IMPLEMENTATION OF DIGITAL PROTECTION IN DISTRIBUTION SYSTEM WITH PENETRATION OF DISTRIBUTED GENERATION

A Thesis submitted to Gujarat Technological University

for the Award of

Doctor of Philosophy

in

Electrical Engineering

by

Desai Ishan Mukeshchandra

[179999914003]

under supervision of

Dr. Nilesh G. Chothani

GUJARAT TECHNOLOGICAL UNIVERSITY

AHMEDABAD

August - 2026

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ABSTRACT

With increase in Integration / Penetration of Distributed Generation (DG) sources like Solar PV, Wind Energy Conversion System and Small Hydro Power Plant, Traditional Radial Distribution Network (TRDN) gets transformed into Modern Active Distribution Network (MADN) with bidirectional power flow, increased normal & fault current levels and dynamic operating conditions in the system. These alterations render conventional protection schemes ineffective that leads to problems like protection miscoordination, relay false tripping and relay blinding. This thesis presents comprehensive analysis to understand various parameters affecting protection coordination of Distribution System integrated with Distributed Generation sources using simulation performed through PSCAD software.

An Overcurrent Protection scheme is proposed for Industrial Distribution System with Distributed Generation sources along with comprehensive simulation for understanding factors affecting protection coordination using ETAP software considering different Setting Groups. Proposed Overcurrent Protection is increasing reliability of Industrial Distribution System under consideration with respective operating sequence of relays for various Setting Groups. Thesis also presents accurate and reliable Hybrid Fault Detection and Classification schemes for protection of Distribution System integrated with Distributed Generation sources.

Two different Fault Detection and Classification (FDC) schemes for Distribution System Protection viz. (i) Principal Component Analysis (PCA) to carry out dimensionality reduction (preservation of more relevant features) combined with Convolutional Neural Network (CNN) for effective Fault Classification and Localization and (ii) Wavelet Packet Transform (WPT) for multi resolution feature extraction from three phase currents combined with Extreme Gradient Boosting (XGBoost) for Fault Detection and Classification are suggested. Proposed combined PCA and CNN based scheme and combined WPT and XGBoost based scheme are validated through extensive simulations on modified IEEE 9-Bus and IEEE 4-Bus Distribution System. Proposed combined WPT and XGBoost based scheme achieves more than 99% Fault Detection and Classification accuracy along with higher F1 score, outperforming combined PCA & CNN based and other Artificial Intelligence / Machine Learning (AIML) based schemes. Proposed hybrid WPT and CNN based scheme ensures reliable protection, maintaining selectivity and sensitivity in presence of various Distributed Generation sources. Work also demonstrates suitability of proposed combined WPT and CNN scheme based Digital Protection for Modern Active Distribution Network, which also will help in developing adaptive, self-healing scheme for Smart Grid.

Acknowledgement

With immense pleasure, I would like to present this Thesis on work related to "Implementation of Digital Protection in Distribution System with Penetration of Distributed Generation". I am very much grateful to each and every person who helped me in completion of my thesis with their valuable guidance, time and support.

I would like to express my sincere gratitude to my supervisor **Dr. Nilesh G. Chothani**, for his invaluable guidance, continuous support and insightful suggestions throughout the course of this work. His expertise and encouragement have been instrumental in completing this Thesis. I would like to extend my sincere thanks to **Late. Dr. Nidhish Mishra**, **Dr. Ritesh Patel** and **Dr. Khyati Mistry**, Members of Doctoral Progress Committee for their valuable support, helpful feedback and expert guidance throughout the journey of this work.

I would also like to thank **Mr. Paul Jacob** for his kind help and support during this Journey. I am also thankful to **Prof. Falguni Talajiya**, **Prof. Rital Gajjar** and all those who have supported me in completing this work.

My special and deepest thanks to my wife **Shivani** and my son **Shivansh**, whose patience, love and understanding allowed me to pursue this journey. Their constant support and sacrifices make this possible. I am very much grateful to my Father **Mukeshchandra** for his unwavering love, encouragement & support and my Late Mother **Bina** for her constant blessings from wherever she is, which have always been a source of strength for me. I would like to thank all my Family members for their constant love, blessings and support.

At last, I would like to take a moment to bow my head with gratitude to **Mahadev** and **Ganpati Bappa** for their divine blessings and strength, without which this work would not have been possible.

Desai Ishan Mukeshchandra

Table of Content

List of Abbreviations

AIML	Artificial Intelligence and Machine Learning
CEA	Central Electricity Authority
CB	Circuit Breaker
CMS	Control & Management System
CNN	Convolutional Neural Network
CT	Current Transformer
CTI	Coordination Time Interval
DER	Distributed Energy Resources
DG	Distributed Generation
DS	Distribution System
DFIG	Doubly Fed Induction Generator
ESS	Energy Storage Systems
FDC	Fault Detection & Classification
FP	False Positive
FN	False Negative
IDMT	Inverse Definite Minimum Time
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IG	Induction Generator
IIDG	Inverter Interfaced Distributed Generator
LFA	Load Flow Analysis
MDN	Modern Distribution Network
MEPS	Modern Electrical Power System
MG	Microgrid
MMTC	Minimum Melting Time Characteristic
OC	Overcurrent
PCA	Principal Component Analysis
PCC	Point of Common Coupling
PSM	Plug Setting Multiplier

PV	Photovoltaic
RES	Renewable Energy Sources
RGP	Relay Setting Group
SCA	Short Circuit Analysis
SG	Synchronous Generator
TCC	Time Current Characteristics
TCTC	Total Clearing Time Characteristic
TDS	Time Dial Settings
TGM	Time Gradient Margin
THD	Total Harmonic Distortion
TP	True Positive
TN	True Negative
TMS	Time Multiplier Setting
VT	Voltage Transformer
WES	Wind Energy Systems
WPT	Wavelet Packet Transform
XGBoost	Extreme Gradient Boosting

List of Symbols

I_p	Pickup Current
T_{op}	Time of Operation
I_{fmin}	Minimum Fault Current
I_{fmax}	Maximum Fault Current
V_S	Sending End Voltage
V_R	Receiving End Voltage
X_L	Line Reactance
δ	Load Angle
P	Real Power in Distribution System
Q	Reactive Power in Distribution System
Pgrid	Real Power Supply from Grid
Qgrid	Reactive Power Supply from Grid
P_{DG}	Real Power Supply from DG
Q_{DG}	Reactive Power Supply from DG
P_{Load}	Real Power Demand
Q_{Load}	Reactive Power Demand
I_f	Fault Current in Distribution Network in absence of DGs
$I_f^{'}$	Fault Current in Distribution Network when DGs are present
$I_{f,grid}$	Fault Current Contribution from Grid
I_{grid}	Nominal from Grid
$I_{f,DG}$	Fault Current Contribution from DGs
I_{DG}	Nominal Current from DGs
I_{Load}	Load Current
V_{grid}, V_{DG}	Grid Bus Voltages & DG Bus Voltages
Z_{grid}, Z_{DG}	Source Impedance (Grid) & Source Impedance (DG)
Z_{line}	Impedance of line between grid & fault location
$Z_{line,DG}$	Impedance of line between DG & fault location
Z_{fault}	Fault Impedance

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CHAPTER - 1

Introduction

1.1 Indian Power Scenario

Power Demand in India is increasing day by day. To fulfil this demand, power generation facilities need to be installed. Fig. 1.1 is showing growth of installed power generation capacity in India. According to CEA, as on 31/03/2026, total installed electrical power generation capacity is 532740 MW. Till now, this power demand was mainly fulfilled by large conventional power plants like coal-based power plants, gas-based power plants or nuclear power plants, which are far from load centres. Because these power generation facilities are far from load centres, a large transmission and distribution line network is required for power to reach the consumer end. These conventional power plants cause environmental pollution as they are burning fossil fuel and as there is requirement of large transmission and distribution network, there are issues like power loss and voltage drop.

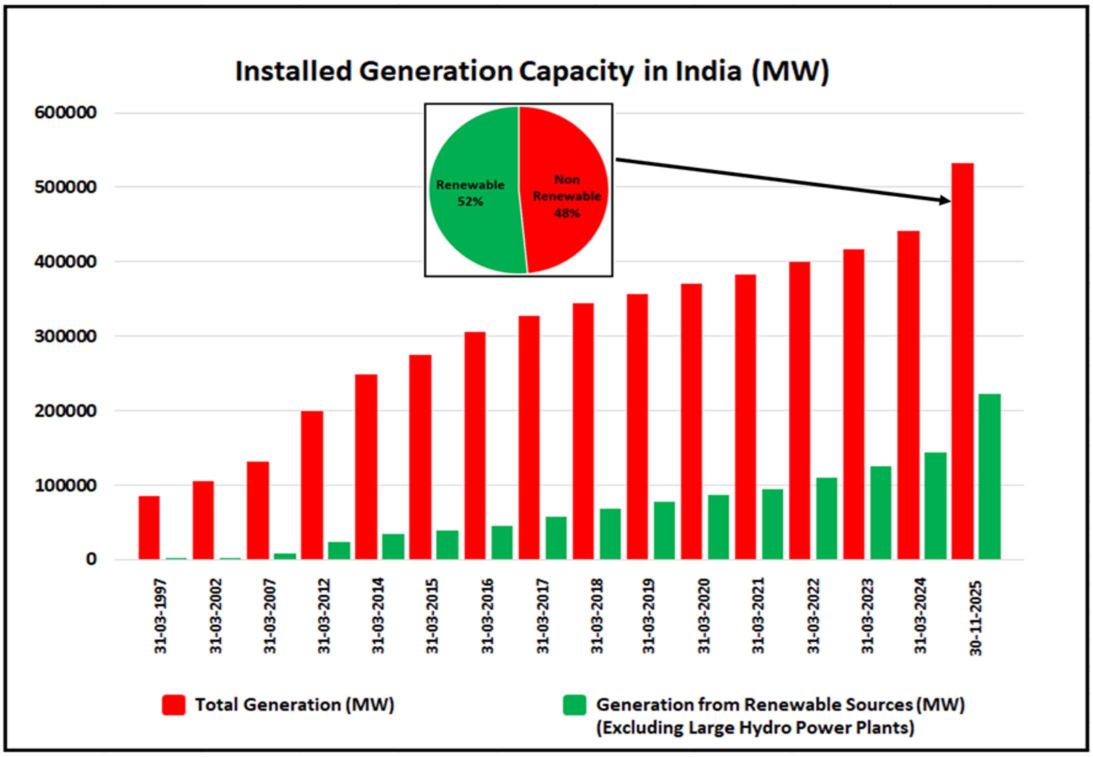


Figure 1.1 Installed Generation Capacity in India (From both Non-Renewable and Renewable Sources)

This demands a type of source that reduces or nullifies power loss, voltage drop, and requirement of large transmission and distribution network, which is Distributed Generation Source. The majority of Distributed Generation Sources are Renewable. Out of the total installed generation of 532740 MW, 223273 MW is generated through Renewable Energy Sources (RES) (excluding large hydro power plants). Including large centralised hydro power plants, total generation through Renewable Energy Sources is 274688 MW, which is 52% of total generation, and it will even be more than 60% in future. By 2030, according to the Ministry of New and Renewable Energy (MNRE), total power generation through non-fossil fuel or source should reach 500000 MW. This increasing installation of Renewable Energy Sources helps in reducing environmental pollution and has other advantages as well.

1.2 Distributed Generation

Distributed Generation (DG) is a type of Electrical Power Generation facility [1] integrated near or directly at the consumer end, mainly in the Distribution Network. Distributed Generation sources are also known as Distributed Energy Resources (DERs), On-Site Generation (OSG) sources or Decentralised Power Generation Resources (DPGRs). Distributed Generation sources are power generation facilities generally with low capacity. They can provide electricity at low cost with high power reliability and security. Distributed Generation is not only restricted to Renewable Energy Sources, but Conventional sources like Synchronous Generators with limited capacity are also considered as Distributed Generation sources. Integrating Distributed Generation sources affects system parameters like voltage and frequency, and to control them or keep them within limits, standards and local regulations need to be followed. Advantages and Disadvantages of using Distributed Generation sources [2]-[4] are mentioned below.

1.2.1 Advantages of Distributed Generation

- Distributed Generation technologies are considered to be reliable and efficient as they are connected at the consumer end.
- As they are connected at the consumer end, they greatly reduce consumer's expenses for electrical energy.
- Owners of Distributed Generation (DG) sources may have DG sources connected at their (load) end. So, owners get power at a cheaper rate as they don't need to pay for costly construction of transmission and distribution system which reduces loss to greater extend.

- Distributed Generation sources help in improving power quality of the electrical power system as well as voltage profile of local distribution network.
- Distributed Generation sources reduce the burden on centralised power plants.
- For critical consumers like oil plants, cement plants, etc., Distributed Generation sources are used as a standby power supply, doubling their power supply capacity & reliability and protecting against potential power outages & catastrophic loss to their businesses.
- The majority of Distributed Generation sources are renewable energy sources, which lowers greenhouse gas emissions and supports sustainable energy transitions.

1.2.2 Disadvantages of Distributed Generation

- Before connecting Distributed Generation (DG) sources in the Distribution System, pre-interconnection studies like short circuit analysis, load flow analysis, etc. need to be done. DG owners have to pay for these studies, which increases the overall cost of integrating DG sources into the Distribution System.
- Utility operators may not have real-time experience in operating and controlling a number of small power generation units like DG sources, distributed at various locations of the distribution network. This also raises the requirement of additional protective relays, transfer switches and other protective devices.
- The majority of Distributed Generation sources are renewable in nature, which have dynamic generation because of dependency on atmospheric conditions. This variable generation continuously alters system parameters like voltage and frequency.
- When Distributed Generation sources are connected in the Distribution Network, there is a risk to human life when unintentional islanding is created.
- Integration of Distributed Generation (DG) sources in the Distribution System (DS) will alter the direction of power flow, which demands additional protection and switchgear devices for reliable protection of the Distribution System.
- Integration of Distributed Generation (DG) sources in the Distribution System (DS) will also increase nominal system current and fault current, which may damage existing switchgear devices provided. The magnitude of nominal and fault current levels also depends on the location of DG source.
- Sudden insertion/removal of Distributed Generation (DG) sources will also affect relay coordination (or relay setting).

1.2.3 Microgrid

When Distributed Generation (DG) sources are connected in the Distribution System (DS) to supply power to consumers, the system altogether is known as Microgrid. It is a small-capacity electrical power grid that can operate independently (Islanded mode) or in collaboration with the utility grid (Grid-connected mode). The main components of a microgrid are Distributed Generation (DG) sources, Loads, Energy Storage Systems (ESS), Overhead Line Conductors, Transformers, Switchgear & Protection Devices and Control & Management System (CMS). Microgrid, in most cases, is supported by renewable energy sources like wind and solar power generation sources and is often used as a backup system for the utility grid when there is heavy demand.

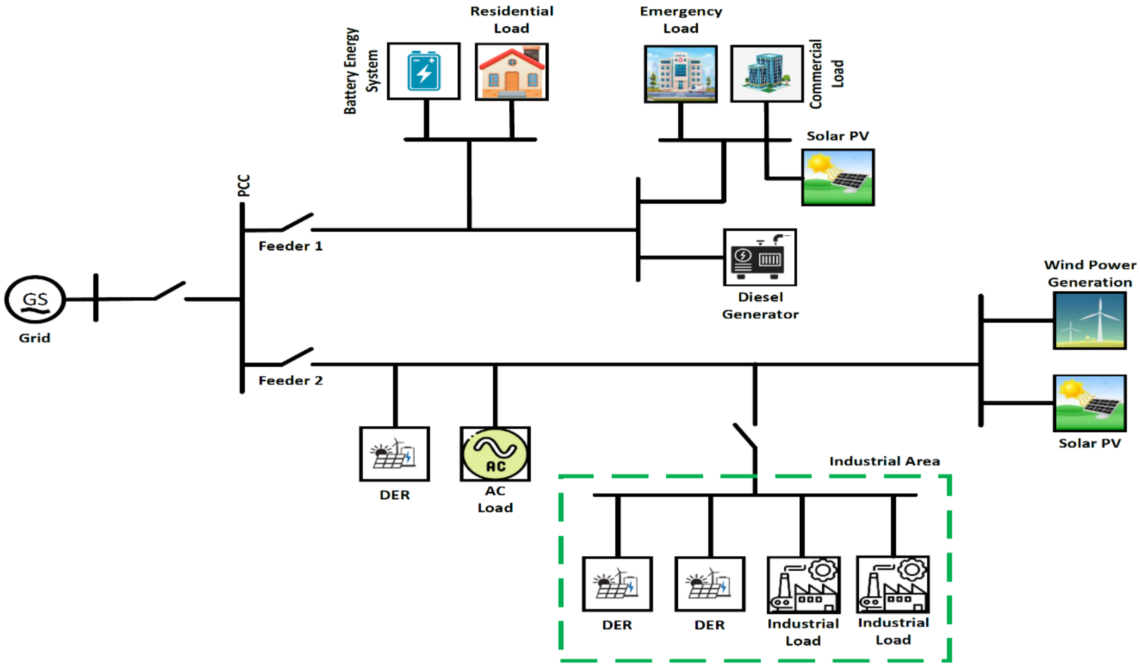


Figure 1.2 Typical Microgrid Structure

There are mainly three types of microgrids, i.e., AC Microgrid, DC Microgrid and Hybrid Microgrid. In the majority of cases, AC microgrid is used to supply power to consumers, as the majority of loads use an AC supply. Typical AC Microgrid structure is shown in Fig. 1.2. Focus of this work is on developing a protection scheme for AC microgrid. Microgrid has increased attention in both industrial and academic areas, considering it as an efficacious solution against growing energy and environmental issues. For securing future energy demands, it plays a major role in the existing electrical power grid.

1.2.4 Standard and Regulation

IEEE Standard 1547:

There are many types of distributed generation sources available according to rating/capacity, types of generations, types of generators etc. When distributed generation sources are interconnected with the distribution system, a standard needs to be followed to maintain uniformity and regularity in the distribution system. IEEE standard 1547 [5] is applicable to interconnection based on the accumulated rating of every DG unit provided,

- Standardisation for the interconnection of distributed generation resources with system.
- Requirements related to performance, operation, safety, maintenance and security considerations when distributed generation sources are connected.
- Synchronisation parameters (voltage, frequency and phase angle difference) limits for distributed generators for synchronous interconnection with the electrical power system.
- Clearing time for Distributed Generators (DG) in which it should stop supplying power to the electrical power system according to the voltage range.
- Clearing time for distributed generators, in which it should stop supplying power to the electrical system according to range of system frequency and DG Capacity.
- Harmonic current injection limits for distributed generators when connected with system.

As many of the Distributed Generation (DG) sources are connected at distribution system voltage level, allowable variation in system parameters should be considered accordingly. Additional and detailed guidelines for interconnection of distributed generation sources with the electrical power system are given in upgraded version of this standard, IEEE 1547-2018.

Central Electricity Authority (CEA) Regulations:

Central Electricity Authority, India has also published technical guidelines [6] for connectivity of distributed generation sources. When Distributed Generation (DG) sources are intended to operate in parallel with the system, following protection shall be provided for sensing abnormal conditions and disconnecting DG sources from the system or preventing DG connection under such conditions.

- Overvoltage and Undervoltage trip functions, if voltage is more than 110% or is below 80%, respectively, with a clearing time of 2 seconds.

- Overfrequency and Underfrequency trip functions, if frequency level reaches above 50.5 Hz and below 47.5 Hz, respectively, with a clearing time of 0.2 seconds.
- Distributed generation sources should stop energising the system to which it is connected in case of a fault.
- Voltage and Frequency sensing and Time Delay function for preventing Distributed Generation (DG) sources from energising a de-energised system or preventing DGs from reconnecting with the electrical system unless voltage and frequency are within prescribed limits and are stable for at least 60 seconds.
- The Distributed Generation sources shall be designed to prevent contribution to an unintentionally islanded system and shall stop energising the system within 2 seconds after detecting an unintentional islanding event.

Equipments at the generating (DG) station should comply with following requirements:

- Circuit Breakers (CB) & other interrupting devices should be suitable for their designated application having capability of interrupting maximum fault current at generator location.
- Distributed Generation source and associated equipments should be designed such that in case of failure of any device or component, safety and reliability of the system should not be compromised.
- Paralleling devices should be capable of resisting 220% of nominal voltage at the point of connection.
- When DGs are synchronised to the system, voltage fluctuation at the point of connection in the system should not be more than ±5%.

1.3 Motivation

Modern Electrical Power System (MEPS) is undergoing a huge transformation because of increasing penetration of Distributed Generation (DG) sources like Solar PV systems, Wind Energy Systems (WES), and Small Hydro Power Plants in the system. These Renewable Power Generation facilities are integrated in distribution networks to address challenges like environmental protection and energy security. But this transformation from traditional centralised generation to distributed generation introduces complexities in distribution system protection.

The primary motivation for this thesis is the necessity to address the adverse impacts of Distributed Generation (DG) sources on traditional Distribution System (DS) protection. Integrating DG sources causes bidirectional power flow, alters normal and fault current levels, which leads to relay/protection blinding, false tripping and/or loss of protection coordination, leading to reliability issues, safety hazards and equipment damage. For the Distribution System, Overcurrent (OC) Protection is mainly used. Because of additional contribution of fault current from DG sources, time-current coordination of relays is also disrupted. Apart from these issues, integration of DG sources also causes alteration in system parameters like voltage and frequency, which is particularly an issue in case of unintentional islanding, in which a portion of the system gets disconnected from the utility grid and continues to be powered by DG sources, which again poses risks to human life and equipments that demands advanced protection. All above challenges are further intensified by dynamic nature of renewable DG source power output, which leads to continuous fluctuations in power flow, voltage and frequency.

Digital or Adaptive protection emerges as a solution to these issues, providing intelligent and coordinated protection strategies. Digital protection has algorithm for fault detection, fault classification, fault location, and adaptive settings to accommodate changes in network topology and parameters to enhance system reliability and efficiency. This thesis is motivated by need to bridge gap between DG technologies and existing protection systems, contributing to more secure and efficient distribution systems. By exploring Digital Protection techniques for DG integrated systems, this work aims to develop protection strategy that can protect the distribution network with increasing penetration of DG sources.

1.4 Objective of Work

Main objective of this work is to do investigation and analysis of factors affecting system parameters and protection coordination and propose an enhanced Digital Protection Scheme with the aim of maintaining selectivity, speed and reliability of Fault Detection & Classification (FDC) and Isolation while overcoming limitations of conventional protection schemes for Modern Distribution Network (MDN) with significant integration of Distributed Generation sources like Solar PV, Wind and Small Hydro. Following objectives should be considered for this work.

- To analyse the effect of Distributed Generation (DG) sources on Distribution System parameters.
- To critically review the impact of penetration of Distributed Generation (DG) sources on traditional protection schemes (mainly overcurrent protection) in the Distribution System and identify key factors that affect system protection and cause problems like protection blinding, false tripping, loss of coordination and islanding.
- To do simulations of the Distribution System with varying levels of DG penetration and location using Power System simulation software like PSCAD/EMTDC, incorporating different types of DG units like synchronous and inverter-interfaced sources and analysing their fault current contribution in case of a fault.
- To analyse the effect of different fault parameters like Fault Location, Fault Types, Fault Impedance (or Resistance) in the presence of DG sources on protection coordination.
- To critically review existing protection schemes and identify issues faced by them if DGs are present.
- To propose an improved Digital Protection Scheme (or Hybrid Scheme) which ensures secure and coordinated operation in the presence of DG sources while minimising the need for a communication network.
- To examine the performance of the proposed scheme through extensive simulations with various operating conditions as mentioned above and do a comparison with other existing schemes considering security, reliability, selectivity and speed of operation.
- To provide recommendations for further solutions with Digital Protection for Distribution System with DG penetration and future research directions.

1.5 Scope of Work

Integration of Distributed Generators like Solar PV, Wind, Small Hydro, etc will introduce significant challenges in the Distribution System and affect the conventional protection scheme provided for Distribution System Protection. This work aims to explore and develop a digital protection scheme for the Distribution System considering penetration of Distributed Generation sources. It also focuses on enhancing system reliability and ensuring safe operation under dynamic generation from DGs. This thesis will cover the following scope of work:

- **Distribution System Considered:** Modified IEEE 4-Bus Distribution System is considered with 12.47 kV system voltage. The system is considered without DG source/s and with DG source/s (Synchronous Generator, Induction Generator, Solar PV) with 1 MW and 0.7 MW capacity. The system is also considered with a load increment of 1 MW.
- **Simulation and Analysis:** Distribution System simulation is performed and required system data is generated using PSCAD/EMTDC software. Generated data is simulated in MATLAB software through coding for calculating performance parameters like accuracy, F1 score, etc. for various methods and to identify a suitable method for Fault Detection and Classification (FDC) for a reliable protection scheme.
- **Address of Protection Challenges:** Protection challenges are addressed by simulating the distribution network considering various fault parameters (Fault Locations, Fault Types, Fault Resistances, Fault Inception Angle), penetration of Distributed Generation sources (DGs of different types and capacity) and increment in system demand.
- **Digital Protection Technique:** After simulation and analysis of different methods, the protection algorithm is finalised considering a Hybrid method for Fault Detection and Classification (FDC) and an adaptive protection scheme.

1.6 Thesis Organization

The Thesis is organized in seven chapters as below, addressing various aspects of work on the implementation of Digital Protection for Distribution System integrated/penetrated with Distributed Generation (DG) Sources. The thesis structure ensures an appropriate flow from fundamental concepts to analysis, proposed solution and conclusion along with Future Scope.

Chapter 1 presents the introduction to the work carried out. It provides an overview of the Indian Power Scenario, including generation from Conventional as well as Distributed Generation (DG) sources, which are mainly Renewable Energy Sources. This chapter gives a basic explanation of Distributed Generation sources, along with the advantages and disadvantages of integrating them into the Distribution System. It also gives a basic introduction of Microgrid (a local Distribution Network with Distributed Generation sources) with an overview of Standards, Rules and Regulations to be followed when DG sources are integrated. The chapter also outlines the motivation and objective of the work, the scope of work, and the overall organisation of the thesis.

Chapter 2 presents a comprehensive review of existing protection and fault detection & classification methodologies for distribution systems when distributed generation sources are integrated, presenting theoretical analysis of various schemes reported in literatures with research gaps/problems faced by these methods.

Chapter 3 discusses various parameters that affect protection coordination of distribution systems penetrated with distributed generation sources. This chapter presents comprehensive analyse of technical parameters that influence protection coordination like bidirectional power flow, impacts of integration of DGs like types of DGs, number & combination of DGs, location of DGs and current contribution from various DGs and fault parameters like types of Faults, Fault Resistance and Fault Locations through extensive simulation through PSCAD/EMTDC software.

Chapter 4 gives a description of the Overcurrent (OC) Protection scheme for the distribution system. In this chapter, detailed analysis of overcurrent protection is presented, followed by implementation of Overcurrent (OC) Protection for an Industrial Distribution System with Distributed Generation sources. Performance is evaluated through detailed simulation under different fault conditions and penetration levels of DGs.

Chapter 5 presents simulation for one of the proposed hybrid schemes using combined PCA and CNN for Fault Detection and Classification (FDC) schemes. The Hybrid PCA and CNN based scheme showcased promising results with better accuracy for Fault Detection and Classification for a Distribution System with Distributed Generation sources but has limitations in terms of handling non-stationary transient signals.

Chapter 6 presents a reliable protection scheme developed for a Distribution System with Distributed Generation sources using a combined WPT and XGBoost based scheme. After observing few limitations with the hybrid PCA and CNN based method, this chapter proposes a comparatively more reliable digital protection scheme. The proposed combined WPT and XGBoost based scheme, with higher accuracy, identifies and classifies different faults and ensures selectivity, sensitivity and speed of operation even under conditions of high DG penetration. The effectiveness of the combined WPT and XGBoost based proposed method is validated through extensive theoretical analysis and detailed simulations.

Chapter 7 consolidates the major findings of the work carried out, highlighting contributions and discussing the benefits of the proposed scheme. It also provides recommendations for future work for methods with hardware implementation.

CHAPTER - 2

Literature Review

2.1 Impact of Integrating Distributed Generation

Integrating Distributed Generation (DG) sources into the Distribution System (DS) has changed the scenario of traditional distribution system, causing bidirectional power flow and transforming it into a Modern Distribution Network (MDN). This transformation introduces various technical challenges, such as dynamic variation in voltage and frequency, reactive power management issues and disruptions to existing protection coordination. A Summary of issues related to the integration of Distributed Generation (DG) sources in the Distribution System is shown in Fig. 2.1. This review helps in having key findings from reviewed research articles, providing a foundation for the importance and need of Digital Protection for Distribution Systems (DS) integrated with Distributed Generation (DG) sources.

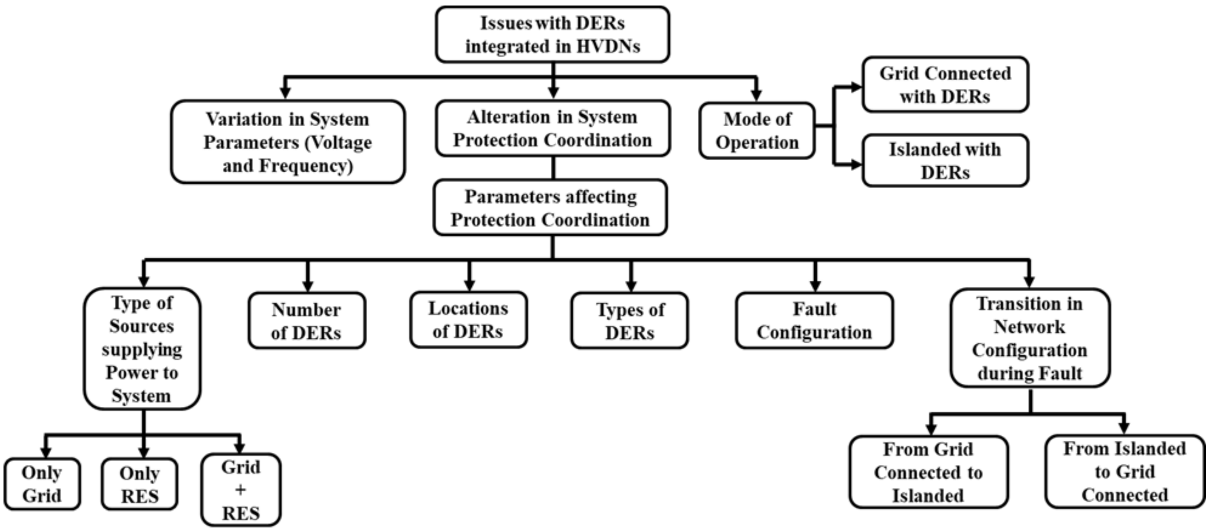


Figure 2.1 Issues with Integration of DGs in Distribution System

2.1.1 Mode of Operation

Distribution System (DS) with Distributed Generation (DG) sources (known as Microgrid) can operate either in grid-connected mode (as shown in Fig. 2.2) or islanded mode (as shown in Fig. 2.3). In grid-connected mode, Microgrid is connected with the main grid where flow of power will be bidirectional depending on conditions like (i) If in Microgrid, generation of power is more than load, then power will flow from Microgrid to Main grid, (ii) If in Microgrid (MG), generation of power is less than load, then power will flow from Main grid to Microgrid and (iii) In absence of DG sources in Microgrid, power will flow from Main grid to Microgrid.

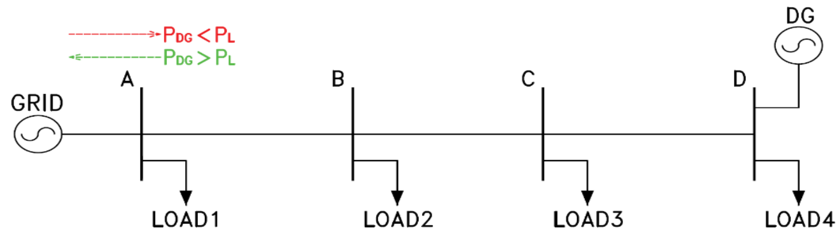


Figure 2.2 Distribution System supplied through Power Grid and DG source (Grid connected mode)

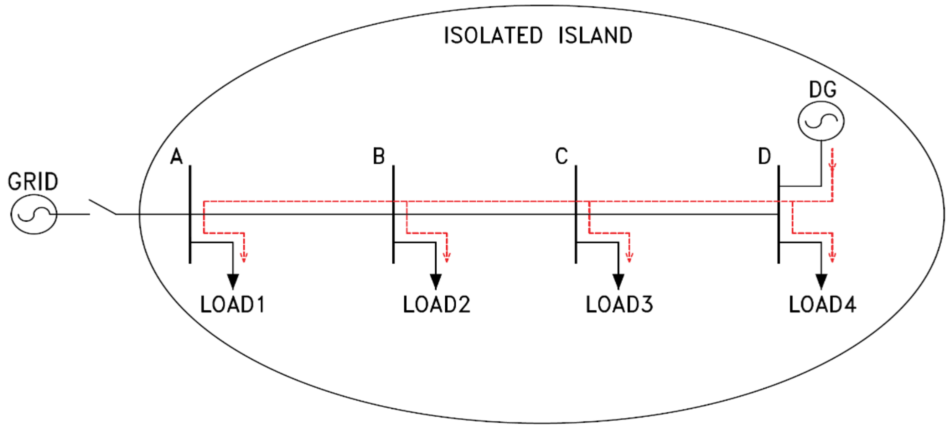


Figure 2.3 Distribution System supplied through Distributed Generation (DG) source (Islanded mode)

In Islanded mode, the Microgrid will be separated from the main grid in case of a fault or abnormal conditions in the main grid. In this condition, loads in the Microgrid will get supply through distributed generation sources. There are two types of Islanding conditions, i.e., Intentional and Unintentional. In case of Unintentional Islanding, there will be huge violations in system parameters like voltage and frequency, which could be hazardous to the system as well as equipment.

2.1.2 Frequency Variation

Indian power system is based on 50 Hz frequency. System frequency will be 50 Hz when load and generation are the same. If load is more than generation, frequency will be less than 50 Hz, and if generation is more than load, frequency will be more than 50 Hz. As per Indian Electricity Grid Code [7], the allowable frequency variation range in the Indian system is

49.5 Hz - 50.2 Hz. Distributed generation sources are mainly of renewable type. Power generation through renewable sources mainly depends on atmospheric conditions and is continuously variable, which leads to continuous variation in system frequency. Some protection schemes have evolved based on the Rate of Change of Frequency (ROCOF). Frequency variation will become more serious when unintentional islanding occurs, where frequency will not be within the prescribed limit.

2.1.3 Voltage Variation and Reactive Power Control

The majority of Distributed Generation sources (i.e., Solar PV) are generating power in DC. To interconnect them with the system, it has to be converted from DC to AC through inverter. Apart from this, the majority of loads are inductive in nature. This increases the demand for reactive power, which affects system voltage as these two parameters have a direct proportional relationship. If voltage variation is out of limit, it may also affect equipment. This voltage variation may even affect real power transfer in the distribution system. In a distribution system, if power is generated mainly through wind energy conversion systems, it will disturb system voltage as Induction Generators are used in it, which demand reactive power from the system. This effect will be more pronounced if a large number of small 1-Φ generators or a smaller number of large-capacity generators are connected at different locations in the system. In a traditional Distribution System, power flow is unidirectional and voltage reduces with distance from the source [8] - [13]. This drop in voltage is predictable, so the network is designed so that the voltage is within limit. In case of integration of Distributed Generation sources in Distribution System, since the power or current flow is bidirectional, voltage may generally increase, making it difficult to predict.

2.1.4 Power Conditioning

In a Microgrid, Solar PV and Wind based power generation sources are mainly connected to the system through converters. These power electronic converters inject harmonics into the distribution system, which will degrade power quality [14] - [15]. Apart from harmonics, power quality concerns are also related to voltage fluctuations, voltage flickering, voltage dips and unbalance, and disturbances because of the connection of distributed generators. Many protection schemes are proposed based on power quality parameters like Total Harmonic Distortion (THD).

2.1.5 Protection

Among various adverse effects, integration of Distributed Generation sources in the Distribution System mainly affects Relay Coordination [16] - [25] used for reliable protection of the Distribution System. Distributed Generation sources increase normal and fault currents, which leads to unwanted operation of relays even if a fault is absent. It causes issues like protection blinding, loss of mains and/or sympathetic tripping. Integration of Distributed Generation (DG) sources in the Distribution System also increases the number of relay and switchgear devices, which eventually will increase the cost and complexity of the protection scheme.

Protection Blindness:

Operation of an overcurrent relay depends mainly on Pick-up current (I_p), which may affect the operating time (T_{op}) of the relay. Care must be taken in selection of Pick-up current (I_p) for the relay. This Pick-up current mainly depends on the feeder impedance. If fault occurs in the distribution system, fault current sensed by the overcurrent relay will be less as compared to distribution system without DG because when DG is added in Distribution System and a downstream fault occurs, the grid impedance (variable subjected to DG location) will increase which in turn decreases the operating range of relay and relay will not be able to sense the fault in faulty condition. In general, when DGs are added in the system, current contribution from the grid when a fault occurs reduces and relay at the Point of Common Coupling will not sense the fault, which leads to protection blinding [26] - [28].

Change in Protection Coordination:

Relay-Relay Coordination

In a radial distribution system without DG as shown in Fig. 2.4, a conventional overcurrent protection scheme is provided to protect the system against abnormal conditions. In this scheme, one overcurrent relay is provided for each section of the feeder. If a fault occurs at location F1, the first relay R1 will operate as primary. If relay R1 fails to operate, R2 will operate as backup, and if R2 fails to operate, R3 will operate as backup. All the relays are Inverse Time Overcurrent Relay (51) type, as in any case, the flow of current will be in the forward direction (from A to D) only.

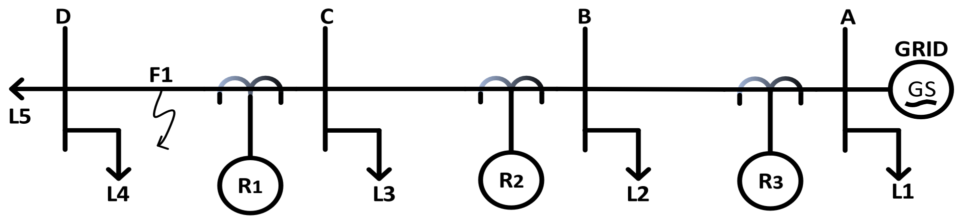


Figure 2.4 Radial distribution system without DGs and traditional relay coordination

Relay coordination will be affected when Distributed Generation sources are added in the distribution system as shown in Fig. 2.5. In the previous system, current was detected by all the relays in the forward direction. But with the system as shown in Fig. 2.5, current seen by relays will be different. With inclusion of DG in the distribution system, current direction will be reversed, and the fault current will also be increased, as DG sources contribute to the fault in addition to the main grid.

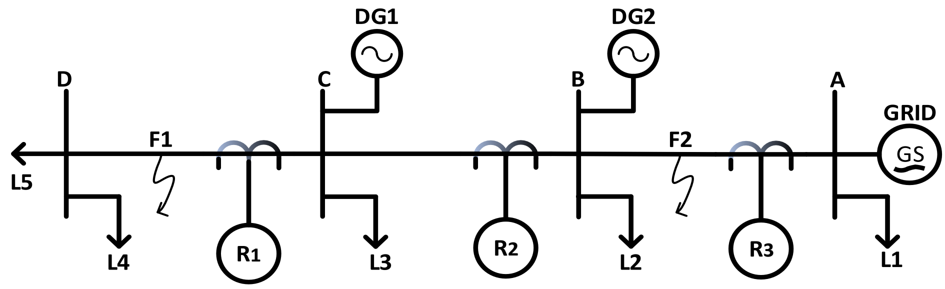


Figure 2.5 Radial distribution system with DGs and traditional relay coordination

There are some cases that can be discussed,

- **Case-1:** When a fault occurs at location F1, all the relays will sense current in the forward direction with an increased value of fault current.
- **Case-2:** When a fault occurs between bus C and B, relay R2 will sense current, but R1 will not sense it. So, to protect section BC, one more relay needs to be added to protect that line section in a faulty condition.
- **Case-3:** When a fault occurs at location F2, both relays R2 and R3 will sense current, but the current direction of R2 will be reversed, and also that relay will not help isolate section AB. Hence, to protect feeder section AB, one more relay needs to be added. So, relay coordination of the distribution system will be modified when DG sources are added, as shown in Fig. 2.6 below. Also, with a change in the location of the fault, current will be different, as it is also affected by the feeder impedance.

