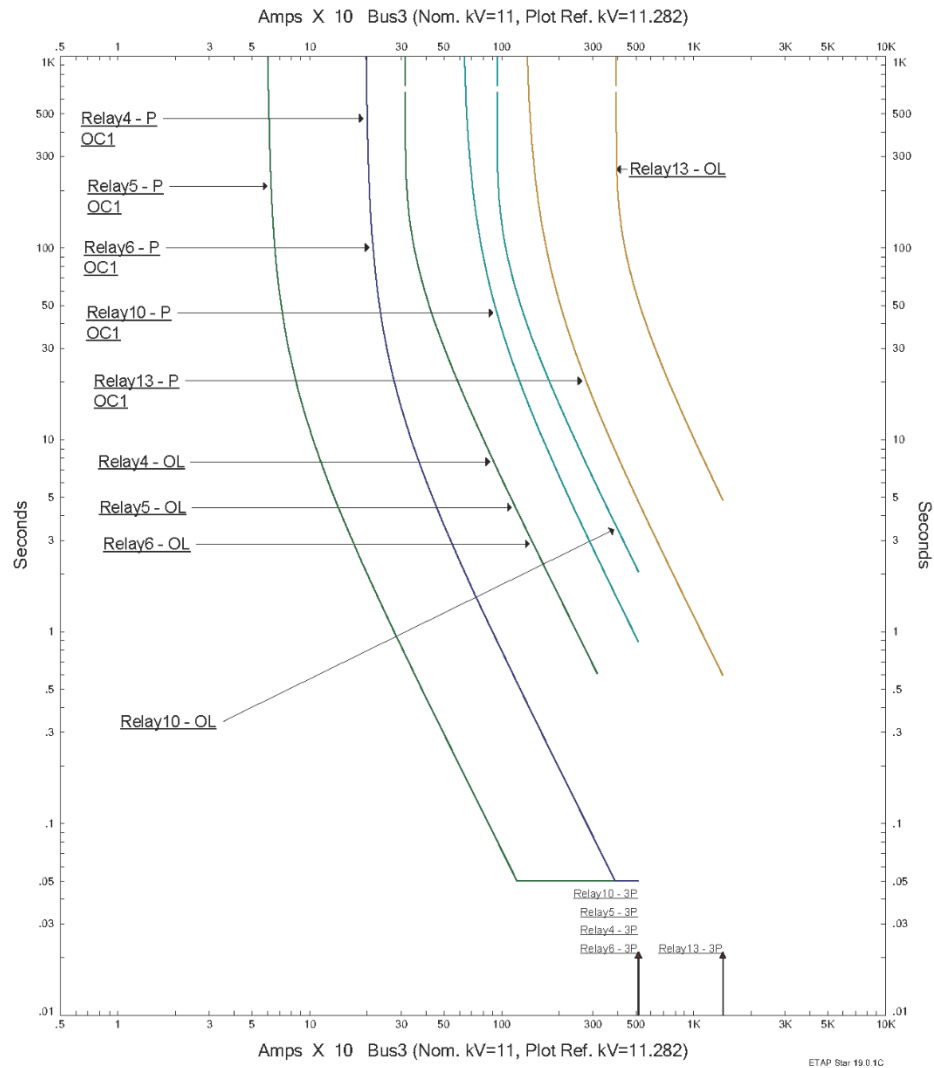


Figure 4.4 TCC of Relay 4, 5, 6, 10 and 13 with existing setting

Figure 4.4 presents time characteristics curve of Relay4, Relay5, Relay6, Relay10 and Relay 13. From this time characteristics curve the coordination could be verified as per IEEE Std. 242-2001 and it is obvious from the curve that only one protective device operates at once to clear the fault starting from load terminal towards the source.

Having completed load flow, short-circuit and protection-coordination analysis the arc-flash analysis have been conducted, and the result obtained could be presented as mentioned following.

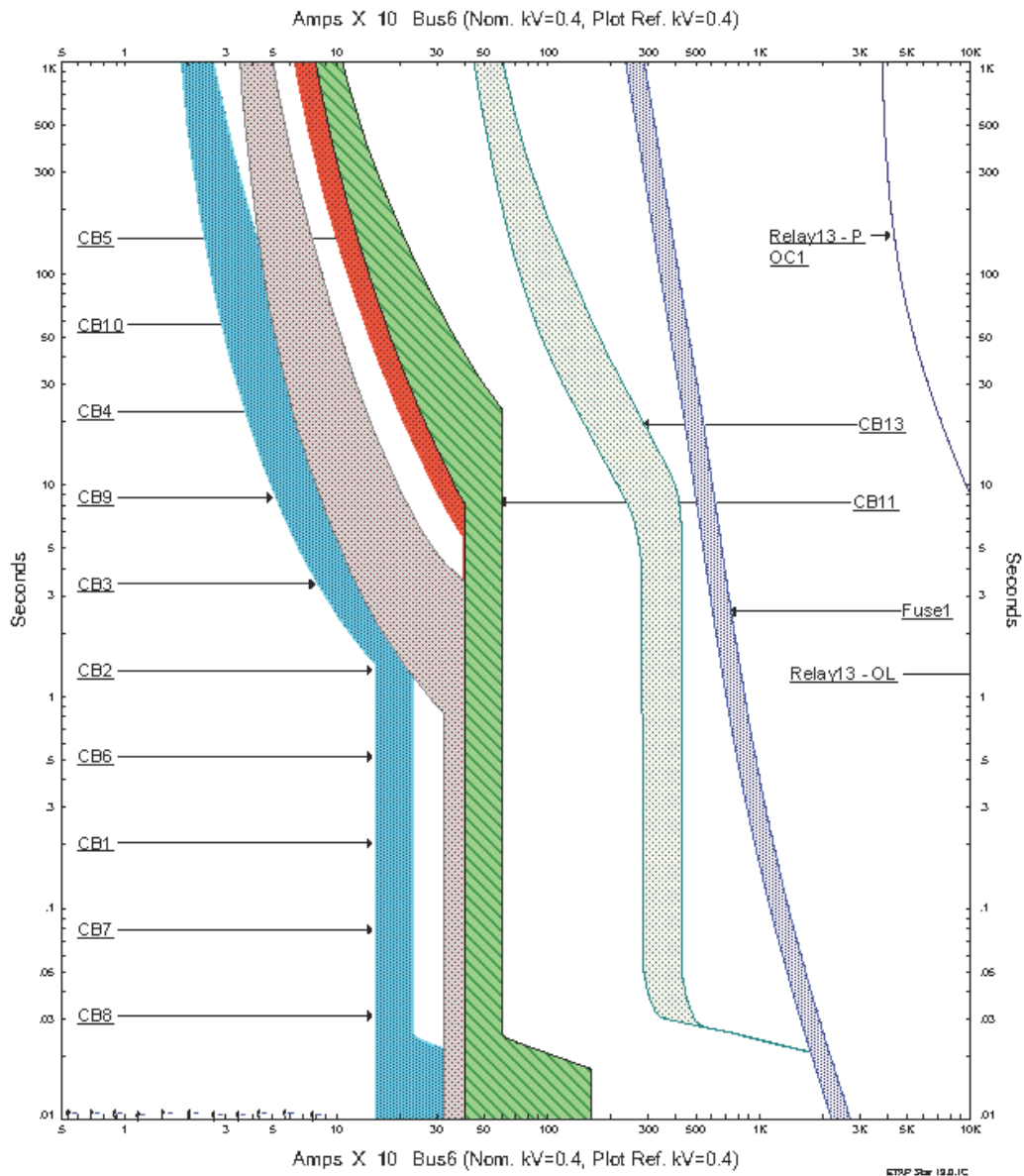


Figure 4.5 TCC of LVCB, HV Fuse and Relay 13 with existing setting

The figure 4.5 shows the time characteristics curve of low voltage circuit breakers (MCB), MCCB, High voltage fuse and source protective device Relay 13. From this time characteristics curve all the protective devices are found to be properly coordinated as per IEEE Std. 242-2001 for a given fault at relevant location.

Table 4.12 AFA Result of Attariya substation Existing Condition

BUS ID	Nominal voltage kV	I <sub>bf</sub> (kA)	I <sub>a</sub> (kA)	Incident Energy (cal/cm <sup>2</sup> )	FCT (sec)	AFB (m)
Bus1	33.00	4.846	4.846	349.3	0.891	7.815
Bus2	11.00	4.777	3.976	20.93	1.8	2.937
Bus3	11.00	4.777	4.331	20.93	1.8	2.937
Bus4	11.00	4.771	4.330	8.46	1.559	3.175
Bus5	11.00	4.770	4.622	8.47	1.56	3.176
Bus6	0.400	7.881	5.298	0.249	0.035	0.228
BusF1	11.00	4.771	4.331	8.46	1.559	3.175
BusF2	11.00	4.771	4.331	8.46	1.559	3.175
BusF3	11.00	4.771	4.331	8.46	1.559	3.175
BusF4	11.00	4.770	4.330	8.47	1.56	3.176
BusF5	11.00	4.770	4.330	8.47	1.56	3.176
BusF6	11.00	4.770	4.330	8.47	1.56	3.176
N1	11.00	4.751	4.026	4.12	0.35	1.016
N2	11.00	4.751	4.026	4.12	0.35	1.016
N3	11.00	4.747	4.022	4.12	0.35	1.015
N4	11.00	4.742	4.018	4.11	0.35	1.014
N5	11.00	4.745	4.021	4.12	0.35	1.015
N6	11.00	4.750	4.026	4.12	0.35	1.015

Table 4.11 shows the result of arc flash analysis obtained for Attariya substation existing condition. The simulation diagram presented in Annex G. Incident energy of 33 kV bus1 is extremely high. Which may cause second degree burn up to around 9 meter from the bus bar. The incident energy of other buses could be observed as mentioned in table 4.11 and the effective mitigation measure shall be identified to reduce the incident-energy economically. The incident-energy levels could be classified according to IEEE 1584-2018 from Class A to Class G and with respective risk level and the NFPA 70E provides guide line for selecting appropriate PPE.. Thus comprehensive arc flash analysis of the Attariya substation has been completed. From the analysis higher level of incident energy have been encountered at various buses, so that our aim is to minimize incident energy there by reducing the risk and vulnerabilities due to arcing and possible consequences. Thus we have done comprehensive arc flash analysis of Attariya substation, which completes the first goal of the study performed. Then, in order to identify the specific vulnerabilities and risk-factors contributing to arc flash hazards in the substation the modeling analysis as well as physical site visit has been conducted. The possible reasons of resulting the fault in the switchgear and cable

terminations have been identified and some of the previous problem and cause have been analyzed.

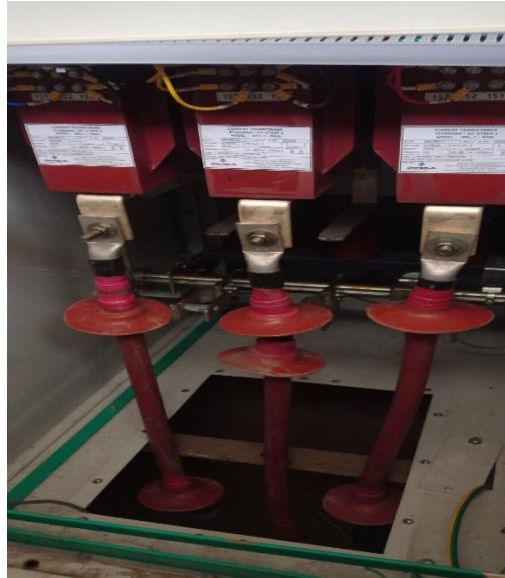


Figure 4.6 11kV termination opening not concealed



Figure 4.7 33 kV UG cable termination damaged

The above figure 4.6 and 4.7 shows the picture from site visit, the explosion of cable termination and burn have been observed.

Based on the analysis there are number of reasons contributing to possible arc flash hazard in Attariya substation as mentioned following:

- i) Water drainage system is not properly managed, which cause the moisture ingress to the bus bar, and cable termination which may resulting arcing and possible consequence. Also spark noise inside the switchgear could be noticed sometimes where there is more moisture and water existed below the switchgear panel. There were unofficial record of getting fire in 11kV switchgear due to heavy moisture ingress to switchgear during rainy season and due to poor drainage system.
- ii) Possible lose clamping of grounding of UG cable and moisture ingress inside the Raychem of UG cable termination might have caused the cable termination explosion and which have resulted arcing. This kind of incident were noticed more than five times and electricity was interrupted to all depending loads from this Attariya substation.
- iii) Some of the circuit breakers are very old with poor gear mechanism, which might malfunction and delay the fault clearing time and resulting to arcing.
- iv) The setting of PD might be cause to arc flash. The alternative setting of PD might be recommended later on this study to reduce the arc flash hazard in the substation.
- v) Personnel training and awareness seems minimum and PPE application is almost nil, therefore that might be contribute to arc flash due to miss operation of the equipment.

Thus, there are number of reasons and possible risk factor contributing arc flash in Attariya substation. This completes the second objective of this study.

Third objective of the study is to evaluate the existing mitigation techniques employed in substation protection systems, considering their effectiveness, practicality, and applicability to the local context. Actually, arc flash analysis was new topic of interest to the substation operational employee and there was not such arc flash specific mitigation but some of the mitigation was there which might help to mitigate the arc flash hazard. Some of those are:

- i) The setting of PD has been done in-order to meet the coordination aiming to clear the fault as immediate as possible.
- ii) The switchgear was inside the control room with proper control of air flow, which help to minimize the moisture ingress to termination.
- iii) Emergency fire extinguisher to suppress the fire

Unfortunately, there was not any method dedicated to mitigate the arc flash hazard in the substation.

The fourth objective of this study is to develop and propose effective mitigation techniques tailored to the Attariya substation to minimize the likelihood and severity of arc flash incidents. There are number of possible methods such as replacing the circuit breaker with faster operating time and adjusting setting of the relay and other actuating protective devices, which can directly reduce the incident energy and which directly reduce the possible arc flash risk. The possible method to implement in Attariya substation. In this study the method of adjusting relay setting in proper coordinated manner to reduce the fault clearing time is proposed as mitigation to arc flash hazard in Attariya substation, because this method cost very less expense than the changing circuit breakers. Now the result arc flash analysis of Attariya substation with new adjusted setting can be presented as mentioned following.

Table 4.13 Alternative PD setting for Attariya substation

Relay ID	CT Ratio	PSM	TDS
Relay 1	300:1	0.65	0.10
Relay 2	300:1	0.65	0.10
Relay 4	300:1	0.65	0.10
Relay 5	300:1	0.20	0.10
Relay 6	300:1	0.65	0.10
Relay 7	900:1	0.69	0.20
Relay 8	900:1	0.69	0.22
Relay 9	900:1	0.69	0.25
Relay 10	900:1	0.69	0.25
Relay 13	900:1	0.50	0.30

Table 4.13 shows the new set of protective device setting proposed for Attariya substation, this setting has been obtained by adjustment of time characteristics curve of the respective device to meet the coordination. Also, The OLR previously set at 1.05 adjusted to 0.95 in order to maintain the proper coordination between time delay trip and instantaneous trip of the relay. The load flow analysis and short circuit studies result

remains unchanged before and after the implementation of new protective device setting, since there is not any device or equipment replacement as the mitigation to arc flash hazard.

With alternative setting of protective devices the protection coordination have been studied and found to meet the coordination requirement. The time characteristics curve of the protective devices can be presented as following.

