



**TRIBHUVAN UNIVERSITY
INSTITUTE OF ENGINEERING
PULCHOWK CAMPUS**

THESIS NO: 078/MSPSE/009

**Optimal Coordination of Directional Overcurrent Relays Using Sine Cosine
Algorithm**

by

Madhav Prasad Nagarkoti

**A THESIS
SUBMITTED TO THE DEPARTMENT OF ELECTRICAL ENGINEERING IN
PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE IN POWER SYSTEM ENGINEERING**

**DEPARTMENT OF ELECTRICAL ENGINEERING
LALITPUR, NEPAL**

APRIL, 2025

COPYRIGHT©

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

Head of Department
Department of Electrical Engineering
Tribhuvan University, Institute of Engineering
Pulchowk Campus, Pulchowk, Lalitpur, Nepal



Accredited by University Grants
Commission (UGC) Nepal 2020

त्रिभुवन विश्वविद्यालय
TRIBHUVAN UNIVERSITY
इन्जिनियरिङ्ग अध्ययन संस्थान
INSTITUTE OF ENGINEERING
पुल्चोक क्याम्पस
PULCHOWK CAMPUS
DEPARTMENT OF ELECTRICAL ENGINEERING
Pulchowk, Lalitpur

Institute of Engineering
Electrical Engineering Department
Pulchowk Campus

CERTIFICATE OF APPROVAL

The undersigned certify that they have read and recommended to the Institute of Engineering for acceptance, a dissertation entitled “**Optimal Coordination of Directional Overcurrent Relays Using Sine Cosine Algorithm**”, submitted by **Madhav Prasad Nagarkoti** in partial fulfillment of the requirement for the award of the degree of **Master of Science in Power System Engineering**.

Assoc. Prof. Jeetendra Chaudhary
Supervisor
Program Coordinator
M.Sc. in Power Electronics and Drives
Department of Electrical Engineering

Asst. Prof. Akhileshwar Mishra
Supervisor
M.Sc. in Power System Engineering
Department of Electrical Engineering

Bodh Nath Neupane
External Examiner

Asst. Manager, Project Management Directorate
Nepal Electricity Authority

Asst. Prof. Dr. Bishal Silwal
Program Coordinator
M.Sc. in Power System Engineering
Department of Electrical Engineering

Assoc. Prof. Dr. Basanta K. Gautam
Head of Department
Department of Electrical Engineering

APRIL, 2025

ABSTRACT

The complexity of protection coordination in modern power systems has significantly increased due to large-scale interconnections. Such networks are protected by directional overcurrent relays (DOCRs), whose optimal coordination is extremely constrained and nonlinear. This study employs the Sine Cosine Algorithm (SCA), a nonlinear optimization method, to address the optimal coordination problem of the DOCRs. Recently, the SCA algorithm was put forth to solve optimization problems with extremely nonlinear constraints. Utilizing the sinusoids cyclic nature, the technique repositions a solution around another optimal solution. This method finds a global optimum by taking use of the area that the constraints define. The SCA is used in this study to maximize the protection coordination issues for the IEEE Three-Bus, Eight-Bus, Fifteen-Bus, and Thirty-Bus test systems. Additionally, this study uses SCA to optimize the coordination issue in the Koshi Province Grid of Integrated Nepal Power System's (INPS). The findings demonstrate the method's dependability in lowering the main relays' total working time while maintaining the CTI between pairs of backup and primary relay.

Keywords: Coordination, CTI, DOCR, Sine Cosine Algorithm

ACKNOWLEDGEMENT

I am grateful to the thesis supervisors, M.Sc. Power Electronics and Drive Program Coordinator Associate Professor Jeetendra Chaudhary and Assistant Professor Akhileswar Mishra, who have been guiding me continuously and sharing invaluable insights, which were of great assistance in this thesis work. Their knowledge and encouragement have given much needed leverage in steering the research. In fact, I also feel greatly indebted to the Head of the Department, Department of Electrical Engineering, Associate Professor Dr. Basanta Kumar Gautam, and to the M.Sc. Power System Engineering Program Coordinator, Dr. Bishal Silwal, for offering valuable feedback and keeping a very healthy academic environment.

My sincere gratitude also goes to the entire staff of the Department of Electrical Engineering, the Institute of Engineering, Pulchowk Campus, for the availability of resources and the academic environment in a timely fashion that would enhance academic growth and learning effectively.

I am also thankful to Er.Chandan Pokhrel for his support throughout this thesis. I am also grateful to my friends and family, who have been very supportive, patient, and understanding of the tough times but enriching experiences. They have always been a moral support and strength throughout my academic journey. This thesis would not have been possible without the contribution and support of those mentioned above, and thanks to all for believing in me, an integral part of the journey.

TABLE OF CONTENTS

COPYRIGHT	i
CERTIFICATE OF APPROVAL	ii
ABSTRACT	iii
ACKNOWLEDGEMENT	iv
TABLE OF CONTENTS	v
LIST OF FIGURES	vii
LIST OF TABLES	viii
LIST OF ABBREVIATIONS	ix
CHAPTER ONE: INTRODUCTION	1
1.1 Background	1
1.2 Problem Statement	2
1.3 Objectives	2
1.4 Scope	3
1.5 Limitation	3
1.6 Thesis Organization	3
CHAPTER TWO: LITERATURE REVIEW	5
2.1 Background	5
2.2 Protection Methods	6
2.3 Directional Overcurrent Relays (DOCRs)	7
2.3.1 Time Multiplier Setting (TMS) and Plug Setting (PS)	8
2.3.2 Various Approaches for Optimizing DOCRs Coordination	8
CHAPTER THREE: METHODOLOGY	10
3.1 Approach	10
3.1.1 Methodology Block Diagram	11
3.1.2 Objective function formulation	12
3.1.3 Sine Cosine Algorithm (SCA)	14
3.2 Software and Tools Used	18

3.2.1	Microsoft Office	18
3.2.2	MATLAB	18
3.2.3	DIgSILENT POWERFACTORY	18
3.2.4	Overleaf	18
3.3	Test Systems	18
3.3.1	IEEE-3 Bus System	19
3.3.2	IEEE-8 Bus System	19
3.3.3	IEEE-15 Bus System	20
3.3.4	IEEE-30 Bus System	22
3.3.5	Koshi Province Grid of INPS	23
CHAPTER FOUR: RESULTS AND DISCUSSION		24
4.1	SCA Applied to IEEE Standard Buses	24
4.1.1	IEEE 3-Bus System	24
4.1.2	IEEE 8-Bus System	27
4.1.3	IEEE 15-Bus System	31
4.1.4	IEEE 30-Bus System	34
4.1.5	Comparison of SCA with various other optimization techniques	37
4.2	SCA applied to Koshi province	37
4.2.1	Data Collection	37
4.2.2	Optimal Setting of Relays	37
CHAPTER FIVE: CONCLUSION		40
REFERENCES		41
APPENDIX A: SLD of Koshi Province		43
APPENDIX B: PUBLICATION		45
APPENDIX C: PLAGIARISM TEST REPORT		56

LIST OF FIGURES

Figure 3.1	Work Flow Diagram	12
Figure 3.2	SCA for Nonlinear Optimization	15
Figure 3.3	SCA Flowchart Diagram	17
Figure 3.4	SLD of IEEE 3-bus system	19
Figure 3.5	SLD of IEEE eight bus system	20
Figure 3.6	SLD of IEEE 15-bus system	21
Figure 3.7	SLD of IEEE 30-bus system	22
Figure 3.8	Sungle line diagram of Koshi Province Grid of INPS	23
Figure 4.1	Convergence characteristics for three-bus system with weight sets to unity	25
Figure 4.2	Coordination of relay pairs for IEEE 3 Bus system with weight sets to unity	25
Figure 4.3	Convergence characteristics for three-bus system with varying weight	26
Figure 4.4	Coordination of relay pairs for IEEE 3 Bus system with varying weight	27
Figure 4.5	Convergence characteristics for eight-bus system with weights set to unity	28
Figure 4.6	Coordination of relay pairs for IEEE 8 Bus system with weights set to unity	29
Figure 4.7	Convergence characteristics for Eight-bus system (Weighted) . . .	30
Figure 4.8	Coordination of relay pairs for IEEE 8-Bus system (Weighted) . .	31
Figure 4.9	Convergence characteristics for fifteen-bus system	33
Figure 4.10	Coordination of relay pairs for IEEE 15 Bus system	34
Figure 4.11	Convergence characteristics for Thirty-bus system	36
Figure 4.12	Coordination of relay pairs for IEEE 30 bus system	36
Figure 4.13	Convergence characteristics for Koshi province system	38
Figure 4.14	Coordination of relay pairs for Koshi Provine Grid	39

LIST OF TABLES

Table 3.1	Relay numbers and associated lines of Koshi Province Grid of INPS	23
Table 4.1	Result obtained for IEEE 3-bus test system for weight sets to unity .	24
Table 4.2	Three-bus test system results (weighted)	26
Table 4.3	Results obtained for IEEE 8-bus test system with weights set to unity	27
Table 4.4	Results obtained for Eight-bus test system (Weighted)	29
Table 4.5	Results obtained for IEEE 15-bus test system	31
Table 4.6	30 bus test system results	34
Table 4.7	Comparison with different optimization approaches	37
Table 4.8	SCA result for Koshi Province	38

LIST OF ABBREVIATIONS

ALO	Ant-lion Optimizer
CTI	Coordination Time Interval
DG	Distributed Generator
DOCRs	Directional Overcurrent Relays
FL	Fuzzy Logic
GA	Genetic Algorithm
HWO	Hybrid Whale Optimization
IDMT	Inverse Definite Minimum Time Relay
IEEE	Institute of Electrical and Electronics Engineers
IGWO	Improved Grey Wolf Optimizer
MIP	Mixed Integer Programming
PS	Plug Setting
SCA	Sine Cosine Algorithm
TMS	Time Multiplier Setting

CHAPTER ONE: INTRODUCTION

1.1 Background

To safeguard the power system network, directional overcurrent relays (DOCRs), distance relays, circuit breakers and isolators are employed. The protection coordination in modern power systems has become increasingly complex due to extensive interconnections. Interconnected power systems pose various challenges that complicate protection coordination. One significant concern is the rise in fault levels due to extensive interconnections, leading to higher short-circuit currents that make setting protective relays more difficult. Additionally, the bidirectional nature of power flow in interconnected networks necessitates the use of advanced directional relays for accurate fault detection and isolation. Coordination among multiple utilities adds another layer of complexity, as different regions operate with distinct protection schemes that must function harmoniously to prevent misoperations or unnecessary tripping. Furthermore, frequent alterations in network topology due to switching operations or system reconfigurations impact relay settings, making it harder to ensure optimal protection coordination. In order to protect the system, the DOCRs must function swiftly and consistently. The optimum coordination between the relays is necessary to protect the system. Relays ought to function in a way that isolates errors without causing harm to the power system.

Primary job of DOCR is to identify the disturbances in its protection region as soon as possible. The term primary protection describes this kind of defense. Sometimes for a variety of reasons including primary relay malfunctions, isolator failures, and more, the primary protection may not be effective. In this situation, the backup protection ought to isolate the fault after a specific amount of time. The backup protection, which is an extra layer of security given to a certain area or protective region and only activates when the primary protection plan fails, takes effect after a predefined period of time.

The total time of operation of individual relay is determined by two settings: Time Multiplier Setting (TMS) and Plug Setting (PS). Various methods have been developed to determine the minimum total operation time by adjusting the TMS and PS. Since the relay's operating duration is a linear function of its TMS and a nonlinear function of its PS, most of these techniques simply optimize the TMS and fix the relay's PS to a preset constant value. To solve this kind of issue, the TMS is optimized only using linear programming techniques such as Simplex, Two-Phase and Dual-Simplex methods.

The DOCR coordination problem can be resolved using nonlinear programming approaches such as Ant-lion Optimization (AO), Fuzzy Logics (FL), Genetic Algorithm (GA), Hybrid Whale Optimization (HWO), Improved Grey Wolf Optimizer (IGWO), Mixed Integer Programming (MIP), and others. Among these methods is the Sine Cosine Algorithm (SCA), which was initially presented in [1] and is employed in this study. The PS and TMS of a relay can be optimized using these nonlinear optimization techniques to guarantee the smallest possible overall working time for the primary relays. Note that the optimization methods based on derivatives may fail to reach the global minimum and instead become stuck in a local minimum. The rates of convergence of these algorithms are modest as system sizes increase and are dependent on the system size under consideration.

1.2 Problem Statement

The time of operation of the relay is a nonlinear function of the Plug Setting (PS), therefore traditional linear programming techniques cannot optimize the PS of the relay. Not only should the primary relays operate for the shortest amount of time possible, but the time of operation of primary and backup relays must also be kept consistent. The non-linearity of the problem is further increased by this. Therefore, the optimization of the DOCR coordination problem cannot be done using traditional linear programming-based techniques.

1.3 Objectives

- Primary objective of this research works is to optimize Plug Setting (PS) and Time Multiplier Setting (TMS) values so that the overall weighted sum of time of operation of all the primary relays in their respective zones can be minimized.
- Maintaining the coordination time interval (CTI) between primary and secondary relay pairs is another goal of this study. This means that in the event that the primary relay is unable to resolve a fault within its operating region for any reason, the backup relays should take over and resolve the issue. Coordination time interval (CTI) is the difference between the backup relay's and primary relay's operating times.
- Optimizing coordination concerns for IEEE Three-Bus, Eight-Bus, Fifteen-Bus, and Thirty-Bus test systems implementing SCA is the ultimate goal of this effort. Additionally, this study attempts to maximize the coordination issue in the Koshi Province Grid of the Integrated Nepal Power System (INPS) by using SCA.

1.4 Scope

- Formulate optimal optimal coordination problem.
- Code the SCA in MATLAB to solve such problems.
- Implement the method on four distinct test bus systems: the three-bus, eight-bus, fifteen-bus, and thirty-bus systems.
- Compare outcomes of the different optimization strategies with the outcomes obtained in test systems.
- Use the algorithm on Koshi Province Grid of Integrated Nepal Power System (INPS).
- Minimizing the total time of operation of the primary relaysop, and optimize the TMS and PS values for each relay separately.

1.5 Limitation

- The findings demonstrate that the TMS and PS values obtained are continuous rather than discrete, meaning they were not acquired in steps.
- In this research, only Koshi Province grid is taken for case study.

1.6 Thesis Organization

The dissertation is organized into five chapters. This section enlists a brief outline of each chapter and its contents.

- Chapter 1 provides a brief introduction to the dissertation. It presents the problem statement, followed by the objectives of the thesis.
- Chapter 2 explores the necessary literature review done for this dissertation. It covers the fundamentals of directional over-current relays, its operation, and coordination, non-linear optimization techniques (SCA).
- Chapter 3 describes the research methodology of the dissertation starting from formulation of objective function, defining constraints, implementing SCA to solve non linear optimization problem and workflow.

- Chapter 4 presents the results obtained using the methodology described in Chapter 3.
- Chapter 5 concludes the thesis work.

Finally, this thesis will end with a list of references and the relevant appendices.

CHAPTER TWO: LITERATURE REVIEW

This chapter explores the necessary literature review done for this dissertation. It covers the fundamentals of directional over-current relays, its operation, and coordination, non-linear optimization techniques (SCA).

2.1 Background

In power system, ensuring safe and reliable operation naturally drives the improvement of existing protection schemes. A power system network normally consists of several closed-state fuses, switches, and circuit breakers. The coordination of protection in modern power systems has become more complicated due to extensive interconnections. Similarly, With the increasing integration of large number of generators and lines into power systems network, their structural configuration changes, necessitating modifications in the protection scheme to ensure effective coordination among various relays positioned at different locations. Generally speaking, adding a generator to the network raises the fault level. [2]. Addition of new generator to a network creates a parallel network, which lowers the effective value of fault impedance between the fault and the equivalent source. This raises the current due fault. Renewable energy sources that rely on inverters, however, have a much lower fault current capacity. Therefore, if traditional generator is replaced by an inverter-based distributed generator (IBDG), the fault level may actually decrease. When the network is fully powered by IBDGs, the fault current can drop to such a low level that it is difficult to distinguish either it is fault current or normal load current.

Changes in fault levels have an impact on the effectiveness of the protection strategy because they change the working zones of the relays, potentially causing coordination issues. This may lead to coverage gaps or overlapping protection zones, which may result in undetected defects or needless customer disconnections. Furthermore, a rise in fault level could surpass the substation equipment's rated capacity, resulting in safety hazards and the need for expensive infrastructure improvements.

Most relays in power system networks are unable to differentiate the direction of current flow, which can initiate the false tripping as fault currents feed into faults on adjacent lines. Whenever network becomes complex due to large integration of generation and lines, protection engineers must evaluate its effect on the system through analysis of fault or studying protection and, if needed, adjust settings of relays. Proper coordination between the relays should ensure minimal relay operating time while maintaining the required coordination time interval (CTI) between relays.

Optimizing protection coordination among relays placed along power lines is the main goal of this research project. Although a lot of research has been done in this field, the majority of it uses methods based on fault currents. These techniques use pickup current values and time dial settings as decision factors, which must be optimized for efficient relay coordination. A definite time relay-based non-communication overcurrent protection system has been suggested in [3]; However, in large power system networks, this approach might lead to longer fault isolation times. Optimizing the relay setting is the central focus of this thesis. The measurement of voltage at each relay determines the best protective coordination. The literature [4], [5] contain a few protection coordination studies that use both current and voltage measurement. [6] gives information on how to assess the working time of relays using the new relay characteristics and local voltage measurement; however, no optimization approaches have been utilized to establish the optimum relay settings. Thus, the primary focus of the research is the analysis of the performance of a voltage-based coordinating system utilizing the meta-heuristic algorithm known as particle swarm optimization. The optimization method listed in [3] is one available for use in this regard. Several algorithms, such as Heuristic Optimization Techniques, Mathematical Programming, and evolutionary algorithms like Artificial Neural Network (ANN), Firefly Algorithm (FA), Genetic Algorithm (GA), Monte Carlo Simulation, Modified Adaptive Firefly Algorithm (MAFA) [3], Cuckoo Search Algorithm (CSA), Particle Swarm Optimization (PSO) [7], [8], [9], etc., have been suggested to choose the right values for the standard characteristics of the proposed relay. The above-mentioned techniques aim to optimize the total operational time of the relays in issue. All of optimization techniques mentioned above have been found to be useful in the process, engineering, and science and technology sectors. To obtain the best value of the relay configuration, a comprehensive literature on the optimal coordination of protection issues is currently accessible in the references.

2.2 Protection Methods

Power system network operator is responsible for ensuring that protection devices are implemented in every system to prevent the flow of any current, including earth leakage, for a duration that could compromise the system's ability to safely carry that current [15]. The protection system must adhere to the following key principles:

- Sensitivity: The system should operate accurately under the least favorable conditions that still warrant activation.

- **Selectivity:** This means that the protection system should be capable of distinguishing between situations that require an immediate response, a delayed action, or no intervention, ensuring that only the minimum number of customers are affected during an abnormal operating condition.
- **Speed:** In order to prevent equipment damage, minimize energy loss, and ensure supply continuity, the system must react in the allotted time.
- **Stability:** External faults and typical load circumstances should not have an impact on the protective mechanism.

To determine the appropriate relay action, continuous monitoring of the actuating quantity is essential. This quantity may include current, voltage, frequency, impedance, pressure, or a combination of these, depending on the specific protection scheme. The need for extra parts, such as pressure sensors, thermometers, or voltage and current transformers, complicates the implementation of such a system. However, their roles is to improve speed, sensitivity, reliability and selectivity of the protection system.

Directional time-graded overcurrent and earth fault relays are a favored protection method in power system networks when large and daily fault level variations are a key concern. The effectiveness of this approach relies on the following assumptions:

- **Loop Network Configuration:** Fault currents flow in any direction from any buses to the fault location.
- **Sufficient Fault Current Availability:** Conventional generators, due to their high thermal inertia and stored energy, contribute significant fault currents, often several times greater than the normal load current.
- **Fault Level Variability:** Fault level variation in power systems occurs due to changes in system impedance, network topology, and the contribution of different power sources. These variations can impact the effectiveness of protection schemes and the stability of the power system.

2.3 Directional Overcurrent Relays (DOCRs)

Fuses, circuit breakers, reclosers, and overcurrent relays (OCRs) are widely used to protect traditional radial power system networks. Due to increase in interconnection of various power generating sources, transmission lines and substations makes traditional power

system radial structure networks become meshed and complex allowing power to flow in both directions. The size of short-circuit currents is greatly influenced by the kind and penetration of the power generating sources. Directional overcurrent relays (DOCRs) are typically recommended over traditional simple overcurrent relays for timely and dependable protection of these intricate networks. Improving the protection scheme's overall performance requires the best possible coordination of DOCRs.

2.3.1 Time Multiplier Setting (TMS) and Plug Setting (PS)

Two settings determine a directional overcurrent relay's (DOCR) operating time: Time Multiplier Setting (TMS) and Plug Setting (PS). A DOCR's main responsibility is to identify and respond to the fault within its specified area as soon as possible; this is referred to as primary protection. Backup protection is required if the primary protection system fails to operate because of malfunction of circuit breakers or relays. When primary protection is unable to operate, backup protection is an extra mechanism that is used to protect the system after a certain time delay. Coordinating DOCRs seek to identify the optimal TMS and PS values for each relay in order to reduce the total working time of all primary relays and eliminate miscoordination between primary and backup relay pairs.

