UNIVERSIDAD AUTÓNOMA DE NUEVO LEÓN

FACULTAD DE INGENIERÍA MECÁNICA Y ELÉCTRICA

DIVISIÓN DE ESTUDIOS DE POSGRADO

REAL TIME COORDINATION OF OVERCURRENT RELAYS BY MEANS OF OPTIMIZATION ALGORITHM

THESIS

IN ORDER TO OBTAIN THE MASTER DEGREE IN ELECTRICAL ENGINEERING

P R E S E N T :

ENG. MENG YEN SHIH

SAN NICOLÁS DE LOS GARZA, N. L. JULY 2013

UNIVERSIDAD AUTÓNOMA DE NUEVO LEÓN

FACULTAD DE INGENIERÍA MECÁNICA Y ELÉCTRICA

DIVISIÓN DE ESTUDIOS DE POSGRADO

REAL TIME COORDINATION OF OVERCURRENT RELAYS BY MEANS OF OPTIMIZATION ALGORITHM

THESIS

IN ORDER TO OBTAIN THE MASTER DEGREE IN ELECTRICAL ENGINEERING

P R E S E N T :

ENG. MENG YEN SHIH

SAN NICOLÁS DE LOS GARZA, N. L. JULY 2013

Universidad **A**utónoma de **N**uevo **L**eón

Facultad de **I**ngeniería **M**ecánica y **E**léctrica

Subdirección de **E**studios de **P**ostgrado

Los miembros del comité de tesis recomendamos que la tesis **REAL TIME COORDINATION OF OVERCURRENT RELAYS BY MEANS OF OPTIMIZATION ALGORITHM***, realizada por el alumno Meng Yen Shih, matrícula 1609597, sea aceptada para su defensa como opción al grado de Maestro en Ingeniería Eléctrica.*

El Comité de Tesis

Asesor
Dr. Arturo Conde Enríquez

Coasesor
Dr. Luis Martín Torres Treviño

Coasesor
Dr. Guillermo Gutierrez

Vo. Bo.
Dr. Moisés Hinojosa Rivera
División de Estudios de Posgrado

DEDICATION

This thesis is dedicated to my parents.

For their endless love, support and encouragement.

ACKNOWLEDGMENTS

First and foremost, I have to thank my parents for their love and support throughout my life. Thank you both for giving me strength to reach for the stars and chase my dreams. My elder and younger sister and all my family in Taiwan, you deserve my wholehearted thanks as well.

I would like to sincerely thank my supervisor, Dr. Arturo Conde Enríquez, for his advice, guidance, insightful criticisms, and patient encouragement aided the writing of this thesis in innumerable ways. I would also like to thank all my teachers who taught and educated me in this master's program, Dr. Manuel Andrade Soto, Dr. Gina María Idárraga Ospina, Dr. Miguel Francisco Escalante Guitierrez, Dr. Jose Antonio De La O Serna, MSc. Luis David Aréchiga Rodríguez.

Also thanks to Dr. Arturo Román Messina and Dr. Ernesto Vázquez Martínez for the acceptance in the scientific summer program 2009 and 2010 (XIX and XX Verano de la Investigación Científica, Academia Mexicana de Ciencias), without these participations I wouldn't have known the schools and accumulate enough courage therefore to assist this postgraduate program.

Thanks to my postgraduate friends, Miguel Jacobo, Luis Trujillo, Carlos Castillo, Mario González, Fernando Salinas, Daniel Guillen, Erika Tejada,Fernando Sanchez, Luis Alfaro, Raúl Tokayo, Raúl Aguirre, Alexander Cruti, Cutberto Conejo, Cesar Ochoa, Mario Lopez, Allan Soriano, Daniel Rivas, Miguel Flores, Omar Donjuan, Ruben Hernandez and especially Jorge Eduardo and Gustavo González who kindly helped in many areas.

Thanks to Consejo Nacional de Ciencia y Tecnología (CONACYT) for supporting me financially throughout the masters program.

Thank you Lord for everything, for accompany me and for teaching me, I shall glory your name and act according to your will till the end.

ABSTRACT

Eng. Meng Yen Shih,Instituto Tecnológico De Chetumal (2006-2010)

Candidate for the degree:
"Master of Science in Electrical Engineering
with Orientation in Electrical Power System"

Universidad Autónoma de Nuevo León
Facultad de Ingeniería Mecánica y Eléctrica

Thesis title:

REAL TIME COORDINATION OF OVERCURRENT RELAYS BY MEANS OF OPTIMIZATION ALGORITHM

Directed by: Professor Arturo Conde Enríquez

ABSTRACT:

Sub-transmission and distribution systems are the most numerous and dynamic parts of the entire power system. Hence economic and robust protection scheme must be implemented. The directional overcurrent relay (DOCR) is the ideal solution to this problem. Despite of its simple operation scheme, it is very complicated when the coordination of DOCRs involves short circuit currents and load demands of huge difference in the interconnected system. But the nature of the sub-transmission and distribution systems cannot be avoided. Therefore, this time consuming task which is traditionally done as manual labor should be replaced by computational resources. The computational resources here refer to optimization algorithms.

As it was mentioned before, the distribution system is numerous and dynamic. In other words, it is complicated and changes unpredictably as time goes by, so an efficient algorithm is indeed needed to face this challenge. The word "efficient" here means to encounter quality relay settings in a reasonable computational time.

The objective of this thesis is to coordinate the protections on a real time basis (online), which is very different from all reported literatures of coordination because such literatures coordinate off line and on fixed networks. This novel idea of "Real Time Coordination" is studied based on the idea of enhancing sensitivity and operation time of DOCRs.

Conventionally, relay settings are not reset every now and then; it depends on the complexity of the system. In radial or industrial systems there may be more resetting frequency. But in a meshed system, re-coordination of DOCRs is a very rare practice, they are often done locally. Therefore, this lead to big advantage of the "Real Time Coordination" compared to conventional practice. As load flow changes drastically from winter to summer and vice versa, relays can be coordinated with the latest system information which enhances sensitivity and operation time of DOCRs. There would also be a significant benefit if DOCRs are re-coordinated every 15 minutes.

In order to accomplish the objective, three algorithms are studied and compared. The Genetic Algorithm (GA) because of its widely implementation and well known fame in the protection area was taken as comparison reference. On the contrary, Ant Colony Optimization (ACO) and Differential Evolution (DE) are unknown algorithms in the protection area. But the ACO has been used lately in different studies such as reactive power flow planning, power flow economic dispatch, power generation scheduling, and has reported to be a powerful tool in solving complex problems in different areas. The DE has not yet been used in any power analysis, but it is reported to be very efficient in different areas [17]. Their advantages and disadvantages are reported and documented, and the outstanding algorithm was selected.

As the optimization algorithm coordinates the DOCRs, the real time algorithm updates entrance data (network topology, contingency load flow currents, and fault currents) for the optimization algorithm. This was developed to monitor the network operation; it is assumed that the hardware has already been manufactured and that the hardware just needs the installation of an appropriate real time algorithm.

The main contribution of this thesis is the comparison of the three algorithms and the development of the real time algorithm. It is demonstrated that sensitivity and operation time were enhanced using real time coordination.

The IEEE 14 and 30 bus systems are used as test systems.

The principal objective of this thesis is to develop the "Real Time Coordination Algorithm". The criteria of implementation or application are not considered as part of this thesis but are briefly described.

TABLE OF CONTENTS

Page

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

CHAPTER 1 INTRODUCTION

1.1 Introduction

Protection is widely used in all different voltage levels of the electrical power system: generation, transmission, sub-transmission and distribution etc. An overcurrent relay is a protection that is widely implemented in the sub-transmission and distribution systems due to its competing cost. Depending on the operative conditions and fault locations in a mesh system, the load or fault currents can circle in or out of the overcurrent relay's protective zone. Hence directional overcurrent relays are used to discriminate whether the fault is located in or out of the protective zone. The propose of coordinating the overcurrent relays is to encounter settings that minimize the operation time for faults within the protective zone and at the same time offering pre-specified timed backup for relays that are in the adjacent zones. So the maximum fault current that the relay detects in its protective zone must be greater than the fault currents in the adjacent zones. The above condition is met in radial systems, one source mesh systems and two source mesh systems where the sources are located symmetrically at the end. But the above condition is not always met in the multi-source mesh systems due to the numerous operative configurations. Since the systems cannot operate in the absence of protection, other protection principles must be used, i.e. impedance relay. It is then said that for certain operative configurations of mesh system, overcurrent protection principle is out of range or in other words reaches the limit of its protection principle [1].

Coordinating the overcurrent relays in the distribution systems is to meet the fundamental requirements of sensitivity, selectivity, reliability and speed [18], which the main objective is to satisfy clients need.

But due to the growing demand of electrical power, new lines and contracts are constructed and signed. This adds another dynamic factor to the dynamic distribution system. So the coordination becomes more difficult.

Coordinating the overcurrent relays by means of a real time optimization algorithm lead us to better results such as: faster fault extinction, lower possibility of false tripping operation and also lower index of fault extinction delay at different seasons of the year.

1.2 State of Art

Although DOCRs have nonlinear characteristic curves (nonlinear function), the coordination is carried out as a linear problem. This is because the coordination of a pair of relays is performed based on one point, which is the maximum coordination current of the pair of relays. Therefore, the relays guarantee coordination at this point; however, there may be a loss of coordination for faults that are located far from this point.

Over the past decades, manual coordination of DOCRs has been the most common practice performed by protection experts. However, due to its complexity and nonlinearity, manual coordination has been formulated as an optimization problem. Several optimization methods have been proposed to attack this problem. Coordination of DOCRs in the frame of deterministic optimization theory using linear programming (LP) was an approach first reported in 1988. The problem was presented as a linear function in which dials were computed for given values of pickup currents [2]. LP was then studied more for this problem due to its simplicity [3], [4].

Heuristic methods, such as the genetic algorithm (GA) and particle swarm optimization (PSO) [5] of the artificial intelligence (AI) family have quickly gained popularity in solving coordination problems [6], [7], [8], [9]. GA has been frequently reported in different literatures due to its simplicity, robustness and easy implementation. This algorithm is based on the evolutionary ideas of natural selection of genes which consist of selection, reproduction and mutation. In this case, the problem was presented as a nonlinear function in which both the dial and the pickup current parameters were computed.

Recently, hybrid methods have also arisen in solving coordination problem. Their main attractions are the reduction of search space, execution time and the number of iterations required in encountering the solution. The hybrid GA and mixed PSO are newly developed methods that are combined with LP, in which their search space are drastically reduced by encoding only the pickup currents as input variable strings, leaving the dials as task for LP to solve [10], [11]. In other words, these hybrid methods solve coordination problems by the linearization of the relay function.

Coordination of DOCRs considering different network topologies has been reported in different occasions [10], [21], [22]. A set of relay settings are encountered which will satisfy the coordination constraints of different cases of the network topology. On the other hand, the real time coordination proposed in this thesis is not to find a set of relay settings that will satisfy the coordination constraints of different cases of the network topology, but to re-coordinate all DOCRs for every change of network topology. The advantages by doing so are minimum relay operation time, increment of sensitivity, and the ability to withstand another unknown contingency. Moreover, the idea is to coordinate DOCRs online, which as a result enhances in meeting the fundamental requirements of the DOCRs.

The Ant Colony Optimization (ACO) has not been implemented in the coordination study but has lately been used for the study of reactive power flow planning [13], power flow economic dispatch [14], power generation scheduling [15], and has reported to be a powerful tool in solving complex problems in different areas [16]. The advantage of this algorithm compared to GA is the role of global memory played by pheromone matrix which leads to better and faster solution convergence.

The Differential Evolution (DE) is a family of the Evolutionary Algorithm (EA). But compared to most other EAs, DE is much more simple and straightforward to implement. Main body of the algorithm takes four to five lines to code in any programming language. The DE is studied and compared with other algorithms, the gross performance of the DE in terms of accuracy, convergence speed, and robustness makes it very attractive for applications to real-world optimization problems, where finding an approximate solution in reasonable amount of computational time is much weighted [17].