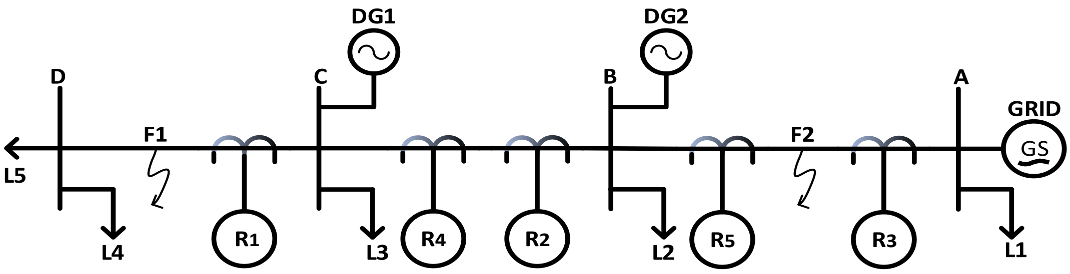


Figure 2.6 Radial distribution system with DGs and modified relay coordination

Fuse-Fuse Coordination

Fuse-Fuse coordination [31] for protection of distribution system is presented in Fig. 2.7 (a). When Fuse1 and Fuse2 are coordinated, if a fault occurs at location F1, Fuse2 should operate (or melt) before Fuse1 gets damaged [29]. This will be achieved when Total Clearing Time Characteristic (TCTC) of Fuse2 is below Minimum Melting Time Characteristic (MMTC) of Fuse1, as depicted in Fig. 2.7 (b). Fuses are said to be coordinated for each of the fault currents between minimum fault current (I_{fmin}) and maximum fault current (I_{fmax}).

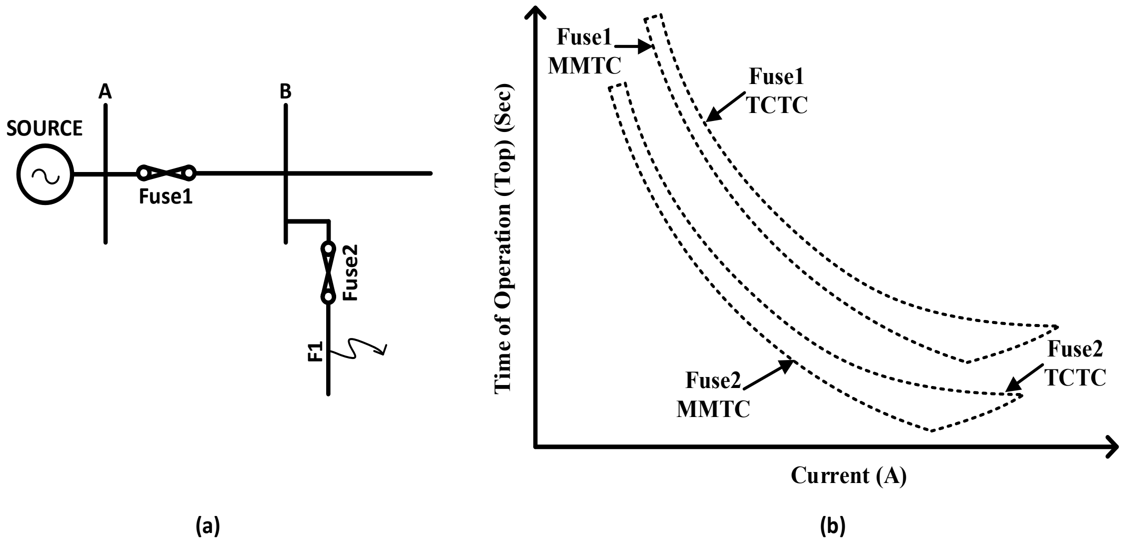


Figure 2.7 Fuse-Fuse Coordination for Distribution Feeder without DG

In the same system, if a Distributed Generation (DG) source is included as shown in Fig. 2.8, Fuse2 melts before Fuse1 as DG also contributes to the fault current and current through Fuse2 increases. Hence, there is no effect of DG. But Fuse-Fuse coordination is affected when a fault occurs at location F2. In this case, Fuse1 should melt, but as the current through Fuse1 decreases because of fault current contribution from DG, it will not melt.

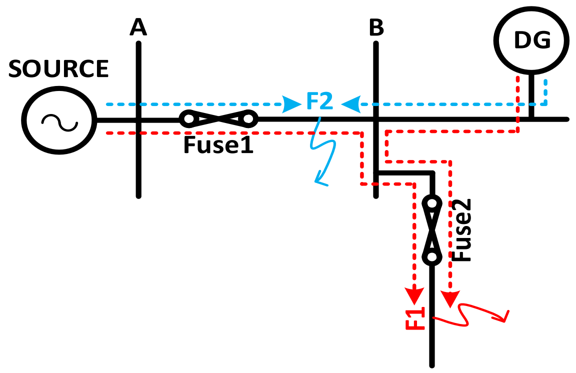


Figure 2.8 Fuse-Fuse Coordination for Distribution Feeder with DG

The principle rule followed for Fuse-Fuse coordination is that the total clearing time for the main fuse should not be more than 75% of the minimum melting time for backup fuse [30], which basically is considered to taken into account the effects of ambient temperature, load current & fatigue caused by fault current flowing through fuse for downstream fault which probably might not be enough to melt fuse element.

Fuse-Recloser Coordination

Fuse-Recloser Coordination [31] - [32] also gets affected when DGs are integrated in the Distribution System. Overcurrent protection provided for protection of the distribution feeder falls into two categories, i.e., Fuse saving or Fuse blowing [33]. The majority of faults are transient or temporary in nature. So, if a fault occurs in a tapped feeder in a radial system, it is cleared by a recloser with minimum time delay before the fuse element blows, and then it recloses automatically. This scheme is known as Fuse Saving scheme. This scheme is useful for distribution feeders used in rural areas having multiple tappings for residential load. If distribution feeders are serving critical loads like industrial load or urban load centre, where occurrence of multiple trip-reclose operation may potentially damage equipment, Fuse Blowing scheme is used, in which the recloser characteristic is set such that the fuse operates first for clearing the fault, and if it fails, then the recloser operates. The Fuse-Recloser coordination scheme is represented in Fig. 2.9 [34]. First, consider the case where DG source is not connected to the distribution feeder. If a fault occurs at location F1, recloser operates as primary to clear the fault before the fuse blows, and then recloses again. In this case, current flowing through Fuse and Recloser is the same. If the fault is permanent in nature, recloser again experiences fault current, and the fault will be cleared by fuse before recloser opens permanently.

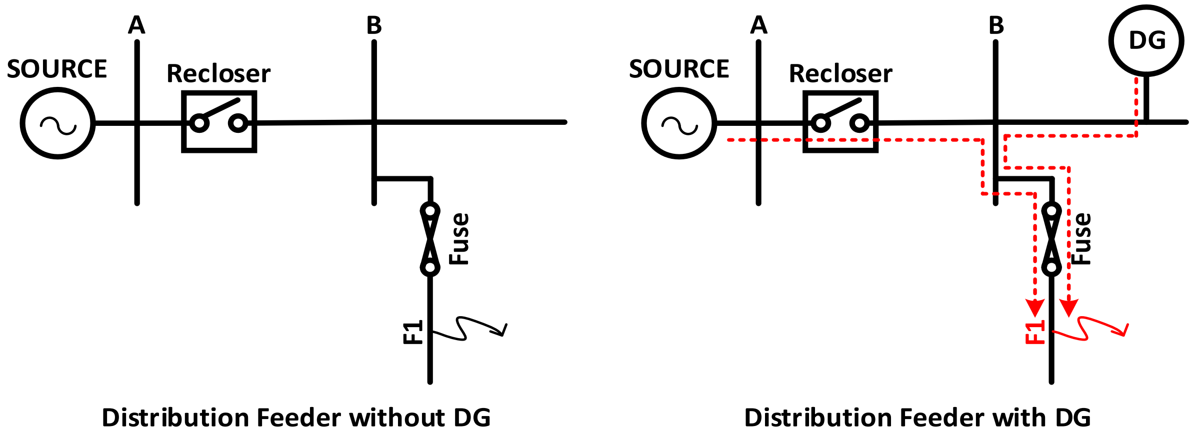


Figure 2.9 Fuse-Recloser Coordination for Distribution Feeder

This Fuse-Recloser coordination is affected if a Distributed Generation (DG) source is connected to the distribution feeder. Current through Fuse increases, and current through recloser decreases because of fault current contribution from DG and fuse may melt before recloser operates, and consumers downstream to the Fuse may face long interruptions. There is miscoordination between Fuse and Recloser, and because of the insertion of DG, the original protection coordination scheme may lose selectivity.

Impact of Fault Location and Type of DGs:

Distributed generation sources have a huge impact when it comes to designing an overcurrent protection scheme for the distribution system. When overcurrent protection relays for the distribution system are to be set, effect of the following needs to be taken into account [34], which are,

- Location of fault
- Type of distributed generation sources

Even though overcurrent protection is the cheapest protection for the distribution system, it is a little complicated to set when DG sources are implemented in the system, as it increases fault as well as normal current levels and reverses the direction of fault current. Along with that, it is also important to consider the location of fault in the system because fault current contribution from the main grid as well as DG sources also varies with the location of fault in the system. Here, the discussion is based on considering two types of location, viz. upstream fault and downstream fault.

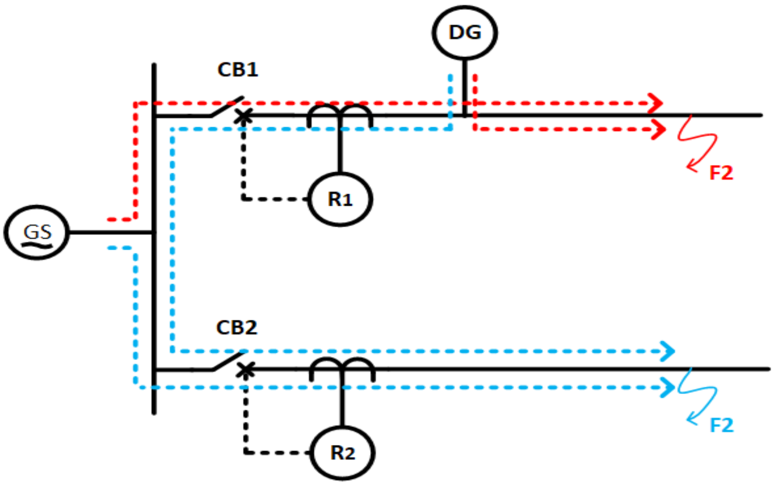


Figure 2.10 Fault on Feeder without DG and Downstream Fault

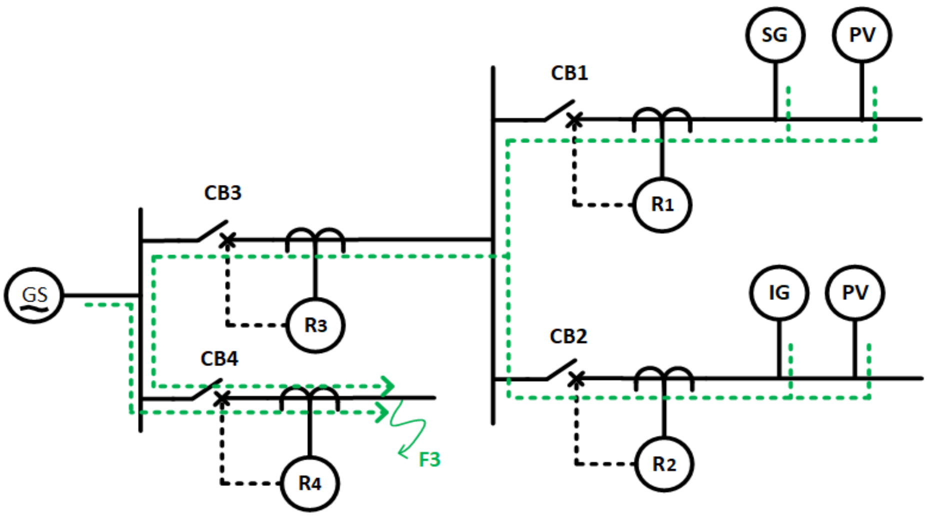


Figure 2.11 Upstream Fault

Table 2.1 Effect of Fault Location on Distribution System with DG

Location of Fault	Breaker to be operated	Breaker not to be operated	Remarks on Effects
Fault on Feeder without DG and Downstream Fault (Fig. 2.10)			
F1	CB2	CB1	• Generator should not trip, but because of fault current contribution from the generator, CB1 malfunctions.
F2	CB1	CB2	• Current through relay R1 reduces and fault may not be detected (Relay blinding).

Upstream Fault (Fig. 2.11)			
F3	CB4	CB1, CB2, CB3	• False tripping experienced by CB1/CB2 (depends on DG capacity and type) and CB3. • For a downstream fault to CB3, CB1 and CB2 maloperate and the whole distribution system may be lost if the fault occurs nearest to CB3.

Fig. 2.10 and 2.11 depict the cases of downstream and upstream faults, respectively. If the location of fault in the system is before the connection of DGs (or any equipment), it is considered an upstream fault, and if it is located after the connection of DGs (or any equipment), it is considered a downstream fault. The effect of these upstream and downstream faults in the system with DGs is explained in Table 2.1.

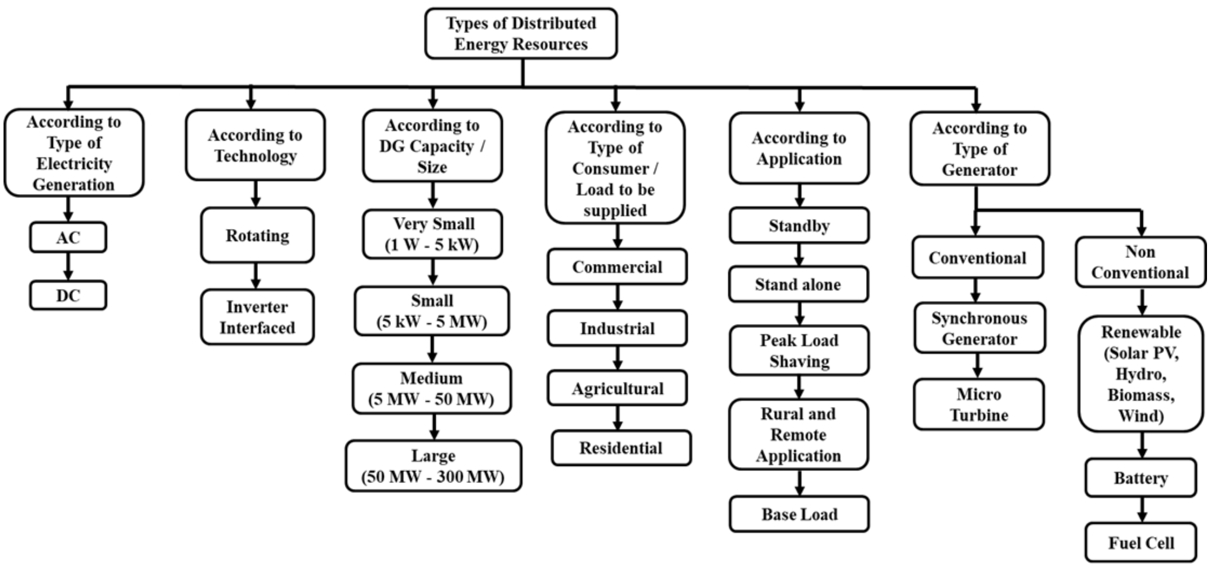


Figure 2.12 Types of Distributed Generation Sources

Tripping logic for Overcurrent protection for the Distribution System (DS) is based mainly on the amplitude of current (mostly an Overcurrent (OC) Relay with IDMT characteristic is used). Directional elements are seldom used, as they increase the number of transducers (CTs & VTs) and other required elements, and the overall cost of the protection scheme is also increased. Directional overcurrent relays are used for a distribution system having number of sections and fed from both ends. There are various types of distributed generation sources interconnected with the distribution system as shown in Fig. 2.12. Fault current contribution is variable for different types of generators. When different distributed generation sources are compared, fault current contribution from a Synchronous Generator (SG) is largest, and sustained contribution is offered by SG for any type of fault. Induction Generator (IG) is used in wind power systems. It does not contribute zero-sequence current to the fault.

Because of the absence of field excitation in Induction Generator (IG), the contribution of induction generator to fault current decays rapidly and disappears in a very small (2-3 cycles) duration after occurrence of the fault. Because of lack of inductive characteristics associated with rotating generators [35], like induction generator and synchronous generator, the fault current contribution of Inverter Interfaced DG sources like Solar PV has a small decay time. Fault current contribution of these DGs depends on penetration factors and location of DGs. These IIDGs behave as ideal current sources only. Fault current contribution from these DGs is minimum and has negligible effect on relay coordination of the distribution system.

2.2 Existing Protection and Fault Detection & Classification (FDC) Techniques

2.2.1 Protection Techniques

Different types of protections are developed by researchers, such as overcurrent protection, pilot protection, anti-islanding protection, differential protection, fault current limiter based protection, adaptive protection, etc. Different existing protection methodologies with their specific limitations are shown in Table 2.2.

Table 2.2 Existing Protection Methods

Protection Methods	Developed Methodologies based on type of Protection **(Methods based on)**	Limitations
Overcurrent (OC) Protection	Plug Setting Multiplier (PSM) based adaptive inverse time protection [36], Communication based protection algorithm [37], Gravitational Search Algorithm overcurrent protection [38],	Protection considered only for radial network, Chances of backup relay tripping

	Overcurrent protection scheme suitable for all the operating modes of microgrid [39], Numerical Directional Overcurrent Relays (DOCRs) [40], Optimization method in case of failure of backup relays to react [41], offline protection scheme for PV dominated distribution systems [42], non-pilot protection scheme for inverter dominated microgrid [43], Communication based Dual Setting Directional Overcurrent Relays [44], Optimized setting for protection of Microgrid (MG) in grid connected and islanded mode [45], Objective Function based OC protection for phase and earth fault [46], Optimization of relay coordination for PV dominated system [47]-[49], Coordinated circuit breaker protection and fault ride through settings for islanded system [50], Hybrid tripping for achieving minimum tripping time and improving overcurrent and earth fault relay coordination [51], Optimized protection coordination minimizing operating time using genetic algorithm [52], Non-standard characteristics for reducing operating time [53], Double Inverse Overcurrent Relay (DIOCR) for proper coordination with distributed generator stability was evolved to find optimal setting of overcurrent relays [54], mixed characteristic curves [55], negative and zero sequence criteria [56], transient configurations [57], realtime protection scheme for redefining settings of OC relays [58].	for fault in forward direction, Not considering symmetrical fault, Optimized calculation assuming fault occurrence in mid-point of line, Operating time for primary as well as backup protection comparatively large, Same pickup current for primary and backup protection, Chances of nuisance tripping, Protection designed only for islanded system and using fixed settings, No device redundancy, R/X ratio uncertainties and load multiplier is not considered, CT saturation can cause problem, may get affected by inrush current, applicability limitation, large relay operating time, not considering LLL fault.
Pilot Protection	Identification of fault and prefault conditions using current phase angles difference [59],	Protection scheme specifically designed

	Blocking pilot protection scheme for close loop distribution system having underground cable [60], Based on On-line estimation of apparent resistance per-phase ac power line [61], Comparison of current phase performed by Remote Terminal Unit (RTU) in Distribution Automation System (DAS) [62], Distance protection relay installed at both the ends of each line section [63].	for ring main system with underground cable, Fault detection margin decreases with very high fault impedances, Ineffective as RNC at bus won't be able to calculate power as voltage transformer is unavailable.
Fault Current Limiter based Protection	Fault Current Limiter (FCL) based protection for active distribution system [64], Fault current limiter (FCL) placement [65] - [67] for restoring fuse-recloser coordination, FCL application [68] - [72] for protection coordination of distribution system, Unidirectional Fault Current Limiter (UFCL) connected between main grid and microgrid at Point of Common Coupling [73], optimal parameter setting of Directional Fault Current Limiter [74].	Limited applicability to future grid structures, Scheme may be costly, not possible to achieve relay coordination keeping all the relays with their original values, installation at PCC can alter fault current and can affect relay coordination.
Differential Protection	Multi-Element Current Differential Protection Scheme [75], Current Differential Protection in Distribution Networks [76], based on non-stationary signal processing algorithm Hilbert–Huang Transform (HHT) [77], Down sampling empirical mode decomposition and Teager energy operator [78], current differential principle with adjusted restrain characteristic [79].	Focuses only on clearing two types of faults, e.g. phase to phase SC and, three phase SC and basically not useful for system having branches, costly as applied to each line section.

Adaptive Protection	Communication based adaptive protection algorithm [80], based on equivalent transformation on the protection backside network eliminating impact of DG branch current [81], communication free adaptive technique is proposed to prevent fuse recloser miscoordination issue [82], based on optimization of protection zones using risk analysis [83], Fast Scalable Adaptable (FSA) computing algorithm for a fault protection system [84], adaptive protection coordination using Artificial Bee Colony (ABC) [85], hybrid pick-up and optimal hierarchy selection of relays [86], microgenetic algorithm-based protection coordination [87], numerical directional overcurrent relays based adaptive protection [88], directional over-current relays with non-standard characteristic [89], GA based optimization method [90], modifying the pre-fault protection setting with the help of voltage profile as pre-fault index and offline technology used for calculating required group setting for each voltage profile [91], dynamic AOCR scheme independent of external controllers to estimate relay pickup [92], SOM clustering technique [93], multi agent dual strategy based adaptive protection [94].	Can't be applied to fault location in conventional distribution systems, faults occurrence at the microgrid side in case of the grid connection operation are skipped and vice versa, for considered system, protection scheme is limited up to two DGs only, reduction in optimality and flexibility, Genetic Algorithm method is used which is comparatively slower than machine learning based schemes, applicable for radial distribution network without branch, dependency on network topology.

2.2.2 Islanding Detection / Anti-Islanding Protection

Islanding, whether Intentional or Unintentional, is undesirable for any distribution system, as frequency and voltage not being within standard permissible limits may further cause damage to equipment or disconnection of DG sources from the system. Islanding Detection and Protection in an Islanded condition are very important as the system is still being energised from Distributed Generation sources, and the system will be more disturbed if a fault occurs during transition from a grid-connected system to an islanded system. It is necessary for any utility to protect its system in such conditions. For any anti-islanding protection, the first step is to detect islanding. There are mainly 3 types of Islanding Detection Methodologies (IDM) viz., Passive, Active and Hybrid. Generalised description and limitations of each Islanding Detection Method are represented in Table 2.3, and existing Islanding Detection methods with their limitations are presented in Table 2.4.

Table 2.3 Islanding Detection (ID) Method and Limitations

Islanding Detection Method	Description	Limitations
Passive Islanding Detection Method (PIDM)	Works with measurement and monitoring of system parameters like phase angle, voltage, frequency, or harmonics, etc., and comparing with preset values at PCC or at DG end by assigned algorithm.	Existence of a large Non-Detection Zone (NDZ) which is created when the power catered by load equals exactly the power generation by DG, causing failure of islanding detection.
Active Islanding Detection Method (AIDM)	A small disturbance component is injected into the system, and based on the response received, it will be decided whether islanding is formed or not.	Power quality reduction, possibility of interference of distortion signal when number of DGs is present in distribution system.
Hybrid Islanding Detection Method (HIDM)	More than one Islanding Detection methods are used.	Expensive to implement.

Table 2.4 Islanding Detection (ID) Method and Limitations

Islanding Detection Method	Existing (or Developed) Methodologies	Limitations
Passive Islanding Detection Method (PIDM)	Passive time frequency islanding detection algorithm [95], artificial neural network	Reliance on selection of appropriate mother wavelet, Requirement of large data,

	(ANN) based islanding detection [96], SVM based Islanding Detection Scheme [97], Random Forest (RF) classifier-based Islanding detection scheme [98], Superimposed Sequence Components of Currents based Islanding Detection [99], rate of change of impedance (dz/dt) [100], sequence component [101], Karl Pearson's coefficient utilizing voltage unbalance signal and negative sequence voltage was proposed [102], voltage index at main bus for detection of islanding for large power mismatch [103].	considering only one DG in system, time consuming prediction process, highly sensitive toward high-resistance faults, not able to detect triple line to ground fault on adjacent feeder, inability to detect the islanding within NDZ, sudden inclusion and removal of DGs not considered, all the DGs used in the system are of same type and capacity.
Active Islanding Detection Method (AIDM)	Waveform shift techniques [104], Active Rate of Change of Frequency (ROCOF) relay-based islanding detection [105], inter-lock method with ROCOF [106], new 'dq0' transformation-based islanding detection [107], modified reactive power control (RPC) for islanding detection [108], adding periodical disturbing current through current controller of the interface VSI [109], Off-Nominal Frequency Injections based scheme [110].	Local protection relay may not work if surges are inserted in line, ROCOF time calculation is assumed to be very less for a fast processor, only resistive load is considered, DGs with same type and capacity are used, capacitive and nonlinear load are generating transient disturbances that are deviating the frequency outside the thresholds range and launches a false islanding detection, only considered bus (PCC) where load and generators are connected.

Hybrid Islanding Detection Method (HIDM)	Remote (power line signalling method) and passive (Rate of Change of Voltage Phase (ROCOVP)) islanding detection method [111], combined approach based on Wavelet Transform for detection of events and Artificial Neural Network (ANN) for classifying islanding and non-islanding events [112], protection technique comprising rate of change of frequency and reactive power variation [113].	Requirement of a new slack busbar during autonomous operation; accuracy is comparatively less in case of non-islanding events, longer islanding detection time and causing abnormal operation when the system experiences continuous frequency surges; if output reactive power variations of all the DG sources occur at different times, the islanding event cannot be detected.

2.2.3 Artificial Intelligence based Protection

Artificial Intelligence based methods enhance the protection of the Distribution System by enabling faster fault detection, accurate fault classification & location, and adaptive protection relaying. Artificial Intelligence based protection schemes developed by researchers are shown in Table 2.5.

Table 2.5 Comparison of Artificial Intelligence (AI) based protection schemes

Artificial Intelligence Method	Developed Techniques	Advantage	Limitations
Artificial Neural Network (ANN) [114]-[115]	Overcurrent protection strategy based on ANN model in control centre trained with real-time data for identification of fault on line segment, Neural network and	Accurate modification of protection settings for new operation as well as identification of faulty line and coordination of relays is possible, Accurate	Large data requirement and dimensionality; difficult in extension for other tasks without retraining the neural network once

	backtracking-based protection using integration of fault location as well as relay coordination strategies, communication-assisted protection scheme.	identification of faulty line and coordination of relays.	it is trained to do a particular task; communication network failure makes the system ineffective.
Genetic Algorithm (GA) [116]-[120]	Overcurrent protection based on optimised calculation of time setting multiplier and plug setting, determination of maximum penetration level, fault current limiter-based overcurrent protection, determination of optimal location and permissible capacity limits of inserting DGs.	Reduction in operating time, harmonic distortion in limit, minimisation of fault current limiter size and effective coordination restoration, fault current reduction and voltage profile improvement.	Less efficient, low computation efficiency and optimisation speed, premature convergence in some cases, issue with fitness function identification, mainly developed for distribution systems with rotating type DG sources.
Fuzzy Logic (FL) or Fuzzy Rule [121]-[123]	Power differential protection (PDP) using the fuzzy rule approach, decision tree-induced fuzzy rule base intelligent protection scheme with fault detection and classification, fuzzy logic control-based overcurrent protection.	Independency of error detection on threshold value selection, applicable to instantaneous values as well as phasors, reliable with different modes of operation, data memory storage space reduction, reduction in mathematical complexity.	Data distortion by CT saturation, difficulty in tuning fuzzy logic controller, costly with differential protection, increment in length of calculation when voltage values are used for relay operating time calculation.

Wavelet Packet Transform (WPT) or Wavelet Transform (WT) [124]-[127]	WPT d-q based passive islanding detection method as well as protection method, digital protection for microgrids operated in grid-connected and standalone modes, Stationary Wavelet Transform based directional protection with phase sequence component units.	Accurate, fast and reliable islanding detection as well as fault detection technique, reduction in NDZ, ability to respond to various transient disturbances, insensitivity to the mode of operating the microgrid, less relay operating time.	Fault didn't present a relevant overcurrent to activate the directional units in case of high-resistance fault; wavelet activators could not allow the proposed wavelet-based directional protection for overdamped transients.
Support Vector Machine (SVM) [127]-[128]	Passive islanding detection technique using multiple feature-based SVM, prevention of maloperation of distance relay in case of unintended bulk DG source tripping following fault.	Works successfully with a high degree of accuracy under different network contingencies, Robustness against PMU data loss or unavailability, highly effective in islanding detection.	Decision boundary needs to be re-established with new training sets, costly if communication medium is used, suitable for DG of any one type (either inverter interfaced or rotating type).
Particle Swarm Optimisation (PSO) [129]	Fault recovery model using particle swarm optimisation.	Effective and feasible, effortless in its concept and coding implementation compared to other heuristic optimisation techniques.	Scheme developed for DGs with the same rating, large distribution system losses.
Hybrid Artificial	Neural Network model + Fast Fourier Transform, deep belief network and	Less time to re-tune the settings of relay, robustness to noisy	High time of operation; gives false alarms for no-fault

Intelligence (HAI) [130]-[133]	time-time transform based intelligent protection, Islanding detection (Wavelet design + SVM), control of renewable distributed switched reluctance generation and feeder protection coordination (GA + ANN), single-phasing detection and classification with high penetration of DG (Wavelet + ANN).	measurements, Elimination of misclassification error in testing data set with highest accuracy, efficient and robust performance in normal as well as abnormal condition, no significant computational burden on protection relays.	scenarios for switching of capacitor in islanded mode; complexity will increase with wavelet transform and machine learning approach, computation time may increase, developed considering only rotating type of DG sources.

2.2.4 Fault Detection and Classification Techniques

When Distributed Generation sources are integrated in the Distribution System, main focus should be on sensible and definitive protection for the system against different faults. For reliable protection coordination, the main task is detection, classification and location of faults. Researchers have explored many Artificial Intelligence and Machine Learning based Fault Detection and Classification (FDC) methods like Artificial Neural Network (ANN), Wavelet Packet Transform (WPT), Support Vector Machine (SVM), Convolutional Neural Network (CNN), K-Nearest Neighbour (KNN), Extreme Gradient Boosting (XGBoost) and Hybrid (Combination of any two), as shown in Table 2.6.

Table 2.6 Existing Fault Detection and Classification (FDC) schemes

Methodology	Description	Limitations
Artificial Neural Network (ANN) [134]-[140]	Fault Localisation and Fault Classification using Artificial Neural Network (ANN), ANN-based approach for fault classification, Communication-assisted protection scheme based on ANN, Fault Detection using	Focusing only on High Impedance Fault, less fault classification accuracy for system with wind-solar PV-diesel

	Artificial Neural Networks (Multi-Layer Perceptron classifier), Customised artificial neural network (CANN) for fault detection.	engine as DG, ANN has computational delay, Issue of large data handling.
Wavelet Packet Transform (WPT) / Wavelet Transform (WT) [141]-[145]	Analysis of wavelet transform (WT) & wavelet packet transform (WPT) based islanding detection in grid-connected PV system, Fault Identification and Location (FIL) technique using wavelet multi-resolution approach, WT based frequency multi-resolution technique for detecting different faults, WT based intelligent technique to detect and classify power system faults, Discrete Wavelet Transform (DWT) to detect and classify High Impedance Fault.	Large errors are produced by wavelet transform, but WPT will provide uniform frequency sub-band with better time-frequency resolution, Methods fail to extract geometric features for disturbance detection whenever the noise level in the voltage function crosses 40 dB.
Support Vector Machine (SVM) [146]-[151]	Support vector machine (SVM) for Fault Detection and Classification (FDC), multiple features-based support vector machine (SVM) for Islanding detection, Multi-class Support Vector Machine (SVMs) based approach for location and diagnosing faults, Support Vector Data Description method - a commonly used one-class classifier, Multiple Features based scheme for Islanding Detection.	Computationally intensive and time consuming; fault inception angles are not considered in the training process; only rotating type of DGs are used; scenario will be different when two different types of DGs are used.
Convolutional Neural Network (CNN) [152]-[154]	Transient Stability Assessment (TSA) and instability mode prediction, 20-layer Deep Neural Network (CNN) for fault detection and location, Fault classification for Distribution Network with DGs using Convolutional Neural Network (CNN) based algorithm.	Effect of Renewable Energy Sources (RES) is not considered.

K-Nearest Neighbour (KNN) [155]-[157]	KNN-based algorithm for Fault Detection & Classification (FDC), Classification and Location (FDCL) method for Power System.	Less classification accuracy and high computational complexity.
Extreme Gradient Boosting (XGBoost) [158]	Fault Detection in Low Voltage Neutral Point Ungrounded (LVNPU) system using Extreme Gradient Boosting (XGBoost).	Careful and time-consuming tuning because of many hyperparameters.
Hybrid [159]-[167]	Discrete Wavelet Transform (DWT) + k-Nearest Neighbor, Single Feedforward Artificial Neural Network (SFANN) + K-Nearest Neighbors (KNN) for estimating fault location, Artificial Neural Network (ANN) + Discrete Wavelet Transform (DWT) for fault detection and classification, Wavelet Transform + Deep Neural Network, Dual Tree Complex Wavelet Transform (DT-CWT) + Data Mining, DWT + Evolving Neural Network, WT + ANN, Multi-Channel Convolutional Neural Network (CNN) + Long Short-Term Memory (LSTM) network for fault detection, Gravitational Search Algorithm + ANN.	Accuracy declines in isolated distribution networks; a single ANN for all fault types can be a source of error; not useful when identifying lost phase; performance drops when there is an abrupt change in fault pattern; computationally complex system to implement for Distribution Network with Distributed Generation Sources.

Researchers have also developed other different Fault Detection, Fault Classification and Fault Location methods. Mathematical Morphology (MM) [168] based Fault Detection and Classification (FDC) technique was developed without considering the effect of Distributed Generation Sources. A High Impedance Fault Detection method [169] using Kullback–Leibler divergence similarity measure was developed, but the method focuses only on one type of Fault. A probabilistic-based intelligent classifier [170] was proposed for detection and classification of power quality disturbances, but effects are not considered for an Islanded Microgrid. High Impedance Fault (HIF) detection using energy raising of linear predictor error signals as an indicator [171] was developed for the distribution system, but it does not consider the effects of distributed generation sources, inrush currents or nonlinear loads. Current signals approach-based Fault Detection and Classification (FDC) for the distribution system [172] with multiple distributed generation facilities was developed utilising a communication system but fails to operate when communication channels fail. A sensor-independent deep learning method [173] was developed for fault detection, classification, and location in a Low Voltage (LV) Distribution System, but deep learning requires a large amount of data for processing.

Fault Detection and Classification (FDC) based on the Teager–Kaiser energy operator [174] for AC Microgrid was developed, where determination of the faulty phase is performed using indices derived from squared currents. Detection and classification of disturbances that evolve in succession using Energy Preserving Ensemble Empirical Mode Decomposition (EPEEMD) and Least Square Support Vector Machine (LSSVM) [175] techniques was developed for a grid-connected system, but it was developed for a system with Inverter Interfaced DGs like Solar PV. A Deep learning approach was developed for Fault Detection and Classification (FDC) [176] for a secondary distribution network where various methods were compared, and the Recurrent Neural Network (RNN) was found to be more suitable. An algorithm based on positive sequence measurement [177] for detection of fault, islanding & power swings was developed for DG-integrated radial distribution networks.

2.3 Problem Identification

Integration of Distributed Generators will introduce (i) bidirectional current flow which causes miscoordination of traditional protection scheme, (ii) reduction in fault current contribution from grid (or from DG, if new DG source is added) which leads to protection blinding, (iii) variable and dynamic fault current contribution from different sources ($I_{f\text{-}SG} > I_{f\text{-}IG} > I_{f\text{-}PV}$) may lead to under reach / over reach of relay, (iv) miscoordination during transition of system topology (ring main to radial) or operating condition (grid connected to isolated islanded), (v) inability to detect low current faults which cannot be detected by traditional methods and (vi) difficulties in protection coordination because of dynamic fault current level. All these issues compromise system stability and reliability, increasing chances of outage and equipment damage. Existing protection schemes and/or Fault Detection and Classification are costly, complex or insufficiently robust to the dynamic nature of DGs, which necessitates a fast, sensitive, reliable protection approach.

From reviewing various articles (as presented in Table 2.2 - Table 2.6), it can be said that each method has its own technical limitations for either protection or fault detection and classification in terms of speed and accuracy but also has one or more limitations like (i) system considering only one type of DG (either rotating or inverter interfaced DG), (ii) considering DGs with fixed or same capacity, (iii) DGs effects are not considered, (iv) focus on detection of only one type of fault, not considering fault location, (v) communication system is used for exchanging required system data which if fails, system will not work properly and (vi) protection or fault detection and classification scheme considered only for radial system without branch.

CHAPTER - 3

Parameters affecting Protection Coordination of Distribution System with Distributed Generation Sources

Protection coordination in the Distribution System ensures selective operation of protective devices like relays in case of faults to maintain system reliability and minimise system outages. Integration of Distributed Generation sources like Wind Power Generation, Solar PV, Small Hydro Power Plant, etc. alters protection coordination and modifies the system from radial to multi-source active distribution system. It introduces challenges like bidirectional power flow and increased normal and fault currents, leading to issues like protection blinding, false tripping, loss of coordination (relay-relay, fuse-fuse, fuse-recloser), nuisance tripping, and unsynchronised reclosing. Various factors affecting protection coordination are,

- In terms of System Topology
  - ➢ Radial / Ring Main
  - ➢ System Transition (from radial to ring main / from ring main to radial)
- In terms of Fault Parameters
  - ➢ Fault Type and Fault Location
  - ➢ Fault Resistance
- In terms of Source
  - ➢ Number of Sources
  - ➢ Type of Source supplying system
    - ✓ Source Type as DG
      - Renewable (Solar PV, Wind, Small Hydro)
      - Non-Renewable (Diesel Generators)
    - ✓ Type of Combination
      - Only Grid / Only DG / Grid + DG
  - ➢ Location and Size of Source
- Inclusion of Transformer

3.1 Distributed Generation Source type

Integrating Distributed Generation sources in the Distribution System causes numerous effects according to their types, like voltage unbalance or voltage flickering, frequency variation, and issues related to Power Quality. One of the reasons for voltage instability is that either a smaller number of large-capacity and/or a large number of low-capacity wind power generators (or induction generators) are integrated in the Distribution System because of reactive power requirements. Most of the DG sources, like Solar PV, generate DC power and utilise a converter system to connect them with AC system. Even Distributed Generators (DGs), such as Wind Power Generation Systems, utilise converter-based systems for integration with the AC grid. However, Induction Generators (IGs) require reactive power support, which may contribute to voltage unbalance in the system. Voltage unbalance affects real power (P) transfer in the system, as real power transfer is directly proportional to the square of the voltage (according to Equation 3.1). Power generation from Distributed Generators like Solar PV and Wind is dynamic in nature because of dependency on the atmosphere. This dynamic generation from DG and the dynamic nature of load demand also affect both real and reactive power flow (Equations 3.2 and 3.3) in the Distribution System.

$$P = \frac{V_S\, V_R}{X_L}\ \sin\delta \qquad (3.1)$$

where,

P = Real Power Flow (MW)

V_S, V_R = Sending & Receiving End Voltages (kV)

X_L = Line Reactance (Ω)

δ = Load Angle (º)

$$P = P_{grid} + \sum_i P_{DG,i} - \sum_i P_{Load,i} \qquad (3.2)$$

$$Q = Q_{grid} + \sum_i Q_{DG,i} - \sum_i Q_{Load,i} \qquad (3.3)$$

where,

P, Q = Real & Reactive Power in Distribution System

Pgrid, Qgrid = Real & Reactive Power Supply from Grid

$P_{DG,i}$, $Q_{DG,i}$ = Real & Reactive Power Supply from DGs at Bus i

$P_{Load,i}$, $Q_{Load,i}$ = Real & Reactive Power Demand at Bus i

$$I_f = I_{f,grid} \qquad (3.4)$$

$$I_f' = I_{f,grid} + \sum_i I_{f,DG,i} \qquad (3.5)$$

where,

I_f = Fault Current in Distribution Network in absence of DGs

I_f' = Fault Current in Distribution Network when DGs are present

$I_{f,grid}$ = Fault Current Contribution from Grid

$$= \frac{V_{grid}}{Z_{grid} + Z_{line} + Z_{fault}}$$

$I_{f,DG}$ = Fault Current Contribution from DGs at Bus i

$$= \frac{V_{DG}}{Z_{DG} + Z_{line,DG} + Z_{fault}}$$

V_{grid}, V_{DG} = Grid and DG Bus Voltages respectively

Z_{grid}, Z_{DG} = Source Impedance (Grid and DG)

Z_{line} = Impedance of line between grid & fault location

$Z_{line,DG}$ = Impedance of line between DG & fault location

Z_{fault} = Fault Impedance

With Wind Energy Conversion System (Induction Generator), capacitor banks are used to satisfy the reactive power requirement. Using cable for power distribution further adds capacitance, which increases the chances of resonance. As already mentioned before, Distributed Generation Sources also increase both normal and fault current magnitude (according to Equations 3.4 and 3.5). When a fault occurs in the Distribution System, fault current contribution ($I_{f,DG}$) is highest from Synchronous Generators. Fault current contribution ($I_{f,DG}$) from Induction Generator (Doubly Fed Induction Generator (DFIG) ($I_{f,DFIG}$) > Induction Generator (IG) ($I_{f,IG}$)) is lesser than Synchronous Generator (SG), and the least fault current contribution is from Solar PV [178]-[180].