2.3.2 Various Approaches for Optimizing DOCRs Coordination

Literature has documented various approaches for the best possible coordination of DOCRs in meshed power systems. At first, relay coordination was frequently accomplished by trial-and-error techniques. These approaches, however, had a slow convergence rate and required a significant number of repeats. In contrast to trial-and-error procedures, topological analysis-based methodologies were eventually developed for optimal coordination of DOCRs, needing fewer iterations to find a satisfactory solution. However, the global optimum values for Plug Setting and Time Multiplier Setting of DOCRs are not always assured by topological analysis techniques. Later, a number of optimization strategies, including traditional optimization strategies based on linear programming, were created to overcome the coordination issues of DOCRs.

Simplex, dual simplex, and two-phase simplex are examples of linear programming (LP) techniques that are renowned for their simplicity and efficiency. However, because a DOCR's operating time is a linear function of Time Multiplier Setting and Linear Programming-based optimization approaches are only useful for optimizing the time multiplier setting. Since DOCR coordination is a nonlinear optimization problem, nonlinear programming techniques including gradient search, random search, and sequential quadratic programming have been developed to address the drawbacks of LP-based approaches. In general,

NLP approaches outperform LP approaches in resolving DOCR coordination issues by simultaneously optimizing the plug setting (PS) and TMS of DOCRs. Nevertheless, both traditional optimization techniques may fail to reach global maxima and that may trap in local minimum. Furthermore, as the system size grows, their rate of convergence tends to decrease.

The effective coordination issues of DOCRs have been successfully solved in recent years using a range of heuristic and nature-inspired approaches. These include the following: Seeker Algorithm (SA), Genetic Algorithm (GA), GA-NLP, Oppositional Jaya Algorithm, Ant-lion Optimization, Firefly Optimization, Hybridized Whale Optimization Algorithm (HWOA), Mixed Integer Linear Programming (MILP), and Improved Grey Wolf Optimizer (IGWO). Artificial Bee Colony, Biogeography-Based Optimization, Non-dominated Sorting Genetic Algorithm-II, Teaching Learning-Based Optimization, Informative Differential Evolution Algorithm, Chaotic Differential Evolution, Cuckoo Search Algorithm, Hybrid Particle Swarm Optimization–Gravitational Search Algorithm, Symbiotic Organism Search, Fuzzy-GA, and Modified Electromagnetic Field Optimization. In terms of reaching global minima. These heuristic and evolutionary optimization methods typically perform better than topological, standard LP and NLP algorithms, and trial-and-error methods. They may, however, have premature convergence and frequently demand extra processing time. Researchers have put a lot of work into finding solutions to optimal relay coordination challenges for DOCRs, with a primary focus on reducing the relays' overall operation time. But there hasn't been much progress on the issues of primary and backup relay pairs coordination. Present study shows better outcomes by addressing relay configuration optimization and primary-backup relay pair coordination at the same time in order to close this research gap.

The Sine Cosine Algorithm (SCA) is a recently proposed population-based optimization approach that was recently presented to solve optimization problems. SCA's main benefit is its ability to use an adaptable range in the sine and cosine functions to seamlessly move from exploration to exploitation. Furthermore, as the iteration counter rises, the ranges of these functions are modified to highlight the exploitation of the search space. SCA is used for this research to optimize DOCR coordination. By generating balanced 3-phase fault at the midway between the lines, the algorithm's efficiency was evaluated on power systems with three, eight, fifteen, and thirty buses. According to the results, the suggested algorithm performs better than four previously presented algorithms (SA, IGWO, HWOA, and MILP) in terms of minimizing the relays' overall operating time.

CHAPTER THREE: METHODOLOGY

This chapter describes the dissertation's research approach, beginning with the definition of constraints, objective function formulation, implementation of SCA to solve nonlinear optimization problems, and the workflow.

3.1 Approach

The thesis begins with a literature review of the protection system, examining various protection methods employed in power system networks, their advantages, limitations, reliability, sensitivity, selectivity, and overall effectiveness. During this review, the impact of intensive interconnection and distributed energy resources (DERs) on power system network protection was assessed, relevant research studies were analyzed, and new perspectives were explored to enhance protection mechanisms.

In order to assure the lowest time for operation while ensuring appropriate relay coordination, directional overcurrent relay (DOCR) optimization is essential for power system protection. This work optimizes the relay settings by identifying the optimal Time Multiplier Setting (TMS) and Plug Setting (PS) using the Sine Cosine Algorithm (SCA), which reduces relay running time and improves protection coordination.

The nonlinear constrained optimization problem is used to formulate the optimization issue for DOCRs, as the objective function being to reduce the total time of operation of relays while meeting system constraints like:

- Relay coordination constraints
- Selectivity and sensitivity requirements
- Limits on TMS and PS.

Standard IEEE-Three bus, Eight bus, Fifteen bus and Thirty bus test systems are considered for validation. System parameters such as line impedance, fault currents, relay locations, and existing relay settings are collected. The power system network is modeled in DIGSILENT to simulate fault scenarios.

The Sine Cosine Algorithm (SCA) is used for the optimization because of its quick convergence and capacity to search globally. The steps for implementing SCA are as follows:

- Step 1: Initialization

Initialize the population of relay settings (TDS, PS) randomly. Define the number of iterations and stopping criteria. Set the control parameters for sine and cosine functions.

- Step 2: Fitness Function Evaluation

Compute the relay operating time using standard inverse time characteristics. Evaluate the objective function based on total operating time. Apply penalty functions for constraint violations.

- Step 3: Updating Relay Settings

Update relay settings using the sine and cosine mathematical model: where and are random numbers, and is the best solution obtained so far.

- Step 4: Constraint Handling

Ensure relay coordination by maintaining proper time margins between primary and backup relays. If constraints are violated, apply a penalty to the fitness function.

- Step 5: Checking for convergence.

Until the convergence criteria (such as the minimum error threshold or maximum iterations) are satisfied, repeat steps 2 to 4. Store the optimal relay configuration that was obtained.

3.1.1 Methodology Block Diagram

Figure 3.1 shows the general tasks and processes to be employed for this research work.

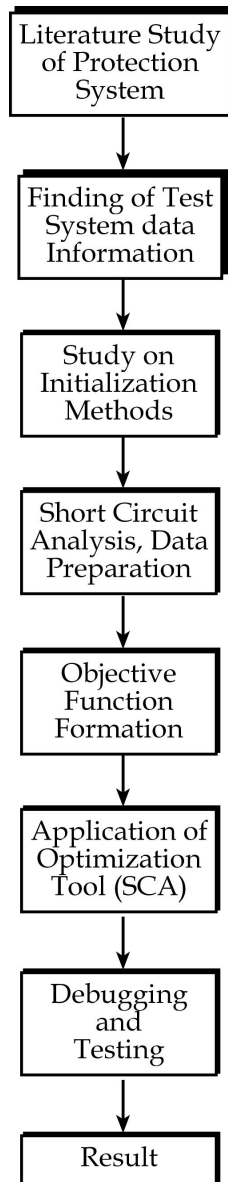


Figure 3.1: Work Flow Diagram

3.1.2 Objective function formulation

It is possible to formulate the relay coordination problem as a linear or nonlinear function. When dealing with a linear function, the time multiplier setting (TMS) is optimized while the plug setting (PS) remains constant within the current flow's lowest and maximum limitations. On the other hand, PS and TMS are optimized simultaneously for a nonlinear function. Furthermore, the coordination challenge is made more complex by the quantized nature of relay settings.

When tackling the coordination issue with DOCR, there are two primary goals to consider. In order to guarantee that faults are fixed as quickly as possible, the primary goal is to reduce overall time of operation all the relays used in the system. The second goal is to make sure that the primary and backup relays are properly synchronized so that, in the event that the primary relay fails, the backup relay will activate after a certain period of time. The following is a mathematical representation of the relay characteristics [10].

$$T_{ik} = \frac{TMS_i * \beta}{\left(\frac{I_{Rik}}{PS_i}\right)^\alpha - 1} \quad (3.1)$$

where,

T_{ik} is the relay i 's operating time for the fault at position k ; TMS_i is the relay i 's time multiplier setting; Relay i 's plug setting is PS_i ; Relay i 's fault current for the fault at position k is I_{Rik} ; the constants α and β vary based on the relay's characteristics.

The α and β values of the Inverse Definite Minimum Time (IDMT) relay are 0.02 and 0.14, respectively [11]. The goal of the relay coordination problem is to determine the TMS and PS values for each relay in order to minimize the total operating time of the primary relays. As a result, the equation of Objective function will:

Minimize (Optimize)

$$Z = \sum_i^n \sum_{k=1}^l w_{ik} \cdot T_{ik} \quad (3.2)$$

For the fault at location k ,

T_{ik} is the operating time for relay i , and

w_{ik} is the product of the likelihood that the fault will occur and the relative importance of the bus or line where the fault has occurred. Assuming w_{ik} equals unity, this approach accounts for the disparity in weight values between IEEE three-bus and eight-bus test systems.

The following constraints apply to the optimization problem:

- **constraints for PS**

PS must be within the specified boundaries as mentioned below:

$$PS_{i,lower} \leq PS_i \leq PS_{i,upper} \quad (3.3)$$

The lowest and highest Plug settings acceptable for all relays are set to 0.5 and 2.5, respectively.

- **Constraints for TMS**

The TMS setting must be within the specified boundaries as mentioned below:

$$TMS_{i,lower} \leq TMS_i \leq TMS_{i,upper} \quad (3.4)$$

TMS settings of 0.1 and 5, respectively, are the smallest and maximum values that are acceptable for all relays.

- **Constraints for time of operation**

Boundaries for the relay operating time must be as follows:

$$T_{ik,lower} \leq T_{ik} \leq T_{ik,upper} \quad (3.5)$$

Each relay should have a minimum working time of 0.10 seconds and a maximum operating time of 2.0 seconds.

- **Constraints for Relay coordination**

For a disturbance at location k, primary relay i should be operated earlier than backup relay j. The Coordination Time Interval (CTI) is the difference in time of operation between backup relay and primary relay and backup relay operated only when primary relay fails to operate. This constraints is mentioned as below:

$$T_{jk} - T_{ik} \geq CTI \quad (3.6)$$

This research work uses a CTI of 0.3 seconds for both primary and backup pairs i and j.

3.1.3 Sine Cosine Algorithm (SCA)

The basic sine and cosine functions are used in SCA, a novel optimization technique that was first put out in [1].

SCA creates an arbitrary beginning population that oscillates outward or inward from the present best result in order to find the another best result by exploring the constraints-defined region. Equation for updating population's position can be stated as [1]

$$X_i^{t+1} = \begin{cases} X_i^t + r_1 \times \sin(r_2) \times |r_3 P_i^t - X_i^t| & \text{if } r_4 < 0.5 \\ X_i^t + r_1 \times \cos(r_2) \times |r_3 P_i^t - X_i^t| & \text{if } r_4 \geq 0.5 \end{cases} \quad (3.7)$$

where the location of the current solution in i^{th} dimension and t^{th} iteration is denoted by X_i^t . The current solution's location in i^{th} dimension is X_i^{t+1} , and its best outcome in i^{th} dimension is P_i^t and $(t+1)^{th}$ iteration.

One major benefit of the Sine Cosine Algorithm (SCA) is that it can investigate a different search space in the event that the limiting values of the sine or cosine functions are not satisfied. When the data fall inside the restrictions, it focuses on exploiting the promising zone. SCA uses an adjustable variable to effectively transition from exploration to exploitation. Any optimization strategy should balance search space exploration and exploitation to produce the best results. Equation (3.8) and Figure 3.2 both state that the variable r_1 governs the adaptive range of sine and cosine functions in SCA.

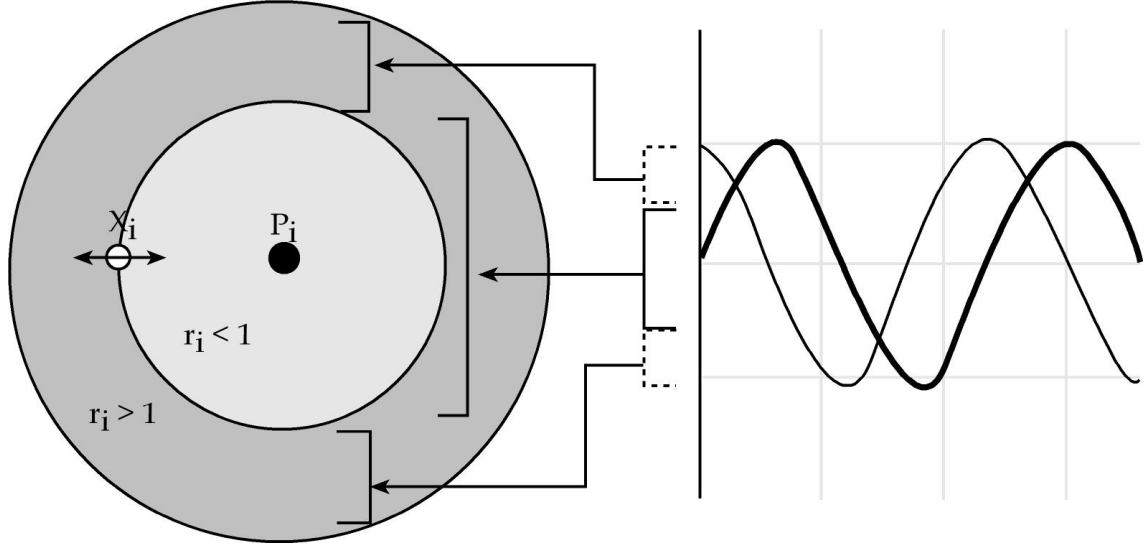


Figure 3.2: SCA for Nonlinear Optimization

$$r_1 = a - t(a/T) \quad (3.8)$$

It is as follows:

$r_2 \in (0, 2\pi); r_3 \in (0, 2); r_4 \in (0, 1)$. and $a = 2$.

'T' represents the maximum number of iterations, while 't' stands for the current iteration.

A random number is represented by r_2 , r_3 , and r_4 .

The SCA uses equation (3.7) to move all other solutions toward the optimum solution, which is stored in a variable P_i^t .

Figure 3.3 shows the SCA approach to solve optimization problem.

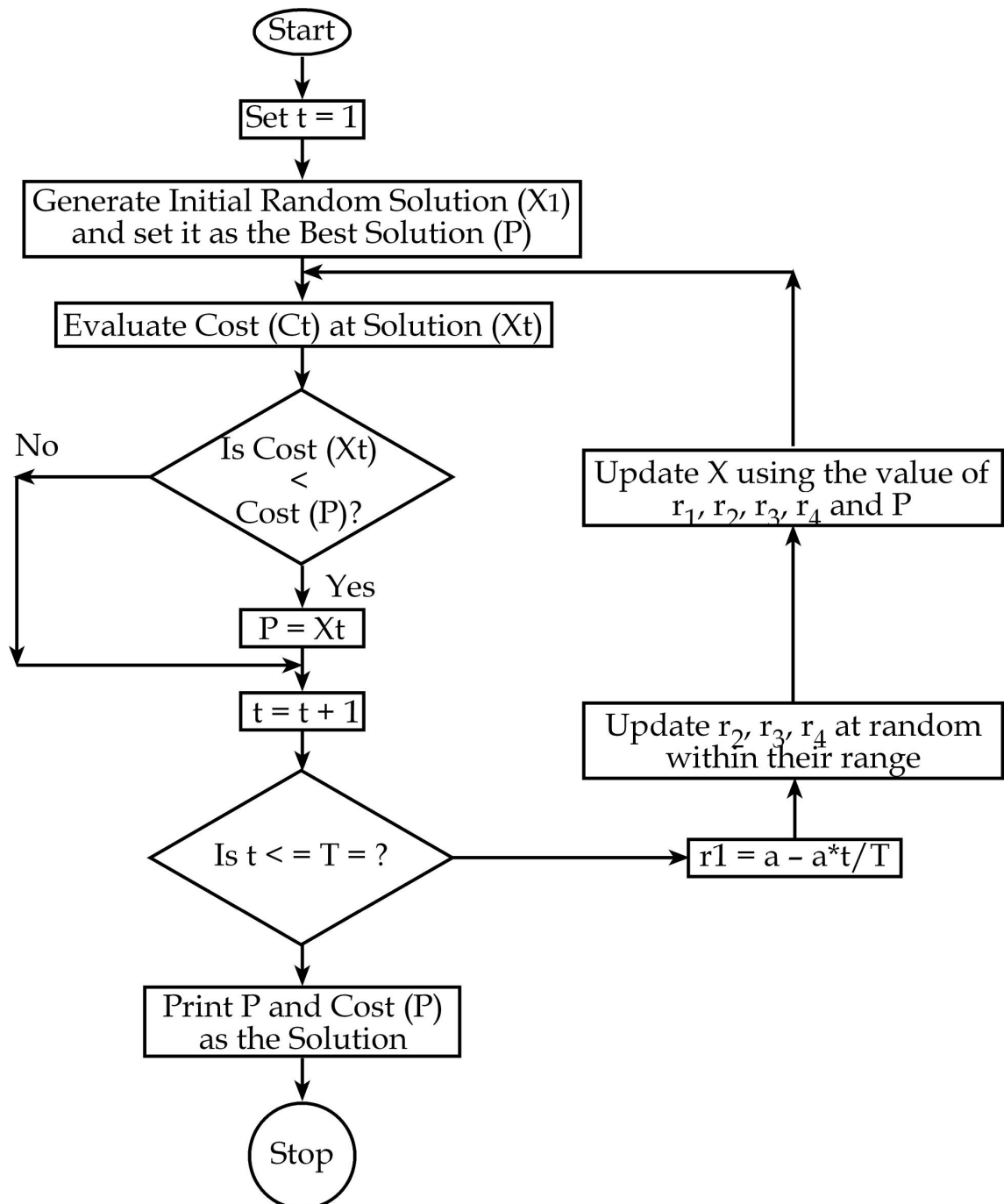


Figure 3.3: SCA Flowchart Diagram

3.2 Software and Tools Used

This section lists the tools and software used in this dissertation.

3.2.1 Microsoft Office

Microsoft Office is a family of softwares developed by Microsoft. It contains a word processor (Word), a spreadsheet program (Excel), and a presentation program (Powerpoint) among others. Word is used in this dissertation for preliminary report writing while Excel is used to store the acquired data of the fault current.

3.2.2 MATLAB

MATLAB is programming and numerical computing platform developed by MathWorks. In this research, MATLAB is used for solving the optimal relay coordination problem.

3.2.3 DIgSILENT POWERFACTORY

DIgSILENT PowerFactory is a comprehensive software tool used for power system analysis and simulation. It is widely used in the electrical engineering field for planning, operating, and analyzing electrical power systems. In this research, DIgSILENT PowerFactory is used to model Koshi Province Network of INPS and to create a fault in the real power system network for case study.

3.2.4 Overleaf

Overleaf is an online LaTeX editor used for writing, editing, and publishing scientific journal and documents. It provides LaTeX templates of various reputed journals. In this dissertation, overleaf is used for preparing the reports.

3.3 Test Systems

Four different IEEE test systems: the three-bus, eight-bus, fifteen-bus, and thirty-bus systems were used to implement the proposed algorithm. IDMT relays with $\alpha = 0.02$ and $\beta = 0.14$ were selected. For every relay, CTI limits of 0.3 seconds were selected. All relays had their CTI restrictions set to 0.3 seconds. After evaluating the algorithm's performance against available literature, it was run on the Koshi Province Grid of the Integrated Nepal Power System. In all four situations, the size of the population was set to 1000, and SCA program ran with a maximum of 1000 iterations.

3.3.1 IEEE-3 Bus System

The IEEE 3-bus test configuration seen in Figure 3.4 consists of three lines, three busses, three generators, and six relays. The ratings for each component are provided in [12]. The calculation of fault current was computed on the idea that balanced three-phase to ground faults would arise halfway down the line section.

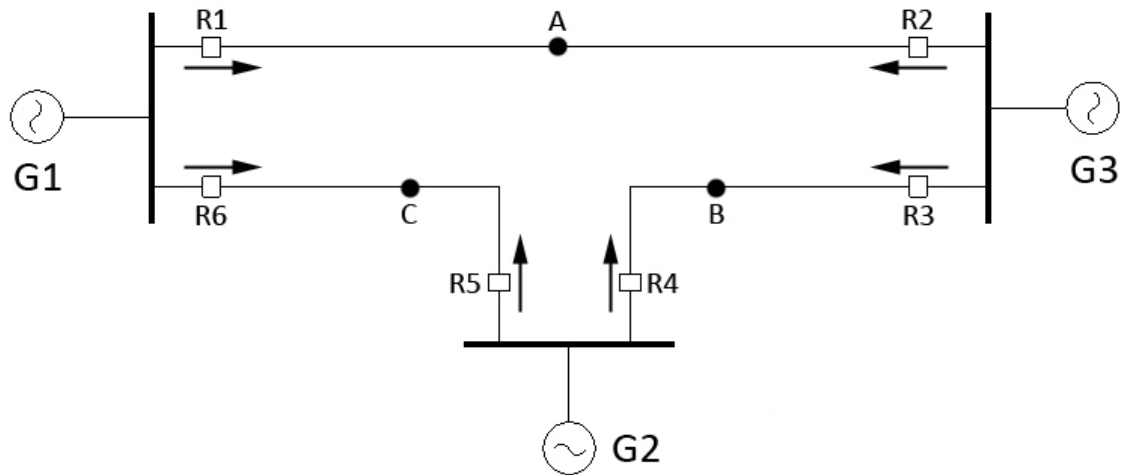


Figure 3.4: SLD of IEEE 3-bus system

3.3.2 IEEE-8 Bus System

Figure 3.5 shows the network for an eight bus (BUS1 to BUS8) test configuration. Seven lines, three generators, and fourteen DOCRs are shown in Figure 3.5. The external grid (EG) connected to B4 is represented by a 400 MVA short circuit power [13]. Relays R1, R2, R4, R5, R6, R8, R10, R11, R12, and R13 have CT ratios of 1200:5, whereas relays R3, R7, R9, and R14 have CT ratios of 800:5. It was believed that balanced three-phase to ground faults would show up in the middle of the line.