Hence, it is a novel idea in this thesis to formulate the coordination problem using ACO and DE. The GA, which is widely known in the coordination area, is used as the comparison reference.

1.2 Justification

DOCRs are the simplest and cheapest, but they are the most difficult to apply and the quickest to need re-setting as system changes. Coincidentally, they are mostly implemented in the distribution network, which is the most dynamic part of the whole power system. Consequently, these dynamic changes affect their sensitivity and selectivity, which cause inappropriate operations. However, due to the fact that DOCRs need to meet the fundamental requirements of sensitivity, selectivity, reliability and speed [12], coordination on a real time basis is proposed in this paper. Moreover, the idea is to coordinate DOCRs online which as a result enhances in meeting the fundamental requirements mentioned above. The developed real time algorithm first updates data from the latest changes of the system, and then computes load flow and fault analysis in order to obtain input data for the optimization algorithms.

In a more detailed way speaking, nowadays primary and secondary DOCRs are coordinated according to the maximum three phase short circuit currents and fixed maximum load currents in the system. As system is perturbed, the use of a fixed maximum load current as reference for coordination can usually cause a fault extinction delay or simply no fault extinction when the actual fault current is below the reference current.

The fault extinction time, correct/false tripping operations of each relay directly impact the fundamental requirements of sensitivity, selectivity, simplicity, reliability, speed and economic. These fundamental requirements were established to meet the desired index of power supply's continuity. And since the utility measures the continuity in monetary values the protections must carry out its function meeting those requirements.

While DOCRs operate as fast and accurate as possible, the primary instruments (transformers) have longer lifetime. Because one shall not forget that the damage of transformers are not reversible but cumulative. Also the enhancement of voltage quality is an important matter.

1.3 Objective

Objective:

Develop a real time algorithm which takes all the changes of elements and network operation into account for coordinating the overcurrent relays.

This algorithm will be gathering all the latest data (Ybus) such as power system's topology and status of the shunt elements (loads and compensators). In this way, the relays will always be updated with the latest reference current data according to the latest Ybus. Bear in mind that even though there might be no fault occurrence in the network (no change of power system topology), the reference current varies constantly due to the natural power demand curve which differs from hour to hour of the day and season to season of the year.

Methodology:

Develop an algorithm which carries out the real time updates of the network topology (Ybus) and another algorithm which carries out the coordination of overcurrent relays by an optimization method.

First, the system's data is updated according to elements and network changes. Then, the Ybus is constructed or modified from the obtained data using the Incident method and the inverse of Inspection method. Next, both lists of “Relay Names” and

“Coordination Pairs” are generated automatically. After that, the load flow analysis is run using the Newton Raphson or another method. Then, the Zbus is constructed or modified by the Block construction method and Partial Inversion Motto. Finally, fault analysis is run using Thevenin's method or Symmetrical Components [18].

Algorithm validation using academic or real network as testing system.

1.4 Hypothesis

The automatic and online re-setting of DOCRs according to the dynamic operations of the electrical system permits the reduction of fault extinction time (relay operation time), the increment of sensitivity, and the ability to tolerate another contingency.

1.5 Thesis Structure

This thesis is divided in five chapters. In chapter one, general introduction, preliminary ideas, hypothesis, objective, coordination problems and difficulties are presented in order to evaluate and sort out the problem.

Chapter two presents the general idea of Directional Overcurrent Relays (DOCRs), theoretical ideas of their fundamental requirements, direction of relays, the relay characteristic curves and effects of each relay parameter, steps of manual coordination of DOCRs, and description of the need of real time coordination. This is to get a closer view of the coordination problem so as to be able to focus on it.

Chapter three presents the coordination of DOCRs on a Real Time basis using optimization algorithms. The coordination problem is formulated as optimization problems using three algorithms: Genetic Algorithm (GA), Ant Colony Optimization (ACO) and Differential Evolution (DE). Basic ideas and detailed description of the algorithms are presented. Gaining knowledge about optimization is very necessary because the most suitable algorithm will be chosen to work hand in hand with the Real Time algorithm.

Chapter four presents the implementation of three algorithms in different cases using the IEEE 14 bus test system. Their speed, result quality, robustness and convergence are evaluated, compared and documented. The outstanding algorithm was chosen and implemented in the IEEE 30 bus test system where the idea of Real Time Coordination is carried out to see whether the hypothesis is correct or wrong.

Chapter five presents the general conclusion of the developed work, highlighted experiences, principal contributions of this thesis, and a list of recommendations for future work.

CHAPTER 2 DIRECTIONAL OVERCURRENT RELAY PROTECTION

2.1 Introduction

Lines are protected by overcurrent, distance, or pilot relays, depending on the requirements. Overcurrent relay is the simplest and cheapest, the most difficult to apply, and the quickest to need readjustment or even replacement as a system changes. It is generally used for phase and ground fault protection on station service and distribution circuits in electric utility and in industrial systems, and on some sub-transmission lines where the cost of distance relay cannot be justified. It is also used for primary ground fault protection on most transmission lines where distance relays are used for phase faults, and for ground backup protection on most lines having pilot relaying for primary protection.

It is generally the practice to use a set of two or three overcurrent relays for protection against inter-phase faults and a separate overcurrent relay for single phase to ground faults. Separate ground relays are generally favored because they can be adjusted to provide faster and more sensitive protection for single phase to ground faults than the phase relays can provide. However, the phase relays alone are sometimes relied on for protection against all types of faults. On the other hand, the phase relays must sometimes be made to be inoperative on the zero phase sequence component of ground fault current.

Overcurrent relay is well suited to distribution system protection for several reasons. Not only is overcurrent relay basically simple and inexpensive but also these advantages are realized in the greatest degree in many distribution circuits.

In electric utility distribution circuit protection, the greatest advantage can be taken of the inverse time characteristic because the fault current magnitude depends mostly on the fault location and is practically unaffected by changes in generation or in the high voltage transmission system. Not only may relays with extremely inverse curves be used for this reason but also such relays provide the best selectivity with fuses and reclosers. However, if ground fault current magnitude is severely limited by neutral grounding impedance, as is often true in industrial circuits, there is little or no advantage to be gained from the inverse characteristic of a ground relay.

2.2 Objectives of Protection Schemes

The fundamental objective of system protection is to isolate a problem area in the power system as soon as possible, so that the impact to the rest of the system is minimized and as much as possible is left intact. There are four basic requirements of a protective relay that one shall take into account: sensitivity, selectivity, reliability and speed. Other factors such as simplicity and economic may be taken into account as well. In this case, the directional overcurrent relay should satisfy all or most of the four basic requirements.

2.2.1 Sensitivity

Sensitivity is the capability of a relay to respond to a minimum fault in the adjacent zone. A relay can reduce its sensitivity due to two cases, fault current location in the vertical asymptotic region or fault current is too close to pickup current. For the first case, one shall bear in mind that there are two asymptotic regions in the relay characteristic curve. The first asymptotic region is vertical, in which operation time is increased exponentially for any fault that occurs in this region, and the second asymptotic region is horizontal, in which operation time is minimum and constant for any fault that occurs in this region. So if a fault is located nearby or in the vertical asymptotic region its sensitivity reduces or losses. For the second case, as fault current tends to be equal to pickup current or vice versa, the operation time increases. Hence sensitivity is reduced or even lost.

2.2.2 Selectivity

Selectivity, which is also known as relay coordination, is the process in which the settings of the relays allow the relays to operate as fast as possible for faults within their primary zone, but have delayed operation in their backup zone. Consequently, selectivity or relay coordination is important to assure maximum service continuity with minimum system disconnection.

2.2.3 Reliability

Reliability has two important aspects, dependability and security. Dependability is defined as "the degree of certainty that a relay or relay system will operate correctly" (IEEE C 37.2). Security "relates to the degree of certainty that a relay or relay system will not operate incorrectly" (IEEE C37.2). In other words, dependability indicates the ability of the protection system to perform correctly when required, whereas security is its ability to avoid unnecessary operation during normal day-after-day operation, and faults and problems outside the designated zone of operation. Thus, the protection must be secure (not operate on tolerable transients), yet dependable (operate on intolerable transients and permanent faults) [12].

2.2.4 Speed

It is one of the objectives that the protection isolates the trouble zone as rapidly as possible. But even though a zero-time or very high speed protection is desirable, it may result in an increased number of undesired operations. As a broad generality, the faster the operation, the higher the probability of incorrect operation. So, a very small amount of time always remains as one of the best means of distinguishing between tolerable and intolerable transients.

2.2.5 Simplicity

A protective relay system should be as simple and straightforward as possible while still accomplishing its intended goals. For every added unit which may enhance the protection scheme should be considered very carefully whether it is or not a basic need of the protection requirements. Because each added unit provides a potential source of trouble and added maintenance, therefore, more probability of failure operations. An incorrect operation may cause a catastrophic problem in the power system.

2.2.6 Economic

As cost is always a major factor, it is fundamental to obtain the maximum protection for the minimum cost. The cost of a protection scheme is relatively high, but it should not be evaluated alone due to the primary equipments it is protecting and cost of an outage through an improper protection. So one shall not save the cost of a protection scheme since it might result to a larger expense which is to repair or replace primary equipments damages.

2.3 Directional Overcurrent Relay

The directional overcurrent relays (67) are designed to sense the actual operating conditions on an electrical circuit and trip circuit breakers when a fault is detected. Phase relationship of voltage and current are used to determine the direction to a fault [19]. The relay first discriminates whether the fault is located in front of or behind the relay. If the fault is located behind the relay, then no operation will take place. But if the fault is located in front of the relay, a comparison of fault magnitude and reference current will take place in order to make the decision whether to operate or not.

2.3.1 Indicator of Fault Locations

The exceeding of actual sensed current from the reference current (I_{pickup}) is called fault or short circuit current (I_{sc}). It is an indicator used to identify the fault location. But the fault current depends on the pre-fault voltage and Thevenin's impedance at the fault point (distance). The further the fault is located from the source the bigger the impedance between the fault and the source, therefore, the smaller the fault magnitude.

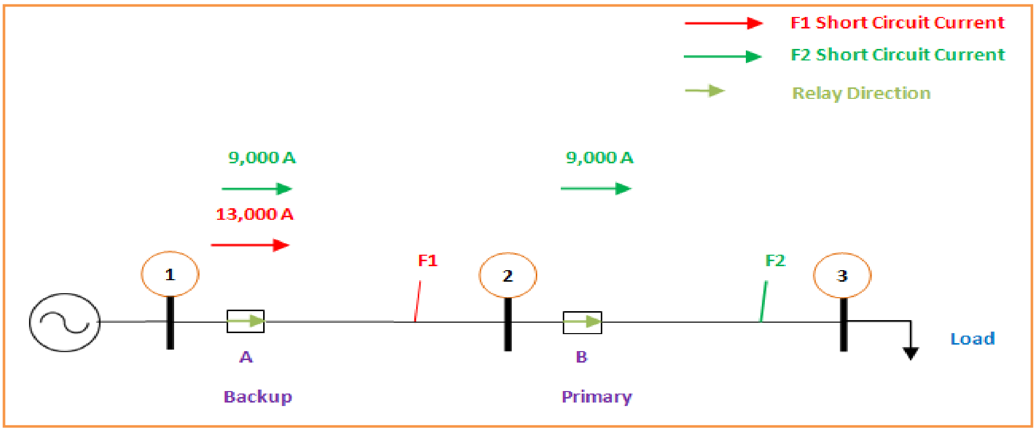


Figure 2.1: Indicator of fault locations: I_{sc}.

It is illustrated in Figure 2.1 that the fault **F1** which is located nearby bus 2 has a fault magnitude of 13,000 A while fault **F2** located nearby bus 3 has a fault magnitude of 9,000 A. The fault is an indicator that indirectly reveals the fault location depending on its magnitude. As pre-fault voltage drops away from 1 per unit, the smaller the fault magnitude becomes. Fault **F1** is greater than **F2** because it is closer to the source thus has smaller impedance from source to fault point than **F2**.