3.2 System Operating Mode

Distribution System (DS) with Distributed Generation (DG) Sources is known as Microgrid (MG). Microgrid can operate in two modes, viz. Isolating Island and/or Grid Connected. In grid-connected mode, power flow is bidirectional, viz. (i) from utility grid to microgrid when the load demand in the microgrid is more than generation from DGs and (ii) from microgrid to utility grid when generation from DGs in the microgrid is higher than load. In the first case, load demand is fulfilled from both the grid as well as DGs (according to Equation 3.6). Because of an abnormal condition in utility grid, the microgrid gets disengaged from the power grid and starts working in Isolated Islanded mode. In this situation, only DGs will fulfil the load demand of the microgrid.

$$I_{Load} = I_{grid} + \sum_i I_{DG,i} \tag{3.6}$$

$$I_{Load} = \sum_i I_{DG,i} \tag{3.7}$$

There are two types of Islanding, i.e., Intentional or Unintentional. In case of Unintentional Islanding, frequency and voltage may not be within the standard limit, which can damage equipment. In case of Unintentional Islanding, three different conditions may arise in terms of frequency variation, viz. (i) load demand is higher than generation from DGs (frequency less than 50 Hz), (ii) generation from DGs is greater than load demand (frequency higher than 50 Hz), and (iii) generation from DGs is the same as load demand. Islanding Detection is one of the paramount tasks for microgrid protection. Islanding Detection (ID) may become difficult when power generation from DGs and load demand are almost the same.

3.3 Analysis for System with One Source

Effect of various parameters on Protection Coordination of Radial Distribution System with one source is discussed in this section. To understand effect on Protection Coordination of Radial Distribution System, two cases are considered viz. (i) Radial Distribution System supplied only through grid (as shown in Fig. 3.1) only and (ii) Radial Distribution System (or Standalone System) supplied only through Distributed Generation Sources (or Renewable Energy Sources) like Small Hydro (Synchronous Generator) or Wind (Induction Generator) Power Generation System (as shown in Fig. 3.2).

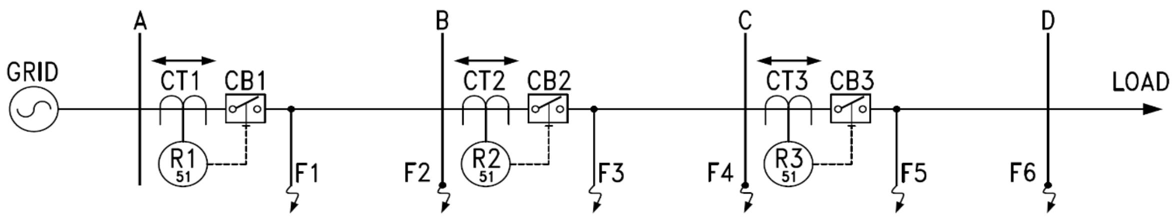


Figure 3.1 Radial Distribution System supplied through one source (grid only)

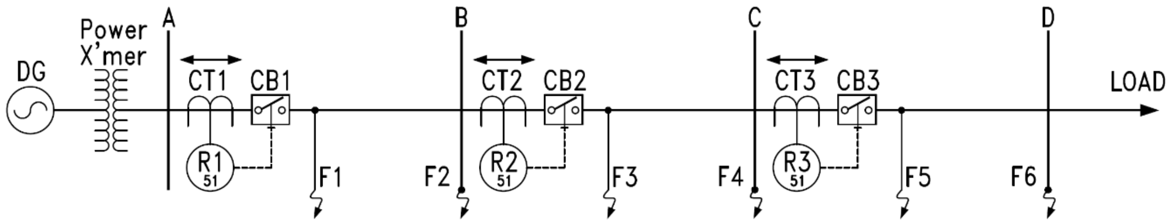


Figure 3.2 Radial Distribution System supplied through one source (standalone system - DG source only)

Overcurrent Protection is generally used for the protection of the Distribution System. For evaluating effects, overcurrent (O/C) Relays with Inverse Definite Minimum Time (IDMT) characteristics following the IEC-60255 standard are used. Equation 3.8 is used for the Time of Operation of the Overcurrent Relay used for protection of the Distribution System.

$$T_{op} = \left(\frac{A}{M^P - 1}\right) \cdot TDS + B \tag{3.8}$$

where,

TDS = Time Dial Setting / Time Multiplier Setting (TMS)

M = Plug Setting Multiplier (PSM)

A, B, P = Constants for IDMT characteristics according to IEC 60255 (as shown in Fig. 3.3)

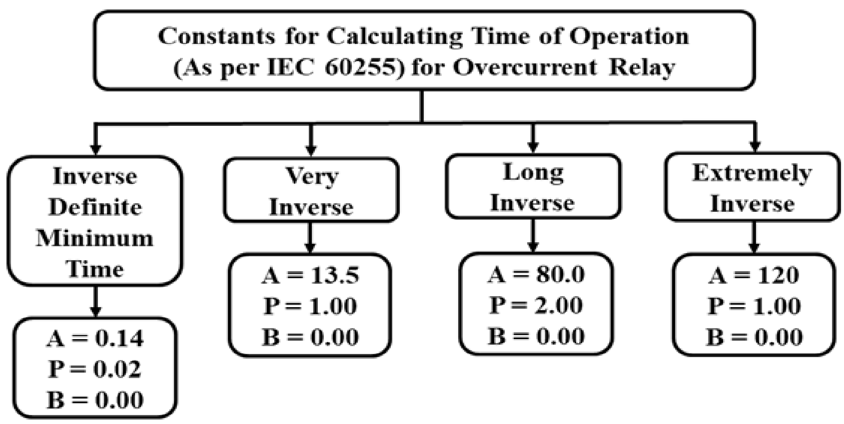


Figure 3.3 Constants for Calculation of Time of Operation (Top)

For protection of the Radial Distribution System with three sections, three non-directional overcurrent relays are needed because in this case current flow will always be unidirectional (from source to load only). Simulation of the modified IEEE 4-Bus Radial Distribution System is performed using PSCAD/EMTDC software (as shown in Fig. 3.4). System voltage is 12.47 kV with frequency 50 Hz and power demand of 6 MW. Each feeder section is 20 km in length with Resistance 0.363 ohm/km & Reactance 1.323 ohm/km. Inverse Time Overcurrent Relays (51) with IDMT characteristics are coordinated for protection of the Distribution System. Radial Distribution System with transformer (as shown in Fig. 3.5) is also considered [181] to understand the effect on protection coordination.

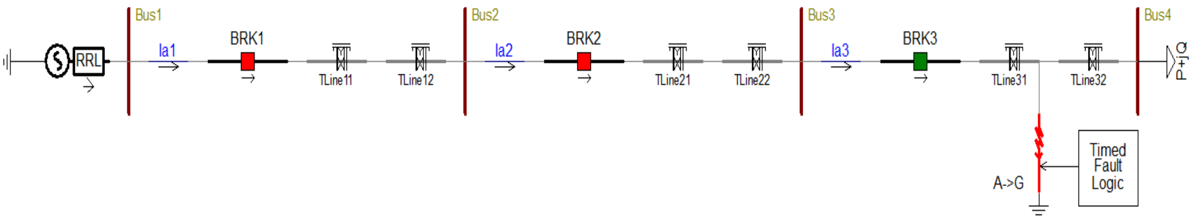


Figure 3.4 Radial Distribution System supplied through one source (grid only - prepared using PSCAD)

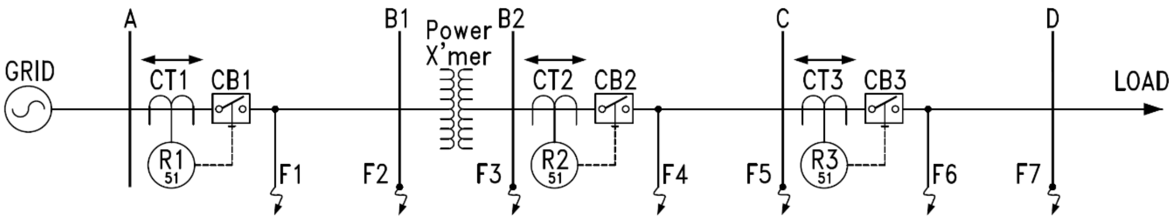


Figure 3.5 Radial Distribution System supplied through Grid (system with transformer)

To do analysis of the effect on Protection Coordination of Distribution System, various factors considered are,

- Fault Locations: Fault Locations are considered at the midpoint (10 km (F1), 30 km (F3) and 50 km (F5) from the source) and at the end (20 km (F2), 40 km (F4) and 60 km (F6) from the source) of each feeder section (as shown in Fig. 3.1 and Fig. 3.2).
- Fault Type: LG and LL faults are considered to analyse the impact of fault types on protection coordination.
- Fault Resistance (R_f): 0 ohm, 4 ohm, 8 ohm and 12 ohm are considered for analysing the effect of Fault Resistance (R_f) on protection coordination.
- Inclusion of Transformer: Because of the inclusion of a transformer in the Radial Distribution System, the system will operate at two different voltage levels with different fault levels on both sides of the transformer. Power Transformer rated 6.3 MVA, 12.47/4.16 kV is included in the Radial Distribution System and in this case, 7 fault locations are considered (as shown in Fig. 3.5).

Table 3.1 Impact of Fault Parameters on Protection Coordination of Distribution System (Grid Only)

$R_f = 0\ \Omega$ and L-G Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3
No Fault	260	260	260	-	-	-
F1	1831	244	244	0.32	-	-
F2	909	244	244	0.44	-	-
F3	601	601	244	-	0.36	-
F4	447	447	244	-	0.53	-
F5	355	355	355	-	-	0.42
F6	292	292	292	-	-	0.57
Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS
	0.26	0.02	0.21	0.01	0.16	0.01

$R_f = 4\ \Omega$ and L-G Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3
No Fault	260	260	260	-	-	-
F1	1156	244	244	0.33	-	-
F2	707	244	244	0.45	-	-
F3	508	508	244	-	0.35	-
F4	397	397	244	-	0.45	-
F5	327	327	327	-	-	0.38
F6	279	279	279	-	-	0.46
Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS
	0.24	0.02	0.19	0.01	0.15	0.01

$R_f = 8\ \Omega$ and L-G Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3
No Fault	260	260	260	-	-	-
F1	855	244	244	0.33	-	-
F2	590	244	244	0.40	-	-
F3	450	450	244	-	0.35	-
F4	365	365	244	-	0.45	-
F5	311	311	311	-	-	0.39
F6	273	273	273	-	-	0.47
Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS
	0.185	0.02	0.18	0.01	0.15	0.01

$R_f = 12\ \Omega$ and L-G Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3
No Fault	260	260	260	-	-	-
F1	687	244	244	0.33	-	-
F2	514	244	244	0.38	-	-
F3	410	410	244	-	0.33	-
F4	343	343	244	-	0.39	-
F5	300	300	300	-	-	0.35
F6	270	270	270	-	-	0.39
Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS
	0.16	0.02	0.16	0.01	0.14	0.01

Table 3.2 Impact of Fault Parameters on Protection Coordination of Distribution System (Grid Only)

$R_f = 0\ \Omega$ and LL Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3
No Fault	260	260	260	-	-	-
F1	2304	244	244	0.30	-	-
F2	1109	244	244	0.39	-	-
F3	712	712	244	-	0.32	-
F4	515	515	244	-	0.41	-
F5	400	400	400	-	-	0.34
F6	326	326	326	-	-	0.41
Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS
	0.25	0.02	0.2	0.01	0.15	0.01

$R_f = 4\ \Omega$ and LL Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3
No Fault	260	260	260	-	-	-
F1	1546	244	244	0.31	-	-
F2	877	244	244	0.40	-	-
F3	603	603	244	-	0.32	-
F4	455	455	244	-	0.41	-
F5	364	364	364	-	-	0.36
F6	306	306	306	-	-	0.42
Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS
	0.24	0.02	0.19	0.01	0.15	0.01

$R_f = 8\ \Omega$ and LL Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3
No Fault	260	260	260	-	-	-
F1	1156	244	244	0.30	-	-
F2	731	244	244	0.36	-	-
F3	529	529	244	-	0.32	-
F4	413	413	244	-	0.40	-
F5	341	341	341	-	-	0.37
F6	295	295	295	-	-	0.43
Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS
	0.185	0.02	0.18	0.01	0.15	0.01

$R_f = 12\ \Omega$ and LL Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3
No Fault	260	260	260	-	-	-
F1	917	244	244	0.30	-	-
F2	629	244	244	0.34	-	-
F3	475	475	244	-	0.30	-
F4	383	383	244	-	0.36	-
F5	326	326	326	-	-	0.33
F6	289	289	289	-	-	0.37
Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS
	0.16	0.02	0.16	0.01	0.14	0.01

Table 3.3 Impact of Fault Parameters on Protection Coordination of Distribution System (Grid Only)

R_f = 0 Ω and LLG Fault							R_f = 4 Ω and LLG Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)			Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3		I1	I2	I3	R1	R2	R3
No Fault	260	260	260	-	-	-	No Fault	260	260	260	-	-	-
F1	2545	244	244	0.29	-	-	F1	1276	244	244	0.31	-	-
F2	1205	244	244	0.37	-	-	F2	802	244	244	0.40	-	-
F3	759	759	244	-	0.31	-	F3	569	569	244	-	0.32	-
F4	536	536	244	-	0.39	-	F4	432	432	244	-	0.41	-
F5	402	402	402	-	-	0.34	F5	346	346	346	-	-	0.36
F6	313	313	313	-	-	0.43	F6	289	289	289	-	-	0.45
Relay Setting	Relay R1		Relay R2		Relay R3		Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS		Ip	TDS	Ip	TDS	Ip	TDS
	0.25	0.02	0.2	0.01	0.15	0.01		0.24	0.02	0.19	0.01	0.15	0.01
R_f = 8 Ω and LLG Fault							R_f = 12 Ω and LLG Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)			Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3		I1	I2	I3	R1	R2	R3
No Fault	260	260	260	-	-	-	No Fault	260	260	260	-	-	-
F1	865	244	244	0.32	-	-	F1	672	244	244	0.32	-	-
F2	617	244	244	0.37	-	-	F2	517	244	244	0.36	-	-
F3	473	473	244	-	0.33	-	F3	417	417	244	-	0.32	-
F4	380	380	244	-	0.41	-	F4	350	350	244	-	0.37	-
F5	321	321	321	-	-	0.38	F5	306	306	306	-	-	0.34
F6	280	280	280	-	-	0.46	F6	275	275	275	-	-	0.38
Relay Setting	Relay R1		Relay R2		Relay R3		Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS		Ip	TDS	Ip	TDS	Ip	TDS
	0.185	0.02	0.18	0.01	0.15	0.01		0.16	0.02	0.16	0.01	0.14	0.01

Table 3.4 Impact of Fault Parameters on Protection Coordination of Distribution System (Grid Only - with Transformer)

$R_f = 0\ \Omega$ and L-G Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3
No Fault	43	121	121	-	-	-
F1	1848	108	108	0.23	-	-
F2	925	108	108	0.24	-	-
F3	826	108	108	0.24	-	-
F4	165	489	108	-	0.29	-
F5	93	271	108	-	0.45	-
F6	65	187	187	-	-	0.35
F7	50	141	141	-	-	0.47
Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS
	0.06	0.01	0.11	0.01	0.07	0.01

$R_f = 4\ \Omega$ and L-G Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3
No Fault	43	121	121	-	-	-
F1	1155	108	108	0.23	-	-
F2	713	108	108	0.24	-	-
F3	240	108	108	0.27	-	-
F4	116	342	108	-	0.28	-
F5	77	223	108	-	0.34	-
F6	58	166	166	-	-	0.30
F7	48	133	133	-	-	0.34
Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS
	0.05	0.01	0.08	0.01	0.06	0.01

$R_f = 8\ \Omega$ and L-G Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3
No Fault	43	121	121	-	-	-
F1	832	108	108	0.23	-	-
F2	579	108	108	0.24	-	-
F3	143	108	108	0.29	-	-
F4	93	271	108	-	0.28	-
F5	68	195	108	-	0.32	-
F6	54	154	154	-	-	0.30
F7	47	129	129	-	-	0.34
Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS
	0.04	0.01	0.07	0.01	0.06	0.01

$R_f = 12\ \Omega$ and L-G Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3
No Fault	43	121	121	-	-	-
F1	646	108	108	0.23	-	-
F2	486	108	108	0.24	-	-
F3	107	108	108	0.29	-	-
F4	79	231	108	-	0.29	-
F5	62	178	108	-	0.33	-
F6	52	147	147	-	-	0.31
F7	46	127	127	-	-	0.34
Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS
	0.03	0.01	0.07	0.01	0.06	0.01

Table 3.5 Impact of Fault Parameters on Protection Coordination of Distribution System (Grid Only - with Transformer)

$R_f = 0\ \Omega$ and LL Fault							$R_f = 4\ \Omega$ and LL Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)			Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3		I1	I2	I3	R1	R2	R3
No Fault	43	121	121	-	-	-	No Fault	43	121	121	-	-	-
F1	2393	108	108	0.23	-	-	F1	1649	108	108	0.23	-	-
F2	1191	108	108	0.23	-	-	F2	974	108	108	0.23	-	-
F3	1002	108	108	0.24	-	-	F3	357	108	108	0.25	-	-
F4	204	601	108	-	0.28	-	F4	148	436	108	-	0.27	-
F5	111	326	108	-	0.38	-	F5	92	268	108	-	0.32	-
F6	76	220	220	-	-	0.33	F6	67	193	193	-	-	0.28
F7	59	166	166	-	-	0.41	F7	54	152	152	-	-	0.32
Relay Setting	Relay R1		Relay R2		Relay R3		Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS		Ip	TDS	Ip	TDS	Ip	TDS
	0.06	0.01	0.11	0.01	0.07	0.01		0.05	0.01	0.08	0.01	0.06	0.01
$R_f = 8\ \Omega$ and LL Fault							$R_f = 12\ \Omega$ and LL Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)			Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3		I1	I2	I3	R1	R2	R3
No Fault	43	121	121	-	-	-	No Fault	43	121	121	-	-	-
F1	1250	108	108	0.23	-	-	F1	999	108	108	0.23	-	-
F2	816	108	108	0.23	-	-	F2	706	108	108	0.23	-	-
F3	209	108	108	0.26	-	-	F3	147	108	108	0.26	-	-
F4	117	343	108	-	0.26	-	F4	98	285	108	-	0.27	-
F5	80	231	108	-	0.30	-	F5	72	206	108	-	0.31	-
F6	62	176	176	-	-	0.29	F6	58	165	165	-	-	0.30
F7	52	145	145	-	-	0.32	F7	50	140	140	-	-	0.33
Relay Setting	Relay R1		Relay R2		Relay R3		Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS		Ip	TDS	Ip	TDS	Ip	TDS
	0.04	0.01	0.07	0.01	0.06	0.01		0.03	0.01	0.07	0.01	0.06	0.01

Table 3.6 Impact of Fault Parameters on Protection Coordination of Distribution System (Grid Only - with Transformer)

$R_f = 0\ \Omega$ and LLG Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3
No Fault	43	121	121	-	-	-
F1	2668	108	108	0.23	-	-
F2	1325	108	108	0.23	-	-
F3	1124	108	108	0.24	-	-
F4	221	655	108	-	0.27	-
F5	117	341	108	-	0.36	-
F6	77	221	221	-	-	0.32
F7	55	155	155	-	-	0.44
Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS
	0.06	0.01	0.11	0.01	0.07	0.01

$R_f = 4\ \Omega$ and LLG Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3
No Fault	43	121	121	-	-	-
F1	1351	108	108	0.23	-	-
F2	896	108	108	0.24	-	-
F3	237	108	108	0.26	-	-
F4	127	376	108	-	0.27	-
F5	85	245	108	-	0.32	-
F6	62	179	179	-	-	0.29
F7	50	140	140	-	-	0.33
Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS
	0.05	0.01	0.08	0.01	0.06	0.01

$R_f = 8\ \Omega$ and LLG Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3
No Fault	43	121	121	-	-	-
F1	886	108	108	0.23	-	-
F2	670	108	108	0.23	-	-
F3	140	108	108	0.28	-	-
F4	95	277	108	-	0.27	-
F5	70	203	108	-	0.31	-
F6	56	161	161	-	-	0.30
F7	48	134	134	-	-	0.33
Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS
	0.04	0.01	0.07	0.01	0.06	0.01

$R_f = 12\ \Omega$ and LLG Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3
No Fault	43	121	121	-	-	-
F1	656	108	108	0.23	-	-
F2	533	108	108	0.23	-	-
F3	105	108	108	0.28	-	-
F4	79	229	108	-	0.28	-
F5	63	181	108	-	0.32	-
F6	53	151	151	-	-	0.31
F7	47	131	131	-	-	0.34
Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS
	0.03	0.01	0.07	0.01	0.06	0.01

Table 3.7 Impact of Fault Parameters on Protection Coordination of Distribution System (Standalone System - Synchronous Generator)

R_f = 0 Ω and L-G Fault							R_f = 4 Ω and L-G Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)			Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3		I1	I2	I3	R1	R2	R3
No Fault	270	270	270	-	-	-	No Fault	270	270	270	-	-	-
F1	1449	251	251	0.32	-	-	F1	1027	251	251	0.33	-	-
F2	816	251	251	0.41	-	-	F2	667	251	251	0.41	-	-
F3	575	575	251	-	0.35	-	F3	500	500	251	-	0.35	-
F4	447	447	251	-	0.47	-	F4	403	403	251	-	0.45	-
F5	369	369	369	-	-	0.44	F5	340	340	340	-	-	0.38
F6	316	316	316	-	-	0.65	F6	296	296	296	-	-	0.49
Relay Setting	Relay R1		Relay R2		Relay R3		Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS		Ip	TDS	Ip	TDS	Ip	TDS
	0.22	0.02	0.2	0.01	0.17	0.01		0.21	0.02	0.19	0.01	0.16	0.01

R_f = 8 Ω and L-G Fault							R_f = 12 Ω and L-G Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)			Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3		I1	I2	I3	R1	R2	R3
No Fault	270	270	270	-	-	-	No Fault	270	270	270	-	-	-
F1	807	251	251	0.32	-	-	F1	674	251	251	0.28	-	-
F2	575	251	251	0.37	-	-	F2	511	251	251	0.30	-	-
F3	450	450	251	-	0.32	-	F3	415	415	251	-	0.28	-
F4	374	374	251	-	0.38	-	F4	354	354	251	-	0.30	-
F5	323	323	323	-	-	0.33	F5	312	312	312	-	-	0.29
F6	288	288	288	-	-	0.38	F6	284	284	284	-	-	0.31
Relay Setting	Relay R1		Relay R2		Relay R3		Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS		Ip	TDS	Ip	TDS	Ip	TDS
	0.17	0.02	0.17	0.01	0.15	0.01		0.13	0.02	0.15	0.01	0.14	0.01

Table 3.8 Impact of Fault Parameters on Protection Coordination of Distribution System (Standalone System - Synchronous Generator)

$R_f = 0\ \Omega$ and LL Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3
No Fault	270	270	270	-	-	-
F1	1512	251	251	0.31	-	-
F2	819	251	251	0.39	-	-
F3	595	595	251	-	0.33	-
F4	472	472	251	-	0.42	-
F5	394	394	394	-	-	0.37
F6	343	343	343	-	-	0.46
Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS
	0.22	0.02	0.2	0.01	0.165	0.01

$R_f = 4\ \Omega$ and LL Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3
No Fault	270	270	270	-	-	-
F1	1090	251	251	0.32	-	-
F2	704	251	251	0.39	-	-
F3	531	531	251	-	0.33	-
F4	432	432	251	-	0.40	-
F5	366	366	366	-	-	0.33
F6	322	322	322	-	-	0.39
Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS
	0.21	0.02	0.185	0.01	0.155	0.01

$R_f = 8\ \Omega$ and LL Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3
No Fault	270	270	270	-	-	-
F1	925	251	251	0.30	-	-
F2	622	251	251	0.35	-	-
F3	485	485	251	-	0.31	-
F4	402	402	251	-	0.36	-
F5	347	347	347	-	-	0.34
F6	310	310	310	-	-	0.40
Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS
	0.17	0.02	0.17	0.01	0.155	0.01

$R_f = 12\ \Omega$ and LL Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3
No Fault	270	270	270	-	-	-
F1	802	251	251	0.26	-	-
F2	560	251	251	0.29	-	-
F3	448	448	251	-	0.29	-
F4	379	379	251	-	0.33	-
F5	333	333	333	-	-	0.32
F6	303	303	303	-	-	0.36
Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS
	0.13	0.02	0.16	0.01	0.15	0.01

Table 3.9 Impact of Fault Parameters on Protection Coordination of Distribution System (Standalone System - Induction Generator)

R_f = 0 Ω and L-G Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3
No Fault	178	178	178	-	-	-
F1	658	143	143	0.31	-	-
F2	427	143	143	0.41	-	-
F3	315	315	143	-	0.34	-
F4	249	249	143	-	0.41	-
F5	206	206	206	-	-	0.37
F6	181	181	181	-	-	0.43
Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS
	0.17	0.01	0.11	0.01	0.09	0.01

R_f = 4 Ω and L-G Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3
No Fault	178	178	178	-	-	-
F1	504	143	143	0.30	-	-
F2	358	143	143	0.36	-	-
F3	278	278	143	-	0.31	-
F4	227	227	143	-	0.34	-
F5	193	193	193	-	-	0.33
F6	176	176	176	-	-	0.35
Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS
	0.14	0.01	0.09	0.01	0.08	0.01

R_f = 8 Ω and L-G Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3
No Fault	178	178	178	-	-	-
F1	415	143	143	0.30	-	-
F2	313	143	143	0.36	-	-
F3	252	252	143	-	0.31	-
F4	214	214	143	-	0.35	-
F5	189	189	189	-	-	0.33
F6	175	175	175	-	-	0.36
Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS
	0.13	0.01	0.09	0.01	0.08	0.01

R_f = 12 Ω and L-G Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3
No Fault	178	178	178	-	-	-
F1	358	143	143	0.31	-	-
F2	288	143	143	0.36	-	-
F3	236	236	143	-	0.31	-
F4	207	207	143	-	0.33	-
F5	186	186	186	-	-	0.33
F6	174	174	174	-	-	0.36
Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS
	0.12	0.01	0.085	0.01	0.08	0.01

Table 3.10 Impact of Fault Parameters on Protection Coordination of Distribution System (Standalone System - Induction Generator)

$R_f = 0\ \Omega$ and LL Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3
No Fault	178	178	178	-	-	-
F1	732	143	143	0.30	-	-
F2	480	143	143	0.38	-	-
F3	354	354	143	-	0.33	-
F4	279	279	143	-	0.38	-
F5	229	229	229	-	-	0.35
F6	194	194	194	-	-	0.40
Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS
	0.17	0.01	0.11	0.01	0.09	0.01

$R_f = 4\ \Omega$ and LL Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3
No Fault	178	178	178	-	-	-
F1	589	143	143	0.28	-	-
F2	411	143	143	0.34	-	-
F3	314	314	143	-	0.30	-
F4	253	253	143	-	0.33	-
F5	213	213	213	-	-	0.32
F6	184	184	184	-	-	0.34
Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS
	0.14	0.01	0.09	0.01	0.08	0.01

$R_f = 8\ \Omega$ and LL Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3
No Fault	178	178	178	-	-	-
F1	493	143	143	0.28	-	-
F2	361	143	143	0.33	-	-
F3	284	284	143	-	0.30	-
F4	235	235	143	-	0.33	-
F5	202	202	202	-	-	0.32
F6	179	179	179	-	-	0.34
Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS
	0.13	0.01	0.09	0.01	0.08	0.01

$R_f = 12\ \Omega$ and LL Fault						
Fault Location	Section wise Current (A)			Time of Operation (Sec)		
	I1	I2	I3	R1	R2	R3
No Fault	178	178	178	-	-	-
F1	425	143	143	0.28	-	-
F2	324	143	143	0.32	-	-
F3	262	262	143	-	0.29	-
F4	221	221	143	-	0.32	-
F5	194	194	194	-	-	0.33
F6	177	177	177	-	-	0.35
Relay Setting	Relay R1		Relay R2		Relay R3	
	Ip	TDS	Ip	TDS	Ip	TDS
	0.12	0.01	0.085	0.01	0.08	0.01

Relays are set such that wherever a fault occurs in the system, respective relay operates and sends a trip signal to respective breaker of the section. Results of the effect on protection coordination considering various parameters are presented in Table 3.1 - Table 3.10.

3.4 Analysis for System with more than One Source

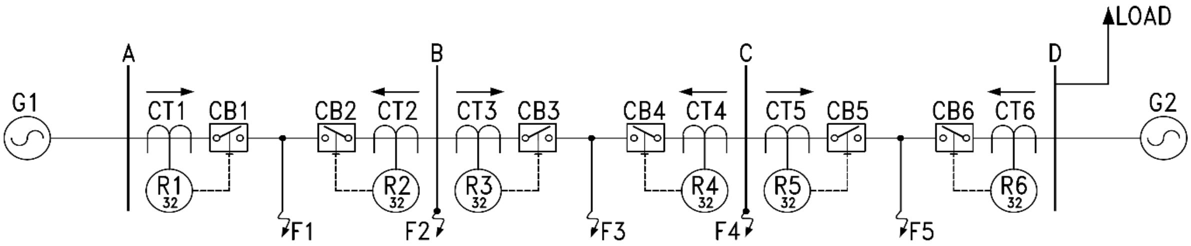


Figure 3.6 Distribution System supplied through two sources (utility grid only)

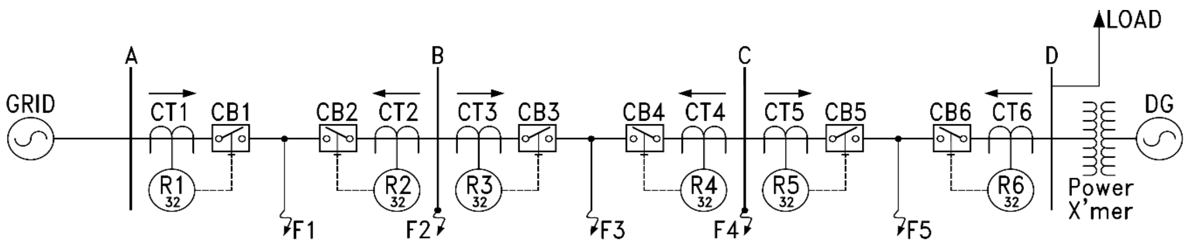


Figure 3.7 Distribution System supplied through two sources (utility grid + 1 DG)

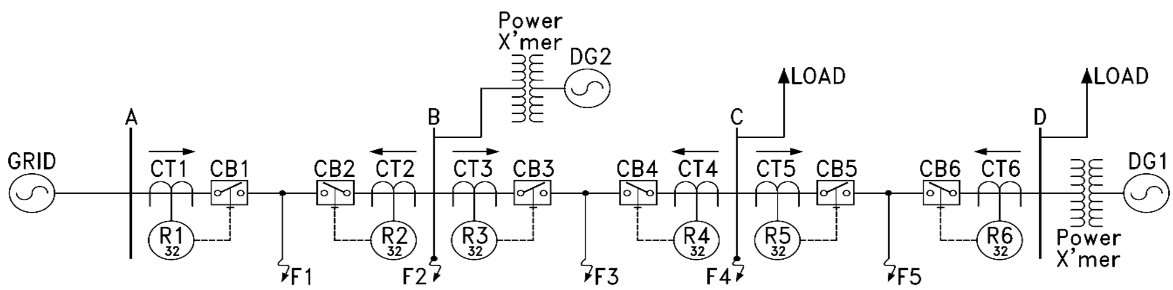


Figure 3.8 Distribution System supplied through three sources (utility grid + 2 DG)

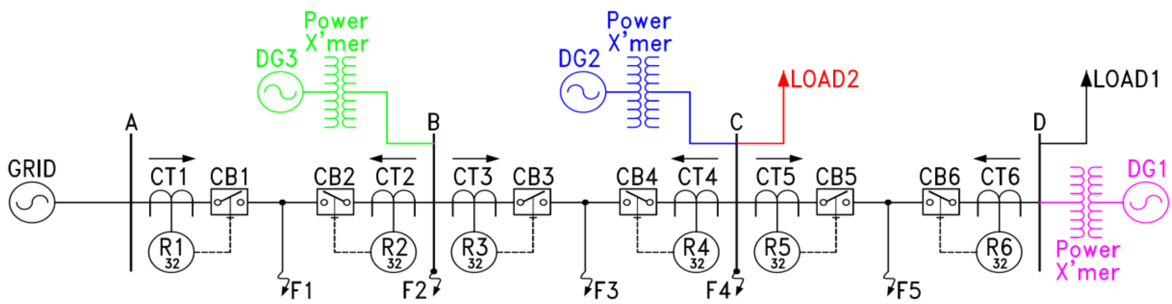


Figure 3.9 Distribution System supplied through four sources (utility grid + 3 DG)

Table 3.11 (a) Impact of Fault Parameters on Protection Coordination of Distribution System with two Sources

$R_f = 0\ \Omega$ and L-G Fault (Both sources as Grid)												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	-	-	-	-	-	-	-	-	-	-	-	-
F1	1847	370	370	370	370	370	0.21	0.21	-	-	-	-
F2	924	924	462	462	462	462	0.22	-	-	0.22	-	-
F3	616	616	616	616	616	616	-	-	0.21	0.21	-	-
F4	462	462	462	462	924	924	-	-	0.22	-	-	0.22
F5	370	370	370	370	370	1846	-	-	-	-	0.21	0.21
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.45		0.07		0.2		0.22		0.09		0.45	

Table 3.11 (b) Impact of Fault Parameters on Protection Coordination of Distribution System with two Sources

$R_f = 4\ \Omega$ and L-G (Both sources as Grid)												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	-	-	-	-	-	-	-	-	-	-	-	-
F1	1071	214	214	214	214	214	0.22	0.21	-	-	-	-
F2	639	639	319	319	319	319	0.24	-	-	0.22	-	-
F3	441	441	441	441	441	441	-	-	0.22	0.22	-	-
F4	319	319	319	319	639	639	-	-	0.22	-	-	0.22
F5	214	214	214	214	214	1070	-	-	-	-	0.22	0.22
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.42		0.05		0.19		0.2		0.085		0.41	

Table 3.11 (c) Impact of Fault Parameters on Protection Coordination of Distribution System with two Sources

R_f = 8 Ω and L-G Fault (Both sources as Grid)												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	-	-	-	-	-	-	-	-	-	-	-	-
F1	806	298	298	298	298	298	0.22	0.24	-	-	-	-
F2	522	522	242	242	242	242	0.24	-	-	0.22	-	-
F3	341	341	341	341	341	341	-	-	0.22	0.22	-	-
F4	242	242	242	242	483	483	-	-	0.22	-	-	0.22
F5	149	149	149	149	149	741	-	-	-	-	0.22	0.22
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.35		0.018		0.165		0.14		0.082		0.32	

Table 3.11 (d) Impact of Fault Parameters on Protection Coordination of Distribution System with two Sources

R_f = 12 Ω and L-G Fault (Both sources as Grid)												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	-	-	-	-	-	-	-	-	-	-	-	-
F1	638	112	112	112	112	112	0.22	0.21	-	-	-	-
F2	460	460	193	193	193	193	0.24	-	-	0.22	-	-
F3	276	276	276	276	276	276	-	-	0.22	0.22	-	-
F4	299	299	299	299	386	386	-	-	0.23	-	-	0.22
F5	264	264	264	264	264	561	-	-	-	-	0.22	0.22
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.3		0.012		0.16		0.12		0.08		0.22	

Table 3.12 (a) Impact of Fault Parameters on Protection Coordination of Distribution System with two Sources and load increment by 1 MW

$R_f = 0\ \Omega$ and L-G Fault (Both sources as Grid)												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	73	73	73	73	145	145	-	-	-	-	-	-
F1	1867	351	351	351	425	425	0.21	0.21	-	-	-	-
F2	947	947	453	453	504	504	0.22	-	-	0.22	-	-
F3	643	643	643	633	651	651	-	-	0.21	0.21	-	-
F4	502	502	502	502	1004	1004	-	-	0.22	-	-	0.22
F5	382	382	382	382	389	1906	-	-	-	-	0.22	0.21
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.4		0.12		0.225		0.225		0.21		0.45	

Table 3.12 (b) Impact of Fault Parameters on Protection Coordination of Distribution System with two Sources and load increment by 1 MW

$R_f = 4\ \Omega$ and L-G Fault (Both sources as Grid)												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	73	73	73	73	145	145	-	-	-	-	-	-
F1	1110	273	273	273	381	381	0.21	0.22	-	-	-	-
F2	671	671	323	323	419	419	0.22	-	-	0.23	-	-
F3	471	471	471	403	505	505	-	-	0.22	0.22	-	-
F4	346	346	346	346	691	691	-	-	0.22	-	-	0.22
F5	344	344	344	344	286	1135	-	-	-	-	0.22	0.21
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.38		0.11		0.19		0.22		0.19		0.35	

Table 3.12 (c) Impact of Fault Parameters on Protection Coordination of Distribution System with two Sources and load increment by 1 MW

R_f = 8 Ω and L-G Fault (Both sources as Grid)												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	73	73	73	73	145	145	-	-	-	-	-	-
F1	791	279	279	279	400	400	0.22	0.23	-	-	-	-
F2	524	524	183	183	341	341	0.22	-	-	0.22	-	-
F3	377	377	377	284	423	423	-	-	0.22	0.22	-	-
F4	384	384	384	384	546	546	-	-	0.23	-	-	0.22
F5	366	366	366	366	296	825	-	-	-	-	0.24	0.22
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.3		0.1		0.16		0.15		0.18		0.28	

Table 3.12 (d) Impact of Fault Parameters on Protection Coordination of Distribution System with two Sources and load increment by 1 MW

R_f = 12 Ω and L-G Fault (Both sources as Grid)												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	73	73	73	73	145	145	-	-	-	-	-	-
F1	617	259	259	259	393	393	0.22	0.23	-	-	-	-
F2	433	433	128	128	305	305	0.22	-	-	0.22	-	-
F3	318	318	318	211	371	371	-	-	0.22	0.22	-	-
F4	367	367	367	367	461	461	-	-	0.23	-	-	0.22
F5	354	354	354	354	266	659	-	-	-	-	0.24	0.22
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.25		0.1		0.14		0.13		0.15		0.22	

Table 3.13 (a) Impact of Fault Parameters on Protection Coordination of Distribution System with two Sources

$R_f = 0\ \Omega$ and L-G Fault (Grid + Synchronous Generator with 1 MW capacity)												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	117	117	117	117	117	117	-	-	-	-	-	-
F1	1853	208	208	208	208	208	0.21	0.21	-	-	-	-
F2	932	932	255	255	255	255	0.22	-	-	0.22	-	-
F3	626	626	626	327	327	327	-	-	0.21	0.22	-	-
F4	475	475	475	475	458	458	-	-	0.22	-	-	0.23
F5	388	388	388	388	388	757	-	-	-	-	0.23	0.21
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.42		0.12		0.19		0.16		0.18		0.26	

Table 3.13 (b) Impact of Fault Parameters on Protection Coordination of Distribution System with two Sources

$R_f = 4\ \Omega$ and L-G Fault (Grid + Synchronous Generator with 1 MW capacity)												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	117	117	117	117	117	117	-	-	-	-	-	-
F1	1109	161	161	161	161	161	0.21	0.22	-	-	-	-
F2	674	674	185	185	185	185	0.22	-	-	0.23	-	-
F3	478	478	478	221	221	221	-	-	0.22	0.22	-	-
F4	364	364	364	364	307	307	-	-	0.24	-	-	0.22
F5	283	283	283	283	283	463	-	-	-	-	0.24	0.22
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.36		0.12		0.18		0.16		0.16		0.23	

