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Optimal coordination for directional over-current relay using different optimization algorithms

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Abstract

Short circuits can occur unexpectedly at any time and in any part of a power system due to various issues, causing a significant amount of fault current to flow through the equipment. These faults are harmful and must be quickly isolated by protective devices. The protective system's role is to swiftly detect faults and remove them from the power network. Among the most important protective components in power networks is the overcurrent relay. Overcurrent relays provide both primary and backup protection for heavily interconnected and multi-source power networks. The pickup value of an overcurrent relay must be set between the maximum load current and the minimum fault current encountered. Directional overcurrent relays (DOCRs) are widely used as primary protection in sub-transmission systems and as backup protection for distance relays in transmission networks. Coordinating DOCRs involves selecting appropriate relay settings, such as plug setting (PS) and time dial setting (TDS), ensuring the primary relay responds faster than any other relays in the system. If the primary relay or its associated circuit breaker fails, backup relays must operate after a set time interval to ensure proper sequential operation. Recently, there has been significant interest in solving the DOCR coordination problem using metaheuristic algorithms. Various techniques, including teaching-learning-based optimization (TLBO), genetic algorithms (GA), particle swarm optimization (PSO), and the modified water cycle algorithm (MWCA), have been proposed to find optimal solutions for DOCR coordination. This research introduces a new formulation and solution for setting and coordinating DOCRs using an efficient optimization technique called improved AVOA. The main goal of optimal DOCR coordination is to minimize the total operating time of all relays while maintaining a time margin between backup and primary relays. Rigorous experiments are conducted on benchmark IEEE 9-bus and IEEE 39-bus test systems to validate the proposed relay coordination methodology. A comparative analysis of the outcomes with other well-known optimization algorithms conclusively shows that the proposed methodology is superior in meeting coordination constraints, with empirical evidence supporting its effectiveness.

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Dedication

To my Beloved Mother and Father , who have

always supported me

throughout this journey.

To my Dear Sisters and Brother , who have stood

by my side

in both the good times and the challenging ones.

To all my relatives and Friends ,

And to all the mentors and teachers,

whose guidance and wisdom have shaped my path.

This work is dedicated to you all.

Thank you for everything.

Chems Eddine & Mohamed Soufiene.

Table of Contents

List of Figures

List of Tables

List of Abreviations

DOCR: Directional over-current relay

PS : Plug Setting

TDS : Time Dial setting

CTI : Coordination time interval

DG : Distributed generator

I : Inverse

V.I : Very inverse

E.I : Extremely inverse

RCT : Relay curve type

PSM : Plug Setting Multiplier

TSM : Time Setting Multiplier

Top,pr : primary relay's operating time

Top,bc : Back-up relay's operating time

OF : Objective function

LP: Linear Programing

NLP : Non Linear Programing

ANSI: American National Standards Institute

IEC : International Electrotechnical Commission

CT : Current transformer

VT : Voltage transformer

HSR : High Setting Relay

PSO : Particle Swarm Optimization

GTO : Gorilla Troops Algorithm

EO : Equilibrium Optimizer

TCB : Circuit Breaker Operating Time

TOS : Over-shot Time

MINLP : Mixed Integer Non Linear Programming

SOTF : Switch -On To Fault

ROT : Relay Operating Time

TCCCs : Time-current characteristic curves

DTOCR : Definite Time Over Current Relay

DCOCR : Definite Current Over Current Relay

Chapter 1

General introduction

1.1 Introduction

Modern electric power systems are designed to meet the demands of wide geographical areas, incorporating major components such as generators, transformers, transmission lines, and distribution lines. These systems enable the transmission of electricity from suppliers to consumers across large distances, utilizing series var compensated devices in transmission lines to enhance power transfer capability and system integrity. The primary goal is to ensure a reliable energy supply with the highest possible continuity, particularly as demand and the need for uninterrupted service have grown.

To meet these demands, equipment with substantial power capacity and complex interconnections is necessary. However, this increased complexity places significant strain on protection systems. Despite power systems typically operating in a steady state, various electrical faults—temporary or permanent—can occur due to the large number of components prone to failure. These faults, often occurring on overhead transmission lines, can result from conductor breakage, insulation failure, or external factors such as bird contact or tree limbs.

Faults can cause large currents to flow in the affected part of the power system, leading to significant damage if not promptly addressed. Situations like dead short circuits can be particularly damaging, not only to the faulty component but also to neighboring parts of the system. Failure to detect and address faults quickly may result in a severe reduction of system voltage, loss of synchronism, revenue loss due to prolonged outages, and permanent damage to equipment.

Therefore, it is crucial to minimize damage by promptly isolating faulty sections from the healthy power system network without disrupting overall system operation. This task is accomplished using sophisticated protective systems in conjunction with appropriate switch-gear mechanisms. Protective relays installed at various points in the power system network detect different types of faults and isolate the affected sections from the rest of the system. These relays continuously monitor system performance and trigger actions when deviations from normal levels are detected, safeguarding the integrity and reliability of the power system. Depending on the application, protective relays receive signal inputs from power system voltages and/or currents via voltage and/or current transformers.[1]. Figure 1.1 shows a hypothetical power system

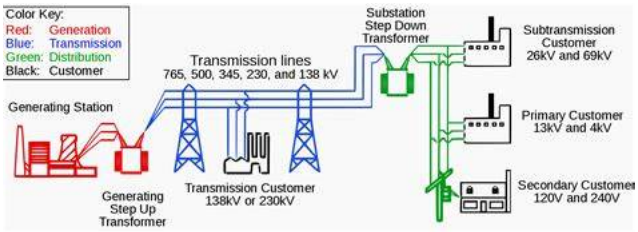


Figure 1.1: Power System presentation
[2]

1.2 Literature review

The protection of the electrical network is a branch of electrical power engineering, tasked with designing a protection system capable of permanently safeguarding the electrical network to ensure continuous and reliable power supply. As developments in the electrical system alter its structure, the design and adjustment of the electrical system protection become increasingly complex. It is primarily based on protection relays of various types and functions. In electrical engineering, a protection relay is a complex digital device designed to continuously measure the operating conditions of an electrical system and trigger the appropriate circuit breakers when a fault is detected.[3]

To design a protection system, it is necessary to understand the characteristics of faults by calculating various associated electrical parameters. These mainly include current, voltage, and frequency. The most common electrical phenomenon in the event of a fault is a sudden and generally significant increase in current; therefore, protection against overcurrent is widely used. Due to their low cost and ease of implementation, directional overcurrent relays (DOCRs) are commonly deployed in distribution electrical networks. For electrical power transmission and distribution systems, they are primarily coordinated with distance relays.

Furthermore, selecting the appropriate tripping characteristic and its settings for protection relays is a crucial task in the design of a protection system. This ensures that the relays are capable of detecting abnormal or undesirable conditions and then triggering the appropriate circuit breaker to disconnect the affected area. According to statistics, a large number of relay trippings are due to incorrect or inadequate settings rather than actual faults. The problem of coordinating protection relays in electrical systems involves choosing their appropriate settings so that the devices' operating characteristics occur in a specific order, fulfilling their fundamental protection function while meeting sensitivity, selectivity, reliability, and speed requirements.[4]

A protection system must meet the following requirements to ensure effective protection:

- A variety of fault conditions must be detected by the appropriate relays.
- Relays located near the fault must have priority operation.
- In case of failure of a primary relay, a secondary relay must operate.
- Relay operation must be as fast as possible to prevent equipment damage and should occur only in the presence of abnormal operating conditions to avoid unnecessary tripping.

• Furthermore, the design of a protection system must satisfy a variety of technical constraints related to relay and equipment technical limitations and the stability of the electrical network.

Consequently, the system's reliability is ensured for its remaining operational duration. . The notion of a backup plan is employed to guarantee the dependability of the protection system, each overcurrent device is paired with a backup overcurrent device. Should a fault occur and the primary device fail to address it, the secondary device steps in to mitigate the fault current and safeguard the system. The better coordination of direction overcurrent relays is essential for improved power system efficiency and to avoid the issue of equipment damage. However, achieving this coordination is a challenging and time-consuming endeavor. DOCRs are essentially a fusion of overcurrent relays (OCRs) with directional units. They activate only when the current magnitude exceeds a specific threshold and flows in the same direction as the DOCR.[5]

DOCRs are characterized by two adjustable parameters: the plug setting (PS) and the time dial setting (TDS), which affect the duration of relay operation. Achieving proper TDS and PS settings is imperative for ensuring the decent operation of DOCRs within a power system.

However, the complex nature of electrical distribution networks make traditional analytical approaches ineffective for computing relay settings.

So let's say that our goal from this research is to find variable values that reduce operating time. Optimization techniques are used in many fields of research, including manufacturing, renewable energy, control systems, computer science, coordination in protection, and so on. Therefore, coordinating DOCR using various optimization techniques is a hot issue right now. The goal is to optimize TDS and PS values in order to preserve different limitations while still meeting the minimum needed operating time .

Usually, the problem of coordinating DOCRs in interconnected electrical systems is formulated as an optimization problem considering conventional time-current operating characteristics [6] [5]. The problem is linearized and expressed as a linear programming (LP) problem in [7]. Additionally, heuristic methods such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and evolutionary methods have been developed to solve the complex and non-convex problem of DOCR coordination [8] [7] . The protection coordination problem is relaxed , and presented as a nonlinear programming (NLP) problem . Another formulation of the protection coordination problem has been studied considering mixed-integer nonlinear programming (MINLP). Another approach that utilizes hybrid algorithms by combining two or more unique optimization algorithms .

As we have already seen, optimization techniques are considered appropriate methods for solving the problem of DOCR coordination. However, in some cases, optimization does not always guarantee adequate coordination. Additionally, the complexity associated with conventional protection relays under such conditions is often emphasized as the most complex problem to achieve a quick response while satisfying all the necessary protection requirements. Therefore, changes must be considered to improve the performance of protection relays. The classical coordination model remains valid, but only for certain constraints. Highly constrained systems require the development of rapid resolution techniques capable of handling dynamic data while maintaining system coordination over time

1.2.1 Thesis organization

This thesis is organized into four chapters, structured as follows:

Chapter I provides the introduction and motivation behind the research work. Besides, a literature review of the previous works is well discussed.

Chapter II summarizes the various types of protection relays, their operating principles, and the importance of their settings and coordination during the design phase of an electrical protection system. Directional Overcurrent Relays (DOCRs) are detailed further for use in this thesis.

Chapter III Algorithms are the backbone of problem-solving, providing systematic approaches to tackle complex tasks efficiently. In my project, I utilized various algorithms to optimize processes and achieve desired outcomes. By leveraging these algorithms, I was able to streamline operations and deliver impactful results. I have significantly enhanced an algorithm within my project, refining its efficiency and accuracy through iterative optimization and fine-tuning.

Chapter IV presents a new optimization technique for optimal coordination of directional overcurrent relays, and a comparative study between other methods using different IEEE power systems.. The IEEE 9-bus and IEEE 39-bus test systems are used to validate the proposed formulation. The results obtained offer more flexibility during the optimization process and thus ensure the satisfaction of coordination constraints and the reduction of the total operating time of DOCRs. Comparison with previous works indicates the ability of the proposed approach to solve the coordination constraint and minimize the number of violations.

Chapter 2

Overview of the protection relays in electrical networks

2.1 Introduction

This chapter is intended to underscore the importance role of power system protection. It provides a various type of open- and short-circuit faults, define specific protection zones, and clarifies the operational principles of both primary and backup relays. This chapter provides an overview of different types of protection relays, their operating principles, and the importance of their configuration and coordination during the design phase of an electrical protection system. Specifically, it delves into the details of : Directional Overcurrent Relays (DOCRs) , is discussed in detail in this chapter for their subsequent utilization in this thesis.

2.2 PROTECTION SYSTEM

In the design of an electrical protection system, careful choices and adjustments of protective elements are made, along with the implementation of an overall structure that is coherent and suitable for the network. As illustrated in Figure 2.1, most protection systems contain the following key electrical components. Firstly, there are equipment used for measuring and monitoring the conditions of the electrical system, such as current transformers (CT) and voltage transformers (VT). Subsequently, protective relays translate signals from these measuring devices into decisions regarding the state of the electrical system, taking action if a fault or undesirable conditions are detected. Additionally, circuit breakers or other switching devices play a crucial role by disconnecting and isolating faulty elements of the installation in response to signals from the protective relays. Finally, communication systems are utilized for data acquisition, sending trip signals, and communicating with remote sites for data and information transfer[9].