Figure 2.2 illustrates the idea that relays sense the same fault magnitude. Fault **F1** which is located immediately after bus 2 has a fault magnitude of 11,000 A while fault **F2** which is located nearby bus 3 has a fault magnitude of 9,000 A. Both relay A and B see the same fault magnitude for faults **F1** and **F2**. This is very important, as this concept is latterly used in coordination of overcurrent relays in a radial system. Keep in mind that there are occasions when the primary and backup relays sense different fault magnitudes. This is due to infeed effect and will be presented afterwards.

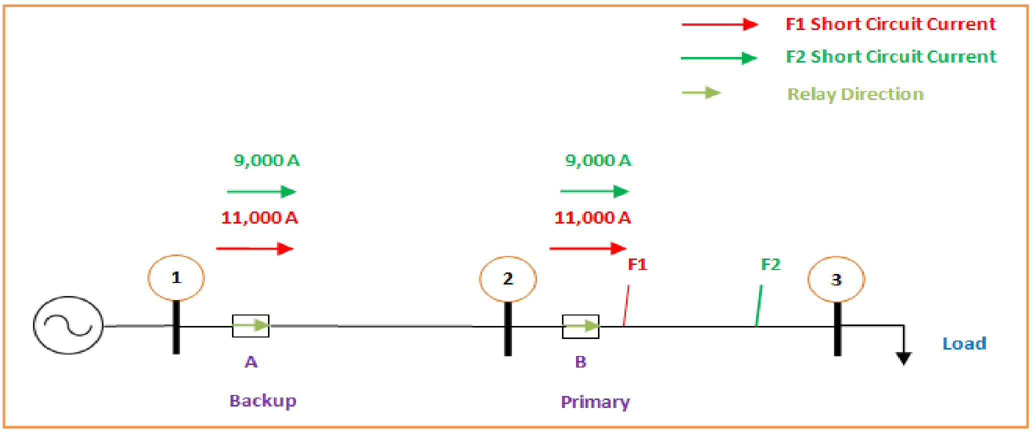


Figure 2.2: Relays and I_{sc}.

Note that faults **F1** and **F2** in Figure 2.1 and Figure 2.2 are not simultaneous and the relays used are non-directional due to the reason that they are in a radial system.

2.3.2 Direction of Relays

The directional overcurrent relays will only operate for events "in front of" them and do not operate for events "behind" them. They are used in mesh systems in order to discriminate the fault location. On the contrary, non-directional overcurrent relays are commonly used in radial systems.

When the current is not in the direction of the relay it will not be seen, thus no operation will ever take place. The Figure 2.3 illustrates that relays A and D sense the load flow current while relays B and C do not because they are in opposite direction of the load flow current. If by any means, there was a fault located between relays C and D; relays A, C and D will see the fault and relay B won't because the fault is located behind B. Similarly, if there was a fault located between relays A and B, relays A, B and D will see the fault and relay C won't because the fault is located behind C.

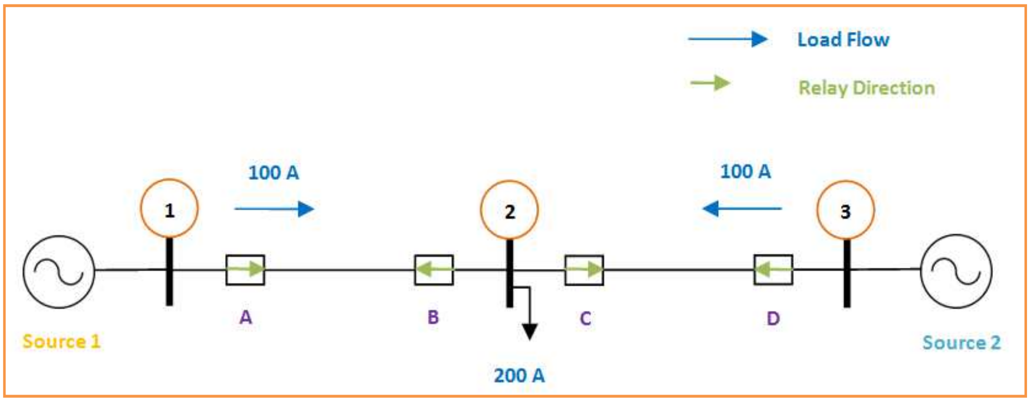


Figure 2.3: Direction of Relays.

2.3.3 Primary and Backup Relays

The directional overcurrent relay is a relative selectivity protection, in other words, these relays can be coordinated, and they can function as primary (principal) and also as secondary (backup) protection as desired. A primary relay is the protection that should operate with minimum time to extinct a fault. Meanwhile a backup relay is the protection that will operate with a pre-specified time delay to extinct a fault when the primary relay fails.

For fault **F1** illustrated in Figure 2.4, relay C functions as primary while relay A functions as backup for relay C, they both see the fault contribution of source 1. On the other hand, relay D functions as primary for the fault contribution of source 2. Note that relay B does not see the fault due to the reason that the fault is situated behind relay B.

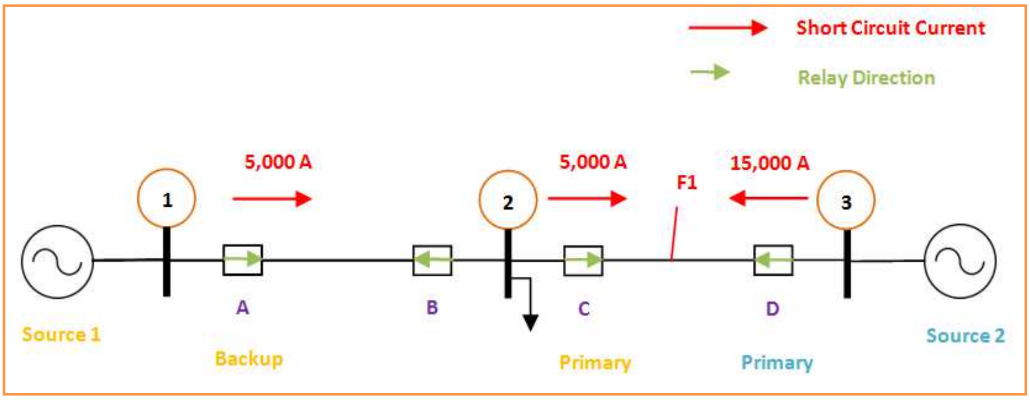


Figure 2.4: Primary and backup relays.

For fault **F2** illustrated in Figure 2.5, relay B functions as primary while relay D functions as backup for relay B, they both see the fault contribution of source 2. On the other hand, relay A functions as primary for the fault contribution of source 1. Note that relay C does not see the fault due to the reason that the fault is situated behind relay C.

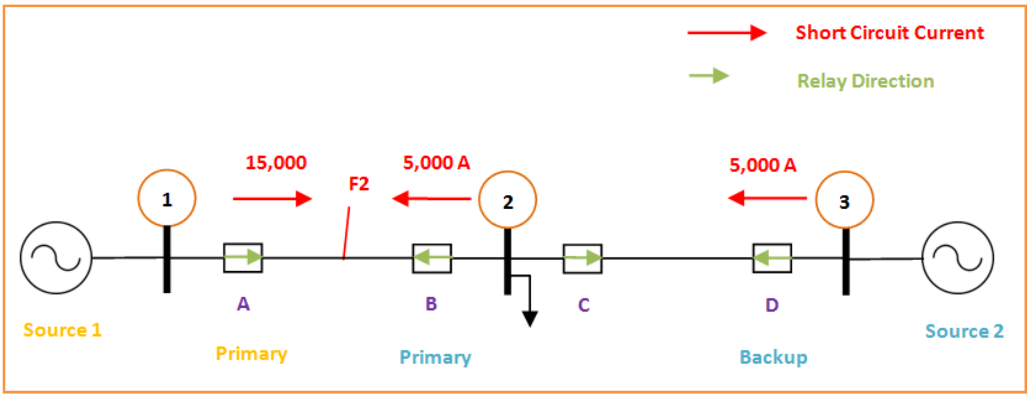


Figure 2.5: Primary and backup of relays.

2.3.4 Relay Characteristic Curve

The relays function accordingly to the relay characteristic curve (inverse time curve). This so called inverse time curve operates with less time as fault magnitude raises and more time as fault magnitude drops. It is given in equation (2.1) IEEE standard norm C37.112-1996.

$$t = \left[\frac{A}{\left(\frac{I_{sc^{3\emptyset}_{max}}}{I_{pickup}}\right)^{n} - 1} + B \right] * dial \qquad (2.1)$$

where:

$$t = relay\ operation\ time$$

$$I_{sc^{3\emptyset}_{max}} = maximum\ three\ phase\ short\ circuit\ current$$

$$I_{pickup} = relay\ pickup\ reference,$$

$$A, B, n = constants\ of\ IEEE\ standard$$

$$dial = time\ dial$$

$I_{sc^{3\emptyset}_{max}}$ is the maximum three phase short circuit current that the relay sees.

I_{pickup} is the relay pickup reference current. It is normally between 1.4 to 2 times load current I_{load}.

$dial$ is the factor that moves the characteristic curve on the vertical axis to a desired time and current conserving the same inversion grade.

The dial represents the journey of the disk (integral of the velocity with respect to time) in electromagnetic relays. It is also known as TDS time-dial setting or TMS time-multiplier setting in different literatures.

For the relay to operate, the fault current (I_{sc}) must be greater than the reference current (I_{pickup}). In other words, the operation time is positive as in equation (2.1). While fault current tends to be equal or very close to reference current the operation time increases. On the contrary, the relay will not operate if the fault current (I_{sc}) is smaller than the reference current (I_{pickup}). In other words the operation time is negative as in equation (2.1).

The IEEE constants of the overcurrent relays are shown in Table 2.1. These are the conventional curves: moderate inverse (MI), very inverse (VI) and extremely inverse (EI).

Norm	Curve Type	A	B	n
IEEE	Moderate Inverse	0.0515	0.114	0.02
	Very Inverse	19.61	0.491	2
	Extremely Inverse	28.2	0.1267	2

Table 2.1: IEEE standard constants.