Table 3.13 (c) Impact of Fault Parameters on Protection Coordination of Distribution System with two Sources

R_f = 8 Ω and L-G Fault (Grid + Synchronous Generator with 1 MW capacity)												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	117	117	117	117	117	117	-	-	-	-	-	-
F1	785	182	182	182	182	182	0.22	0.23	-	-	-	-
F2	528	528	185	185	185	185	0.22	-	-	0.23	-	-
F3	389	389	389	211	211	211	-	-	0.22	0.23	-	-
F4	299	299	299	299	232	232	-	-	0.24	-	-	0.22
F5	239	239	239	239	239	329	-	-	-	-	0.24	0.22
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.30		0.08		0.17		0.15		0.14		0.18	

Table 3.13 (d) Impact of Fault Parameters on Protection Coordination of Distribution System with two Sources

R_f = 12 Ω and L-G Fault (Grid + Synchronous Generator with 1 MW capacity)												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	117	117	117	117	117	117	-	-	-	-	-	-
F1	613	99	99	99	99	99	0.22	0.22	-	-	-	-
F2	451	451	201	201	201	201	0.22	-	-	0.23	-	-
F3	330	330	330	191	191	191	-	-	0.22	0.22	-	-
F4	278	278	278	278	191	191	-	-	0.25	-	-	0.22
F5	235	235	235	235	235	257	-	-	-	-	0.24	0.22
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.24		0.04		0.165		0.13		0.12		0.16	

Table 3.14 (a) Impact of Fault Parameters on Protection Coordination of Distribution System with three Sources and load increment by 1 MW

R_f = 0 Ω and L-G Fault (Grid + two Synchronous Generators with 1 MW capacity each)												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	295	295	279	279	86	86	-	-	-	-	-	-
F1	1846	981	323	323	116	116	0.21	0.21	-	-	-	-
F2	1003	1003	297	297	286	286	0.21	-	-	0.22	-	-
F3	512	512	1157	339	325	325	-	-	0.24	0.22	-	-
F4	395	395	748	748	477	477	-	-	0.22	-	-	0.22
F5	358	358	545	545	533	762	-	-	-	-	0.21	0.21
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.38		0.08		0.26		0.20		0.135		0.26	

Table 3.14 (b) Impact of Fault Parameters on Protection Coordination of Distribution System with three Sources and load increment by 1 MW

R_f = 4 Ω and L-G Fault (Grid + two Synchronous Generators with 1 MW capacity each)												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	295	295	279	279	86	86	-	-	-	-	-	-
F1	839	667	314	314	112	112	0.21	0.21	-	-	-	-
F2	388	388	196	196	134	134	0.22	-	-	0.22	-	-
F3	367	367	820	196	241	241	-	-	0.21	0.22	-	-
F4	354	354	569	569	257	257	-	-	0.22	-	-	0.22
F5	301	301	445	445	343	420	-	-	-	-	0.22	0.22
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.34		0.07		0.22		0.16		0.13		0.20	

Table 3.14 (c) Impact of Fault Parameters on Protection Coordination of Distribution System with three Sources and load increment by 1 MW

$R_f = 8\ \Omega$ and L-G Fault (Grid + two Synchronous Generators with 1 MW capacity each)												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	295	295	279	279	86	86	-	-	-	-	-	-
F1	508	534	313	313	111	111	0.22	0.21	-	-	-	-
F2	295	295	196	196	136	136	0.24	-	-	0.22	-	-
F3	354	354	664	212	267	267	-	-	0.22	0.22	-	-
F4	357	357	486	486	167	167	-	-	0.25	-	-	0.22
F5	295	295	396	396	258	278	-	-	-	-	0.22	0.22
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.28		0.06		0.20		0.12		0.12		0.16	

Table 3.14 (d) Impact of Fault Parameters on Protection Coordination of Distribution System with three Sources and load increment by 1 MW

$R_f = 12\ \Omega$ and L-G Fault (Grid + two Synchronous Generators with 1 MW capacity each)												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	295	295	279	279	86	86	-	-	-	-	-	-
F1	343	471	313	313	111	111	0.22	0.21	-	-	-	-
F2	295	295	201	201	136	136	0.23	-	-	0.22	-	-
F3	361	361	573	196	256	256	-	-	0.25	0.22	-	-
F4	354	354	437	437	270	270	-	-	0.22	-	-	0.23
F5	295	295	367	367	211	204	-	-	-	-	0.22	0.22
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.18		0.05		0.15		0.09		0.10		0.15	

Table 3.15 (a) Impact of Fault Parameters on Protection Coordination of Distribution System with three Sources and load increment by 1 MW

$R_f = 0\ \Omega$ and L-G Fault (Grid + two Synchronous Generators (with 1 MW and 0.7 MW capacity))												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	217	217	251	251	73	73	-	-	-	-	-	-
F1	1863	776	281	281	121	121	0.21	0.22	-	-	-	-
F2	999	999	279	279	282	282	0.21	-	-	0.21	-	-
F3	502	502	1006	341	331	331	-	-	0.21	0.21	-	-
F4	391	391	684	684	482	482	-	-	0.22	-	-	0.23
F5	334	334	506	506	496	763	-	-	-	-	0.22	0.21
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.40		0.40		0.24		0.16		0.20		0.26	

Table 3.15 (b) Impact of Fault Parameters on Protection Coordination of Distribution System with three Sources and load increment by 1 MW

$R_f = 4\ \Omega$ and L-G Fault (Grid + two Synchronous Generators (with 1 MW and 0.7 MW capacity))												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	217	217	251	251	73	73	-	-	-	-	-	-
F1	917	512	273	273	77	77	0.22	0.24	-	-	-	-
F2	474	474	170	170	141	141	0.24	-	-	0.22	-	-
F3	325	325	735	189	235	235	-	-	0.21	0.22	-	-
F4	281	281	520	520	312	312	-	-	0.22	-	-	0.23
F5	261	261	409	409	311	437	-	-	-	-	0.24	0.22
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.38		0.30		0.20		0.14		0.18		0.22	

Table 3.15 (c) Impact of Fault Parameters on Protection Coordination of Distribution System with three Sources and load increment by 1 MW

R_f = 8 Ω and L-G Fault (Grid + two Synchronous Generators (with 1 MW and 0.7 MW capacity))												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	217	217	251	251	73	73	-	-	-	-	-	-
F1	583	462	269	269	76	76	0.22	0.24	-	-	-	-
F2	313	313	170	170	137	137	0.24	-	-	0.22	-	-
F3	284	284	599	209	263	263	-	-	0.22	0.22	-	-
F4	281	281	443	443	288	288	-	-	0.22	-	-	0.23
F5	249	249	369	369	282	301	-	-	-	-	0.23	0.22
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.32		0.26		0.16		0.12		0.16		0.18	

Table 3.15 (d) Impact of Fault Parameters on Protection Coordination of Distribution System with three Sources and load increment by 1 MW

R_f = 12 Ω and L-G Fault (Grid + two Synchronous Generators (with 1 MW and 0.7 MW capacity))												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	217	217	251	251	73	73	-	-	-	-	-	-
F1	414	399	269	269	76	76	0.22	0.24	-	-	-	-
F2	229	229	170	170	134	134	0.22	-	-	0.23	-	-
F3	283	283	519	185	254	254	-	-	0.22	0.22	-	-
F4	280	280	397	397	267	267	-	-	0.22	-	-	0.23
F5	238	238	363	363	255	229	-	-	-	-	0.24	0.22
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.20		0.24		0.135		0.105		0.14		0.16	

Table 3.16 (a) Impact of Fault Parameters on Protection Coordination of Distribution System with three Sources and load increment by 1 MW

$R_f = 0\ \Omega$ and L-G Fault (Grid + one Synchronous Generator (SG) and one Induction Generator (IG) (both with 1 MW capacity))												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	285	285	133	133	111	111	-	-	-	-	-	-
F1	1818	232	199	199	232	232	0.21	0.21	-	-	-	-
F2	895	895	220	220	249	249	0.22	-	-	0.23	-	-
F3	658	658	554	315	319	319	-	-	0.21	0.21	-	-
F4	549	549	428	428	468	468	-	-	0.22	-	-	0.23
F5	469	469	334	334	338	745	-	-	-	-	0.22	0.21
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.28		0.12		0.18		0.14		0.16		0.22	

Table 3.16 (b) Impact of Fault Parameters on Protection Coordination of Distribution System with three Sources and load increment by 1 MW

$R_f = 4\ \Omega$ and L-G Fault (Grid + one Synchronous Generator (SG) and one Induction Generator (IG) (both with 1 MW capacity))												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	285	285	133	133	111	111	-	-	-	-	-	-
F1	1121	232	166	166	212	212	0.21	0.22	-	-	-	-
F2	673	673	182	182	204	204	0.22	-	-	0.23	-	-
F3	531	531	418	168	240	240	-	-	0.22	0.22	-	-
F4	446	446	318	318	318	318	-	-	0.22	-	-	0.23
F5	402	402	262	262	223	475	-	-	-	-	0.24	0.22
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.24		0.11		0.14		0.14		0.16		0.18	

Table 3.16 (c) Impact of Fault Parameters on Protection Coordination of Distribution System with three Sources and load increment by 1 MW

R_f = 8 Ω and L-G Fault (Grid + one Synchronous Generator (SG) and one Induction Generator (IG) (both with 1 MW capacity))												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	285	285	133	133	111	111	-	-	-	-	-	-
F1	824	232	162	162	216	216	0.21	0.22	-	-	-	-
F2	556	556	169	169	219	219	0.22	-	-	0.23	-	-
F3	461	461	345	194	248	248	-	-	0.22	0.23	-	-
F4	434	434	310	310	249	249	-	-	0.25	-	-	0.22
F5	399	399	263	263	204	357	-	-	-	-	0.24	0.22
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.15		0.10		0.12		0.12		0.14		0.13	

Table 3.16 (d) Impact of Fault Parameters on Protection Coordination of Distribution System with three Sources and load increment by 1 MW

R_f = 12 Ω and L-G Fault (Grid + one Synchronous Generator (SG) and one Induction Generator (IG) (both with 1 MW capacity))												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	285	285	133	133	111	111	-	-	-	-	-	-
F1	664	240	149	149	208	208	0.21	0.22	-	-	-	-
F2	485	485	153	153	210	210	0.22	-	-	0.23	-	-
F3	417	417	299	172	240	240	-	-	0.22	0.23	-	-
F4	420	420	297	297	210	210	-	-	0.25	-	-	0.22
F5	401	401	270	270	187	290	-	-	-	-	0.25	0.22
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.13		0.10		0.105		0.11		0.125		0.10	

Table 3.17 (a) Impact of Fault Parameters on Protection Coordination of Distribution System with three Sources and load increment by 1 MW

R_f = 0 Ω and L-G Fault (Grid + one Synchronous Generator and one Solar PV (both with 1 MW capacity))												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	211	211	197	197	99	99	-	-	-	-	-	-
F1	1836	231	185	185	219	219	0.21	0.22	-	-	-	-
F2	913	913	228	228	257	257	0.22	-	-	0.22	-	-
F3	627	627	650	326	327	327	-	-	0.21	0.21	-	-
F4	503	503	517	517	480	480	-	-	0.22	-	-	0.23
F5	402	402	403	403	394	759	-	-	-	-	0.24	0.21
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.28		0.17		0.18		0.16		0.18		0.24	

Table 3.17 (b) Impact of Fault Parameters on Protection Coordination of Distribution System with three Sources and load increment by 1 MW

R_f = 4 Ω and L-G Fault (Grid + one Synchronous Generator and one Solar PV (both with 1 MW capacity))												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	211	211	197	197	99	99	-	-	-	-	-	-
F1	1098	193	171	171	209	209	0.21	0.22	-	-	-	-
F2	656	656	154	154	205	205	0.22	-	-	0.23	-	-
F3	479	479	502	173	241	241	-	-	0.21	0.22	-	-
F4	387	387	395	395	318	318	-	-	0.22	0.23	-	-
F5	318	318	318	318	225	476	-	-	-	-	0.22	0.21
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.26		0.15		0.14		0.15		0.15		0.20	

Table 3.17 (c) Impact of Fault Parameters on Protection Coordination of Distribution System with three Sources and load increment by 1 MW

R_f = 8 Ω and L-G Fault (Grid + one Synchronous Generator and one Solar PV (both with 1 MW capacity))												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	211	211	197	197	99	99	-	-	-	-	-	-
F1	786	201	166	166	205	205	0.21	0.22	-	-	-	-
F2	521	521	131	131	205	205	0.22	-	-	0.23	-	-
F3	399	399	419	201	255	255	-	-	0.22	0.23	-	-
F4	373	373	367	367	246	246	-	-	0.25	-	-	0.22
F5	316	316	320	320	240	354	-	-	-	-	0.24	0.22
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.22		0.12		0.13		0.14		0.14		0.14	

Table 3.17 (d) Impact of Fault Parameters on Protection Coordination of Distribution System with three Sources and load increment by 1 MW

R_f = 12 Ω and L-G Fault (Grid + one Synchronous Generator and one Solar PV (both with 1 MW capacity))												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	211	211	197	197	99	99	-	-	-	-	-	-
F1	622	168	171	171	208	208	0.22	0.23	-	-	-	-
F2	437	437	112	112	186	186	0.22	-	-	0.23	-	-
F3	349	349	368	177	237	237	-	-	0.22	0.23	-	-
F4	355	355	356	356	206	206	-	-	0.25	-	-	0.23
F5	322	322	322	322	219	286	-	-	-	-	0.25	0.22
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.20		0.08		0.12		0.13		0.13		0.12	

Table 3.18 (a) Impact of Fault Parameters on Protection Coordination of Distribution System with four Sources and load increment by 1 MW

R_f = 0 Ω and L-G Fault (Grid + one Synchronous Generator, one Induction Generator and one Solar PV (all with 1 MW capacity))												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	284	284	124	124	108	108	-	-	-	-	-	-
F1	1807	245	217	217	206	206	0.21	0.22	-	-	-	-
F2	884	884	242	242	224	224	0.23	-	-	0.23	-	-
F3	647	647	536	350	296	296	-	-	0.21	0.22	-	-
F4	537	537	409	409	449	449	-	-	0.21	-	-	0.22
F5	456	456	313	313	374	733	-	-	-	-	0.22	0.21
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.28		0.16		0.13		0.16		0.195		0.20	

Table 3.18 (b) Impact of Fault Parameters on Protection Coordination of Distribution System with four Sources and load increment by 1 MW

R_f = 4 Ω and L-G Fault (Grid + one Synchronous Generator, one Induction Generator and one Solar PV (all with 1 MW capacity))												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	284	284	124	124	108	108	-	-	-	-	-	-
F1	1102	238	183	183	177	177	0.21	0.22	-	-	-	-
F2	656	656	193	193	182	182	0.22	-	-	0.23	-	-
F3	514	514	393	209	209	209	-	-	0.21	0.22	-	-
F4	428	428	290	290	286	286	-	-	0.22	-	-	0.23
F5	379	379	229	229	208	447	-	-	-	-	0.22	0.22
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.24		0.16		0.12		0.145		0.16		0.17	

Table 3.18 (c) Impact of Fault Parameters on Protection Coordination of Distribution System with four Sources and load increment by 1 MW

R_f = 8 Ω and L-G Fault (Grid + one Synchronous Generator, one Induction Generator and one Solar PV (all with 1 MW capacity))												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	284	284	124	124	108	108	-	-	-	-	-	-
F1	803	237	177	177	177	177	0.21	0.22	-	-	-	-
F2	537	537	180	180	175	175	0.22	-	-	0.23	-	-
F3	443	443	317	215	205	205	-	-	0.22	0.23	-	-
F4	378	378	235	235	243	243	-	-	0.22	-	-	0.23
F5	374	374	226	226	221	322	-	-	-	-	0.24	0.22
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.18		0.16		0.10		0.135		0.15		0.14	

Table 3.18 (d) Impact of Fault Parameters on Protection Coordination of Distribution System with four Sources and load increment by 1 MW

R_f = 12 Ω and L-G Fault (Grid + one Synchronous Generator, one Induction Generator and one Solar PV (all with 1 MW capacity))												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	284	284	124	124	108	108	-	-	-	-	-	-
F1	642	236	159	159	160	160	0.21	0.22	-	-	-	-
F2	466	466	164	164	167	167	0.22	-	-	0.23	-	-
F3	399	399	269	189	194	194	-	-	0.22	0.23	-	-
F4	350	350	203	203	217	217	-	-	0.22	-	-	0.23
F5	365	365	218	218	198	253	-	-	-	-	0.24	0.22
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.16		0.14		0.09		0.13		0.12		0.12	

Table 3.19 (a) Impact of Fault Parameters on Protection Coordination of Distribution System with four Sources and load increment by 1 MW

$R_f = 0\ \Omega$ and L-G Fault (Grid + three Synchronous Generators (all with 1 MW capacity))												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	371	371	82	82	291	291	-	-	-	-	-	-
F1	1825	1127	221	221	322	322	0.21	0.24	-	-	-	-
F2	997	997	639	639	263	263	0.21	-	-	0.21	-	-
F3	479	479	1104	945	258	258	-	-	0.21	0.21	-	-
F4	431	431	749	749	508	508	-	-	0.21	-	-	0.22
F5	380	380	312	312	1118	758	-	-	-	-	0.24	0.21
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.32		0.14		0.28		0.22		0.16		0.32	

Table 3.19 (b) Impact of Fault Parameters on Protection Coordination of Distribution System with four Sources and load increment by 1 MW

$R_f = 4\ \Omega$ and L-G Fault (Grid + three Synchronous Generators (all with 1 MW capacity))												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	371	371	82	82	291	291	-	-	-	-	-	-
F1	768	774	175	175	318	318	0.21	0.24	-	-	-	-
F2	371	371	271	271	256	256	0.22	-	-	0.22	-	-
F3	371	371	697	522	254	254	-	-	0.22	-	-	0.21
F4	371	371	364	364	205	205	-	-	0.22	-	-	0.22
F5	379	379	204	204	755	412	-	-	-	-	0.21	0.22
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.30		0.12		0.24		0.20		0.16		0.26	

Table 3.19 (c) Impact of Fault Parameters on Protection Coordination of Distribution System with four Sources and load increment by 1 MW

R_f = 8 Ω and L-G Fault (Grid + three Synchronous Generators (all with 1 MW capacity))												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	371	371	82	82	291	291	-	-	-	-	-	-
F1	449	639	167	167	318	318	0.22	0.21	-	-	-	-
F2	371	371	171	171	254	254	0.24	-	-	0.22	-	-
F3	371	371	469	356	254	254	-	-	0.21	0.22	-	-
F4	371	371	266	266	205	205	-	-	0.22	-	-	0.23
F5	378	378	157	157	602	367	-	-	-	-	0.21	0.22
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.26		0.10		0.16		0.16		0.14		0.17	

Table 3.19 (d) Impact of Fault Parameters on Protection Coordination of Distribution System with four Sources and load increment by 1 MW

R_f = 12 Ω and L-G Fault (Grid + three Synchronous Generators (all with 1 MW capacity))												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	371	371	82	82	291	291	-	-	-	-	-	-
F1	371	567	165	165	318	318	0.22	0.21	-	-	-	-
F2	371	371	128	128	256	256	0.25	-	-	0.22	-	-
F3	371	371	365	430	254	254	-	-	0.21	0.21	-	-
F4	371	371	211	211	205	205	-	-	0.22	-	-	0.22
F5	378	378	133	133	520	312	-	-	-	-	0.24	0.22
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.22		0.08		0.12		0.12		0.10		0.12	

Table 3.20 (a) Impact of Fault Parameters on Protection Coordination of Distribution System with four Sources and load increment by 1 MW

$R_f = 0\ \Omega$ and L-G Fault (Grid + two Synchronous Generators (SG) and one Induction Generator (IG) (all with 1 MW capacity))												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	304	304	294	294	82	82	-	-	-	-	-	-
F1	1834	962	325	325	149	149	0.21	0.21	-	-	-	-
F2	993	993	241	241	308	308	0.21	-	-	0.22	-	-
F3	489	489	1154	269	330	330	-	-	0.24	0.22	-	-
F4	383	383	692	692	435	435	-	-	0.22	-	-	0.23
F5	363	363	532	532	468	723	-	-	-	-	0.21	0.21
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.30		0.17		0.20		0.22		0.15		0.20	

Table 3.20 (b) Impact of Fault Parameters on Protection Coordination of Distribution System with four Sources and load increment by 1 MW

$R_f = 4\ \Omega$ and L-G Fault (Grid + two Synchronous Generators (SG) and one Induction Generator (IG) (all with 1 MW capacity))												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	304	304	294	294	82	82	-	-	-	-	-	-
F1	837	655	320	320	107	107	0.21	0.22	-	-	-	-
F2	387	387	223	223	156	156	0.22	-	-	0.24	-	-
F3	365	365	779	223	251	251	-	-	0.21	0.22	-	-
F4	353	353	530	530	307	307	-	-	0.22	-	-	0.23
F5	317	317	439	439	296	399	-	-	-	-	0.22	0.22
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.28		0.16		0.16		0.22		0.15		0.17	

Table 3.20 (c) Impact of Fault Parameters on Protection Coordination of Distribution System with four Sources and load increment by 1 MW

R_f = 8 Ω and L-G Fault (Grid + two Synchronous Generators (SG) and one Induction Generator (IG) (all with 1 MW capacity))												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	304	304	294	294	82	82	-	-	-	-	-	-
F1	486	543	318	318	107	107	0.21	0.22	-	-	-	-
F2	303	303	223	223	157	157	0.22	-	-	0.24	-	-
F3	362	362	631	223	256	256	-	-	0.21	0.22	-	-
F4	354	354	456	456	280	280	-	-	0.22	-	-	0.23
F5	315	315	407	407	259	262	-	-	-	-	0.23	0.22
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.20		0.15		0.12		0.16		0.15		0.14	

Table 3.20 (d) Impact of Fault Parameters on Protection Coordination of Distribution System with four Sources and load increment by 1 MW

R_f = 12 Ω and L-G Fault (Grid + two Synchronous Generators (SG) and one Induction Generator (IG) (all with 1 MW capacity))												
Fault Location	Section wise Current (A)						Time of Operation (Sec)					
	I1	I2	I3	I4	I5	I6	R1	R2	R3	R4	R5	R6
No Fault	304	304	294	294	82	82	-	-	-	-	-	-
F1	322	484	317	317	107	107	0.21	0.22	-	-	-	-
F2	303	303	233	233	151	151	0.22	-	-	0.24	-	-
F3	363	363	545	223	246	246	-	-	0.24	0.22	-	-
F4	363	363	557	557	259	259	-	-	0.27	-	-	0.23
F5	309	309	393	393	229	188	-	-	-	-	0.24	0.22
Relay Current Setting (A)	IR1		IR2		IR3		IR4		IR5		IR6	
	0.14		0.15		0.10		0.132		0.15		0.12	

For analysis of impact on Protection Coordination of Distribution System with more than one sources, two types of Distribution Systems are considered viz. (i) Distribution System supplied through two Grids (as shown in Fig. 3.6) and (ii) Distribution System supplied through Grid and DGs (as shown in Fig. 3.7 to Fig. 3.9). Effect of fault parameters on protection coordination is presented in Table 3.11 to Table 3.20.

Various factors considered for analysis of impact on Protection Coordination are,

- Fault Locations: Fault Locations are considered at 10 km (F1), 20 km (F2), 30 km (F3), 40 km (F4) and 50 km (F5) from the first source of the right-hand side (as shown in Fig. 3.6 to Fig. 3.9).
- Fault Type: LG fault is considered to analyse the effect on protection coordination.
- Fault Resistance: 4 Ω and 12 Ω are considered for analysing the effect of fault resistance on protection coordination.
- Multiple sources: Analysis of the effect of integration of Distributed Generation (DG) sources in the Distribution System is performed with sources of either different (Synchronous Generator, Induction Generator and Solar PV) or the same type and capacity. As already mentioned before, fault current contribution is different for Induction Generator, Synchronous Generator and Solar PV ($I_{f,SG} > I_{f,IG} > I_{f,PV}$), which again affects protection coordination. The effect will be more when only Wind Power or Solar PV is used as Distributed Generation (DG) sources.

3.5 Effect of Change in Network Topology

Protection Coordination may also vary with different types of Distribution System Topologies. Protection coordination will be different for Radial Distribution System and Ring Main Distribution System. For a Radial Distribution System, 3 relays (in case of a system with one source) and 4-6 relays (in case of a system with more than one source and depending on the location of the source) are required for protection. For a Ring Main Distribution System, current / power flow is different in various branches and demands more relays & switchgear devices, which makes the process of protection coordination a little difficult. If a fault occurs in any one branch of the system, the Distribution System gets converted from Ring Main to Radial (as shown in Fig. 3.10), which again alters protection coordination of the system. Protection Coordination should be able to adapt to alterations in the system and system parameters, protecting the remaining part of healthy system.

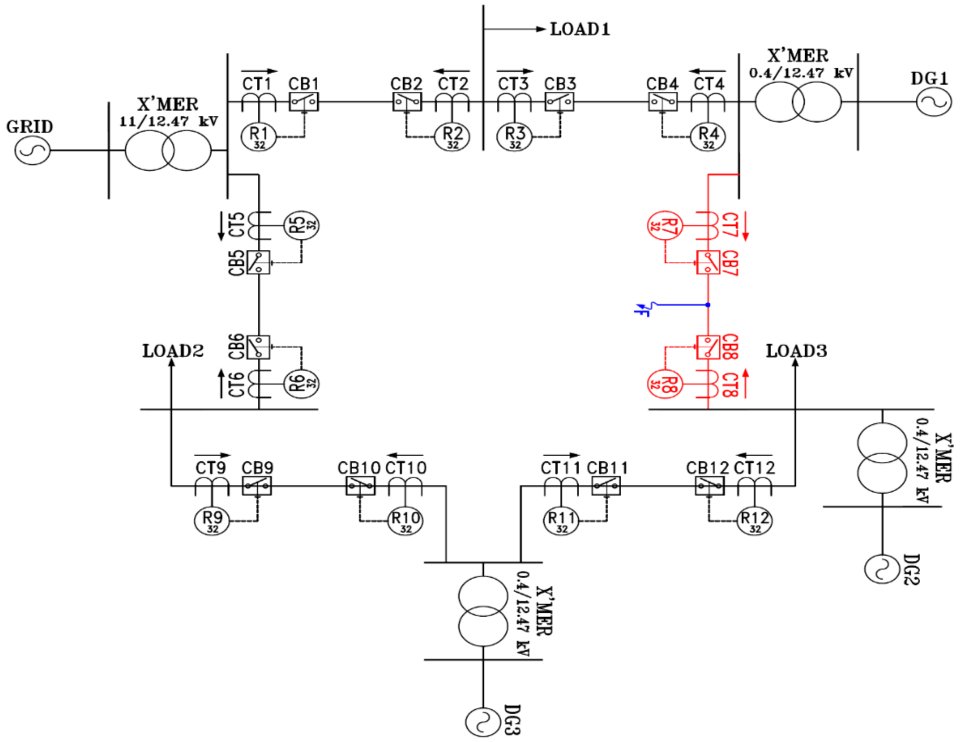


Figure 3.10 Modified IEEE 9-Bus Ring Main Distribution System

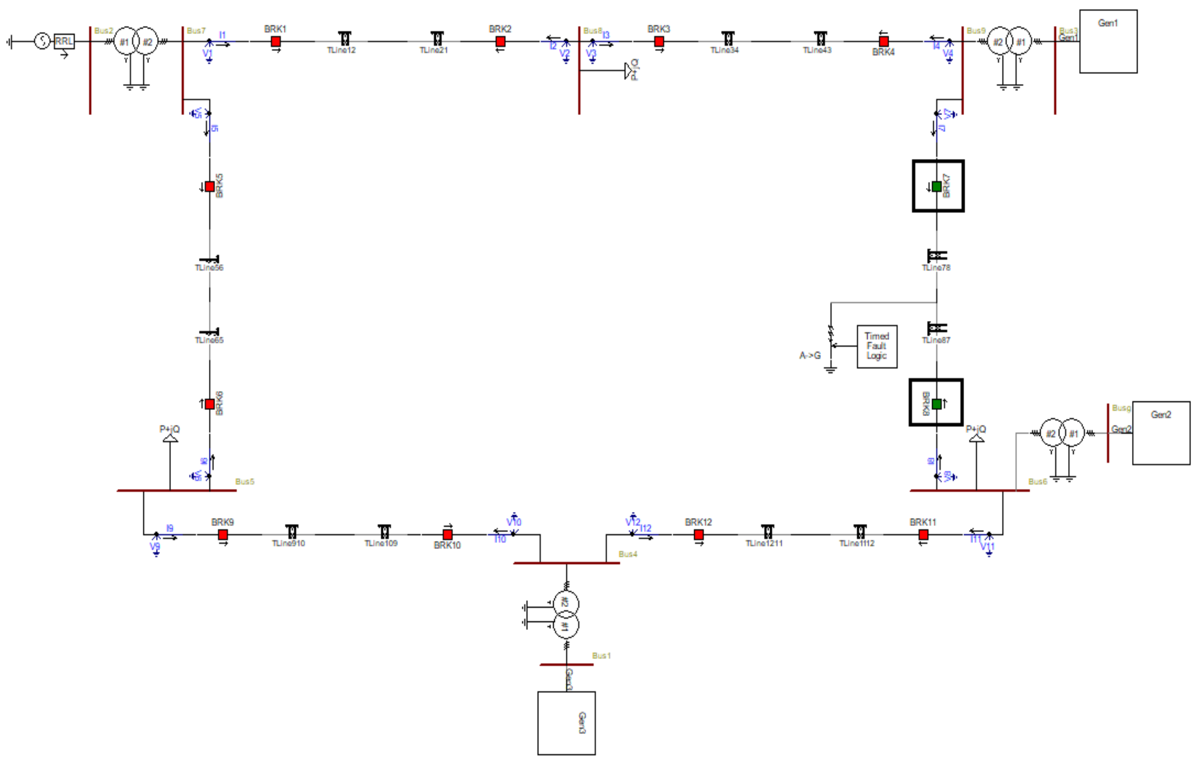


Figure 3.11 Modified IEEE 9-Bus Ring Main Distribution System (prepared in PSCAD/EMTDC)

Table 3.21 Cases for Modified IEEE 9-Bus Distribution System

Case No.	Type & Number of DG source connected				DG source Capacity	
	Grid	SG*	IG!	PV@	Same	Different
1	1	-	-	-	-	-
2	1	2	-	-	√	-
3	1	2	-	-	-	√
4	1	-	2	-	√	-
5	1	1	1	-	√	-
6	1	2	1	-	√	-
7#	1	2	1	-	√	-
8	1	1	1	1	√	-

Same Capacity = 1 MW

Different Capacity = 1 MW and 0.7 MW

* = Synchronous Generator

! = Induction Generator

@ = Solar Photovoltaic

= with change in DG location

Table 3.22 Relay settings for different cases of Effect of DG sources in Protection of Distribution System

Relay	Case-1	Case-2	Case-3	Case-4	Case-5	Case-6	Case-7	Case-8
Relay-1	0.2	0.19	0.18	0.06	0.18	0.19	0.19	0.18
Relay-2	0.16	0.28	0.26	0.2	0.26	0.26	0.26	0.26
Relay-3	0.26	0.26	0.24	0.09	0.24	0.24	0.24	0.24
Relay-4	0.24	0.175	0.16	0.07	0.16	0.17	0.17	0.16
Relay-5	0.28	0.22	0.22	0.16	0.18	0.18	0.17	0.18
Relay-6	0.14	0.14	0.14	0.16	0.14	0.12	0.12	0.14
Relay-7	0.28	0.185	0.17	0.06	0.1	0.09	0.18	0.09
Relay-8	0.2	0.2	0.2	0.08	0.18	0.19	0.17	0.19
Relay-9	0.13	0.16	0.16	0.12	0.15	0.16	0.16	0.15
Relay-10	0.2	0.2	0.2	0.05	0.14	0.19	0.155	0.14
Relay-11	0.13	0.13	0.13	0.09	0.12	0.12	0.12	0.12
Relay-12	0.2	0.18	0.18	0.05	0.11	0.105	0.14	0.105

For analysis of the effect of fault parameters on the Distribution System with Distributed Generation Sources, a modified IEEE 9-Bus Ring Main Distribution System is prepared in PSCAD/EMTDC (Fig. 3.11). System voltage is 12.47 kV, and load demand in the system is 7 MW. Various cases (as shown in Table 3.21) are considered for analysis of the effect of fault parameters on protection coordination, and the result (in terms of relay current setting) is presented in Table 3.22.

3.6 Analysis and Discussion

Protection Coordination is the most important task for the distribution system for ensuring sensitive, reliable and fast isolation of faults. Because of unidirectional power flow, conventional Radial Distribution Systems were generally protected through overcurrent relays (51/50), fuses or reclosers that are coordinated via time-current characteristics, pickup current settings, time multiplier settings and coordinated time intervals. Integration of Distributed Generation sources causes bidirectional power flow in the system along with an increment in fault current that alters protection coordination of the conventional system and may even lead to protection blinding, false tripping & loss of coordination. This section represents a detailed analytical discussion of various variables that influence protection coordination of a distribution system integrated with distributed generation sources. In the absence of Distributed Generation sources (DGs), only Utility Grid will supply Fault, but when DGs are present, both the Utility Grid and DGs will supply Fault. In the second case, fault current contribution from Utility Grid will reduce, leading to protection blinding.

Table 3.23. Cases for Analysis of impact on Protection Coordination (System with One Source)

Case No.	Description
1	Radial System without transformer (fed at one end (grid only)) (I_{Grid})
2	Radial System with transformer (fed at one end (grid only)) (I_{GridT})
3	Radial System without transformer (fed at one end (synchronous generator only)) (I_{SG})
4	Radial System without transformer (fed at one end (induction generator only)) (I_{IG})

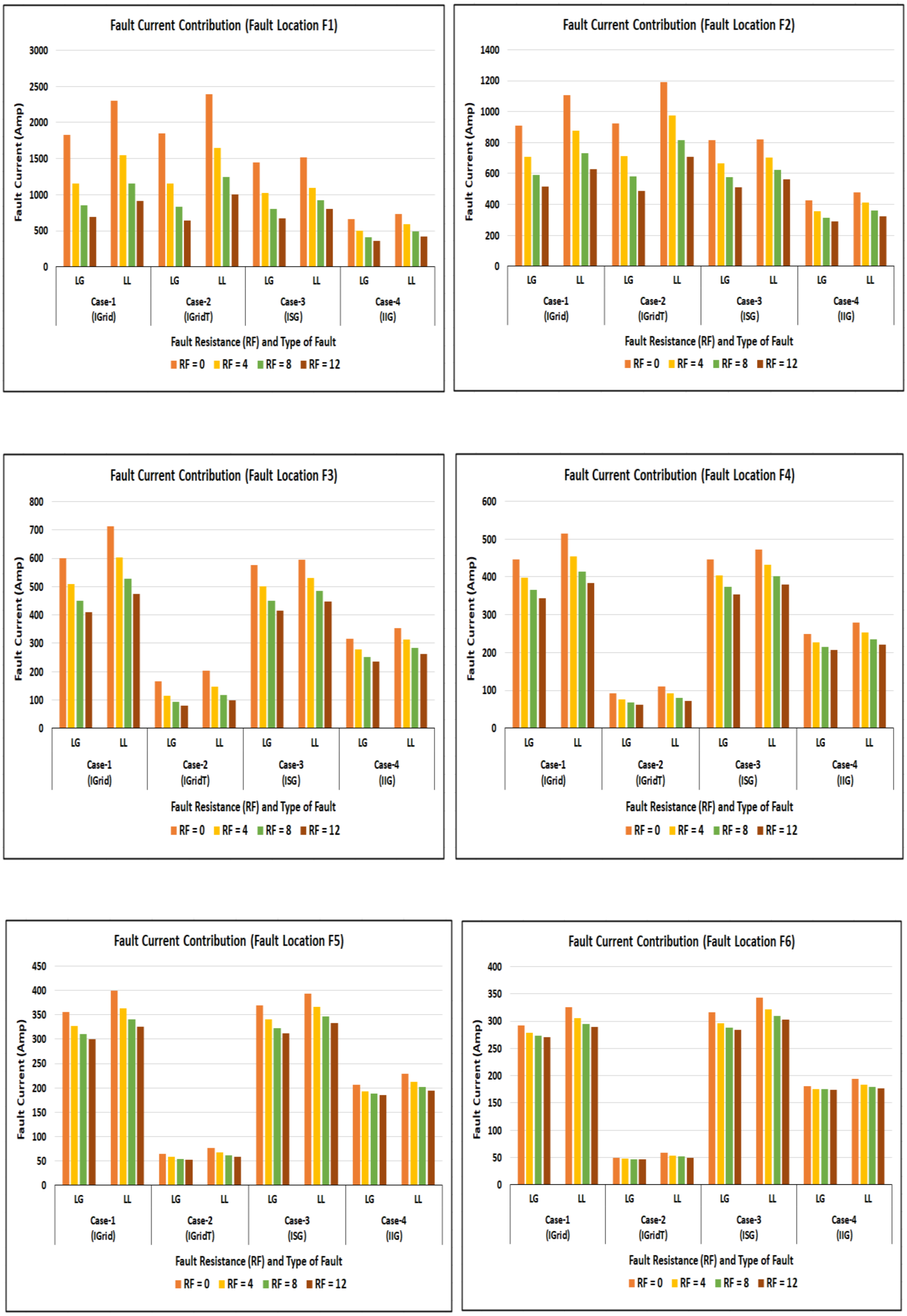


Figure 3.12 Fault Current Contribution from Various types of Sources (System with One Source)

For a system with one source, fault current contribution from various types of sources (considering cases presented in Table 3.23) is presented in Fig. 3.12, and for a system with more than one source, fault current contribution from various types of sources (considering cases presented in Table 3.24) is presented in Table 3.25. It is observed that the fault current contribution from Synchronous Generator is higher than that from Induction Generator, and Solar PV contributes the least fault current, which also affects the protection coordination of the distribution system because normal current as well as fault current will be different with various combinations of sources as Distributed Generation (DG) sources.

Table 3.24. Cases for Analysis of impact on Relay Coordination (System with more than One Source)

Case No.	Grid connection point/s	Type and Number of DG Sources			Load Increment
		SG	IG	PV	
1	2	-	-	-	-
2	2	-	-	-	1 MW
3	1	1 (1 MW)	-	-	-
4	1	2 (1 MW)	-	-	1 MW
5	1	2 (1 MW and 0.7 MW)	-	-	1 MW
6	1	1 (1 MW)	1 (1 MW)	-	1 MW
7	1	1 (1 MW)	-	1 (1 MW)	1 MW
8	1	1 (1 MW)	1 (1 MW)	1 (1 MW)	1 MW
9	1	3 (1 MW)	-	-	1 MW
10	1	2 (1 MW)	1 (1 MW)	-	1 MW

To investigate the effect on protection coordination of Distribution System (DS) with Distributed Generation (DG) sources, Overcurrent Relays (OCR) (for systems with one source) and Negative Sequence Directional Element Relays (for systems with more than one source) are used for distribution system protection. Fault current is increased by 10-20%, and current contribution from the grid is reduced by 10-15% when Distributed Generation sources are integrated in the Distribution System. These analytical results are variable, subject to the types, capacity & combination of sources and fault parameters like fault location, fault resistance and fault type. This demands alteration in relay settings (presented as a summary of relay settings for all the cases for a system with one source and a system with more than one source in Table 3.26 and Table 3.27, respectively).