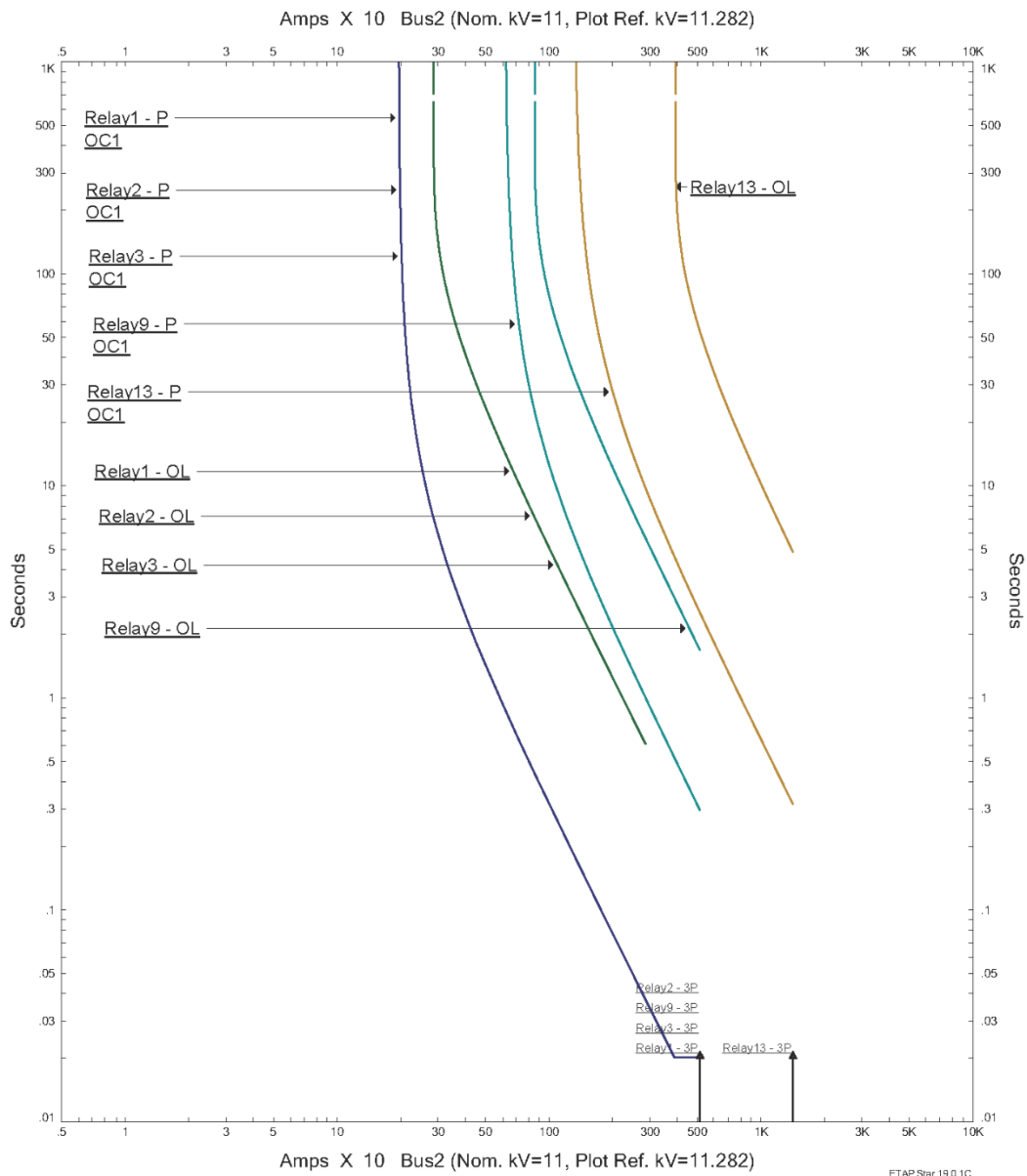


Figure 4.8 TCC of Relay1, 2, 3, 9 and 13 with alternative setting

The Figure 4.8 shows the time characteristics curve of relays 1, 2, 3, 9 and 13 during normal operation configuration of substation. These shows coordination have been met

appropriately as per IEEE Std. 242-2001, since there is not any intersection point of two different relays.

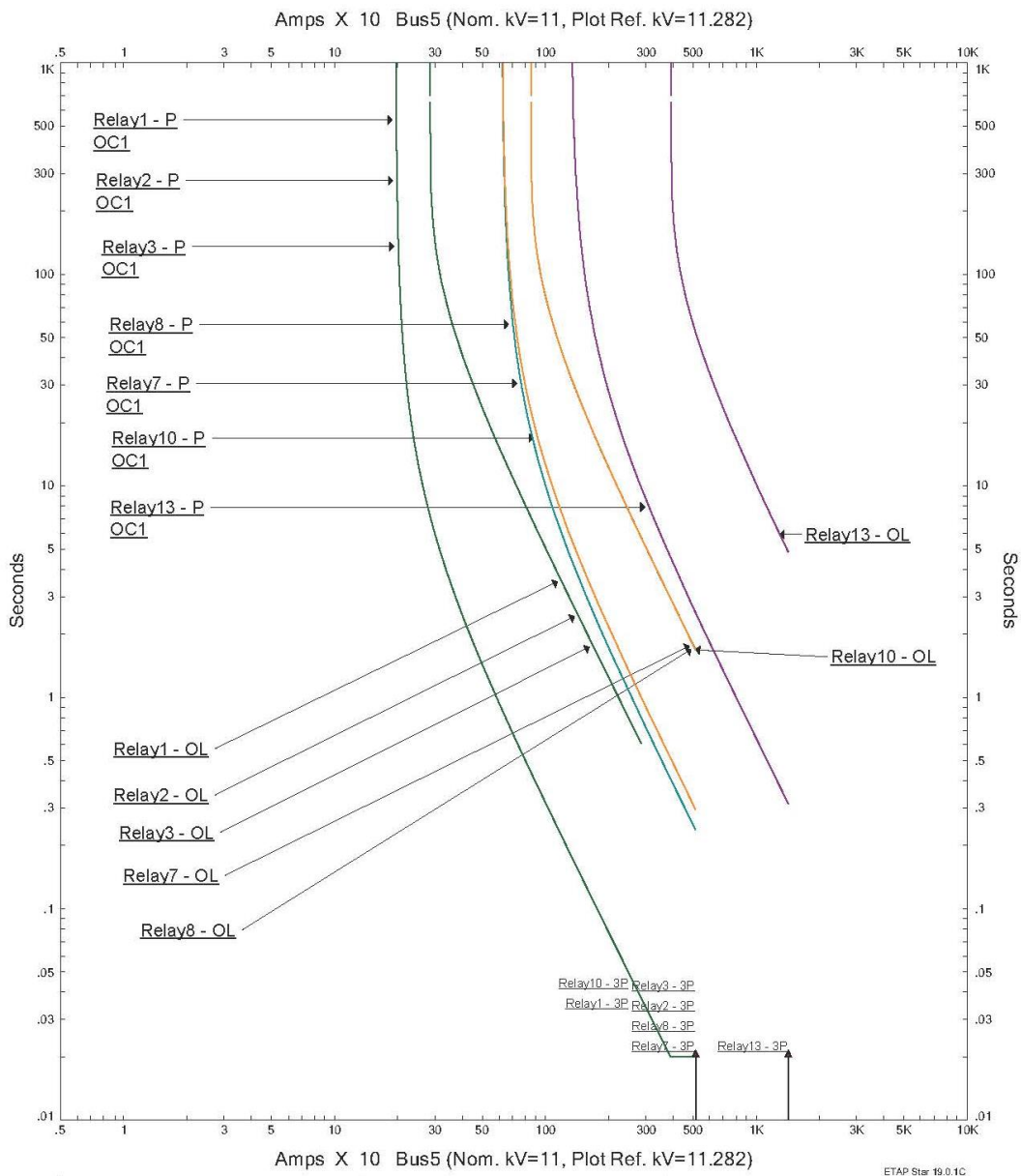


Figure 4.9 TCC of Relay1, 2, 3, 7, 8, 10 and 13 with alternative setting

The figure 4.9 represents the time characteristics curve of protective devices when bus tie circuit breaker CB13 has been closed. It shows proper coordination between the protective devices and coordination requirement has been met with reference to our coordination study conducted in ETAP 19.01.

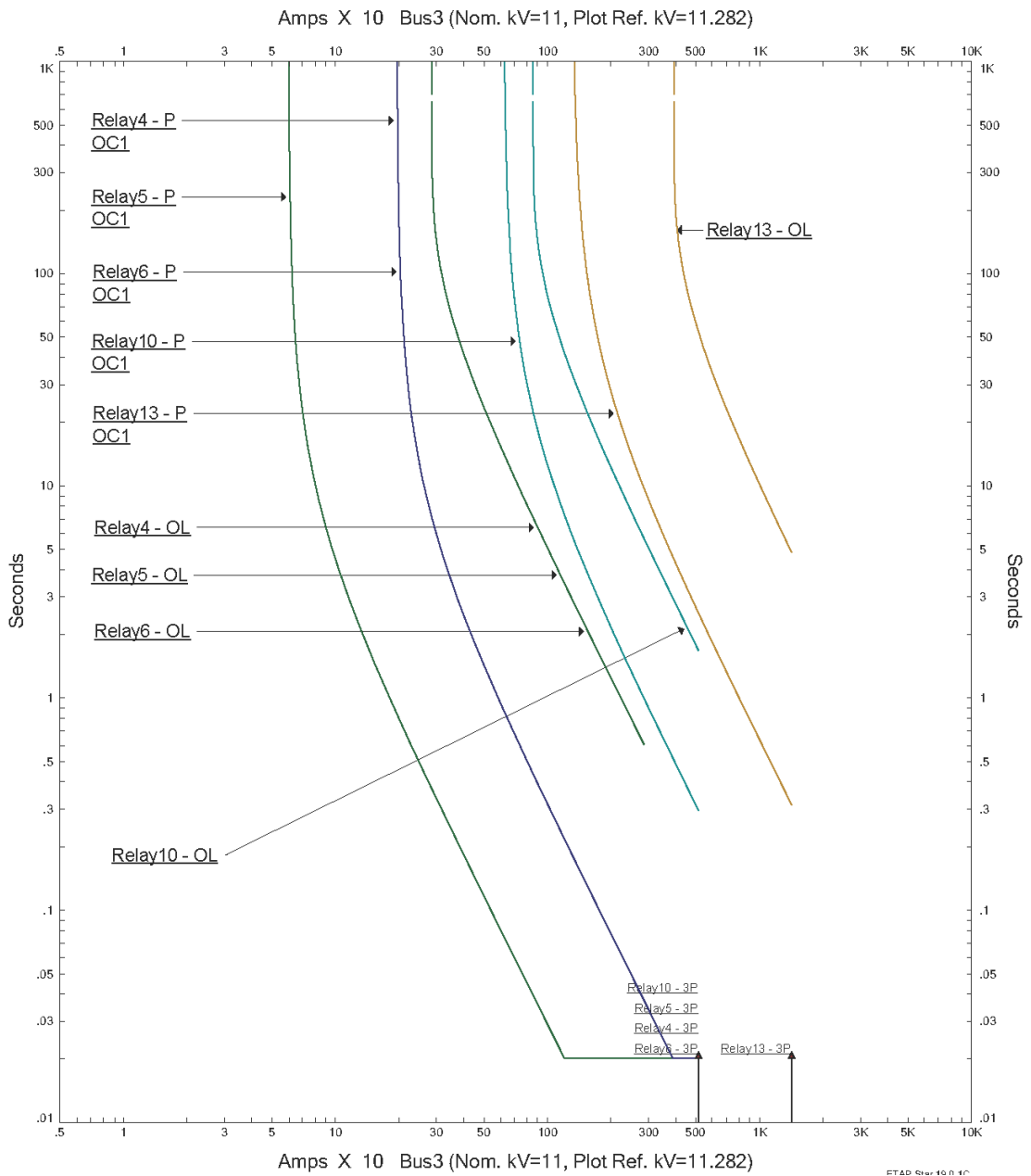


Figure 4.10 TCC of Relay 4, 5, 6, 10 and 13 with alternative setting

Figure 4.10 presented above, shows the time characteristics curve of relay 4, 5, 6, 10 & 13 with alternative setting of the protective devices. The time characteristics curve also shows coordination between the relays have been properly obtained. There are not any intersection point, signifying that only one device will be operated for a given fault.

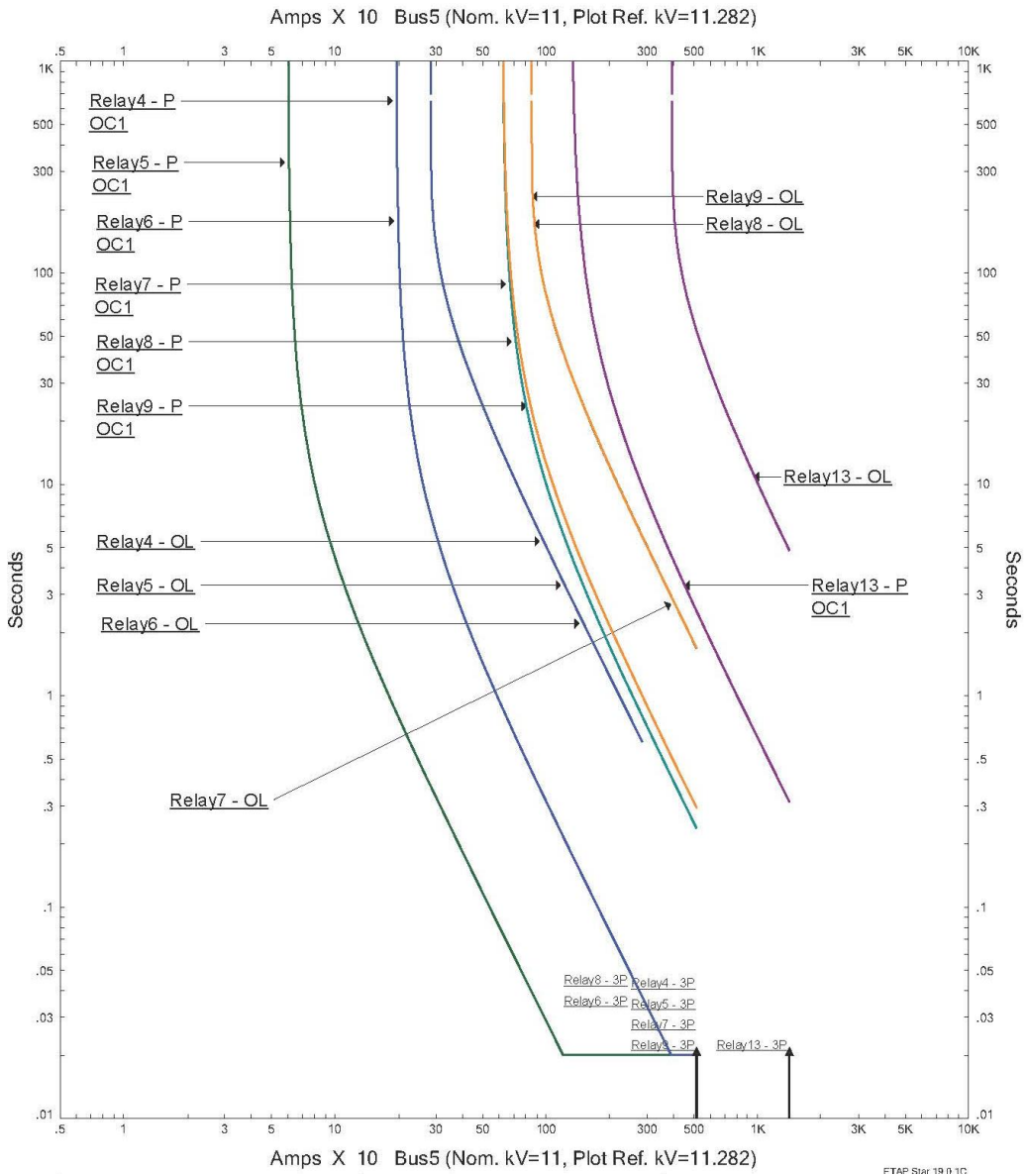


Figure 4.11 TCC of Relay 4, 5, 6, 7, 8, 9 and 13 with alternative setting

Figure 4.11 presented above, shows the time characteristics curve of relay 4, 5, 6, 7, 8, 9 & 13 with alternative setting of the protective devices. This shows the coordination between the mentioned relays. From the curves, the coordination of the protective devices could be observed, and the coordination found to be as per IEEE Std.242-2001.