2.3.4.1 Effects of Relay Parameters

The effect of each parameter of equation (2.1) is presented in Figure 2.6:

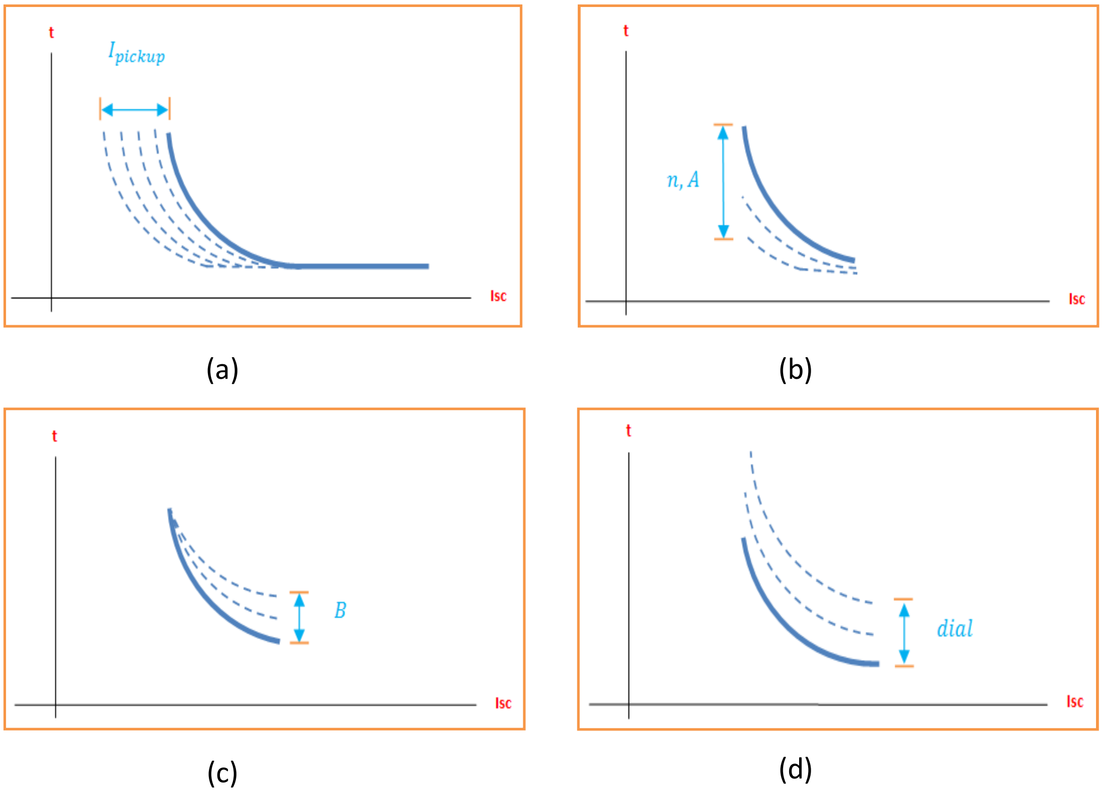


Figure 2.6: Effect of parameters I_{pickup}, A, B, n and $dial.$

The variation of I_{pickup} affects the time-current curve by moving the curve left or right as shown in Figure 2.6 (a). The variation of n, A affect the curvature of the head of the time-current curve as shown in Figure 2.6 (b). The variation of B affects the tail of the time-current curve as shown in Figure 2.6 (c). The $dial$ affects the time-current curve by moving the curve up or down as shown in Figure 2.6 (d). The different curves resulted by different dials are the curve family.

2.4 Coordination of Directional Overcurrent Relays

"Coordination" can also be known as "selective setting". When the directional overcurrent relays (DOCRs) are implemented on the lines they can offer protection to adjacent lines, buses, transformers, motors etc. The overcurrent relays' settings must ensure that the primary protection has enough time to clear the fault in its protected zone before the backup comes in. A backup device that should not trip "selects" with the downstream device that is close to the fault. The downstream device that is closer to the fault and should trip "coordinates" with the backup device that should not trip. Coordination on feeders or radial lines is the same, except that it moves only in one direction: from the power source to the loads [12]. The idea of coordination of DOCRs in radial system is illustrated in Figure 2.7.

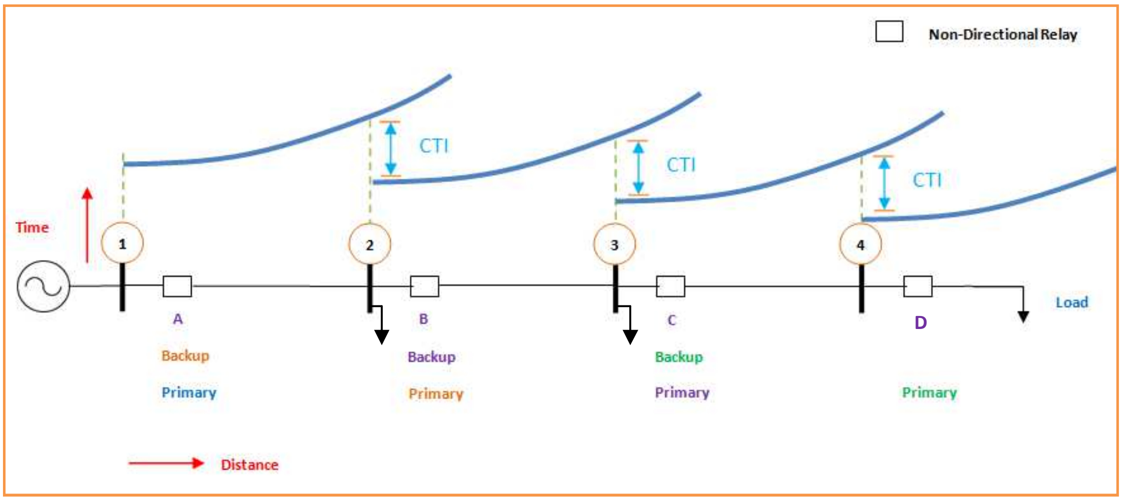


Figure 2.7: Coordination of DOCRs in a radial system.

Coordination a mesh system will be explained using Figure 2.8. Relays R12, R23 and R31 are in clockwise direction. R12 offers backup for R23, R23 offers backup for R31 and R31 offers backup for R12. By doing so the clockwise coordination circle is closed. Meanwhile relays R21, R13 and R32 are in anticlockwise direction. R21 offers backup for R13, R13 offers backup for R32 and R32 offers backup for R21. Then the anticlockwise coordination circle is closed too. Note that each relay functions as primary for faults in its own zone and backup for adjacent zone.

For convenience, the relay names are no longer named with alphabets A, B, C, D as in a radial system but by location of each relay. This is due to the reason that a ring fed system can consist of hundreds of relays, so it will be very advantageous if each relay revels its location in the network. For example, R12 represents relay connected near bus 1 facing bus 2. Similarly, R21 represents relay connected near bus 2 facing bus 1, and so on.

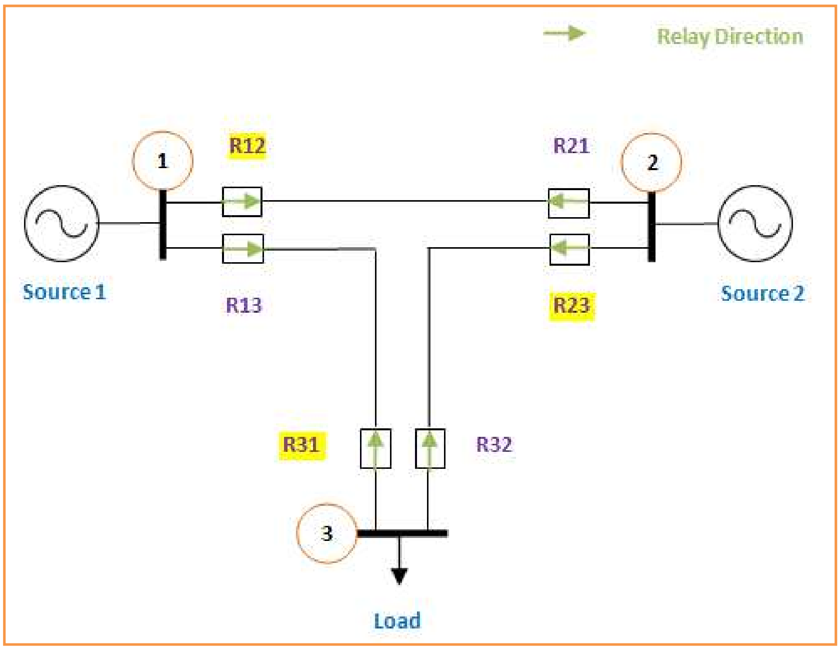


Figure 2.8: Coordination of DOCRs in a ring fed system.

The idea is ***"to set the protection to operate as fast as possible for faults in its primary zone, and yet delay sufficiently for faults in its backup zones"*** [12].

Or ***"the process to decide the sequence of the relay operations for each possible fault location and to provide sufficient coordination margins without excessive time***

delay, taking into account the desired protection qualities of selectivity, reliability, sensitivity, and speed".

In a radial system it is recommended to start the coordination from the relay nearest to the load toward the source. On the other hand, there is no such recommendation in a mesh system but arbitrary choose a start point and coordinate the relays. This might result to a bad coordination at the moment closing the mesh system, meaning the last relay which must be coordinated with the first relay that was chosen as start point do not satisfy the coordination idea. In other words, the first relay that was chosen as the start point fails to offer backup for the last relay that was to be coordinated with at the moment of closing the ring fed system. This is very common scenery, so if it happens one must start the coordination all over again from selecting a new start point. As a result, optimization algorithms were implemented to avoid the repetitive and extreme time consumption of coordinating a mesh system. This will be discussed in detail in chapter 3.

2.4.1 Procedure of Manual Coordination

The procedure of manual coordination is presented as followed:

1. Select one of the IEEE conventional curves

Choose one of the following: moderate inverse (MI), very inverse (VI) or extremely inverse (EI). By doing so you will have the constants A, B and n. Other types of curves published by different standards or manufactures may be chosen as well.

2. Propose a dial for the first primary relay

$$dial_{primary} = 0.5$$

It is recommended to start with a small or the smallest dial available of the relay so that the other relays that come after will not have a big operation time.

3. Calculate operation time of primary relay

$$t_{primary} = \left[\frac{A}{\left(\frac{I_{sc3\emptyset_{max\ primary}}}{I_{pickup_{primary}}} \right)^{n} - 1} + B \right] * dial_{primary} \tag{2.2}$$

The three-phase fault current, pickup current and dial of the primary relay will be used in this calculation.

4. Calculate operation time of backup relay

$$t_{backup} = t_{primary} + CTI \tag{2.3}$$

Calculate the backup time by adding a desired and pre-specified CTI to the primary time. The CTI is a pre-specified time called "Coordination Time Interval". It is a controlled time delay of each coordination pair. In that way, whenever the primary relay fails to extinct the fault the backup relay enters and tries to extinct the fault after the pre-specified delay. This CTI is the time summation of breaker operation, over journey of the electro-mechanic relay's disk and a security factor. It is normally between 0.2 and 0.5 seconds, but 0.3 seconds is mostly used. In digital relays, the CTI normally lies between 0.2 and 0.3 seconds.

5. Calculate dial of backup relay

$$dial_{backup} = \frac{t_{backup}}{\left[\frac{A}{\left(\frac{I_{sc^{3\emptyset}_{max\ backup}}}{I_{pickup_{backup}}}\right)^{n} - 1} + B\right]} \tag{2.4}$$

The three-phase fault current, pickup current and dial of the backup relay will be used in this calculation.

Steps 3, 4 and 5 are repeated continuously until the coordination task is accomplished while steps 1 and 2 are performed only once at the beginning.

Note that in a radial system with only one source both primary and backup relays sense the same three-phase fault current ($I_{sc^{3\emptyset}_{max\ primary}} = I_{sc^{3\emptyset}_{max\ backup}}$). But in a mesh system where there are many sources located at different geographic points, the three-phase fault current that the backup sense is sometimes much more smaller than what the primary see ($I_{sc^{3\emptyset}_{max\ primary}} \neq I_{sc^{3\emptyset}_{max\ backup}}$). This is called the infeed effect and can often cause mal-coordination (loss of coordination). Hence the reason why it is necessary to specify which three-phase fault current it is in the equations above. The three-phase fault current of the backup relay is called "coordination current". This coordination current is defined as the maximum current that the coordination pair can see.

It is recommended to use the same curve type throughout the coordination process so as to avoid the intersection of time-current curves which might lead to coordination loss. But by using the same curve type throughout the whole coordination process does not guarantee that there will be no loss of coordination, therefore, it is justified to use different types of curves throughout the process as one wish to, due to the reason that they might give better results.

2.5 The Need of Real Time Coordination of Directional Overcurrent Relays

The sub-transmission and distribution systems are the most dynamic part of the power system. The protections directly suffer the consequences of the following changes:

Dynamic changes	Consequences (Variation)
Input/output of generators	[Ipickup, Isc]
Input/output of distribution lines	[Ipickup, Isc]
Input/output of loads	[Ipickup]
Increase/decrease of generation	[Ipickup, Isc]
Increase/decrease of load demand	[Ipickup, Isc]

Table 2.2: Consequences affecting DOCRs' settings.