Table 3.25. Fault Current Contribution from Various Types of Sources (System with more than One Source) (considering Fault Location F3)

Current Contribution from Different Sources (A)	Case-1	Case-2	Case-3	Case-4	Case-5	Case-6	Case-7	Case-8	Case-9	Case-10
IGrid1	616	643	625	468	501	657	627	646	478	462
IGrid2	1517	1563	-	-	-	-	-	-	-	-
ISG1	-	-	993	976	981	963	980	943	888	939
ISG2	-	-	-	918	667	-	-	-	908	878
ISG3	-	-	-	-	-	207	-	-	979	-
IIG	-	-	-	-	-	-	-	207	-	178
IPV	-	-	-	-	-	-	151	149	-	-

Table 3.26. Relay Current Settings (Ip) for Different Cases (System with One Source)

Fault Resistance	**Relay**	**Relay Current Settings (Ip) (A)**			
		Case - 1	**Case - 2**	**Case - 3**	**Case - 4**
RF = 0 Ω	**R1**	0.25	0.06	0.22	0.17
	R2	0.2	0.11	0.2	0.11
	R3	0.15	0.07	0.17	0.09
RF = 4 Ω	**R1**	0.24	0.05	0.21	0.14
	R2	0.19	0.08	0.19	0.09
	R3	0.15	0.06	0.16	0.08
RF = 8 Ω	**R1**	0.185	0.04	0.17	0.13
	R2	0.18	0.07	0.17	0.09
	R3	0.15	0.06	0.15	0.08
RF = 12 Ω	**R1**	0.16	0.03	0.15	0.12
	R2	0.16	0.07	0.15	0.085
	R3	0.14	0.06	0.14	0.08

Table 3.27. Relay Current Settings (Ip) for Different Cases (System with more than One Source)

Fault Resistance	**Relay**	**Relay Current Settings (Ip) (A)**									
		Case-1	**Case-2**	**Case-3**	**Case-4**	**Case-5**	**Case-6**	**Case-7**	**Case-8**	**Case-9**	**Case-10**
RF = 0	**R1**	0.45	0.40	0.42	0.38	0.40	0.28	0.28	0.28	0.32	0.30
	R2	0.07	0.12	0.12	0.08	0.40	0.12	0.17	0.16	0.14	0.17
	R3	0.20	0.22	0.19	0.26	0.24	0.18	0.18	0.13	0.28	0.20
	R4	0.22	0.22	0.16	0.20	0.16	0.14	0.16	0.16	0.22	0.22
	R5	0.09	0.21	0.18	0.13	0.20	0.16	0.18	0.19	0.16	0.15
	R6	0.45	0.45	0.26	0.26	0.26	0.22	0.24	0.20	0.32	0.20
RF = 4	**R1**	0.42	0.38	0.36	0.34	0.38	0.24	0.26	0.24	0.30	0.28
	R2	0.05	0.11	0.12	0.07	0.30	0.11	0.15	0.16	0.12	0.16
	R3	0.19	0.19	0.18	0.22	0.20	0.14	0.14	0.12	0.24	0.16
	R4	0.20	0.22	0.16	0.16	0.14	0.14	0.15	0.14	0.20	0.22
	R5	0.08	0.19	0.16	0.13	0.18	0.16	0.15	0.16	0.16	0.15
	R6	0.41	0.35	0.23	0.20	0.22	0.18	0.20	0.17	0.26	0.17
RF = 8	**R1**	0.35	0.30	0.30	0.28	0.32	0.15	0.22	0.18	0.26	0.20
	R2	0.01	0.10	0.08	0.06	0.26	0.10	0.12	0.16	0.10	0.15
	R3	0.16	0.16	0.17	0.20	0.16	0.12	0.13	0.10	0.16	0.12
	R4	0.14	0.15	0.15	0.12	0.12	0.12	0.14	0.13	0.16	0.16
	R5	0.08	0.18	0.14	0.12	0.16	0.14	0.14	0.15	0.14	0.15
	R6	0.32	0.28	0.18	0.16	0.18	0.13	0.14	0.14	0.17	0.14
RF = 12	**R1**	0.30	0.25	0.24	0.18	0.20	0.13	0.20	0.16	0.22	0.14
	R2	0.01	0.10	0.04	0.05	0.24	0.10	0.08	0.14	0.08	0.15
	R3	0.16	0.14	0.16	0.15	0.13	0.10	0.12	0.09	0.12	0.10
	R4	0.12	0.13	0.13	0.09	0.10	0.11	0.13	0.13	0.12	0.13
	R5	0.08	0.15	0.12	0.10	0.14	0.12	0.13	0.12	0.10	0.15
	R6	0.22	0.22	0.16	0.15	0.16	0.10	0.12	0.12	0.12	0.12

With the addition of a transformer in the Distribution System, there is a large variation in currents of all the feeder sections, which leads to alteration in relay current settings (as shown in Table 3.26). When more than two sources are used, it is noticed that protection coordination is more affected if Solar PV and Induction Generator are used as DGs because of the dynamic nature of power generation and lesser Fault Current Contribution (FCC) compared to a synchronous generator. When three dissimilar DGs are integrated along with the Grid in Distribution System (as presented in Fig. 3.9 and considering Case-8 from Table 3.24), fault current contribution from Synchronous Generator ($I_{f,SG}$), Induction Generator ($I_{f,IG}$) and Solar PV ($I_{f,PV}$) is 48%, 11% and 8% respectively. Again, these results are subject to variation because of types, capacity & combination of sources and fault parameters like fault location, fault resistance and fault type. Location of DGs in the Distribution System also plays a vital role in modification of protection coordination.

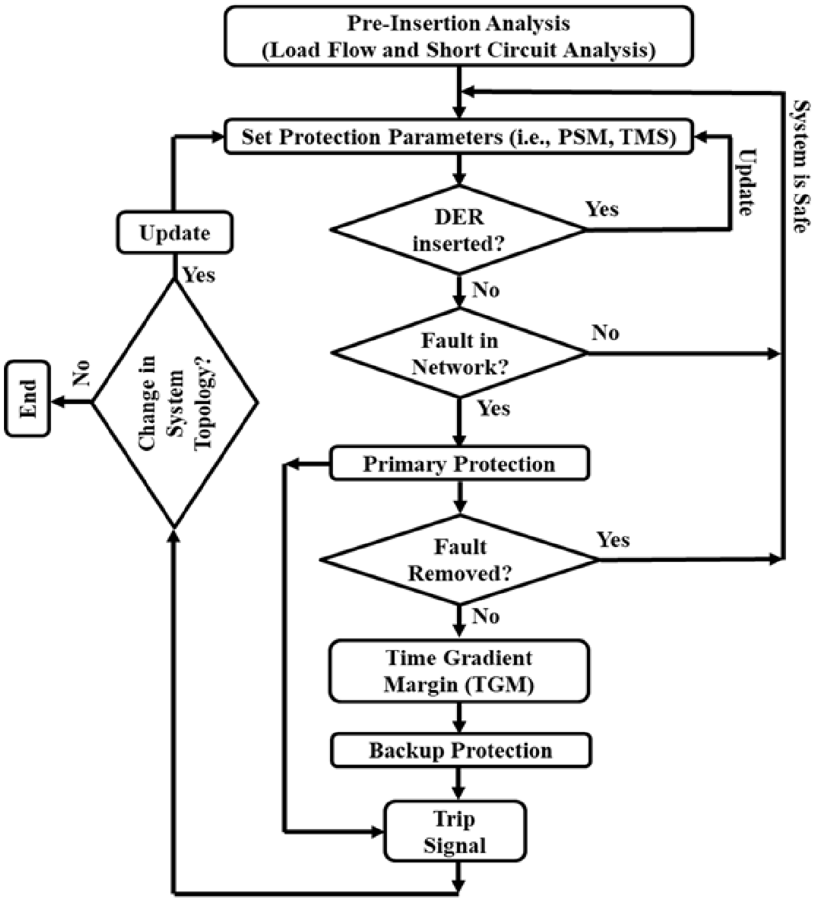


Figure 3.13 Generalised Protection Algorithm for Protection of Distribution System

Ring Main Distribution System presents better system reliability compared to Radial Distribution System. But this advantage is offset by increase in the number of required relays for protection and difficulty in relay settings, where improper relay settings/coordination led to nuisance tripping when DG penetration is higher. Apart from this, network topology transition (from ring main to radial) is also one of the major issues. In a Ring Main system, when a fault occurs in one of the sections (highlighted in red in Fig. 3.10), respective feeder section relays will sense it, send a trip command to the circuit breakers, and isolate that faulty section, which converts the Ring Main System into Radial. Because of this transition, there will be a big change in system parameters, and relays should be adaptive enough to accept changes in the system. It is observed that DG penetration can cause redistribution, changes in the direction of power flow, and changes in fault current as well, necessitating development of reliable and adaptive protection to address these issues related to integration of Distributed Generation (DG) sources in Distribution System (DS). A generalised protection algorithm for protection of the distribution system is presented in Fig. 3.13.

CHAPTER - 4

Overcurrent Protection Scheme for Industrial Distribution System

4.1 Overcurrent Protection

In a distribution system, overcurrent protection is the most common scheme of protection for feeders as well as equipments. Overcurrent protection can be used as primary protection as well as backup protection. Overcurrent relays operate when current sensed by the relay exceeds its pickup or preset value. Overcurrent relays can either be directional or non-directional. A combination of overcurrent relays for protection coordination, in general, can be considered of three types in distribution system, i.e., only directional, only non-directional or a combination of directional and non-directional, selection of which depends on technical requirements as well as in which type of distribution system it is implemented. Inclusion of Distributed Generation has a huge impact on the protection scheme for distribution system.

DG sources will increase the system fault current, as along with the grid, DG sources will also contribute to the system fault current (I_f). Most of the overcurrent relays in use have inverse time characteristics, so with an increase in fault current, fault clearing time will decrease. When the Microgrid (MG) is operating in grid-connected mode, the fault current contribution from Distributed Generators (DG) is relatively lower as the utility grid provides a significant portion of the fault current. Therefore, current detected by the DG-side relay is lower, resulting in a longer relay operating time. However, when the microgrid operates in Islanded mode, the utility grid is entirely lost, and fault current contribution is solely dependent on DG sources, which causes a significant change in fault current contribution. As fault current contribution from DGs increases comparatively, DG side relay operating time decreases due to higher current detected by the relay. Additionally, direction and magnitude of fault current in the distribution system may change depending on the location of the fault, operating conditions, and type of DG units, which can affect protection coordination of the Distribution System. So, the protection system must be designed in such a way that it will sense the operating mode of microgrid and give reliable protection in both operating modes. For all types of Overcurrent relays, one common point is that they will operate once the relay current exceeds its pickup value. The difference lies in the time of operation. Overcurrent relays, classified based on different characteristics, are Definite Time Overcurrent Relay, Instantaneous Overcurrent Relay and Inverse Time Overcurrent Relay.

4.1.1 Instantaneous Overcurrent Relay

A relay that operates immediately once current exceeds the pickup value is known as an Instantaneous Overcurrent Relay (IOCR). No relay can operate in zero time (instantaneously). There is a definite time (not intentional time delay) in which this type of relay will operate, which is independent of current value.

4.1.2 Definite Time Overcurrent Relay

A relay that operates once current exceeds the pickup value, and after a predefined time delay, is known as a Definite Time Overcurrent Relay. In this relay also, the Operating Time (Top) is independent of current value. A time-delay mechanism is provided for the desired and definite time of operation.

4.1.3 Inverse Time Overcurrent Relay

A relay that operates when current exceeds its pickup current value but its Operating Time (Top) depends on the amplitude of fault current, i.e., Top $\propto$ ($1/I_{fault}$), is known as an inverse time overcurrent relay. The Time of Operation of the relay will decrease with an increase in fault current. Types of Inverse Time Overcurrent Relays are (a) Standard Inverse Time Overcurrent Relay, (b) Inverse Definite Minimum Time (IDMT) Overcurrent Relay, (iii) Very Inverse Time Overcurrent Relay and (iv) Extremely Inverse Time Overcurrent Relay.

Standard Inverse Time Overcurrent Relay:

This relay will operate after current exceeds the preset value, and Operating Time (Top) of the relay is inversely proportional to the actuating quantity (current amplitude). Relay will never operate if current value is less than the pickup value. There is a steady decrement in the time of operation of this relay at a higher value of current seen by the relay. Inverse Time Overcurrent Relay possesses more inverse characteristics near the pickup value. For an inverse time overcurrent relay, more severe fault is cleared quickly. Electromechanical relays were used with a particular inverse time characteristic, but with the development of numerical relays, it is possible to set any type of inverse time characteristics in a relay.

Inverse Definite Minimum Time (IDMT) Overcurrent Relay:

For lower values of current, this relay follows inverse time characteristics, and for higher values of fault current, it follows definite time characteristics. This type of relay will follow inverse time characteristics if the value of Plug Setting Multiplier (PSM) is less than 10, and when the value of Plug Setting Multiplier (PSM) is more than 10, the time of operation of the relay is approximately constant (characteristics becoming almost straight line). So, it follows definite time characteristics if the value of PSM is more than 10. This type of relay is mainly used for the protection of distribution feeders.

Very Inverse Time Overcurrent Relay:

The Time Current Characteristics (TCC) of a Very Inverse Time Overcurrent Relay lie between the characteristics of IDMT and Extremely Inverse Time Overcurrent Relay. It gives more inverse characteristic than standard inverse and IDMT relays. If good reliability and selectivity are not achieved with an IDMT relay, a very inverse time overcurrent relay is preferred. This type of relay is suggested where there is considerable reduction in fault current, as moving away from the source end and is preferred for protection against ground fault.

Extremely Inverse Overcurrent Relay:

The main difference between all the types of inverse time overcurrent relay is reduction in time of operation with the same magnitude of fault current. Compared to IDMT and Very Inverse Time Overcurrent relay, Extremely Inverse Time Overcurrent relay gives more inverse characteristics, meaning that for the same magnitude of fault current, the time of operation for this relay is minimum. If better selectivity is not achieved with IDMT and Very Inverse Time Overcurrent relay, Extremely Inverse Time Overcurrent relay is suitable. Generally, for protection of large machines against overheating, an extremely inverse time overcurrent relay is preferred, as the law by which heating characteristics of electrical machines are observed is similar to that by which the extremely inverse time overcurrent relay is governed. Extremely inverse time overcurrent relay is used for the protection of large electrical power apparatus like generators, power transformers, reactors, HV & EHV cables, etc. This type of relay should operate for short-circuit current that persists in the system for a longer duration, and not for the temporary overload condition in the system which lasts for a few milliseconds. For a power transformer where a differential relay is used as primary protection, this type of overcurrent relay is used as backup protection.

Radial Feeder System

A Radial system is a basic system that has been used for years for the distribution of power among customers. A Radial system is divided into more than one section for supplying power to the consumers and is provided with more than two overcurrent relays, whether directional or non-directional, to protect the system. For a radial system, two types of protection schemes are used, i.e., time-graded scheme and current-graded scheme.

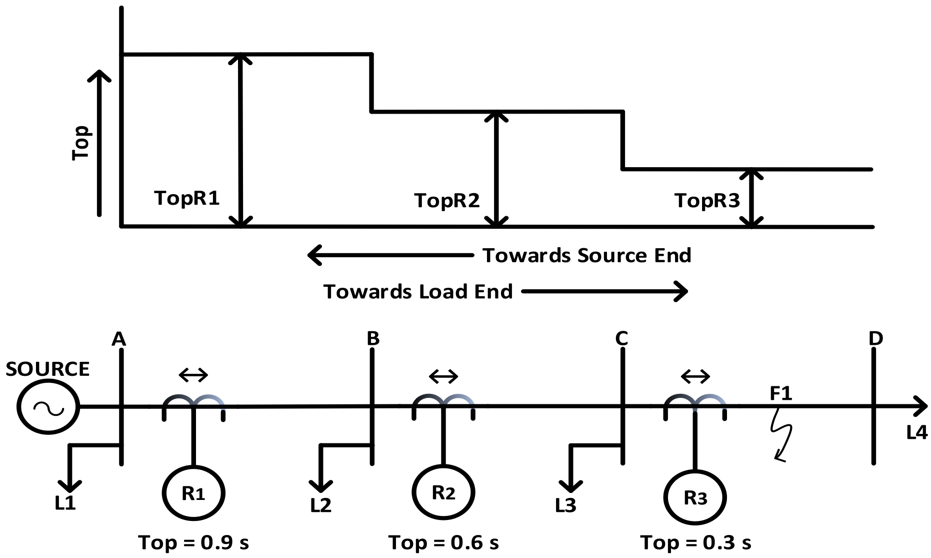


Figure 4.1 Time Graded Overcurrent Protection Scheme

Table 4.1 Coordination Time Interval (CTI) for Relays

Type of Relay	CTI*!
Induction Disc Overcurrent Relays (Including Disc Overtravel Component)	0.3 s to 0.4 s
Static Overcurrent Relays (Excluding Disc Overtravel Component)	0.2 s to 0.3 s
Numerical Overcurrent Relay (Excluding Disc Overtravel Component)	0.2 s to 0.3 s

* Field Calibration further reduces Coordination Time Interval (CTI) by 0.05 s

! CTI is summation of circuit breaker opening time, relay overtravel, relay tolerance & setting errors

For any distribution system, it is common that in case of a fault, the primary relay will operate first, and if the primary relay is not able to protect the system, the backup relay will protect the system. In Time Graded Scheme (TGS) as shown in Fig. 4.1, definite time relays are used. Each relay will operate after a predefined time delay when the current exceeds the pickup value and sends a trip command to the respective breaker of feeder section. The operating time of relays is increased in a progressive fashion when moving towards the source. Coordination Time Interval (CTI) between operation of primary & backup relays is considered as represented in Table 4.1.

When a fault occurs at location F1, all the relays in the radial feeder will sense the fault. Relay R3 operates first as primary, as it has the least time of operation of 0.3 sec. If relay R3 or the respective breaker fails to isolate the fault for any reason, relay R2 will operate as backup. Relay R2 also operates after 0.3 sec, but keeping CTI between relays R3 and R2 as 0.3 sec, it will operate after 0.6 sec. If Relay R2 fails to operate or isolate the fault, R1 will operate after 0.9 sec. Main drawback of this scheme is that near the source, where the fault current (I_f) magnitude is highest, the time of operation of the relay is more, which should actually be less. Operating time (Top) of this relay is not dependent on the magnitude of current, so even though the magnitude of current is high, it still takes a longer time to operate, which may cause huge damage to the system. In the Current Graded Scheme (CGS) as shown in Fig. 4.2, instantaneous type overcurrent relays are used, which are set based on the pickup value of current.

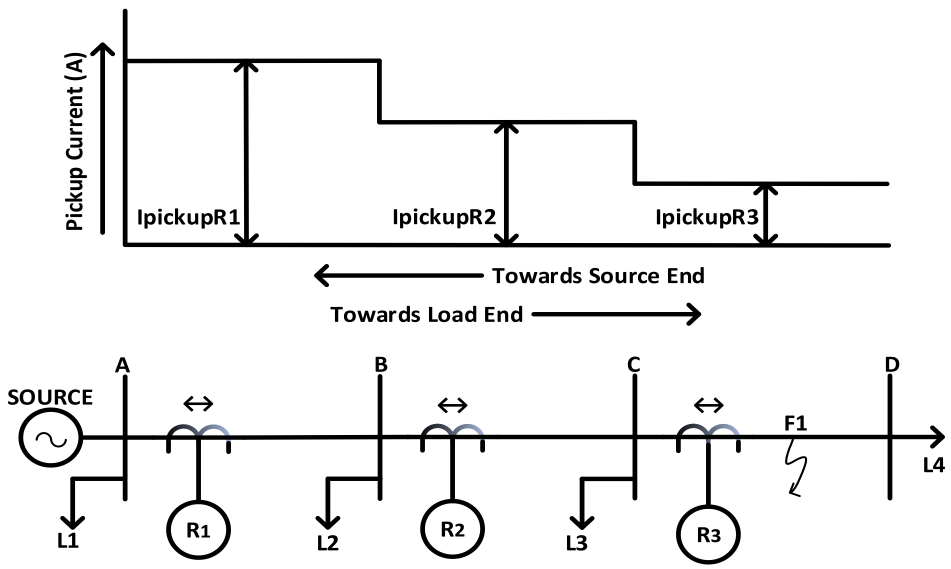


Figure 4.2 Current Graded Overcurrent Protection Scheme

Higher pickup current is selected when moving towards the source from the load end, but the operating time of all the relays is kept the same. These relays are only concerned with the fault current of their respective sections. One of the main disadvantages of this protection scheme is that backup protection cannot be achieved. Also, relay R2 may not be able to recognise whether the fault occurs in its section or in the subsequent section if it occurs nearer to Bus C but in CD section. For appropriate discrimination, relays are set to protect only 80% of the line section, which will not protect the entire feeder section. As a solution against issues that occur with time-graded and current-graded schemes, Inverse Definite Minimum Time overcurrent relays, which have combined characteristics of current and time grading are used.

4.2 Proposed Protection Scheme and Simulation Setup

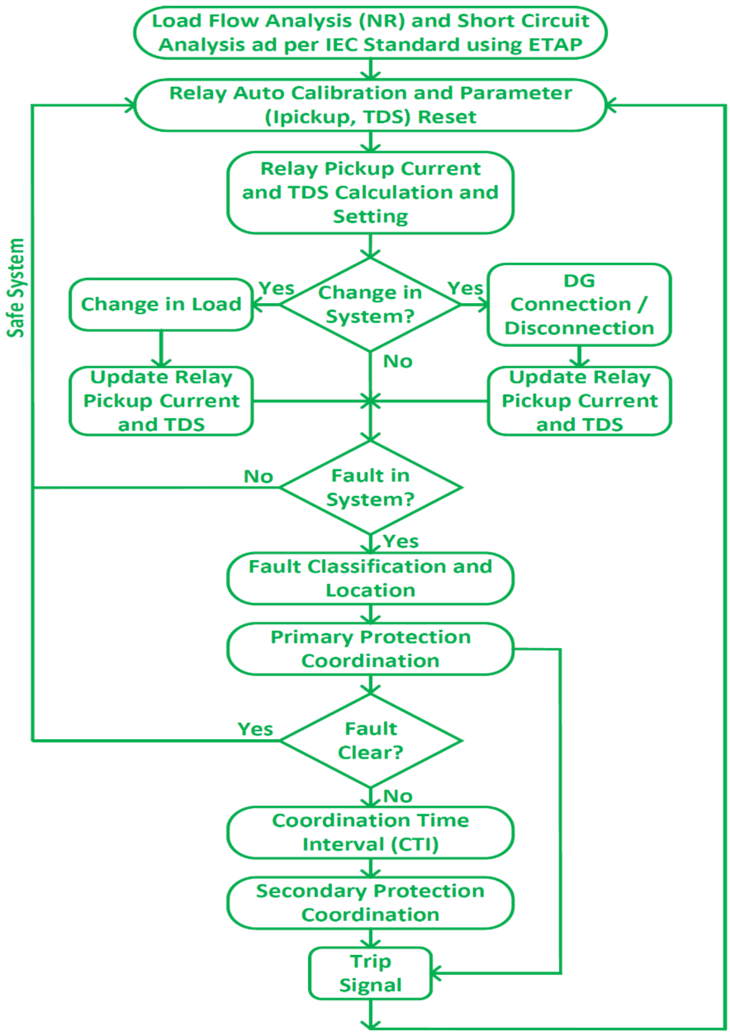


Figure 4.3 Proposed Overcurrent Protection Algorithm

Integration of various types of Distributed Generation (DG) sources into Conventional Distribution Systems has transformed the system into a Modern Active System with bidirectional power flow. While Distributed Generation (DGs) sources are improving reliability, reducing power losses and supporting renewable energy goals, they also introduce significant protection coordination challenges that traditional overcurrent relays cannot handle effectively. Adaptive protection emerges as a key solution, dynamically adjusting relay settings to maintain sensitivity, speed and coordination in dynamically variable system conditions. Adaptivity is an activity that reacts to alterations in the system and its requirements with altered protection and necessary control actions [182].

When fault current (I_f) changes during a change in system topology or condition, adaptive protection will update required settings of overcurrent protection. For this protection scheme, programming can be prepared for the Overcurrent Relay (OCR) for simulation of automatic Relay Setting Group (RSG). Switchgear devices in Microgrid (MG) are controlled by auto selection of operating mode, adequate protection and control logic restoration. Various faults are simulated at different system locations for calculation of fault current, relay operating time and identification of relay pairs for system protection. The protection relay collects real-time data from the Distribution System to perform the task and gathers locally measured data, such as 3-ϕ line currents from Current Transformers (CT) with details such as Circuit Breaker (CB) status and fault directions for other relays. The proposed protection scheme for the Industrial Distribution System is shown in Fig. 4.3.

ETAP Software is used for Pre-Installation Analysis (PIA) like Load Flow Analysis (LFA) using Newton-Raphson (NR) method and Short Circuit Analysis (SCA) following IEC standards for calculation and setting of required relay parameters like Pickup Current (Ipickup considering safety margin) and Time Multiplier Setting (TMS) for coordination of primary and secondary protection considering fault locations and system operating modes. The protection relay will first perform re-calibration automatically and reset relay parameters. If any change in system configuration or topology is observed, data will be sent to the relay, which modifies its parameters (i.e., Pickup Current (Ipickup) and Time Multiplier Setting (TMS)). It then detects whether a fault is present in the system or not. Equation 3.8 is followed with IEC standard for an overcurrent relay. Primary protection will be actuated when fault current (If) on the secondary side of the CT is higher than the pickup current, and a trip signal will be sent to respective circuit breaker to isolate the faulty section.

When primary protection fails to operate or if the fault is still present, secondary protection will be actuated. To maintain selectivity of protection coordination, Primary and Backup (or Secondary) protections are coordinated with enough time delay for the backup relay to operate, known as Time Gradient Margin (TGM) or Coordinated Time Interval (CTI), as shown in Table 4.1. After fault clearance, the relay resets itself back to the original position. Coding for the algorithm (shown in Fig. 4.3) can be implemented in Fuzzy Logic Controller for real-time use. Protection coordination will behave adaptively with real-time calculated settings using Fuzzy Logic Designer (FLD) application, which requires a system model for Load Flow (LF) calculation along with measurement integration for online data collection.

4.2.1 Simulation Setup for Industrial Distribution System

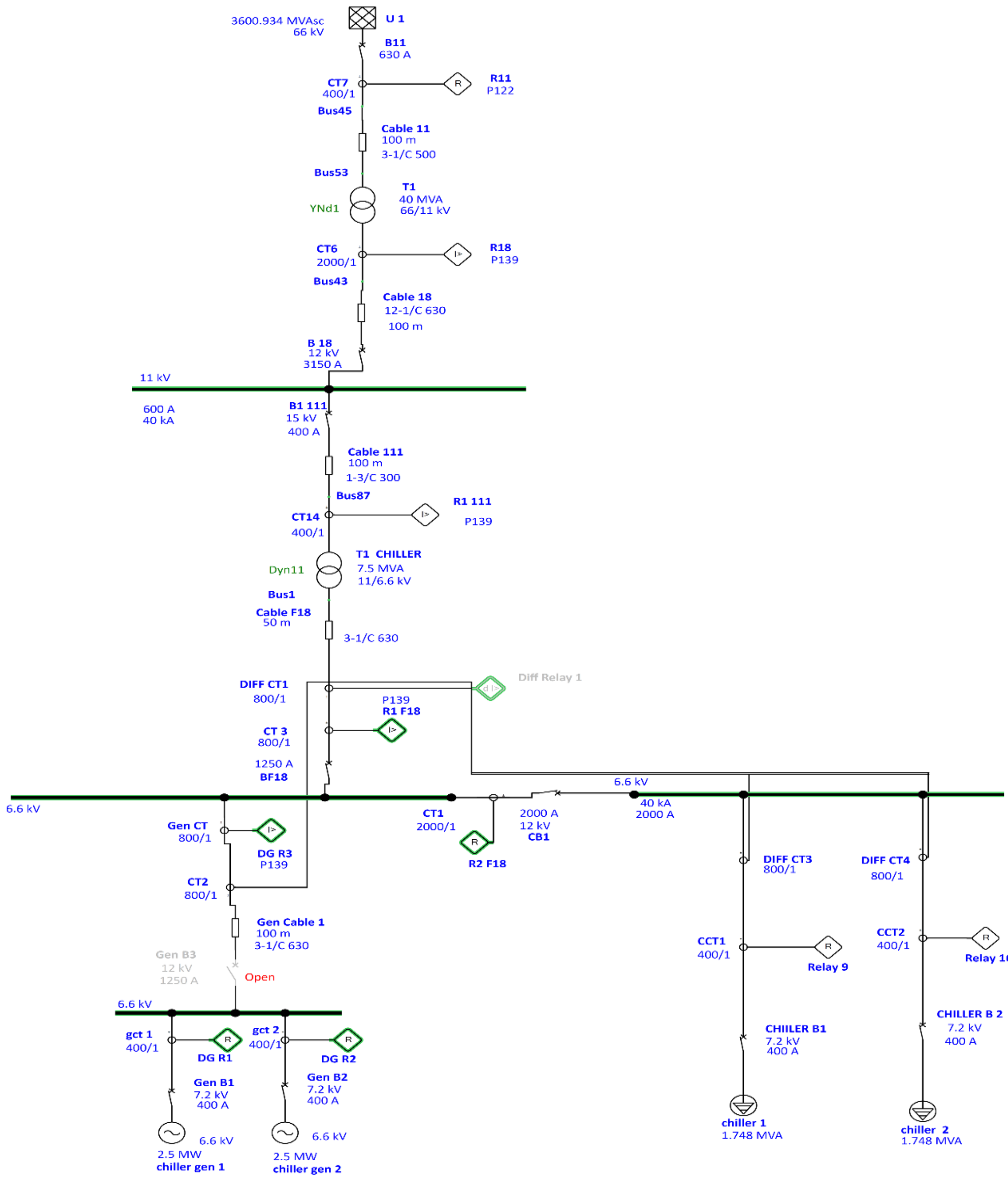


Figure 4.4 Industrial Distribution System (9-Bus)

An Industrial Distribution System is considered for performing protection coordination with the proposed scheme. Electrical Transient Analyser Program (ETAP) software is used for preparing the System Single Line Diagram (SLD), simulation of Load Flow Analysis (LFA), Short Circuit Analysis (SCA) and Protection Coordination studies. Verification of relays and switchgear devices and finalisation of the Master Single Line Diagram (SLD) is done before doing data entry in ETAP software. Detailed analysis is performed on 9-Bus Industrial Distribution System (part of the Industrial Network), as shown in Fig. 4.4, to obtain protection coordination values for this system.

Load Flow Analysis (LFA) for 9-Bus Industrial Distribution System:

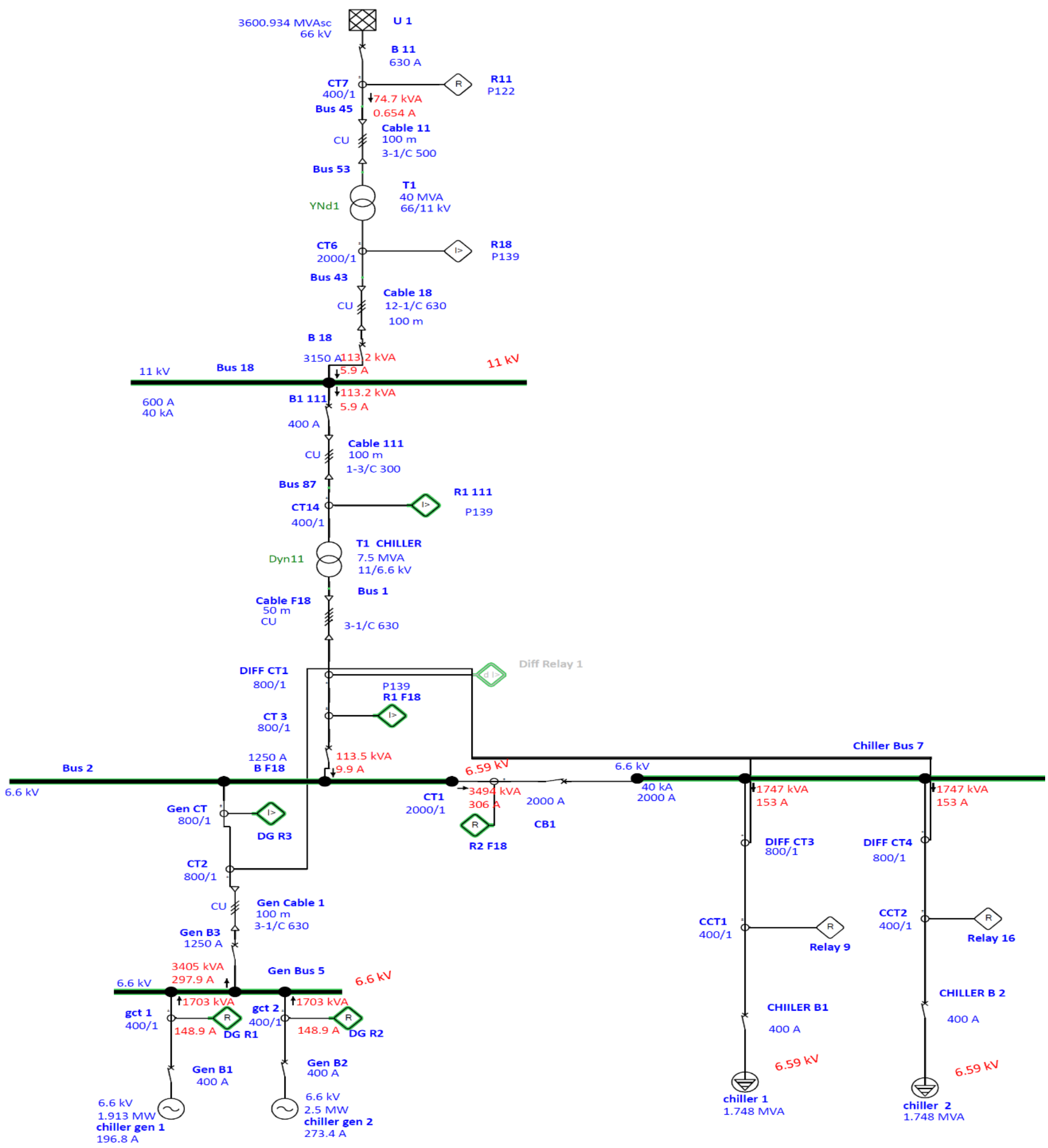


Figure 4.5 Load Flow Analysis for Industrial Distribution System (9-Bus) for RSG#3

Table 4.2. Type of Relay Setting Groups (RSG)

RSG No.	Relay Setting Group (RSG) Configurations
1	PG* only
2	PG + 1 DG**
3	PG + 2 DG
4	Island + 1 DG
5	Island + 2 DG
* PG = Power Grid ** DG = Distributed Generation	

Table 4.3. Load Flow Analysis Summary for RSG#1, 2 and 3

Description	MW	MVar	MVA	PF
Source (Swing Bus)	2.952	1.929	3.526	0.83 Lag
Total Demand	2.952	1.929	3.526	0.83 Lag
Total Motor Load	2.377	1.473	2.796	0.85 Lag
Total Static Load	0.564	0.350	0.664	0.85 Lag

Table 4.4. Load Flow Analysis Summary for RSG#4

Description	MW	MVar	MVA	PF
Source (Swing Bus)	1.486	0.876	1.725	0.86 Lag
Total Demand	1.486	0.876	1.725	0.86 Lag
Total Motor Load	1.188	0.737	1.398	0.85 Lag
Total Static Load	0.297	0.184	0.349	0.85 Lag

Table 4.5. Load Flow Analysis Summary for RSG#5

Description	MW	MVar	MVA	PF
Source (Swing Bus)	2.973	1.799	3.475	0.85 Lag
Total Demand	2.973	1.799	3.475	0.85 Lag
Total Motor Load	2.377	1.473	2.796	0.85 Lag
Total Static Load	0.593	0.367	0.697	0.85 Lag

Load Flow Analysis (LFA) is a major tool for knowing the steady-state behaviour of any Industrial Distribution System. Load Flow Analysis is performed on a 9-Bus Industrial Distribution System (as shown in Fig. 4.4) to assess the impact of Distributed Generation (DG) sources on Load Flow and its impact on overcurrent protection coordination. The

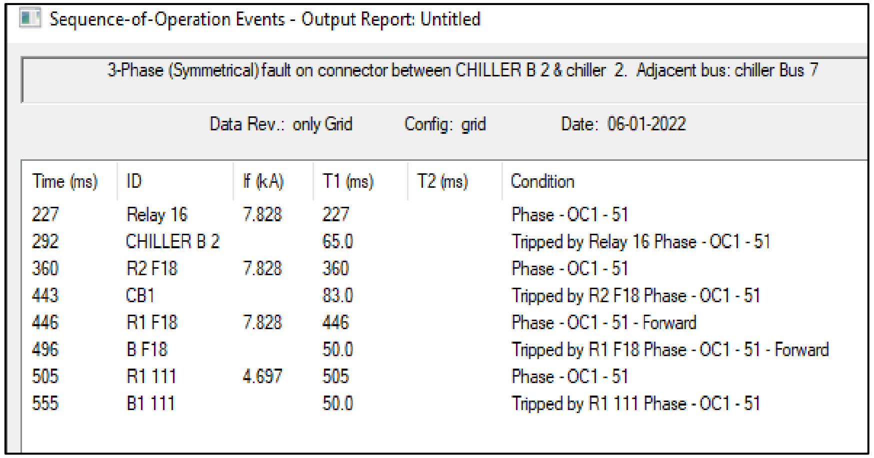
Adaptive Newton Raphson (ANR) method is considered for Load Flow Analysis (LFA) using ETAP software. Different Relay Setting Group (RSG) configurations considered are represented in Table 4.2. Load Flow Analysis for Relay Setting Group#3 is presented in Fig. 4.5. Summary of Generation, Loading, and Load Demand from the Load Flow Analysis performed is presented in Tables 4.3, Table 4.4 and Table 4.5.

Short Circuit (SCA) for 9-Bus Industrial Distribution System:

Industrial Distribution System incorporating Distributed Generation (DG) Sources to strengthen reliability and sustainability may complicate short-circuit behaviour in the System. Short Circuit Analysis (SCA) is conducted to assess the fault level of the system and optimise the overcurrent protection scheme. Short Circuit Analysis (as per IEC 60909) for the selected 9-Bus Industrial Distribution System is carried out, and readings from simulated faults are used for setting relay parameters. The effect of Distributed Generation (DG) sources on fault current (I_f) magnitude is presented in Table 4.6. Short Circuit Analysis is also helpful in understanding the effects of different types of faults and DG sources on fault current magnitude. Alteration in fault current demands an update in the relay parameters and also necessitates an adaptive protection scheme which can adapt to system changes.

4.2.2 Simulation of Protection Coordination for Industrial Distribution System

It is very much necessary for an Industrial Distribution System to have adequate protection coordination to ensure system reliability, equipment safety, and system safety. Relay (or Protection) Coordination involves the design and strategic adjustment of protection device (Relay) parameters so that they can operate sequentially, isolate faults and minimise power supply disruptions to the consumers (important mainly for Industrial Consumers). For any Protection Coordination, key elements are Time Gradient Margin (TGM) or Coordinated Time Intervals (CTI), Time-Current Characteristics (TCC), and device (relay) settings like Pickup Current and Time Multiplier Setting. Through ETAP software, protection coordination simulation for this study with fault creation is performed using ETAP Star Coordination module. International Electrotechnical Commission (IEC) standard Inverse Curve is used for coordination of Overcurrent Relays (OCR) in 9-Bus Industrial Distribution System (as shown in Fig. 4.4). For each Relay Setting Group (RSG), all the relay setting parameters are reviewed for correct operating sequence and Time of Operation (Top).