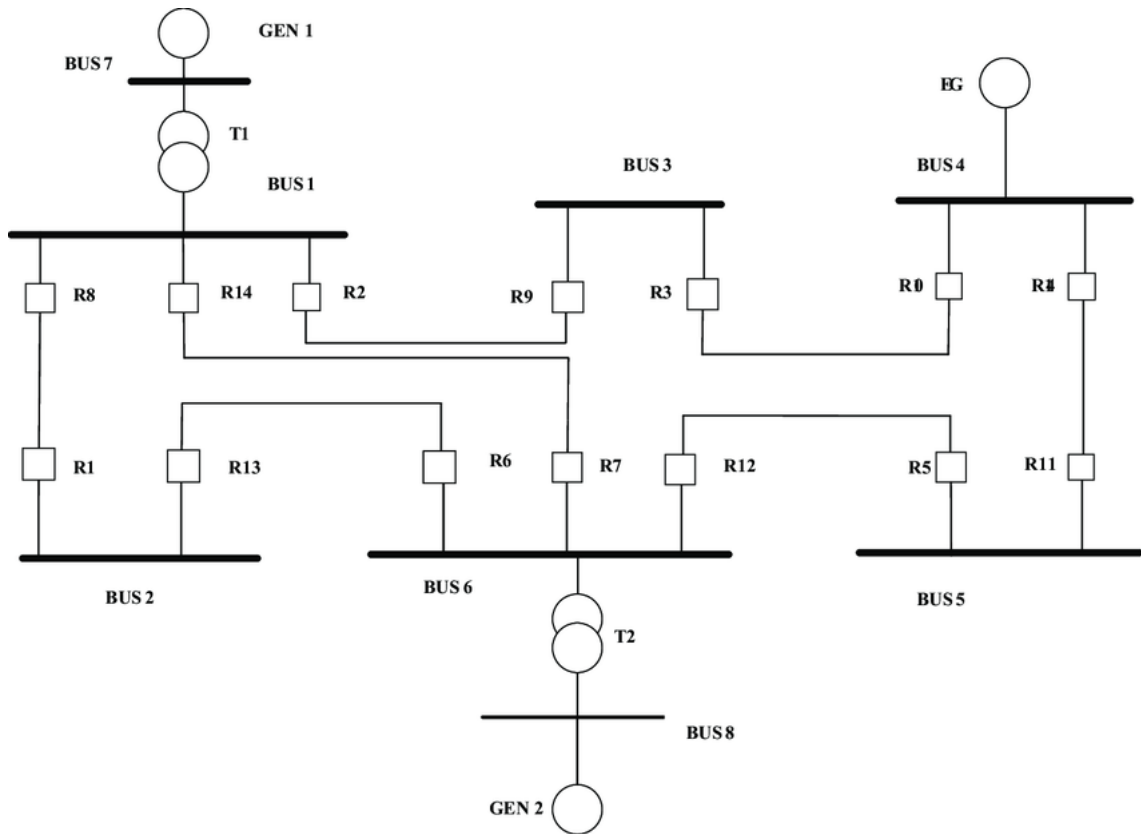


Figure 3.5: SLD of IEEE eight bus system

3.3.3 IEEE-15 Bus System

Figure 3.6 depicts a fifteen-bus test system with forty-two relays, six generators, and twenty-one lines. An external grid is attached to bus number eight. Each component's rating is given in [13]. It was believed that balanced three phase-to-ground faults were located halfway down the line.

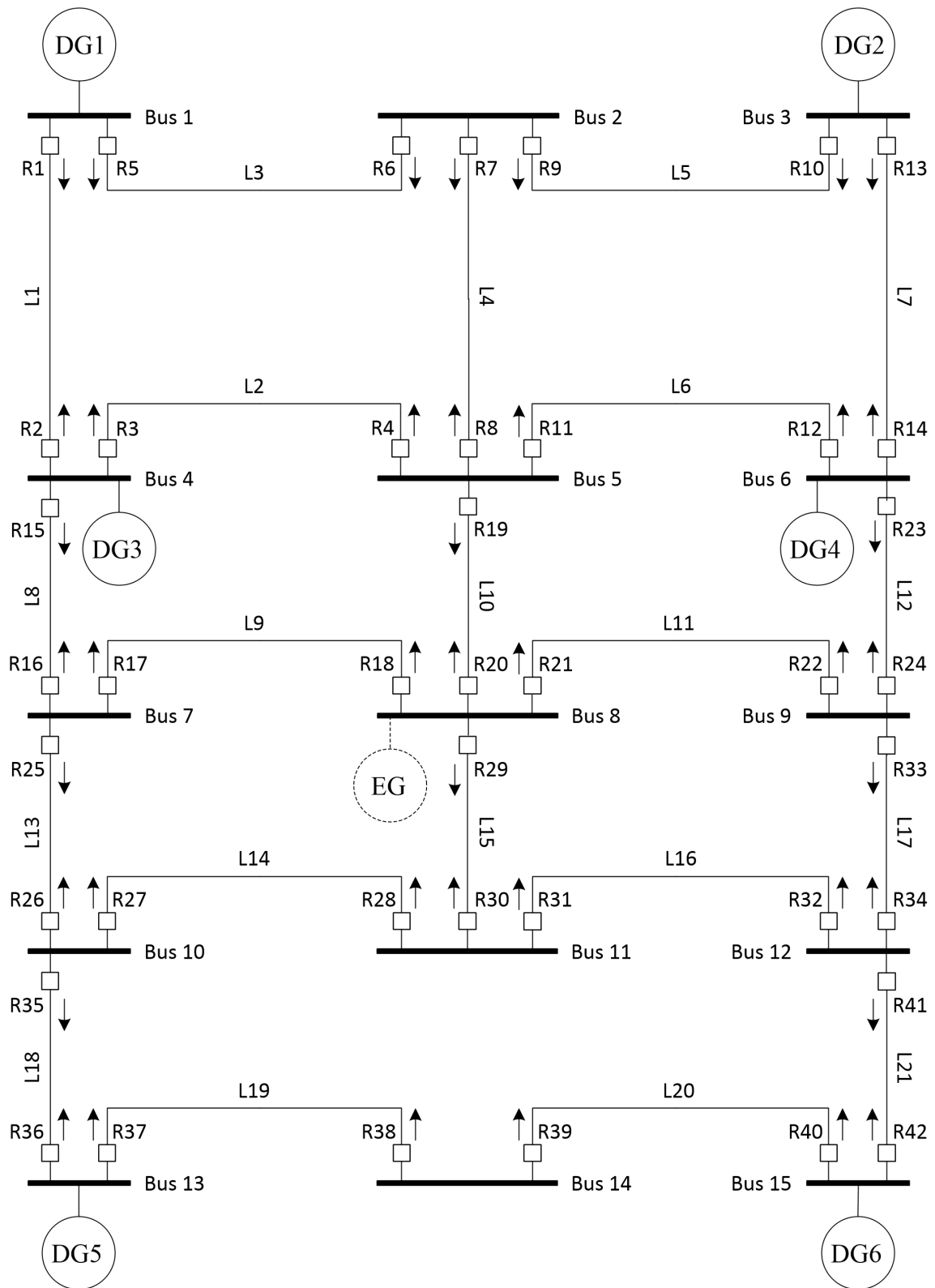


Figure 3.6: SLD of IEEE 15-bus system

3.3.4 IEEE-30 Bus System

Figure 3.7 depicts a thirty-bus test system with thirty-nine relays, six generators, four transformers, and thirty-seven lines. Each component's ratings are given in [14]. It was believed that balanced three-phase to ground faults would manifest at the midpoint of the line.

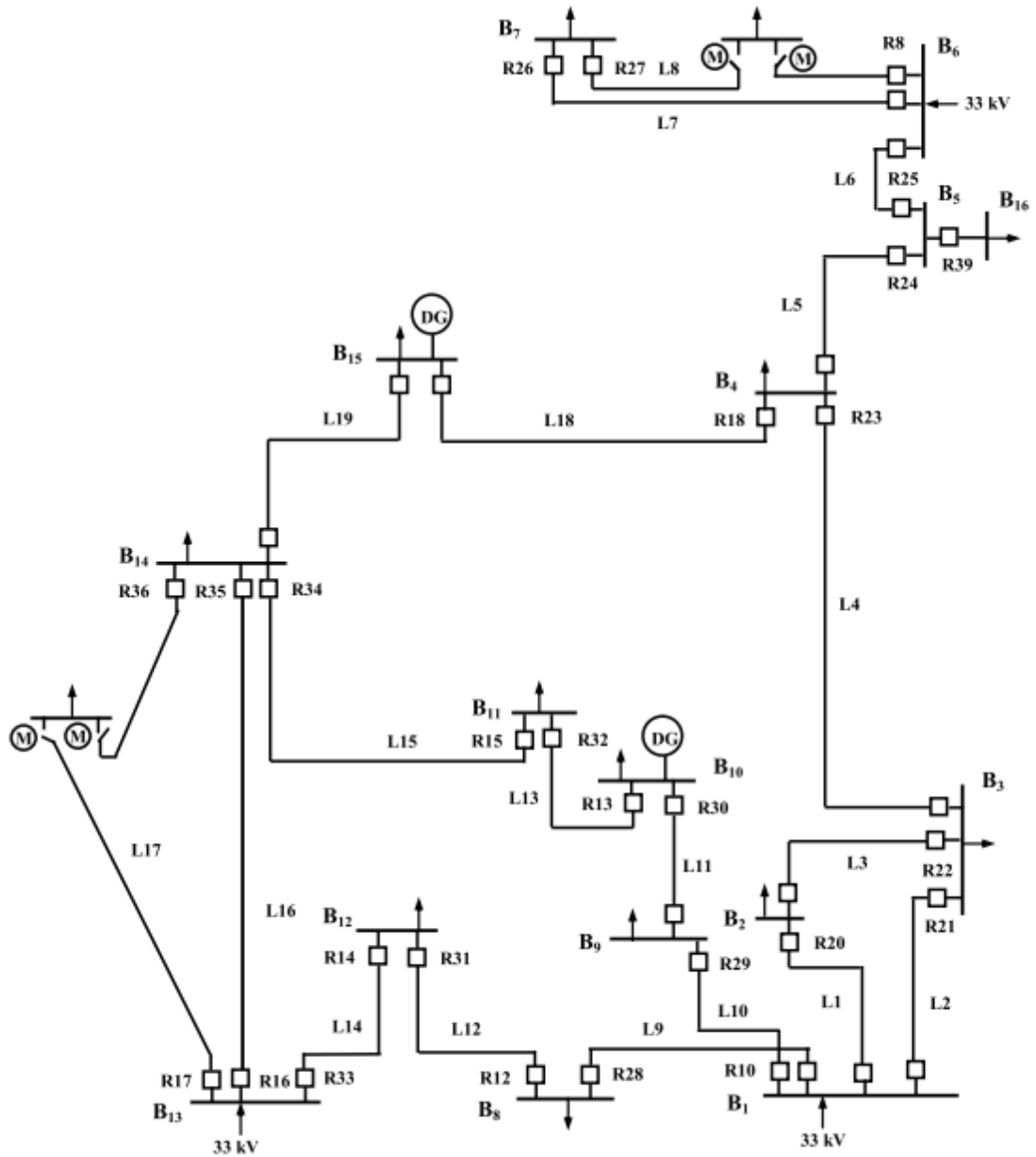


Figure 3.7: SLD of IEEE 30-bus system

3.3.5 Koshi Province Grid of INPS

Figure 3.8 shows a single line diagram of Koshi Province Grid of INPS. The Koshi Province Grid of the INPS network is used to implement the SCA, with a population size of 1000 and a maximum iteration count of 1000. Table 3.1 displays the relay number and its accompanying line.

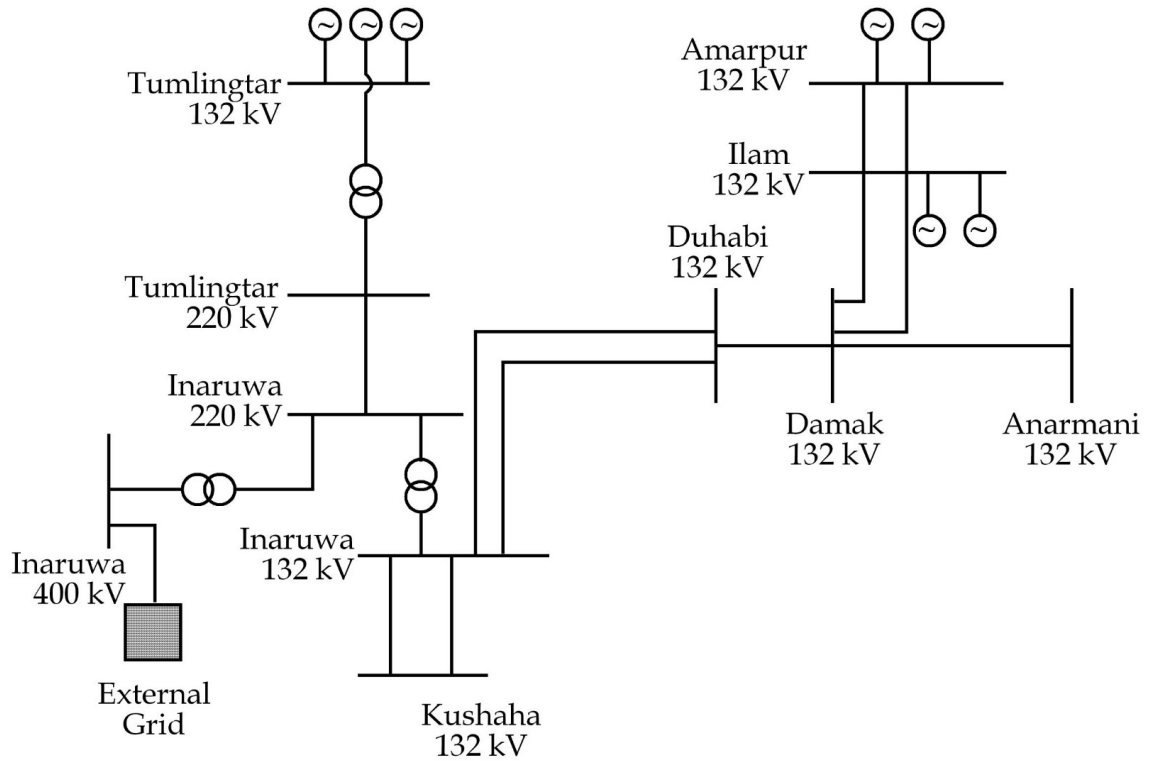


Figure 3.8: Single line diagram of Koshi Province Grid of INPS

Table 3.1: Relay numbers and associated lines of Koshi Province Grid of INPS

Relay	Line
1	Tumlingtar-Inaruwa 220 kV
2	Inaruwa-Kusaha 132 kV
3	Inaruwa-Duhabi 132 kV
4	Duhabi-Damak 132 kV
5	Damak-Anarmani 132 kV
6	Damak-Godak 132 kV
7	Godak-Amarpur 132 kV

CHAPTER FOUR: RESULTS AND DISCUSSION

This chapter outlines the outcomes obtained by using methodology described in Chapter 3.

4.1 SCA Applied to IEEE Standard Buses

4.1.1 IEEE 3-Bus System

Table 4.1 depicts the results obtained with running the proposed SCA approach for the IEEE 3-bus test system with weight set to unity. Operating all of the principal relays is estimated to take 1.33514 seconds using the proposed strategy. Furthermore, it is noted that every restriction is satisfied. Additionally, the convergence properties of a three-bus test system with weight set to unity are shown in Figure 4.1. The convergence curve demonstrates that the Sine Cosine Algorithm (SCA) rapidly finds the better solutions in the beginning. Improvements then take longer to occur. The flat regions of the curve indicate that the algorithm is fine-tuning its solution. Finally, the curve becomes steady, indicating that the algorithm has identified the best or near-best outcome. After roughly 300 rounds, it is clear that the algorithm was able to converge.

Figure 4.2 illustrates the coordination of each relay pair in an IEEE three bus test system with weight set to unity. It is evident that the primary operation times for all relay pairs are roughly identical. Backup operation periods are longer than primary times, and they vary significantly between pairs. The CTI (Coordination Time Interval) remains above the CTI limit, ensuring proper coordination between primary and backup relays.

Table 4.1: Result obtained for IEEE 3-bus test system for weight sets to unity

Relay	Primary Operation			Backup Operation			CT(s)
	TMS	PS	T _{op} (s)	TMS	PS	T _{op} (s)	
1	0.13089	0.52292	0.22107	0.33287	0.6639	0.7671	0.54603
2	0.10672	1.5493	0.22144	0.27734	0.6165	0.69013	0.46869
3	0.13886	0.66325	0.22092	0.24633	1.2068	0.68818	0.46727
4	0.10263	1.3664	0.22101	0.28583	0.59299	0.65156	0.43055
5	0.1	2.0032	0.22742	0.17998	1.7752	0.71555	0.48813
6	0.1	1.1086	0.22328	0.2454	0.88076	0.77131	0.54803
Total Operation Time			1.33514				

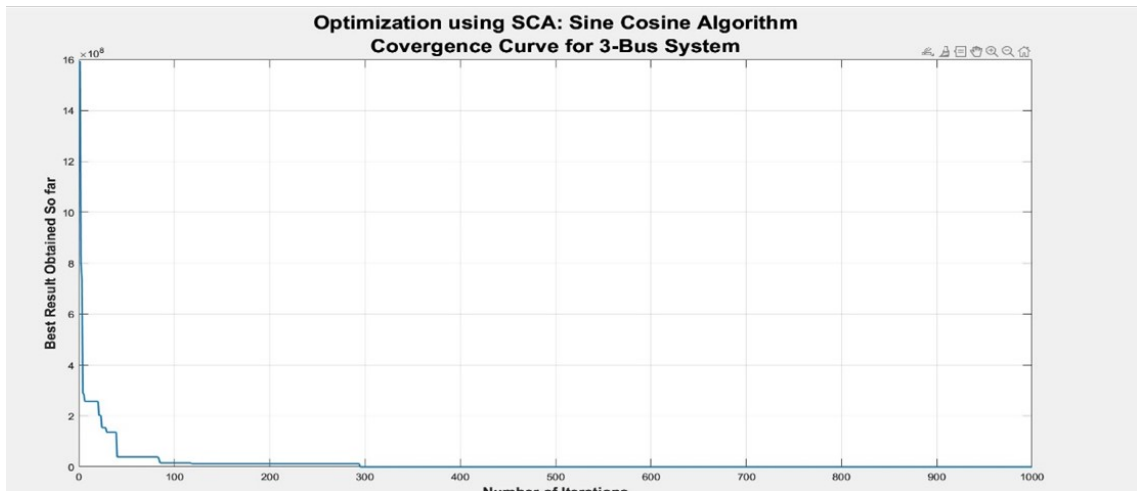


Figure 4.1: Convergence characteristics for three-bus system with weight sets to unity

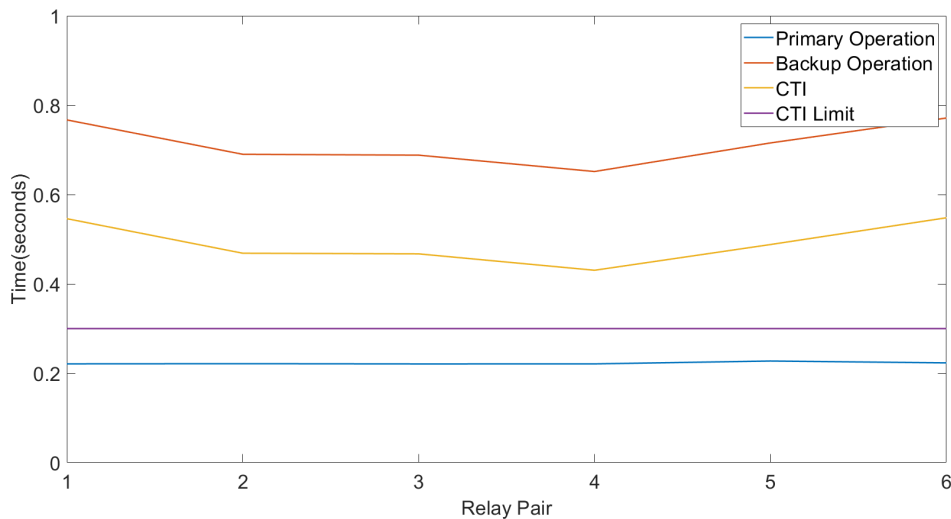


Figure 4.2: Coordination of relay pairs for IEEE 3 Bus system with weight sets to unity

The results of running the SCA program for the IEEE Three bus test system with various line weights depending on their relative importance are shown in Table 4.2. According to the results, the major relays' total operating time is 1.341743 seconds, and when all restrictions are satisfied, the Functional Value ($\sum WT_{op}$) obtained is 1.673376 seconds. Figure 4.2 shows the convergence characteristics for a three-bus test system with different weights. This characteristic demonstrates the SCA's initial rapid discovery of better solutions followed by a later slowdown. The graph indicates that the SCA program was able to converge after roughly 280 iterations.