As presented in Table 2.2, the distribution system suffers constant changes. Here are some possible cases that can cause coordination problems to the system:

2.5.1 Effect of Input/output of Generators.

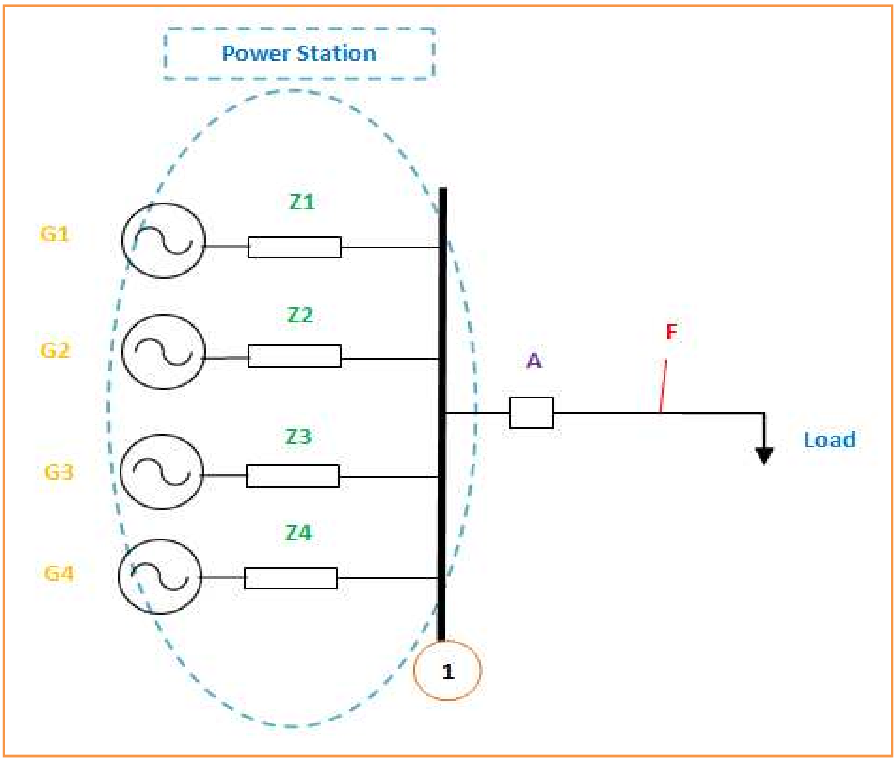


Figure 2.9: Effect input/output of Generators.

Figure 2.9 illustrates the effect of system's I_{sc} variation when sources input/output to/from the system. Note that the generators' resistances were neglected. This example illustrates the idea with generators of the same capacity for easier comprehension. But generators of different capacity follow the same logic.

Suppose the load consumes 500 A constantly and that all four generators above are of the same capacity (MVA), then all of them will have the same impedance. $Z_1 = Z_2 = Z_3 = Z_4 or X'd_1 = X'd_2 = X'd_3 = X'd_4$ so each generator will contribute the same amount of I_{sc}.

Now suppose that each generator contributes 1,000 A I_{sc}. Then for a fault at point **F** relay A will see $I_{sc1} = 4{,}000\ A$, contribution of all four generators. This big I_{sc1} is due to: $Z_{thnode1} = X'd_{eq} = \frac{1}{\frac{1}{X'd_1}+\frac{1}{X'd_2}+\frac{1}{X'd_3}+\frac{1}{X'd_4}} = \frac{X'd_1}{4}$.

Now if G3 and G4 are out of service for maintenance then for a fault at point **F** relay A will only sense $I_{sc2} = 2{,}000\ A$, contribution of only G1 and G2. This I_{sc2} which is smaller than I_{sc1} is due to bigger Z_{th} on node one: $Z_{thnode1} = X'd_{eq} = \frac{1}{\frac{1}{X'd_1}+\frac{1}{X'd_2}} = \frac{X'd_1}{2}$.

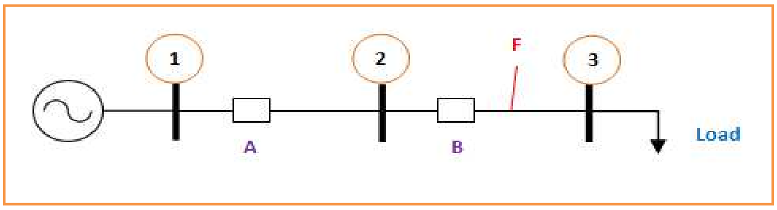
So if relay A's setting (dial) remained the same as if all generators were in service $I_{sc} = I_{sc1}$, then it will operate with more time delay when the fault occurs at point **F** with $I_{sc} = I_{sc2}$ when the actual system is operating with G3 and G4 out of service. This is because $I_{sc2} < I_{sc1}$ && I_{sc2} is closer to I_{pickup} than I_{sc1}.

Note: the more a I_{sc} is located to the left of the relay characteristic curve the more time delay it has (proof by observing the relay curve). The closer a I_{sc} is to I_{pickup} the more time delay (less sensitive) there will be for the relay to operate (proof by calculating the IEEE relay formula).

For the case that the load current of relay A is 2,500 A instead of 500 A. Then for the example illustrated above, the relay A will simply not function because $I_{pickup} > I_{sc2}$. So relay A will never operate.

With Real Time Coordination, the above can be avoided. The relay will get its latest setting according to the latest change of system's power plant. Being that there is a change source's Z_{th} and consequently a change of I_{sc}.

(a)



(b)

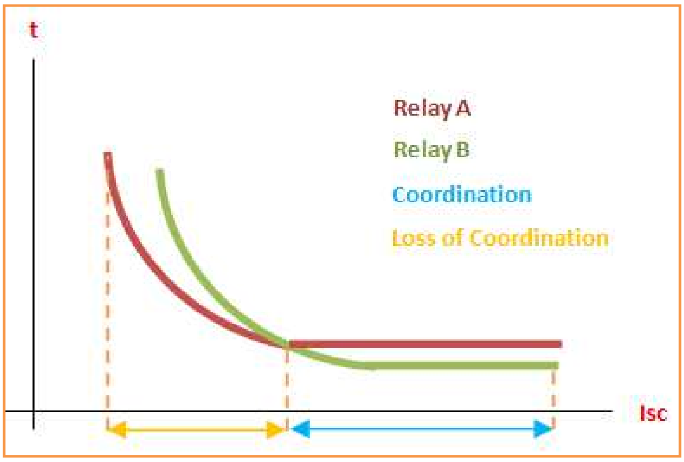


Figure 2.10: Effect input/output of Generators.

Figure 2.10 illustrates the effect of system's I_{sc} variation when sources input/output to/from the system. When we coordinate two relays based on a point ($I_{sc^{3\emptyset}{}_{max}}$) with a specified CTI, it surely guarantee the coordination of both relays nearby this point. But as further the fault is located from the coordination point ($I_{sc^{3\emptyset}{}_{max}}$), the lesser the coordination of this pair of relays is guaranteed. In other words there is possibility of coordination loss on the left hand side of the curves if there is an intersection. This can be observed in the Figure 2.10 (b). By using relay B as reference, the blue arrow indicates a good coordination for faults within its zone while the yellow arrow indicates loss of coordination for faults with minor magnitude.

Faults of minor magnitude are more often to occur than $I_{sc^{3\emptyset}{}_{max}}$ such as: $I_{sc^{1\emptyset}}, I_{sc^{2\emptyset}}$ etc so it increases the probability of false operation of the relays (loss of coordination) if we use a fixed setting for the relays.

Note that with Real Time Coordination, the relays will always have the fastest time settings for the latest system's topology and load flow. Hence, the relays will operate faster with better sensitivity and selectivity which consequently increases the voltage quality. While minimizing the I_{sc} duration the better the power quality becomes.

Thus the real time coordination of overcurrent relays must be done in order to fulfill the requirements. An optimization algorithm must be developed to facilitate and improve the process of real time coordination.

2.5.2 Effect of Input/output of Distribution Lines.

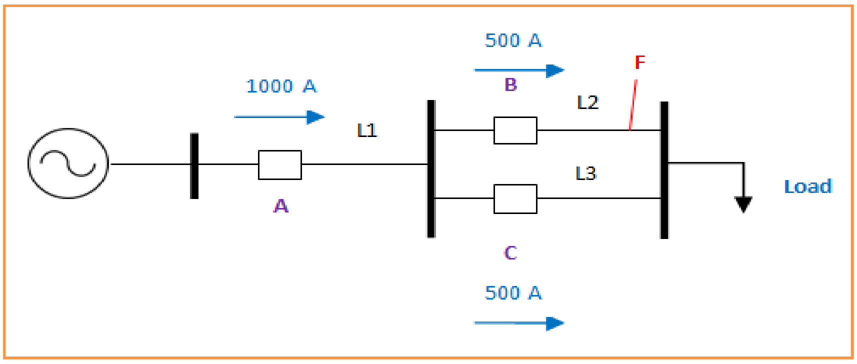


Figure 2.11: Effect of input/output of Distribution Line.

Figure 2.11 illustrates the effect of system's I_{pickup} variation when L_3 is frequently out of service. The I_{sc} doesn't affect in this study because the fault at piont **F** has almost the same magnitude with or without L_3.

If L_2 and L_3 have the same impedance then they'll have the same I_{load} flow; if any of them has more impedance than the other, then the 1,000 A of I_{load} will be distributed more passing the line with smaller impedance and less passing the line with bigger impedance.

Suppose that in this case $Z_{L_2} = Z_{L_3}$ so $I_{load_{L_2}} = I_{load_{L_3}}$ which are 500 A and 500 A. Then:

$$I_{pickup_B} = k * I_{load_B} = (1.5)(500A) = 750\ A$$

$$I_{pickup_C} = k * I_{load_C} = (1.5)(500A) = 750\ A$$

Now, if both L_2 and L_3 are in service most of the time then the established I_{pickup_B} and I_{pickup_C} have no problem, but if one of them is out of service frequently, then the other relay must take the value of I_{pickup_A} because the line left in service will have the same amount of load flow as L_1.

If L_3 is frequently out, then:

$$I_{pickup_B} = k * I_{load_B} = (1.5)(1{,}000A) = 1{,}500\ A$$

If the above is not taken into account, then whenever L_3 is out of service, relay B will operate even when there is no fault occurrence. Because L_2 will have a load flow of 1,000 A, in other words relay B will see 1,000A. So $I_{load_{L_2}} = 1{,}000\ A > I_{pickup_B} = 750\ A$.

So this will make relay B operate even though it is just a n-1 contingency, loss of a line which leads to an increment of load flow on the other line.

But now if we set $I_{pickup_B} = 1{,}500\ A$ due to the reason that L_3 is frequently out of service, the disadvantage will be when both L_2 and L_3 are in service and when a fault **F** occurs on L_2, relay B will respond to the fault with a greater time (become less sensitive due to a bigger I_{pickup_B}).

With Real Time Coordination, the above can be avoided. And all relays are going to be more sensitive because they will get the latest settings every time according to the latest change of the network topology.

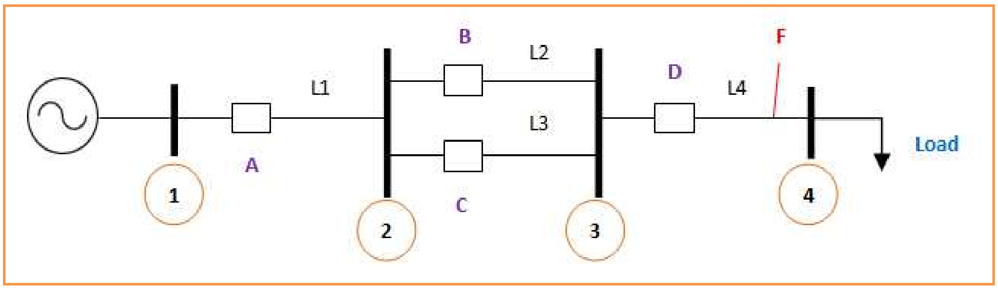


Figure 2.12: Effect of input/output of Distribution Line.

Figure 2.12 illustrates the effect of system's I_{pickup} variation when L_3 is suddenly out of service. Suppose that all lines are in service then the relays A, B, C, D are all coordinated according to the $I_{sc^{3\emptyset}}{}_{max}$ that each of them senses.