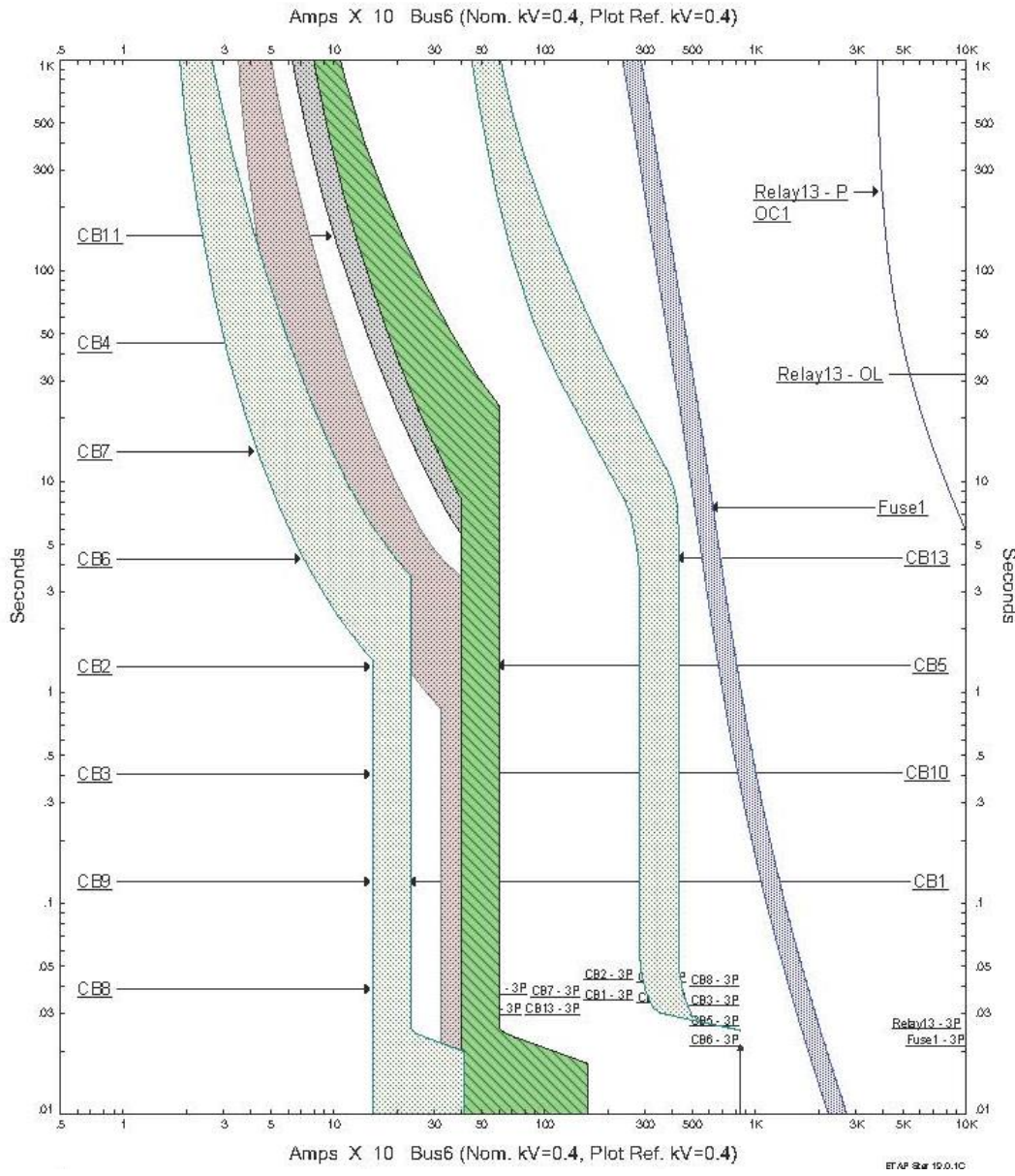


Figure 4.12 TCC of LVCB, HV Fuse and Relay 13 with alternative setting

The Figure 4.12 shows the time characteristics curve of low voltage circuit breaker, high voltage fuse and Relay 13, here only the setting of Relay 13 has been adjusted, and the setting of low voltage circuit breaker (LVCB) and high voltage (HV) fuse are maintained same since there was comparatively less incident energy calculated for Bus 6, which is supplying power to the station service. Thus with all the time characteristics curve of various protective devices and relative references the coordination of all the

protective devices have found to be in good condition required for clearing relevant fault. Then the result of arc flash analysis of the Attariya can be analyzed as following.

Table 4.14 AFA Result of Attariya substation with alternative PD setting

BUS ID	Nominal voltage kV	I <sub>bf</sub> (kA)	I <sub>a</sub> (kA)	Incident Energy (cal/cm <sup>2</sup> )	FCT (sec)	AFB (m)
Bus1	33.00	4.846	4.846	240.24	0.613	6.481
Bus2	11.00	4.777	3.976	9.3	0.8	1.729
Bus3	11.00	4.777	3.976	9.3	0.8	1.729
Bus4	11.00	4.771	4.331	3.91	0.72	1.939
Bus5	11.00	4.770	4.330	3.91	0.72	1.94
Bus6	0.400	7.881	5.298	0.248894	0.035	0.228
BusF1	11.00	4.771	4.331	3.91	0.72	1.939
BusF2	11.00	4.771	4.331	3.91	0.72	1.939
BusF3	11.00	4.771	4.331	3.91	0.72	1.94
BusF4	11.00	4.770	4.330	3.91	0.72	1.94
BusF5	11.00	4.770	4.330	3.91	0.72	1.94
BusF6	11.00	4.770	4.330	3.91	0.72	1.94
N1	11.00	4.751	4.026	3.77	0.32	0.958
N2	11.00	4.751	4.026	3.77	0.32	0.958
N3	11.00	4.747	4.022	3.76	0.32	0.957
N4	11.00	4.743	4.018	3.76	0.32	0.957
N5	11.00	4.746	4.021	3.76	0.32	0.957
N6	11.00	4.750	4.025	3.77	0.32	0.958

The table 4.14 presents the arc flash analysis of Attariya substation with alternative setting of protective device mentioned in Table 4.13. The simulation diagram can be presented in Appendix H. The result could be observed that the fault clearing time is within the standard range as specified by IEEE Std. 242-2001 and IEEE Std. 1584-2018 for the valid arc flash analysis. From this result, it is clear enough that the incident-energy have been reduced significantly with the improvement of the fault-clearing time, for fault at respective bus location. Thus the arc-flash boundary also reduced significantly due to decrease in incident energy that means the potential area that could be affected by arc flash incident have been significantly reduced, Thus alternative setting of protective devices for Attariya substation found to be viable which helps to reduce arc flash hazards in the substation. With the reduction of the incident energy the potential damage to the critical electrical equipment, injury to the operating personnel can be minimized and with proper work execution plan and utilization of proper PPE can make effect of arc flash almost nil. With reference to fault clearance time (FCT)

shown in Table 2.6 for the arc-flash analysis outcome for the LPV-configuration and JG3225, for PNL\_4 Bus having nominal voltage 0.480 kV, the fault clearance time for this bus is 0.029 Seconds. And with reference to the result obtained for Attariya substation Bus 6 having nominal voltage of 0.400 kV from the table 4.14, its fault clearing time is 0.035 seconds, which implies our result obtained is comparable to the result obtained for reference study [5]. The other buses fault clearing time for Attariya substation is below one second and little bit more than the result obtained in reference study [5], this is possible due to different characteristics of high voltage relay and circuit breaker compared to characteristics of low voltage circuit breakers.

Table 4.15 AFA Result Comparison Existing vs Alternative setting

BUS ID	Incident Energy Existing (cal/cm <sup>2</sup> )	Incident Energy Alt. (cal/cm <sup>2</sup> )	FCT Existing (sec)	FCT Alt. (sec)	IE Reduced (cal/cm <sup>2</sup> )	FCT Reduced (sec)
Bus1	349.3	240.24	0.891	0.613	109.06	0.278
Bus2	20.93	9.3	1.8	0.8	11.63	1.000
Bus3	20.93	9.3	1.8	0.8	11.63	1.000
Bus4	8.46	3.91	1.559	0.72	4.55	0.839
Bus5	8.47	3.91	1.56	0.72	4.56	0.840
Bus6	0.249	0.249	0.035	0.035	0.00	0.000
BusF1	8.46	3.91	1.559	0.72	4.55	0.839
BusF2	8.46	3.91	1.559	0.72	4.55	0.839
BusF3	8.46	3.91	1.559	0.72	4.55	0.839
BusF4	8.47	3.91	1.56	0.72	4.56	0.840
BusF5	8.47	3.91	1.56	0.72	4.56	0.840
BusF6	8.47	3.91	1.56	0.72	4.56	0.840
N1	4.12	3.77	0.35	0.32	0.35	0.030
N2	4.12	3.77	0.35	0.32	0.35	0.030
N3	4.12	3.76	0.35	0.32	0.36	0.030
N4	4.11	3.76	0.35	0.32	0.35	0.030
N5	4.12	3.76	0.35	0.32	0.36	0.030
N6	4.12	3.77	0.35	0.32	0.35	0.030

Above table 4.15 shows incident energy and fault clearing time reduction with the implementation of the alternative setting of protective devices. Thus with the arc flash analysis of Attariya substation, the arc flash risk can be identified with quantification of the incident energy, fault clearing time and arc flash boundary, thus it significantly helps reduce the possible consequence of arc flash incident. Also, the alternative setting of protective devices sound to be effective mitigation technique with almost nil expenses, thus it fulfills the fourth objective of this study. Along with the setting

adjustment the following actions could be taken in order to minimize possible arc flash hazards in Attariya substation.

- i) Arc flash hazard or warning labeling in the relevant locations
- ii) Proper administrative control of work planning by implementing permit authorization system
- iii) Lockout/Tagout procedures for operation of breaker and other protective devices.
- iv) Implementing proper arc rated PPE while working nearby possible source of arcing.
- v) Regular maintenance of circuit breaker, and other fault clearing devices.
- vi) Avoid working on live line.

From the arc flash analysis, the incident energy levels can be classified according to IEEE 1584-2018 such as Class A, B, C, D, E, F, G with energy level 2, 4, 8, 25, 40, 100 and 120 cal/cm<sup>2</sup> respectively. The respective PPE could be selected according to NFPA 70E Standard. The categories of PPE are class 0, 1, 2, 3 and 4 with incident energy levels of 1.2, 4, 8, 25, 40 cal/cm<sup>2</sup> respectively. According the different level of incident energy levels there are different levels of risk of injury starting from minimal risk of injury from category 0 to Extreme risk of severe burns and life-threatening injuries for category 4. With the alternative setting of protective devices the level of risk at Bus 1 is extremely high with beyond the class G indicating to remain away from the arc flash boundary. With alternative setting of protective devices Bus 2 and Bus 3 having incident energy level of 9.3 cal/cm<sup>2</sup> nearly equal to category 2, and all the 11kV switchgear buses have incident energy level below 4 cal/cm<sup>2</sup> with category level 1 indicating minimal risk of injury according to IEEE Std. NFPA 70E [7]. It is observed that with existing setting of protective devices the incident energy level of 11kV buses were above 4 cal/cm<sup>2</sup> with higher risk of injury and burns. In overall, we have completed the arc flash analysis of Attariya substation using ETAP 19.01 and all the objectives of this study have been accomplished. This study may initiate to quantify the arc flash hazard in Nepal electrical power system, with arc flash analysis. This kind of study might be viable to prevent possible damage to the equipment and operating personnel from possible arc flash incident. The possible arc flash risk can be minimized and save cost of arc flash incident with almost nil expense. Thus this proves the significance of arc flash analysis in substation protection. Arc flash analysis involves

load flow, short circuit, protection coordination studies and then finally incident energy and fault clearing time calculation so that this study is the power system study. In overall, this study offers valuable insights into arc flash incidents and mitigation techniques within the context of the Attariya Substation in Nepal. The research encompasses comprehensive data collection, analysis, and discussion, shedding light on the significant risks associated with arc flash incidents in substations, including the potential for severe injury, equipment damage, and operational disruptions. Factors contributing to arc flash incidents, such as equipment design, maintenance practices, operational procedures, and human factors, are thoroughly examined, providing critical insights into root causes and areas for improvement. Evaluation of mitigation techniques, including equipment labeling, protective clothing, arc-resistant equipment design, and personnel training, demonstrates their effectiveness in reducing the severity and frequency of arc flash incidents. Importantly, while the study briefly touches upon the introduction of feeder analysis, its primary focus remains on substations. The findings have practical implications for substation design, operation, and maintenance, not only in Nepal but also in similar regions facing infrastructure challenges. By implementing the recommendations outlined in this study, stakeholders can enhance the safety and reliability of substation operations, minimizing the risk of arc flash incidents and ensuring the integrity of the electrical system.

## CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

### 5.1 Conclusion

This study presents a comprehensive arc flash analysis of the Attariya substation, a vital source of electricity for Kailali district, Nepal. The study, the first of its kind in Nepal, focuses on the real-world scenario of Attariya, chosen based on past incidents and upgrades. The analysis reveals that existing protective settings, while within IEEE Std. 242-2001 limits, pose heightened risks, potentially requiring costly measures. However, alternative coordinated settings significantly reduce fault clearing time, arc flash risk, and incident energy, emphasizing the importance of arc flash analysis for substation protection. The study underscores the need for safety measures, connecting with broader power system studies. As Nepal's power system expands, implementing arc flash analysis becomes crucial for safety, operational efficiency and robust substation electrical infrastructure, aligning with global practices.

The study shows that initially the incident energy level, fault clearing time and possible risk of arch flash were very high with respect to NFPA 70E and IEEE 1584-2018, however with alternative settings of the protective devices and fault clearing devices the incident energy level at 33kV bus has been significantly reduced by 109.06 cal/cm<sup>2</sup> in magnitude, 31.22 % with respect to initial magnitude and fault clearing time reduced by 0.278 second. The incident energy level at 11kV incomers reduced by 11.63 cal/cm<sup>2</sup> in magnitude, 55.5 % with respect to initial magnitude and fault clearing time reduced by 1.00 second. The incident energy level at 11kV feeder switchgears reduced by 4.55 cal/cm<sup>2</sup> in magnitude, 53.78 % with respect to initial magnitude and fault clearing time reduced by 0.840 second. The fault clearing time and coordination meets the requirement by IEEE Std. 242-2001. Unfortunately, the awareness about the arc flash hazards are found to below required level. Also, the preventive measures and action plan for possible arc flash hazards are found below the required level as per NFPA70E.

The comprehensive arc flash analysis of selected substation has been completed, the identification of potential hazards and risk has been completed and analyzed. Also, the evaluation of existing mitigation along with its effectiveness have been accomplished. The mitigation techniques has been identified and recommended for reduction of arc flash incident energy there by reducing possible consequences. Overall, All the objectives of the proposed study have been accomplished.