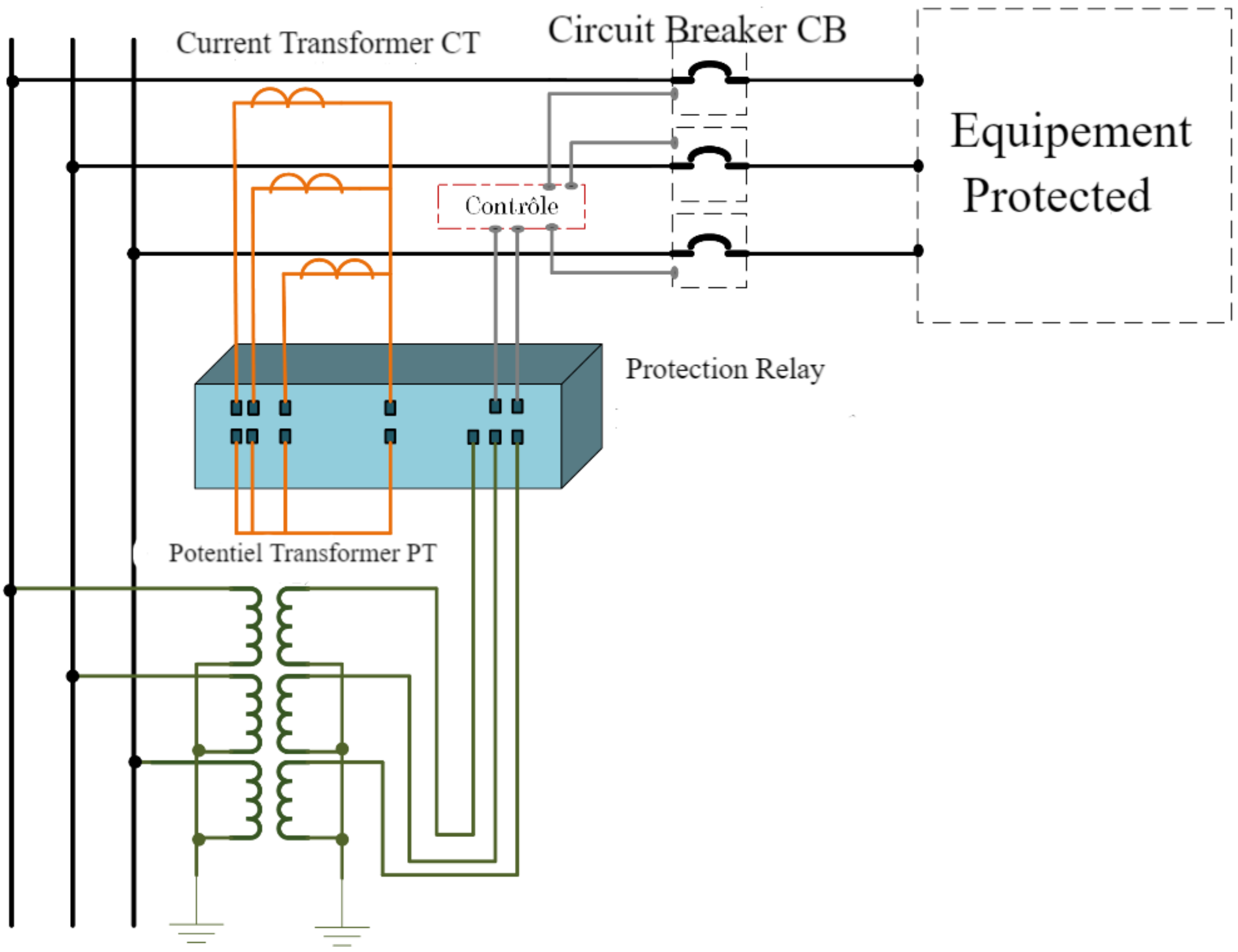


Figure 2.1: Protection System

2.2.1 Measurement transformer

Measurement transformers play several crucial roles in electrical systems:

a. Voltage and current levels in electrical systems can often be very high, making them unsuitable for direct measurement by protection relays. So Measurement transformers step down these high voltages and currents to values that are easy to handle for protection relays

b. Isolating relays by acting as a barrier between the high voltage primary system and the relays and measuring instruments connected to it , what will ensure the safety of personal working on the system

c. Providing the ability to standardize relays and instruments to a few nominal currents and voltages.

Potential Transformer

according to the IEC, we have essentially two types of potential transformers commonly used for protection relays:

- **Electromagnetic Type** : This type of VT, commonly known as a voltage transformer (VT) or Potentiel Transformer (PT)
- **Capacitive type** (refered to as capacitor voltage transformer or CVT)

The electromagnetic type is a step down voltage transformer whose primary and secondary windings are connected by a number of turns directly proportional to the open-circuit voltage measured or generated at its terminals. Most VTs are designed to provide 120 volts at the secondary terminals when the nominal voltage is applied to the primary. Standard nominal values are indicated in**Table 2.1** [7]

The standard nominal values for VTs, including both electromagnetic and capacitive types, are typically specified by regulatory standards and manufacturer datasheets. These values ensure consistency and compatibility across different VT models and applications.

‘

Table 2.1: Standard Nominal values

Primary voltage	**Secondary voltage**	**Transformation Ratio**
120	120	1 :1
240	120	2 :1
480	120	4 :1
600	120	5 :1
2400	120	20 :1
4200	120	35 :1
4800	120	40 :1
7200	120	60 :1
8400	120	70 :1
12000	120	100 :1
14400	120	120 :1
24000	120	200 :1
36000	120	300 :1
48000	120	400 :1
72000	120	600 :1
96000	120	800 :1
120000	120	1000 :1
144000	120	1200 :1
168000	120	1400 :1
204000	120	1700 :1
240000	120	2000 :1
300000	120	2500 :1
360000	120	3000 :1

Current Transformer

All current transformers used in protection have a construction fundamentally similar to that of standard transformers in that they consist of primary and secondary windings magnetically coupled, wound on a common iron core, with the primary winding connected in series with the network, unlike voltage transformers. Therefore, they must withstand the network's short-circuit current. There are two types of current transformers:

- **The wound primary type**
- **The bar-type primary**

The wound primary type is used for lower currents, but it can only be applied to installations with a low level of fault due to thermal limitations and structural requirements because of high magnetic forces. For currents greater than 100 A, the bar-type primary is used because if the secondary winding is evenly distributed around the entire iron core, its leakage reactance is eliminated. Protection CTs are most often of the bar type primary type,toroidal core with uniformly distributed secondary winding

The nominal value of a CT consists of a primary nominal current and an associated secondary nominal current. These values are related by the nominal transformation ratio of the CT, which is generally also the physical transformation ratio of the transformer. According to IEEE standards, most CTs have a secondary nominal current of 5 amperes. Table I.1, excerpted from IEEE Std C57.13TM-2008, lists the standard nominal ANSI values for single ratio CTs.[10]

Table 2.2: Nominal values of CTs according to IEEE standard for single-ratio CTs

10 :5	800 :5
15:5	1200 :5
25 :5	1500 :5
40 :5	2000 :5
50 :5	3000 :5
75 :5	4000 :5
100 :5	5000 :5
200 :5	6000 :5
300 :5	8000 :5
400 :5	1200 :5

IEC standards define CTs' secondary nominal current as 1 A, 2 A, or 5 A, with 5 A being the most used nominal current. They also provide a collection of common and recommended main current values. The standard nominal values are 10 A, 12.5 A, 15 A, 20 A, 25 A, 30 A, 40 A, 50 A, 60 A, 75 A, and their multiples, with the lowest range matching one of the standard ranges.

2.2.2 Protective Relays

In the previous century, protective relays have gone through major transitions with the change in technology. Electromechanical relays, the oldest in the family of protective relays, served the power system quite reliably. With the developments in electronics, static or solid-state relays were developed. Small size, light weight, and quiet operation are the main advantages of the static relays over the electromechanical relays. Technology based on microprocessors has made the relays even more compact, multifunctional, and flexible. These types of relays, which use digital technology, are known as digital/numerical relays [11]

a) **Electromechanical Relays :**

Electromechanical relays were among the first types of devices used to protect the electrical power systems. Electromechanical relays have a long history of application. The electromechanical devices consist of an induction disc, an induction cup, or a plunger-type construction. In these devices, the actuating forces were produced by a combination of the input signals and energy stored in springs and dashpots. Electromechanical relays possess several important features, such as high speed of operation, high torque, ruggedness, reliable, and immune to transients. However, as they consist of moving parts, there are problems of friction, high burden, and high power consumption for the auxiliary mechanisms [12] [11].

b) **Static Relays :**

Static relays or solid-state relays were developed during 1950s, using solid-state devices and other associated components. They have many advantages such as high speed of operation, low burden, precise, reliable, immune to vibration, and small in size. All of the protection functions, characteristics and other facilities available in the electromechanical relays can be performed by static relays. In addition, the main advantage of solid-state relays was that their characteristics can be shaped by adjusting logic elements. However, their cost was little high as compared to the electromechanical relays. Further, the static relays are affected by transients, which, if present in the inputs, may cause them to malfunction. Moreover, electronic components used in the static relays may drift due to high ambient temperature and aging. A major drawback of the static relays is that they are not having continuous check facility on their operational integrity [12].

c) **Digital Relays :**

Digital protection relays revolutionized technology by replacing analog circuits in static relays with microprocessors and microcontrollers. They were first introduced around 1980 and remain current for many applications, although they are expected to be replaced by numerical relays in the next five years. Digital relays perform A/D conversion of analog quantities and use microprocessors to implement protection algorithms, often employing techniques like counting or the Discrete Fourier Transform (DFT). Despite offering additional functionality compared to electromechanical or static relays, their limited processing capacity and memory restrict their functionality primarily to protection functions. This includes a wider range of settings, greater accuracy, and possibly a communication link to a remote computer. However, their limited processing power restricts the number of waveform samples they can measure per cycle, impacting their speed of operation in some applications. As a result, they may have a longer operation time than static relays, but this generally does not significantly affect overall tripping time or power system stability.[13]

d) **Numerical Relays:**

The distinction between digital and numerical relays primarily lies in subtle technical aspects and is mainly observed within the field of protection. Numerical relays can be seen as natural progressions from digital relays due to advancements in technology. Typically, they utilize specialized digital signal processors (DSPs) as computational hardware along with associated software tools. Analog input signals are converted into digital format and processed using the appropriate mathematical algorithms. Processing occurs through a specialized microprocessor optimized for signal processing tasks, known as a digital signal processor (DSP). Real-time digital signal processing demands a high-power microprocessor. [13] [14]

2.2.3 Requirements of Protection System

A fundamental requirement of a protective system is to swiftly clear faults to minimize their adverse effects. To meet this requirement, a protective system must possess the following characteristics:[1]

- Selectivity

  The system must isolate only the faulty section while leaving the rest of the network unaffected. This can be achieved through absolute selectivity, where the system responds only to faults within its zone, or relative selectivity, achieved by coordinating protective relays.

- Reliability

  It's crucial for the system to operate effectively throughout its service life, ensuring secure fault clearance and resilience against unintended clearances. Reliability is quantified as the inverse of the probability of failure, and every component of the system must be considered a potential source of failure.

- Speed

  The system should swiftly clear faults, including the time taken by relays to trip and breakers to open and extinguish arcs. Faster operation reduces damage to system components, limits ionization, enhances auto-reclosing chances, and minimizes system downtime, contributing to overall stability

- Discrimination

  The system must differentiate between fault conditions and normal loads, even when fault currents are lower than maximum load currents. This capability prevents false trips and ensures appropriate response to actual faults.

- Stability

  The system should remain inactive except when detecting faults within its designated zone, maintaining stability against disturbances across the power system.

- Sensitivity

  Protective relays should react accurately to low fault currents and operate at the minimum required level to detect potential faults promptly, ensuring the system's effectiveness in identifying various fault conditions [1]

2.3 Main and Back-up Protection

Two levels of protection, called primary and back-up, are usually provided to each portion of a power system. A main or primary protection scheme is always there as a first line of defense. Equally important is a second line of defense called a back-up protection. The back-up protection schemes will clear the fault if a primary protection scheme fails to operate for any reasons. There are three kinds of back-up protection schemes[15]

- **Remote back-up protection**: In this type of backup protection, the primary and backup protections are located at different stations and are desirably operated independently of the factors causing failure of primary protection. It is most widely used for the protection of transmission lines.

- **Relay Back-up Protection** : Both primary and backup protections are provided for the same circuit breaker. In case the primary fails, the backup trips the breaker without delay. Separate trip coils are provided for the same circuit breaker. The principles of operation of both primary and backup protection are different. This type of backup is provided where remote backup is not possible.

Bus Back-up Protection: When a fault occurs on a system and the circuit breaker fails to trip, then the fault is called a bus fault. Such type of backup protection is provided with an appropriate time delay. Bus backup protection is used in case of a bus-bar system with a number of circuit breakers connected to it and all the circuit breakers connected to the bus are opened.[16]

2.4 Overcurrent Protection

Overcurrents in electrical systems occur when there is an excess of current flowing through the system, which can lead to various issues including damage to equipment or even electrical fires. These overcurrents can be caused by faults, such as short circuits or ground faults, where the normal flow of current is disrupted, or by overloads, where the current drawn by the connected devices exceeds the rated capacity of the system.

To protect the electrical system and the connected equipment from the harmful effects of overcurrents, protective devices are employed. One common type of protective device used for this purpose is the Overcurrent Relay, often referred to as DOCRs (Directional Overcurrent Relays). These relays are designed to monitor the magnitude of the current flowing through the system and to trip or open the circuit when the current exceeds a predetermined threshold known as the pickup current (Is).[17]

When an overcurrent condition is detected and the current exceeds the pickup current threshold, the relay acts to trip or open the circuit by closing its tripping contacts. This action signals the circuit breaker, which is the primary protective device, to interrupt the flow of current by opening its contacts. Additionally, the tripping coils of the circuit breaker are energized to facilitate the opening of the contacts.

Overall, overcurrent relays play a crucial role in safeguarding electrical systems by quickly detecting and responding to abnormal current conditions, thereby preventing potential damage to equipment and ensuring the safety and reliability of the electrical network.

2.4.1 Overcurrent Protective Relays

Overcurrent protection devices, such as fuses and breakers, serve as the first line of defense against excessive currents. They are designed to detect and interrupt electrical circuits when current levels exceed the rated capacity of the system. By interrupting the circuit, these devices prevent the occurrence of electrical fires, equipment damage, and potential electric shock to people.

overcurrent protection can be achieved by the use of fuses or relays . OCRs are more suitable for large and complex networks because the coordination between different devices becomes very hard. However, because fuses are cheap and available with different time responses, they are still used in combination with protective OCRs in some large networks. In comparison with other expensive relays, OCRs can compromise between different design criteria, and this is why they are popular and widely used in power system protection ,Non-directional OCRs have only currents as inputs from power networks. These input currents are provided by current transformers (CTs). The main setting of OCRs is called plug setting (PS); which is also known as current setting multiplier (CSM) in some references. The other setting is called time dial setting (TDS); which is also known as time setting multiplier (TSM) in some references. It has to be remembered that there are two standards here; European and North American. Thus, in some references, the plug setting is also known as pickup setting (Ip), pickup current setting (PCS), and current tap setting (CTS). For the time multiplier setting, the other name is time lever setting (TLS). [18] The fault severity can be seen by OCRs via the following equation:

$$PSM = \frac{Ir_{relay}}{Ps} \tag{2.1}$$

where :

PSM : plug setting multiplier

I-relay : the faulted current sensed by the relay

If $PSM < 1$, it means that no fault exists in the system.