If L_3 is suddenly out of service and a fault occured at point **F** on L_4, then the relay D will be sensing less $I_{sc^{3\emptyset}}{}_{max}$ than it normally sees; because when both L_2 and L_3 are in service there's less line impedance between nodes 2 and 3, so $I_{sc^{3\emptyset}}{}_{max}$ was greater.

Under this circumstance the relay D will become slower to operate (less sensitive) or even loss of coordination (loss of relays' selectivity) because relay B might operate before relay D. This is because relay B will see almost the same $I_{sc^{3\emptyset}}{}_{max}$ with or without L_3, while relay D will suffer big change/reduction of $I_{sc^{3\emptyset}}{}_{max}$ when L_3 is out.

2.5.3 Effect of Increase/decrease of Load Demands.

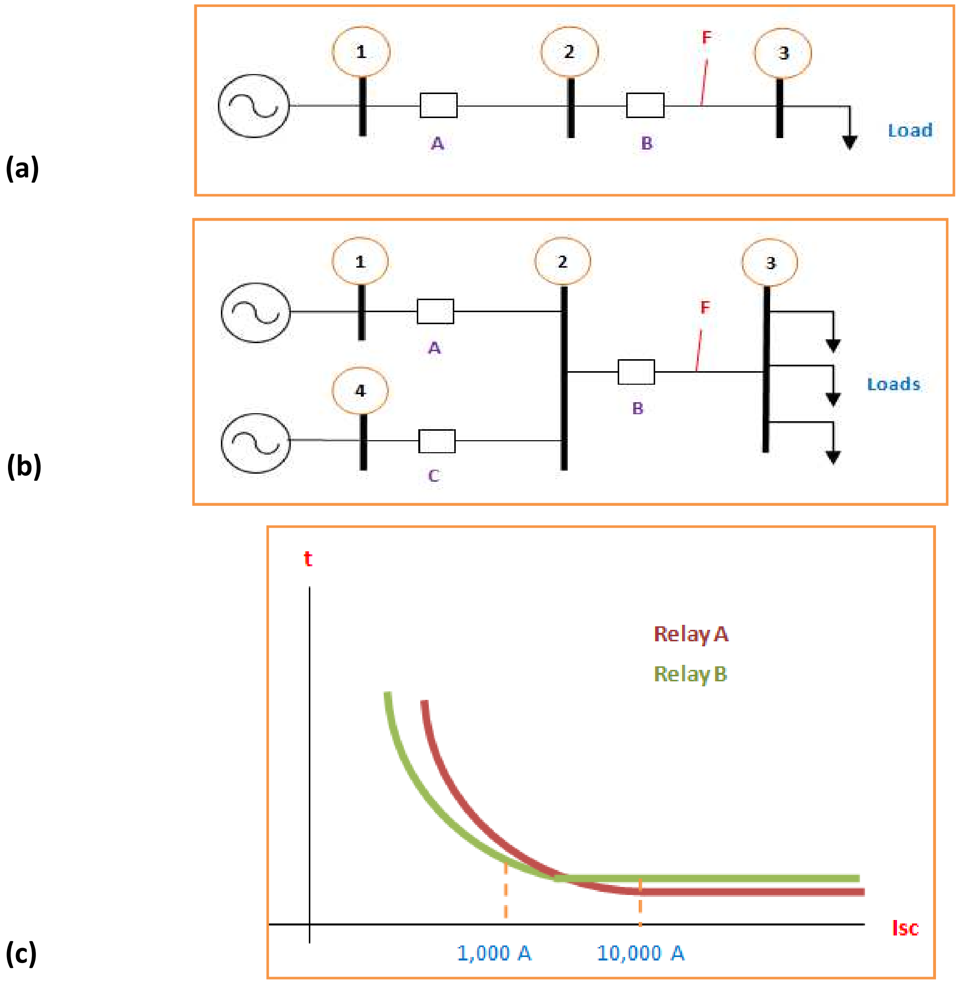


Figure 2.13: Effect of increase/decrease of Load Demands.

Figure 2.13 illustrates the effect of system's I_{sc} variation due to system's constant growing. More loads and sources.

The Figure 2.13 (a) illustrates a radial system that was constructed many years ago. Relays A and B were coordinated according to the fault at point **F**. $I_{sc3\emptyset_{max}} = 1{,}000\ A$. Relay A operates as backup for relay B.

Many years after, the simple radial system in Figure 2.13 (a) has now more loads and an additional equivalent source connected to node 2 as shown in Figure 2.13 (b).

This made the fault at the point **F** larger. $I_{sc^{3\emptyset}_{max}} = 10{,}000\,A$. If there were no intersection of curves then there'll be no problem because the effect of increment of $I_{sc^{3\emptyset}_{max}}$ will only accelerate the operation of relay B. But according to the example illustrated in the Figure 2.13 (c), the curves' tails of relays A and B did intersect. This means that there is a loss of coordination (loss of selectivity) so relay A will now operate before relay B. The false operation of relay A leads to no backup relay for relay B.

The use of different types of relay curves in coordination normally leads to intersection of curves. But bear in mind that the example above is to illustrate intersection of curves due to I_{sc} variation and not due to the use of different types of curves. Being that there is a change of I_{sc}.

2.6 Conclusion

Requirements such as sensitivity, selectivity, reliability, speed, simplicity and economic, that a DOCR need to fulfill are presented. The relay shall fulfill as many requirements as possible but due to the different network operations, DOCRs can never fulfill all at once.

Indicator of fault locations for relays, directions of relays, primary and backup of relays, relay characteristic curves and the effects of each parameter are presented. The short circuit current is of great importance for the DOCRs. If the short circuit current (Isc) is too small in certain area of the network, then relays located in that area become insensitive. Under this circumstance, other protection principles must be implemented to replace the absence of DOCRs. DOCRs are implemented in the distribution network in order to discriminate the fault location. If a relay shall offer backup for more than one relay, it can just coordinate with the slowest primary relay, because by doing so, all other primary relays will have backup as well.

Also some examples illustrating the need of real time coordination due to the dynamic operations of the network are presented.

CHAPTER 3 REAL TIME COORDINATION OF PROTECTIONS USING OPTIMIZATION ALGORITHMS

3.1 Introduction

One of the most fundamental principles in our world is the search for an optimal state. For example, biological principle of *survival of the fittest* [1940] which, together with the biological evolution, leads to better adaptation of the species to their environment. Here, a local optimum is a well-adapted species that dominates all other animals in its surroundings. Homo sapiens have reached this level, sharing it with ants, bacteria, flies, cockroaches, and all sorts of other creepy creatures.

As long as humankind exists, perfection is one of the objectives. People want to reach a maximum degree of happiness with least amount of effort. In the economy, profit and sales must be maximized and costs should be as low as possible. Therefore, optimization is one of the oldest of sciences which even extends into daily life.

Optimization is defined as ***"finding an alternative with the most cost effective or highest achievable performance under the given constraints, by maximizing desired factors and minimizing undesired ones"*** [23].

In other words, the goal is to ***find the values of controllable factors determining the behavior of a system (i.e. a production process, control of robots) that maximize productivity or minimize waste***.

Some problems have many solutions while some have only one solution when optimization algorithms are implemented. Thus for complicated problems which have many solutions, one must establish an objective function to evaluate the fitness value of the solution, whether the solution is a global or local best solution.

An **objective function** is ***an equation to be optimized given certain constraints and with controllable variables that need to be minimized or maximized.*** The objective function affects directly the quality of the optimization algorithm in getting a global or local solution. The *global best solution* is of course the most desirable solution because it's the setting that will make the process carry out its function to the maximum or minimum. But one must take the simulation time into account and thus satisfy with a *suitable solution*. Practice of optimization is restricted by the lack of full information and the lack of time to evaluate what information is available.

Nowadays coordination of overcurrent relays is a very important subject in different networks. On the contrary to other kinds of relays, fuses and reclosers, overcurrent relays coordination has been presented in many methods. As of such techniques are optimal coordination methods that have advantages as compared to common coordination techniques. The operation of relays in network is considered linear and symmetrical attribute of $dial$ [25]. Whereas that isn't like this and the attributes of $dial$ and I_{pickup} are unknown quantities. Thus the objective function converts this problem into a nonlinear problem.

It is a very time consuming task coordinating hundreds of directional overcurrent relays manually in a meshed distribution system. Besides, for online (real time) coordination a powerful and adequate optimization algorithm must be implemented.

3.2 Real Time Coordination of Protections

3.2.1 Introduction

The coordination of directional overcurrent relays is mostly studied based on fixed network topology in an interconnected mesh power system (IMPS), and is formulated as an optimization problem. In practice, the system is constantly operated in different topologies due to outage of distribution lines, transformers and generating units. There are some situations for which the changes in the network topology or element's operation could cause the protective system to operate without selectivity (loss of coordination). The objective of this thesis is to coordinate all the protections at every moment of element's operation change or network topology change. To accomplish this, real time algorithm must be developed and work hand in hand with the optimization algorithm.

The flow diagram of the coordination of overcurrent relays on a real time basis is shown in Figure 3.1:

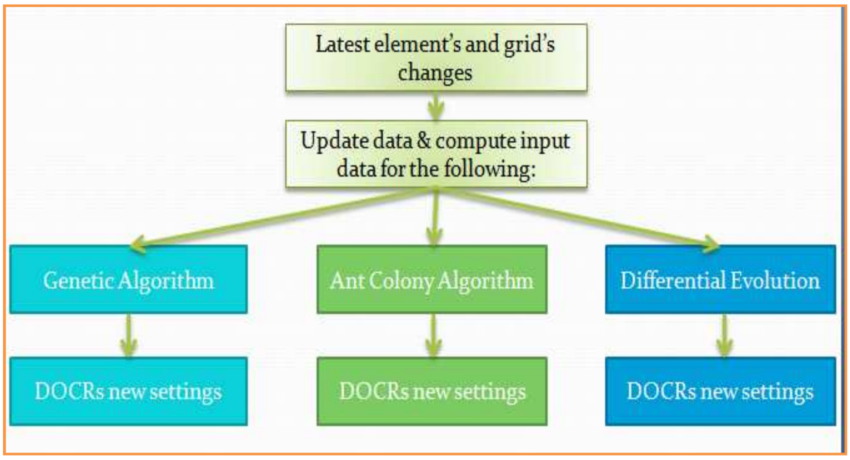


Figure 3.1: Flow Diagram of Real Time Coordination.

The real time algorithm is a very important segment of this thesis as was presented in Figure 3.1. This real time algorithm generates the input data for the optimization algorithms. The details will be presented in section 3.2.2.

3.2.2 Real Time Algorithm

The real time algorithm consists of collecting data of the latest elements and network changes, from which input data for posterior relay coordination are computed. The online update hardware system is assumed to have already been manufactured; the hardware requires only the installation of an appropriate real time algorithm.

The detailed description of the algorithm is as follows: first, the system's data is updated according to elements and network changes. Then, the Ybus is constructed or modified from the obtained data using the Incident method and the inverse of Inspection method. Next, both lists of “Relay Names” and “Coordination Pairs” are generated automatically. After that, the load flow analysis is run using the Newton Raphson or another method. Then, the Zbus is constructed or modified by the Block construction method and Partial Inversion Motto. Finally, fault analysis is run using Thevenin's method or Symmetrical Components [18]. When all of the above are done, the algorithm will have defined the coordination pairs and computed the maximum load currents and fault currents (3-ph principal, 3-ph backup, 2-ph backup, 1-ph) of each relay for the optimization algorithms of the original network topology. This is presented in Figure 3.2.