Sequence-of-Operation Events - Output Report: Untitled

3-Phase (Symmetrical) fault on connector between CHILLER B 2 & chiller 2. Adjacent bus: chiller Bus 7

Data Rev.: only Grid Config: grid Date: 06-01-2022

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
227	Relay 16	7.828	227		Phase - OC1 - 51
292	CHILLER B 2		65.0		Tripped by Relay 16 Phase - OC1 - 51
360	R2 F18	7.828	360		Phase - OC1 - 51
443	CB1		83.0		Tripped by R2 F18 Phase - OC1 - 51
446	R1 F18	7.828	446		Phase - OC1 - 51 - Forward
496	B F18		50.0		Tripped by R1 F18 Phase - OC1 - 51 - Forward
505	R1 111	4.697	505		Phase - OC1 - 51
555	B1 111		50.0		Tripped by R1 111 Phase - OC1 - 51

Figure 4.6 (a) Relay Response Sequence for RSG#1

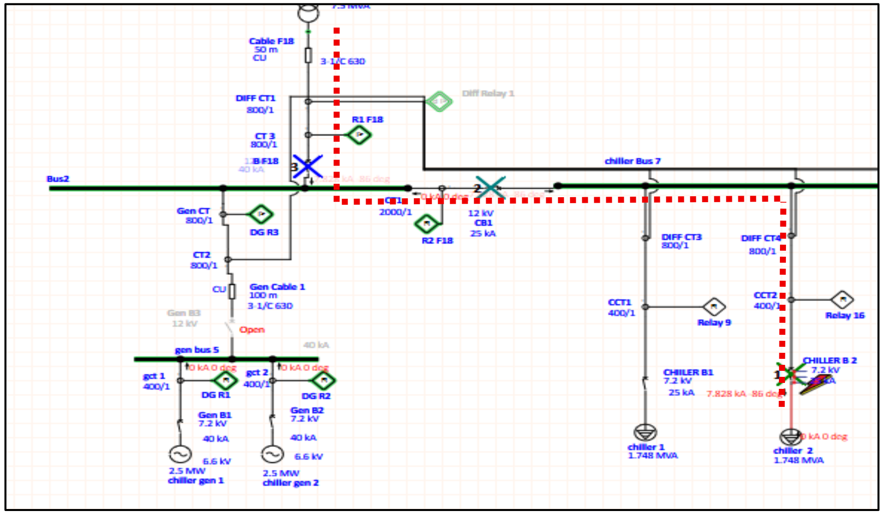


Figure 4.6 (b) Fault Simulation Relays Operation Report for RSG#1

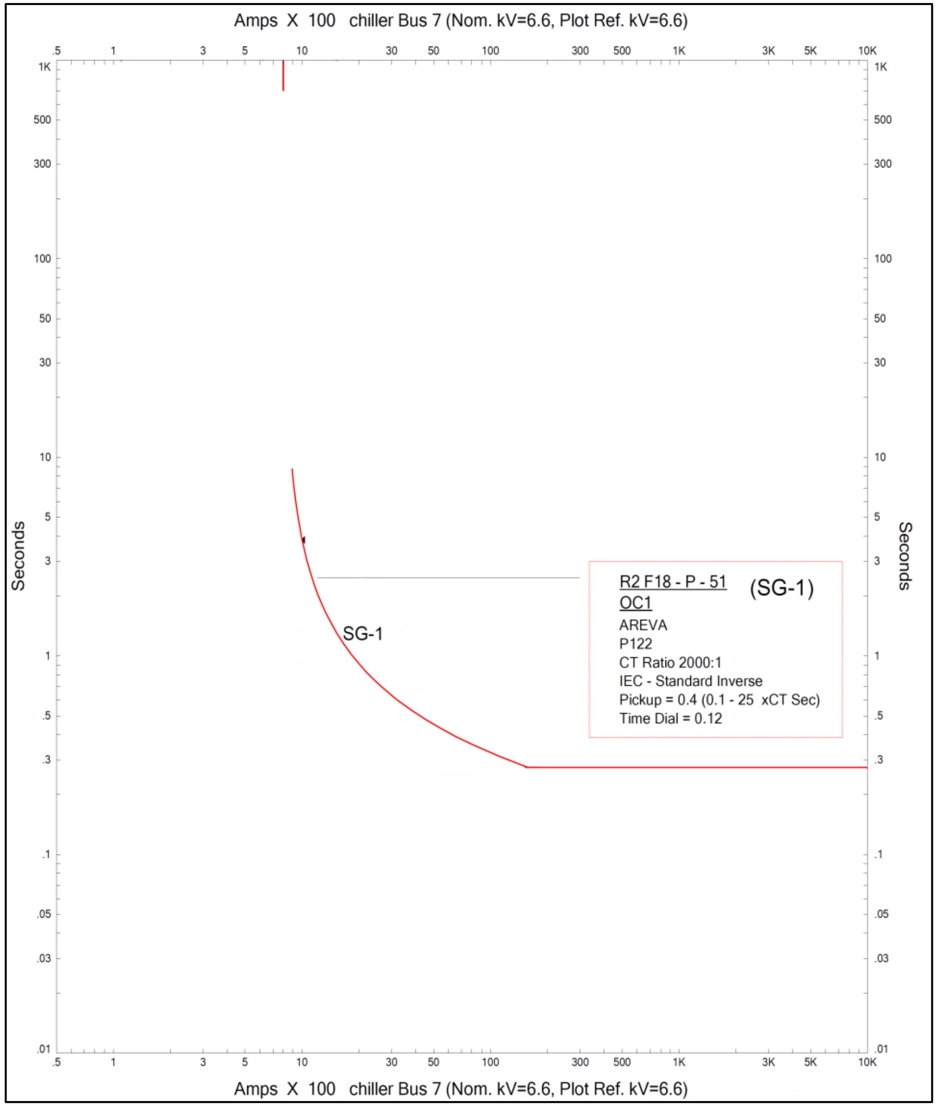


Figure 4.6 (c) TCC Curve (Relay R2F18) for RSG#1

Sequence-of-Operation Events - Output Report: Untitled

3-Phase (Symmetrical) fault on connector between CHILLER B 2 & chiller 2. Adjacent bus: chiller Bus 7

Data Rev.: grid+gen1 Config: grid+ only1 Date: 06-01-2022

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
227	Relay 16	9.309	227		Phase - OC1 - 51
292	CHILLER B 2		65.0		Tripped by Relay 16 Phase - OC1 - 51
385	R2 F18	9.309	385		Phase - OC1 - 51
446	R1 F18	7.828	446		Phase - OC1 - 51 - Forward
468	CB1		83.0		Tripped by R2 F18 Phase - OC1 - 51
496	B F18		50.0		Tripped by R1 F18 Phase - OC1 - 51 - Forward
505	R1 111	4.697	505		Phase - OC1 - 51
555	B1 111		50.0		Tripped by R1 111 Phase - OC1 - 51
620	DG R3	1.48	620		Phase - OC1 - 51
658	DG R1	1.48	658		Phase - OC1 - 51
685	Gen B3		65.0		Tripped by DG R3 Phase - OC1 - 51
723	Gen B1		65.0		Tripped by DG R1 Phase - OC1 - 51
945	R2 F18	9.309	< 945		Overload Phase - Thermal
1028	CB1		83.0		Tripped by R2 F18 Overload Phase - Thermal

Figure 4.7 (a) Relay Response Sequence for RSG#2

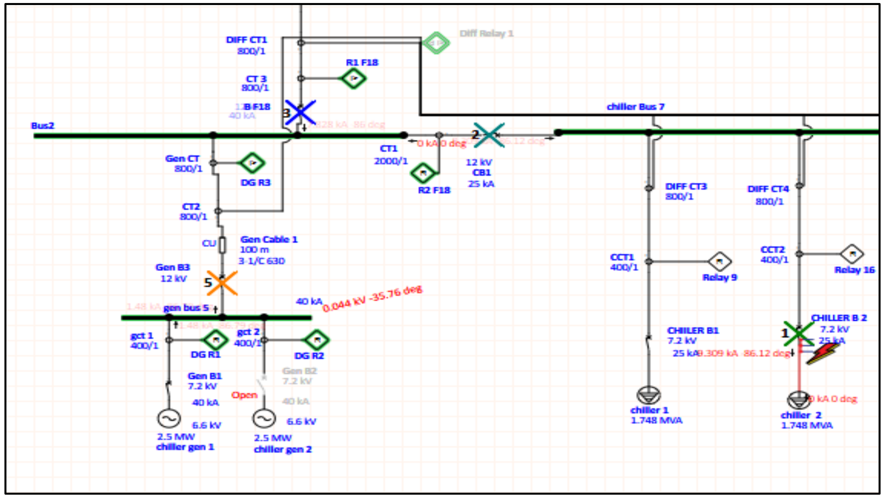


Figure 4.7 (b) Fault Simulation Relays Operation Report for RSG#2

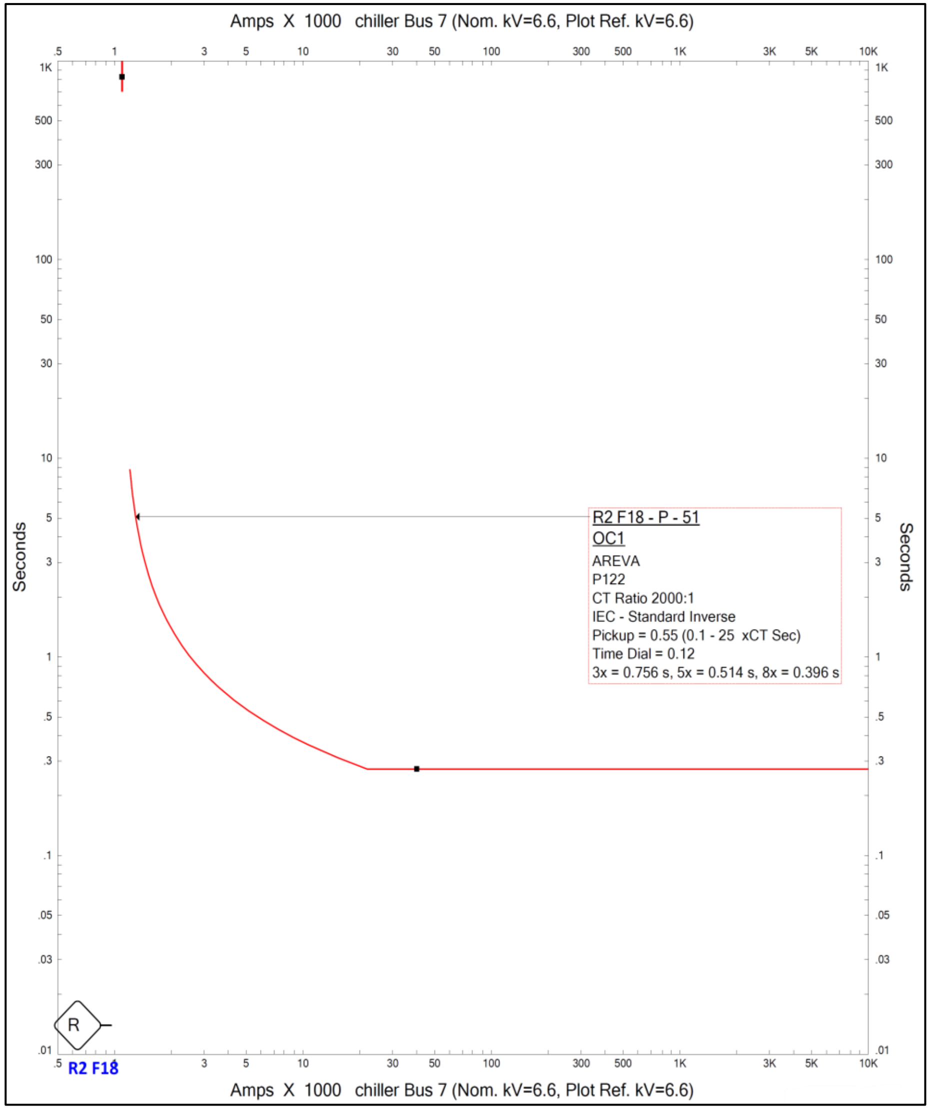


Figure 4.7 (c) TCC Curve (Relay R2F18) for RSG#2

Sequence-of-Operation Events - Output Report: Untitled

3-Phase (Symmetrical) fault on connector between CHILLER B 2 & chiller 2. Adjacent bus: chiller Bus 7

Data Rev.: grid+gen1,2 Config: grid+generat Date: 06-01-2022

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
227	Relay 16	10.885	227		Phase - OC1 - 51
292	CHILLER B 2		65.0		Tripped by Relay 16 Phase - OC1 - 51
386	R2 F18	10.885	386		Phase - OC1 - 51
421	R1 F18	7.828	421		Phase - OC1 - 51 - Forward
469	CB1		83.0		Tripped by R2 F18 Phase - OC1 - 51
471	B F18		50.0		Tripped by R1 F18 Phase - OC1 - 51 - Forward
505	R1 111	4.697	505		Phase - OC1 - 51
555	B1 111		50.0		Tripped by R1 111 Phase - OC1 - 51
604	DG R3	3.057	604		Phase - OC1 - 51
662	DG R2	1.584	662		Phase - OC1 - 51
669	Gen B3		65.0		Tripped by DG R3 Phase - OC1 - 51
693	DG R1	1.473	693		Phase - OC1 - 51
727	Gen B2		65.0		Tripped by DG R2 Phase - OC1 - 51
758	Gen B1		65.0		Tripped by DG R1 Phase - OC1 - 51

Figure 4.8 (a) Relay Response Sequence for RSG#3

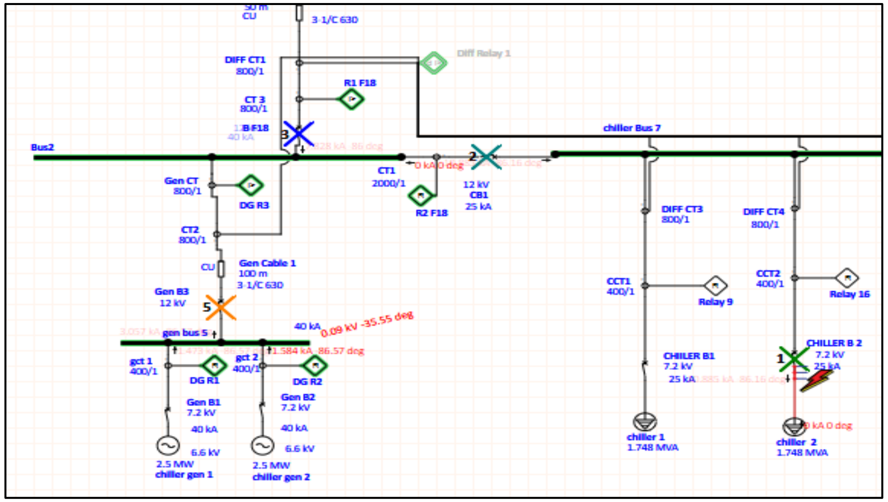


Figure 4.8 (b) Fault Simulation Relays Operation Report for RSG#3

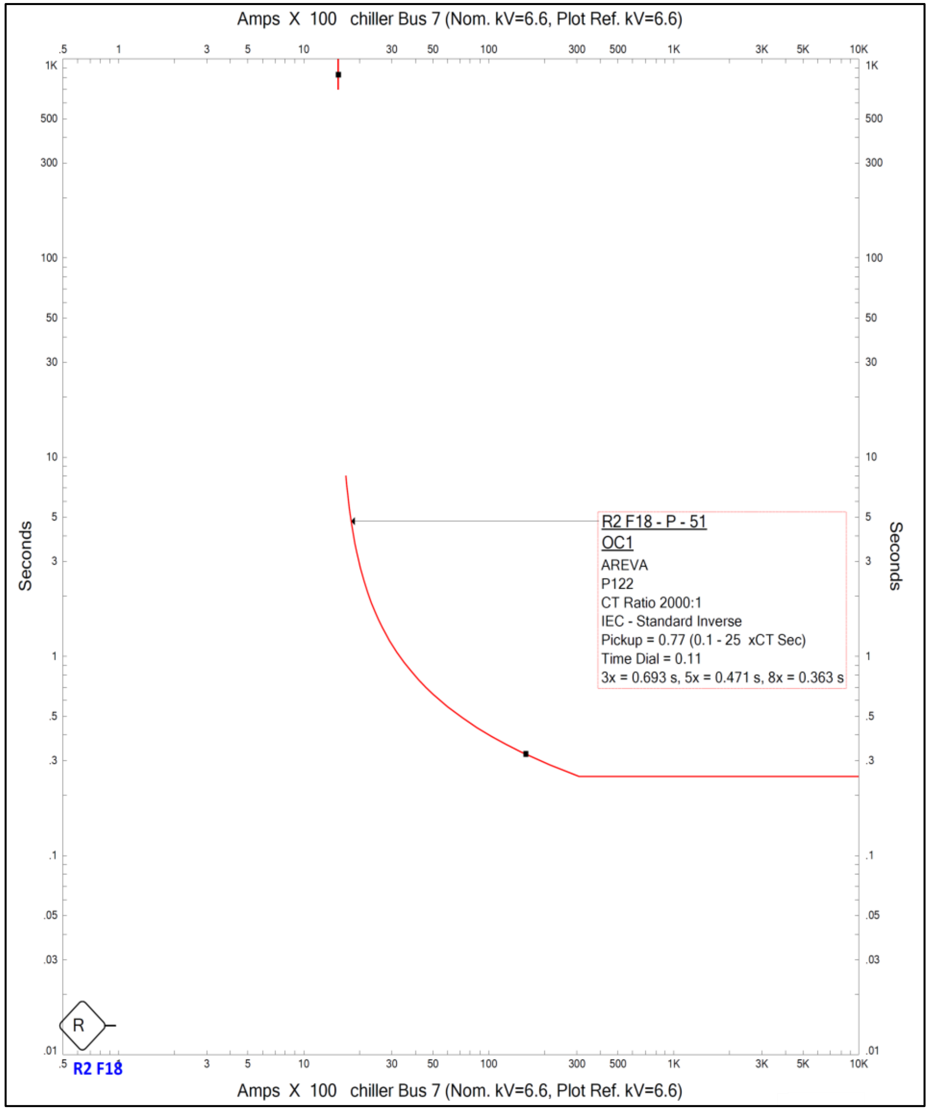


Figure 4.8 (c) TCC Curve (Relay R2F18) for RSG#3

Sequence-of-Operation Events - Output Report: Untitled

3-Phase (Symmetrical) fault on connector between CHILLER B 2 & chiller 2. Adjacent bus: chiller Bus 7

Data Rev.: gen 1 Config: generator 1 Date: 06-01-2022

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
329	Relay 16	1.48	329		Phase - OC1 - 51
394	CHILLER B 2		65.0		Tripped by Relay 16 Phase - OC1 - 51
540	R2 F18	1.48	540		Phase - OC1 - 51
620	DG R3	1.48	620		Phase - OC1 - 51
623	CB1		83.0		Tripped by R2 F18 Phase - OC1 - 51
658	DG R1	1.48	658		Phase - OC1 - 51
685	Gen B3		65.0		Tripped by DG R3 Phase - OC1 - 51
723	Gen B1		65.0		Tripped by DG R1 Phase - OC1 - 51
1105	R2 F18	1.48	1105		Overload Phase - Thermal
1188	CB1		83.0		Tripped by R2 F18 Overload Phase - Thermal

Figure 4.9 (a) Relay Response Sequence for RSG#4

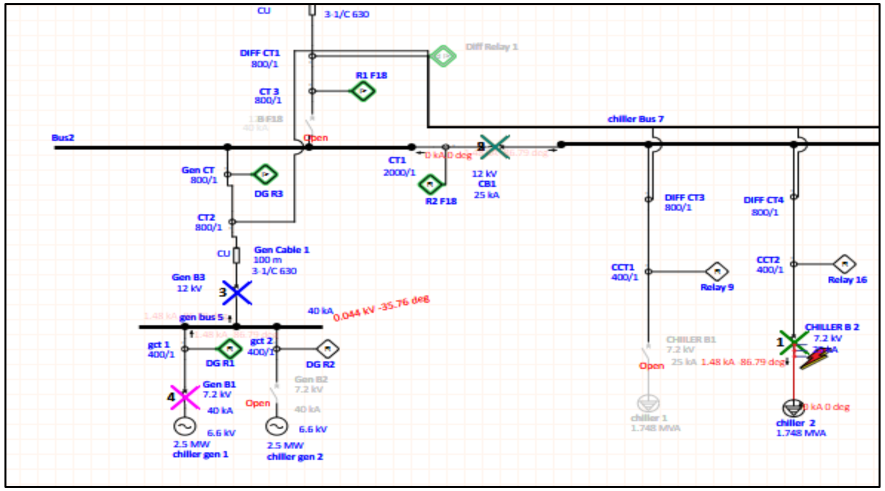


Figure 4.9 (b) Fault Simulation Relays Operation Report for RSG#4

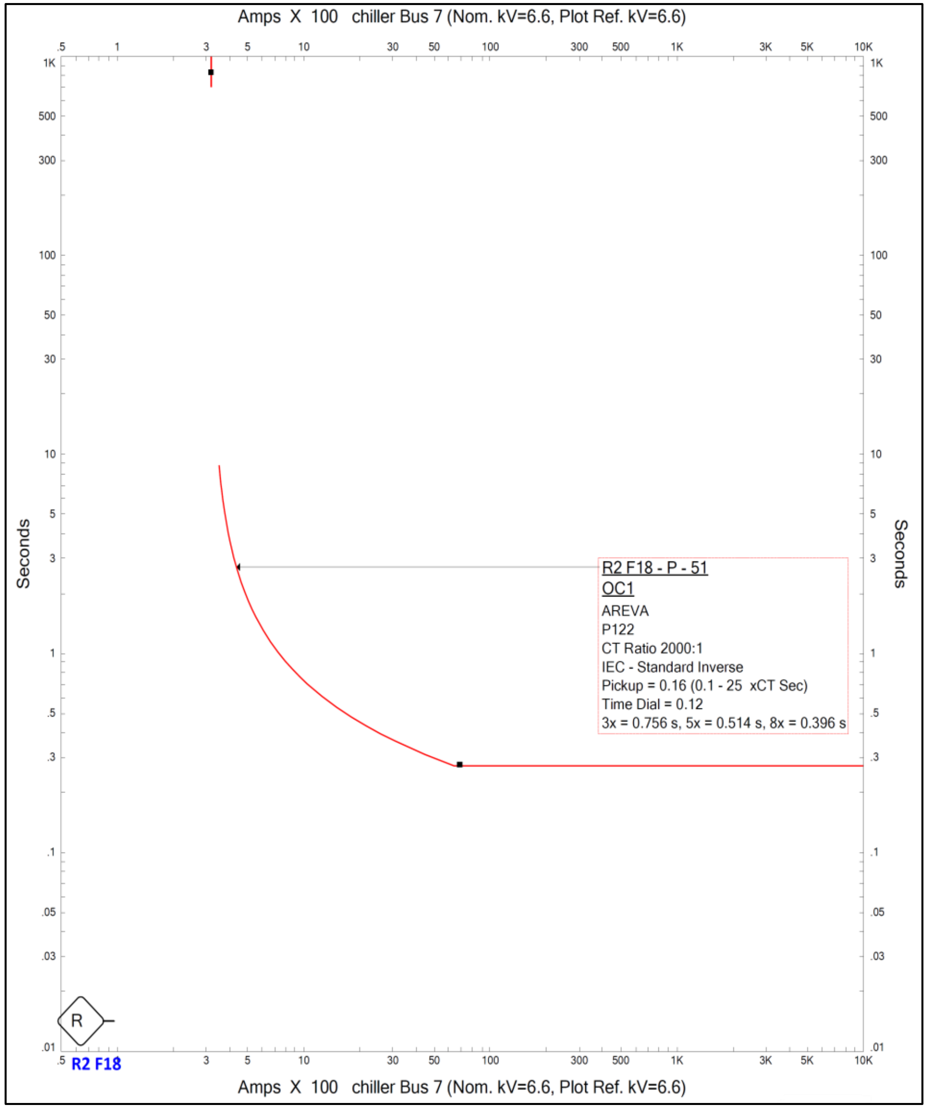


Figure 4.9 (c) TCC Curve (Relay R2F18) for RSG#4

Sequence-of-Operation Events - Output Report: Untitled

3-Phase (Symmetrical) fault on connector between CHILLER B 2 & chiller 2. Adjacent bus: chiller Bus 7

Data Rev.: gen 1,2 Config: generator Date: 06-01-2022

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
242	Relay 16	3.057	242		Phase - OC1 - 51
307	CHILLER B 2		65.0		Tripped by Relay 16 Phase - OC1 - 51
518	R2 F18	3.057	518		Phase - OC1 - 51
601	CB1		83.0		Tripped by R2 F18 Phase - OC1 - 51
604	DG R3	3.057	604		Phase - OC1 - 51
662	DG R2	1.584	662		Phase - OC1 - 51
669	Gen B3		65.0		Tripped by DG R3 Phase - OC1 - 51
693	DG R1	1.473	693		Phase - OC1 - 51
727	Gen B2		65.0		Tripped by DG R2 Phase - OC1 - 51
758	Gen B1		65.0		Tripped by DG R1 Phase - OC1 - 51

Figure 4.10 (a) Relay Response Sequence for RSG#5

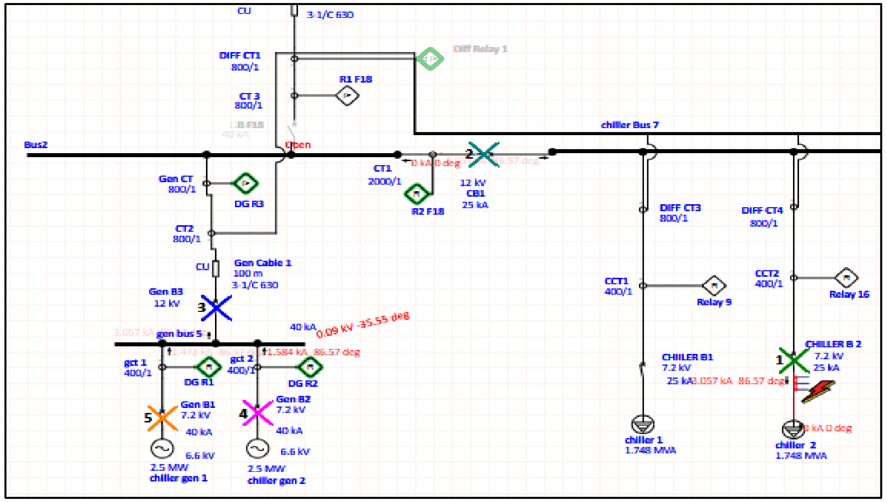


Figure 4.10 (b) Fault Simulation Relays Operation Report for RSG#5

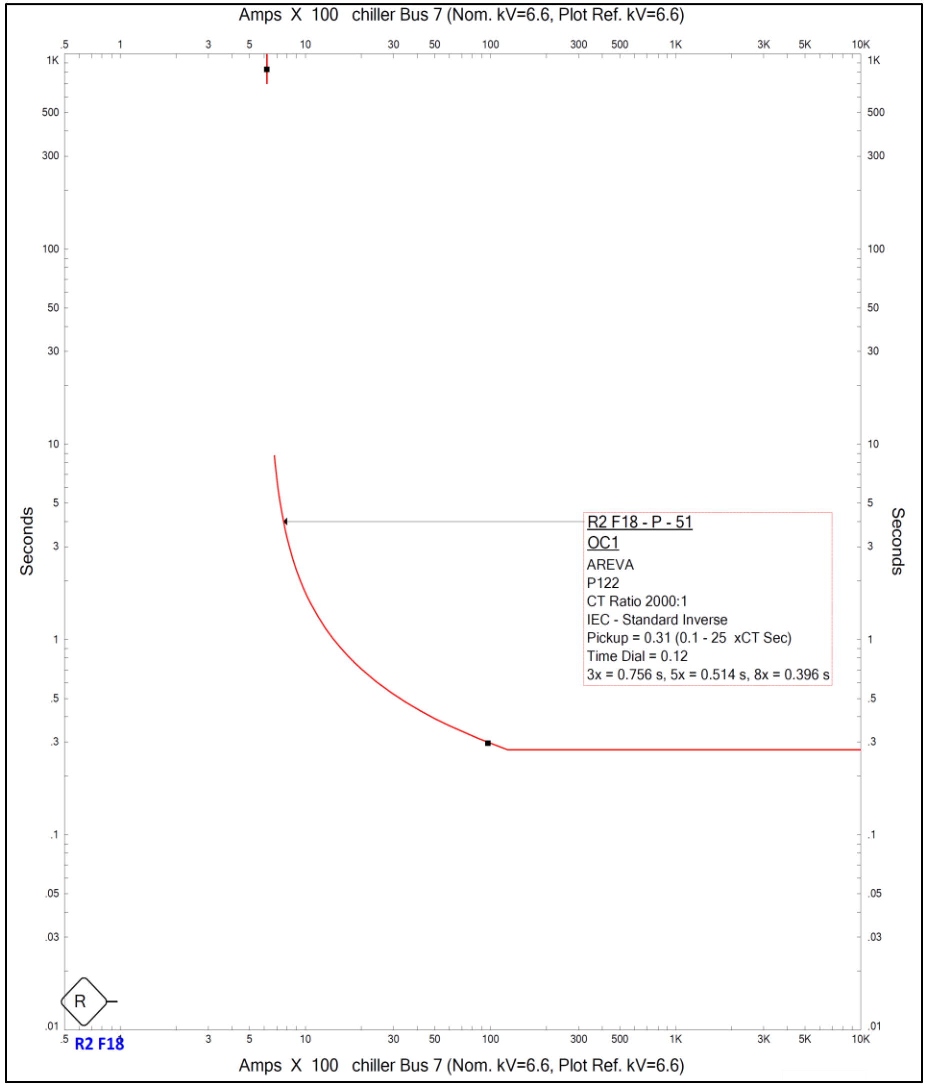


Figure 4.10 (c) TCC Curve (Relay R2F18) for RSG#5

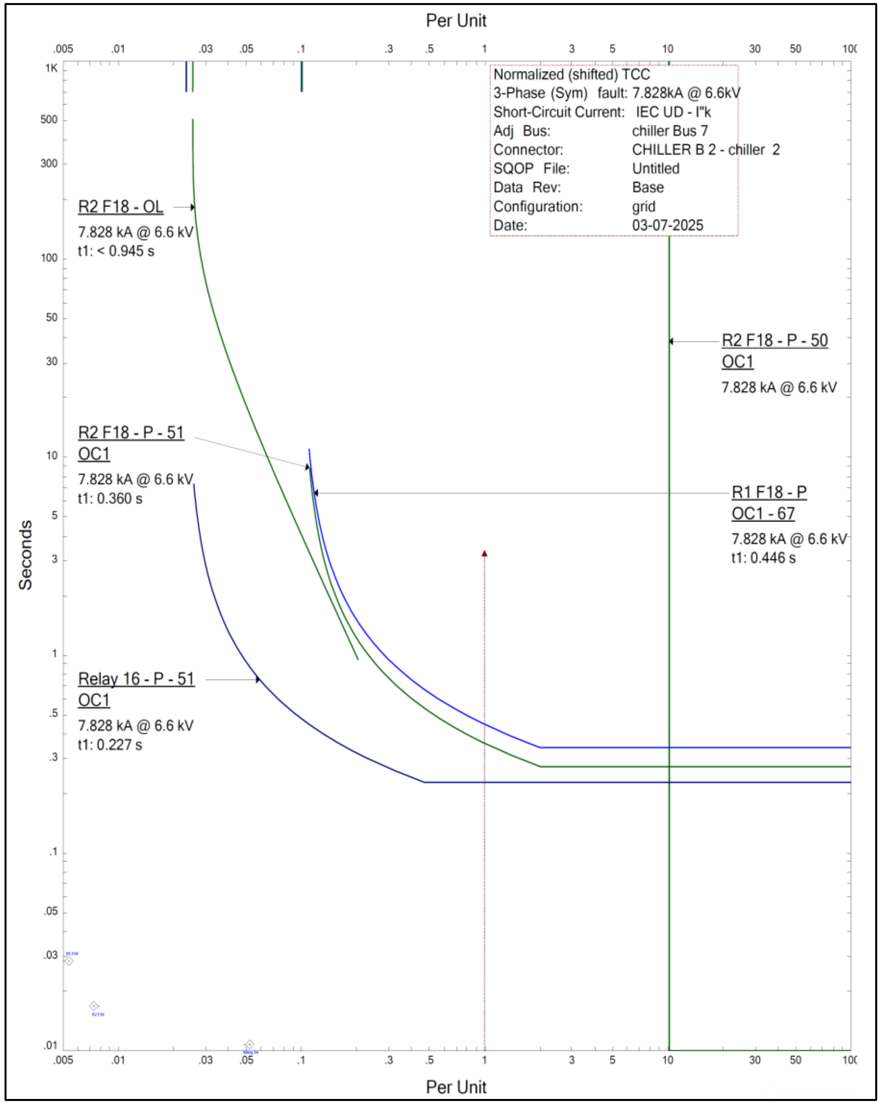


Figure 4.11 TCC Curve for Relay Setting Group (RSG)#1

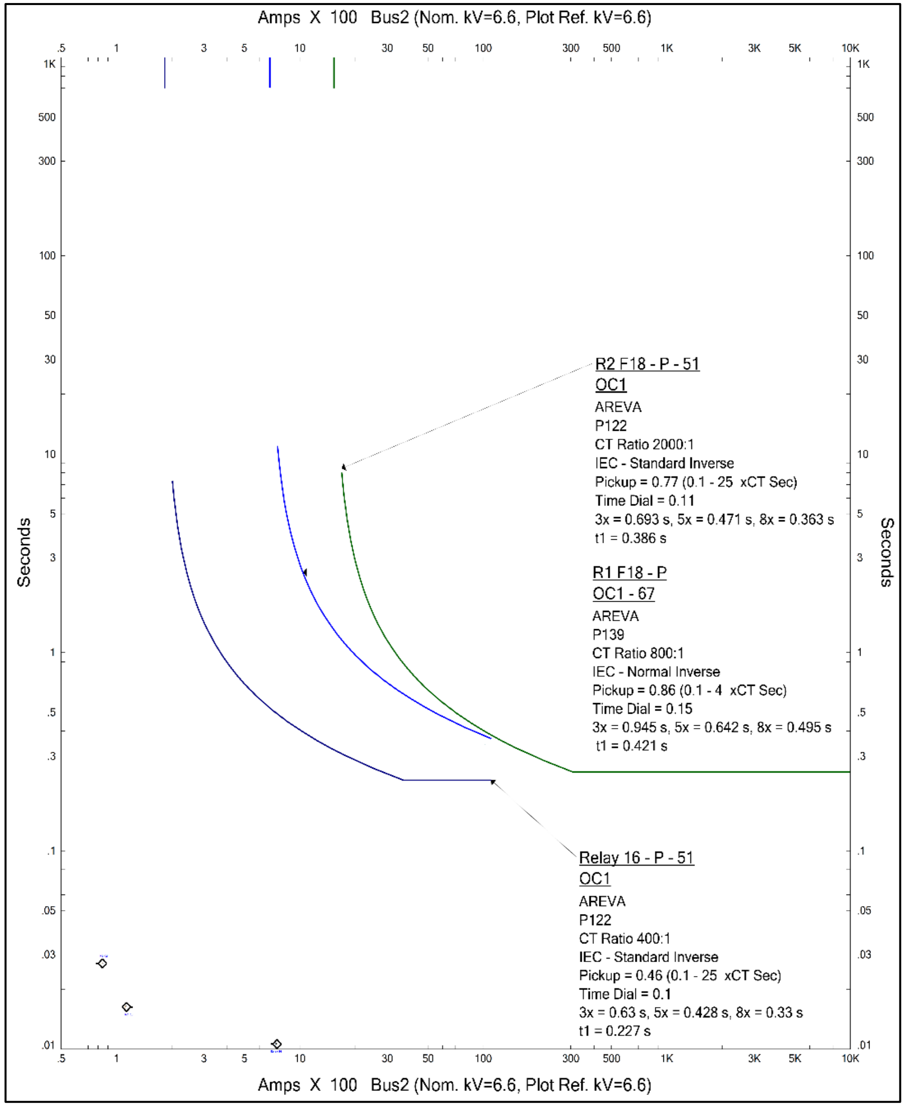


Figure 4.12 TCC Curve for Relay Setting Group (RSG)#3

Table 4.6. CTI report and Relay Operating Time (Top) summary

RSG No.	Relay Setting Group (RSG) Arrangement	Relay	System Fault Current seen by Relays (kA)	Ipickup (Amp)	Time Dial Setting (TDS)	T1 (Top) (ms)
1	PG Only	R16	7.828	0.98	0.1	0.227
		R2 F16	7.828	0.40	0.12	0.360
		R1 F16	7.828	0.98	0.15	0.446
2	PG + 1 DG	R16	9.309	1.17	0.1	0.227
		R2 F16	9.309	0.55	0.12	0.385
		R1 F16	7.828	0.98	0.15	0.446
3	PG + 2 DG	R16	10.885	1.37	0.1	0.227
		R2 F16	10.885	0.77	0.11	0.386
		R1 F16	7.828	0.86	0.15	0.421
4	Island + 1 DG	R16	1.48	0.46	0.1	0.329
		R2 F16	1.48	0.16	0.12	0.540
		DGR3	1.48	0.39	0.14	0.620
5	Island + 2 DG	R16	3.057	0.46	0.1	0.242
		R2 F16	3.057	0.31	0.12	0.518
		DGR3	3.057	0.77	0.14	0.604

In the 9-Bus Industrial Distribution System (as shown in Fig. 4.4), for analysis, the location of fault is considered to be on Feeder of Chiller 2. From the results presented in Fig. 4.6 to Fig. 4.10 (considering sub-figures a, b and c), it is clear that relay R2 F16 is the main and common relay for all the Relay Setting Groups (RSG) for protection. Fig. 4.11 and Fig. 4.12 represent Time Current Characteristics (TCC) curves of Fault Simulation with Relay Setting Groups RSG#1 and RSG#3, respectively. In Fig. 4.11, the x-axis parameter is shown in pu, whereas in Fig. 4.12, it is shown in Amps. Table 4.6 represents a CTI report summary presenting various details like system fault current observed by relays, relay Pickup Current and Time Dial Setting for different Relay Setting Groups from RSG#1 to RSG#5. Analysis is performed with various Relay Setting Groups, optimum Time Current Characteristics (TCC) curves and relay pairs, which helps in creating relay programming. If fault location is considered to be on Feeder of Chiller 1, instead of Relay 16, Relay 9 will operate, and the operating sequence of the remaining relays of the system will be the same, and there is little difference in parameters like System Fault Current seen by Relays (kA), Ipickup (Amp) and Time Dial Setting (TDS).

4.3 Overcurrent Relay (OCR) Validation and Discussion

Connection of Distributed Generation (DG) Sources into the Industrial Distribution System has changed the dynamics of overcurrent protection schemes. If the Industrial Distribution System considered in this chapter relies on traditional protection, it may face significant disruptions because of Distributed Generation sources. Analysis of the effect of Distributed Generation sources on Protection Coordination with different Relay Setting Groups (RSG) is presented by simulating a 9-Bus Industrial Distribution System through ETAP software. From Table 4.6, it is observed that the operating time of relay and system fault currents are different for all the Relay Setting Groups (RSG). The proposed overcurrent protection scheme, which employs a Fuzzy Logic Controller, offers better performance against the conventional scheme being used for the Industrial Distribution System.

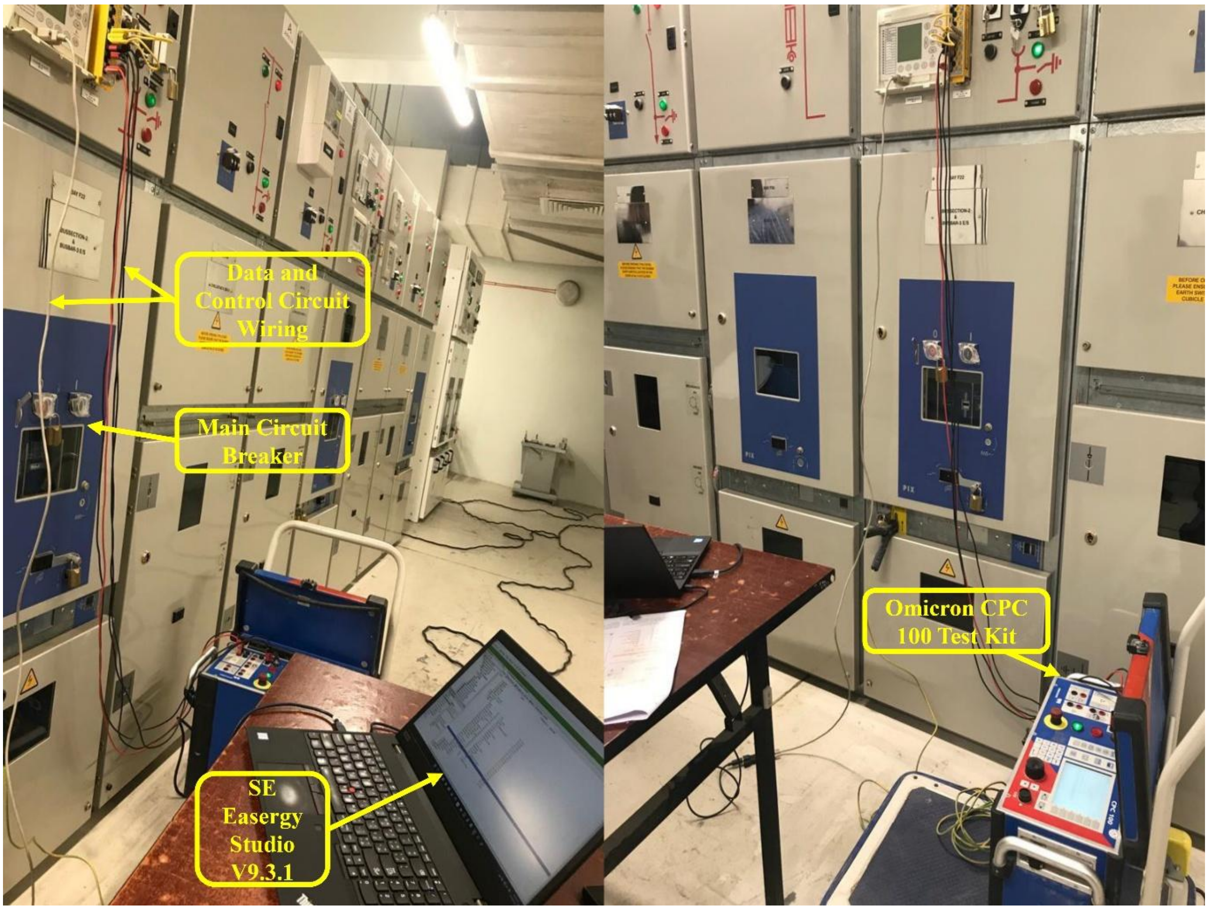


Figure 4.13 Test Setup (Hardware In Loop (HIL))

For verification of the Overcurrent (OC) function, SE P139 relay is used, in which programming of Relay Setting Groups (RSG) is done with pre-computed values of Time

Dial Setting (TDS) and Pickup Current (Ip) identified through Short Circuit Analysis and Coordinated Time Interval (CTI) settings, simulated through ETAP software. Programming of the relay is prepared through Easergy Studio V9.3.1-SE and determines pairs of relays for control action of the Circuit Breaker.