Based on their time-current characteristic curves (TCCCs), OCRs can be classified into three categories:[19]

1. Definite current (instantaneous) relays
2. Definite time (independent) relays
3. Inverse time (dependent) relays

1. **Instantaneous OCR (IOCR):**

   This type of relay operates instantly when the current reaches a predetermined value I > Is (Figure 2.2). The setting choice is made so that, in the substation farthest from the source, the relay operates for a low current value, and the operating currents of the relay increase progressively at each substation, heading towards the source. Thus, the relay with the lower setting operates first and disconnects the load at the point closest to the fault.[19]

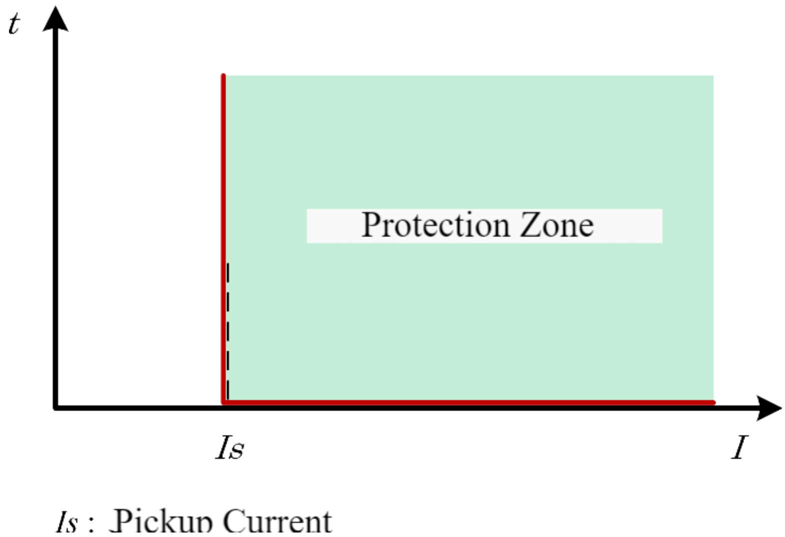


Figure 2.2: Time-current characteristic curve of ITOCR/DCOCR[5]

2. **Definite Time OCR (DTOCR):**

   The time delay T is constant and independent from the measured current value, provided that it is greater than the set threshold: $I > Is$, $t > T$ (Figure 2.3) The current threshold and the time delay are typically adjustable by the user.

   This type of relay allows for various adjustments to manage different current levels with different operating times.

   The parameters can be adjusted so that the breaker closest to the fault triggers in the shortest time frame, then uses a longer delay to sequentially trip the remaining breakers, moving towards the source. The difference between the tripping times for the same current is referred to as discrimination margin (or selectivity interval). Since the operating time of the independent delayed relay can be adjusted in fixed steps, the protection becomes more selective. Their major drawback is that faults occurring close to the source (resulting in high currents) may take a relatively long time to be cleared.

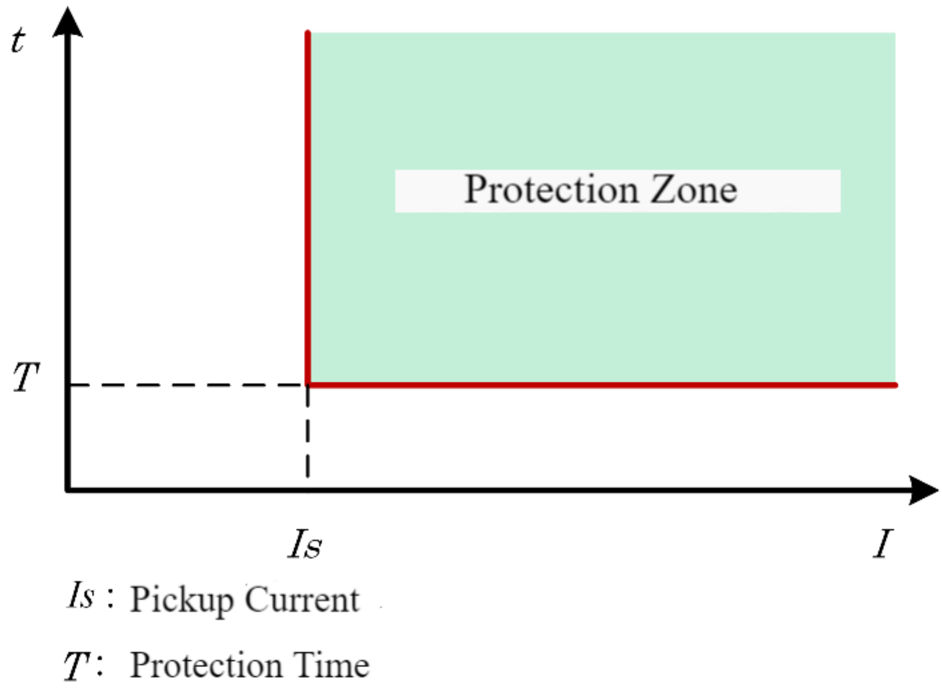


Figure 2.3: Time-current characteristic curve of DTOCR
[5]

3. **Inverse Time OCR (ITOCR):**

   The time delay depends on the relationship between the measuring current and the operating threshold. The higher the current, the shorter the delay. Timing settings are determined to achieve the selectivity interval Δt

   For the maximum current detected by downstream protection. Their advantage over time-delay relays is that for very high currents, shorter delays can be achieved without compromising protection selectivity.

   These relays operate with a time that is inversely proportional to the fault current (see Figure 2.4). Their advantage over time-independent relays is that for very high currents, shorter delays can be obtained without risking protection selectivity. Depending on their characteristic curve, time-dependent relays can be: inverse, very inverse, or extremely inverse.[19]

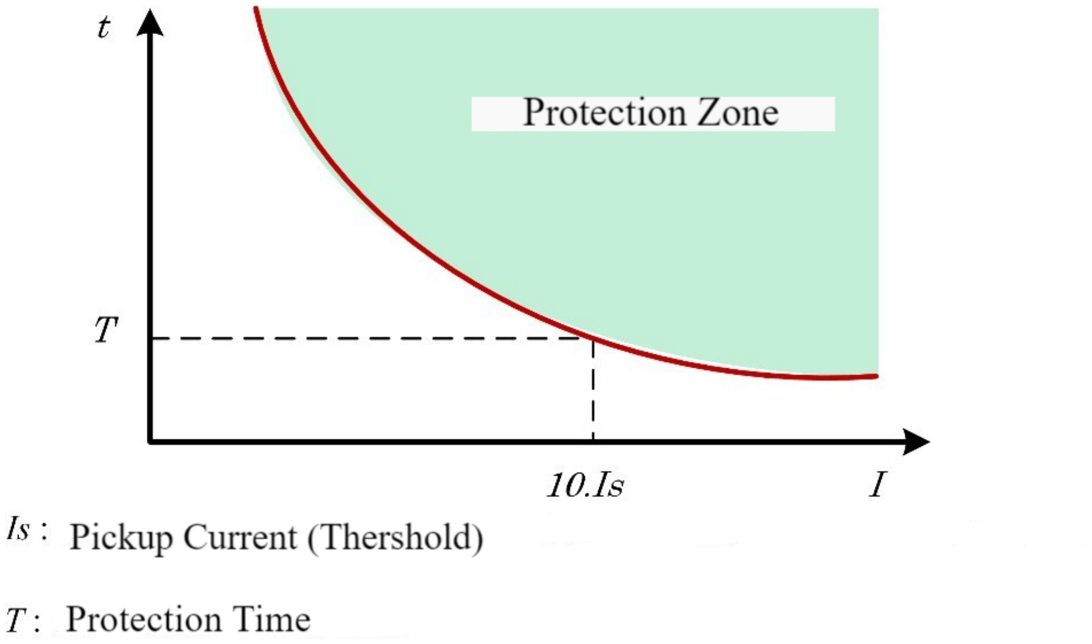


Figure 2.4: Time-current characteristic curve of ITOCR [5]

3.1 I.D.M.T. Overcurrent Relays

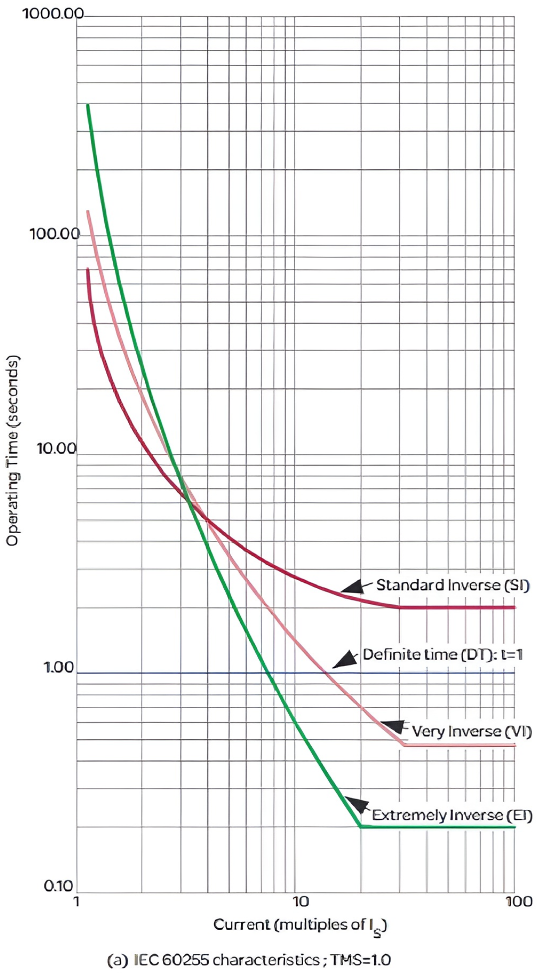
The current/time tripping characteristics of **IDMT** relays may need to be varied according to the tripping time required and the characteristics of other protection devices used in the network. For these purposes, IEC 60255 defines a number of standard characteristics as follows:

- Standard Inverse (SI)
- Very Inverse (VI)
- Extremely Inverse (EI)
- Definite Time (DT)

The mathematical descriptions of the curves are given in Table 2.3 . the curves are only shown for discrete values of TMS, continuous adjustment may be possible in an electromechanical relay. For other relay types, the setting steps may be so small as to effectively provide continuous adjustment. In addition, almost all overcurrent relays are also fitted with a high-set instantaneous element.In most cases, use of the standard SI curve proves satisfactory, but if satisfactory grading cannot be achieved, use of the VI or EI curves may help to resolve the problem,. When digital or numeric relays are used, other characteristics may be provided, including the possibility of user-definable curves.[13]

Table 2.3: Standard Relay Characteristic to IEC 60255

Relay characteristic	**Equation IEC 60255**
Standard inverse (SI)	$t = TMS \times \frac{0.O14}{Ir^{(0.02)}-1}$
Very inverse (VI)	$t = TMS \times \frac{13.5}{Ir-1}$
Extremly inverse (EI)	$t = TMS \times \frac{80}{Ir^2-1}$
Long time standard earth fault t TMS	$t = TMS \times \frac{120}{Ir-1}$



(a) IEC 60255 characteristics ; TMS=1.0

Figure 2.5: Standard Relay characteristic to IEC 60255

2.4.2 Directional OverCurrent Rleay

System faults typically lead to notable alterations in system measurements. These variations are instrumental in distinguishing between acceptable and unacceptable system states. Such dynamic changes encompass a spectrum of factors like overcurrent, voltage fluctuations (both excess and insufficient), power levels, power factors, phase angles, current flow directions, impedance, frequency shifts, temperature fluctuations, physical displacements, pressure changes, and alterations in insulation integrity.

Directional overcurrent relays serve to detect the direction of current or power flow at specific locations, thus pinpointing the fault's direction. To achieve this, a directional-sensing unit necessitates a stable reference quantity against which the current in the safeguarded circuit can be evaluated. In setups tailored for identifying phase-type faults, one of the system voltages typically serves as this reference. In practical scenarios, most system voltages maintain relatively constant phase positions during a fault. Conversely, line currents may undergo a reversal of around 180 degrees for faults occurring on one side of the circuit compared to current transformers (CTs) relative to a fault on the opposite side. This reference quantity is commonly referred to as the "polarizing" quantity.[20] [21]

2.4.3 Coordination of DOCR

It is a critical stage in any security design. Correct relay coordination entails choosing the appropriate relay configuration to ensure that faults in the protected zone are cleared first by the associated main relays, and that if they fail, the corresponding backup relays act after a coordination time interval (CTI), which may be calculated as: CTI = TCB + TOS + TSM ; where TCB is the CB's operating time after receiving a trip signal from the primary relay, TOS is the over-shoot time, and TSM is a safety margin supplied to the model to allow for mismatches due to relay timing error, CT-ratio error, current magnitude measurement error, and so on. CTI values range from 0.2 and 0.5 s With the exception of some radial network specific situations, the coordination issue may be modeled as a highly restricted MINLP problem, where

TMS is continuous and PS is discrete. An expert protection engineer is required to address such a situation logically, where all fault possibilities, system contingencies, and anomalies are examined and planned. Alternatively, it is simple to solve using optimization methods.[19]

2.4.4 General Mechanism to Optimally Coordinate Directional Overcurrent Relays

The historical chronology of the ORC issue has been described based on the literature study. In addition, several foundations have been discussed in this Chapter, which are critical for individuals seeking to understand the optimal coordination of DOCRs. This issue may be solved numerically, and the optimal (or near-optimal) solution can be reached by employing a variety of optimization techniques. The purpose of this section is to demonstrate how to construct the coordination issue of DOCRs into a mathematical model that can subsequently be addressed using any available n-dimensional optimization approach. General Program Requirements: The stages outlined in Figure 2.6's flowchart must be met in order to develop a program as a numerical ORC solver to optimally coordinate all the relays amongst each other[19]

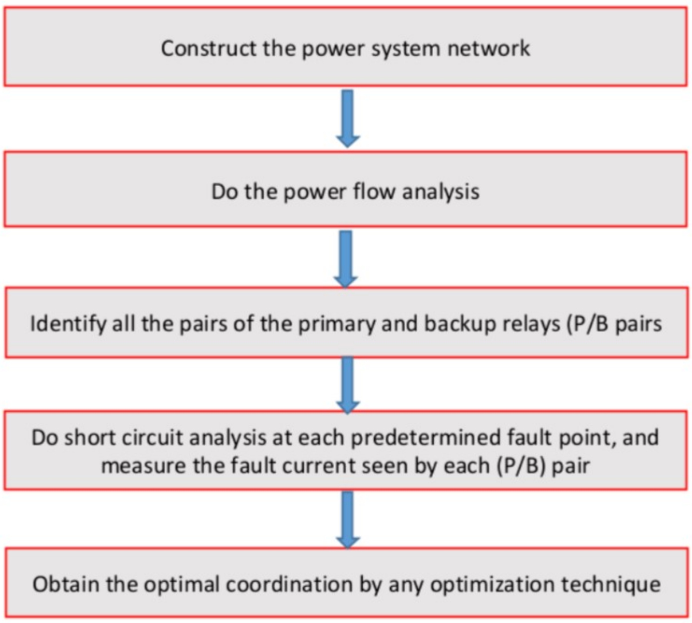


Figure 2.6: Flow chart to optimally coordinate DOCRs

2.5 differentiel protection

A relay which senses and operates the phase difference between the current entering into the electrical system and the current leaving the electrical system is called a current differential relay. An arrangement of overcurrent relay connected to operate as a differential relay is shown in the figure (2.7) .