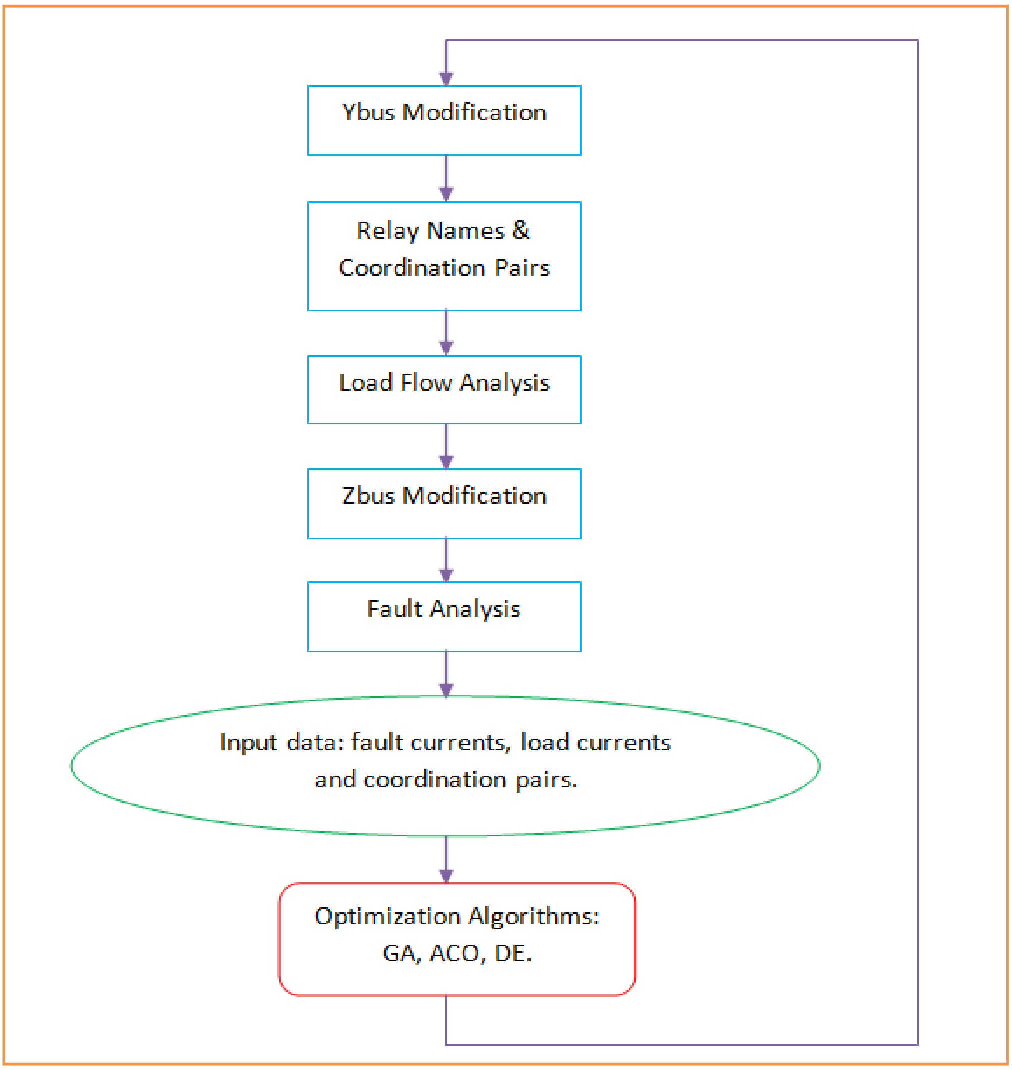


Figure 3.2: Detailed Flow Diagram of Real Time Coordination.

However, to ensure that relay settings obtained from the posterior coordination algorithm are suitable for at least one element output without coordination loss, the maximum load and fault currents must be computed according to the different *n*-1 contingency topologies. All elements are taken out one at a time and the simulation is carried out over and over again for the different *n*-1 contingency topologies. Only the maximum load and fault currents are stored as data for coordination use.

Finally, this algorithm performs a sensitivity filtration before passing the data to the optimization algorithms which coordinate the overcurrent relays. This step ensures that all coordination pairs can be coordinated. The coordination pairs that do not satisfy the requirement of sensitivity analysis will be omitted from the coordination process. In this way, the optimization algorithms will not spend extra time on trying to find settings for these insensitive pairs of relays, which have no settings that will suit them. The formula for sensitivity analysis is given in equation (3.1):

$$sensitivity = \frac{I_{sc^{2\emptyset}backup}}{k * I_{load}} \tag{3.1}$$

where $k = 1.4$, the smallest value within the range $[1.4, 1.6]$. So relays that do not fulfill sensitivity even using the minimum k will be filtered. Sensitivity is the ratio between relay's two-phase short circuit current and its pickup current. A good sensitivity should at least guarantee the two-phase short circuit current to be 1.5 times the pickup current. This is due to the reason that currents that are located nearby the vertical asymptotic region of the relay characteristic curve have large operation time, thus, taking pickup current as reference a fault that is located nearby or inside the vertical asymptotic region or located too near the pickup current will reduce its sensitivity, and in some cases loss of sensitivity.

3.3 Objective Function of the Optimization Algorithms

It is of great importance to establish the objective function that is going to evaluate the fitness of the settings, that is, the capability of a setting to meet requirements [24]. This objective function can be the sum of several objective functions. This objective function will directly impact the quality of result of the optimization algorithms (GA, ACO and DE). An indicator must give the information whether it is bad (not within satisfaction limit), good (within satisfaction limit) or ideal result of the settings so that they can be awarded or penalized before their evaluation in the objective function. This indicator in the case of coordination of relays is the time, CTI.

All the settings of each relay of the population must be evaluated first. This evaluation is to use equation 2.1 for both primary ($t_{primary}$) and backup (t_{backup}) relays. The only data that differs now is the short circuit current that primary and backup relays see. This procedure is different from the manual procedure presented in chapter 2, but even so, it has the same logic of CTI. Hence primary time will be subtracted from backup time to get real CTI as shown in equation (3.2).

$$CTI_{real} = t_{backup} - t_{primary} \tag{3.2}$$

This is the real CTI that the relays have and is also known as primary and backup relay constraint. Now subtract the pre-specified CTI from the real CTI and the indicator is obtained as shown in equation (3.3).

$$CTI_{indicator} = CTI_{real} - CTI_{pre-specified} \tag{3.3}$$

The CTI indicator as presented before indicates whether the settings are bad (not within satisfaction limit), good (within satisfaction limit) or ideal result so that they can be awarded or penalized before entering the objective function. Due to the subtraction of two CTI, the CTI indicator can also be known as CTI error. If the error is zero then the settings are ideal, which is very hard to get so most of the relays will not have these ideal settings. In this case no penalization should take place. If the error is positive then the settings are good or tolerable, they maintain the coordination but with a higher time delay than the pre-specified. It is recommended to penalize this a little bit so as to help it converge to zero error (meeting the pre-specified CTI). If the error is negative then there is a loss of coordination and must be penalized heavily in order to avoid this mal-coordination.

The limits of the relay settings are given in equations (3.4) and (3.5).

$$dial_{min} \leq dial \leq dial_{max} \tag{3.4}$$

$$I_{pickup_{min}} \leq I_{pickup} \leq I_{pickup_{max}} \tag{3.5}$$

where $dial$ is the relay dial setting found within its maximum $dial_{max}$ and minimum $dial_{min}$ range. And I_{pickup} is the relay pickup current found within its maximum $I_{pickup_{max}}$ and minimum $I_{pickup_{min}}$ range.

The objective function of this thesis is the sum of number of violations, sum of primary and backup time, and also the sum of number of coordinated pairs CTI error. This objective function is used in all of the three algorithms: Genetic Algorithm, Ant Colony Algorithm and Differential Evolution Algorithm. It is shown in equation (3.6).

$$fitness = \left(\frac{NV}{NCP}\right) + \left(\frac{\sum_{a=1}^{NCP} t_{principal_a}}{NCP}\right) * \alpha + \left(\frac{\sum_{b=1}^{NCP} t_{backup_b}}{NCP}\right) * \beta + \left(\sum_{L=1}^{NCP} E_{CTI_L}\right) * \delta \tag{3.6}$$

Where α, β and δ are factors that increase or decrease the influence of each sub-objective function and will do for any other system. NV is the number of violation of coordination constraints, NCP is the number of coordination pairs, $t_{principal_a}$is the primary operation time of relay *a*, t_{backup_b} is the backup operation time of relay *b*, and $E_{CTI_L}$is the CTI error of *L*-th coordination pair.

3.4 Coordination of Protections using Genetic Algorithm

3.4.1 Introduction

Genetic algorithms (GA) are a part of evolutionary computing; they are adaptive heuristic search algorithm based on evolutionary ideas of natural selection of genes.

The idea of evolutionary computing was introduced in the 1960s by I. Rechenberg in his work "Evolution Strategies". His idea was then developed by other researchers. Genetic Algorithms (GAs) were invented by John Holland and developed by him and his students and colleagues. He published "Adaption in Natural and Artificial Systems" in 1975.

3.4.2 Basic Description of Genetic Algorithm

All living organisms consist of cells. In each cell there is the same set of *chromosomes* (individuals). Each chromosome consists of *genes* or blocks of DNA. Each gene encodes a particular protein or trait (i.e. color of eyes) and has its own position in the chromosome. The chromosome contains a set of possible solution information. The chromosome can have genes of binary, integer, real or floating point elements.

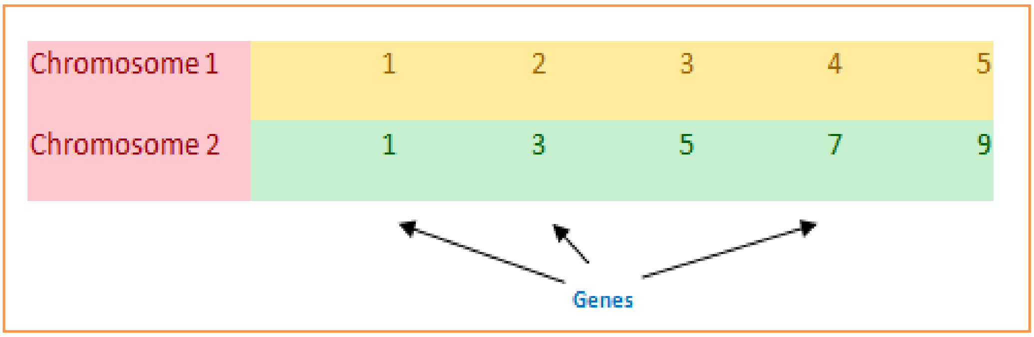


Figure 3.3: Chromosome.

Reproduction is a recombination (or crossover). Sons or new chromosomes are formed by the recombination of the genes of certain chromosomes called parents. Normally the chromosomes that have good fitness value will be chosen as parents, but keep in mind that one shall not reproduce by using only the best chromosomes because it will lead to a premature solution (local optimum).

A *mutation* is to change the DNA a little bit. These changes are mainly caused by errors in copying genes from parents and are normally in very small amount.

Search space is the space of all feasible solutions. Each point in the search space represents a feasible solution and each feasible solution can be marked by its fitness value for the problem. This feasible solution is then a maximum or a minimum.

The algorithm is started with many sets of solutions (chromosomes), together all the chromosomes form a population. Solutions from one population are taken and used to form a new population. This is motivated by hoping that the new population will be better than the old one. Solutions which are selected to form new solutions are selected according to their fitness; the more suitable they are the more chances they have to reproduce.

The whole process is repeated until some condition (reached the number of maximum iterations, improvement of the best solution) is met. This is called *stopping criteria.*

The population size indicates how many chromosomes are there in the population (in one generation). If there are too few chromosomes, the algorithm will have a few possibilities to perform crossover and only a small part of the search space is explored. On the other hand, if there are too many chromosomes, the algorithm will explore more variety of feasible solutions but the execution time is excessively increased.