Table 4.2: Three-bus test system results (weighted)

		Primary Operation				Backup Operation			
Relay	Weight	TMS	PS	T _{op} (s)	WT _{op} (s)	TMS	PS	T _{op} (s)	CTI(s)
1	1	0.102	1.635	0.226	0.226	0.238	0.888	0.609	0.383
2	1	0.117	1.121	0.220	0.220	0.254	1.074	0.796	0.576
3	2	0.106	1.767	0.221	0.442	0.311	0.685	0.700	0.479
4	1	0.114	1.059	0.227	0.227	0.192	1.281	0.594	0.367
5	1	0.100	1.95	0.225	0.225	0.279	0.677	0.705	0.479
6	1.5	0.100	1.083	0.222	0.332	0.211	0.902	0.670	0.449
Total Weighted Operation Time					1.673				
Total Operation Time				1.342					

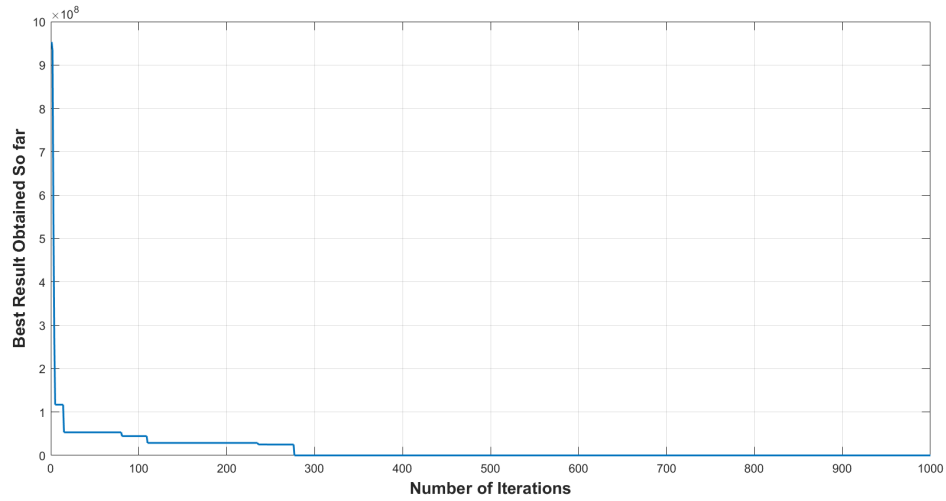


Figure 4.3: Convergence characteristics for three-bus system with varying weight

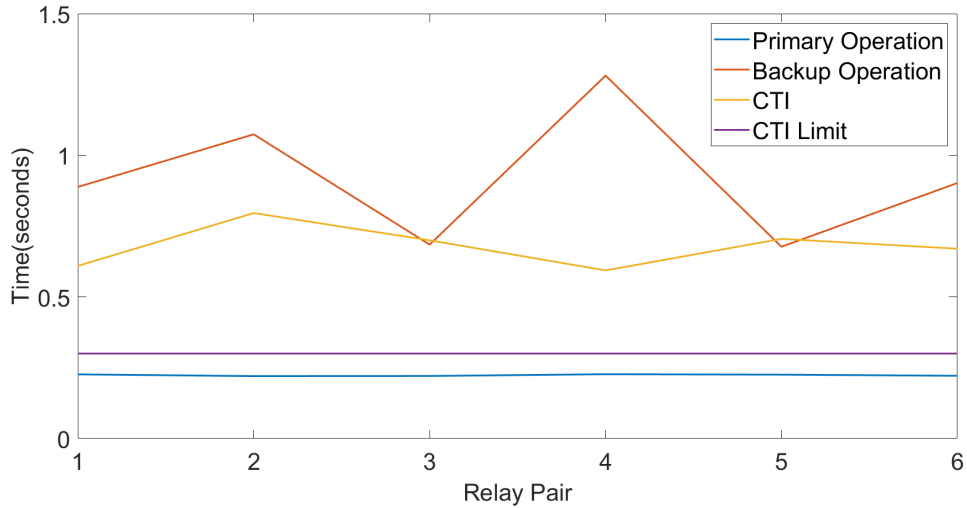


Figure 4.4: Coordination of relay pairs for IEEE 3 Bus system with varying weight

4.1.2 IEEE 8-Bus System

The results of executing the created SCA application on the IEEE Eight bus test system are displayed in Table 4.3. According to the proposed strategy, operating all of the major relays will take 3.321888 seconds. Furthermore, it is found that every restriction is satisfied. Additionally, the fifteen-bus testing system's convergence characteristics are shown in Figure 4.5. The convergence curve demonstrates that the Sine Cosine Algorithm (SCA) soon identifies superior solutions at the start. Improvements then take longer to occur. The flat regions of the curve indicate that the algorithm is fine-tuning its solution. Finally, the curve becomes steady, indicating that the algorithm has identified the best or near-best outcome. After roughly 700 iterations, the algorithm was clearly able to converge.

Figure 4.6 depicts the coordination between each relay pair. It is obvious that the principal operation times are roughly constant for all relay pairs. Backup operation times are longer than primary times and differ slightly between pairings. The CTI (Coordination Time Interval) remains above the CTI limit, ensuring effective coordination between the primary and backup relays.

Table 4.3: Results obtained for IEEE 8-bus test system with weights set to unity

Relay	Primary Operation			Backup Operation			CTI(s)
	TMS	PS	T _{op} (s)	TMS	PS	T _{op} (s)	
1	0.11278	0.52786	0.2359	0.18101	1.29739	1.07725	0.84134

Continued on next page

Relay	Primary Operation			Backup Operation			CTI(s)
	TMS	PS	T _{op} (s)	TMS	PS	T _{op} (s)	
2	0.10198	0.84002	0.20411	0.34408	0.50427	0.68868	0.48457
3	0.11464	0.77742	0.23138	0.50664	1.36924	1.48967	1.25829
4	0.10268	0.54821	0.20689	0.30574	0.5	0.69324	0.48635
5	0.10275	0.7051	0.26403	0.23252	1.05276	1.03016	0.76614
6	0.10271	1.39674	0.24048	0.51078	1.05015	1.36597	1.12548
7	0.10029	1.78258	0.23442	0.86659	0.54944	1.91753	1.6831
8	0.10199	1.31023	0.23377	0.76954	0.59486	1.71728	1.48351
9	0.10487	0.72521	0.23231	0.142	1.265	0.55804	0.32573
10	0.11847	0.93984	0.28316	0.2114	1.76113	0.8208	0.53764
11	0.13598	0.51474	0.27038	0.40821	1.96637	1.75431	1.48393
12	0.1	1.14512	0.22128	0.32297	0.98227	0.79812	0.57684
13	0.10002	0.93188	0.263	0.32098	0.79225	1.34185	1.07885
14	0.11801	0.62367	0.20076	0.66761	0.68543	1.60014	1.39938
Total Operation Time			3.3219	Seconds			

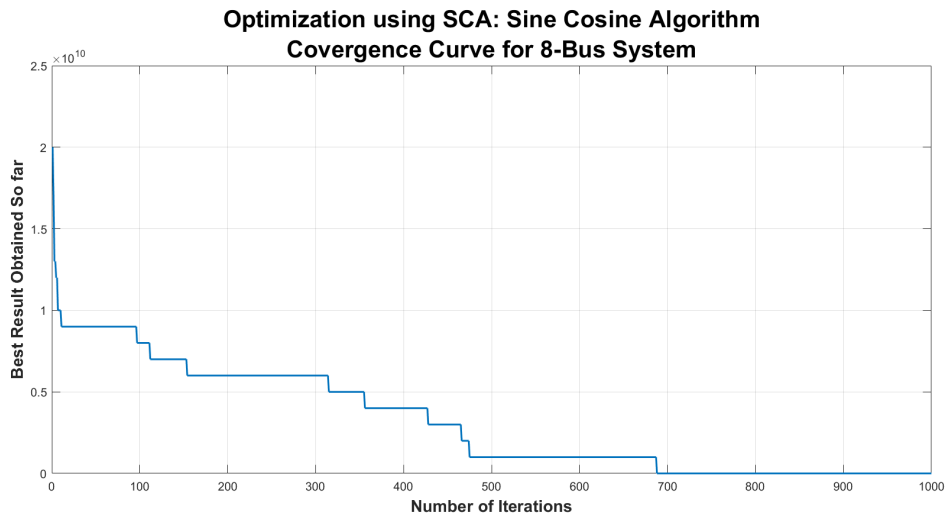


Figure 4.5: Convergence characteristics for eight-bus system with weights set to unity

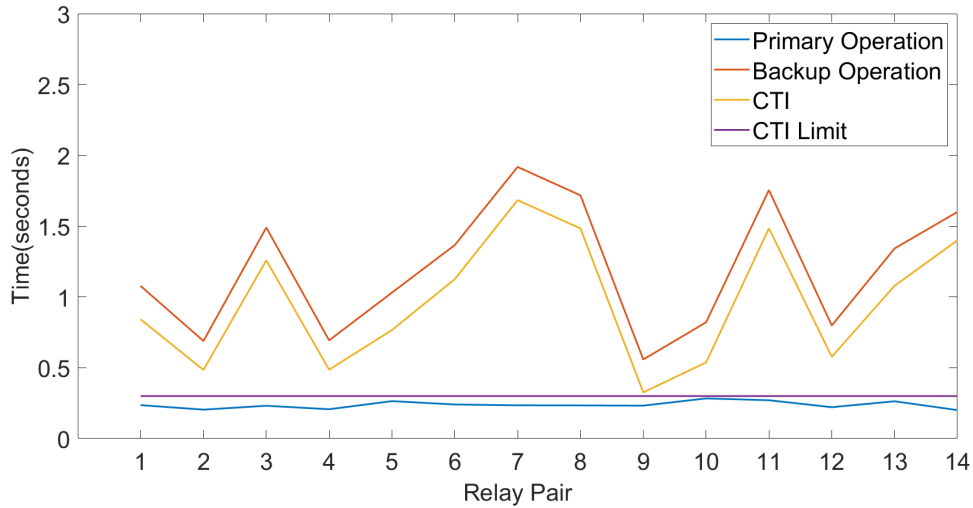


Figure 4.6: Coordination of relay pairs for IEEE 8 Bus system with weights set to unity

The SCA program was run again for the IEEE Eight bus test system, but this time with varied line weights based on their importance. Table 4.4 summarizes the findings. When all constraints are met, the total operating time of primary relays is 3.463614 seconds, with a functional value (ΣWT_{op}) of 3.949156 seconds. Figure 4.7 depicts the convergence characteristics for three bus test systems of varying weights. This feature highlights how the SCA rapidly discovers better solutions before slowing down. The curve indicates that after roughly 655 iterations, the SCA program was able to converge.

Figure 4.8 depicts the coordination of each relay pair in an IEEE eight bus test system with varying weight. It is obvious that the primary operation times for each relay pair stay rather consistent. The backup operational periods are longer than the primary ones and differ slightly between pairings. The primary and backup relays are synced correctly when the CTI (Coordination Time Interval) surpasses the CTI limit.

Table 4.4: Results obtained for Eight-bus test system (Weighted)

		Primary Operation				Backup Operation			
Relay	Weight	TMS	PS	$T_{op}(s)$	$WT_{op}(s)$	TMS	PS	$T_{op}(s)$	CTI(s)
1	2	0.100	0.508	0.207	0.413	0.33	0.568	1.138	0.929
2	1	0.151	0.793	0.297	0.297	0.454	0.878	1.092	0.873
3	1	0.100	1.101	0.226	0.226	0.322	1.139	0.877	0.656
4	1	0.113	0.902	0.268	0.268	0.6	0.92	1.719	1.472

Continued on next page

		Primary Operation				Backup Operation			
Relay	Weight	TMS	PS	T _{op} (s)	WT _{op} (s)	TMS	PS	T _{op} (s)	CTI(s)
5	1.5	0.101	0.555	0.237	0.356	0.185	1.169	0.879	0.644
6	1	0.122	0.719	0.230	0.230	0.804	0.598	1.752	1.546
7	1	0.147	1.716	0.340	0.340	0.246	1.402	0.789	0.575
8	1	0.100	1.229	0.225	0.225	0.387	0.500	0.816	0.581
9	1	0.104	0.636	0.222	0.222	0.411	0.549	1.084	0.867
10	1	0.100	0.829	0.229	0.229	0.238	1.603	0.878	0.649
11	1	0.121	0.753	0.271	0.271	0.156	2.43	0.773	0.561
12	1.75	0.108	0.810	0.214	0.374	0.599	1.023	1.504	1.271
13	1	0.100	0.636	0.229	0.229	0.223	1.002	1.09	0.823
14	1	0.102	2.416	0.269	0.269	0.305	1.573	1.041	0.789
Total Weighted Operation Time					3.949				
Total Operation Time				3.464					

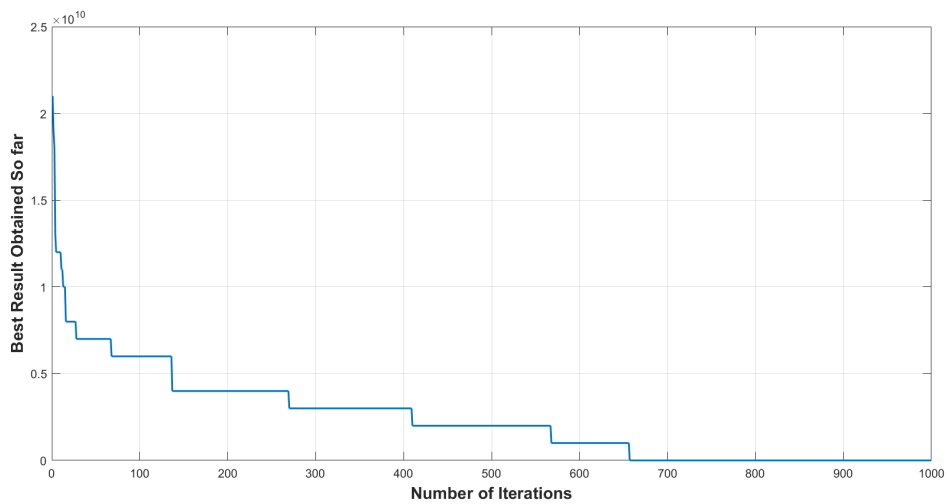


Figure 4.7: Convergence characteristics for Eight-bus system (Weighted)

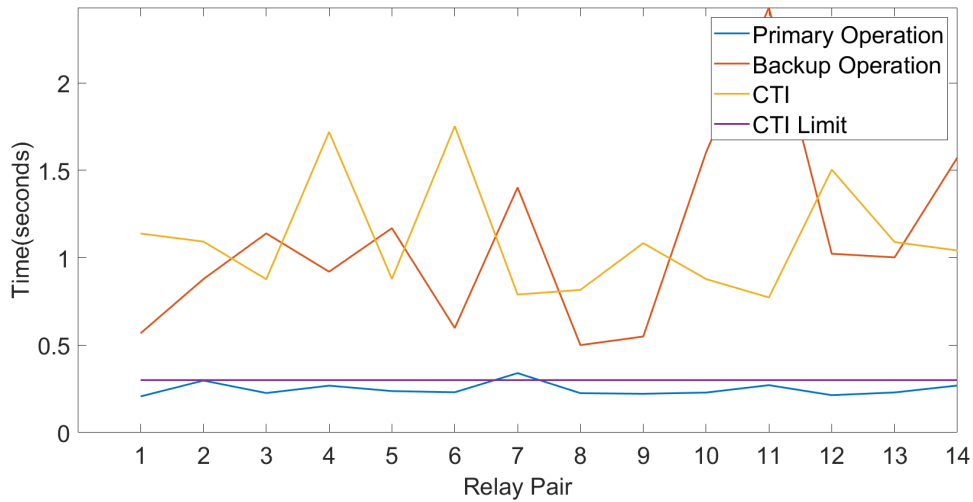


Figure 4.8: Coordination of relay pairs for IEEE 8-Bus system (Weighted)

4.1.3 IEEE 15-Bus System

The results of the application of the generated SCA software are displayed in Table 4.5. According to the proposed method, operating all of the primary relays will take 12.0078624 seconds. Additionally, it is discovered that every requirement is met. Additionally, the IEEE Fifteen-bus test system’s convergence characteristics are displayed in Figure 4.9. The convergence curve shows that the Sine Cosine Algorithm (SCA) quickly finds better solutions in the beginning. After that, improvements happen more slowly. The flat parts of the curve mean the algorithm is fine-tuning the solution. In the end, the curve becomes steady, showing that the algorithm has found the best or nearly best result. The program’s ability to converge at about 900 iterations is evident.

The coordination between each relay pair is shown in Figure 4.10. It is clearly seen that the primary operation times remain nearly constant for all relay pairs. The backup operation times are higher than primary times and vary slightly across pairs. The CTI (Coordination Time Interval) stays above the CTI limit, ensuring proper coordination between primary and backup relays.

Table 4.5: Results obtained for IEEE 15-bus test system

Relay	Primary Operation			Backup Operation			CTI(s)
	TMS	PS	T _{op} (s)	TMS	PS	T _{op} (s)	
1	0.10407	1.1962	0.24056	0.25405	1.4514	1.3492	1.1086409

Continued on next page

Relay	Primary Operation			Backup Operation			CTI(s)
	TMS	PS	T _{Op} (s)	TMS	PS	T _{Op} (s)	
2	0.19147	0.68061	0.38835	0.1	2.4777	1.58877	1.2004251
3	0.17549	0.55252	0.31048	0.50358	0.5909	1.26474	0.9542591
4	0.16313	1.3247	0.42397	0.45696	0.51096	1.25364	0.82967
5	0.174	0.51164	0.31691	0.72766	0.62029	1.87559	1.5586771
6	0.10154	0.98778	0.22179	0.69369	0.74057	1.79809	1.5762947
7	0.10207	2.0015	0.29802	0.31542	2.3633	1.59492	1.2969065
8	0.16818	0.50335	0.31002	0.24506	2.4527	1.75706	1.4470452
9	0.15485	0.53893	0.2732	0.44964	1.4071	1.72916	1.4559543
10	0.18406	0.79938	0.37436	0.31917	1.5226	1.45985	1.0854863
11	0.12724	0.657	0.25976	0.26254	2.4685	1.99639	1.7366266
12	0.1	0.52566	0.19284	0.28763	2.0831	1.85501	1.6621686
13	0.10002	1.2048	0.23699	0.30521	0.69027	0.79716	0.5601698
14	0.10883	1.0615	0.25562	0.10321	1.8291	0.72657	0.4709489
15	0.12348	0.53496	0.23139	0.3977	0.93006	1.86836	1.6369712
16	0.13304	0.98164	0.30766	0.30765	1.052	1.19353	0.8858663
17	0.14401	0.58925	0.26375	0.64879	0.68538	1.85441	1.5906624
18	0.1143	0.92426	0.23097	0.15782	1.7501	1.27747	1.046504
19	0.20434	0.50415	0.35244	0.23601	2.351	1.26037	0.9079274
20	0.13539	0.59669	0.24731	0.36862	0.5713	1.10062	0.8533029
21	0.10022	2.0736	0.2696	0.1869	1.6816	1.43754	1.1679312
22	0.13124	0.50012	0.22731	0.48278	1.0048	1.59292	1.3656078
23	0.10112	0.52394	0.18616	0.3825	0.77588	1.5867	1.4005414
24	0.11523	0.56638	0.22124	0.23595	0.57622	0.67531	0.454064
25	0.14789	1.7271	0.42071	0.29627	1.4842	1.25701	0.8363011
26	0.1719	2.0523	0.52662	0.3533	2.2232	1.99997	1.4733491
27	0.10173	1.9193	0.32157	0.3592	0.99772	1.13876	0.8171926
28	0.18267	0.61511	0.34935	0.35858	2.2573	1.66907	1.3197268
29	0.10129	0.60821	0.18164	0.69665	0.52819	1.9997	1.8180659
30	0.10192	2.5	0.32293	0.49312	1.4568	1.92179	1.598865
31	0.1428	0.52758	0.25225	0.40354	0.72054	1.23522	0.982966
32	0.11035	1.724	0.32775	0.32776	1.3724	1.5673	1.2395457
33	0.15125	1.0564	0.35443	0.47166	0.53386	1.10654	0.7521081
34	0.14292	1.2731	0.34462	0.24666	1.026	0.682	0.3373836

Continued on next page

Relay	Primary Operation			Backup Operation			CTI(s)
	TMS	PS	T _{op} (s)	TMS	PS	T _{op} (s)	
35	0.11961	0.53432	0.23186	0.42043	0.54577	1.08916	0.8573046
36	0.13232	1.4455	0.33992	0.29033	1.0182	1.0395	0.6995788
37	0.10353	1.0793	0.23849	0.2385	1.3265	0.85724	0.6187495
38	0.11086	0.51752	0.21264	0.59212	1.4462	1.99939	1.7867551
39	0.10662	1.5705	0.29913	0.72843	0.53311	1.62446	1.3253353
40	0.10374	1.4863	0.27416	0.11849	2.2872	0.60898	0.3348194
41	0.10297	0.53251	0.18086	0.63955	0.91369	1.88395	1.7030877
42	0.10378	0.5	0.18821	0.31585	1.4842	1.62778	1.43956995
Total Operation Time			12.0079	Seconds			