The arrangement of the overcurrent relay is shown in the figure (2.8). The dotted line shows the section which is used to be protected. The current transformer is placed at both the ends of the protection zone. The secondary of the transformers is connected in series with the help of the pilot wire. Thereby, the current induces in the CTs flows in the same direction. The operating coil of the relay is connected on the secondary of the CTs.

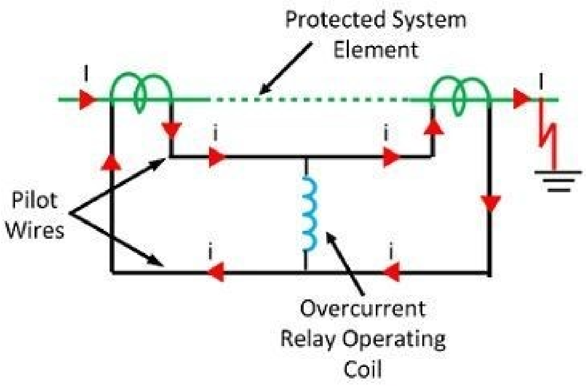


Figure 2.7: For an external load or fault

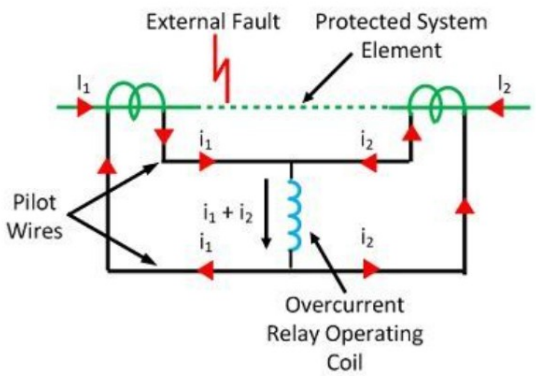


Figure 2.8: For an internal load or fault

2.6 Distance Relay

Since the impedance of a transmission circuit is relative to its length, it is suitable to use a relay capable of measuring the impedance of a circuit up to a present point (the reach point). Such protection relays are known as “distance protection relays” and only function in case of faults that occur between the location of the protection relay and the chosen reach point. Therefore, they provide discrimination for short circuits that may occur in different line portions.

The fundamental rule of distance protection includes the division of the voltage at the relaying point by the measured current. The calculated impedance is equated with the reach point impedance. When the measured impedance is lower than the reach point impedance, it is presumed that a fault is on the circuits between the relay and the reach point. The reach point of a protection relay is the point along the transmission line impedance locus that is crossed by the boundary feature of the protection relay. Since this depends on the ratio of voltage and current, and the phase angle between them, it may be shown on an R/X graph. The loci of electrical power system impedances, as detected by the protection relay during faults, power swings and load changes, may be shown on the same graph. The service of the protection relay in the presence of electrical system faults and disturbances may be examined using this method.[22]

2.6.1 Distance relay characteristics

The operating characteristics of distance relays typically take the form of geometric figures, such as circles, straight lines, or combinations thereof. However, in digital relays, it is possible to design various common operating characteristics. These include impedance, offset impedance, mho, polarized mho, reactance, and quadrilateral characteristics, as illustrated in Figure (2.9).

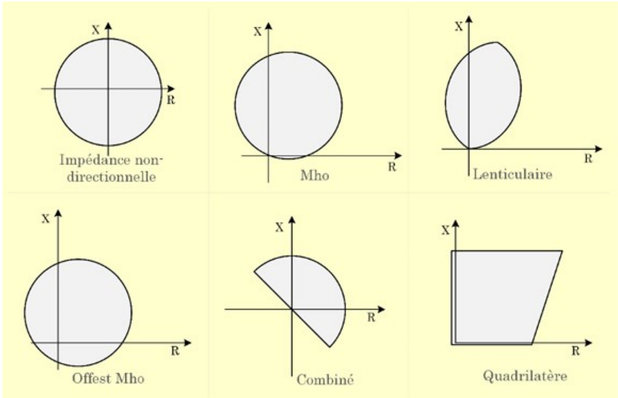


Figure 2.9: operating characteristics of distance relays

2.6.2 RELAY OPERATION

Distance protection relay operation is expressed in terms of reach exactness and operating time. Reach exactness is a comparison between the real ohmic reach of the protection relay under real circumstances with the protection relay setting value in ohms. Reach exactness is especially dependent on the level of voltage shown to the protection relay during the fault period. The impedance measuring methodologies used in special relay arrangements also have an influence. Functioning times can change with short circuit current, short circuit position relative to the protection relay setting, and the point on the voltage wave at which the short circuit happens. Depending on the measuring processes used in a specific relay arrangement, measuring signal transient errors, such as those made by capacitor voltage transformers or saturating CTs, can adversely slow down the relay function for short circuit currents close to the reach point. It is typical for electromechanical and static distance protection relays to claim both maximum and minimum functioning times. Nevertheless, for modern digital or numerical distance protection relays, the change between them is negligible over a wide range of electrical system operating states and fault locations.

2.6.3 DISTANCE PROTECTION ZONES

The careful choice of reach settings and operation times for the different zones allows proper coordination between distance protection relays on an electric power system. Fundamental distance protection will contain an instantaneous directional Zone 1 relay protection and one or more time-delayed zones. Common reach and time settings for a 3-zone distance relay protection are presented in Figure 2.10. Digital and numerical distance protection relays may have up to five or six protection zones, some are set to sense in the reverse direction. The common settings for three forward-looking zones of a basic distance relay protection are shown in the following paragraphs. To find out the settings for a specific protection relay arrangement or a specific distance tele-protection arrangement that involves end-to-end signaling, the producer's suggestions and manuals should be considered.

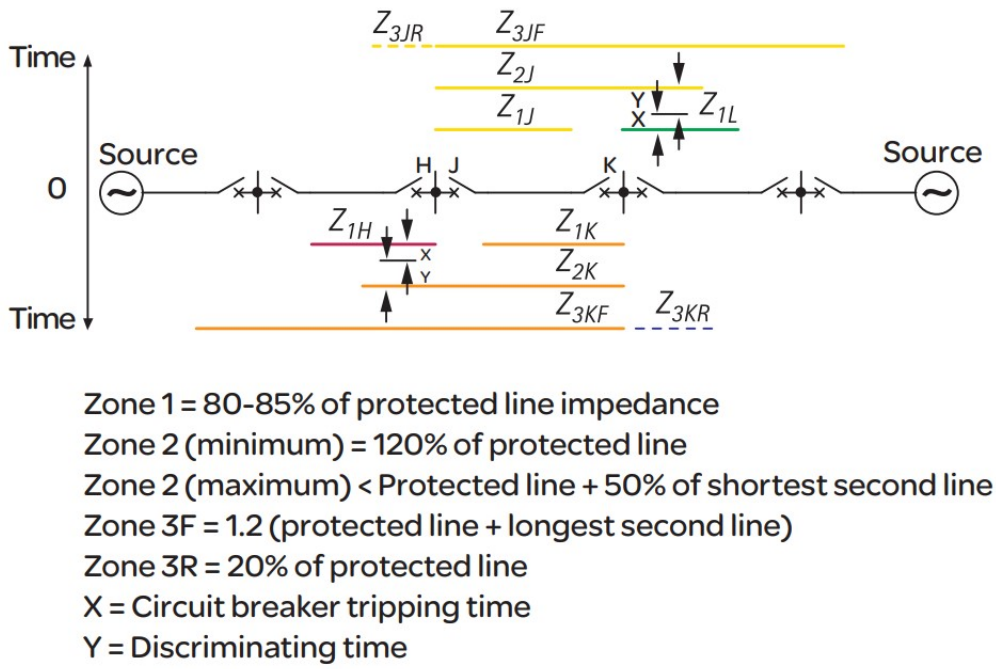


Figure 2.10: Typical time/distance characteristics for three zone distance protection

- **ZONE 1 PROTECTION SETTING**

  Electromechanical/static protection relays typically have a reach setting of up to 80% of the protected transmission line impedance for instantaneous Zone 1 protection. For digital/numerical distance protection relays, settings of up to 85% may be adequate. The obtained 15-20% safety margin assures the Zone 1 protection from overreaching the protected transmission circuit due to errors in the current and voltage transformers, and inaccuracies in transmission line impedance information. Otherwise, there would be improper discrimination with fast functioning relay protection on the following transmission line section. Zone 2 of the distance relay protection has to cover the remaining 15-20% of the transmission line

- **ZONE 2 PROTECTION SETTING**

  To assure complete coverage of the transmission line with provision for the sources of error already presented in the previous paragraph, the reach protection setting of the Zone 2 protection needs to be at least 120% of the protected transmission line impedance. In many cases it is a typical practice to set the Zone 2 reach to be same as the protected transmission line section and +50% of the shortest adjacent transmission line. Where feasible, this assures that the maximum effective protection Zone 2 reach does not go beyond the minimum effective protection Zone 1 reach of the adjacent transmission line protection. This eliminates the requirement to grade the protection Zone 2 time settings between upstream and downstream protection relays. In electromechanical and static protection relays, Zone 2 protection is given either by different elements or by extending the protection reach of the Zone 1 devices after a time delay that is started by a fault detector. In the majority of digital and numerical protection relays, the Zone 2 devices are put in software. Zone 2 tripping has to be time-delayed to assure grading with the primary protection relay used in adjacent transmission circuits that fall within the Zone 2 protection reach. Hence, full coverage of a transmission line portion is achieved, with fast clearance of short circuits in the first 80-85slower short circuit current clearance in the remaining portions of the transmission circuit.

- **Zone 3 Setting**

  Remote back-up relay protection, for all short circuit currents on adjacent transmission lines, can be given by a third zone that is time delayed to discriminate with Zone 2 relay protection and the circuit breaker operation time for the adjacent transmission line. Protection Zone 3 reach should be adjusted to at least 1.2 times the impedance given to the protection relay for a short circuit at the remote end of the second transmission line portion. On interconnected electrical power systems, the impact of short circuit current infeed at the remote bus will create a much higher impedance at the protection relay than the actual impedance to the short circuit. This has to be considered when setting the protection Zone 3. In some electrical systems, differences in the remote bus infeed can prohibit the usage of remote back-up protection Zone 3. However, there should not be any problem on radial distribution electrical systems with single end infeed

- **Settings for Reverse Reach and Other Zones**

Modern digital or numerical relays can include extra impedance zones for enhanced protection. For example, Zone 4 can serve as backup protection for the local busbar, while Zone 3 may have a reverse offset reach. Non-directional impedance measurement offers advantages, especially for zero-impedance faults. By bypassing delays, "Switch-on-to-Fault" (SOTF) protection is enabled, crucial for swift tripping in certain scenarios. These additional zones can be part of a distance protection scheme, often paired with teleprotection signaling channels.

Zone 4 is a reverse zone, with the highest time delay amongst all the protection zones (over 1.5 s), and serves both as a delayed backup for faults near the protected line at the local substation, and as a blocking element to the communication assisted trip schemes. Its setting is given depending on the application, and it usually does not require further performance evaluation, given its high delay time and short coverage.

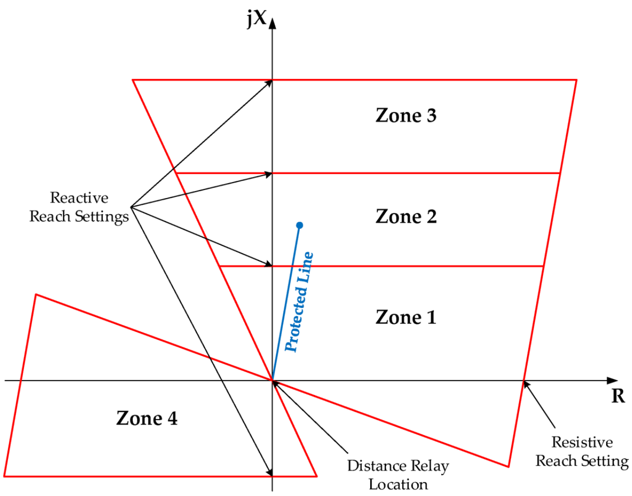


Figure 2.11: Typical time/distance characteristics for three zone distance protection

2.7 Zones of Protection and selectivity

The protective relays must be an integral part of the planning, design, and operation of the entire system. Circuit breakers should be placed in appropriate locations. The components or equipment and parts of the system that need to be protected by circuit breakers must be clearly identified, Here's a breakdown of some needed points: [18]

- **Protective Zones**

  A power system is divided into protective zones to safeguard major components like generators, transformers, buses, transmission lines, distribution lines, or motors. These zones overlap to ensure comprehensive protection across the entire power system.

- **Components of Protective Zones**

  Each protective zone is associated with circuit breakers and relays, which are responsible for protecting one or more components of the power system.

- **Isolation of Fault**

  Circuit breakers are strategically placed to isolate the protected zone in the event of a fault, while allowing the rest of the power system to continue supplying power to customers. When a fault occurs, protective relays detect the abnormal condition and send trip signals to the appropriate circuit breakers to isolate the affected zone.

In essence, the protective zones, circuit breakers, and relays work together to detect and isolate faults, ensuring the safety and reliability of the power system. Figure 2.12 illustrates this identification and delineation of zones. Each zone typically covers one or two elements of the electrical system.