## 5.1 Recommendation

The possible risk of arc flash hazards are significantly high for the existing condition of Attariya substation. With reference to this study results and analysis the recommendation is that the alternative setting of protective devices could be viable and low cost mitigation to reduce the possible incident energy, fault clearing time and hence significantly reducing the risk of arc flash hazard in Attariya substation, Nepal. The alternative setting includes the TDS adjustment of the protective devices with proper coordination according to IEEE 242-2001. Also, the proper awareness and training shall be provided to the substation operating personnel and all related employees. The labeling of equipment, switchgear panels and bus bars shall be provided. The label included all the related information about arc flash boundary, maximum possible incident energy, arcing current etc. The label might be provided according to NFPA 70E and IEEE 1584. There shall be proper maintenance of the protective and fault clearing devices ensuring there are not any malfunction during actual fault condition. One of the recommendation is to prepare action plan for arc flash hazards and make ready all necessary tools and emergency response kit for arc flash hazards. Thus, this is the beginning of study of this kind in Nepal.

It is recommended to consider the arc flash hazard analysis for design of the new substation and selecting protective devices, because the proper fault withstand capacity and arc rating must meet the standard global practices ensuring safe and robust substation operation. Thus arc flash analysis helps to reduce the possible damage to substation equipment, infrastructure and injury to the personnel, there by significant reduction in relevant cost. It is also recommended to consider the arc flash hazard analysis for changing or upgrading the substation's major equipment, which might result change in fault level of the power system and alter the fault clearing time, such as transformer, circuit breaker, relay etc. The analysis ensures the proper devices and equipment have been selected according to standard global practices. Beside these recommendation, proper preventive maintenance and testing of functionality of relevant devices periodically helps to find out problem and proper action could be taken thus preventing the possible arc flash and consequences. Hence, arc flash analysis is the crucial and important part of power system study in order to ensure safe and reliable operation of substation and electrical power system.

## REFERENCES

- [1] C.M. Wellman, "OSHA arc-flash injury data analysis," *IEEE IAS Electrical Safety Workshop*, pp. 1-5, 2012.
- [2] "IEEE Guide For Performing Arc-Flash Hazard Calculations," *IEEE Standard 1584*, 2018.
- [3] Marroquin, A. Rehman and A. Madani, "High-Voltage Arc Flash Assessment and Applications," *IEEE Transactions on Industry Applications*, vol. 56, no. 3, pp. 2205-225, 2020.
- [4] G. Praise and P.A. Scarpino, "A Basic Assessment of Arc Flash in Low Voltage AC," *IEEE Transactions on Industry Applications*, vol. 57, no. 5, pp. 4513-4519, 2021.
- [5] A. Ansari, B. Ramos, S. Lavoie and M. Churilla, "Arc flash analysis of silver springs north switchyard — A case study in North Florida," in *North American Power Symposium (NAPS)*, Morgantown, WV, USA, pp. 1-6, 2017.
- [6] "OSHA Fatality and Catastrophe Investigation Summaries," <http://www.osha.gov/pls/imis/accidentsearch.html>.
- [7] T. Gammon, W. -J. Lee, Z. Zhang and B. C. Johnson, "Electrical Safety, Electrical Hazards, and the 2018 NFPA 70E," *IEEE Transactions on Industry Applications*, vol. 51, no. 4, pp. 2709-2716, 2015.
- [8] Z. Zang, Y. Nie and W. J. Lee, "Approach of Voltage Characteristics Modeling for Medium-Low-Voltage Arc Fault in Short Gaps," *IEEE Transactions on Industry Applications*, vol. 55, no. 3, pp. 2281-2289, 2019.
- [9] T.A. Short and M L Eblen, "Medium Voltage arc flash in open air and padmounted equipment," *IEEE Transactions on Industry Applications*, vol. 48, no. 1, pp. A21-A29, 2012.
- [10] M.A. Gana, A. Bukar . and Smaila Y.A., "Arc Flash Study of IEEE 8 Bus Test System Using Digital Simulation and Electrical Network Analysis Platform,"

*Arid Zone Journal of Engineering, Technology & Environment*, vol. 19, no. 2545-5818, pp. 1-12, 2023.

- [11] Resources, "IEEE PES Test Feeder Working Group, 4-Bus Test Feeder," July 2017. [Online]. Available: <http://sites.ieee.org/pes-testfeeders/resources..> [Accessed 03 January 2024].
- [12] IEEE, "IEEE Std 242-2001 - IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems (IEEE Buff Book)," IEEE Industry Application Society, 2001.

APPENDIX A: SLD and LFA simulation diagram of IEEE 4 node test feeder existing condition

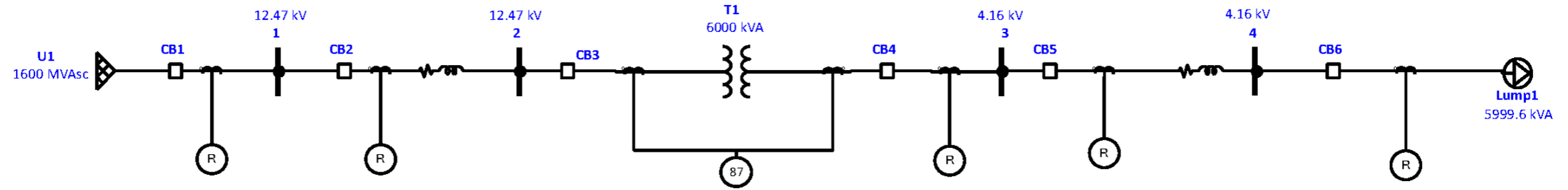


Figure A.1 Single line diagram of IEEE 4 node test feeder load flow analysis [11]

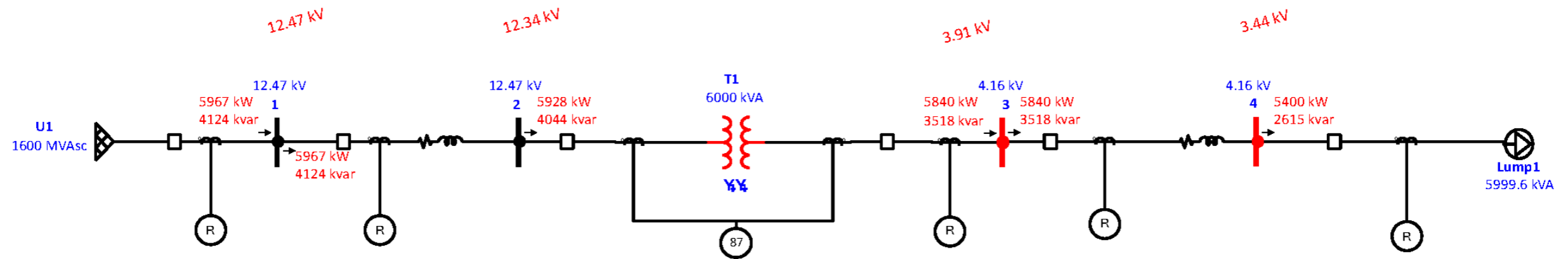


Figure A.2 Simulation diagram of IEEE 4 node test feeder load flow analysis

APPENDIX B: SCS and AFA simulation diagram of IEEE 4 node test feeder existing condition

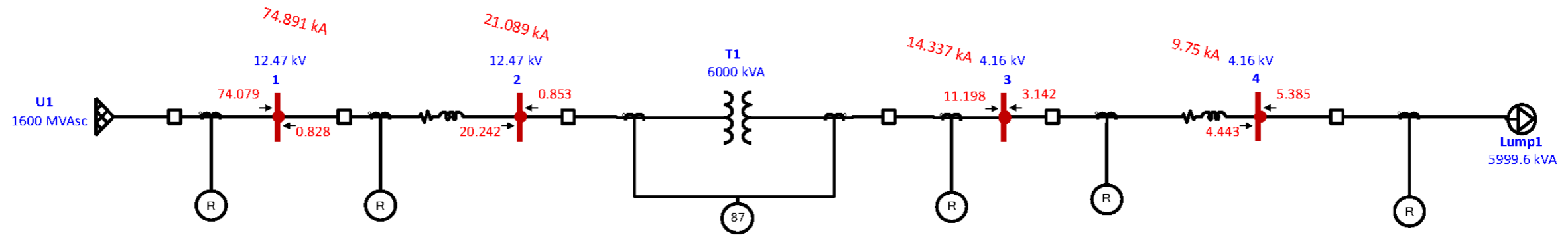


Figure B.1 Simulation diagram of IEEE 4 node test feeder short circuit studies

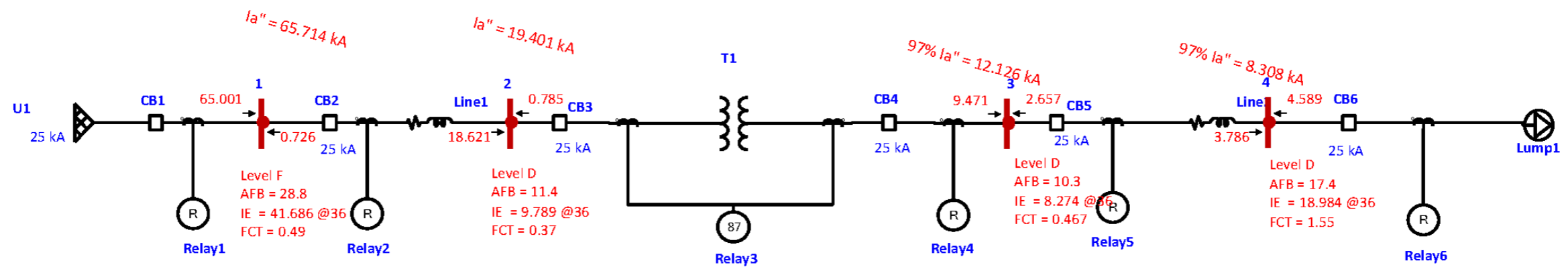


Figure B.2 Simulation diagram of IEEE 4 node test feeder arc flash analysis

APPENDIX C: AFA simulation diagram of IEEE 4 node test feeder with alternative setting