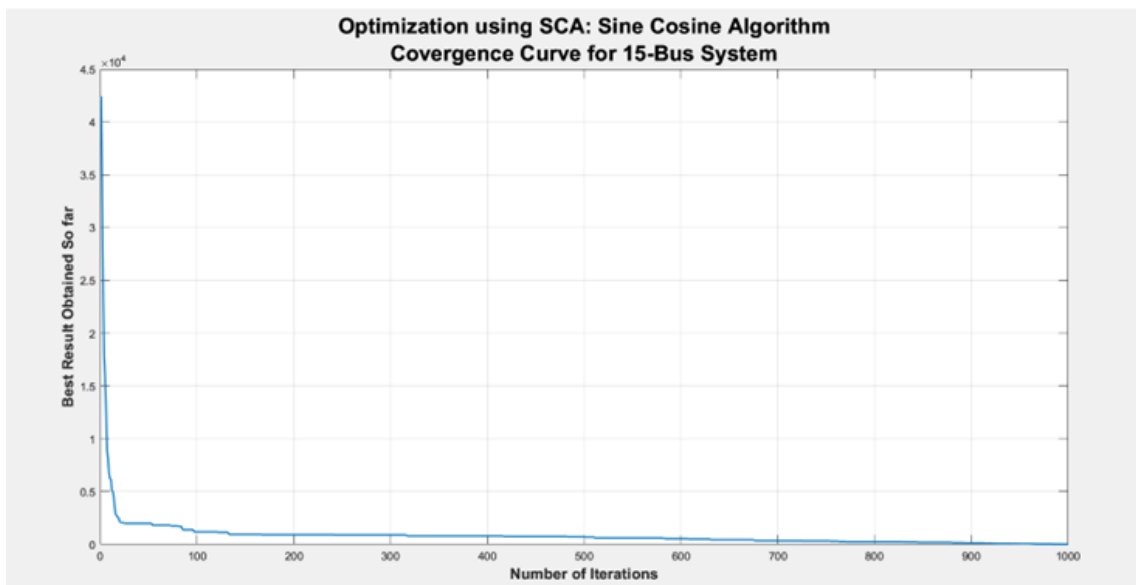


Figure 4.9: Convergence characteristics for fifteen-bus system

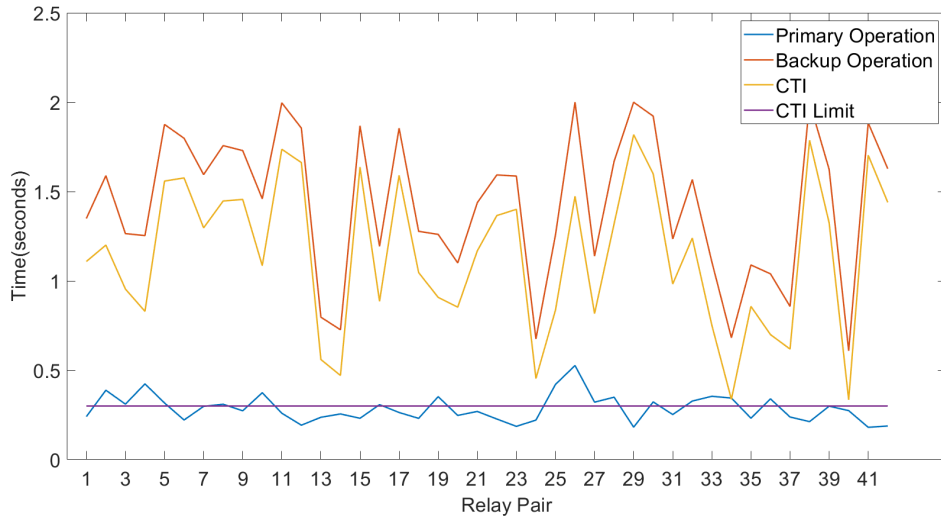


Figure 4.10: Coordination of relay pairs for IEEE 15 Bus system

4.1.4 IEEE 30-Bus System

The results of using the designed SCA program are shown in Table 4.6. Operating all of the primary relays is expected to take 15.59827 seconds using the proposed strategy. In addition, it is found that every constraint is fulfilled. The IEEE fifteen-bus test system’s convergence characteristics are depicted in Figure 4.11. The Sine Cosine Algorithm (SCA) quickly produces better solutions in the beginning, as seen by the convergence curve. Then, improvements take longer to happen. The curve’s flat areas show that the algorithm is working well to discover the solution. At last, the curve stabilizes, signifying that the algorithm has found the optimal or nearly optimal result. After roughly 900 iterations, the algorithm clearly managed to converge.

Figure 4.12 depicts the coordination between each relay pair. It is evident that the primary operation times for all relay pairs are roughly identical. Backup operation periods are longer than primary times, and they vary significantly between pairs. The CTI (Coordination Time Interval) remains above the CTI limit, ensuring proper coordination between primary and backup relays.

Table 4.6: 30 bus test system results

Relay	Primary Operation			Backup Operation			CTI(S)
	TMS	PS	T _{op} (S)	TMS	PS	T _{op} (S)	
1	0.24378	1.17221	0.41382	0.2848	1.63040	0.76863	0.35482
Continued on next page							

Relay	Primary Operation			Backup Operation			CTI(S)
	TMS	PS	T _{op} (S)	TMS	PS	T _{op} (S)	
2	0.12223	0.50545	0.30155	0.1841	1.9049	0.73415	0.4326
3	0.22559	0.50181	0.34345	0.24956	2.2334	0.8599	0.51645
4	0.23715	1.3746	0.58188	0.38125	1.0184	0.96556	0.38368
5	0.24537	1.4807	0.6077	0.25874	1.99	0.98596	0.37826
6	0.12979	0.65199	0.35402	0.4704	0.52599	1.129	0.77498
7	0.1202	0.50079	0.20018	0.28001	0.53041	0.72575	0.52557
8	0.10347	0.66358	0.18632	0.11191	1.0523	0.48649	0.30017
9	0.12399	0.71131	0.1713	0.23046	1.0322	0.48914	0.31784
10	0.1779	0.50142	0.35481	0.52424	0.67714	1.0964	0.74159
11	0.41835	1.4075	0.81718	0.36326	1.5186	1.1061	0.28892
12	0.28902	0.5015	0.44712	0.41456	1.4533	1.2315	0.78438
13	0.11368	1.1927	0.56858	0.26462	2.2163	1.0152	0.44662
14	0.10838	1.3924	0.2801	0.27019	0.64778	0.7214	0.4413
15	0.11375	0.53959	0.26551	0.11358	1.9722	0.57941	0.3139
16	0.31127	0.55813	0.38234	0.30873	1.8949	1.0024	0.62006
17	0.14957	0.70268	0.39301	0.31427	0.53499	1.0708	0.67779
18	0.2104	0.5016	0.31541	0.27041	1.3394	0.86289	0.54748
19	0.14832	1.5894	0.45573	0.37645	1.4235	1.1024	0.64667
20	0.18264	0.75182	0.30332	0.22236	1.4597	1.197	0.89368
21	0.1341	0.7054	0.24292	0.20102	0.7687	0.91536	0.67244
22	0.18509	1.414	0.45936	0.43356	1.4834	1.2023	0.74294
23	0.2447	0.82127	0.54577	0.4023	0.61604	0.95015	0.40438
24	0.16437	2.2544	0.45404	0.23955	2.0012	1.1345	0.68046
25	0.23221	0.68268	0.75012	0.31475	1.9672	1.1231	0.37298
26	0.1043	0.9787	0.30511	0.37375	0.95432	0.92074	0.61563
27	0.10458	0.5	0.5857	0.26753	1.0013	0.72657	1.31227
28	0.13754	0.82906	0.31348	0.25001	1.6117	1.0961	0.78262
29	0.1027	1.607	0.22525	0.13136	2.0012	0.73388	0.50863
30	0.10966	0.62741	0.38289	0.35608	1.2348	1.0485	0.66561
31	0.1389	0.86591	0.21938	0.16495	2.2239	0.74728	0.5279
32	0.24032	0.51542	0.48594	0.50132	0.50702	1.1145	0.62856
33	0.12653	0.5071	0.33929	0.2831	2.4222	1.0191	0.67981
34	0.16117	1.1425	0.24557	0.17508	1.932	0.59269	0.34712

Continued on next page

Relay	Primary Operation			Backup Operation			CTI(S)
	TMS	PS	T _{op} (S)	TMS	PS	T _{op} (S)	
35	0.10007	0.67991	0.19279	0.161	1.8106	0.67186	0.47907
36	0.15916	1.2631	0.54535	0.24761	1.5632	1.0923	0.54695
37	0.16596	0.81726	0.30793	0.25393	1.7567	1.016	0.70807
38	0.11637	0.93111	0.28046	0.20888	2.2078	0.9922	0.71174
39	0.12123	0.73835	0.24701	0.30054	1.5634	1.0862	0.83919
Total Operation Time			15.9827	Seconds			

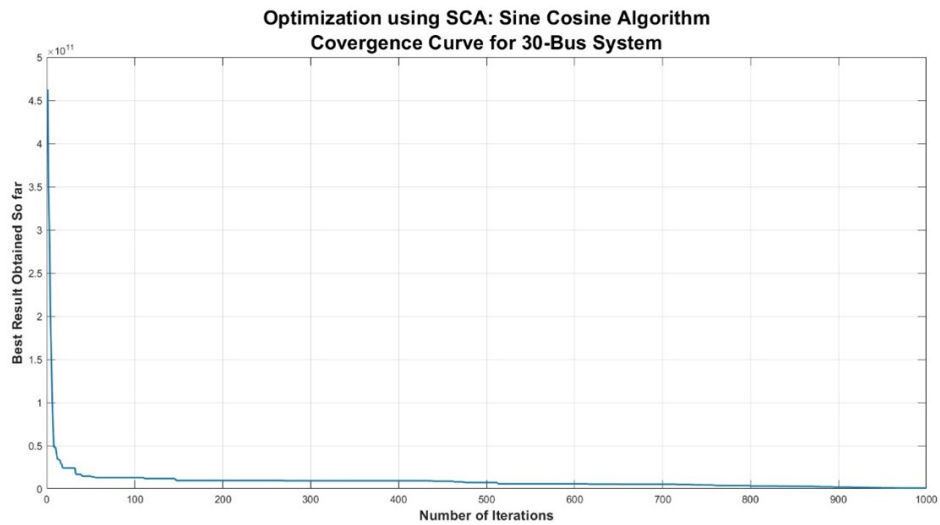


Figure 4.11: Convergence characteristics for Thirty-bus system

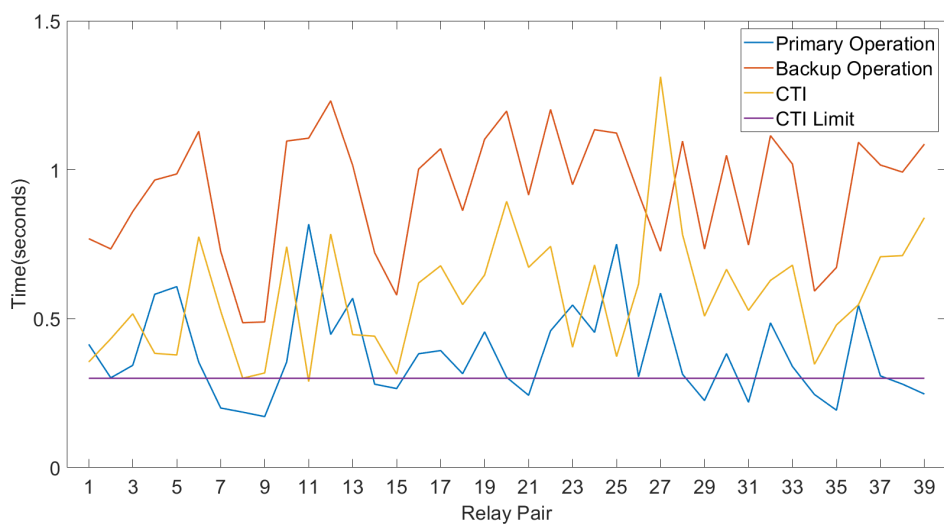


Figure 4.12: Coordination of relay pairs for IEEE 30 bus system

4.1.5 Comparison of SCA with various other optimization techniques

The results for the IEEE test system derived from SCA are compared with several optimization methods, including Simulated Annealing (SA), Improved Gray Wolf Optimization (IGWO), Hybrid Whale Optimization Algorithm (HWOA), Standard Branch-and-Bound Algorithm (SBBA), Differential Evolution (DE), and Harmonic Search (HS), based on various existing literatures. This comparison is detailed in Table 4.7.

Table 4.7: Comparison with different optimization approaches

SYSTEM	Total Operation Time (s)						
	SCA	SA[13]	IGWO[14]	HWOA[15]	SBBA[13]	DE[16]	HS[16]
3 BUS	1.33514	1.599	1.4789	1.5029	-	-	-
8 BUS	3.32188	5.8568	-	5.2422	-	-	-
15 BUS	12.00786	12.227	12.6446	-	15.335	-	-
30 BUS	15.59287	-	-	-	-	17.8122	19.2133

Table 4.7 demonstrates that the proposed SCA outperforms existing algorithms for determining the TMS and PS of relays.

4.2 SCA applied to Koshi province

4.2.1 Data Collection

The power system network of Koshi province was developed in DIgSILENT POWERFACTORY. The network developed in DIgSILENT POWERFACTORY is shown in Appendix A and SLD in Figure 3.8.

4.2.2 Optimal Setting of Relays

The results of applying the SCA algorithm to the INPS grid for Koshi Province are shown in Table 4.8. According to the proposed strategy, operating all of the major relays will take 2.91221 seconds.

The convergence curve for the system is shown in Figure 4.13. The convergence curve shows that the Sine Cosine Algorithm (SCA) quickly finds better solutions in the beginning. After that, improvements happen more slowly. The flat parts of the curve mean the algorithm is fine-tuning the solution. In the end, the curve becomes steady, showing that the algorithm has found the best or nearly best result. After about 280 iterations, it is clear that the program was able to converge.

Figure 4.14 shows how relay pairs coordinate. It is clearly seen that the primary operation times remain nearly constant for all relay pairs. The backup operation times are higher than primary times and vary slightly across pairs. The CTI (Coordination Time Interval) stays above the CTI limit, ensuring proper coordination between primary and backup relays.

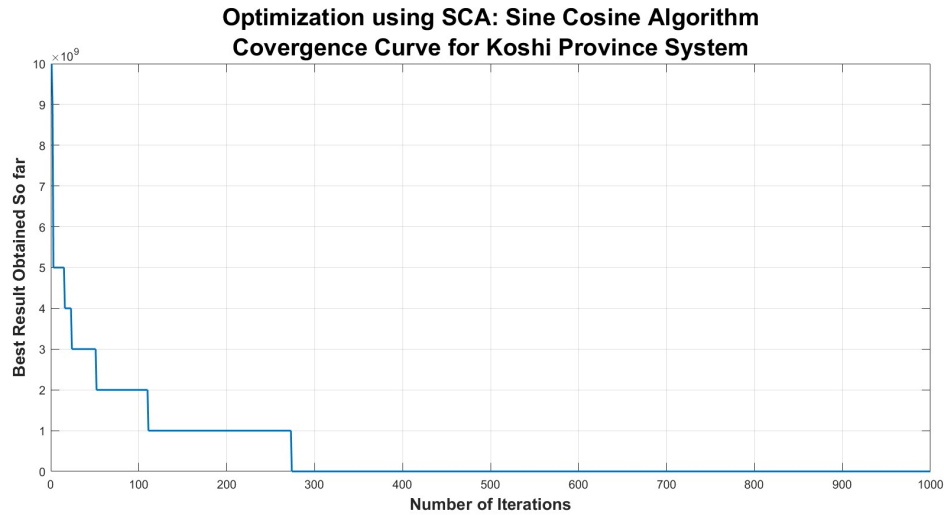


Figure 4.13: Convergence characteristics for Koshi province system

The relay settings obtained from the algorithm is shown in Table 4.8.

Table 4.8: SCA result for Koshi Province

Relay	Primary Operation			Backup Operation			CT(s)
	TMS	PS	T _{op} (s)	TMS	PS	T _{op} (s)	
1	0.10417	0.50131	0.38269	0.321790	0.57444	1.46909	1.08639
2	0.10391	0.51408	0.34748	0.10007	0.74395	1.33059	0.98310
3	0.10000	0.5	0.47324	0.18243	0.53375	1.43441	0.96116
4	0.10110	0.5	0.60440	0.19426	0.69671	1.57715	0.97274
5	0.1	0.50198	0.32783	0.1	0.55921	1.68872	1.36088
6	0.10117	0.50435	0.33958	0.11710	0.50034	1.74790	1.40831
7	0.1	0.50290	0.43694	0.14196	0.82075	0.80829	0.37134
Total Operation Time			2.91221	Seconds			

According to the proposed SCA, operating all of the major relays will take 2.91221 seconds. Furthermore, it has been verified that every restriction is met.

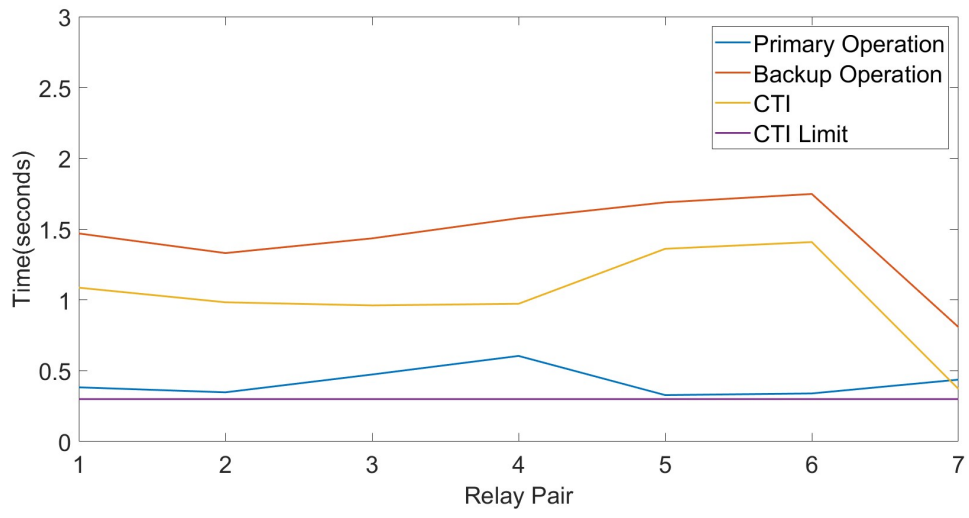


Figure 4.14: Coordination of relay pairs for Koshi Province Grid

CHAPTER FIVE: CONCLUSION

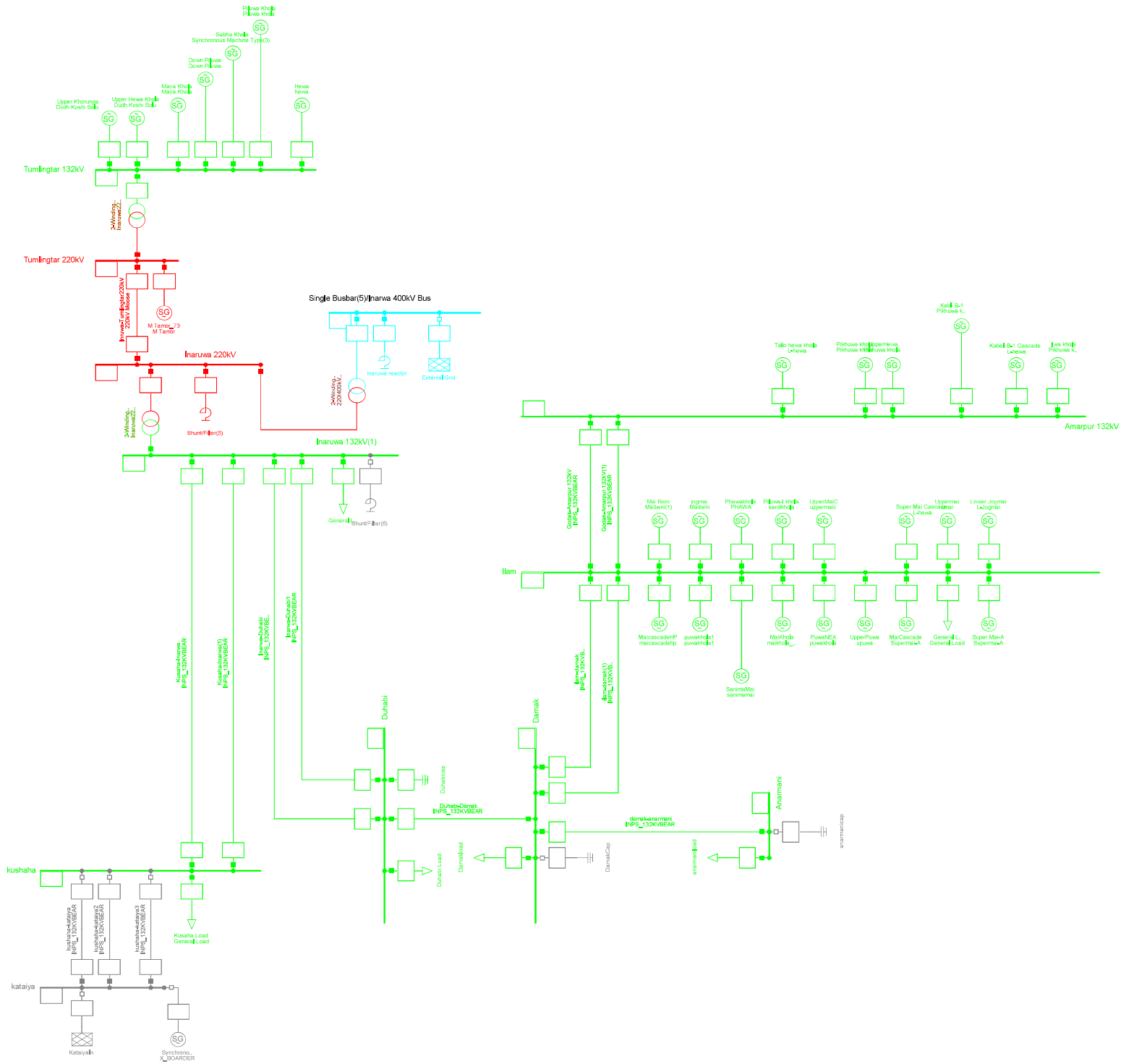
The optimal DOCRs coordination problem was formulated in this study, and a MATLAB SCA method was created to solve it. The developed program was subsequently implemented to address the coordination issue with DOCR. The method was used on four different test bus systems: the IEEE three-bus, eight-bus, and thirty-bus test systems. The optimal TMS and PS values for each relay were determined to minimize the overall operating time of the primary relays, and the results are shown in Chapter 4. The resulting findings are shown in Table 4.7 after being compared with the outcomes of the different optimization techniques. Further, SCA was adopted to improve coordination in Koshi Province Grid of Integrated Nepal Power System (INPS). The outcomes show how well the suggested approach works for nonlinear optimization issues and how it may be applied to the DOCR coordination problem. Because the obtained PS values are continuous rather than discrete, the results imply that they were not obtained in steps. Typically, PS levels are provided in distinct 0.5 increments. Using the SCA in conjunction with mixed integer programming approaches, the PS and, if necessary, the TMS might be retrieved as discrete values.