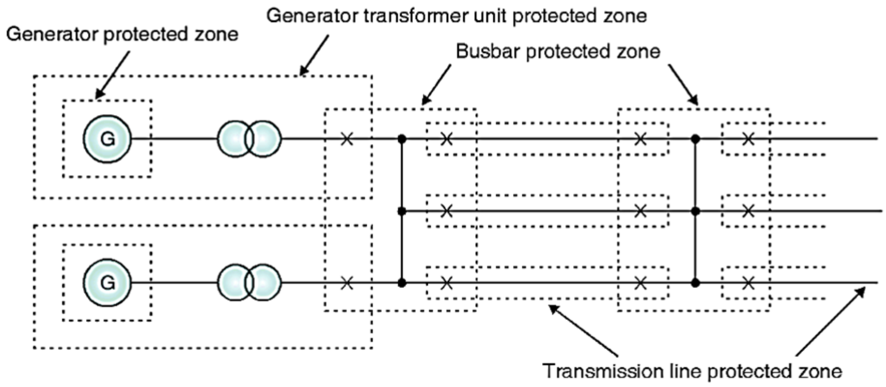


Figure 2.12: protection of zones
[23]

Figure 2.13 illustrates a typical arrangement of overlapping zones.Alternatively, the zone may be unrestricted; the start will be defined but the extent (or 'reach') will depend on measurement of the system quantities and will therefore be subject to variation, owing to changes in system conditions and measurement errors

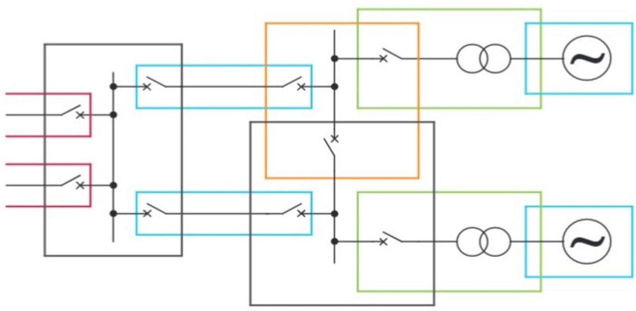


Figure 2.13: overlapping zones of protection system

2.8 Conclusion

This Chapter to conclude an overview of power system protection, focusing on the critical aspects of overcurrent protection and the concept of zones of protection. Overcurrent protection ensures the safety and reliability of power systems by detecting and isolating faults that cause excessive current flow. The strategic division of power systems into distinct protection zones enhances fault detection and mitigation, preventing widespread damage and maintaining system stability.

As we have established the foundational principles of power system protection, the subsequent chapter will delve into optimization techniques. Optimization in power systems aims to enhance performance, efficiency, and reliability by fine-tuning various protective mechanisms and operational strategies. By integrating optimization methodologies, we can achieve more effective power system protection solutions, ensuring a robust and resilient electrical infrastructure.

Chapter 3

Optimization techniques for practical applications

3.1 Introduction

When a power system is mathematically modelled some concerns as control goals, operation requirements, energy effeciency and return on investment have to be taken into account. These aspects set the base of the optimization problems about power system to be solved.

Solving an optimization problem means to get the best suitable value for an objective function which is subject to several constraints. When dealing with power system problems, these constraints are referring to operational or design limits. To find the solution of this problem different methods can be used but normally the objective function and/or the constraints of the system present non linearities that transform the optimization problem into a non linear one. Real power systems have dimensions that can make very difficult applying conventional computational techniques and that is the reason why metaheuristic techniques can be a good manner to solve the optimization problem.

Metaheuristic methods can provide good results in acceptable simulation times and be implemented to obtain the solution of a wide range of optimization problems irrespective of their specific objective function or constraints, but they are not able to guarantee a global optimum as a conventional technique would do.[24]

3.2 Optimization problem

An optimization problem involves finding the best set of inputs to maximize or minimize a target function, known as the objective function. This function may need to meet specific conditions, called constraints, which can be either equalities or inequalities. Optimization problems are categorized into constrained and unconstrained problems based on whether they include constraints. Additionally, they are classified as Linear Programming (LP) or Nonlinear Programming (NLP) problems based on the nature of the objective function.

Solving an optimization problem involves performing a series of operations using an optimization algorithm. This algorithm iterates through a search space to find suitable solutions, comparing them until it converges on the best solution, which may be the optimal or near-optimal solution. The number of iterations and convergence depend on factors such as whether the objective function is linear or nonlinear and whether there are constraints, as well as the optimization method used.

3.3 Optimization methods

Real-life problems can be modeled as optimization problems with a specific mathematical objective function. Multiple optimization methods were developed to solve optimization problems. Depending on the characteristics of the optimization problem mainly the objective function type, constraints, and the decision variables types a suitable method is selected.

Optimization methods are classified into two main types: analytical methods and Stochastic methods.

3.3.1 Analytical Methods

Also known as deterministic or exact methods, these classical optimization methods use traditional mathematical theories such as calculus, algebra, and matrices to model systems and find optimal values for system variables. They are especially useful when the objective functions can be differentiated. Examples of these methods include the Simplex method, Gradient method, Newton's method, Interior-point method, and Sequential quadratic programming. The main advantage is their quick convergence to a unique solution. However, their effectiveness depends on the objective function's characteristics. Additionally, these methods require the objective function and constraints to be continuous, with existing and continuous first and second derivatives throughout the search space.

3.3.2 Stochastic methods

Stochastic methods refer to a collection of methods for minimizing or maximizing an objective function when randomness is present . These algorithms are applicable for any optimization problem. However, finding the global optimal solution requires an infinite computation time, thus, it is typically impossible to reach the global optimal solution using stochastic methods but an approximation to it can be found. Hence, these methods are also known as approximate algorithms. Both heuristic and metaheuristic methods are classified in this category. [25]

Heuristic Methods

Heuristic methods in computing are artificial intelligence-driven approaches aimed at finding optimal solutions to optimization problems. They typically have a simple mathematical structure and draw inspiration from nature, hence termed Nature-Inspired Algorithms. These methods are particularly useful for dealing with complex, nonlinear objective functions and large sets of variables and constraints. Additionally, they offer advantages such as reducing development time and being robust in the face of missing data. Heuristic optimization techniques are versatile, effective for solving large-scale problems, and often the preferred choice for handling highly complex optimization tasks due to their independence from specific function and constraint types, lack of reliance on derivatives, and overall efficiency.

Metaheuristic methods

Generally inspired by nature and species social behavior, these methods have become prevalent, especially with the increasing demand for more efficient systems with reduced costs. This has led researchers to develop and implement these methods in the field of power system. These algorithms are adapted to large scale optimization issues in order to find the optimum solution with the least amount of computing complexity. Meta-heuristic are accurate, robust, and resistant to local optima.

Meta-heuristics, characterized as high-level methodologies or broad algorithmic models, often lack adaptability to specific problems but are adept at addressing a diverse array of issues. The term "meta," signifying "beyond" or "higher-level methodology," implies that these algorithms operate as elevated heuristics. Additionally, meta-heuristics relying on hybrid approaches are further classified as such. Over the past decades, researchers have increasingly focused on meta-heuristics, recognizing them as effective tools for addressing complex optimization problems. Various algorithms fall under this umbrella, such as simulated annealing (SA), ant colony optimization (ACO), particle swarm optimization (PSO), equilibrium optimizer (EO), Jaya algorithm (JAYA), and Bat algorithm (BA). Notably, there is no consensus on the definitions of heuristics and meta-heuristics, with some literature using the terms interchangeably. However, the prevailing trend is to designate as meta-heuristics all stochastic algorithms employing randomness and local search.[26] [27]

3.4 Basic concepts of the optimization problem

The main fundamental concepts used in optimization problems are based on the following keys element:

a) **The objective function :** expresses the main purpose of the model, which is either to be minimized or maximized. It is also known as the optimization criterion, cost function, and fitness function.

Based on the objective function, two types of optimization problems can be distinguished:

Mono-objective function problem: an optimization problem with a single objective function to be optimized. Multi-objective function problem: an optimization problem with several objective functions to be optimized.

b) **Variables:**

They are presented by a set of unknowns, which control the value of the objective function. They are adjusted iteratively during the optimization process to obtain optimal solutions. They are also known as design variables or project variables.

c) **Constraints:**

They are presented by a set of conditions, which allow the variables to take certain values and exclude others. The constraints present the conditions that the variables must satisfy, which can be in the form of inequality, equality, or side constraints.

3.5 Analysis of optimization algorithms

3.5.1 Exploration and Exploitation

a-Exploration:

The technique of diversification is utilized to increase the efficiency of exploring the search space and generate solutions with adequate diversity. The global scale of the phenomenon reduces the likelihood of being stuck in a local mode. Although it presents promising advantages such as improved accuracy and efficiency, it also possesses certain limitations, including slow convergence and the waste of compu tational efforts due to many new solutions being far from global optimality.[26]

b-Exploitation:

Generating new and better solutions relies on information from the problem at hand. This search process uses derivative information, like gradients, and is usually local. While this method often converges quickly, it can get stuck in a local optimum because the final solution is strongly affected by the starting point.

The optimal balance is essential for an algorithm to achieve good performance. Too much exploitation and too little exploration can cause the search path to wander around with slow convergence, while too little exploitation and too much exploration can cause the search path to wander around with slow convergence. The optimal balance should mean the right amount of exploration and exploitation, which may lead to the optimal performance of an algorithm. However, finding the way to achieve such a balance is still an open problem, as it depends on many factors, such as the working mechanism of an algorithm, its setting of parameters, the tuning and control of these parameters, and even the problem to be considered.[26]

3.5.2 Initialization

Initializing the population in stochastic algorithms is crucial when the objective landscape is uneven and the global optimum is in a small, isolated region. However, this requires good knowledge of the problem and might not work for every algorithm. To address this, the algorithm can be run multiple times with different starting points, or it can run long enough to find the true global optimum. In practice, most algorithms use some form of initialization to ensure that new solutions are spread out as much as possible in the search space.[26]

3.5.3 Randomization

Randomization is a method for allowing an algorithm to explore more of the search space; it can also be viewed as a means for diversification or intensification. There are various methods for implementing intensification and diversification, and each algorithm and its variants employ a unique method for balancing exploration and exploitation. Using a uniformly distributed random variable to sample the search space is one of the simplest and most frequently employed randomization techniques.

$$x_{\text{new}} = L + (U - L) \cdot r$$

where L and U are the lower-bound and upper-bound vectors, respectively. r is a uniformly distributed random variable in [0, 1]

3.5.4 Parameter setting

Most metaheuristics are nature-inspired (inspired by some principles in physics, bi ology, etc.) and contain stochastic components. These methods typically offer users the ability to adjust various parameters to better suit the specific problem being ad dressed [28],The setting of these parameters can largely influence the behavior and performance of an algorithm. How to best tune and control these algorithms is still a very challenging problem . And it can be primarily categorized into:

- **Parameter tuning:**

  Identifying optimal parameter values before applying an algorithm, known as off-line tuning, is essential for effective problem-solving. Using these optimal settings is important because they remain consistent throughout the algorithm's run.[29]

- **Parameter control:**

  On-line tuning involves directly modifying controlled parameter values according to specific strategies during the algorithm's execution. In this approach, initial values and suitable control strategies for the parameters, which adapt or change during the run, are necessary. These control strategies can be deterministic, adaptive, or self-adaptive.

  Parameter tuning is a time-consuming process that requires numerous algorithm runs to assess performance thoroughly. Despite its time investment, it offers universality, applying to various meta-heuristics. In contrast, parameter control lacks universality and isn't suitable for all algorithms. Implementing parameter control effectively demands a clear grasp of the necessary adjustments to optimize performance during runtime.[30]

3.5.5 No free lunch theorem

The No Free Lunch (NFL) theorem of optimization states that no universal algorithm can perform well for all optimization problems. This highlights the need to adapt algorithms for specific problems to enhance performance and achieve optimal solutions. As a result, parameter setting is not a one-time task. Researchers and users must revisit parameter settings when encountering new problems. Therefore, the challenge of setting an algorithm's parameters to maximize its performance is a common issue for both algorithm designers and users.[26]

3.6 Particle Swarm Optimization(PSO)

Based on the study of the movement of organisms in a bird flock or fish school, Particle Swarm Optimization (PSO) optimizes a problem by improving, in an iterative way, candidate solutions called particles regarding a given measure of quality. The algorithm is initialized with a population of particles, with random position and velocity values, which are moving around in the search space. Influenced by its local best known position, each movement is guided toward the best known positions in the search space. Since PSO can handle both discrete and continuous variables, it has been found to be notably efficient in solving an extensive range of engineering problems in a short simulation time.

In the Figure 3.1 is presented the PSO process diagram. Once initialized the population, each candidate solution is evaluated in order to establish its tness. If the position tness of a particle is better than the so far value, it is set as new best position, pbest(the best position of particle i). When all particles tness are evaluated, the algorithm moves to the second iteration, in which among all pbest, the best value obtained so far by any particle in the neighborhood of pbest is called gbest(global best position). The main advantage of swarm intelligence techniques is that they are impressively resistant to the local optima problem [31]

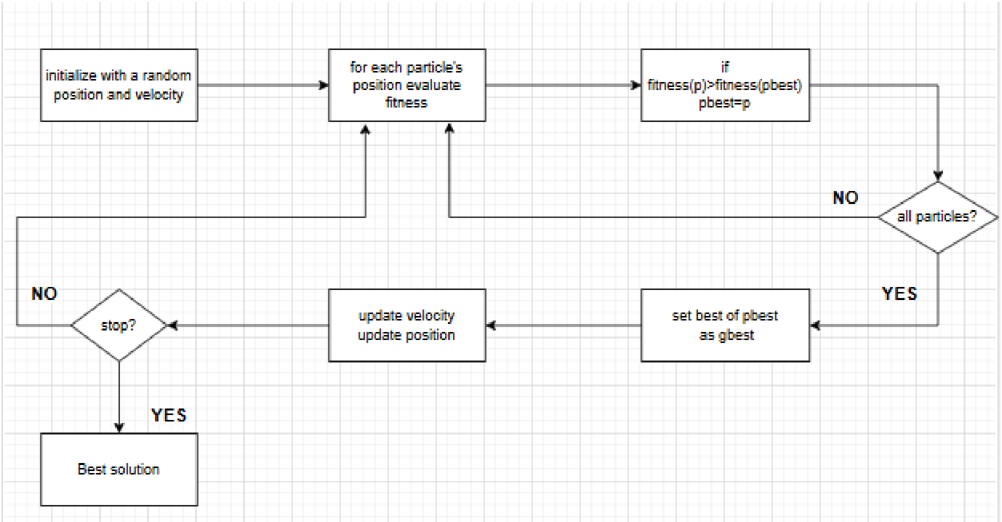


Figure 3.1: Particel Swarm Optimization

The following sketched diagram clarifies the particle trajectory "Figure 3.2": Where each particle in the swarm is defined by the following characteristics:

- Xi and Vi: The current position and the current velocity of particle
- XiBest : The personal best position vector achieved by particle i or simply best "remembered" individual particle position.
- Xg Best : The global best position vector for all the particles of the swarm or simply the best "remembered" swarm position.