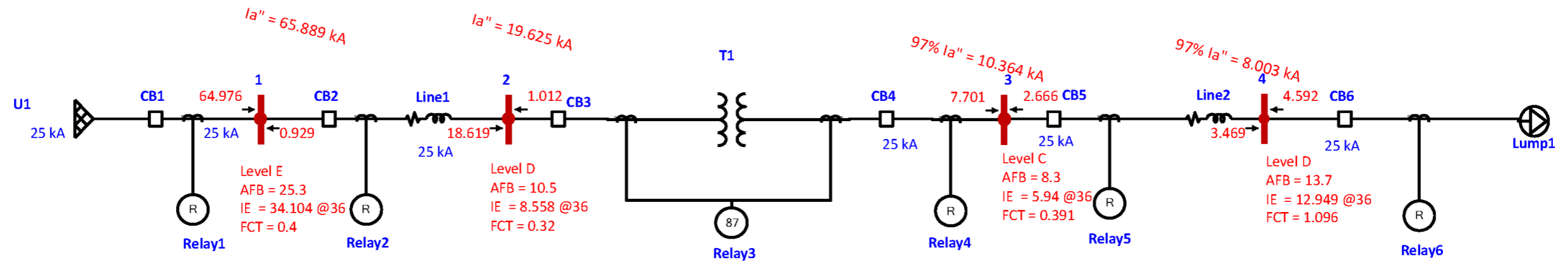


Figure C.1 Simulation diagram of IEEE 4 node test feeder arc flash analysis

APPENDIX D: Single line diagram of Attariya Substation

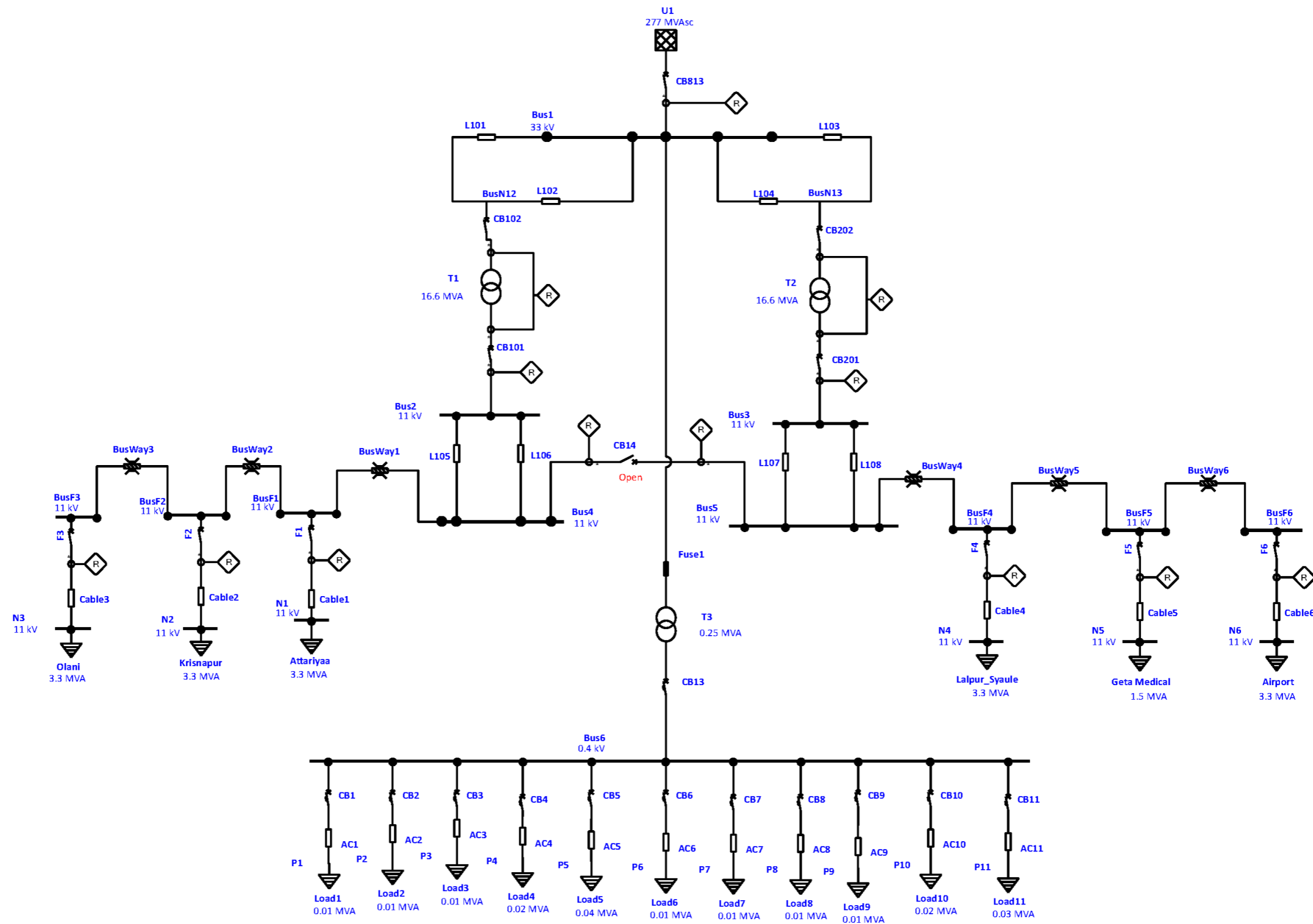


Figure D.1 Single line diagram of Attariya substation

APPENDIX E: LFA simulation diagram of Attariya substation existing condition

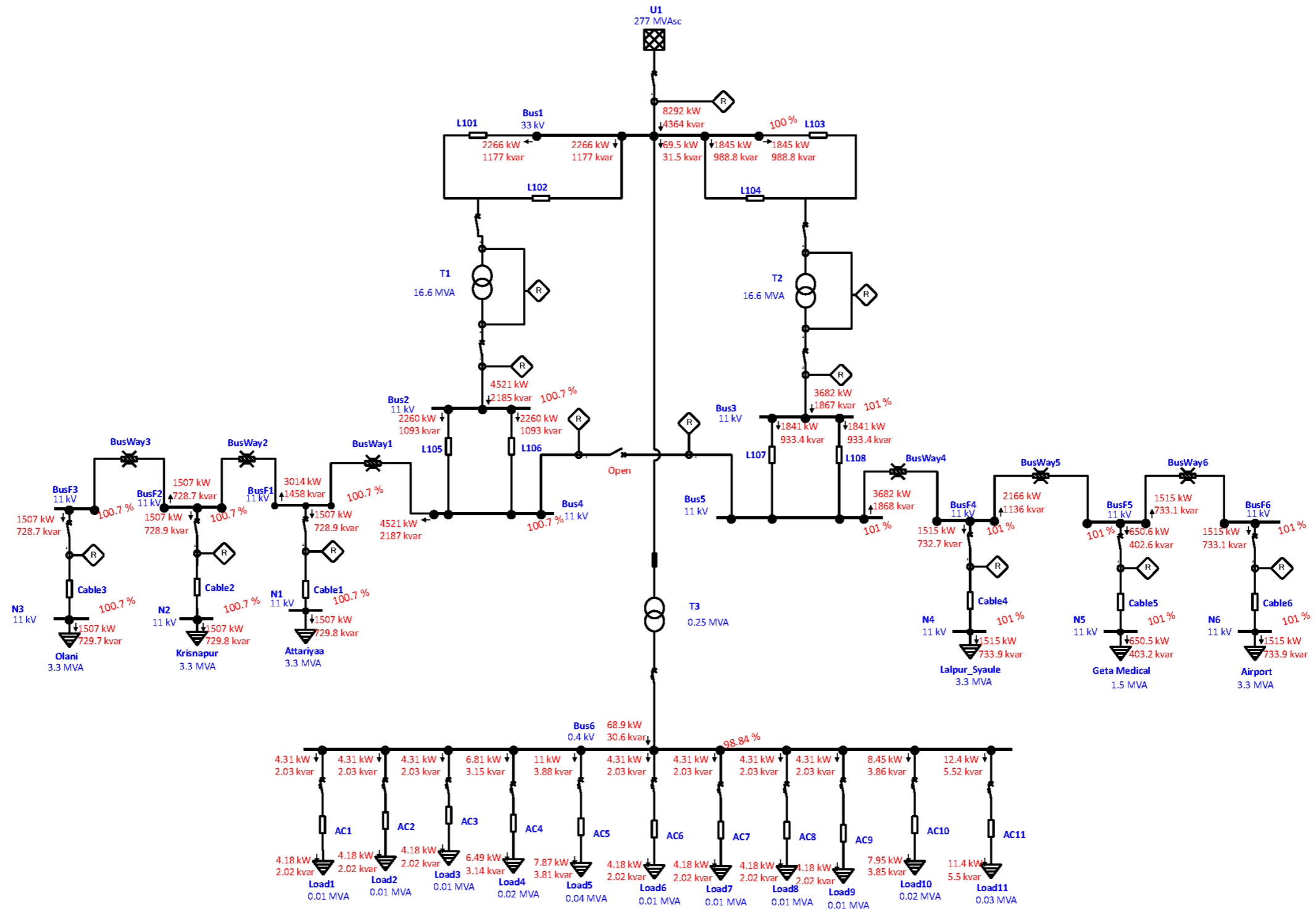


Figure E.1 Simulation diagram of Attariya substation load flow analysis

APPENDIX F: SCS simulation diagram of Attariya substation existing condition

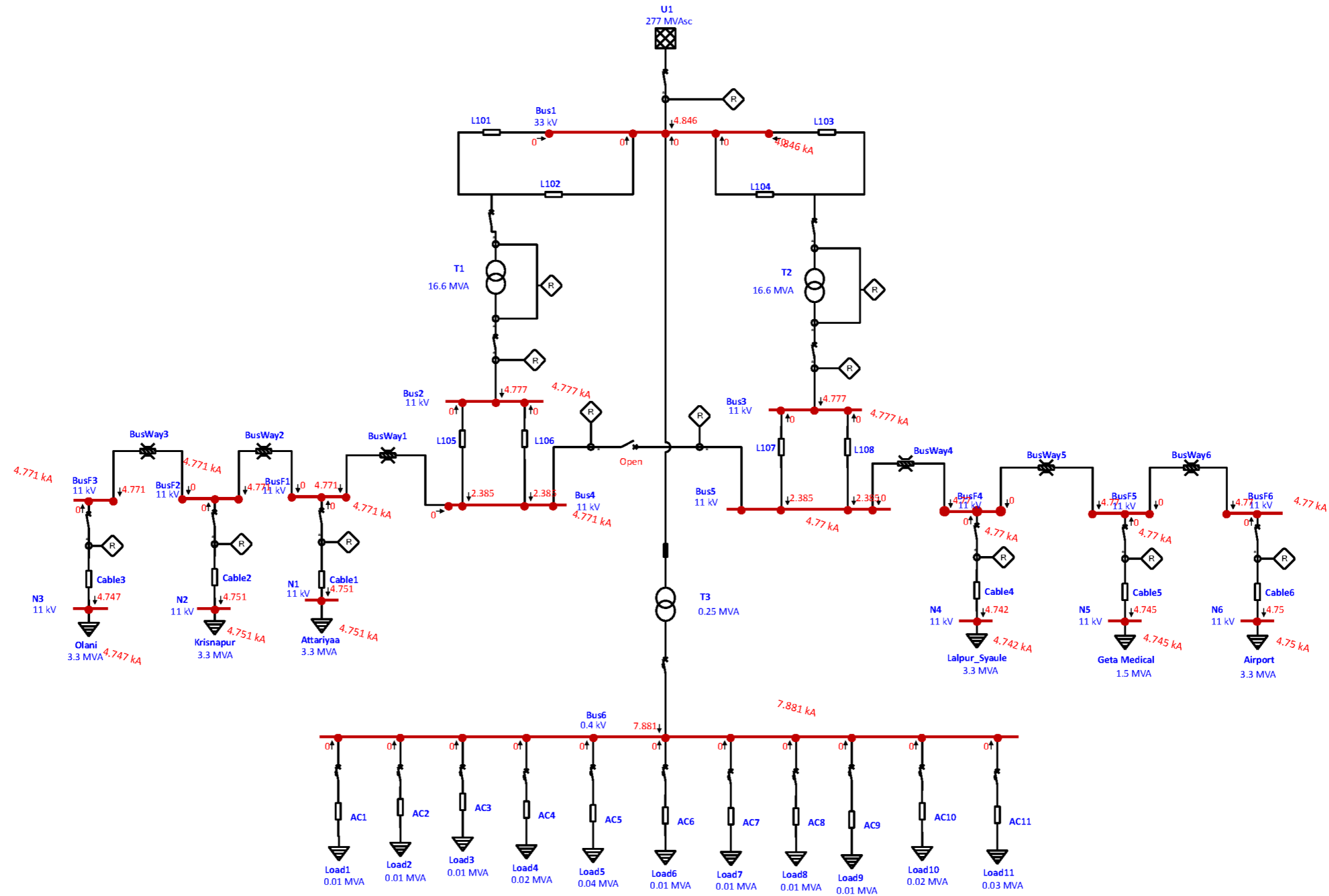


Figure F.1 Simulation diagram of Attariya substation short circuit studies

APPENDIX G: AFA simulation diagram of Attariya substation existing condition

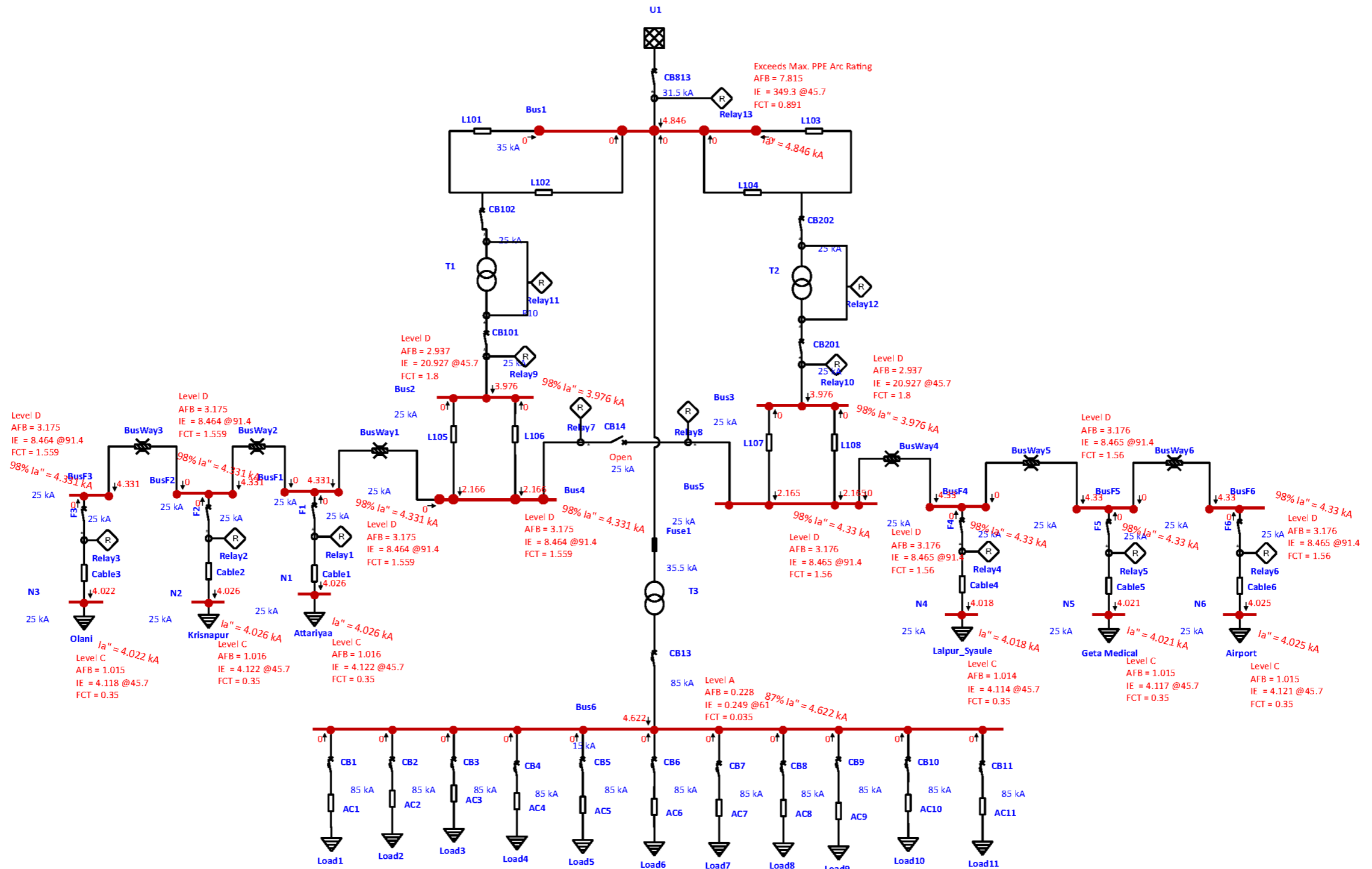


Figure G.1 AFA Simulation diagram of Attariya SS with existing PD setting

APPENDIX H: AFA simulation diagram of Attariya substation with alternative PD setting

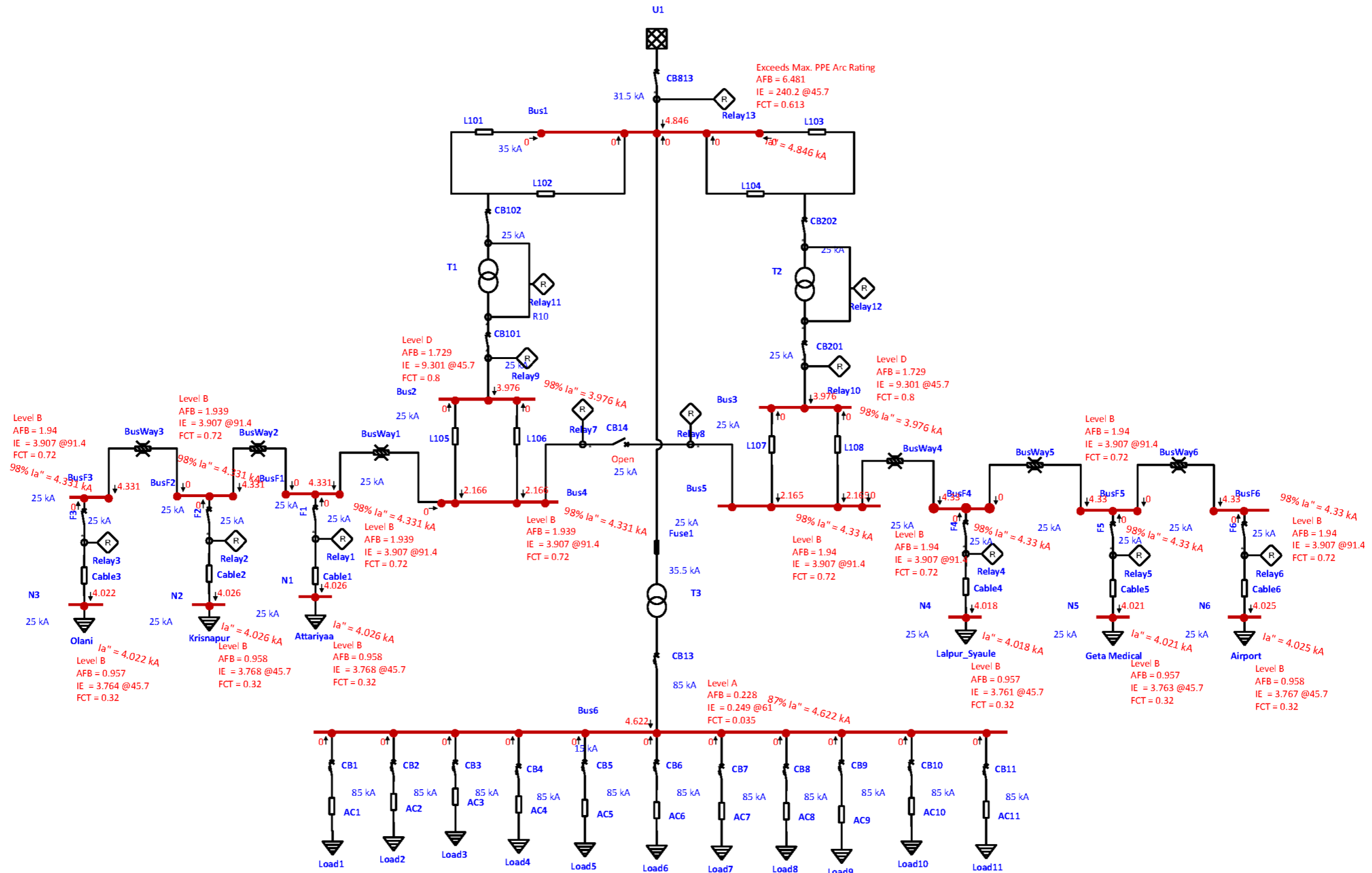


Figure H.1 AFA Simulation diagram of Attariya SS with existing PD setting

## APPENDIX I: PAPER ACCEPTANCE NOTIFICATION

6/11/24, 9:40 AM

Gmail - [IOEGC15] Editor Decision

# Gmail

In Rai <inrai509@gmail.com>

---

### [IOEGC15] Editor Decision

1 message

---

**IOEGC15 Publication Committee** <conference-noreply@ioe.edu.np>

Sun, Jun 9, 2024 at 8:35 AM To: In Bahadur Rai <inrai509@gmail.com>, Akhileshwar Mishra <akhileshwar@ioe.edu.np>, Jeetendra Chaudhary <jeetendra@ioe.edu.np>

In Bahadur Rai; Akhileshwar Mishra , Jeetendra Chaudhary :

We have reached a decision regarding your submission to 15th IOE Graduate Conference, "Analysis of Arc Flash and Mitigation Techniques in Substation Protection of Attariya Substation Nepal".