REFERENCES

- [1] S. Mirjalili, "Sca: a sine cosine algorithm for solving optimization problems," *Knowledge-based systems*, vol. 96, pp. 120–133, 2016.
- [2] W. K. A. Najy, H. H. Zeineldin, and W. L. Woon, "Optimal protection coordination for microgrids with grid-connected and islanded capability," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 4, pp. 1668–1677, 2013.
- [3] M. N. Alam, B. Das, and V. Pant, "Optimum recloser–fuse coordination for radial distribution systems in the presence of multiple distributed generations," *IET Generation, Transmission & Distribution*, vol. 12, pp. 2585–2594, 2018.
- [4] A. Tjahjono, D. O. Anggriawan, A. K. Faizin, A. Priyadi, M. Pujiantara, T. Taufik, and M. H. Purnomo, "Adaptive modified firefly algorithm for optimal coordination of overcurrent relays," *IET Generation, Transmission & Distribution*, vol. 11, pp. 2575–2585, 2017.
- [5] A. Cornelis, "Fault response of inverter-based distributed generation," *Ph. D. dissertation*, 2011.
- [6] K. A. Saleh, H. H. Zeineldin, and E. F. El-Saadany, "Optimal protection coordination for microgrids considering $n - 1$ contingency," *IEEE Transactions on Industrial Informatics*, vol. 13, no. 5, pp. 2270–2278, 2017.
- [7] S. Jamali and H. Borhani Bahabadi, "Recloser time–current–voltage characteristic for fuse saving in distribution networks with dg," *IET Generation, Transmission & Distribution*, vol. 11, pp. 272–279, 2017.
- [8] J. Ehrenberger and J. Švec, "Directional overcurrent relays coordination problems in distributed generation systems," *Energies*, vol. 10, no. 10, 2017. [Online]. Available: <https://www.mdpi.com/1996-1073/10/10/1452>
- [9] K. A. Saleh, H. Zeineldin, A. Al-Hinai, and E. F. El-Saadany, "Optimal coordination of directional overcurrent relays using a new time–current–voltage characteristic," *IEEE Transactions on Power Delivery*, vol. 30, no. 2, pp. 537–544, 2014.

- [10] M. Singh, B. Panigrahi, and A. Abhyankar, "Optimal coordination of directional over-current relays using teaching learning-based optimization (tlbo) algorithm," *International Journal of Electrical Power & Energy Systems*, vol. 50, pp. 33–41, 2013.
- [11] P. Bedekar and S. Bhide, "Overcurrent relay coordination using the hybrid ga-nlp approach," *IEEE Trans. Power Del*, vol. 26, pp. 109–19, 2011.
- [12] A. Urdaneta, R. Nadira, and L. Perez Jimenez, "Optimal coordination of directional overcurrent relays in interconnected power systems," *IEEE Transactions on Power Delivery*, vol. 3, no. 3, pp. 903–911, 1988.
- [13] T. Amraee, "Coordination of directional overcurrent relays using seeker algorithm," *IEEE Transactions on Power Delivery - IEEE TRANS POWER DELIVERY*, vol. 27, pp. 1415–1422, 07 2012.
- [14] N. Z. Jamal, M. H. Sulaiman, O. Aliman, and Z. Mustaffa, "Optimal overcurrent relays coordination using an improved grey wolf optimizer," *International Journal of Advanced Computer Science and Applications*, vol. 9, 01 2018.
- [15] T. Lone, A. Wadood, S. Gholami Farkoush, J. Yu, C. Kim, and R. Bong, "An improved optimal solution for the directional overcurrent relays coordination using hybridized whale optimization algorithm in complex power systems," *IEEE Access*, vol. PP, pp. 1–1, 07 2019.
- [16] M. Alam, B. Das, and V. Pant, "A comparative study of metaheuristic optimization approaches for directional overcurrent relays coordination," *Electric Power Systems Research*, vol. 128, pp. 39–52, 11 2015.

APPENDIX A: SLD OF KOSHI PROVINCE GRID OF INPS



APPENDIX B: PUBLICATION

IEEE PES Nepal Chapter Conference Paper Acceptance Notification



MADHAV NAGARKOTI <078mspse009.madhav@pcampus.edu.np>

Submission of Revised Manuscript –Sine Cosine Algorithm Based Optimization of Directional Overcurrent Relay Coordination in Koshi Province System

3 messages

MADHAV NAGARKOTI <078mspse009.madhav@pcampus.edu.np>
To: ieeeepesnp@gmail.com

Tue, Apr 15, 2025 at 10:19 PM

Dear Sirs,


We hope this message finds you well.

Please find attached the revised version of our manuscript titled "Sine Cosine Algorithm Based Optimization of Directional Overcurrent Relay Coordination in Koshi Province System", which we are resubmitting for your kind consideration. We have carefully addressed all the comments and suggestions provided by the reviewers and incorporated the necessary revisions to enhance the quality and clarity of the paper.

We sincerely thank the reviewers and the committee for their valuable feedback, which has significantly helped improve our work. We hope the revised manuscript meets your expectations and look forward to your positive response.

Please let us know if any further information is required.

Warm regards,
Madhav Prasad Nagarkoti
9804307810

 **Madhav_P__Nagarkoti_PES__Research_Paper_Comments Incorporated.pdf**
778K

IEEE Power & Energy Society Nepal Chapter <ieeeepesnp@gmail.com>
To: MADHAV NAGARKOTI <078mspse009.madhav@pcampus.edu.np>

Tue, Apr 15, 2025 at 11:53 PM

Dear Authors

RESSD-2025 technical committee is pleased to inform you that your paper **has been Accepted** to be presented in the conference, congratulations!
Additional details will be sent in the upcoming days.

Regards,
RESSD2025 Technical Committee

[Quoted text hidden]

MADHAV NAGARKOTI <078mspse009.madhav@pcampus.edu.np>
To: IEEE Power & Energy Society Nepal Chapter <ieeeepesnp@gmail.com>

Wed, Apr 16, 2025 at 12:04 PM

Thank you so much for the great news!

[Quoted text hidden]

Sine Cosine Algorithm Based Optimization of Directional Overcurrent Relay Coordination in Koshi Province System

Madhav Prasad Nagarkoti

Department of Electrical Engineering
Pulchowk Campus, Tribhuvan University
Lalitpur, Nepal
078mspse009.madhav@pcampus.edu.np

Jeetendra Chaudhary

Department of Electrical Engineering
Pulchowk Campus, Tribhuvan University
Lalitpur, Nepal
jeetendra@ioe.edu.np

Akhileshwar Mishra

Department of Electrical Engineering
Pulchowk Campus, Tribhuvan University
Lalitpur, Nepal
akhileshwar@ioe.edu.np

Abstract—The complexity of protection coordination in modern power systems has significantly increased due to large-scale interconnections. Directional Overcurrent Relays (DOCRs) play a crucial role in ensuring system protection, but their optimal coordination remains a nonlinear and constrained problem. This study applies the Sine Cosine Algorithm (SCA), a metaheuristic optimization technique, to achieve optimal DOCR coordination. The SCA utilizes sinusoidal and cosinusoidal mathematical functions to efficiently explore and exploit search spaces for optimal relay settings. The proposed methodology is tested on IEEE 8-bus test systems, as well as the Koshi Province Grid of the Integrated Nepal Power System (INPS). Simulation results demonstrate that SCA effectively minimizes the total operating time of primary relays while maintaining the required Coordination Time Interval (CTI) with backup relays. Comparative analysis with other optimization techniques highlights the superiority of SCA in achieving faster convergence and better coordination performance.

Index Terms—Coordination Time Interval, Directional Overcurrent Relay, INPS, Koshi Province, Optimization, Relay Coordination, Sine Cosine Algorithm

I. INTRODUCTION

The protection coordination in modern power systems has become increasingly complex due to extensive interconnections. Interconnected power systems pose various challenges that complicate protection coordination. Ensuring fast and reliable operation of Directional Overcurrent Relays (DOCRs) is essential to isolate faults and prevent damage. Effective relay coordination, where primary protection responds quickly and backup activates only if needed is crucial for system reliability.

Traditional methods often use linear programming to optimize only the Time Multiplier Setting (TMS), keeping the Plug Setting (PS) fixed due to its nonlinear behavior. This limits coordination performance. To improve results, recent studies use nonlinear techniques such as Genetic Algorithm [1], Particle Swarm Algorithm [1], and Grey Wolf Optimizer [2] to optimize both TMS and PS. These methods aim to reduce total relay operation time but may suffer from slow convergence or getting stuck in local optima.

This work uses the Sine Cosine Algorithm (SCA), a simple yet powerful optimization method, to coordinate DOCRs by

optimizing both TMS and PS. Unlike many existing approaches, this method improves accuracy and minimizes total operation time, offering better system protection and faster fault clearance.

II. PROBLEM FORMULATION

Relay coordination problem can be formulated as a linear or nonlinear function. In case of linear approach PS is kept constant while the TMS is optimized whereas in case of nonlinear function both the PS and TMS are simultaneously optimized for the minimum total operational time of the primary relays. The relay characteristics can be mathematically expressed as [3].

$$T_{ik} = \frac{TMS_i * \beta}{\left(\frac{I_{Rik}}{PS_i}\right)^\alpha - 1} \quad (1)$$

where, T_{ik} is the operational time of the relay i for the fault at location k ; TMS_i is the Time Multiplier Setting of the relay i ; PS_i is the Plug Setting of the relay i ; I_{Rik} is the fault current seen by relay i for the fault at location k ; α and β are constants which vary with the characteristics of the relay.

For Inverse Definite Minimum Time (IDMT) relay α and β have values 0.02 and 0.14 respectively [4]. The objective of the relay coordination problem is to determine the values of TMS and PS for each relay such that the total operation time of the primary relays will be minimum. Therefore, the objective function will be

Minimize

$$Z = \sum_i^n \sum_{k=1}^l w_{ik} T_{ik} \quad (2)$$

where,

T_{ik} is the operation time of relay i for the fault at location k . w_{ik} is the product of probability of occurrence of the fault and relative importance of the line/bus on which the fault occurs. In this paper, w_{ik} is taken to be 1.

The optimization problem has the following constraints

- Plug Setting Constraints

The PS settings should be within the available range. i.e.,

$$PS_{i,min} \leq PS_i \leq PS_{i,max} \quad (3)$$

The minimum and maximum PS setting available for all the relays are taken to be 0.5 and 2.5 respectively.

- Time Multiplier Settings Constraints

The TMS settings should be within the available range. i.e.,

$$TMS_{i,min} \leq TMS_i \leq TMS_{i,max} \quad (4)$$

The minimum and maximum TMS setting available for all the relays are taken to be 0.1 and 5 respectively.

- Operating time Constraints

The limits on the relay operating time can be expressed as

$$T_{ik,min} \leq T_{ik} \leq T_{ik,max} \quad (5)$$

The minimum and maximum operating time of all the relays are taken to be 0.1 seconds and 2 seconds respectively.

- Coordination Constraints

For a fault at location k, the primary relay i should operate before backup relay j. The time delay after which the backup relay works if the primary relay fails to isolate the fault is known as Coordination Time Interval (CTI) and this constraint can be expressed as

$$T_{jk} - T_{ik} \geq CTI \quad (6)$$

For all primary and backup pairs i and j, the CTI used in this paper is 0.3 seconds.

III. SINE COSINE ALGORITHM

The SCA is a unique optimization technique which is inspired from the basic sinusoidal and co-sinusoidal function and was first introduced in [5]. The SCA develops a set of random initial population which oscillates inward or outwards of the current best solution to achieve the next best solution by exploring the region defined by the constraints. The equation to update the position of the population can be expressed as (7).

$$X_i^{t+1} = \begin{cases} X_i^t + r_1 \times \sin(r_2) \times |r_3 P_i^t - X_i^t| & \text{if } r_4 < 0.5 \\ X_i^t + r_1 \times \cos(r_2) \times |r_3 P_i^t - X_i^t| & \text{if } r_4 \geq 0.5 \end{cases} \quad (7)$$

where, X_i^t is the position of the current solution in i^{th} dimension and t^{th} iteration X_i^{t+1} is the position of the current solution in i^{th} dimension and $(t+1)^{th}$ iteration P_i^t is the best position of the current solution in i^{th} dimension and upto t^{th} iteration $r_1 = a - t(a/T)$, $r_2 \in [0, 2\pi]$, $r_3 \in [0, 2]$, $r_4 \in [0, 1]$

$a = 2$, t is the current iteration and T is the maximum number of iterations.

r_2 , r_3 and r_4 are the random numbers.

The SCA stores the best solution in a variable P_i^t as a destination point and all the other solution moves toward that destination using (7).

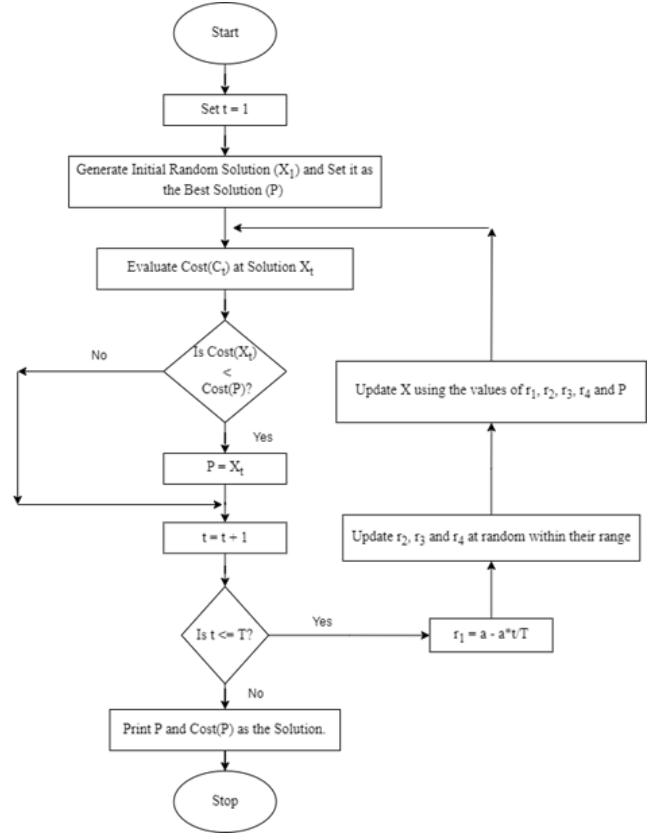


Fig. 1. Flowchart of SCA for Nonlinear optimization

The SCA can be described best by the flowchart shown in Fig. 1.

IV. RESULT AND DISCUSSION

The proposed algorithm was tested on IEEE 8-bus system before applying to Koshi province system. The IDMT relays were chosen with $\alpha = 0.02$ and $\beta = 0.14$. The CTI constraints for all the relays were assumed to be 0.3 seconds. In all three cases the population size was taken to be 1000 and the SCA program was run for 1000 iterations. The obtained results is then compared with various other optimization techniques shown in Table IV.

A. IEEE-8 Bus Test Case

The network for 8-bus (B1 to B8) test system is shown in Fig. 2. As shown in the Fig. 2, it consists of three generators, seven lines and fourteen DOCRs. The external grid (EG) connected at B4 is modelled with a short circuit power of 400 MVA [6]. The CT ratios of relays R1, R2, R4, R5, R6, R8, R10, R11, R12 and R13 are 1200:5, whereas CT ratios of relays R3, R7, R9 and R14 are 800:5. The three phase to ground faults were considered to occur at the mid-point of the line. The developed SCA program was then run to obtain the following results shown in Table I. The proposed algorithm shows that it will take 3.320 seconds to operate all the primary

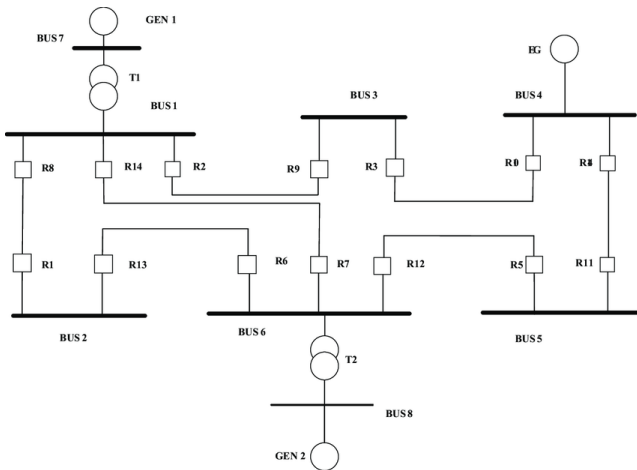


Fig. 2. SLD of Eight-bus test system

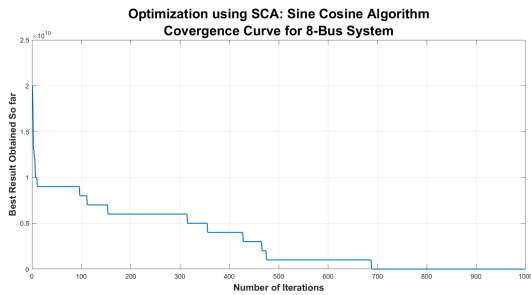


Fig. 3. Convergence characteristics for eight-bus system

relays. Also, it is found that all of the constraints are met. Furthermore, Fig. 3 shows the convergence characteristics for the fifteen-bus test system. It is clearly seen that the program was able to converge at around 700 iterations. The coordination of each relay pair is shown in Fig. 4.

B. Koshi Province Network

The power system network of Koshi province was developed in DIGSILENT POWERFACTORY. The network developed is shown in Fig. 5. The SCA with population size and maximum number of iterations both set to 1000, was applied to the Koshi

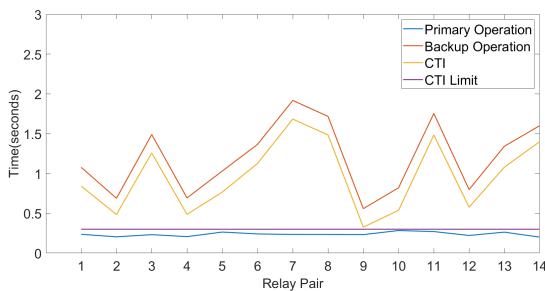


Fig. 4. Coordination of relay pairs for IEEE 8 Bus system

TABLE I
SCA RESULT FOR EIGHT-BUS TEST SYSTEM

Relay	Primary Operation			Backup Operation			CTI
	TMS	PS	T_p (s)	TMS	PS	T_b (s)	
1	0.113	0.528	0.236	0.181	1.297	1.077	0.8
2	0.102	0.84	0.204	0.344	0.504	0.689	0.485
3	0.115	0.777	0.231	0.507	1.369	1.49	1.258
4	0.103	0.548	0.207	0.306	0.5	0.693	0.486
5	0.103	0.705	0.264	0.233	1.053	1.03	0.766
6	0.103	1.397	0.24	0.511	1.05	1.366	1.125
7	0.1	1.783	0.234	0.867	0.549	1.918	1.683
8	0.102	1.31	0.234	0.77	0.595	1.717	1.484
9	0.105	0.725	0.232	0.142	1.265	0.558	0.326
10	0.118	0.94	0.283	0.211	1.761	0.821	0.538
11	0.136	0.515	0.27	0.408	1.966	1.754	1.484
12	0.1	1.145	0.221	0.323	0.982	0.798	0.577
13	0.1	0.932	0.263	0.321	0.792	1.342	1.079
14	0.118	0.624	0.201	0.668	0.685	1.6	1.399
Total Primary Operation Time = 3.320 s							

where,

T_p is the operation time of primary relay, and
 T_b is the operation time of backup relay

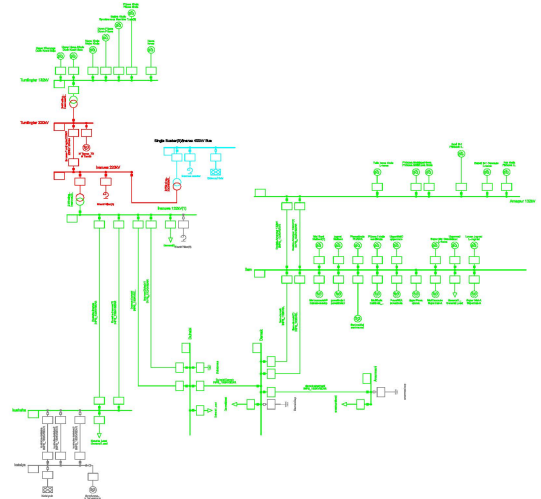


Fig. 5. SLD of Koshi Province Grid of INPS

province network. The result of the SCA algorithm is shown in Table III. The convergence curve for the system is shown in Fig. 6. The relay number and corresponding line is given in Table II. The coordination of relay pairs is shown in Fig. 7.