3.6.1 The Pseudo code of PSO algorithm

Each particle represents a candidate solution to the optimization problem, it adjusts its trajectory toward both of its own previous best position and the previous best position attained by any member of its topological neighborhood. So the position of a particle is influenced by the best position visited by itself and the position of the best particle in its neighborhood, when the neighborhood of a particle is the entire

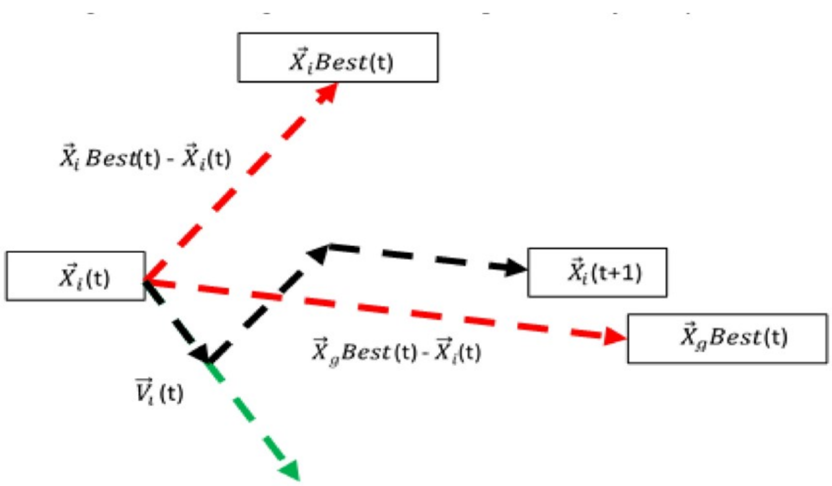


Figure 3.2: Particel trajectory for PSO

swarm. The best position achieved by each particle is referred to as local best position (Xi.Best - the best position of particle i) while the best position in the entire swarm is referred to as the global best position (Xg.Best).

The pseudo code of the PSO algorithm is presented in Figure 3.3:

```
Procedure PSO
 Initialize particles population
do
        for each particle p with position x_p do
                calculate fitness value f(x_p)
                if  f(x_p) is better than pbest_p then
                        pbest_p ← x_p
                endif
        endfor

        Define gbest_p as the best position found so far by any of
        p's neighbors

        for each particle p do
                v_p ← compute_velocity(x_p, pbest_p, gbest_p)
                x_p ← update_ position(x_p, v_p)
        endfor

while   (Max iteration is not reached or a stop criterion is
         not satisfied)
```

Figure 3.3: The pseudo code of the PSO algorithm.[32]

3.7 Gorilla troops optimizer

Gorilla troops optimizer is a recently proposed nature-inspired and gradient-free optimization algorithm, which emulates the gorillas' lifestyle in the group . The gorilla lives in a group called troop, composed of an adult male gorilla also known as the silverback, multiple adult female gorillas and their posterity. A silverback gorilla typically has an age of more than 12 years and is named for the unique hair on his back at puberty. Besides, the silverback is the head of the whole troop, taking all decisions, mediating disputes, directing others to food resources, determining group movements, and being responsible for safety. Younger male gorillas at the age of 8 to 12 years are called blackbacks since they still lack silver-colouredback hairs. They are affiliated with the silverback and act as backup defenders for the group. In general, both female and male gorillas tend to migrate from the group where they were born to a second new group. Alternatively, mature male gorillas are also likely to separate from their original group and constitute troops for their own by attracting migrating females. However, some male gorillas sometimes choose to stay in the initial troop and continue to follow the silverback. If the silverback dies, these males might engage in a brutal battle for dominance of the group and mating with adult females. Based on the above concept of gorillas group behaviour in nature, the specific mathematical model for the GTO algorithm is developed. As with other intelligent algorithms, GTO contains three main parts: initialization, global exploration, and local exploitation, which are explained thoroughly below.[27]

3.7.1 The Pseudo code of GTO algorithm

Algorithm : Gorilla troops optimizer

1: Initialize the population size N and the maximum number of iterations Maxiter

2: Initialize the random gorilla population X_i (i = 1, 2, . . . , N)

3: Calculate the fitness values of all gorilla individuals

4: **While** $t <$ Maxiter **do**

5: Update the parameter c

6: Update the parameter L

7: For each gorilla X_i do // Exploration stage

8: Update the position of the current gorilla

9: End For

10: Evaluate the fitness values of all gorillas

11: Save the optimal solution as a $X_silverblack$

12: For each gorilla X_i do //Exploitation stage

13: **If** $C \geq W$ **then**

14: Update the position of the current gorilla

15: Else

16: Update the position of the current gorilla

17: End If

18: End For

19:Update the fitness values of all gorillas

20:Update the global best solution $X_silverback$

21:$t = t + 1$

22: **End While**

23:**Output** the global best solution $X_silverback$ and its fitness value

Chapter 4

Optimal coordination for directional overcurrent relay in electrical power systems

4.1 Introduction

Protection schemes aim to safeguard power systems against faults by quickly isolating the smallest possible section of the system. Typically, the design of a protection scheme involves pairing primary protective devices with backup protective devices for each line in the system. When a fault occurs on a line, the primary protective devices should activate. If they fail, the backup protective devices should engage after a set time delay. The process of determining the operational sequence for each primary and backup protective device pair associated with each fault location is known as protection coordination.

The coordination problem of directional overcurrent relays (DOCRs) is a complex and nonlinear optimization issue that involves determining appropriate time dial settings (TDS) and plug settings (PS) to reduce relays operating time while maintaining sensitivity and selectivity characteristics. The tripping operation of a DOCR is typically governed by an inverse time-current characteristic that depends on the TDS and the pickup current setting (Ip).

In this Chapter a modified AVOA algorithm is developed for the optimal coordination of DOCRs. Therefore, the MAVOA method is used to find out the optimal settings for the DOCRs problem ,The efficiency and performance of the proposed approach are validated on IEEE 9-bus and 39-bus test systems. The findings are compared with the traditional AVOA and with other recent optimization methods (GTO and PSO) to prove superiority of the improved AVOA in reducing relay operation time for optimal DOCRs coordination.

4.2 DIgSILENT PowerFactory

PowerFactory, developed by the German company DIgSILENT (Digital SimuLator for Electrical NeTwork), is a versatile power system simulation tool utilized for various electrical network analyses. These encompass power flow computations, dynamic simulations, short-circuit assessments, harmonic investigations, and more. In steady-state simulations, the electrical system is represented through a single-line diagram, with each component modeled using distinctive parameters. These parameters encompass positive, negative, and zero sequence impedances, load flow characteristics, short-circuit behavior, and numerous other options.[33]

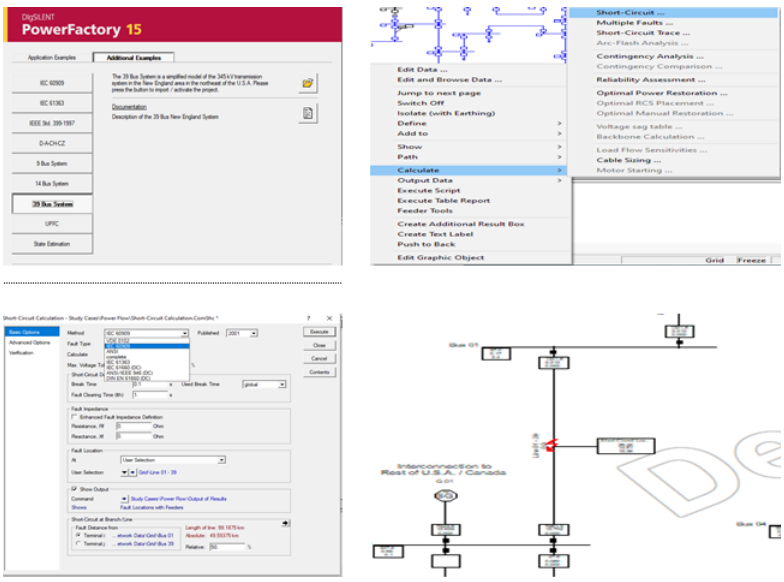


Figure 4.1: DIgSILENT PowerFactory

4.3 PROPOSED FORMULATION FOR THE PROTECTION COORDINATION PROBLEM

To achieve protection coordination in electrical networks, it is necessary to model each function that constitutes the protection system.

The coordination problem is formulated as a mathematical optimization problem, containing an objective function responsible for minimizing relay tripping times and a set of constraints to satisfy. Distance and overcurrent relays are considered in the formulation either individually or as a group.

4.3.1 Objective function

DOCRs are installed at both ends of the transmission line to protect the electric system. The coordination between the DOCRs is considered a non-linear optimization problem. This problem has many limitations. The main goal of solving the coordination problem is to keep the continuity of the electrical networks. This target can be accomplished by getting the DOCRs setting, TDS and Ip, These settings shall minimize the summation of the operating times for all DOCRs primary relays , The coordination problem of directional overcurrent relays is considered a constraint optimization problem[34].The objective function of the coordination problem can be described as follows:

$$Top = \sum_{i=1}^{n} T_{pr_i} \tag{4.1}$$

Where Top is the total operating time, n denotes the overall number of primary relays and Tpr_i denotes the main relay's operational time of the relay (R_i)

The T_i is the operating time of primary of DOCRs, which can be described according to IEC-60225 as :

$$t_{ij} = \frac{TDS_i \cdot A}{(\frac{I_{sc_{ij}}}{I_{pi}})^B - 1} \tag{4.2}$$

$$I_i\text{pickup} = CT_i \cdot PS_i \tag{4.3}$$

where i is the relay identifier and j is the fault location identifier. A and B are the constants that control the (time/current) characteristic of the relay. In this thesis, A and B are chosen to be 0.14 and 0.02, respectively, CT is the current transformer ratio,I_sc is the short circuit current,Ip is the pickup current ,and $PS$is the plug setting multiplier of DOCR and TDS is the time dial setting .

The constants A and B are chosen from the values indicated in Table II.1 to obtain a normal inverse (NI), very inverse (VI), or extremely inverse (EI) characteristic. Graphical representations of the standard IEC characteristics for different fault current magnitudes are illustrated in table (4.1)

Table 4.1: Constants of overcurrent relays' time-current characteristics.

No.	Curve Type	A	B
1	Normally inverse (NI)	0.14	0.02
2	Very inverse (VI)	13.5	1
3	Extremely inverse (EI)	80	2

4.3.2 Coordination constraints

The Objectif function (OF) is subject to the following restrictions:

- The coordination time margin (CTI) is necessary between backup and main relays to ensure system stability. To meet the selectivity criterion, the backup relays should be activated if the main relays fail to operate, as both the backup and main relays detect faults simultaneously. The Directional Overcurrent Relays (DOCRs) can function as either backup or main relays.using the constraint specified in Eq:4.4

$$T_{bc_i} - T_{pr_i} \geq CTI \tag{4.4}$$

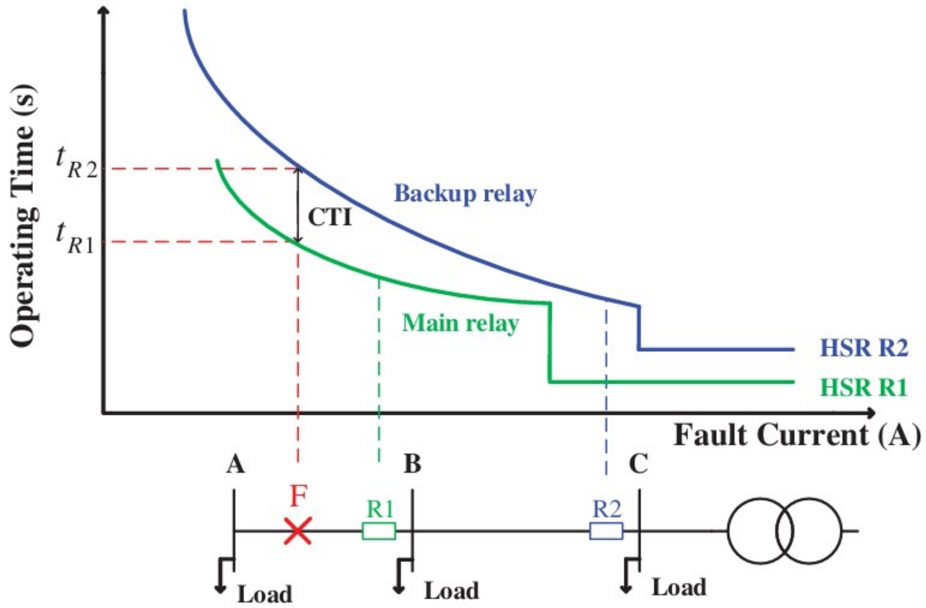


Figure 4.2: Protection coordination between the main and backup DOCRs [35]

The coordination time interval(CTI), is a crucial parameter in electrical systems that refers to the time it takes for protective devices, such as circuit breakers, to coordinate with one another during a fault event. This time interval is measured in seconds and takes into account various factors that affect the speed and selectivity of the protection scheme. Typically, electromechanical and microprocessor-based relays have CTIs of 0.3–0.4 and 0.1–0.2 s, respectively

- A set of relay settings and coordination constraints are included in the optimization model of this problem. The TDS set ting for each relay is limited between a lower and upper bounds ($TDS_{i-\min}$ and $TDS_{i-\max}$). On the other hand, the lower bound of the pickup current tap setting ($I_{p_i-\min}$) for each relay is chosen so that the resultant current threshold ($CTR \times I_p$) is higher than the rated load current of the respective protected line. This ensures that each DOCR will trip only if a fault occurs[36]. The constraints imposed on the DOCR settings can be expressed as follows:

$$\mathrm{TDS}_{i-\min} \leq TDS_i \leq TDS_{i-\max}$$

$$\mathrm{PSi}_{\min} \leq \mathrm{PSi} \leq \mathrm{PSi}_{\max}$$

$$\mathrm{I}_{p_{i-\min}} \leq I_{p_i} \leq I_{p_{i-\max}}$$

Where: The minimum and maximum PS_i values are designated as PSi_{min} and PSi_{max}, Also Ipi_{min} and Ipi_{max} are the minimum and maximum limits for relay pick up current setting and they are based on the load current calculations. $TDSi_{min}$ and $TDSi_{max}$ are the minimum and maximum limits for relay i Time Dial Setting which will depend on the relay manufacturer values.