Our decision is to: **Accept Submission**

---

[ This email is auto-generated from 15th/OE Graduate Conference web portal ]

<https://mail.google.com/mail/u/O/?ik=005bee2907&view=pt&search=all&permthid=thread-f:1801350225494083664&simpl=msg:f:18013502254940836...>



त्रिभुवन विश्वविद्यालय  
Tribhuvan University  
इन्जिनियरिङ अध्ययन संस्थान  
Institute of Engineering

## डीनको कार्यालय OFFICE OF THE DEAN

GPO box- 1915, Pulchowk, Lalitpur  
Tel: 977-5-521531, Fax: 977-5-525830  
dean@ioe.edu.np, www.ioe.edu.np  
गोश्वारा पो. व. न- १९१५, पुल्चोक, ललितपुर  
फोन- ५५२१५३१, फ्याक्स- ५५२५८३०

Date: July 7, 2024

### To Whom It May Concern:

This is to certify that the paper titled “*Analysis of Arc Flash and Mitigation Techniques in Substation Protection of Attariya Substation Nepal*” (Submission# 20) submitted by **In Bahadur Rai** as the first author, which had been accepted for presentation after the peer-review process, has successfully been presented at the 15<sup>th</sup> IOE Graduate Conference held during May 17 & 18, 2024. Kindly note that the final revision of the papers and publication process of the conference proceedings is still underway and hence inclusion of the accepted manuscript in the conference proceedings is contingent upon timely response to further edits during the publication process.

Bhim Kumar Dahal, PhD  
Convener,  
15<sup>th</sup> IOE Graduate Conference



# Analysis of Arc Flash and Mitigation Techniques in Substation Protection of Attariya Substation Nepal

In Bahadur Rai <sup>a</sup>, Akhileshwar Mishra <sup>b</sup>, Jeetendra Chaudhary <sup>c</sup>

<sup>a, b, c</sup> Department of Electrical Engineering, Pulchowk Campus, IOE, Tribhuvan University, Nepal

✉ <sup>a</sup> 078mspse008.in@pcampus.edu.np, <sup>b</sup> akhileshwar@ioe.edu.np, <sup>c</sup> jeetendra@ioe.edu.np

## Abstract

Arc flash is a type of electrical explosion that can occur when there is a sudden and high current flow either between a conductor and ground or between two conductors. Arcing flash produces intense heat and light, and can release large amounts of energy. Arc flash analysis is required to quantify the associated risk and minimize the possible consequences with optimal protective measures. The electrical power system in Nepal is in growing phase. There are number of substations being upgraded, new substation being constructed. However, the consideration of arc flash analysis in substation protection system are not found to the level it required. The arc flash analysis is one of the important consideration for protection and control design of substation. The principal objective of this study is to quantify potential risks associated with arc flash events in the Attariya Substation and devise effective mitigation techniques. The Attariya substation is located in Far western province, Kailali District, Nepal. There were unofficial record of number of incidents related to arc flash in Attariya substation such as fire in low voltage (LV) switchgear and arcing due to underground (UG) cable termination explosion. The transformers in Attariya substation has been upgraded with higher capacity, which might have resulted in higher fault level in the substation. Thus, this study presents result of comprehensive analysis of arc flash and mitigation technique in Attariya substation. The substation's electrical power system model is created and assessed through the utilization of ETAP 19.01 software, known as the Electrical Transients Analyzer Program. There are two 16.6 MVA 33/11 kV transformers each of them connected to respective incomer and a normally open 11 kV bus tie circuit breaker. While analyzing the substation with existing protection devices (PD) and circuit breaker (CB) setting the fault clearing time and incident energy are observed to be at higher level than the proposed alternative setting of protective devices and circuit breakers. With alternative setting of protective devices the possible risk from arc flash incidents have been minimized significantly and minimize possible risk of equipment damage and injury to operating personnel.

## Keywords

Time-current curve (TCC), Arc flash, Fault Clearing Time (FCT), Arc Flash Boundary (AFB), Incident Energy

## 1. Introduction

The analysis of arc flash hazards and implementation of effective mitigation techniques are of utmost importance in ensuring the safe operation of electrical system and preventing possible consequences. Understanding the hazards associated with arc flashes and implementing appropriate protection measures are critical for safeguarding personnel and infrastructure. Arc flash is an electrical explosion that can occur when there is a sudden and high-current flow either between a conductor and ground or between two conductors. Arc flashes produces intense heat and light, and can release large amounts of energy. It can also create a shock wave that can travel through the air and cause damage to equipment and structures. An Arc Flash Hazard is defined as a potential source of harm or damage linked to the discharge of energy resulting from an electric arc. The significant decrease in injuries, damages, and their respective costs underscores the importance of conducting thorough arc flash analysis. However, in Nepal the classification of electrical incidents have not started yet but with the increase in power system the classification and standard record is required to identify the specific cause and take possible action. Number of fire incident have been noticed in industries and commercial building due to electric faults and the failure to promptly clear in a safe manner. Comprehensive analysis of arc flash hazard is required in electrical power system with the

increase in its complexity as well as with increase in capacity, without proper analysis the coordination of protective devices could not be identified and the fault may not be cleared in safe timing which cause the arc flash with possible consequences. In this paper, result of arc flash analysis of Attariya Substation Nepal is presented to show the level of arc flash hazard present in the substation and to minimize the arc flash hazard with proper method of mitigation with minimum cost.

The Attariya substation is located in Far Western province, Kailali district, Godawari municipality, Nepal. The Attariya Substation is a major substation of supplying electricity in Kailali District. To the best of my knowledge and study, there are not any practice of recording the incident of arc flash of the Attariya substation as well as in so many other substations in Nepal. Since the commissioning of the initial Attariya substation, the number of changes recorded in the substation including transformer and circuit breakers upgrade. This study demonstrates the extent to which incident energy levels can be minimized through alternative settings of the protective and fault-clearing devices at the Attariya substation, as examined in the case study. With the obtained results possible risk of arc flash can be quantified and recommend the suitable action of minimizing the possible risk, thus saving the cost of injury and damage to the electrical equipment and infrastructures.

## 2. Literature Review

In [1], the authors discuss the types and volume of arc flash injuries documented by OSHA inspectors in the United States from April 1984 to June 2007. The authors consider various injury types and occurrences categorized by voltage class (ranging from 120 V to 240 kV), the frequency of events across different equipment classes and typical tools used, as well as the detailed descriptions of numerous incidents. In [2], IEEE Std. 1584 provides a standardized procedure for carrying out arc flash analysis. Its range of application includes fault current from 500A to 106kA and three phase voltages between 208 V and 15 kV. For the voltage above 15 kV Lee method of formulae can be applied [3]. In [4], the authors discuss the necessity of high voltage arc flash examination. The authors contrasts the many arc flash analysis methods that are available and examines the consistency of the findings. In [5], the authors presents a case study of SSN substation situated in North Florida. The authors have modeled electrical power system of SSN substation utilizing ETAP 14.01. Then, the authors have evaluated with reference to standard method and guidelines. Various substation configurations were taken into consideration when performing study. For the analysis, the IEEE Std. 1584 guidelines were employed. In [6], the standard has provided guidelines and standards for workplace electrical safety, emphasizing the dangers associated with electrical systems and arc flash incidents. Primary goals of NFPA 70E-2018 are to safeguard employees from electrical hazards and lower the possibility of accidents and fatalities. In [3], the authors have conducted an analysis of arc flash on the IEEE 8 bus test system using the DIgSILENT software. The determination of incident energy (IE) involved applying the methodology outlined in the IEEE Std. 1584 and NFPA 70E-2018. In [7], the IEEE Std. 242-2001, commonly referred to as the IEEE Buff Book, offers standardized guidelines for conducting protection coordination studies in power systems. This guide delineates key principles for ensuring the protection and efficient coordination of industrial and commercial power systems, aimed at safeguarding them against potential anomalies expected during operation. In [8], the authors provides IEEE four node test feeder, with a simple test feeder to examine our method of arc analysis. The authors explain all the necessary data and parameters required to model the test system using selected tool.

## 3. Methodology

[2] IEEE Std. 1584 is the main reference of arc flash analysis of this study and [7] IEEE Std. 242-2001 is the reference for protection coordination study. This study initiated with the collection of all the necessary data from Attariya substation Nepal and proceeding system modeling in ETAP 19.01. Performed sequential checks of load flow, short circuit fault level, protection coordination and finally arc flash analysis is performed for existing system. Then effective method of reducing incident energy and possible risk of arc flash has been identified and presented in this study.

### 3.1 Equations for Arc Flash Calculations

The criteria under which the IEEE Std. 1584 calculation method remains applicable are as follows [2]:

1. Range of Voltage: 208 V-15 kV
2. System frequency: Sixty or Fifty Hertz
3. Current in bolted fault condition
  - (a) For voltage-208V to 600V: 500A to 106kA
  - (b) For voltage-601V to 15kV: 200A to 65kA
4. Gaps between conductors:
  - (a) For voltage-208V to 600V: 6.35mm to 76.2mm
  - (b) For voltage- 601V to 15kV: 19.05mm to 254mm
5. Working distances of 305 millimeters or more
6. Electrode configuration: VCB,VCBB,HCBB,VOA and HOA

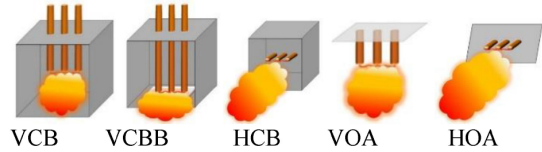


Figure 1: Electrode configuration [4]

Figure 1 represents electrode configurations as per IEEE Std. 1584, where VCB stands for vertical electrodes contained within enclosures, VCBB signifies vertical electrodes terminated within an insulating barrier inside an enclosure, HCB refers to horizontal electrodes housed within enclosures, VOA indicates vertical electrodes located in open air, and HOA denotes horizontal electrodes situated in open air. Incident Energy ( $E$ ), Arcing fault current ( $I_a$ ), and Arc Flash Boundary (AFB) are calculated with the following equations [2, 5]:

$$\log I_a = k + 0.662 \log I_{bf} + 0.000526G + 0.0966V - 0.00304G \log I_{bf} + 0.5588V \log I_{bf} \quad (1)$$

$$\text{Log } E_n = k_1 + k_2 + 0.0011G + 1.081 \log I_a \quad (2)$$

$$E = C_f \cdot E_n \left( \frac{610^x}{D^x} \right) \cdot \left( \frac{t}{0.2} \right) \quad (3)$$

$$D_B = \left[ C_f \cdot E_n \left( \frac{610^x}{E_B} \right) \cdot \left( \frac{t}{0.2} \right) \right]^{1/x} \quad (4)$$

Where,  $I_a$  and  $I_{bf}$  are arcing and bolted fault currents in kA respectively.  $k$  and  $k_1$  equal  $-0.097$  and  $-0.555$  for box configuration, and  $-0.153$  and  $0.792$  for open configurations respectively.  $V$  is the system voltage in kV.  $G$  denotes gap between conductors in millimeters.  $k_2$  is  $0$  and  $-0.113$  for ungrounded (high-resistance grounded) and grounded system respectively.  $E_n$  signifies normalized incident energy in  $\text{cal/cm}^2$ . For voltages exceeding  $1$  kV,  $C_f$  is set to  $1$ , while for voltages below  $1$  kV, it is adjusted to  $1.5$ . The parameter  $D$  and  $t$  represents working distance in millimeters and arcing time respectively. Distance exponent, denoted by  $x$ , is determined according to IEEE Std. 1584.  $E_B$  represents incident-energy  $\text{cal/cm}^2$  at boundary distance  $D_B$  measured in mm. It is obvious that IEEE Std. 1584 guidelines, provides the calculation only up

to 15 kV. In cases where the voltage surpasses 15 kV or the gap extends beyond the model's specified range, the Lee method might be implemented to determine the incident energy, employing the following equation:

$$E = 2.142 \times 10^6 \times \left(\frac{t}{D^2}\right) \times I_{bf} \quad (5)$$

$$D_B = \left[2.142 \times 10^6 \times V \times \left(\frac{t}{E_B}\right) \times I_{bf}\right]^{1/2} \quad (6)$$

Where,  $I_{bf}$ ,  $E$ ,  $V$ ,  $t$ ,  $D$ ,  $D_B$  and  $E_B$  represents incident energy in cal/cm<sup>2</sup>, kV voltage, arcing time-seconds, distance from possible arcing point, boundary distance measured in millimeters and incident energy at boundary in cal/cm<sup>2</sup> respectively.

### 3.2 Data Collection and System Modeling

The site visit to Attariya substation has been completed and all the necessary data have been collected. The gathered information encompasses equipment specifications, including voltage rating, MVA rating, impedance, system fault level, X/R ratio, and protection settings of the substation. The panel's electrode configuration was validated and documented following the guidelines specified in IEEE Std. 1584 [2]. The substation electrical system has been modeled in ETAP 19.01 with reference to the collected data and information. The modeling of system includes 33kV Bus-bar system and all the 11kV distribution switchgears. Figure 2 shows the single line diagram of Attariya Substation. It contains two 16.6 MVA, 33/11 kV power transformer, One 0.250 MVA, 33/0.400 kV station service transformer, five 3.3 MVA feeders and one 1.5 MVA feeders. There are two incomers in 11 kV switchgear with a bus tie circuit breaker in normally open configuration. The main 33 kV incomer has been protected by OCR, two power transformer have been protected by differential relays separately, 11 kV incomers are protected by multifunction relay with OCR and EF enabled, six outgoing feeders are also protected by multifunction relay with over current relay (OCR) and Earth Fault (EF) enabled. The Station service transformer high voltage (HV) side protected by fuse element and LV side protected by molded case circuit breaker (MCCB). Original setting of protective device and circuit breaker have been recorded and implemented in the substation model prepared for the analysis.

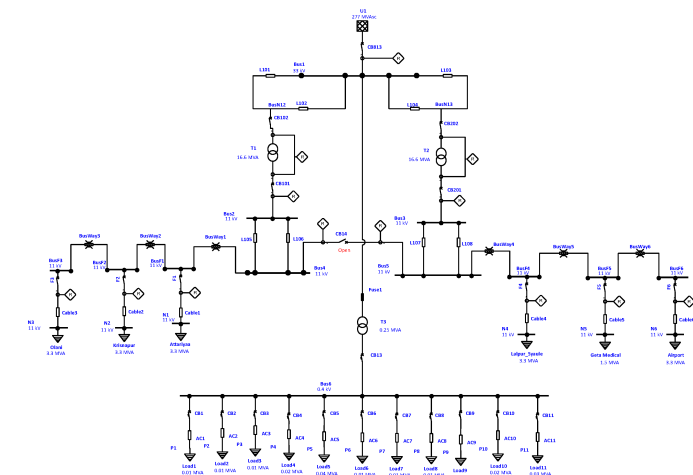
There are 11 outgoing circuits from station service distribution panel, each circuit protected with 4 pole miniature circuit breaker (MCB). The loading of the outgoing feeders are considered with respect to the average loading of the feeders, normally feeders loading found to be 50 percent of the total MVA rating. The OCR of five feeders have been set to trip at 195 A, one 1.5 MVA feeder OCR has been set to trip at 60 A. All the outgoing feeder circuit breakers are rated 1250 A, with breaking Capacity 25 kA and making capacity of 63 kA. While two incomers CB rated 2000 A, with braking capacity of 25 kA, and making capacity of 63 kA. The Bus bars and Bus ways are rated 2500A, with 25kA Peak and electrode configuration in panel are HCB with reference to Std.1584 Guideline [2]. General Spacing line-line are 152 mm while line-ground spacing noted 52mm. The UG cables connected from the indoor switchgear panel to the outdoor distribution pole termination in open air horizontal that means HOA configuration. Power transformer breaker are rated 2000A, with breaking capacity 25kA and making capacity 65 kA. The Bus 1 is considered as swing bus which will be connected to 132 kV bus bar through grid transformer. The six 630 mm<sup>2</sup> UG cable connects 33 kV Bus bar to transformer 1, that means two 630 mm<sup>2</sup> cable in each phase and similar applies to transformer 2. The 11kV output from 16.6 MVA transformer has been connected to indoor switchgear Incomer 1 by six 400 mm<sup>2</sup> UG cable, that means two cable in each phase, and similar applies connection between transformers to incomer 2. The 11kV switchgear to outdoor distribution pole has been connected by 300 mm<sup>2</sup> UG cable. For one 1.5 MVA feeder 95 mm<sup>2</sup> cables have been installed.