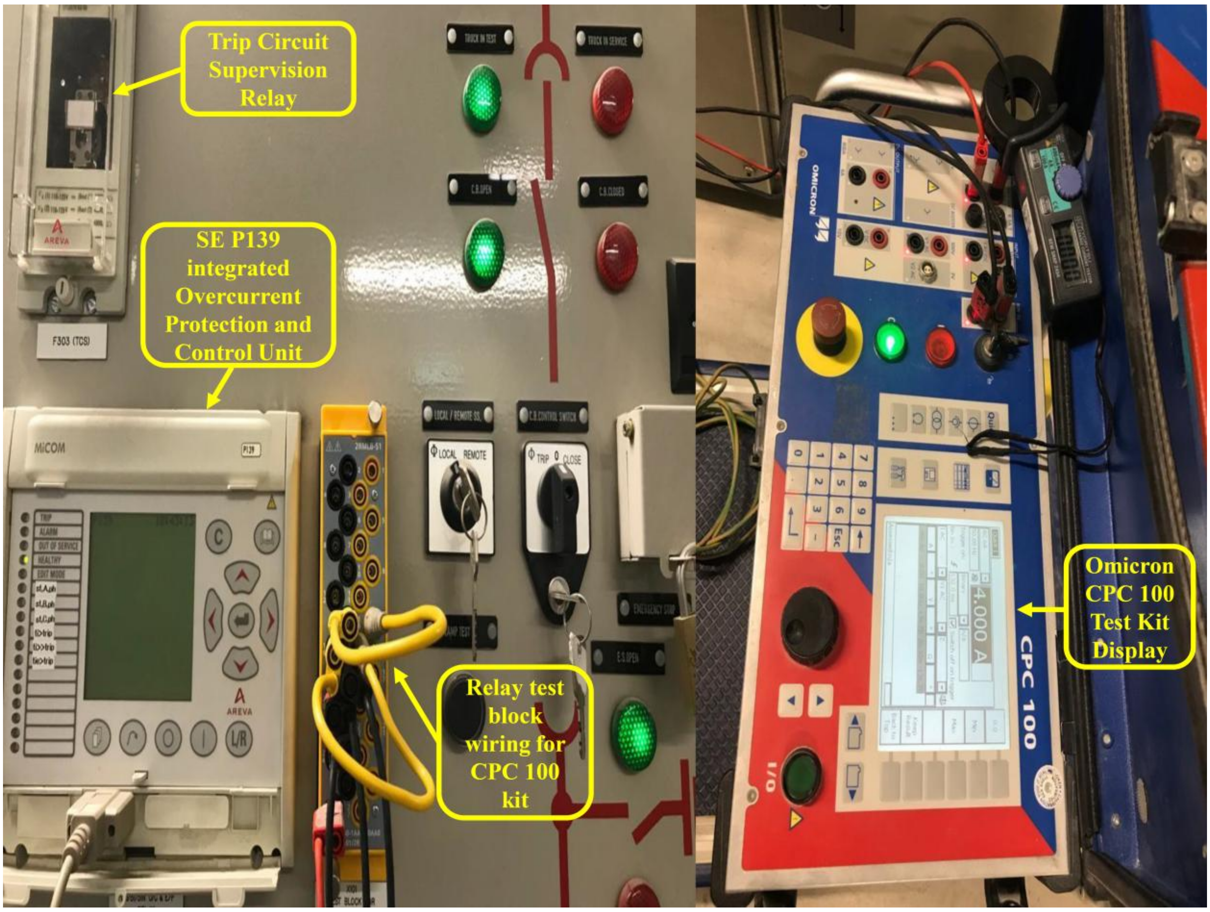


Figure 4.14 Relay Panel and Omicron CPC 100 Test Kit display from Test Setup

Distribution System panels are set up for Hardware In Loop (HIL) tests (as shown in Fig. 4.13 and Fig. 4.14) through secondary injection method. Wiring of the relay test block was done properly, connected through Omicron CPC 100 testing kit and Ethernet is used to establish relay control. Summary and event activity log are downloaded for analysis. The proposed overcurrent protection presented in this chapter effectively addresses challenges imposed when Distributed Generation sources are integrated by enhancing fault detection and system reliability. Analysis is done to get optimum CTI values, and relays are set with different parameters for various relay setting groups, which give better response and operate in less time. It is also seen that the risk of miscoordination is reduced with the proposed scheme, ensuring sensitive and reliable protection under different operating conditions.

CHAPTER - 5
Combined PCA and CNN based Fault Detection and Classification (FDC) Scheme

Distributed Generation (DG) sources integrated in the Distribution System (DS) change the direction of power flow, increase fault current level and complexity because of various types of Distributed Generation sources like Solar PV, Wind Power Generation, Small Hydro, etc. Conventional Protection schemes depend on fixed thresholds, but Distributed Generation sources introduce two-way power flows, dynamic fault inception angles & fault current levels, and dynamic system variables. These factors lead to protection miscoordination, protection blinding or failure to detect/classify various faults. A Hybrid Principal Component Analysis (PCA) and Convolutional Neural Network (CNN) based Fault Detection and Classification (FDC) scheme is proposed and presented in this chapter, which addresses problems that occur because of DG integration in the Distribution System. The main objective is to develop and validate a hybrid PCA and CNN based Fault Detection and Classification (FDC) scheme that outperforms traditional schemes in terms of response time and fault detection accuracy under various dynamic fault scenarios and DG penetrations. This method's ability to detect faults and classify fault types is presented by performing simulations of different fault scenarios in the modified IEEE 9-Bus system using PSCAD/EMTDC software.

5.1 Fault Detection and Classification Algorithm using combined PCA and CNN

Principal Component Analysis (PCA) combined with Convolutional Neural Network (CNN) is proposed to enable an automatic Fault Detection and Classification (FDC) in Distribution System (DS) integrated with Distributed Generation (DG) sources. PCA is used for dimensionality reduction (preserving more relevant features), which is advantageous for improving computational efficiency and/or avoiding redundancy. Once dimensionality reduction is done, extracted features are fed into a CNN architecture, which is used to ensure effective fault classification and localisation. This model uses 3-phase voltage and current waves (time series data) as input features from instrument transformers. The gathered data is preprocessed by normalising (ensuring zero mean and unit variance) and removing noise content because PCA is sensitive to scale. Preparation of standardised dataset matrix $X \in R^{n \times m}$ is done with n samples and m features (voltage or current per phase).

$$X_{ij} = \frac{x_{ij} - \mu_j}{\sigma_j} \tag{5.1}$$

where μ_j is the mean, and σ_j is the standard variability for each feature (j).

$$\mu_j = \frac{1}{n} \sum_{i=1}^{n} x_{ij} \tag{5.2}$$

$$\sigma_j = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left(x_{ij} - \mu_j\right)^2} \tag{5.3}$$

Dimensionality reduction of the high-dimensional input dataset is done with retention of the majority of variance for simplification of CNN training & enhancing fault-relevant features. Once the construction of the standardised matrix is done, the covariance matrix ($Xc \in R^{m \times m}$) will be prepared.

$$X_C = \frac{1}{n-1} X^T X \tag{5.4}$$

Eigenvalue decomposition will be performed once the covariance matrix is prepared.

$$X = USV^T \tag{5.5}$$

where U & V are orthogonal matrices, and S is a diagonal matrix of singular values. V is the matrix of eigenvectors (Principal Components). With respect to the largest eigenvalues, the top k (k < m) eigenvectors are selected for forming a projection matrix ($W \in R^{m \times k}$). Where k is determined by maintaining a certain percentage (e.g. 95%) of the cumulative or total variance ratio with eigenvalues (λi).

$$\text{Cumulative Variance Ratio} = \frac{\sum_{i=1}^{k} \lambda i}{\sum_{i=1}^{m} \lambda i} \tag{5.6}$$

Data will be transformed from standardised to reduced-dimensional space.

$$Z = XW \tag{5.7}$$

where $Z \in R^{n \times k}$ is the data transformed through Principal Component Analysis (PCA). To detect abnormalities, statistical metrics will be used. Reshaping of the reduced-dimensional matrix Z into a 1D or 2D format, which is suitable for Convolutional Neural Network (CNN) input (e.g., a matrix resembling an image / time-frequency representation), is performed if the generated data is sensor-based or time-series. Data augmentation will be done to increase dataset robustness, mainly for imbalanced fault classes. Then, a Convolutional Neural Network (CNN) structure will be prepared for fault classification based on data transformed through Principal Component Analysis (PCA).

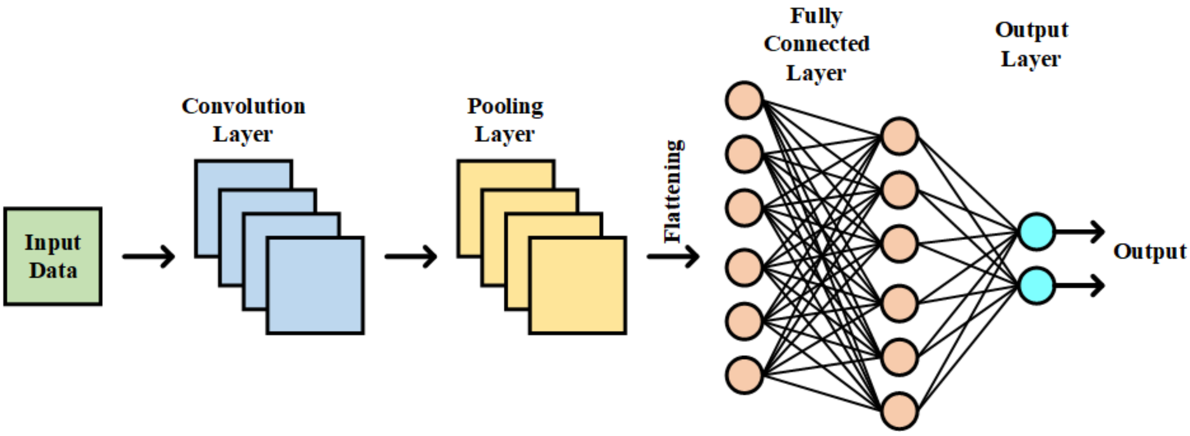


Figure 5.1 Convolutional Neural Network (CNN) structure

The Structure of the Convolutional Neural Network (CNN) (as shown in Fig. 5.1) involves five layers in total. Those are Input Layer, Convolutional Layer, Pooling Layer, Fully Connected Layer, and Output Layer. Data transformed through Principal Component Analysis (PCA) is taken in the Input Layer. Convolution operations are conducted for extraction of spatial features in the Convolutional Layer with W as the convolutional kernel, I as input, b as bias & σ as activation function.

$$Y_{i,j} = \sigma \left(\sum_{m,n} Wm,n \cdot I_{i+m+n} + b\right) \quad (5.8)$$

After the data passes through the Convolutional Layer, it passes through the Pooling Layer, where max pooling (Pi,j) is used to reduce spatial dimensions while preserving main features. The Fully Connected Layer flattens feature maps and passes them through dense layers, with W_f as weights and b_f as biases of the Fully Connected Layer.

$$h = \sigma(W_f \cdot \text{Flatten}(P) + b_f) \quad (5.9)$$

In the Output Layer, softmax activation is used for output probability for each of the fault classes (e.g., no fault, LG, LL, LLL).

$$\widehat{y}_c = \frac{e^{zc}}{\sum_{j=1}^{c} e^{zj}} \tag{5.10}$$

where $\widehat{y}_c$ is the predicted probability of fault class. Training (70%) & Testing (30%) of the Convolutional Neural Network (CNN) model is considered. To optimise the Convolutional Neural Network (CNN), categorical cross-entropy is used.

$$L = - \sum_{i=1}^{c} yi \ \log(\widehat{y}_i) \tag{5.11}$$

where yi is the true label, $\widehat{y}_i$ is the predicted probability, and c is the number of classes.

5.2 System Simulation & Data Creation

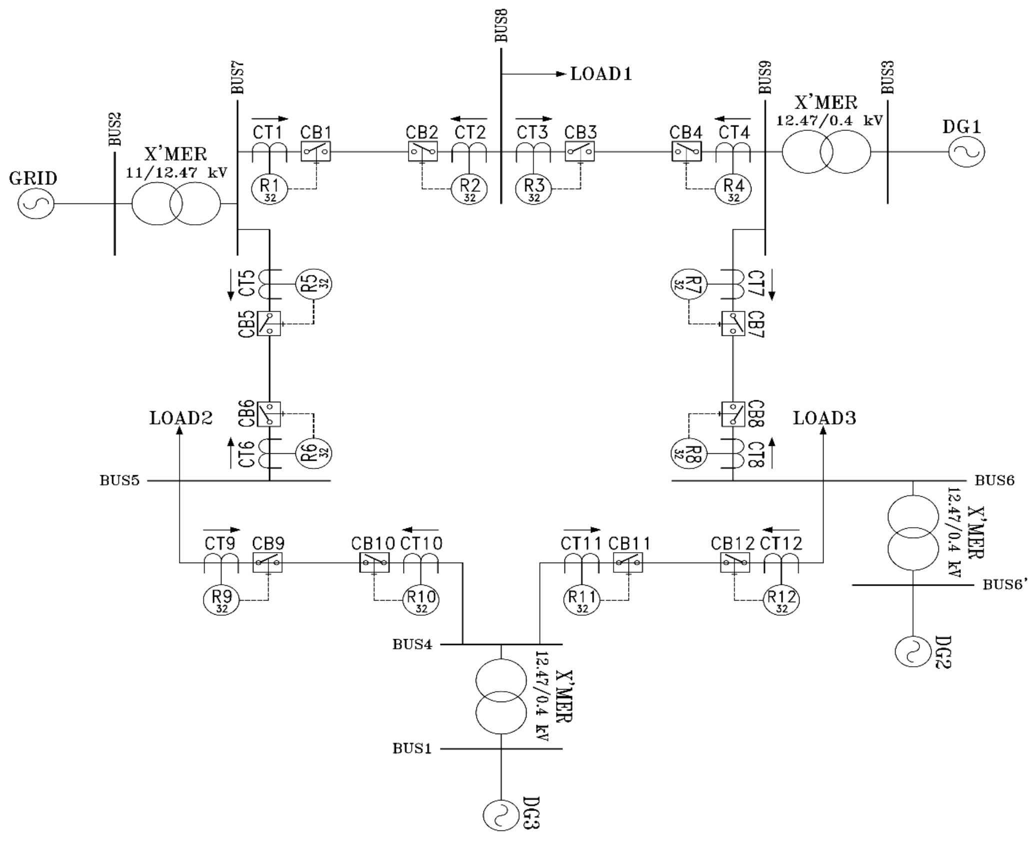


Figure 5.2 Modified IEEE 9-Bus System

IEEE 9-Bus system is used as a benchmark Ring Main System for various analyses related to power systems. A modified IEEE 9-Bus Distribution System (as shown in Fig. 5.2) is prepared through PSCAD/EMTDC software for data generation to develop the proposed fault detection and classification algorithm for the protection scheme of the Distribution System. 12.47 kV is the system voltage, with each feeder section length of 20 km. This Distribution System is connected to the power grid through 11/12.47 kV transformer. Three Distributed Generation (DG) sources (Two Synchronous Generators (SG) and one Induction Generator (IG)), all with 1 MW power generation capacity, are interconnected in the Distribution System through 0.4/12.47 kV transformers at Bus 3, Bus 4 & Bus 6 respectively, to analyse their effects and data generation. Three loads connected at Bus 5, Bus 6 and Bus 8 with a total capacity of 7 MW are supplied through the Distribution System. Total 12 Negative Sequence Directional Elements (represented as Relay 32Q in PSCAD/EMTDC) are used for reliable protection of the modified IEEE 9-Bus Distribution System.

Table 5.1 Configuration of Different Fault Simulation Cases

System / Fault Parameters	**Various Configuration**	**Data Counts**
Type of Faults	LG (Rg, Yg, Bg), LL (RY, YB, BR), LLG (RYg, YBg, BRg), LLL (RYB)	10
Faulty Lines between Buses	4-5, 4-6, 5-7, 6-9, 7-8, 8-9	6
Fault Location (FL)	Every 20 % of line length (in km)	5
Fault Resistance (Rf) (Ω)	0.01, 0.1, 1, 5, 10, 25, 50	7
Fault Inception Angle (FIA)	0° to 360° (with a step of 30°)	12
Load angle (δ)	0°, 5°, 10°, 15°	4
Source Impedance (Zs)	80%, 100% and 120%	3

Table 5.2. Fault Data Generation (Faulty Line Identification)

Label / Tag	**Faulty Feeder Sections / Lines**	**Data Counting**	**Generated Cases**
1	4-5	10 × 5 × 7 × 12 × 4 × 3	50400
2	4-6	10 × 5 × 7 × 12 × 4 × 3	50400
3	5-7	10 × 5 × 7 × 12 × 4 × 3	50400
4	6-9	10 × 5 × 7 × 12 × 4 × 3	50400
5	7-8	10 × 5 × 7 × 12 × 4 × 3	50400
6	8-9	10 × 5 × 7 × 12 × 4 × 3	50400
Total Generated Cases			**302400**

Table 5.3 Fault Data Generation (Fault Location on line)

Label / Tag	**Fault Location on Line (% of line length in km)**	**Data Counting**	**Generated Cases**
1	**20%**	10 × 6 × 7 × 12 × 4 × 3	60480
2	**40%**	10 × 6 × 7 × 12 × 4 × 3	60480
3	**60%**	10 × 6 × 7 × 12 × 4 × 3	60480
4	**80%**	10 × 6 × 7 × 12 × 4 × 3	60480
5	**100%**	10 × 6 × 7 × 12 × 4 × 3	60480
Total Generated Cases			**302400**

Table 5.4 Fault Data Classification

Label / Tag	**Fault Type & Phase**	**Data Counting**	**Generated Cases**
1	Rg	6 × 5 × 7 × 12 × 4 × 3	30,240
2	Yg	6 × 5 × 7 × 12 × 4 × 3	30,240
3	Bg	6 × 5 × 7 × 12 × 4 × 3	30,240
4	RY	6 × 5 × 7 × 12 × 4 × 3	30,240
5	YB	6 × 5 × 7 × 12 × 4 × 3	30,240
6	BR	6 × 5 × 7 × 12 × 4 × 3	30,240
7	RYg	6 × 5 × 7 × 12 × 4 × 3	30,240
8	YBg	6 × 5 × 7 × 12 × 4 × 3	30,240
9	BRg	6 × 5 × 7 × 12 × 4 × 3	30,240
10	RYB	6 × 5 × 7 × 12 × 4 × 3	30,240
Total Generated Cases			**302400**

The proposed combined PCA and CNN based scheme is able to work with local transient voltages/currents recorded at line terminals when various faults occur. Transient signatures are mainly controlled through the nature of faults, type of faults, location of faults and fault inception angle but are not dependent on the size of the system. As distributed measurement devices, including digital relays and Phasor Measurement Units (PMUs), are increasingly being utilised in modern power systems, it is possible to deploy the proposed approach or scheme in a modular fashion. A multirun facility in PSCAD/EMTDC software is used to generate data for training and testing of the suggested Fault Detection and Classification (FDC) scheme. A Total of 302400 cases are generated for training and testing of the suggested Fault Detection and Classification (FDC) algorithm. Various fault simulation cases and variable parameters are described in Table 5.1. Proposed scheme execution is verified considering faulty line, fault location as a percentage of line length, and fault type classification as shown in Table 5.2, Table 5.3 and Table 5.4, respectively.

5.3 Proposed Fault Detection and Classification (FDC) Algorithm

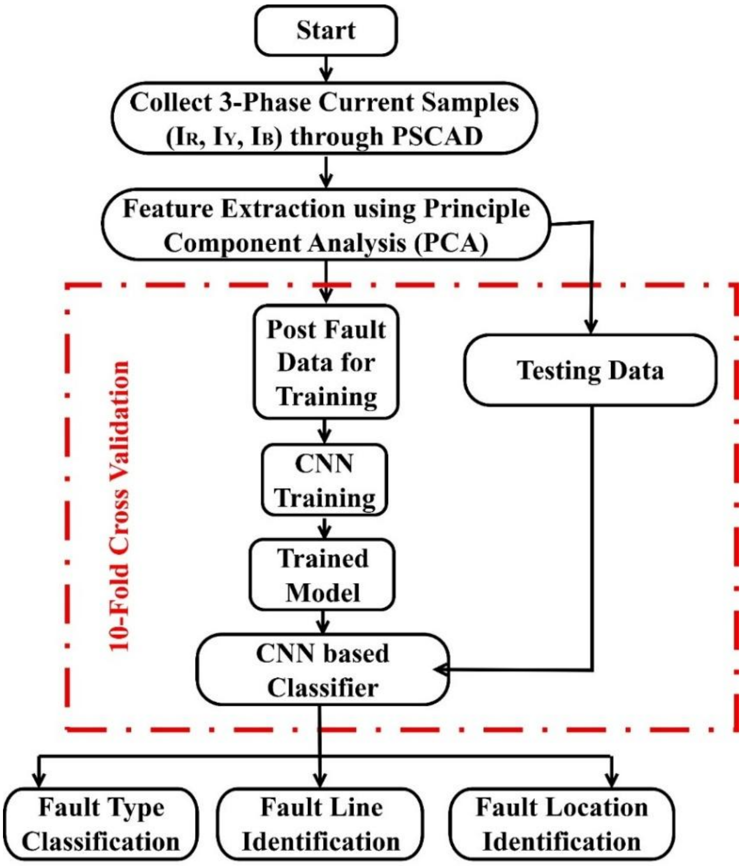


Figure 5.3 Proposed Fault Detection and Classification (FDC) Algorithm

The algorithm of Fault Detection and Classification (FDC) scheme proposed for the Distribution System (DS) with Distributed Generation (DG) is shown in Fig. 5.3. For the algorithm used to detect and classify faults in the Distribution System, preprocessing is done on collected voltage and current signals and Principal Component Analysis (PCA) is used for feature extraction. Apart from feature extraction, PCA is also useful for reducing dimensionality (for high-dimensional input data) before it is given to Convolutional Neural Network (CNN), which simplifies CNN training and enhances fault-relevant features. Principal Component Analysis (PCA) also filters out noisy and unrelated variations in data and focuses on principal components with higher variance. A reduced and relevant feature set usually leads to superior performance for classifiers like CNN by concentrating on most instructive features. The entire process is performed in independent implementations within MATLAB software for both training and testing using a 10-fold cross-validation system with Principal Component Analysis (PCA) based feature extraction and a tailored 1D Convolutional Neural Network (CNN) architecture.

As the extracted features are given to Convolutional Neural Network (CNN) classifier, main attention is on CNN-based fault classification in the proposed scheme. Using a CNN classifier is advantageous as it can classify numerous types of faults simultaneously by learning different patterns for each fault class & improvise its ability to differentiate between various fault scenarios. With an optimised architecture, CNN processes extracted data quickly and enables real-time fault classification, which is very important in the area of power system protection. For time-series data, CNN is able to apprehend temporal dependencies or spatial relationships, enabling precise fault classification, and its fault classification accuracy depends on appropriate raw signal pre-processing, CNN architecture & training process. Convolutional Neural Network (CNN) architecture is presented in Fig. 5.1. Chances of overfitting in fault classification are addressed by splitting the dataset into training, validation and testing sets with the help of 10-fold cross-validation for improving generalisation and using Principal Component Analysis (PCA) for eliminating redundant features. Further, a slim CNN with early termination provides strong results in obscured fault circumstances. Once the fault is detected, a trip signal is generated & sent to respective Circuit Breakers (CB) for isolating the faulty feeder section of the Distribution System.

5.4 Result Analysis and Discussion

The proposed hybrid PCA and CNN scheme improves classification precision, reduces training time, and improves robustness against variabilities produced by Distributed Generation sources, making it acceptable for real-time application in a Modern Active Distribution System. To obtain time-series voltage and current data, the modified IEEE

9-Bus Distribution System (DS) is simulated through PSCAD/EMTDC software. To evaluate the performance of the suggested method, the dataset is randomly split into training and testing subsets with a ratio of 80:20. 80% of the data is used for training, which is used to learn the model, and the remaining 20% is divided into equal parts to form the validation (10%) and test (10%) sets. This data division helps us detect overfitting and differences in the model's performance. Implementation of 10-fold cross-validation for overall evaluation of the algorithm is shown in Fig. 5.4.

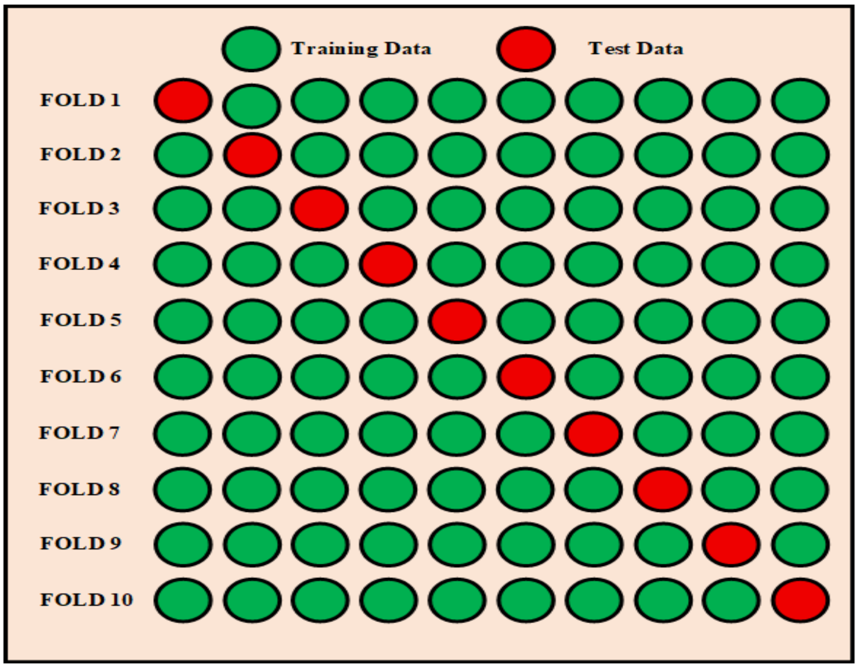


Figure 5.4 Process of 10-fold cross-validation

5.4.1 Convolutional Neural Network (CNN) parameter tuning

For processing 302400 fault cases generated from a 9-Bus Distribution System for precise Fault type Classification and Location, 1D Convolutional Neural Network (CNN) classifier is proposed. Raw 3-phase current and voltage signals are pre-processed by Principal Component Analysis (PCA) to extract dominant features and reduce data redundancy. For real-time applications, a feature-reduced expression is given to a computationally efficient 1DCNN architecture. The implemented 1DCNN model has 3 Convolutional Layers followed by 2 Fully Connected (MLP) Layers, which provides a better trade-off between computational cost and accuracy. Convolutional Layers use 64, 48 and 32 filters with a kernel size (K) of 5 and Rectified Linear Unit (ReLU) activation functions are used to introduce non-linearity. Each Convolutional Layer is followed by max-pooling with Sub-Sampling (SS) 2 for further reducing dimensionality. Multilayer Perceptron (MLP) Layers have 32 neurons in the first hidden layer & 10 neurons in the output layers that consist of 10 Fault categories considered for this investigation.

Adam optimiser with an initial learning rate (e) of 0.001 is utilised for training purposes, and 128 is the batch size. Two-fold termination criteria is used: the backpropagation algorithm ends when the training Classification Error (CE) is less than 0.005 or the maximum iteration number is 85. Implementation of an adaptive learning rate is also done, which increases by 0.05 when training loss is reduced by 30%. To achieve statistical reliability, each experiment is replicated 10 times over various data partitions (as shown in Fig. 5.4), and average classification accuracy is reported to examine the robustness of the proposed model.

5.4.2 Classification Task

Certain metrics are used to assess the classification performance of the suggested model, which include Accuracy, Precision and Recall. Mathematical formulae for each of these metrics are shown below:

$$\text{Accuracy} = \frac{TP + TN}{TP + FP + TN + FN} \tag{5.12}$$

$$\text{Precision} = \frac{TP}{TP + FP} \tag{5.13}$$

$$\text{Recall} = \frac{TP}{TP + FN} \tag{5.14}$$

FN, TN, FP, and TP are False Negative, True Negative, False Positive and True Positive, respectively. False Negative is actual fault instants that the algorithm fails to detect. True Negative is instants that the algorithm correctly identifies as normal state. False Positive is non-faulty events identified as fault. True Positive is instants that are correctly identified as fault.

Results obtained from the proposed model/scheme for fault type classification, faulty line localisation & fault location in % of line length, considering both validation and testing datasets, are presented in Table 5.5, Table 5.6 and Table 5.7 respectively. From Table 5.5 for fault type classification, Table 5.6 for faulty line localisation and Table 5.7 for fault location in % of line length, it is observed that overall accuracy achieved by the proposed scheme for all tasks is more than 99%. Model generalisation is confirmed further by achieving the same classification performance when the test dataset is compared with the validation dataset. Confusion matrices for Fault type classification, Faulty line localisation, and Fault location on line are presented in Fig. 5.5, Fig. 5.6, and Fig. 5.7. It is noted from the results that the proposed scheme showcased better performance with an average accuracy of >99%.

The proposed combined PCA and CNN based scheme achieves higher classification proficiency in all types of faults, with accuracy, precision & recall values greater than 99% for both validation and test datasets. This indicates that the proposed model is capable of successfully extracting discriminative features & differentiate correctly between all types of faults under various system and fault conditions. Similarity between testing & validation metrics shows that the model performs better, confirming that it is not overfitted and has good reliability when observed on unseen fault patterns.

Table 5.5 Testing and Validation results obtained by suggested model for fault type classification

Class Name (Fault Type)	**Validation Accuracy (%)**	**Validation Precision (%)**	**Validation Recall (%)**	**Testing Accuracy (%)**	**Testing Precision (%)**	**Testing Recall (%)**
Rg	99.62	99.58	99.71	99.54	99.50	99.63
Yg	99.57	99.49	99.66	99.48	99.42	99.59
Bg	99.66	99.61	99.74	99.58	99.51	99.70
RY	99.81	99.79	99.85	99.73	99.70	99.78
YB	99.77	99.71	99.82	99.69	99.64	99.75
BR	99.74	99.68	99.80	99.67	99.61	99.73
RYg	99.69	99.63	99.77	99.62	99.55	99.71
YBg	99.71	99.66	99.78	99.64	99.56	99.72
BRg	99.73	99.67	99.81	99.65	99.60	99.74
RYB	99.92	99.90	99.94	99.85	99.82	99.88
Average	**99.72**	**99.67**	**99.80**	**99.64**	**99.59**	**99.72**

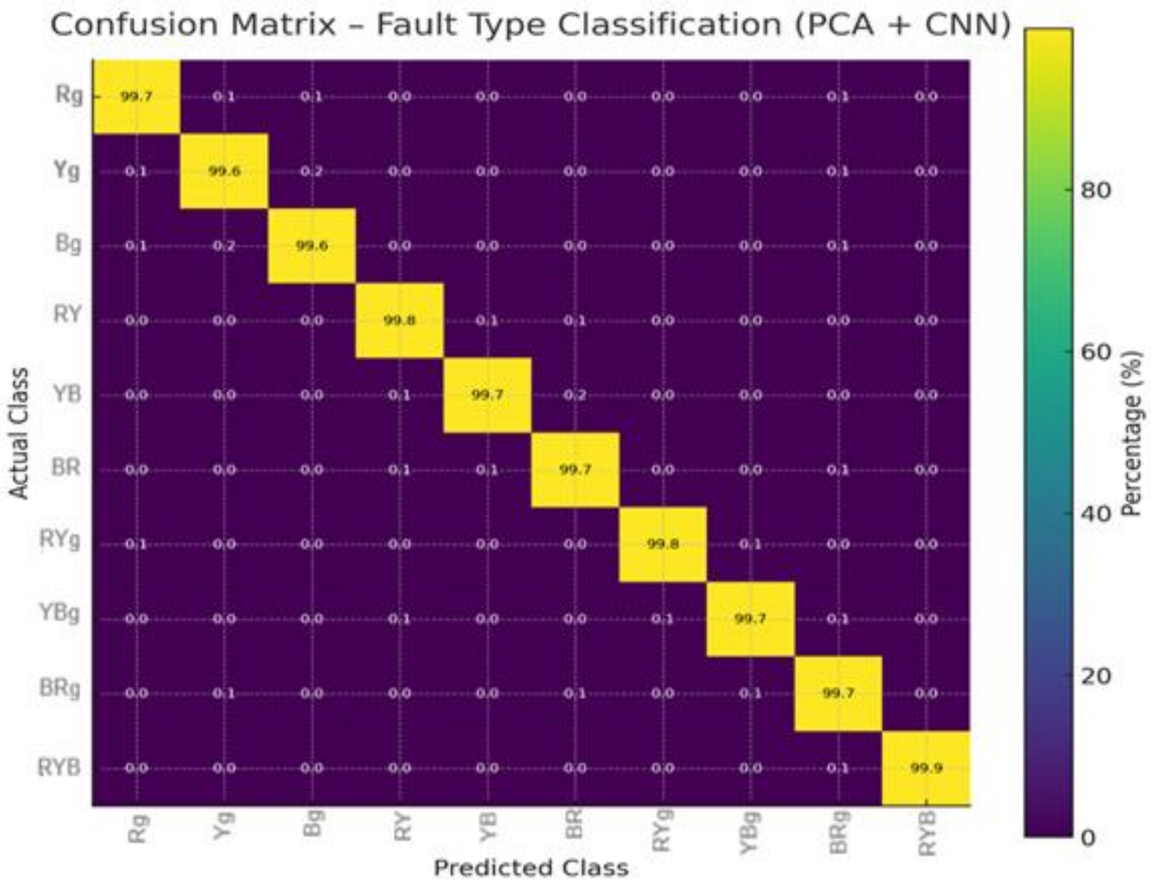


Figure 5.5 Confusion matrix for fault type classification

Table 5.6 Testing and Validation results obtained by the proposed model for faulty line localisation

Class Name (Faulty Line)	Validation Accuracy (%)	Validation Precision (%)	Validation Recall (%)	Testing Accuracy (%)	Testing Precision (%)	Testing Recall (%)
Line 4–5	99.68	99.61	99.74	99.59	99.51	99.70
Line 4–6	99.71	99.65	99.79	99.63	99.57	99.73
Line 5–7	99.76	99.70	99.82	99.67	99.62	99.78
Line 6–9	99.81	99.76	99.87	99.74	99.68	99.83
Line 7–8	99.74	99.68	99.80	99.66	99.60	99.75
Line 8–9	99.79	99.73	99.86	99.71	99.66	99.81
Average	**99.75**	**99.69**	**99.82**	**99.67**	**99.60**	**99.77**

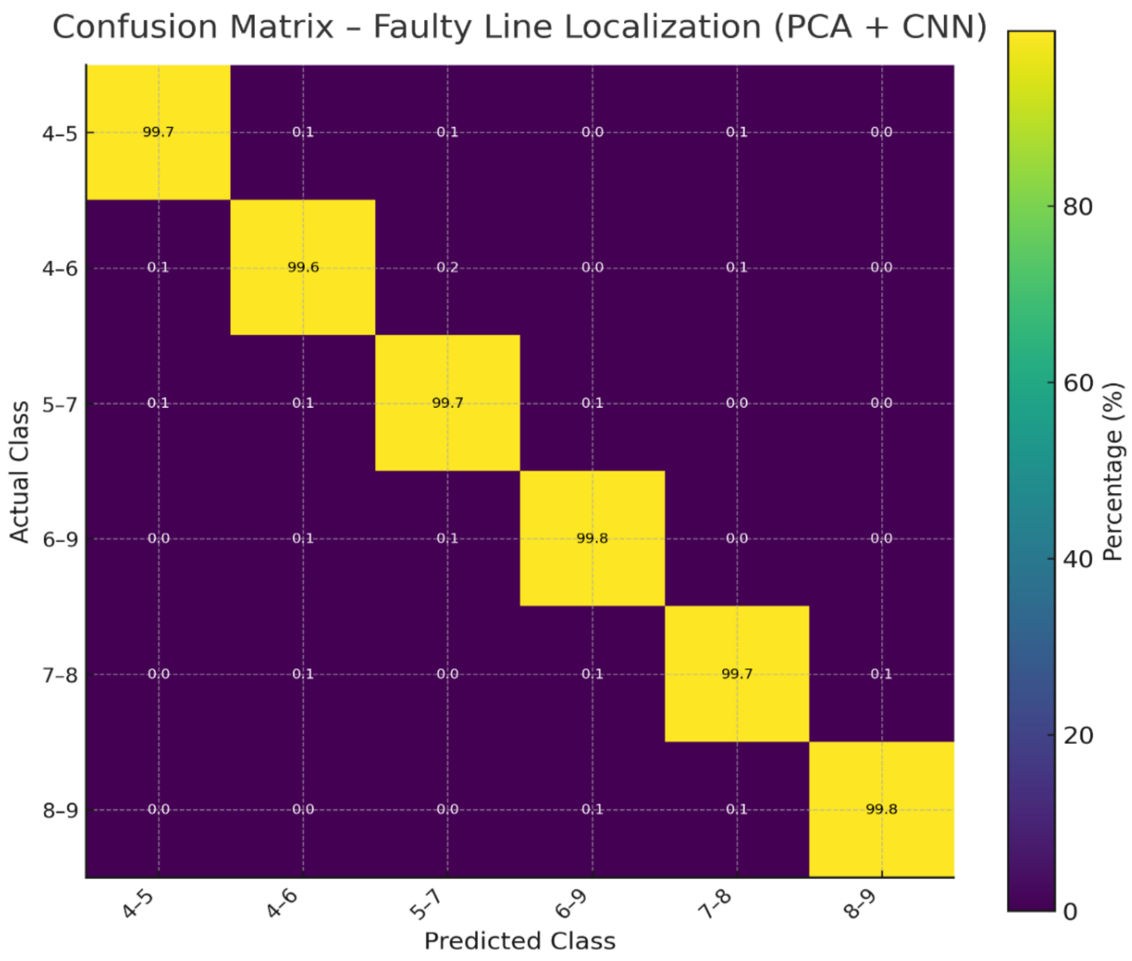


Figure 5.6 Confusion matrix for faulty line localisation classification

Table 5.7 Testing and Validation results obtained by the proposed model for fault location on Line (Fault Location on Line in % of line length)

Class (Fault Location on Line)	Validation Accuracy (%)	Validation Precision (%)	Validation Recall (%)	Testing Accuracy (%)	Testing Precision (%)	Testing Recall (%)
20%	99.8	99.7	99.8	99.7	99.6	99.7
40%	99.9	99.8	99.9	99.8	99.7	99.8
60%	99.9	99.9	100	99.9	99.8	99.9
80%	99.8	99.7	99.8	99.7	99.6	99.7
100%	100	100	100	99.9	99.9	99.9
Average	**99.9**	**99.8**	**99.9**	**99.8**	**99.7**	**99.8**

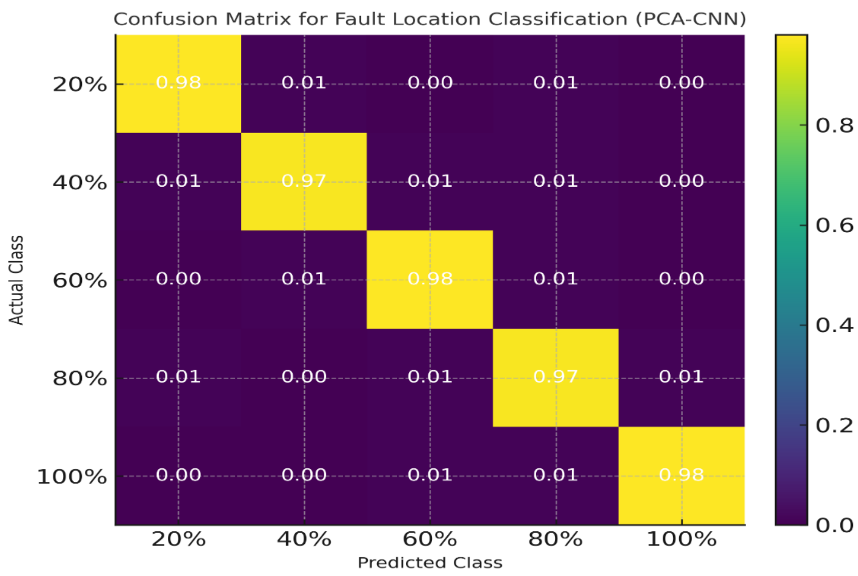


Figure 5.7 Confusion matrix for fault location on the line

For faulty line identification, accuracy, precision, and recall results are also more than 99% using the proposed hybrid PCA and CNN based scheme for all feeder lines in testing and validation datasets. The proposed scheme can accurately identify the line section on which fault is occurring in the presence of variation in parameters like fault location, fault resistance, fault inception angle and source impedance. Steady high accuracy and recall values show low false alarms and precise fault localisation, ensuring reliable operation of the protection model and demonstrating the model's robustness and generalisation capacity. The proposed combined PCA and CNN based method also showcased higher reliability and compatible performance for all five fault location categories, with validation & testing accuracies above 99%. Higher values of precision and recall are the factors that confirm minimum misclassification cases for the proposed model. These results show good accuracy for the proposed scheme in determining the location of faults along the line, which makes it satisfactory for real-time protection schemes and self-healing operation in modern distribution systems.