TDS and PS have upper and lower limits of 0.05 to 1.1 and 0.1 to 5 respectively. A 0.2 second CTI min was chosen

4.4 SYSTEM DETAILS AND SIMULATION SETUP

The effectiveness of the proposed formulation for the DOCR protection coordination problem was assessed using two standard IEEE test systems. It was employed to address the optimal coordination problem of DOCRs within the 9-bus and 39-bus reference systems, showcasing its superior performance compared to previous similar algorithms. flowchart of figure 4.3 presents a description of The mechanism used under study.

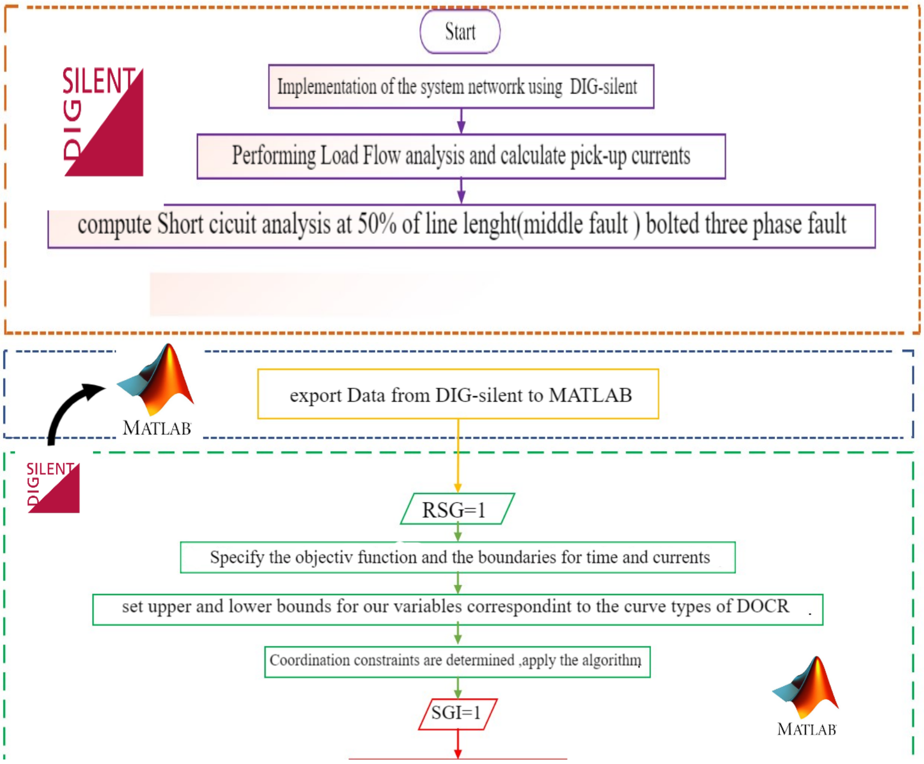


Figure 4.3: Flow-chart for solving the coordination problem between DOCRs

4.4.1 Description of the Test Systems Under Study:9-Bus system

The 9- Bus test system shown in Fig 4.4, is based on 3 synchronous generators, nine buses, six transmission lines, three transformers and three P-Q loads. The interconnection of these devices is depicted in fig 4.4 with Generator, load and transmission line data is given in (see Figure (A.1) ,(A.2) , (A.3) in Appendix A).

In this system,6 nodes denoted by(F1-F6) are the locations at which bolted three phase faults are performed, each fault location is associated with up to two primary DOCRs.However,due to the looped nature of this system,each primary DOCR can be associated with its backup DOCRs.

The DigSILENT PowerFactory software is used to compute the electrical variables that define the characteristics of the relays, which include the short-circuit currents

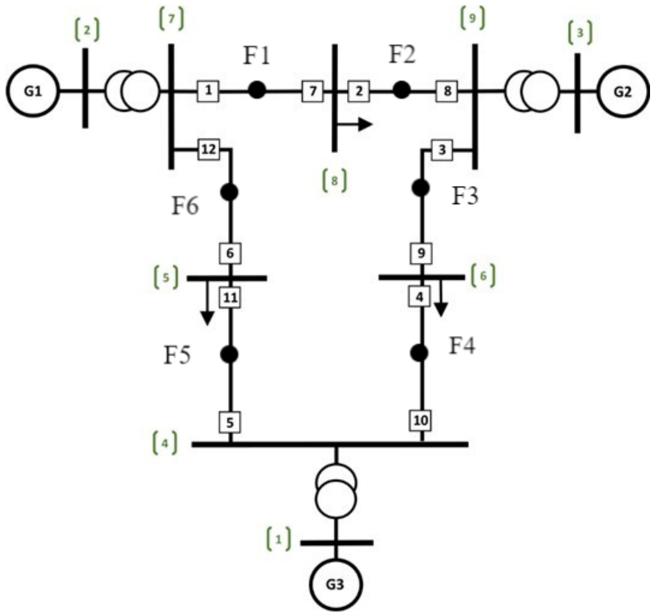


Figure 4.4: IEEE 9-node test system
[37]

Where Short circuit currents flowing through pairs of PR-BR relays in the 9-bus system are:

Table 4.2: Short-circuit currents (A) flowing through pairs of PR-BR relays

Fault	Short-circuit currents (A)		Fault	Short-circuit currents (A)	
	Primary relay	back-up relay		Primary relay	back-up relay
F1	R1	R6	F4	R10	R11
	1741	457		1707	415
	R7	R8		R4	R3
	905	905		711	711
F2	R8	R9	F5	R5	R4
	1381	419		1715	385
	R2	R1		R11	R12
	1072	1072		781	781
F3	R3	R2	F6	R12	R7
	1238	447		1308	35
	R9	R10		R6	R5
	88	88		94	94

The coordination problem of Directional Overcurrent Relays (DOCRs) in the 9-bus test system was optimized using both the African vultures optimization Algorithm (AVOA) and the improved African vultures optimization Algorithm (IAVOA) and two other algorithm (PSO) and (GTO). Table 4.3 presents the optimal values for the Time

Dial Setting (TDS) and Plug Setting (PS) control variables, along with a comparison of the objective function values obtained by the proposed algorithm and the original AVOA. Additionally, Table 4.4 displays the operating time (OT) and coordination time interval (CTI) values for 12 primary/backup relay pairs. The results show that the Improved Algorithm significantly reduced the total OT of the primary relays, and all values are within acceptable limits. Table 4.4 provides a comparison of the results produced by various optimization approaches, highlighting that the best value achieved by the IAVOA approach is the lowest among the methods compared.

Table 4.3: Comparison of The improved AVOA with PSO ,GTO and The original AVOA

Relays	**PSO**		**GTO**	
	TDS	**PS**	**TDS**	**PS**
1	0.0986	1.9313	0,1760	2.8349
2	0,3091	0,2738	0,0711	1.4646
3	0,0723	5	0,1305	4.6762
4	0,1180	4,5888	0.05	2.7251
5	0.05	5	0,1301	3.4220
6	0.1361	4.9999	0.05	3.2229
7	0,2669	0,7681	0.05	3.2814
8	0,2889	1,9756	0.1035	4.2448
9	0,3304	0,8244	0.0977	2.9862
10	0,1880	3,3666	0.0926	4.4354
11	0,2954	0,8435	0.1005	2.8843
12	0,3329	0.6601	0.1100	2.5184
OF (s)	6.3285		4.1551	

4.4.2 Description of the Test Systems Under Study:39-Bus system

For further confirmation of the effectiveness of the IAVOA approach, the proposed technique was applied to a large and highly integrated system with various DG units, as shown in Figure 4.8 , The IEEE 39-bus standard system is a power network in the New England area of the United States. The system consists of 10 generators, 39 busbars and 12 transformers.

The topology of the IEEE 39-bus system is as follows, where bus 39 is a slack bus. Except for the slack bus, the buses (30-38) connected to each motor have a voltage level of 20kV, and the bus is 25kV, and all other buses voltages are 500kV;Generator, load and transmission line data is given in (see Figure (A.4),(A.5) and (A.6) in Appendix A) In this system,34 nodes denoted by(F1-F34)are the locations at which bolted three phase faults are performed (middle fault), each fault location is associated with up to two primary DOCRs.However,due to the looped nature of this system,each primary DOCR can be associated with up to two backup DOCRs.

The DigSILENT Power Factory software is used to compute the electrical variables that define the characteristics of the relays, which include the short-circuit currents [38]

Where Short circuit currents flowing through pairs of PR-BR relays in the 39-bus system are:

Table 4.4: Short-circuit currents (A) flowing through pairs of PR-BR relays

Fault	Short-circuit currents (A)		Fault	Short-circuit currents (A)	
	Primary relay	back-up relay		Primary relay	back-up relay
F1	R2	R8	F18	R40	R15
	5428	1764		6200	3144
	R1	R4		R39	R33
	3859	3859		5761	5373
F2	R4	R29	F19	R41	R39
	12717	177		5640	2958

Continued on next page

Table 4.4 – continued from previous page

Fault	Short-circuit currents (A)		Fault	Short-circuit currents (A)	
	Primary relay	back-up relay		Primary relay	back-up relay
	R3	R2		R42	R44
	2732	2732		5153	5153
F3	R5	R8	F20	R44	R46
	7897	2768		9973	3262
	R6	R10		R43	R41
	5820	2987		3502	3502
F4	R7	R6	F21	R45	R48
	9093	3234		9142	3353
	R8	R66		R46	R54
	5338	2169		5522	3230
F5	R9	R5	F22	R47	R46
	6012	3732		7474	2817
	R10	R14		R48	
	5614	3129		5586	
F6	R11	R5	F23	R49	R46
	6941	4176		8815	3160
	R12	R53		R50	R60
	5078	5078		3783	3783
F7	R14	R18	F24	R41	R46
	6524	4936		11739	3793
	R13	R09		R52	R63
	5879	2956		4558	4558
F8	R15	R9	F25	R53	R45
	6166	3127		7980	5890
	R16	R39		R54	R11
	5756	2956		4558	4558
F9	R18	R24	F26	R55	R45
	8396	3927		7226	4813
	R17	R13		R56	R67
	5463	3104		3275	3275
F10	R19	R18	F27	R60	R62
	7108	3836		6380	2728
	R20	R28		R59	R49
	4350	2508		4835	4835
F11	R21	R24	F28	R61	R59
	8321	3404		6760	2788
	R22	R26		R62	R64
	3441	3441		4960	2085

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Table 4.4 – continued from previous page

Fault	Short-circuit currents (A)		Fault	Short-circuit currents (A)	
	Primary relay	back-up relay		Primary relay	back-up relay
F12	R23	R17	F29	R64	R51
	7668	3304		4633	4633
	R24	R31		R63	R61
	5422	5075		4395	2467
F13	R26	R19	F30	R65	R07
	6208	3540		5357	3464
	R25	R21		R66	R68
	4843	4843		3928	2103
F14	R27	R19	F31	R67	R65
	4612	2457		4926	2680
	R28	R30		R68	R55
	4068	4068		4284	4284
F15	R30	R03	F32	R69	R68
	12719	191		3742	1842
	R29	R27		R70	R74
	2594	2594		2450	2450
F16	R31	R34	F33	R71	R68
	7243	3202		3138	1659
	R32	R23		R72	R73
	5703	5499		2863	140
F17	R33	R32	F34	R74	R72
	8009	4007		5234	1059
	R34	R40		R73	R69
	4665	3375		1924	1924

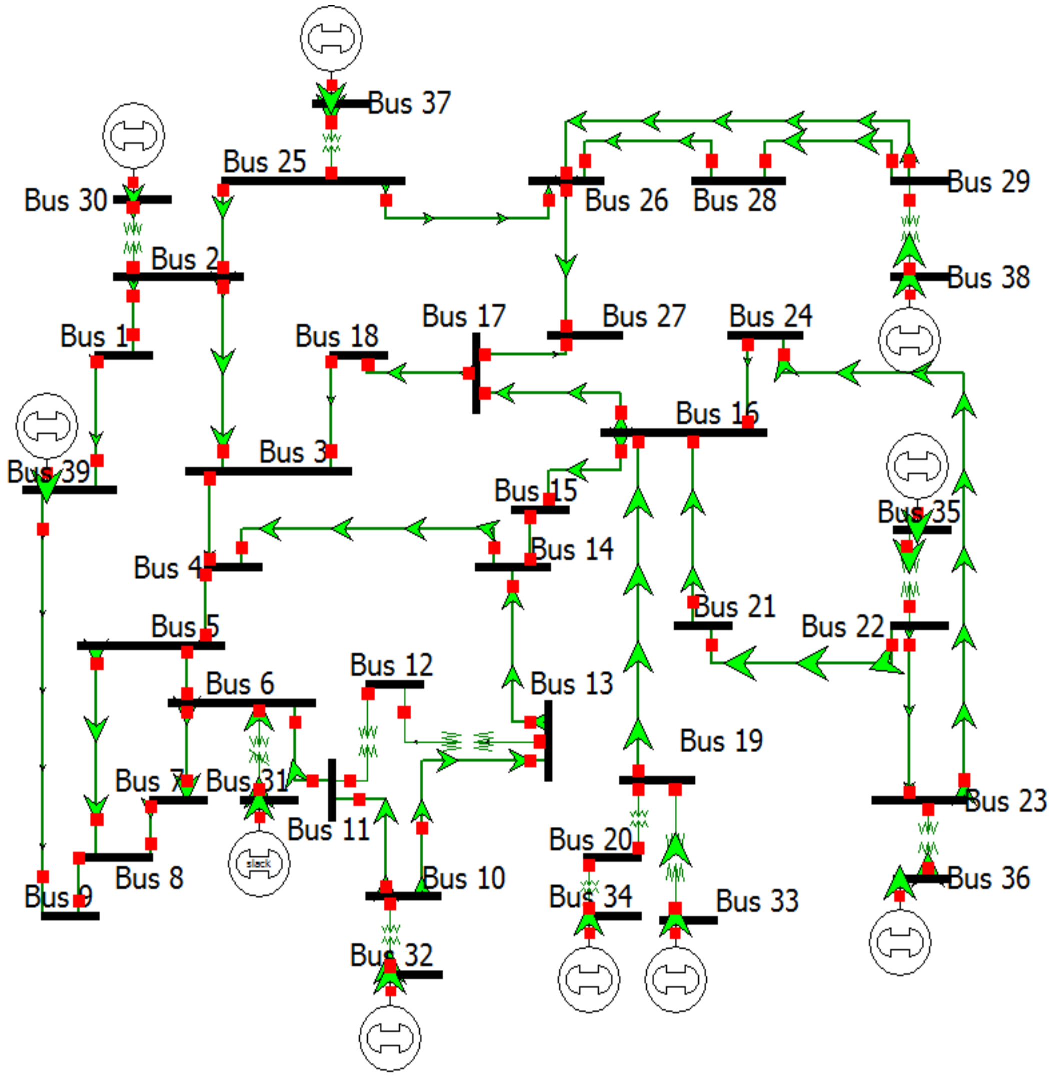

Figure 4.5: IEEE 39-node test system [38]

The TDS and PS values were set between 0.1 to 1.1 and 0.1 to 5, respectively. The CTI value was chosen to be a minimum of 0.2 seconds to determine the optimal relay setting. Table 4.6 illustrates the optimal TDS and PS for DOCRs achieved by the proposed IAVOA compared to other algorithms, while Table 4.7 compares these results with those of the proposed IAVOA and a recently published method. This comparison validates the effectiveness of the proposed method in the DOCR coordination scheme.