C. Comparison of SCA with various other optimization techniques

The results for the IEEE test system derived from SCA are compared with several optimization methods, including Simulated Annealing (SA), Improved Gray Wolf Optimization (IGWO), and Hybrid Whale Optimization Algorithm (HWOA) based on various existing literatures. This comparison is detailed in Table IV

TABLE II
RELAY NUMBERS AND CORRESPONDING LINES OF KOSHI PROVINCE

Relay	Line
1	Tumlingtar-Inaruwa 220 kV
2	Inaruwa-Kusaha 132 kV
3	Inaruwa-Duhabi 132 kV
4	Duhabi-Damak 132 kV
5	Damak-Anarmani 132 kV
6	Damak-Godak 132 kV
7	Godak-Amarpur 132 kV

TABLE III
SCA RESULT FOR KOSHI PROVINCE

Relay	Primary Operation			Backup Operation			CTI
	TMS	PS	T_p (s)	TMS	PS	T_b (s)	
1	0.104	0.501	0.383	0.322	0.574	1.469	1.086
2	0.104	0.514	0.347	0.1	0.744	1.331	0.983
3	0.1	0.5	0.473	0.182	0.534	1.434	0.961
4	0.101	0.5	0.604	0.194	0.697	1.577	0.973
5	0.1	0.502	0.328	0.1	0.559	1.689	1.361
6	0.101	0.504	0.34	0.117	0.5	1.748	1.408
7	0.1	0.503	0.437	0.142	0.821	0.808	0.371

Total Primary Operation Time = 2.912 s

where,

T_p is the operation time of primary relay, and

T_b is the operation time of backup relay

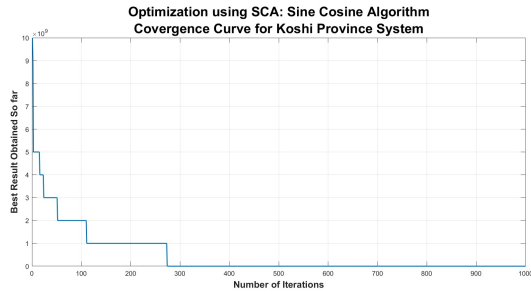


Fig. 6. Convergence characteristics for Koshi province system

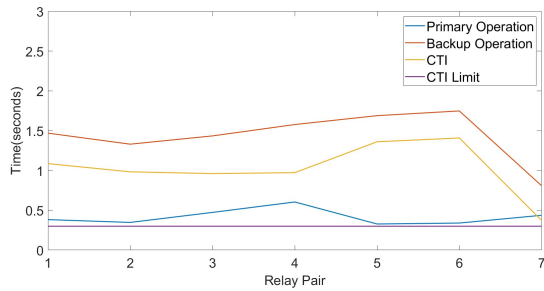


Fig. 7. Coordination of relay pairs for Koshi Province Grid

TABLE IV
COMPARISON WITH VARIOUS OTHER OPTIMIZATION TECHNIQUES

System	Total Operation Time (s)		
	SCA	SA [6]	HWOA [7]
8 BUS	3.322	5.8568	5.2422

From Table IV, it is clear that the proposed SCA is superior to existing algorithm to determine the TMS and PS of the relays.

V. CONCLUSION

In this research optimal coordination problem was formulated and the SCA program was coded in MATLAB to solve such problems. Then the said program was run to solve the coordination problem. The algorithm was used on four different test bus system viz. three-bus test system, and eight bus test system. The optimized values of the TMS and PS settings for individual relays were obtained for the minimum total operation time of the primary relays and were tabulated in Section IV. The results obtained were then compared with the results from the various optimization techniques shown in Table IV. Also, SCA were implemented to optimize coordination problem in Koshi Province Grid of Integrated Nepal Power System (INPS). The result shows the effectiveness of the proposed algorithm to solve non linear optimization problem which can also be applied to solve the DOCR coordination problem. The results shows that the obtained PS values are continuous rather than discrete i.e., the obtained values are not obtained in steps. The PS values are generally available in discrete steps of 0.5. The SCA could be coupled with mixed integer programming techniques to obtain the PS as a discrete value, and if required TMS also could be obtained as a discrete value.

REFERENCES

- [1] M. Alam, B. Das, and V. Pant, "A comparative study of metaheuristic optimization approaches for directional overcurrent relays coordination," *Electric Power Systems Research*, vol. 128, pp. 39–52, 11 2015.
- [2] N. Z. Jamal, M. H. Sulaiman, O. Aliman, and Z. Mustafa, "Optimal overcurrent relays coordination using an improved grey wolf optimizer," *International Journal of Advanced Computer Science and Applications*, vol. 9, 01 2018.
- [3] M. Singh, B. Panigrahi, and A. Abhyankar, "Optimal coordination of directional over-current relays using teaching learning-based optimization (tlbo) algorithm," *International Journal of Electrical Power & Energy Systems*, vol. 50, pp. 33–41, 2013.
- [4] P. Bedekar and S. Bhide, "Overcurrent relay coordination using the hybrid ga-nlp approach," *IEEE Trans. Power Del.*, vol. 26, pp. 109–19, 2011.
- [5] S. Mirjalili, "SCA: a sine cosine algorithm for solving optimization problems," *Knowledge-based systems*, vol. 96, pp. 120–133, 2016.
- [6] T. Amraee, "Coordination of directional overcurrent relays using seeker algorithm," *IEEE Transactions on Power Delivery - IEEE TRANS POWER DELIVERY*, vol. 27, pp. 1415–1422, 07 2012.
- [7] T. Lone, A. Wadood, S. Gholami Farkoush, J. Yu, C. Kim, and R. Bong, "An improved optimal solution for the directional overcurrent relays coordination using hybridized whale optimization algorithm in complex power systems," *IEEE Access*, vol. PP, pp. 1–1, 07 2019.

IOE 15th Graduate Conference Paper Acceptance Letter



त्रिभुवन विश्वविद्यालय
Tribhuvan University
इन्जिनियरिङ अध्ययन संस्थान
Institute of Engineering

डीनको कार्यालय
OFFICE OF THE DEAN

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

Date: July 7, 2024

To Whom It May Concern:

This is to certify that the paper titled "**Optimal Coordination of Directional Over-Current Relays in IEE 3-Bus, 15-Bus and 30-Bus Networks Using Sine Cosine Algorithm**" (Submission# 57) submitted by **Madhav Prasad Nagarkoti** as the first author, which had been accepted for presentation after the peer-review process, has successfully been presented at the 15th IOE Graduate Conference held during May 17 & 18, 2024. Kindly note that the final revision of the papers and publication process of the conference proceedings is still underway and hence inclusion of the accepted manuscript in the conference proceedings is contingent upon timely response to further edits during the publication process.

Bhim Kumar Dahal, PhD
Convener,
15th IOE Graduate Conference



Optimal Coordination of Directional Overcurrent Relays Using Sine Cosine Algorithm

Madhav Prasad Nagarkoti ^a, Jeetendra Chaudhary ^b, Akhileshwor Kumar Mishra ^c

^{a, b, c} Department of Electrical Engineering, Pulchowk Campus, IOE, Tribhuvan University, Nepal

✉ ^a 078mspse009.madhav@pcampus.edu.np

Abstract

Integration of the distributed generator (DG)s into the power system and distribution network has increased the complexity of protection coordination. The Optimal coordination of directional overcurrent relay (DOCR)s used for the protection of such networks is highly constrained and nonlinear. A nonlinear optimization technique called Sine Cosine Algorithm (SCA) is used in this paper to solve the optimal coordination problem of the DOCRs. The SCA is a recently proposed algorithm for solving highly nonlinear constrained optimization problems. The method uses the cyclic nature of the sinusoids to reposition a solution around another best solution. This is used to exploit the region defined by the constraints to look for a global optimum value. This work implements the SCA to optimize the coordination problems for the IEEE 3-Bus, 15-Bus and 30-Bus test systems. The result shows the robustness of the algorithm to reduce the total operating times of primary relays while simultaneously maintaining the coordination time intervals (CTI) between the primary and backup relay pairs.

Keywords

Directional Over-current Relay Coordination, Coordination Time Interval, Distributed Generator, Sine Cosine Algorithm

1. Introduction

Directional Overcurrent Relay (DOCR)s along with isolators and circuit breakers are used in the protection of the power system network. Due to high penetration of renewable energies and the distributed generators, the structure of the power system as well as distribution system network has become meshed. The integration of the distributed generation has various technical, environmental and economic benefits. The magnitude of the short circuit current depends upon the nature and the penetration of the DGs. In order to protect the system, fast and reliable operation of the DOCR is required. The optimal coordination of the relays plays a vital role in protecting the system. The relays should operate such that the fault is isolated without damaging the network. The main function of the DOCR is to detect the fault in its protective zone without any intentional delay. This type of protection is known as the primary protection. Sometime the primary protection may fail to protect due to various reason such as disfunction of primary relays, isolator not working and so on. In this case, after certain interval of time the backup protection should isolate the fault. The backup protection is an additional security measure that is provided to a section or protective zone which activates only if the primary protection fails to operate after a certain intentional delay. The operation time of the individual relay depends upon the two settings available. These are the Time Multiplier Settings (TMS) and the Plug Settings (PS). There have been different approaches to adjust the TMS and the PS to obtain the minimum total operation time. Most of these approaches fix the PS of the relay to predetermined constant value and only optimizes the TMS. This is done due to the reason that the operation time of the relay is nonlinear function of its PS while a linear function of its TMS. This approach uses linear programming techniques such as Simplex, Dual-Simplex and Two-Phase

methods to optimize the values of the TMS only.

The nonlinear programming techniques such as Genetic Algorithm, Improved Grey Wolf Optimizer, Hybrid Whale Optimization, Fuzzy logics, Mixed Integer Programming, Ant-lion Optimization and so on can be used to solve the DOCR coordination problem. One of the such techniques is Sine Cosine Algorithm (SCA), which is used in this work and was first introduced in [1]. These nonlinear optimization techniques can be used to optimize both the PS and the TMS of a relay to ensure the minimum total operating time of the primary relays. It should be noted that the derivative based optimization techniques could be trapped in a local minima and fails to achieve the global minimum. The rate of convergence of such algorithms depends on the system size being considered and are slow with the increase in system size.

2. Approach

2.1 Formulation of the objective function

Relay coordination problem can be formulated as a linear or nonlinear function. In case of linear approach PS is kept constant while the TMS is optimized whereas in case of nonlinear function both the PS and TMS are simultaneously optimized for the minimum total operational time of the primary relays. The relay characteristics can be mathematically expressed as [2].

$$T_{ik} = \frac{TMS_i \times \beta}{\left(\frac{I_{Rik}}{PS_i}\right)^\alpha - 1} \quad (1)$$

where,

T_{ik} is operational time of the relay i for the fault at location k ;

TMS_i is the Time Multiplier Setting of the relay i ;
 PS_i is the Plug Setting of the relay i ;
 I_{Rik} is fault current seen by relay i for the fault at location k ;
 α and β are constants which vary with the characteristics of the relay.

For Inverse Definite Minimum Time (IDMT) relay α and β have values 0.02 and 0.14 respectively [3]. The objective of the relay coordination problem is to determine the values of TMS and PS for each relay such that the total operation time of the primary relays will be minimum. Therefore, the objective function will be

Minimize

$$Z = \sum_i^n \sum_{k=1}^l w_{ik} T_{ik} \quad (2)$$

where,
 T_{ik} is the operation time of relay i for the fault at location k .
 w_{ik} is the product of probability of occurrence of the fault and relative importance of the line/bus on which the fault occurs. In this paper, w_{ik} is taken to be 1.

The optimization problem has the following constraints

- Plug Setting Constraints

The PS settings should be within the available range. i.e.,

$$PS_{i,min} \leq PS_i \leq PS_{i,max} \quad (3)$$

The minimum and maximum PS setting available for all the relays are taken to be 0.5 and 2.5 respectively.

- Time Multiplier Settings Constraints

The TMS settings should be within the available range. i.e.,

$$TMS_{i,min} \leq TMS_i \leq TMS_{i,max} \quad (4)$$

The minimum and maximum TMS setting available for all the relays are taken to be 0.1 and 5 respectively.

- Operating time Constraints

The limits on the relay operating time can be expressed as

$$T_{ik,min} \leq T_{ik} \leq T_{ik,max} \quad (5)$$

The minimum and maximum operating time of all the relays are taken to be 0.1 seconds and 2 seconds respectively.

- Coordination Constraints

For a fault at location k , the primary relay i should operate before backup relay j . The time delay after which the backup relay works if the primary relay fails to isolate the fault is known as Coordination Time Interval (CTI) and this constraint can be expressed as

$$T_{jk} - T_{ik} \geq CTI \quad (6)$$

For all primary and backup pairs i and j , the CTI used in this paper is 0.3 seconds.

2.2 Sine Cosine Algorithm to solve nonlinear optimization problem

The SCA is a unique optimization technique which is inspired from the basic sinusoidal and co-sinusoidal function and was first introduced in [1].

The SCA develops a set of random initial population which oscillates inward or outwards of the current best solution to achieve the next best solution by exploring the region defined by the constraints. The equation to update the position of the population can be expressed as [1]

$$X_i^{t+1} = \begin{cases} X_i^t + r_1 \times \sin(r_2) \times |r_3 P_i^t - X_i^t| & \text{if } r_4 < 0.5 \\ X_i^t + r_1 \times \cos(r_2) \times |r_3 P_i^t - X_i^t| & \text{if } r_4 \geq 0.5 \end{cases} \quad (7)$$

where, X_i^t is the position of the current solution in i^{th} dimension and t^{th} iteration X_i^{t+1} is the position of the current solution in i^{th} dimension and $(t+1)^{th}$ iteration P_i^t is the best position of the current solution in i^{th} dimension and upto t^{th} iteration $r_1 = a - t(a/T)$, $r_2 \in [0, 2\pi]$, $r_3 \in [0, 2]$, $r_4 \in [0, 1]$

$a = 2$, t is the current iteration and T is the maximum number of iterations.

r_2 , r_3 and r_4 are the random numbers.

The SCA stores the best solution in a variable P_i^t as a destination point and all the other solution moves toward that destination using equation 7.

The SCA can be described best by the flowchart shown in Figure 1.

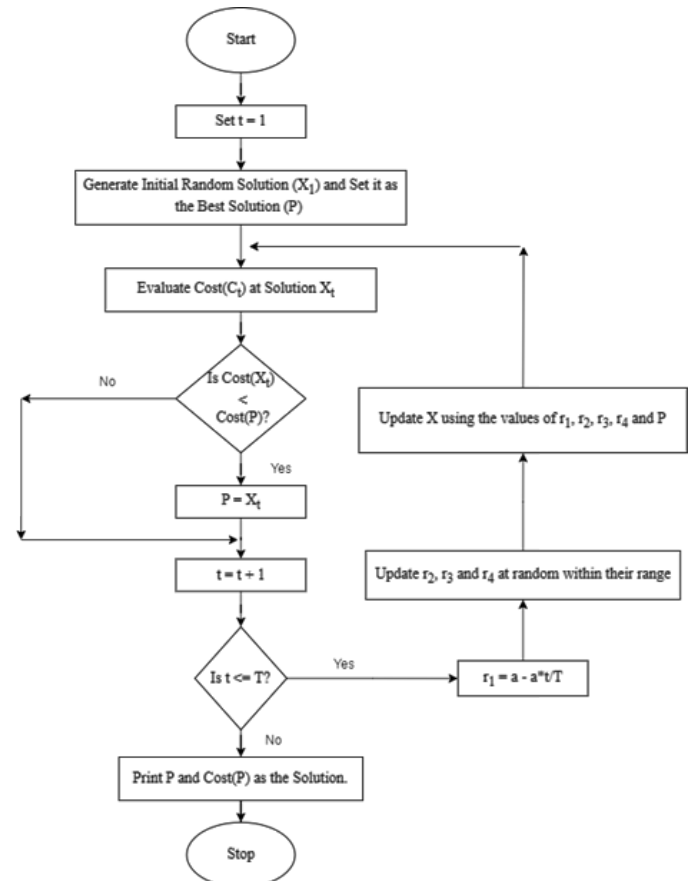


Figure 1: SCA for nonlinear optimization

3. Result and Discussion

The proposed algorithm was tested on three different test systems: 3-bus, 15-bus and 30-bus system. The IDMT relays were chosen with $\alpha = 0.02$ and $\beta = 0.14$. The CTI constraints for all the relays were assumed to be 0.3 seconds. In all three cases the population size was taken to be 1000 and the SCA program was run for 1000 iterations. The obtained results is then compared with various other optimization techniques shown in Table 4.

3.1 Three-bus test system

A three-bus test system having three buses, three lines, three generators and six relays as shown in Figure 2. was considered. The rating of each of the components is given in [4]. The three phase to ground faults were considered to occur at the mid-point of the line. The developed SCA program was then run to obtain the following results as shown in Table 1.

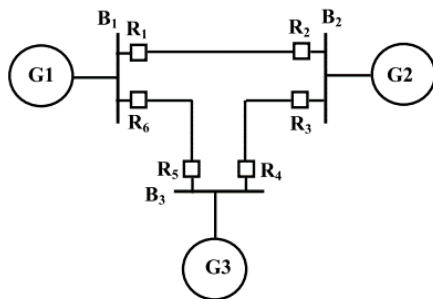


Figure 2: SLD of three-bus test system

Table 1: Results for three-bus test system

Relay	Primary Operation			Backup Operation			CTI (seconds)
	TMS	PS	Top (seconds)	TMS	PS	Top (seconds)	
1	0.13089	0.52292	0.22107	0.33287	0.6639	0.7671	0.54603
2	0.10672	1.5493	0.22144	0.27734	0.6165	0.69013	0.46869
3	0.13886	0.66325	0.22092	0.24633	1.2068	0.68818	0.46727
4	0.10263	1.3664	0.22101	0.28583	0.59299	0.65156	0.43055
5	0.1	2.0032	0.22742	0.17998	1.7752	0.71555	0.48813
6	0.1	1.1086	0.22328	0.2454	0.88076	0.77131	0.54803
Total Operation Time			1.33514 seconds				

Table 1 shows the simulation results for three-bus test system. The proposed algorithm shows that it will take 1.33514 seconds to operate all the primary relays. Also, it is found that all of the constraints are met. Furthermore Figure 3 shows the convergence characteristics for the three-bus test system. It is clearly seen that the program was able to converge at around 300 iterations.

3.2 Fifteen-bus test system

A fifteen-bus test system connected to an external grid at bus eight and having six generators, twenty-one lines and forty-two relays as shown in Figure 4 was considered. The rating of each of the components is given in [5]. The three phase to ground faults were considered to occur at the mid-point of the line. The developed SCA program was then run to obtain the following results as shown in Table 2.