### 4. Comprehensive System Analysis

Comprehensive analysis of Attariya substation includes the following power system analysis: (a) Load-Flow (b) Short-Circuit (c) Protection-Coordination and (d) Arc Flash Analysis

**Table 1:** Load Flow Result

Bus ID	Voltage kV	Voltage %	Current	%PF
Bus1	33.00	100.00	163.9	88.5
Bus2	11.00	100.746	261.6	90
Bus3	11.00	101.033	214.4	89.2
Bus4	11.00	100.739	261.6	90
Bus5	11.00	101.026	214.5	89.2
Bus6	0.400	98.703	110.1	91.4
BusF1	11.00	100.739	261.6	90.0
BusF2	11.00	100.739	174.4	90.0
BusF3	11.00	100.739	87.2	90.0
BusF4	11.00	101.026	214.5	89.2
BusF5	11.00	101.026	127.1	88.6
BusF6	11.00	100.026	87.5	90.0
N1	11.00	100.731	87.2	90.0
N2	11.00	100.731	87.2	90.0
N3	11.00	101.729	87.2	90.0
N4	11.00	101.015	87.2	90.0
N5	11.00	101.018	39.8	85.0
N6	11.00	101.018	87.5	90.0



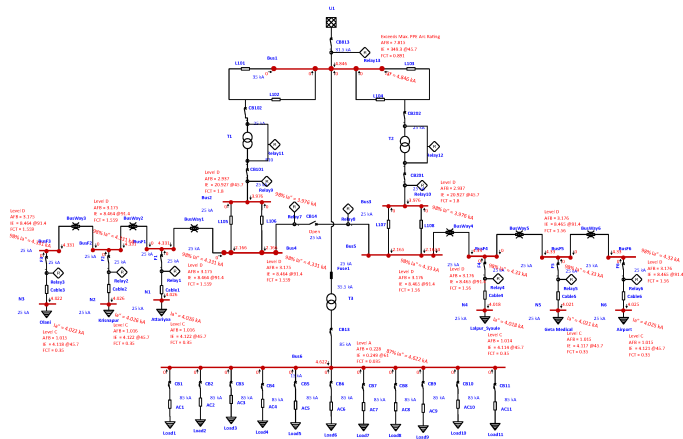
**Figure 2:** Single line diagram of case study Attariya substation

Table 1 presents the load flow result of Attariya substation

considering normal operation configuration, where Bus tie breaker CB13 have been in normally open condition. The loading of all the buses are normal, there are not any constraints violations. The voltage kV represents nominal voltage and current presented in Ampere. Table 2 presents short circuit study result of Attariya substation for the fault at the given Bus ID location. Table 3 presents the result of arc flash analysis (AFA) obtained for Attariya substation existing condition. The simulation diagram is presented in Figure 3. Incident energy of 33 kV bus1 is extremely high. Which may cause second degree burn up to around 9 meter from the bus bar. The fault clearing time are different for different buses range from 0.035 Sec to 1.8 Sec. The result is obtained for the existing setting of protective devices and circuit breakers. The incident energy of other buses could be observed as mentioned in Table 3 and the effective mitigation measure shall be identified to reduce the incident energy as well as FCT related to the fault at respective bus.

**Table 3:** Existing Condition Arc Flash Analysis Result

Bus ID	Voltage (kV)	I <sub>bf</sub> (kA)	I <sub>a</sub> (kA)	IE cal/cm <sup>2</sup>	FCT (sec)	AFB (m)
Bus1	33.00	4.846	4.846	349.3	0.891	7.815
Bus2	11.00	4.777	3.976	20.93	1.8	2.937
Bus3	11.00	4.777	4.331	20.93	1.8	2.937
Bus4	11.00	4.771	4.330	8.46	1.559	3.175
Bus5	11.00	4.770	4.622	8.47	1.56	3.176
Bus6	0.400	7.881	5.298	0.249	0.035	0.228
BusF1	11.00	4.771	4.331	8.46	1.559	3.175
BusF2	11.00	4.771	4.331	8.46	1.559	3.175
BusF3	11.00	4.771	4.331	8.46	1.559	3.175
BusF4	11.00	4.770	4.330	8.47	1.56	3.176
BusF5	11.00	4.770	4.330	8.47	1.56	3.176
BusF6	11.00	4.770	4.330	8.47	1.56	3.176
N1	11.00	4.751	4.026	4.12	0.35	1.016
N2	11.00	4.751	4.026	4.12	0.35	1.016
N3	11.00	4.747	4.022	4.12	0.35	1.015
N4	11.00	4.742	4.018	4.11	0.35	1.014
N5	11.00	4.745	4.021	4.12	0.35	1.015
N6	11.00	4.750	4.026	4.12	0.35	1.015



**Figure 3:** AFA simulation diagram for existing condition

**Table 2:** Short Circuit Result

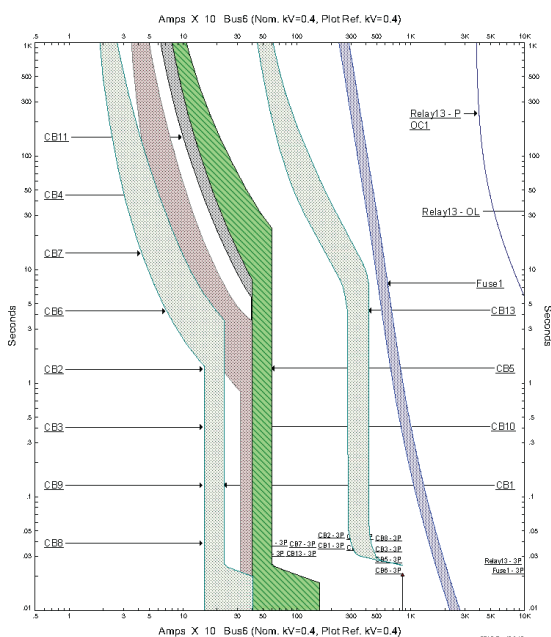
Bus ID	Voltage kV	Symm. kA rms	Asymm. kA rms
Bus1	33.00	4.846	7.375
Bus2	11.00	4.777	7.269
Bus3	11.00	4.777	7.269
Bus4	11.00	4.771	7.250
Bus5	11.00	4.770	7.247
Bus6	0.400	7.881	8.011
BusF1	11.00	4.771	7.250
BusF2	11.00	4.771	7.249
BusF3	11.00	4.771	7.249
BusF4	11.00	4.770	7.247
BusF5	11.00	4.770	7.247
BusF6	11.00	4.770	7.247
N1	11.00	4.751	7.817
N2	11.00	4.751	7.816
N3	11.00	4.747	7.174
N4	11.00	4.742	7.519
N5	11.00	4.745	7.101
N6	11.00	4.750	7.184

### 5. Analysis of Mitigation and Recommendation

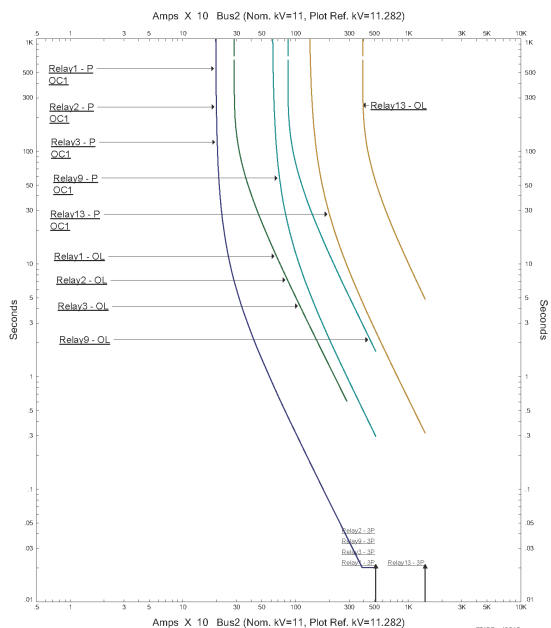
From the analysis of the existing conditions, fault clearing times are found to be within the range of seconds. This has resulted in high incident energy levels at various buses, ranging from risk category 1 to beyond risk category 5. The arc flash is new to the substation personnel at Attariya substation, where there was a lack of protective gear for arc flash incidents, and no warning or caution labels about possible arc flash incidents were present. The awareness of arc flash hazards is found to be below the required level. In addition to these existing conditions for mitigating arc flash hazards in the substation, there are several possible methods to reduce fault clearing times and minimize incident energy levels. One method is to replace circuit breakers and protective devices, but this approach incurs a significant cost for the utility, which might become uneconomical. On the other hand, the settings of protective devices could be adjusted alternatively with proper coordination to achieve a lower fault clearing time than the existing one. This second method reduces incident energy with almost no expenses and is considered economical. The analysis of the Attariya substation has been conducted with alternative settings of protective devices, as shown in Table 4. With the new settings of devices, the coordination has been studied and found to be accurate according to IEEE Std 242-2001. The TCC curves can be observed in Figure 4, Figure 5, and Figure 6. Additionally, calculated fault clearing time falls within the range specified by IEEE Std. 242-2001. A significant improvement in fault clearing time and a reduction in incident energy levels have been observed, as shown in Table IV. This adjustment of settings for protective devices will significantly reduce the risk of arc flash hazards and minimize possible consequences. Table 4 represents the recommended alternative settings for protective devices for Attariya Substation Nepal to reduce both fault clearing time and incident energy. It is also essential to maintain regular monitoring and assessments to uphold the sustained effectiveness of the implemented measures.

**Table 4:** Alternative Protective Device Setting

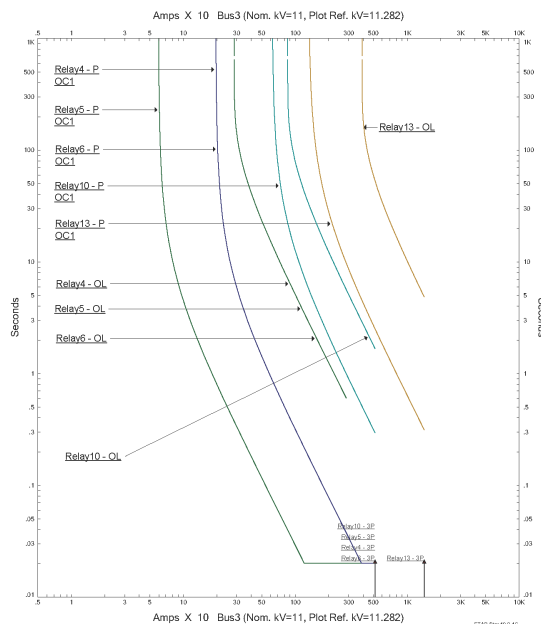
Relay ID	CT Ratio	PSM	TDS
Relay1	300:1	0.65	0.10
Relay2	300:1	0.65	0.10
Relay4	300:1	0.65	0.10
Relay5	300:1	0.20	0.10
Relay6	300:1	0.65	0.10
Relay7	900:1	0.69	0.20
Relay8	900:1	0.69	0.22
Relay9	900:1	0.69	0.25
Relay10	900:1	0.69	0.25
Relay13	900:1	0.50	0.30



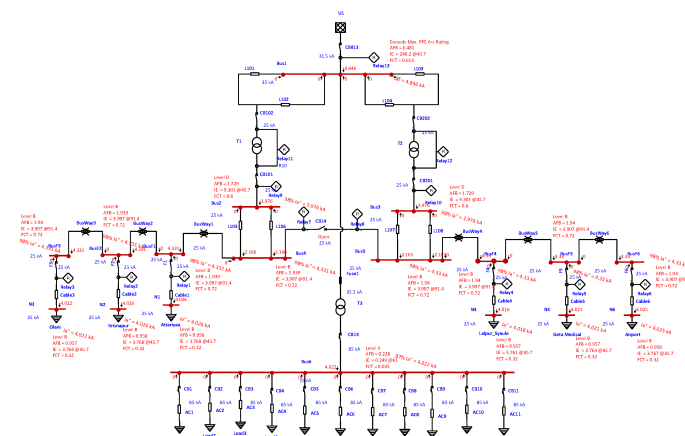
**Figure 4:** TCC of LVCB, HV Fuse and Relay 13 with alternative setting



**Figure 5:** TCC of Relay 1, 2, 3, 9 and 13 with alternative setting



**Figure 6:** TCC of Relay 4, 5, 6, 10 and 13 with alternative setting



**Figure 7:** AFA simulation diagram of with Alternative Protective Device Setting

The TCC curves for various protective devices installed in the Attariya substation are depicted in Figure 4, Figure 5, and Figure 6. From the TCC curve analysis, it is evident that there are no intersections between the curves. This implies that only one device will be actuated at a time, ensuring proper coordination. The protection coordination study was conducted using ETAP 19.01, applying faults at various locations within the system model. The sequence of operation for protective devices and fault clearing devices was observed and found to be well-coordinated according to IEEE Std 242-2001. Table 4 presents the results of the arc flash analysis for the Attariya substation with alternative settings for protective devices, as mentioned in Table 4. It is observed that the incident energy level at 11kV buses has significantly reduced, mitigating the risk of injury and burns in accordance with NFPA 70E due to alternative protective device settings. The simulation diagram is shown in Figure 7. The calculated fault clearing time falls within the range specified by IEEE Std. 242-2001.