Table 4.5: Comparison of The improved AVOA with PSO, GTO, and The original AVOA

Relays	**PSO**		**GTO**	
	TDS	**PS**	**TDS**	**PS**
1	0.6958	1.5117	1.1167	2.1524
2	0.4901	1.4118	0.9815	5
3	0.4879	1.6667	0.6913	1.5674
4	1.0591	1.4504	0.9852	3.4694
5	0.9357	1.4218	0.5715	0.4482
6	0.8642	1.6860	0.5205	0.8696
7	0.9347	1.4738	0.2636	0.1
8	0.7121	1.5523	0.7055	0.9432
9	0.9548	1.5076	0.4464	0.2904
10	0.7827	1.7114	0.7729	5
11	0.8913	1.6774	0.9732	5
12	0.5788	2.0386	0.3472	0.9998
13	0.8627	1.3806	0.9061	3.7304
14	0.6613	1.5568	0.5194	1.3988
15	0.8108	1.3229	0.7636	1.9568
16	0.0526	1.2651	0.4981	3.4515
17	1.0826	1.4411	0.9532	7

Continued on the next page

Table 4.5: Continued: Comparison of The improved AVOA with PSO, GTO, and The original AVOA

Relays	**PSO**		**GTO**	
	TDS	**PS**	**TDS**	**PS**
18	0.6776	1.6112	0.7459	4.7651
19	0.7946	1.3724	0.7395	2.6246
20	0.05	2.1862	0.05	3.5202
21	0.7840	2.1282	0.3466	3.9787
22	0.0507	1.6256	0.05	5
23	0.9117	1.6255	0.8350	4.8430
24	0.8114	1.2951	0.9475	5
25	0.0500	1.3923	0.1133	3.1808
26	0.1696	1.9889	0.1827	3.6917
27	0.89498	1.6250	0.1558	0.1
28	0.6887	4.9985	0.4783	2.1696
29	0.0534	1.8099	0.1410	2.5802
30	0.6862	1.3257	1.0468	5.0000
31	0.9432	1.4454	1.1000	5.0000
32	0.9439	1.4450	0.8079	5.0000
33	0.9848	1.4622	0.6673	3.1270
34	0.9947	1.5676	0.6911	0.5901

Continued on the next page

Table 4.5: Continued: Comparison of The improved AVOA with PSO, GTO, and The original AVOA

Relays	**PSO**		**GTO**	
	TDS	**PS**	**TDS**	**PS**
35	0.8927	1.5882	0.3757	0.7865
36	0.8278	1.3353	1.1000	4.8507
37	0.9516	3.9130	0.2071	5.0000
38	0.8091	1.3062	0.0500	5.0000
39	0.7392	1.4111	0.0500	2.4891
40	0.9847	1.9970	0.7318	4.0039
41	1.0815	1.1983	1.1000	5.0000
42	0.8583	1.5301	0.8583	2.9750
43	0.7472	1.4654	0.8178	3.5274
44	0.7319	1.3547	0.7038	1.9813
45	0.8808	1.2265	0.9978	5.0000
46	0.0500	2.0114	0.3588	2.8917
47	1.0034	1.5864	0.8437	5.0000
48	0.6300	4.9949	0.0646	5.0000
49	0.8989	1.7688	0.7878	5.0000
50	0.7010	1.1658	0.3132	0.3171
51	1.0155	1.5602	0.5485	0.5270

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Table 4.5: Continued: Comparison of The improved AVOA with PSO, GTO, and The original AVOA

Relays	**PSO**		**GTO**	
	TDS	**PS**	**TDS**	**PS**
52	0.5831	1.4567	0.3218	2.1595
53	0.5978	1.4091	0.7674	5.0000
54	0.5737	1.5496	0.6044	3.2910
55	0.6230	1.3651	0.6675	5.0000
56	0.6669	1.5664	0.3805	0.8756
57	0.5604	1.3400	0.1809	5.0000
58	0.9262	1.3989	0.7365	5.0000
59	0.9043	2.0226	0.7838	3.7518
60	0.7425	1.6784	0.4638	1.3171
61	0.7035	1.5996	0.3403	0.4962
62	0.6220	1.4148	0.5208	2.1459
63	0.1546	1.7296	0.6368	3.0786
64	0.0500	1.7668	0.3294	1.5152
65	0.3480	1.5747	0.2360	0.6930
66	0.0527	1.4907	0.05	1.3939
67	0.1204	1.6064	0.7408	3.8514
68	0.6451	1.5415	0.5560	1.4345

Continued on the next page

Table 4.5: Continued: Comparison of The improved AVOA with PSO, GTO, and The original AVOA

Relays	**PSO**		**GTO**	
	TDS	**PS**	**TDS**	**PS**
OF (s)	59.86		76.12	

4.5 Conclusion

In conclusion, The purpose of this research work was focused on achieving optimal coordination for directional overcurrent relays for middle line failures through using two different algorithms, we have demonstrate the effeciency through comparison with both other . Utilizing both the 9-bus and 39-bus systems as test cases.

Through comprehensive analysis and simulation, we have validated the effectiveness of our algorithm in achieving optimal coordination for directional overcurrent relays.

4.6 General Conclusion & Future Directions

⇒ The objective of This work is to provide a comprehensive review of the application of optimization techniques for optimal DOCR (Directional Overcurrent Relays) coordination. This review highlights the increasing significance of optimization algorithms in tackling the challenges associated with DOCR coordination. It presents an overview of various optimization methods, such as PSO (Particle Swarm Optimization), GTO (Genetic Algorithm Optimization) , as discussed in the literature. The results demonstrate that optimization algorithms are effective tools for solving the DOCR coordination problem. Additionally, the study identifies several key findings and concerns related to the use of optimization algorithms for DOCR coordination.

Key findings include:

• Optimization techniques can significantly enhance the coordination of DOCRs, resulting in faster fault clearance times and improved system reliability.

• The significant reduction in the operating time of DOCRs without any violation of constraints compared to other existing conventional characteristics.

• The results obtained for the coordination of DOCRs have shown that the proposed approach offers more flexibility during the optimization process and thus ensures the satisfaction of coordination constraints and the reduction of total average discrimination time.

⇒ Based on these findings, the study also identified several potential future directions for research:

• Study of the impact of intermittent renewable energies on the performance of electrical protection systems.

• Develop a methodology for adaptive protection relay settings, capable of overcoming the problem of continuous variation in the structure and topology of electrical networks.

• Conducting field tests and implementing the proposed coordination mechanisms in real-world network environments would provide valuable insights.

There are many exciting opportunities for future research The methodologies outlined in this paper establish a robust groundwork for upcoming studies, the optimization algorithms will play an increasingly important role in the coordination of DOCRs in the years to come. The optimization problem of DOCRs coordination is a challenging one, but it is also a very rewarding one.Crafting efficient optimization algorithms for this purpose stands to greatly enhance the reliability and efficiency of power systems.

Appendix A

Description of the Appendix

A.1 Data for IEEE 9-bus and IEEE 39-bus test networks

A.1.1 IEEE 9-bus system

This appendix serves as a reference to the test systems utilized in the thesis. The model of the IEEE 9-Bus electrical systems is directly obtained from DigSILENT PowerFactory with a set of element parameters. However, the only elements included in this appendix are the following: line, synchronous generator (SG), and load.

Generator	S_n [MVA]	V_n [kV]	H [s]	P [MW]	V_{set} [p.u]
G1	247.5	16.5	4.775	163	1.04
G2	192	18.0	1.77	163	1.025
G3	128	13.8	1.175	85	1.025

Table A.1: Generator Parameters of the IEEE 9-bus System

Load	P [MW]	Q [Mvar]	Power Factor
A	125	50	0.928 lagging
B	90	30	0.948 lagging
C	100	35	0.943 lagging

Table A.2: Load Parameters of the IEEE 9-bus System

Line	Terminal i	Terminal j	Length [Km]	R [Ω/km]	L [mH/km]	C [µF/km]
Line 1	B 5	B 4	100	0.0529	1.431	0.01059
Line 2	B 7	B 5	100	0.1693	2.711	0.01841
Line 3	B 7	B 8	100	0.0449	1.212	0.00896
Line 4	B 8	B 9	100	0.0629	1.697	0.01257
Line 5	B 9	B 6	100	0.2063	2.862	0.02154
Line 6	B 6	B 4	100	0.0899	1.549	0.00951

Table A.3: Line Parameters of the IEEE 9-bus System

A.1.2 IEEE 39-bus system

In a similar manner, the elements of the IEEE 39-Bus system are presented in this section. The elements can be located in the system layout of Figure 4.5 Table A.4 presents the Generator parameters, while the Line and loads are presented in Tables A.5 and A.6 respectively.

Table A.4: enerator Parameters of the IEEE 39-bus System

Generator	S_n **[MVA]**	V_n **[kV]**	H **[s]**	P **[MW]**	V_{set} **[p.u]**
G1	10000	34.5	5.000	1000	1.0300
G2	700	16.5	4.329	520.8	0.9820
G3	800	16.5	4.475	650	0.9310
G4	800	16.5	3.575	632	0.9972
G5	300	16.5	4.333	254	1.0123
G6	800	16.5	4.350	650	1.0493
G7	700	16.5	3.771	560	1.0635
G8	700	16.5	3.471	540	1.0278
G9	1000	16.5	3.450	830	1.0265
G10	1000	16.5	4.200	250	1.0475

Table A.5: Line Parameters of the IEEE 39-bus System

Line	**Bus** i	**Bus** j	**Length [km]**	R **[Ω/km]**	L **[mH/km]**	C **[μF/km]**
1-2	BbB 1	JD 2	163.06	0.0255	0.7958	0.00954
1-39	B 1	JD 39	99.188	0.0120	0.7958	0.01685
2-3	B 2	JD 3	59.909	0.0258	0.7958	0.00956
2-25	B 2	JD 25	34.120	0.2442	0.7958	0.00953
3-4	B 3	JD 4	84.508	0.0183	0.7958	0.00583
3-18	B 3	B 18	52.768	0.0248	0.7958	0.00902
4-5	B 4	B 5	50.784	0.0187	0.7958	0.00588
4-14	B 4	B 14	51.181	0.0186	0.7958	0.00601
5-6	B 5	B 6	10.316	0.0231	0.7958	0.00937
5-8	B 5	B 8	44.436	0.0214	0.7958	0.00740
6-7	B 6	B 7	36.501	0.0196	0.7958	0.00689
6-11	B 6	B 11	32.533	0.0256	0.7958	0.00951
7-8	B 7	B 8	18.251	0.0261	0.7958	0.00952
8-9	B 8	B B9	144.02	0.0190	0.7958	0.00588
9-39	B 9	B 39	99.188	0.0120	0.7958	0.00269
10-11	B 10	B 11	17.063	0.0279	0.7958	0.00952
10-13	B 10	B 13	17.063	0.0279	0.7958	0.00952
13-14	B 13	B 14	40.072	0.0268	0.7958	0.00958
14-15	B 14	B 15	86.095	0.0249	0.7958	0.00947
15-16	B 15	B 16	37.294	0.0287	0.7958	0.01021
16-17	B 16	B 17	35.311	0.0236	0.7958	0.00846
B 16-19	B 16	B 19	77.366	0.0246	0.7958	0.00875
16-21	B 16	B 21	53.561	0.0178	0.7958	0.01060
16-24	B 16	B 24	23.408	0.0153	0.7958	0.00647
17-18	B 17	B 18	32.533	0.0256	0.7958	0.00903
17-27	B 17	B 27	68.638	0.0225	0.7958	0.01044
21-22	B 21	B 22	55.545	0.0171	0.7958	0.01029
22-23	B 22	B 23	38.088	0.0188	0.7958	0.01080
23-24	B 23	B 24	138.86	0.0188	0.7958	0.00579
B 25-26	B B 25	B 26	128.15	0.0297	0.7958	0.00892
26-27	B 26	B 27	58.322	0.0286	0.7958	0.00915
26-28	B 26	B 28	188.06	0.0272	0.7958	0.00924
26-29	B 26	B 29	247.97	0.0274	0.7958	0.00924
28-29	B 28	B 29	59.909	0.0278	0.7958	0.00926

Table A.6: enerator Parameters of the IEEE 39-bus System

Bus	P **[MW]**	Q **[MVar]**	M	**Power Factor**
3	322	2.4	0.99997	ind
4	500	184	0.93847	ind
7	233.8	84	0.94110	ind
8	522	176	0.94758	ind
12	7.5	88	0.08491	ind
15	320	153	0.90218	ind
16	329	32.3	0.99521	ind
18	158	30	0.98244	ind
20	628	103	0.98681	ind
21	274	115	0.92207	ind
23	247.5	84.6	0.94624	ind
24	308.6	-92.2	0.95815	ind
25	224	47.2	0.97851	ind
26	139	17	0.99114	ind
27	281	75.5	0.96574	ind
28	206	27.6	0.99114	ind
29	283.5	26.9	0.99552	ind
31	9.2	4.6	0.89442	ind
39	1104	250	0.97530	ind

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