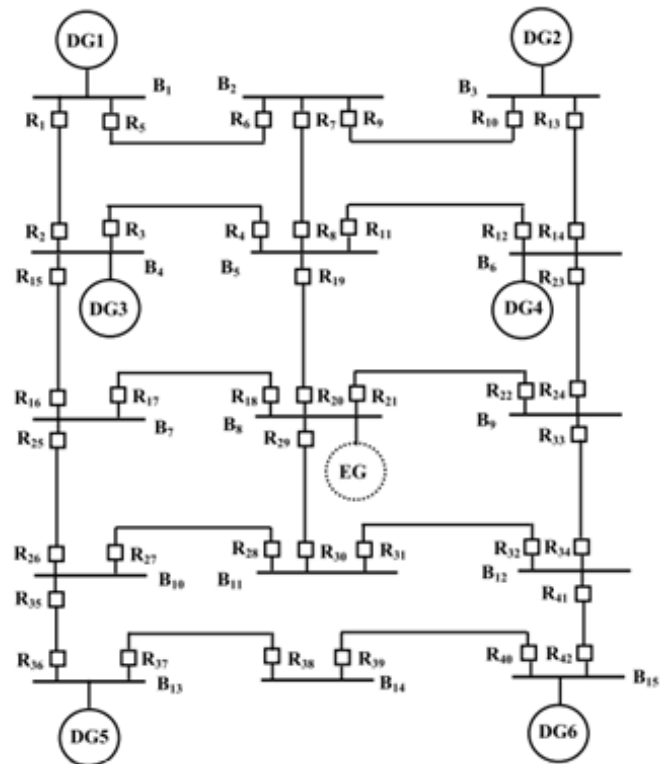


Figure 3: SLD of fifteen-bus test system

Table 2: Results for fifteen-bus test system

Relay	Primary Operation			Backup Operation			CTI (seconds)
	TMS	PS	Top (seconds)	TMS	PS	Top (seconds)	
1	0.10407	1.1962	0.24056	0.25405	1.4514	1.3492	1.1086409
2	0.19147	0.68061	0.38835	0.1	2.4777	1.58877	1.2004251
3	0.17549	0.55252	0.31048	0.50358	0.5909	1.26474	0.9542591
4	0.16313	1.3247	0.42397	0.45696	0.51096	1.25364	0.82967
5	0.174	0.51164	0.31691	0.72766	0.62029	1.87559	1.5586771
6	0.10154	0.98778	0.22179	0.69369	0.74057	1.79809	1.5762947
7	0.10207	2.0015	0.29802	0.31542	2.3633	1.59492	1.2969065
8	0.16818	0.50335	0.31002	0.24506	2.4527	1.75706	1.4470452
9	0.15485	0.53893	0.2732	0.44964	1.4071	1.72916	1.4559543
10	0.18406	0.79938	0.37436	0.31917	1.5226	1.45985	1.0854863
11	0.12724	0.657	0.25976	0.26254	2.4685	1.99639	1.7366266
12	0.1	0.52566	0.19284	0.28763	2.0831	1.85501	1.6621686
13	0.10002	1.2048	0.23699	0.30521	0.69027	0.79716	0.5601698
14	0.10883	1.0615	0.25562	0.10321	1.8291	0.72657	0.4709489
15	0.12348	0.53496	0.23139	0.3977	0.93006	1.86836	1.6369712
16	0.13304	0.98164	0.30766	0.30765	1.052	1.19353	0.8858663
17	0.14401	0.58925	0.26375	0.64879	0.68538	1.85441	1.5906624
18	0.1143	0.92426	0.23097	0.15782	1.7501	1.27747	1.046504
19	0.20434	0.50415	0.35244	0.23601	2.351	1.26037	0.9079274
20	0.13539	0.59669	0.24731	0.36862	0.5713	1.10062	0.8533029
21	0.10022	2.0736	0.2696	0.1869	1.6816	1.43754	1.1679312
22	0.13124	0.50012	0.22731	0.48278	1.0048	1.59292	1.3656078
23	0.10112	0.52394	0.18616	0.3825	0.77588	1.5867	1.4005414
24	0.11523	0.56638	0.22124	0.23595	0.57622	0.67531	0.454064
25	0.14789	1.7271	0.42071	0.29627	1.4842	1.25701	0.8363011
26	0.1719	2.0523	0.52662	0.3533	2.2232	1.99997	1.4733491
27	0.10173	1.9193	0.32157	0.3592	0.99772	1.13876	0.8171926
28	0.18267	0.61511	0.34935	0.35858	2.2573	1.66907	1.3197268
29	0.10129	0.60821	0.18164	0.69665	0.52819	1.9997	1.8180659
30	0.10192	2.5	0.32293	0.49312	1.4568	1.92179	1.598865
31	0.1428	0.52758	0.25225	0.40354	0.72054	1.23522	0.982966
32	0.11035	1.724	0.32775	0.32776	1.3724	1.5673	1.2395457
33	0.15125	1.0564	0.35443	0.47166	0.53386	1.10654	0.7521081
34	0.14292	1.2731	0.34462	0.24666	1.026	0.682	0.3373836
35	0.11961	0.53432	0.23186	0.42043	0.54577	1.08916	0.8573046
36	0.13232	1.4455	0.33992	0.29033	1.0182	1.0395	0.6995788
37	0.10353	1.0793	0.23849	0.2385	1.3265	0.85724	0.6187495
38	0.11086	0.51752	0.21264	0.59212	1.4462	1.99939	1.7867551
39	0.10662	1.5705	0.29913	0.72843	0.53311	1.62446	1.3253353
40	0.10374	1.4863	0.27416	0.11849	2.2872	0.60898	0.3348194
41	0.10297	0.53251	0.18086	0.63955	0.91369	1.88395	1.7030877
42	0.10378	0.5	0.18821	0.31585	1.4842	1.62778	1.43956995
Total Operation Time			12.0079 seconds				

Table 2: shows the simulation results for fifteen-bus test system. The proposed algorithm shows that it will take 12.0078624 seconds to operate all the primary relays. Also, it is found that all of the constraints are met. Furthermore Figure 5. shows the convergence characteristics for the fifteen-bus test system. It is clearly seen that the program was able to converge at around 900 iterations.

3.3 Thirty-bus test system

A thirty-bus test system with thirty buses, twenty lines and thirty-nine relays as shown in Figure 6. was considered. The rating of each of the components is given in [6]. The three phase to ground faults were considered to occur at the mid-point of the line. The developed SCA program was then run to obtain the following results as shown in Table 3 which shows the simulation results for thirty-bus test system.

Table 3: Results for thirty-bus test system

Relay	Primary Operation			Backup Operation			CTI (seconds)
	TMS	PS	Top (seconds)	TMS	PS	Top (seconds)	
1	0.24379	1.1722	0.41383	0.2848	1.6304	0.76864	0.35481
2	0.12223	0.50545	0.30155	0.1841	1.9049	0.73415	0.4326
3	0.22559	0.50181	0.34345	0.24956	2.2334	0.8599	0.51645
4	0.23715	1.3746	0.58188	0.38125	1.0184	0.96556	0.38368
5	0.24537	1.4807	0.6077	0.25874	1.99	0.98596	0.37826
6	0.12979	0.65199	0.35402	0.4704	0.52599	1.129	0.77498
7	0.1202	0.50079	0.20018	0.28001	0.53041	0.72575	0.52557
8	0.10347	0.66358	0.18632	0.11191	1.0523	0.48649	0.30017
9	0.12399	0.71131	0.1713	0.23046	1.0322	0.48914	0.31784
10	0.1779	0.50142	0.35481	0.52424	0.67714	1.0964	0.74159
11	0.41835	1.4075	0.81718	0.36326	1.5186	1.1061	0.28892
12	0.28902	0.5015	0.44712	0.41456	1.4533	1.2315	0.78438
13	0.11368	1.1927	0.56858	0.26462	2.2163	1.0152	0.44662
14	0.10838	1.3924	0.2801	0.27019	0.64778	0.7214	0.4413
15	0.11375	0.53959	0.26551	0.11358	1.9722	0.57941	0.3139
16	0.31127	0.55813	0.38234	0.30873	1.8949	1.0024	0.62006
17	0.14957	0.70268	0.39301	0.31427	0.53499	1.0708	0.67779
18	0.2104	0.5016	0.31541	0.27041	1.3394	0.86289	0.54748
19	0.14832	1.5894	0.45573	0.37645	1.4235	1.1024	0.64667
20	0.18264	0.75182	0.30332	0.22236	1.4597	1.197	0.89368
21	0.1341	0.7054	0.24292	0.20102	0.7687	0.91536	0.67244
22	0.18509	1.414	0.45936	0.43356	1.4834	1.2023	0.74294
23	0.2447	0.82127	0.54577	0.4023	0.61604	0.95015	0.40438
24	0.16437	2.2544	0.45404	0.23955	2.0012	1.1345	0.68046
25	0.23221	0.68268	0.75012	0.31475	1.9672	1.1231	0.37298
26	0.1043	0.9787	0.30511	0.37375	0.95432	0.92074	0.61563
27	0.10458	0.5	1.31227	0.26753	1.0013	0.72657	0.5857
28	0.13754	0.82906	0.31348	0.25001	1.6117	1.0961	0.78262
29	0.1027	1.607	0.22525	0.13136	2.0012	0.73388	0.50863
30	0.10966	0.62741	0.38289	0.35608	1.2348	1.0485	0.66561
31	0.1389	0.86591	0.21938	0.16495	2.2239	0.74728	0.5279
32	0.24032	0.51542	0.48594	0.50132	0.50702	1.1145	0.62856
33	0.12653	0.5071	0.33929	0.2831	2.4222	1.0191	0.67981
34	0.16117	1.1425	0.24557	0.17508	1.932	0.59269	0.34712
35	0.10007	0.67991	0.19279	0.161	1.8106	0.67186	0.47907
36	0.15916	1.2631	0.54535	0.24761	1.5632	1.0923	0.54695
37	0.16596	0.81726	0.30793	0.25393	1.7567	1.016	0.70807
38	0.11637	0.93111	0.28046	0.20888	2.2078	0.9922	0.71174
39	0.12123	0.73835	0.24701	0.30054	1.5634	1.0862	0.83919
Total Operation Time	15.59827 seconds						

The proposed algorithm shows that it will take 15.59827 seconds to operate all the primary relays. Also, it is found that all of the constraints are met. Furthermore Figure 7: shows the convergence characteristics for the fifteen-bus test system. It is clearly seen that the program was able to converge at around 900 iterations.

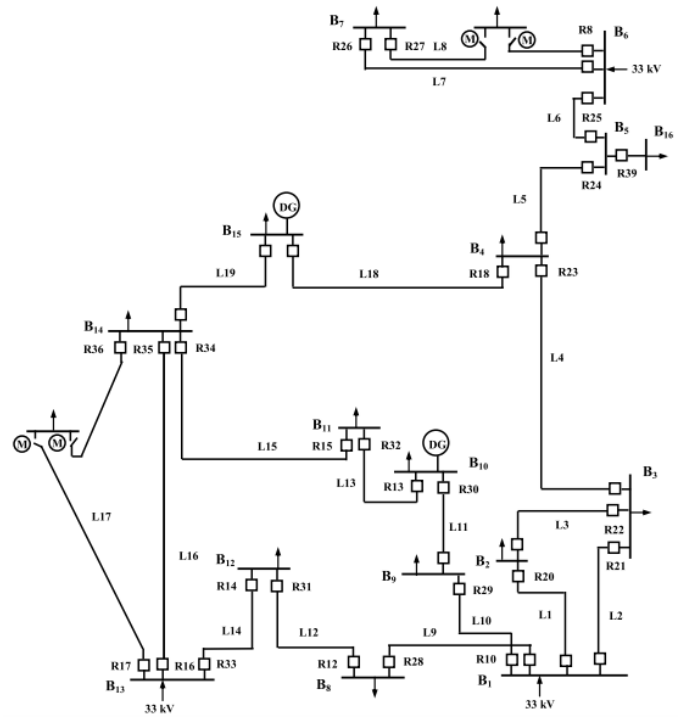


Figure 4: SLD of thirty-bus test system

Table 4: Comparison with various other optimization techniques

SYSTEM	Total Operation Time (s)						
	Proposed (SCA)	SA [5]	IGWO [7]	HWOA [8]	SBB [5]	DE [9]	HS [9]
3 BUS	1.33514	1.599	1.4789	1.5029	-	-	-
15 BUS	12.00786	12.227	12.6446	-	15.335	-	-
30 BUS	15.59287	-	-	-	-	17.8122	19.2133

4. Conclusion

In this paper optimal coordination problem was formulated and the SCA program was coded in MATLAB to solve such problems. Then the said program was run to solve the coordination problem. The algorithm was used on three different test bus system viz. three-bus test system, fifteen-bus test system and thirty-bus test system. The optimized values of the TMS and PS settings for individual relays were obtained for the minimum total operation time of the primary relays and were tabulated in section 3. The results obtained were then compared with the results from the various optimization techniques shown in Table 4. The result shows the effectiveness of the proposed algorithm to solve non linear optimization problem which can also be applied to solve the DOCR coordination problem. The results shows that the obtained PS values are continuous rather than discrete i.e., the obtained values are not obtained in steps. The PS values are generally available in discrete steps of 0.5. The SCA could be coupled with mixed integer programming techniques to obtain the PS as a discrete value, and if required TMS also could be obtained as a discrete value.


References

- [1] S. Mirjalili, "Sca: a sine cosine algorithm for solving optimization problems," *Knowledge-based systems*, vol. 96, pp. 120–133, 2016.
- [2] M. Singh, B. Panigrahi, and A. Abhyankar, "Optimal coordination of directional over-current relays using teaching learning-based optimization (tlbo) algorithm," *International Journal of Electrical Power & Energy Systems*, vol. 50, pp. 33–41, 2013.
- [3] P. Bedekar and S. Bhide, "Overcurrent relay coordination using the hybrid ga-nlp approach," *IEEE Trans. Power Del.*, vol. 26, pp. 109–19, 2011.
- [4] A. Urdaneta, R. Nadira, and L. Perez Jimenez, "Optimal coordination of directional overcurrent relays in interconnected power systems," *IEEE Transactions on Power Delivery*, vol. 3, no. 3, pp. 903–911, 1988.
- [5] T. Amraee, "Coordination of directional overcurrent relays using seeker algorithm," *IEEE Transactions on Power Delivery* - *IEEE TRANS POWER DELIVERY*, vol. 27, pp. 1415–1422, 07 2012.
- [6] R. Mohammadi, H. A. Abyaneh, H. M. Rudsari, S. H. Fathi, and H. Rastegar, "Overcurrent relays coordination considering the priority of constraints," *IEEE Transactions on Power Delivery*, vol. 26, pp. 1927–1938, 2011.
- [7] N. Z. Jamal, M. H. Sulaiman, O. Aliman, and Z. Mustafa, "Optimal overcurrent relays coordination using an improved grey wolf optimizer," *International Journal of Advanced Computer Science and Applications*, vol. 9, 01 2018.
- [8] T. Lone, A. Wadood, S. Gholami Farkoush, J. Yu, C. Kim, and R. Bong, "An improved optimal solution for the directional overcurrent relays coordination using hybridized whale optimization algorithm in complex power systems," *IEEE Access*, vol. PP, pp. 1–1, 07 2019.
- [9] M. Alam, B. Das, and V. Pant, "A comparative study of metaheuristic optimization approaches for directional overcurrent relays coordination," *Electric Power Systems Research*, vol. 128, pp. 39–52, 11 2015.

APPENDIX C: PLAGIARISM TEST REPORT

Madhav Prasad Nagarkoti

Optimal Coordination of Directional Overcurrent Relays Using Sine Cosine Algorithm

 Tribhuvan University

Document Details

Submission ID

trn:oid:::3117:451041052

Submission Date

Apr 21, 2025, 6:38 PM GMT+5:45

Download Date

Apr 21, 2025, 6:40 PM GMT+5:45

File Name

ooooooooooooo.pdf

File Size

5.2 MB

43 Pages

9,871 Words

49,034 Characters





11% Overall Similarity

The combined total of all matches, including overlapping sources, for each database.




Filtered from the Report

- Bibliography

Match Groups

-  **108** Not Cited or Quoted 10%
Matches with neither in-text citation nor quotation marks
-  **8** Missing Quotations 1%
Matches that are still very similar to source material
-  **0** Missing Citation 0%
Matches that have quotation marks, but no in-text citation
-  **0** Cited and Quoted 0%
Matches with in-text citation present, but no quotation marks

Top Sources

- 6%  Internet sources
- 10%  Publications
- 0%  Submitted works (Student Papers)

Integrity Flags

0 Integrity Flags for Review

No suspicious text manipulations found.

Our system's algorithms look deeply at a document for any inconsistencies that would set it apart from a normal submission. If we notice something strange, we flag it for you to review.

A Flag is not necessarily an indicator of a problem. However, we'd recommend you focus your attention there for further review.

Match Groups

- **108** Not Cited or Quoted 10%
Matches with neither in-text citation nor quotation marks
- **8** Missing Quotations 1%
Matches that are still very similar to source material
- **0** Missing Citation 0%
Matches that have quotation marks, but no in-text citation
- **0** Cited and Quoted 0%
Matches with in-text citation present, but no quotation marks

Top Sources

- 6% Internet sources
- 10% Publications
- 0% Submitted works (Student Papers)

Top Sources

The sources with the highest number of matches within the submission. Overlapping sources will not be displayed.

1	Publication	"Soft Computing Applications in Modern Power and Energy Systems", Springer Sc...	<1%
2	Internet	www.researchgate.net	<1%
3	Publication	Mohammedi Ridha Djamel, Mosbah Mustafa, Zine Rabie, Khattara Abdelouahab, ...	<1%
4	Publication	Kumari Sarwagya, Paresh Kumar Nayak, Suman Ranjan. "Optimal coordination of...	<1%
5	Internet	dlibrary.univ-boumerdes.dz:8080	<1%
6	Internet	conference.ioe.edu.np	<1%
7	Publication	Dina K. Mahmoud, Shady H. E. Abdel Aleem, Ahmed M. Ibrahim, Mahmoud M. Say...	<1%
8	Internet	elibrary.tucl.edu.np	<1%
9	Publication	Tareq Foqha, Samer Alsadi, Osama Omari, Shady S. Refaat. "Optimization Techniq...	<1%
10	Internet	ebin.pub	<1%

11	Internet	www.tandfonline.com	<1%
12	Internet	mdpi-res.com	<1%
13	Publication	Suzana Pil Ramli, Hazlie Mokhlis, Wei Ru Wong, Munir Azam Muhammad, Nurulaf...	<1%
14	Internet	eprints.uanl.mx	<1%
15	Publication	An Liu, Ming-Ta Yang. "A New Hybrid Nelder-Mead Particle Swarm Optimization f...	<1%
16	Publication	Abdelmonem Draz, Mahmoud M. Elkholy, Attia A. El-Fergany. "Soft Computing Me...	<1%
17	Publication	Alexandre A. Kida, Angel E. Labrador Rivas, Luis A. Gallego. "An improved simulat...	<1%
18	Publication	Harikrishna Muda, Premalata Jena. "Real time simulation of new adaptive overcu...	<1%
19	Internet	core.ac.uk	<1%
20	Publication	Dhivya Sampath Kumar, Dipti Srinivasan, Anurag Sharma, Thomas Reindl. "Adapt...	<1%
21	Publication	Ali Ridha Al-Roomi. "Optimal Coordination of Power Protective Devices with Illust...	<1%
22	Publication	Dehghanpour, Ehsan, Hossein Karegar, Reza Kheirollahi, and Tohid Soleymani. "O...	<1%
23	Internet	www.mdpi.com	<1%
24	Publication	Forhad Zaman, Saber M. Elsayed, Tapabrata Ray, Ruhul A. Sarker. "Co-evolutionar...	<1%

25	Internet	coek.info	<1%
26	Internet	joape.uma.ac.ir	<1%
27	Internet	www.elixirpublishers.com	<1%
28	Publication	Emmanuel, Osaji, Mohammad Lutfi Othman, Hashim Hizam, and Muhammad Mu...	<1%
29	Publication	Mahamad Nabab Alam, Biswarup Das, Vinay Pant. "Protection scheme for reconfi...	<1%
30	Publication	Naser El Naily, Saad. M. Saad, Mohammed M. El Misslati, Faisal A. Mohamed. "Opt...	<1%
31	Publication	Samia Batool, Sadiq Ahmad, Abdullah Shoukat, Faiza Mobeen. "A Data Driven App...	<1%
32	Publication	Youssef H. El Gohary, Talal Elemamali Sati, Ahmed H. Osman, Mostafa Shaaban. "...	<1%
33	Publication	Amol A. Kalage, Nitin D. Ghawghawe. "Optimum Coordination of Directional Over...	<1%
34	Publication	Arathi Pothakanahalli Bheemasenarao, Shankaralingappa C Byalihal. "Optimal pr...	<1%
35	Publication	Kimhok Chheng, Ardyono Priyadi, Margo Pujiantara, Vincentius Raki Mahindara. "...	<1%
36	Publication	Rizk M. Rizk-Allah, Ragab A. El-Sehiemy. "A novel sine cosine approach for single a...	<1%
37	Publication	Vipul N. Rajput, Kartik S. Pandya. "A hybrid improved harmony search algorithm-...	<1%
38	Internet	khazna.ku.ac.ae	<1%

39	Internet	www.emeraldinsight.com	<1%
40	Publication	Adhishree Srivastava, Sanjoy Kumar Parida. "Adaptive Protection Strategy in a Mi...	<1%
41	Publication	Ahmed Korashy, Salah Kamel, Abdel-Raheem Youssef, Francisco Jurado. "Modifie...	<1%
42	Publication	Mansour Sheikhan, S. Amir Ghoreishi. "Antiviral therapy using a fuzzy controller ...	<1%
43	Publication	Sherif M. Ismael, Shady H. E. Abdel Aleem, Almoataz Y. Abdelaziz. "Optimal selecti...	<1%
44	Internet	d-nb.info	<1%
45	Internet	downloads.hindawi.com	<1%
46	Internet	ijisae.org	<1%
47	Internet	semarakilmu.com.my	<1%
48	Internet	thunderbox.uwaterloo.ca	<1%
49	Publication	Ahmed Balyith, H. M. Sharaf, M. F. Shaaban, E. F. El-Saadany, H. H. Zeineldin. "Non...	<1%
50	Publication	Hamza Jouhari, Deming Lei, Mohammed A. A. Al-qaness, Mohamed Abd Elaziz, Ah...	<1%
51	Publication	Mahamad Nabab Alam, Biswarup Das, Vinay Pant. "An interior point method bas...	<1%
52	Publication	Saad.M. Saad, Naser El-Naily, Faisal A. Mohamed. "A New Constraint Considering ...	<1%

53	Publication	Sadegh Jamali, Hossein Borhani-Bahabadi. "Protection Method for Radial Distribu...	<1%
54	Publication	Seyedali Mirjalili. "Handbook of Moth-Flame Optimization Algorithm - Variants, H...	<1%
55	Publication	Soham Chakraborty, Sarasij Das. "Communication-less protection scheme for AC ...	<1%
56	Publication	Zengli Yang, Dongyuan Shi, Xianzhong Duan. "Optimal Coordination of Distance ...	<1%
57	Internet	eprints.umm.ac.id	<1%
58	Internet	umpir.ump.edu.my	<1%
59	Publication	Jiangtao Yu, Chang-Hwan Kim, Sang-Bong Rhee. "Oppositional Jaya Algorithm Wit...	<1%
60	Publication	Jiangtao Yu, Chang-Hwan Kim, Sang-Bong Rhee. "The Comparison of Lately Propo...	<1%
61	Publication	Moravej, Zahra, Farhad Adelnia, and Fazel Abbasi. "Optimal coordination of direct...	<1%
62	Publication	Prashant P. Bedekar, Sudhir R. Bhide, Vijay S. Kale. "Determining optimum TMS a...	<1%
63	Publication	Faraj Al-Bhadely, Aslan İnan. "An Innovative Approach for Enhancing Relay Coord...	<1%
64	Publication	H. Zeineldin, E.F. El-Saadany, M.A. Salama. "Optimal coordination of directional ov...	<1%
65	Publication	Hasan Can Kiliçkiran, İbrahim Şengör, Hüseyin Akdemir, Bedri Kekezoğlu, Ozan E...	<1%
66	Publication	Mostafa Meshkat, Mohsen Parhizgar. "A novel weighted update position mechani...	<1%

67

Publication

Salah K. ElSayed, Ehab E. Elattar. "Hybrid Harris hawks optimization with sequenti...

<1%