5.4.3 Comparison between proposed combined PCA & CNN based and other existing method

For comparison of the proposed hybrid PCA and CNN based scheme with other existing methods, all other models are trained & evaluated with a similar dataset partition strategy. The total dataset is divided into 80% for training and 20% for evaluation (10% for validation and 10% for testing). To ensure the best performance, hyperparameters are optimised for benchmark models like KNN, ANN, SVM and GRU. All the models are trained on the same training samples and tested with similar performance metrics (i.e., Accuracy, precision, and recall), allowing direct comparison of classification capabilities for each model considering the same task as the proposed method, such as fault type identification, faulty line selection, and fault location determination.

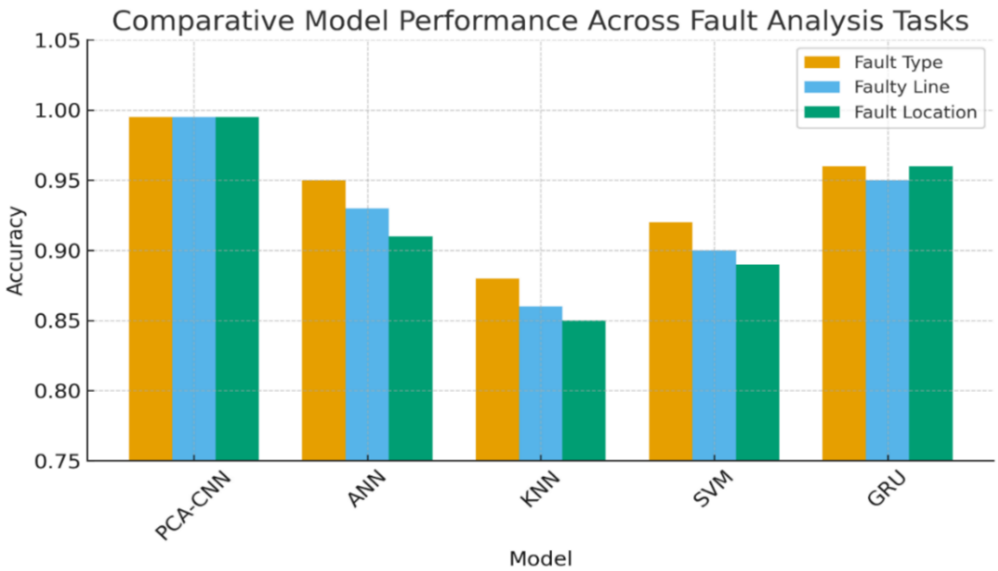


Figure 5.8 Comparison bar chart of the proposed and existing methods for fault classification

Comparison using bar chart for suggested and existing benchmark methods like ANN, KNN, SVM and GRU for fault classification is also shown in Fig. 5.8. Because of advantages like simultaneous noise suppression through Principal Component Analysis (PCA) & spatial pattern extraction of discriminative features with Convolutional Neural Network (CNN), proposed hybrid PCA and CNN based scheme is achieving more than 99% accuracy for all the three tasks. Overall results validate the proposed method as compelling in terms of classification accuracy and prove to be reliable, scalable & computationally efficient compared to other existing methods.

CHAPTER - 6

Combined WPT and XGBoost based Fault Detection and Classification (FDC) scheme for Protection of Distribution System with Distributed Generation Sources

The existence of Distributed Generation (DG) sources can cause fluctuations and an increase in fault currents, changes in current direction and make it bidirectional with changes in operating conditions. These factors make the existing system more complex, convert it into a dynamic active distribution system, and make traditional Fault Detection and Classification (FDC) schemes less efficient. Traditional schemes generally fail under dynamic DG output, load fluctuations and system conditions. To address these issues, various Artificial Intelligence and Machine Learning (AIML) based methods have been developed. These schemes are generally categorized in two types viz. (i) individual methods like Artificial Neural Network (ANN), Wavelet Packet Transform (WPT), Support Vector Machine (SVM), K-Nearest Neighbors (KNN), Convolutional Neural Network (CNN) and Extreme Gradient Boosting (XGBoost) and (ii) hybrid (combining any two methods) which are used for Fault Detection & Classification (FDC) schemes.

Based on various literature references related to Fault Detection and Classification (FDC) ([134]-[167], [176], [183]-[186]), a theoretical comparison between these methods is prepared (as shown in Table 6.1). Comparison is done qualitatively based on different parameters like robustness, computational speed, data requirement, strengths, and limitations, which reflect the performance of a particular method in the context of DG integrated Distribution Systems. From this comparison, it is observed that the Hybrid scheme is superior to individual AIML-based schemes. Considering the advantages of Hybrid schemes, two methods, i.e., (i) Combined PCA & CNN and (ii) Combined WPT & XGBoost are suggested for Fault Detection and Classification (FDC). Combined Principal Component Analysis (PCA) & Convolutional Neural Network (CNN) based scheme (as presented in

Chapter-5) gives FDC accuracy of more than 99% for fault type classification, faulty line localisation, and fault location in % of line length, but has limitations when compared with the hybrid Wavelet Packet Transform (WPT) and Extreme Gradient Boosting (XGBoost) based method as presented in this Chapter. Both schemes are compared based on performance parameters for Fault Detection and Classification (FDC) for Distribution System (DS) with Distributed Generation (DG) sources.

Table 6.1 Theoretical Comparison of Fault Detection and Classification (FDC) Schemes

Method	Robustness	Computational Speed	Data Requirement	Strength	Limitations
KNN	Low-Medium (sensitive to noise)	Medium (optimizable)	Medium-High (stores training instances)	Simple implementation	Poor scalability and robustness
ANN	Medium (sensitive to DG variability)	Medium (Training scales poorly with data)	High (Needs large labelled datasets)	Simple Architecture	Prone to Overfitting
WPT	High (decomposes signals for transient capture)	High (fast decomposition)	Low (works on raw signals)	Excellent for extracting energy features from fault transients	Not a classifier; standalone accuracy is less
SVM	High (effective with kernel)	High (fast for small-medium datasets)	Medium (better on balanced data)	Handles high-dimensional features	Requires manual feature selection
CNN	High (end-to-end learning; noise-resistant)	Medium (GPU-accelerated inference)	High (benefits from large simulated fault data)	Feature extraction from raw signals	Intensive training; less interpretable

XGBoost	High (gradient boosting handles DG noise)	High (parallelizable; fast on tabular features)	Medium (ensemble reduces overfitting)	Efficient dimensionality reduction before classification	Less suited for raw time-series without pre processing
Hybrid	**Very High (combines strengths,**	**Medium (varies by combo**	**Medium-High**	**Best overall**	**Increased complexity**

Though combined PCA and CNN based scheme gives results with high accuracy (>99%) through deep learning features, hybrid WPT and XGBoost based scheme delivers better results overall for Distribution System integrated with DG sources because of (i) superior feature extraction from transient or non-stationary fault signal (WPT >> PCA), (ii) better suitability for classification (XGBoost >> CNN), (iii) computationally efficient, (iv) robustness to challenges related to DG integration and (v) accuracy. In short, WPT+XGBoost is a better method for Fault Detection and Classification (FDC) in a DG integrated distribution system, as it combines time-frequency decomposition (WPT) with a robust and efficient ensemble classifier (XGBoost) (as per comparison given in Table 6.2).

Table 6.2 Point-to-Point Comparison of PCA+CNN and WPT+XGBoost method for Fault Detection and Classification (FDC)

Particular	PCA+CNN	WPT+XGBoost
Feature Extraction	Dimensionality reduction, good for correlated data but limited in capturing non-stationary transient details.	Multi-resolution Time-Frequency decomposition, better in case of non-stationary DG-induced signals.
Classifier Characteristics	Deep Learning, handles complex patterns.	Ensemble tree boosting, excellent in handling of imbalance/noisy data.
Accuracy Performance	Approx. 99.0-99.6%	Comparable (can reach up to 99.8-100%)
Data Requirement	High	Moderate

Robustness to DG Effects	Good (PCA mitigates noise and reduces dimensionality)	Excellent (WPT captures transients despite low/variable fault currents)
Computational Speed	High	Comparatively higher
Generalization	Excellent	Comparatively strong

A generalized protection algorithm (as presented in Fig. 3.13) with generalized Fault Detection & Classification (FDC) process is presented in Fig. 6.1. Proposed WPT+XGBoost method is later compared (K-Nearest Neighbors (KNN) not considered because of poor overall performance) with Artificial Neural Network (ANN), Wavelet Packet Transform (WPT), Convolutional Neural Network (CNN), Support Vector Machine (SVM), Extreme Gradient Boosting (XGBoost) and hybrid (Wavelet Packet Transform (WPT)+Convolutional Neural Network (CNN) & Principal Component Analysis (PCA)+Convolutional Neural Network (CNN)) schemes in terms of performance parameters.

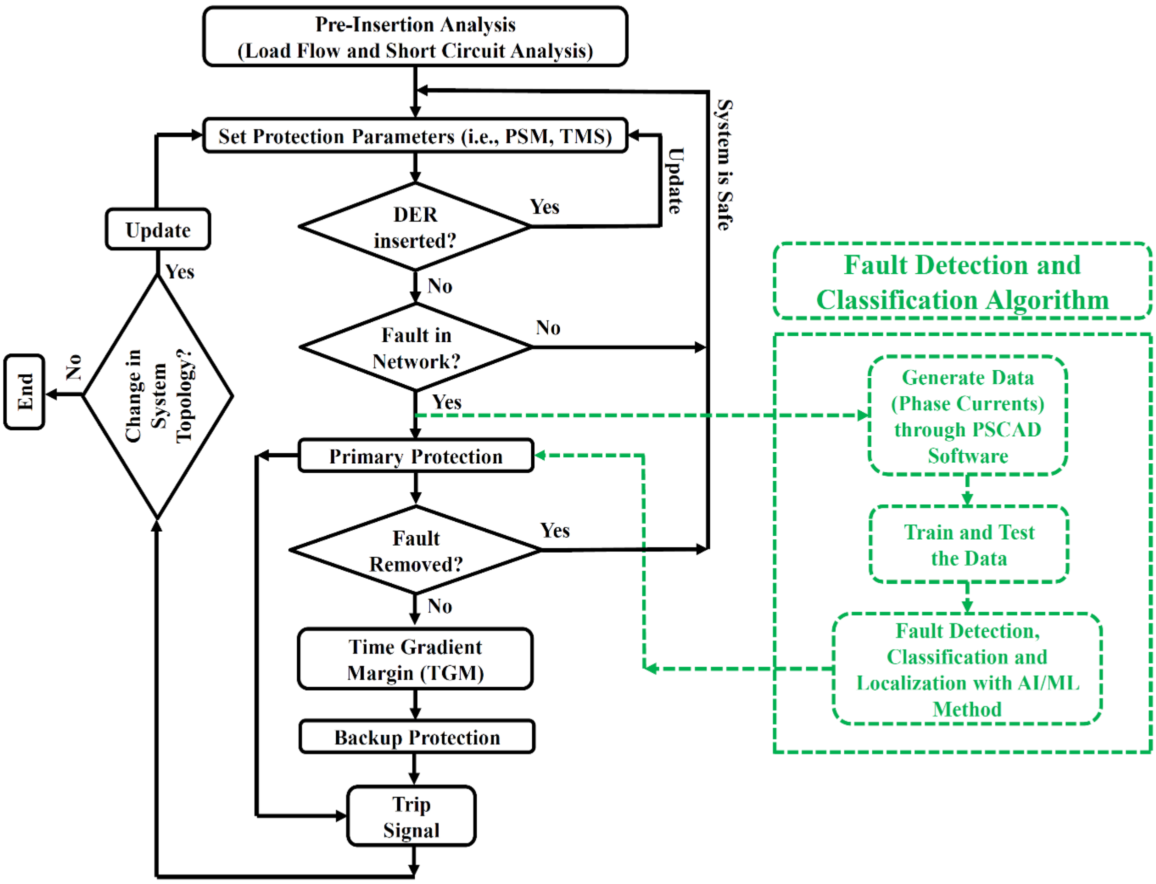


Figure 6.1 Generalized protection algorithm with generalized FDC process

6.1 Combined WPT and XGBoost based Fault Detection and Classification

A combined Wavelet Packet Transform (WPT) and Extreme Gradient Boosting (XGBoost) based approach is proposed for a Distribution System integrated with Distributed Generation sources. This approach uses Wavelet Packet Transform (WPT) to learn multi-resolution characteristics of non-stationary transient signals and utilises it in an ensemble classifier like Extreme Gradient Boosting (XGBoost) for getting accurate and dependable fault detection and classification. This proposed scheme can handle inverter-interfaced low fault currents, noise and variable operating modes. WPT provides better high-frequency sub-band decomposition to capture transient signals in DG integrated systems, and XGBoost excels in handling high accuracy for multi-class fault classification.

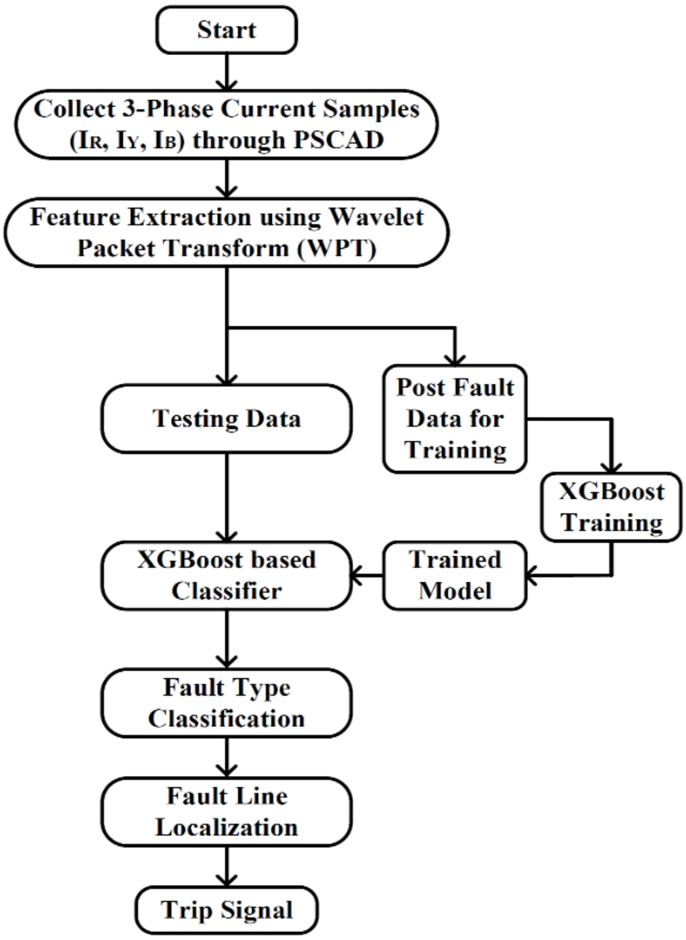


Figure 6.2 Proposed WPT+XGBoost based FDC algorithm

In the algorithm combining WPT and XGBoost (as shown in Fig. 6.2), the very first step is data acquisition/collection, where current data is collected from various selected locations.

For current dataset generation, the IEEE 4-Bus Distribution System is simulated in PSCAD/EMTDC software. Feature extraction is done with Wavelet Packet Transform (WPT), which is used to decompose signals into both approximation and detail packets at various levels and offers full binary decomposition. Wavelet Packet function at level j and node p,

$$W_{j,p}(t) = 2^{\frac{j}{2}} W\left(2^{-j}t - p\right) \tag{6.1}$$

In equation 6.1, W is the mother wavelet function, which is generally db4. For node (j,p)

$$d_{j+1,2p}(k) = \sum_n h\ (n - 2k)\ d_{j,p}\ (n) \tag{6.2}$$

$$d_{j+1,2p+1}(k) = \sum_n g\ (n - 2k)\ d_{j,p}\ (n) \tag{6.3}$$

Where h and g are low and high pass filters modulated for packet p. Per-phase and zero-sequence extraction is done using common features. Extracted features are given to the Extreme Gradient Boosting (XGBoost) classifier, which is a scalable tree boosting ensemble that minimises a regulated objective.

$$L = \sum_i l\ (\hat{y}_i, y_i) + \sum_k \Omega\ (f_k) \tag{6.4}$$

where l is the cross-entropy loss and regularisation,

$$\Omega\ (f) = \gamma T + \frac{1}{2}\ \lambda\ \|w\|^2 \tag{6.5}$$

T represents the number of leafs, and w denotes the weight. Labels like No-Fault, LG, LL, etc are considered. For tuning hyperparameters, a multi-class objective or binary classifier per fault type is used. With the integration of a DG source, zero-sequence current features should be taken into account. Tuning is done with different cases like fault inception angle and fault impedance, and then validation is performed.

This combined WPT and XGBoost based algorithm is computationally efficient for modern relays and outperforms conventional schemes, as it provides better transient capture and robust classification of fault events.

6.2 Simulation, Results and Discussion for WPT+XGBoost based FDC scheme

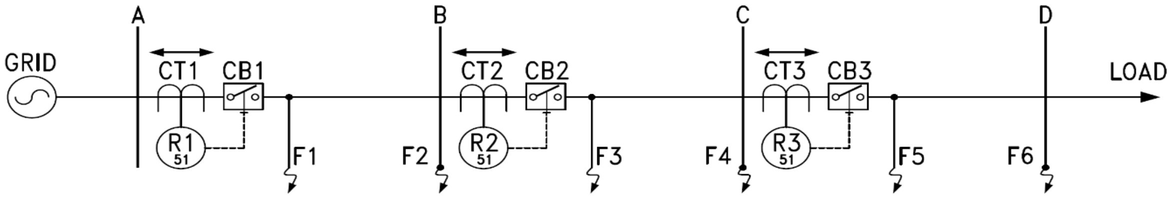


Figure 6.3 IEEE 4-Bus Radial Distribution System (with one source)

The modified IEEE 4-Bus Distribution System (DS) (as shown in Fig. 6.3) is prepared through PSCAD/EMTDC (as shown in Fig. 6.4) software for data generation (post-fault data), which will be used in the proposed algorithm for performance parameter calculation using MATLAB software. Equations for performance parameters like Accuracy, Precision, Recall & F1 Score are presented in Equations 6.6, 6.7, 6.8 and 6.9, respectively.

$$\text{Accuracy} = \frac{TP + TN}{TP + FP + TN + FN} \tag{6.6}$$

$$\text{Precision} = \frac{TP}{TP + FP} \tag{6.7}$$

$$\text{Recall} = \frac{TP}{TP + FN} \tag{6.8}$$

$$\text{F1 Score} = \frac{2 * (\text{Precision} * \text{Recall})}{\text{Precision} + \text{Recall}} \tag{6.9}$$

Table 6.3 Fault Simulation Cases Count (For system with one source) (as shown in Fig. 6.4)

System Parameters	Configuration	Data Counts
Fault Locations	At Mid-Point (10 km, 30 km, 50 km from grid) and End of each line section (20 km, 40 km, 60 km from grid)	6
Fault Resistances	0 ohm, 3 ohm, 6 ohm, 9 ohm, 12 ohm, 15 ohm, 18 ohm	7
Fault Types	LG (Rg, Yg, Bg), LL (RY, YB, BR), LLG (Ryg, YBg, BRg), LLL	10
Fault Inception Angle	0°, 5°, 10°, 15°, 20°	5
	Total Fault Simulation Cases	**2100**

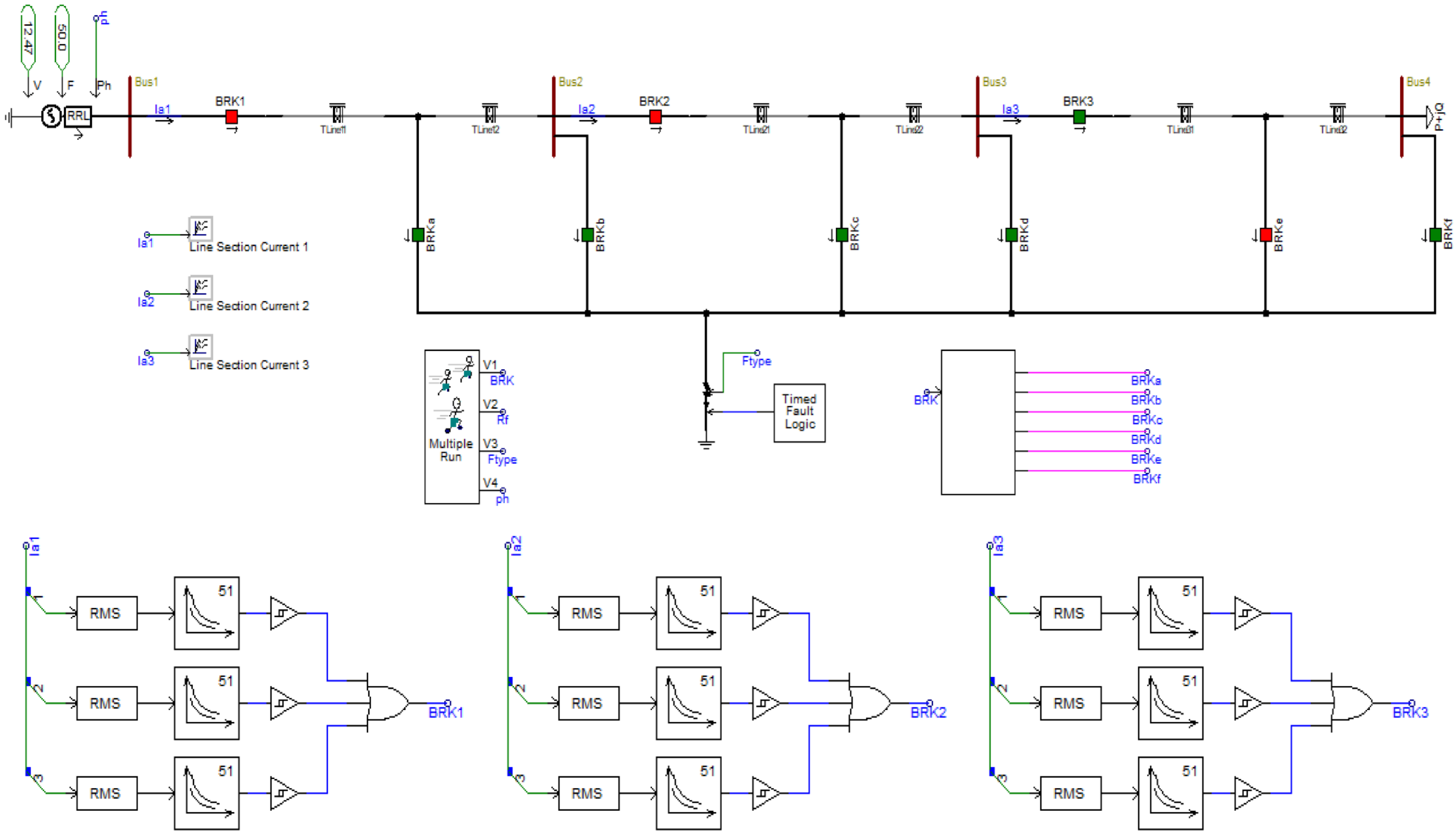


Figure 6.4 PSCAD Simulation of IEEE 4-Bus System for Dataset Generation (with one source)

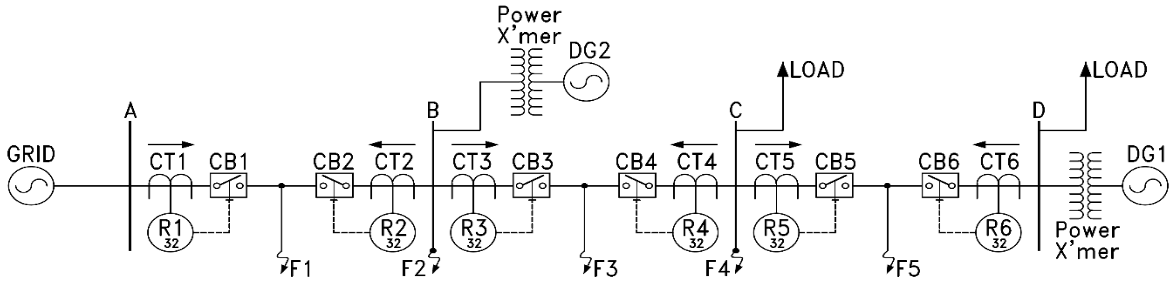


Figure 6.5 IEEE 4-Bus Distribution System (with more than one source)

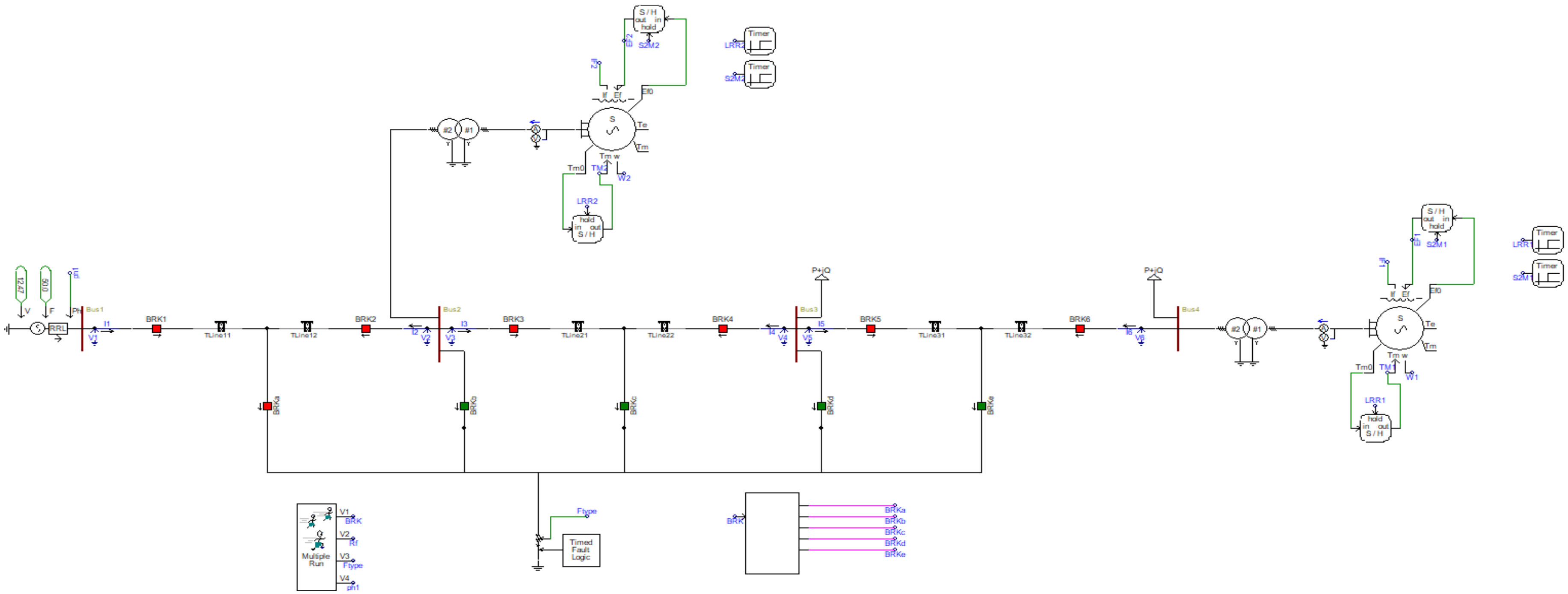


Figure 6.6 PSCAD Simulation of IEEE 4-Bus System for Dataset Generation (with more than one source)

Table 6.4 Fault Simulation Cases Count (For system with more than one source) (as shown in Fig. 6.6)

System Parameters	**Configuration**	**Data Counts**
Fault Locations	10 km, 20 km, 30 km, 40 km, 50 km from grid	5
Fault Resistances	0 ohm, 3 ohm, 6 ohm, 9 ohm, 12 ohm	5
Fault Types	LG (Rg, Yg, Bg)	3
Fault Inception Angle	0°, 5°, 10°, 15°	4
	Total Fault Simulation Cases	**300**

All these performance parameters are calculated for various methods like ANN, WPT, SVM, CNN, XGBoost, WPT+CNN, and PCA+CNN to compare with the proposed combined WPT and XGBoost based method with 2400 generated cases. Fault simulation cases through PSCAD/EMTDC software are generated as shown in Table 6.3 & Table 6.4, and the extracted data is then used in the proposed (combined WPT and XGBoost based) algorithm for performance parameter calculation and comparison. For comparison, mainly two parameters, viz. Accuracy and F1 score are considered. Performance of each method in terms of these two performance parameters is shown in Table 6.5.

PREDICTED CLASS

ACTUAL CLASS	RG	YG	BG	RY	YB	BR	RYG	YBG	BRG	RYB
RG	99.8	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1
YG	0.0	99.8	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0
BG	0.0	0.0	99.8	0.0	0.0	0.1	0.0	0.0	0.1	0.0
RY	0.0	0.0	0.0	99.9	0.0	0.0	0.0	0.0	0.0	0.1
YB	0.1	0.0	0.1	0.0	99.7	0.0	0.0	0.0	0.1	0.0
BR	0.0	0.0	0.0	0.0	0.0	99.9	0.0	0.0	0.1	0.0
RYG	0.0	0.0	0.1	0.0	0.0	0.0	99.9	0.0	0.0	0.0
YBG	0.0	0.0	0.0	0.0	0.1	0.0	0.0	99.8	0.1	0.0
BRG	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.0	99.8	0.0
RYB	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.0	99.8

Figure 6.7 Confusion Matrix for Proposed WPT+XGBoost based FDC scheme

Table 6.5 Fault Detection and Classification (FDC) performance comparison

Method	Accuracy	F1 Score
ANN	94.75	95.10
WPT	98.65	98.77
SVM	97.69	97.07
CNN	98.92	95.40
XGBoost	94.59	95.06
WPT+CNN	98.81	98.14
PCA+CNN	99.22	98.97
WPT+XGBoost	**99.87**	**99.69**

After simulating and generating data for 2400 cases, considering the advantages of the hybrid method presented in Table 6.1 and combining benefits from WPT and XGBoost, the results shown in Table 6.5 indicate that the proposed WPT+XGBoost method is better in Fault Detection and Classification, with accuracy more than 99.5%. This proposed scheme has also achieved a higher F1 score (as presented in Table 6.5). The confusion matrix for the proposed WPT+XGBoost method is also presented in Fig. 6.7. These results support selection of the proposed scheme for Fault Detection and Classification (FDC) for a Distribution System with Distributed Generation sources. The proposed combined WPT and XGBoost-based scheme also exhibits faster computation, making it more suitable for real-time implementation, and it contributes towards an enhanced protection scheme for Distribution System (DS) with Distributed Generation (DG) sources with higher reliability.

CHAPTER - 7
Conclusion and Future Scope

7.1 Conclusion

Increasing usage and integration of Distributed Generation (DG) sources like Solar PV, Wind Power Generation and other Inverter Interfaced Distributed Generation (IIDG) sources in the Distribution System brings opportunities as well as various challenges. It mainly affects conventional protection schemes because of bidirectional power flow, dynamically varying normal as well as fault currents, and reduced current contribution from the grid (or DG in case a new DG source is added), which leads to protection blinding. Conventional protection schemes face problems like sympathetic tripping, loss of coordination, nuisance tripping of DG units and potentially undetected faults or islanding and fail in maintaining sensitivity and selectivity under dynamic conditions, which demands an accurate and reliable Fault Detection and Classification (FDC) scheme for protection of the Distribution System with Distributed Generation sources.

For the study, a comprehensive literature review and extensive simulation-based analysis performed through PSCAD/EMTDC software highlight various factors that have a significant impact on protection coordination, such as fault current contribution from DGs ($I_{f\text{-}SG}>I_{f\text{-}IG}>I_{f\text{-}PV}$), DG penetration and network topology. Through simulational analysis, it is also found that protection coordination is affected by DG location, combination of DG types integrated in the system, fault types, fault location and fault resistance. An adaptive overcurrent protection is also developed for an Industrial Distribution System, where, with different source combinations and system conditions (grid-connected or islanded), analysis for calculating protection parameters is also performed using ETAP software. Through extensive simulations with various setting groups, it is concluded that the risk of protection miscoordination is mitigated with the proposed overcurrent protection.

Combined Principal Component Analysis (PCA) and Convolutional Neural Network (CNN) based Fault Detection and Classification (FDC) scheme is developed for the Distribution

System with Distributed Generation Sources which achieves accuracy more than 99% with fault classification, fault line identification and fault location on line in % of line length but has limitation in terms of handling non-stationary transient signals, also achieves less accuracy and F1 score compared to combined WPT and XGBoost based hybrid method. This study also proposes a hybrid method for Fault Detection and Classification (FDC) for reliable protection of the distribution system with distributed generation sources, combining Wavelet Packet Transform (WPT) for feature extraction with Extreme Gradient Boosting (XGBoost) as a powerful ensemble classifier with higher accuracy.

Simulation of various cases for a Distribution System (DS) with Distributed Generation (DG) sources for data generation is performed, and the generated data is used in MATLAB to calculate performance parameters for various methods like ANN, CNN, SVM, WPT, XGBoost and Hybrid schemes for comparison with the proposed method. The hybrid technique combining WPT with XGBoost for fault detection and classification achieves more than 99% accuracy, along with a better F1 score. The proposed method exhibits faster computation, making it more feasible for real-time implementation. WPT+XGBoost approach contributes towards an enhanced protection scheme with higher reliability. This proposed scheme also ensures reliable and selective operation, maintaining protection coordination of the Distribution System even under high DG penetration levels.

7.2 Future Scope

Categorical Boosting (CatBoost) is theoretically more accurate than Extreme Gradient Boosting (XGBoost). Future work can explore the possibility of integrating the CatBoost algorithm either as a standalone classifier or as a hybrid ensemble classifier combined with advanced signal processing techniques like Wavelet Packet Transform (WPT) or other machine learning approaches like Convolutional Neural Network (CNN) to increase Fault Detection & Classification accuracy. CatBoost offers distinct benefits over similar gradient boosting methods, with efficient handling of categorical features, reduced overfitting with its ordered boosting mechanism, strong generalisation performance with minimum hyperparameter tuning and better accuracy & training efficiency on non-stationary transient datasets, which makes CatBoost well suited for complex and real-time digital protection in highly dynamic active distribution systems with distributed generation sources.

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List of Publications

Published Papers

[1] Desai, I. & Chothani, N. (2026). Fault Detection and Classification for Distribution Network with Decentralized Power Generation Sources using combined WPT and XGBoost. Proceedings of International Conference on Electrical, Electronics, and Sustainable Innovations (ICEESI 2026), 1-5. doi: https://doi.org/10.1109 /ICEESI68020.2026.11583159.

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[4] Desai, I., Jacob, P., Chothani, N., & Mangroliya, D. (2026). Overcurrent Protection Scheme for Industrial Distribution System with Decentralized Power Generation Resources. SSRG International Journal of Electrical and Electronics Engineering, 13(1), 19-30. doi: https://doi.org/10.14445/23488379/IJEEE-V13I1P103. **(SCOPUS Indexed)**

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[6] Desai, I., Chothani, N., & Jacob, P. (2025). Comprehensive review on implementation of digital protection in distribution system with distributed generation sources. Proceedings of Parul University International Conference on Engineering and Technology 2025 (PiCET 2025), 1-8. doi: https://doi.org/10.1049/icp.2025.1563 (published in IET Conference Proceeding 2025). **(SCOPUS Indexed)**

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[8] Chothani, N., & Desai, I. (2021). Fourier Transform and Probabilistic Neural Network based Fault Detection in Distribution System Containing DGs. Proceedings of 2021 Innovations in Power and Advanced Computing Technologies (i-PACT), 1-6. doi: https://doi.org/10.1109/i-PACT52855.2021.9696718.

Appendix - A
Protection Relays for Distribution System Protection in PSCAD

A.1 Inverse Time Overcurrent Relay for Distribution System without Distributed Generation Sources

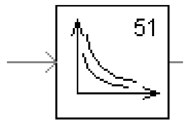

Figure A.1 PSCAD representation of Inverse Time Overcurrent Relay

Description

Inverse Time Overcurrent Relay exhibits an inverse time-current characteristic by integrating a current-dependent function F(I) with respect to time. F(I) is positive above and negative below pickup current. The Pickup Current is the minimum current at which the integration process begins. Once the accumulated integral reaches a predetermined positive threshold, the relay operates and gives an output of 1. The relay gives an output of 1 (trip) when the input current is higher than the pickup current and resets when the current is less than the pickup current value.

Input Parameters

- **Data Entry Format:** Select Explicit, Automatic_Standard or Automatic_Company for defining the characteristics for the Relay.
  - In Explicit data entry, constants for the equation of relay operating time (Top) can be entered manually.
  - If Automatic_Standard option is selected, constants for the equation of relay operating time (Top) are taken automatically based on the selected standard (IEEE Standard

C37.112 or IEC standard 60255-3) and characteristics (Moderately Inverse, Inverse, Very Inverse or Extremely Inverse).

- If Automatic_Company option is selected, constants for the equation of relay operating time (Top) are taken automatically based on Company Curve (Type CO, Type IAC, Alstom MCGG or SEL) and characteristics (Moderately Inverse, Inverse, Very Inverse or Extremely Inverse).

- **Resettable:** Select Yes or No. Relay resets forcibly if Yes is selected.
- **Pickup Current:** Pickup Current is the current above which the relay operates and produces an Output '1'.
- **Time Dial Setting:** Time Dial Setting (TDS) controls the time scale of time-current characteristics or operating time of the Relay.

A.2 Negative Sequence Directional Element Relay for Distribution System with Distributed Generation Sources

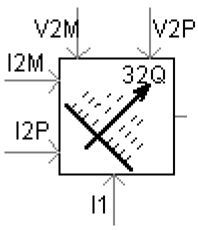

Figure A.2 PSCAD representation of Negative Sequence Directional Element Relay

Description

Negative Sequence Directional Element (NSDE) works on the principle that (i) for forward fault, negative sequence impedance is negative and (ii) for reverse fault, it is positive. Considering a strong source behind the relay terminal, it may result in low negative sequence voltage. To overcome this situation, a compensating quantity is added to boost negative sequence voltage, which introduces forward and reverse thresholds. In that case, if $Z_2 < Z_{2f}$, then the fault is forward and if Z2 > Z2r, the fault is reverse. To avoid overlapping, the forward threshold must be less than the reverse threshold. If the ratio of negative sequence current to positive sequence current exceeds a particular limit, output will be generated. Also, the negative sequence current has to be more than another specified setting.

Inputs for this component are:

- **I2M:** Magnitude of negative sequence current.
- **I2P:** Phase of negative sequence current [rad] or [deg].
- **V2M:** Magnitude of negative sequence voltage.
- **V2P:** Phase of negative sequence voltage [rad] or [deg].
- **I1:** Positive sequence restraint current.

The output of this relay will be '1' for a forward fault and '-1' for a reverse fault.