**Table 5:** Arc Flash Analysis Result With Alternative PD Setting

Bus ID	Voltage (kV)	I <sub>bf</sub> (kA)	I <sub>a</sub> (kA)	IE cal/cm <sup>2</sup>	FCT (sec)	AFB (m)
Bus1	33.00	4.846	4.846	240.24	0.613	6.481
Bus2	11.00	4.777	3.976	9.3	0.8	1.729
Bus3	11.00	4.777	3.976	9.3	0.8	1.729
Bus4	11.00	4.771	4.331	3.91	0.72	1.939
Bus5	11.00	4.770	4.330	3.91	0.72	1.94
Bus6	0.400	7.881	5.298	0.249	0.035	0.228
BusF1	11.00	4.771	4.331	3.91	0.72	1.939
BusF2	11.00	4.771	4.331	3.91	0.72	1.939
BusF3	11.00	4.771	4.331	3.91	0.72	1.94
BusF4	11.00	4.770	4.330	3.91	0.72	1.94
BusF5	11.00	4.770	4.330	3.91	0.72	1.94
BusF6	11.00	4.770	4.330	3.91	0.72	1.94
N1	11.00	4.751	4.026	3.77	0.32	0.958
N2	11.00	4.751	4.026	3.77	0.32	0.958
N3	11.00	4.747	4.022	3.76	0.32	0.957
N4	11.00	4.743	4.018	3.76	0.32	0.957
N5	11.00	4.746	4.021	3.76	0.32	0.957
N6	11.00	4.750	4.025	3.77	0.32	0.958

**Table 6:** AFA Comparison Existing Vs Alternative

Bus ID	IE Exist. cal/cm <sup>2</sup>	IE Alt. cal/cm <sup>2</sup>	FCT Exist. Sec	FCT Alt. Sec	IE Red. cal/cm <sup>2</sup>	FCT Red. Sec
Bus1	349.3	240.24	0.891	0.613	109.06	0.278
Bus2	20.93	9.3	1.8	0.8	11.63	1.000
Bus3	20.93	9.3	1.8	0.8	11.63	1.000
Bus4	8.46	3.91	1.559	0.72	4.55	0.839
Bus5	8.47	3.91	1.56	0.72	4.56	0.840
Bus6	0.249	0.249	0.035	0.035	0.000	0.000
BusF1	8.46	3.91	1.559	0.72	4.55	0.839
BusF2	8.46	3.91	1.559	0.72	4.55	0.839
BusF3	8.46	3.91	1.559	0.72	4.55	0.839
BusF4	8.47	3.91	1.56	0.72	4.56	0.840
BusF5	8.47	3.91	1.56	0.72	4.56	0.840
BusF6	8.47	3.91	1.56	0.72	4.56	0.840
N1	4.12	3.77	0.35	0.32	0.35	0.030
N2	4.12	3.77	0.35	0.32	0.35	0.030
N3	4.12	3.76	0.35	0.32	0.36	0.030
N4	4.11	3.76	0.35	0.32	0.35	0.030
N5	4.12	3.76	0.35	0.32	0.36	0.030
N6	4.12	3.77	0.35	0.32	0.35	0.030

A comparison between existing (Exist.) and alternative (Alt.) protective device settings at the Attariya substation is presented in Table 6. Results show a noteworthy reduction (Red.) in incident energy (IE) and improved fault clearing times at bus locations, leading to a significantly reduced arc flash boundary. The alternative settings are considered viable, effectively reducing arc flash hazards and minimizing potential damage and injuries. Fault clearing times for all buses with alternative settings are below one second. Additionally, we recommend including warning labels at key locations with information on required PPE, arc flash boundary, and incident energy levels,

contributing to cost-effective prevention of arc flash incidents.

## 6. Conclusion

This paper presents a comprehensive arc flash analysis of the Attariya substation, a vital source of electricity for Kailali district, Nepal. The study, the first of its kind in Nepal, focuses on the real-world scenario of Attariya, chosen based on past incidents and upgrades. The analysis reveals that existing protective settings, while within IEEE Std. 242-2001 limits, pose heightened risks, potentially requiring costly measures. However, alternative coordinated settings significantly reduce fault clearing time, arc flash risk, and incident energy, emphasizing the importance of arc flash analysis for substation protection. The study underscores the need for safety measures, connecting with broader power system studies. As Nepal’s power system expands, implementing arc flash analysis becomes crucial for safety, operational efficiency and robust substation electrical infrastructure, aligning with global practices.

## Acknowledgments

The authors would like to extend their sincere appreciation to the Nepal Electricity Authority Attariya Grid Branch for generously providing access and necessary information, allowing for the successful execution of the analysis. Furthermore, the authors express their gratitude to all the dedicated supporting personnel whose contributions were instrumental in the completion of this study.

## References

- [1] C.M. Wellman. OSHA arc-flash injury data analysis. In *IEEE IAS Electrical Safety Workshop*, pages 1–5. IEEE IAS Electrical Safety Workshop, 2012.
- [2] IEEE. IEEE guide for performing arc - flash hazard calculations 1584-2018. *IEEE Industry Application Society*, 2018.
- [3] A. Bukar M.A. Gana and Smaila Y.A. Arc flash study of IEEE 8 bus test system using digital simulation and electrical network analysis platform. *Arid Zone Journal of Engineering, Technology and Environment*, 19:1–12, 2023.
- [4] G. Praise and P.A. Scarpino. A basic assessment of arc flash in low voltage ac. *IEEE Transactions on Industry Applications*, 57:4513–4519, 2021.
- [5] A. Asrari, B. Ramos, S. Lavoie, and M. Churilla. Arc flash analysis of silver springs north switchyard — a case study in North Florida. In *North American Power Symposium (NAPS)*, pages 1–6, 2017.
- [6] National Fire Protection Association. Standard for electrical safety in workplace NFPA70E 2018. *IEEE Transactions on Industry Applications*, 51:2709–2716, 2018.
- [7] IEEE. IEEE std 242-2001 - IEEE recommended practice for protection and coordination of industrial and commercial power systems (ieec buff book). *IEEE Industry Application Society*, 2001.
- [8] IEEE PES Test Feeder Working Group. 4-bus test feeder, July 2017. Accessed on March 3, 2024.

# Analysis of Arc Flash and Mitigation Techniques in Substation Protection of Attariya Substation Nepal

---

ORIGINALITY REPORT

---

4%

SIMILARITY INDEX

---

PRIMARY SOURCES

---

- |   |   |                 |
|---|---|-----------------|
| 1 | <a href="http://stax.strath.ac.uk">stax.strath.ac.uk</a><br>Internet  | 35 words — < 1% |
| 2 | Mahmood Hosseini Aliabadi, Hassan Farrokhi. "Arc Flash decreasing by using re-closer relay on a 20kV network", 2016 21st Conference on Electrical Power Distribution Networks Conference (EPDC), 2016<br>Crossref | 32 words — < 1% |
| 3 | <a href="http://azojete.com.ng">azojete.com.ng</a><br>Internet  | 32 words — < 1% |
| 4 | Liang, Xiaodong, Bagen Bagen, and David Gao. "An Effective Approach to Reducing Arc Flash Hazards in Power Systems", IEEE Transactions on Industry Applications, 2015.<br>Crossref                                | 31 words — < 1% |
| 5 | Yoshihide Hase, Tanuj Khandelwal, Kazuyuki Kameda. "Power System Dynamics with Computer-Based Modeling and Analysis", Wiley, 2019<br>Crossref   | 28 words — < 1% |
| 6 | <a href="http://pemakzwangchuk.blogspot.com">pemakzwangchuk.blogspot.com</a><br>Internet  | 28 words — < 1% |
| 7 | <a href="http://digital.library.unt.edu">digital.library.unt.edu</a><br>Internet  |                 |

27 words — < 1%

8 [etj.uotechnology.edu.iq](http://etj.uotechnology.edu.iq)  
Internet

27 words — < 1%

9 Craig M. Wellman. "OSHA arc-flash injury data analysis", 2012 IEEE IAS Electrical Safety Workshop, 2012  
Crossref

20 words — < 1%

10 [etap.in](http://etap.in)  
Internet

20 words — < 1%

11 [arcadvisor.com](http://arcadvisor.com)  
Internet

18 words — < 1%

12 [doaj.org](http://doaj.org)  
Internet

18 words — < 1%

13 [repositorio.ufsm.br](http://repositorio.ufsm.br)  
Internet

18 words — < 1%

14 Giuseppe Parise, Pietroantonio Scarpino. "A Basic Assessment of Arc Flash in Low Voltage A.C.", IEEE Transactions on Industry Applications, 2021  
Crossref

17 words — < 1%

15 [www3.dicca.unige.it](http://www3.dicca.unige.it)  
Internet

16 words — < 1%

16 K.J. Lippert. "Safety standards - A clarification of the use of the arc flash calculator - Understanding IEEE 1584 arc flash calculations", IEEE Industry Applications Magazine, 5/2005  
Crossref

15 words — < 1%

---

17 Zhenyuan Zhang, Peng Wang, Shiuan-Hau Rau, Wei-Jen Lee. "Effect of Electrode Geometry on Arc Flash Protection Boundary", 2019 IEEE/IAS 55th Industrial and Commercial Power Systems Technical Conference (I&CPS), 2019

15 words — < 1%

Crossref

---

18 Abdelhay Sallam, Om Malik. "Electric Distribution Systems, Second Edition", Wiley, 2018

14 words — < 1%

Crossref

---

19 nerdist.com

Internet

14 words — < 1%

---

20 Elaheh Mashhour, Seyed-Masoud Moghaddas-Tafreshi. "Three-Phase Distribution Power Flow Solution Considering Symmetrical and Unsymmetrical Three-Phase Voltage Control Mode of PV Nodes", International Journal on Energy Conversion (IRECON), 2019

13 words — < 1%

Crossref

---

21 K.J. Lippert, D.M. Colaberardino, C.W. Kimblin. "Understanding arc flash hazards", Conference Record of 2004 Annual Pulp and Paper Industry Technical Conference (IEEE Cat. No.04CH37523), 2004

13 words — < 1%

Crossref

---

22 pdfcoffee.com

Internet

11 words — < 1%

---

23 repository.smuc.edu.et

Internet

11 words — < 1%

---

24 www.epfl.ch

Internet

11 words — < 1%

---

25 www.scitechnol.com

Internet

11 words — < 1%

26 D. Kosc, P.S. Hamer. "Grounding practices - A system-wide systematic approach", IEEE Transactions on Industry Applications, 2003

Crossref

10 words — < 1%

27 Diosdado V. Hernandez, Robert Mac. "Electrical hazard prevention program at a water and wastewater utility", 2016 IEEE IAS Electrical Safety Workshop (ESW), 2016

Crossref

10 words — < 1%

28 Giuseppe Parise, Pietro Antonio Scarpino. "Generalized Model of an ARC Fault Current in A.C. & D.C.", 2023 IEEE Industry Applications Society Annual Meeting (IAS), 2023

Crossref

10 words — < 1%

29 Han, Sang-Hyuck, Min-Hyung You, Jin-Hyeok Im, and Young-Kuk Kim. "Development of a transmission simulator based on hierarchical model", 2011 IEEE INTERNATIONAL CONFERENCE ON ELECTRO/INFORMATION TECHNOLOGY, 2011.

Crossref

9 words — < 1%

30 S. Arias-Guzman, A.J. Ustariz-Farfan, E.A. Cano-Plata. "Integral Protection of Electrical Systems A Power Quality Approach", IEEE Transactions on Industry Applications, 2023

Crossref

9 words — < 1%

31 kipdf.com

Internet

9 words — < 1%

32 www.howecool.co.uk

Internet

9 words — < 1%

- 
- 33 [www.mdpi.com](http://www.mdpi.com) 9 words — < 1%  
Internet
- 
- 34 Abeera Khan, Mohammad Mohsin Aman. "Investigation of the effects of critical incident energy parameters using ETAP® to reduce arc flash hazards", 2018 1st International Conference on Power, Energy and Smart Grid (ICPESG), 2018 8 words — < 1%  
Crossref
- 
- 35 Albert Marroquin, Terry McKinch. "Methods for Evaluating DC Arc-Flash Incident Energy in Battery Energy Storage Systems", 2023 IEEE IAS Electrical Safety Workshop (ESW), 2023 8 words — < 1%  
Crossref
- 
- 36 Antony C. Parsons, W. Blane Leuschner, Kevin X. Jiang. "Simplified Arc-Flash Hazard Analysis Using Energy Boundary Curves", IEEE Transactions on Industry Applications, 2008 8 words — < 1%  
Crossref
- 
- 37 Arash Asrari, Benito Ramos. "Screen Wash Pump Power System Study—An Industrial Project for Hines Energy Complex", 2018 Clemson University Power Systems Conference (PSC), 2018 8 words — < 1%  
Crossref
- 
- 38 Julius Ndirangu, Eliud Limo, Peter Kimemia. "Arc - Flash Calculations Using IEEE Std 1584-2018 and Mitigation Measures - Case Study", 2023 IEEE AFRICON, 2023 8 words — < 1%  
Crossref
- 
- 39 Mukesh Gautam, Mohammed Benidris. "A graph theory and coalitional game theory-based pre-positioning of movable energy resources for enhanced 8 words — < 1%

# distribution system resilience", Sustainable Energy, Grids and Networks, 2023

Crossref

40 Nelson, John P., Joshua Billman, and James Bowen. "The effects of system grounding, bus insulation and probability on arc flash hazard reduction - The missing links", 2012 Petroleum and Chemical Industry Conference (PCIC), 2012. 8 words — < 1%

Crossref

41 Short, . "Grounding and Safety", Electric Power Distribution Handbook Second Edition, 2014. 8 words — < 1%

Crossref

42 Walker, Christopher G.. "Arc flash energy reduction techniques zone selective interlocking & energy-reducing maintenance switching", IEEE/IAS Pulp & Paper Industry Technical Paper Conference, 2011. 8 words — < 1%

Crossref

43 Yu, Yu-Ting. "Parameterization of Vertical Dispersion Coefficient (İfz) near Roadway: Vehicle Wake, Density and Types.", Illinois Institute of Technology, 2020 8 words — < 1%

ProQuest

44 cired.net 8 words — < 1%

Internet

45 journal.esj.edu.iq 8 words — < 1%

Internet

46 vdocuments.mx 8 words — < 1%

Internet

47 www.scitepress.org 8 words — < 1%

Internet

---

48 Kevin X. Jiang. "Simplified Arc-Flash Hazard Analysis Using Energy Boundary Curves", 2007 7 words — < 1%  
IEEE Industry Applications Annual Meeting, 09/2007  
Crossref

---

49 Mohammed M. Islam. "Shipboard Power Systems Design and Verification Fundamentals", Wiley, 2018 7 words — < 1%  
Crossref

---

50 Todd R. Sauve, Richard P. Anderson, Tryton Bower, Kurt R. Mickler. "Using IEEE Standard 1683 in Designing and Specifying Motor Control Centers: Helping to Ensure Safe Performance and Reducing Hazards and Risks", IEEE Industry Applications Magazine, 2019 7 words — < 1%  
Crossref

---

51 Xiaodong Liang, Jeffrey Lim. "Power systems protection in an oil field distribution system", Conference Record 2009 IEEE Industrial & Commercial Power Systems Technical Conference, 2009 7 words — < 1%  
Crossref

---

52 Arash Asrari, Benito Ramos, Steven Lavoie, Mark Churilla. "Arc flash analysis of silver springs north switchyard — A case study in North Florida", 2017 North American Power Symposium (NAPS), 2017 6 words — < 1%  
Crossref

---

53 B. Muruganantham, R. Gnanadass, N.P. Padhy. "Challenges with renewable energy sources and storage in practical distribution systems", Renewable and Sustainable Energy Reviews, 2017 6 words — < 1%  
Crossref

---

54 Christopher G. Walker. "Arc-Flash Energy Reduction Techniques: Zone-Selective Interlocking and 6 words — < 1%

Energy-Reducing Maintenance Switching", IEEE Transactions on Industry Applications, 2013

Crossref

---

55 Nancy LaFlair, Mark H. McKinney, Ramtin Hadidi. "Arc flash risk assessment for a megawatt scale medium voltage research and testing facility", 2017 North American Power Symposium (NAPS), 2017 6 words — < 1%

Crossref

---

56 Robert J. Burns, Daniel E. Hrncir, Austin M. Johnson. "Arc Quenching Technology in Switchgear: Surpassing IEEE C37.20.7", IEEE Industry Applications Magazine, 2024 6 words — < 1%

Crossref

---

57 S. Arias-Guzman, A. J. Ustariz-Farfan, E. A. Cano-Plata. "Integral Protection Methodology for Steel Manufacturer Users", 2021 IEEE Industry Applications Society Annual Meeting (IAS), 2021 6 words — < 1%

Crossref

---

EXCLUDE QUOTES ON

EXCLUDE SOURCES OFF

EXCLUDE BIBLIOGRAPHY ON

EXCLUDE MATCHES OFF