3.4.3 Steps of Protection Coordination using Genetic Algorithm

1. Generate the initial population randomly of n chromosomes in which each gene is a possible solution to the problem.
2. Compute primary and backup time of each relay according to each chromosome.
3. Evaluate the fitness $f(x)$ of each chromosome x in the population.
4. Creating a new population in each iteration:
    a. Selection: select parent chromosomes from population according to their fitness by performing roulette wheel, rank and elitism.
    b. Reproduction: use a crossover probability to crossover the parents to form a new child or children. Perform non-uniform crossover.
    c. Mutation: use a mutation percentage to mutate the genes of the chromosomes. Perform non-uniform mutation at the first stages of the algorithm then perform intelligent mutation at the posterior stages.
    d. Position: place the results of reproduction, mutation (new children) and elitism in the new population.
5. Execute the algorithm again using the new population.
6. Terminate the algorithm if stopping criteria is met, if not, then continue all steps from 2 to 5.

3.4.4 Initial Population

Create a new population randomly with reasonable genes. That is to create a new population which all genes of all chromosomes are initialized somewhere in their feasible numerical range of the corresponding setting of overcurrent relay. Each row is an individual or chromosome and each column is a gene/variable/setting of a relay. The size of the population is $(NC, NV * NR)$ where NC represents number of chromosomes, NV number of control variables and NR number of relays. For example if a system has 10 relays with 1 degree of freedom $(dial)$, then the size of the population for 10 individuals will be (10,10). On the other hand, if a system has 10 relays with 2 degrees of freedom $(dial\ and\ k)$, then the size of the population for 10 individuals will be (10,20). But if a system has 10 relays with 3 degrees of freedom $(dial, k\ and\ A, B, n)$, then the size of the population for 10 individuals will be (10,50), and there will be a total of 300 genes or settings of relays. As more degrees of freedom are added to the population, the population size increases. Bear in mind that the discrete settings A, B, n are values taken from the IEEE standard in Table 2.1 and are considered all three together as 1 degree of freedom. This is because the three together form a different curve type and not one by one. The idea of population is shown in equation (3.7) below.

$$P=\begin{bmatrix} dial_{(1,1)} & \cdots & dial_{(1,NR)} & k_{(1,NR+1)} & \cdots & k_{(1,NR*2)} & A_{(1,NR*2+1)} & \cdots & A_{(1,NR*3)} & B_{(1,NR*3+1)} & \cdots & B_{(1,NR*4)} & n_{(1,NR*4+1)} & \cdots & n_{(1,NR*5)} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ dial_{(NC,1)} & \cdots & dial_{(NC,NR)} & k_{(NC,NR+1)} & \cdots & k_{(NC,NR*2)} & A_{(NC,NR*2+1)} & \cdots & A_{(NC,NR*3)} & B_{(NC,NR*3+1)} & \cdots & B_{(NC,NR*4)} & n_{(NC,NR*4+1)} & \cdots & n_{(NC,NR*5)} \end{bmatrix} \quad (3.7)$$

First create the population randomly with values between 0 and 1 then the equation (3.8) is applied as presented below in order to let the narrow the initial random population to be within its superior and inferior limits.

$$P(p, q) = limit_{lower} + \left(limit_{upper} - limit_{lower}\right) * P(p, q)_{random} \quad (3.8)$$

3.4.5 Selection

Chromosomes are selected from the population to be parents to crossover. It is of great importance the selection of parents. According to Darwin's evolution theory the best ones should survive and create new generation. There are many ways in selecting best chromosomes such as: roulette wheel selection, tournament selection, rank selection, steady state selection and some others. But only roulette wheel, rank and elitism selection will be presented because they were used in this thesis.

Roulette wheel selection: parents are selected according to their fitness. The better the chromosomes are, the more opportunity they have to be selected. Imagine a roulette wheel where all chromosomes of the population are placed. Each chromosome occupies its portion accordingly to its fitness value as illustrated in Figure 3.4. Chromosomes 1, 2, 3 and 4 have 5%, 15%, 20% and 60% respectively according to their fitness value.

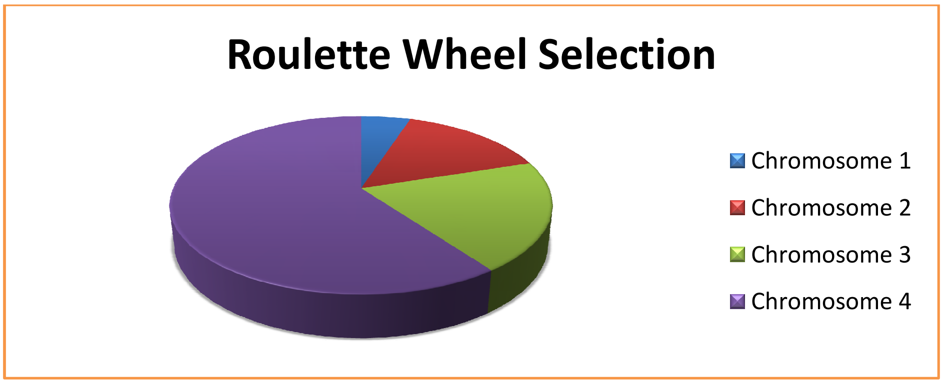
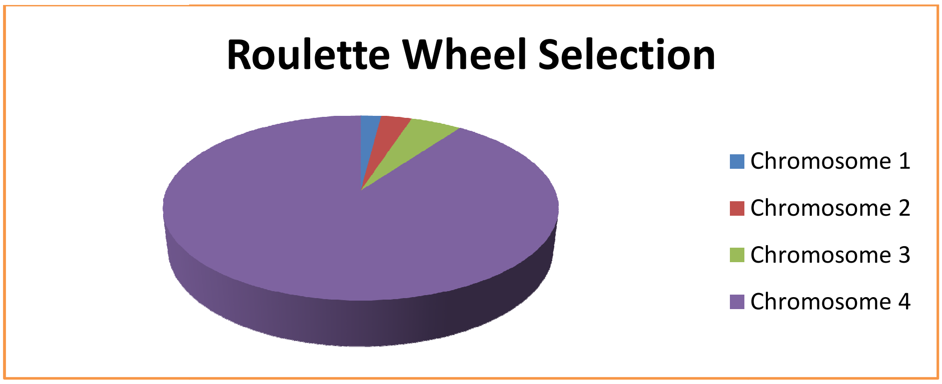


Figure 3.4: Roulette Wheel Selection.

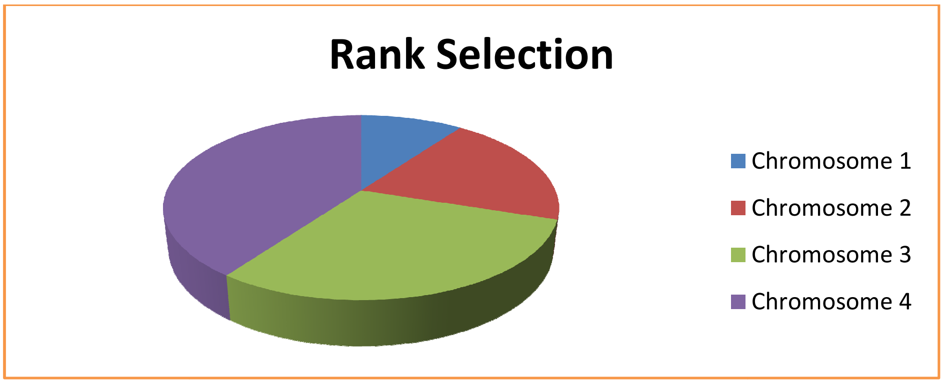
A marble is thrown there and selects the chromosome. Chromosome with bigger fitness will have more probability to be selected or to be selected more times. The problem comes when the fitness values differs very much. For example, if the fitness value of the best chromosome is 90% of the roulette wheel, then the other chromosomes will have very small probability to be selected. As mentioned before this cause premature solution (local optimum). This is performed in every iteration.

Steady-State Selection: the issue of this method is not the selection of parents. The idea of this selection is that a big part of chromosomes of the population should survive to the next generation. In every generation some good chromosomes (with high fitness) are chosen to crossover and create new chromosomes, while some bad chromosomes (with low fitness) are eliminated from the population. The rest of the untouched population survives to the next generation. In the thesis this idea was performed in each iteration but in a very little different way. The parents that are chosen in each iteration are the ones that survive to the next generation untouched.

Rank selection: this method first ranks each chromosome of the population according to their fitness value. Then a new fitness value will be assigned to each chromosome according to the ranking. The worst will have fitness value 1, the second worst 2 etc. and the best will have fitness N (number of chromosomes in population). Imagine that the fitness of the best chromosome is 90%, see the comparison of roulette wheel selection and rank selection probability difference in Figure 3.5 (a) and (b). Chromosomes 1, 2, 3 and 4 have 2%, 3%, 5% and 90% respectively according to their fitness value. When the chromosomes of the population are ranked, the new values assigned to each chromosome are 1, 2, 3 and 4 respectively.



(a)



(b)

Figure 3.5: Comparison of Roulette Wheel and Rank Selection.

It can be seemed that the rank selection redistributed the selection area in such way that solution will not fall into a local optimum as easily as using roulette wheel selection. The disadvantage is that it will slow down the convergence because the best chromosome does not differ a lot from the other ones. This is performed in each iteration.

Elitism: the elitism method first copies the best chromosome or some of the best to the new population, and leaves them there untouched. Then it follows the same reproduction and mutation process. Elitism can increase the performance of the algorithm because it prevents losing the best found solution. In this thesis elitism is performed every time after reaching a pre-specified iteration such as 200, 240, 260, 280, 300 etc. The global best chromosome data was accessed and placed in all rows, making the whole population start searching at the same start point. The advantage of doing so is to speed up the searching process by searching for another optimum result at a desired start point. The disadvantage is that the posterior results might be a local optimum. This was done due to the reason that the algorithm can keep searching until the maximum iteration has reached and still doesn't find a good result. So by forcing the algorithm to start searching at a specific point, the number of maximum iteration can be reduced because it was observed that the result converged after certain iteration.

3.4.6 Reproduction

Crossover is made in hope that new chromosomes will have good parts of old chromosomes and maybe the new chromosomes will be even better. However it is good to leave some part of population survive to the next generation. Crossover selects genes from parent chromosomes and creates new children. The simplest way is to choose randomly one or some crossover point(s), and everything before this point is a copy of the first parent and then everything after the crossover point is a copy of the second parent, as shown in Figure 3.6.

Crossover point

Parent 1	1	2	3	4	5
Parent 2	1	3	5	7	9
Child 1	1	2	5	7	9
Child 2	1	3	3	4	5

Figure 3.6: Reproduction.

There are many ways doing crossover, for example more crossover points could have been chosen. Specific crossover made for specific problem can improve the performance of the genetic algorithm. In this thesis non-uniform crossover was performed. A random vector of values is generated in each iteration to represent the location of first copy of genes from parents, then the rest of the values are computed using simple arithmetic recombination, which is actually an average of genes of the parents [12]. The idea is illustrated in Figure 3.7.

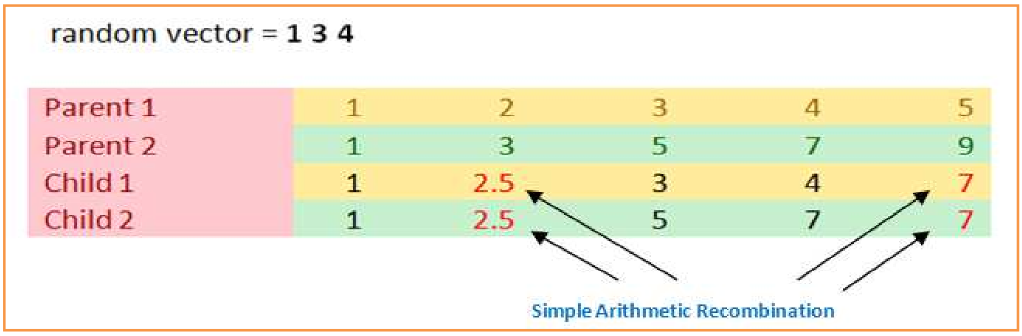


Figure 3.7: Reproduction. Simple Arithmetic Recombination.

Note that the reproduction is performed only for $dial$ and I_{pickup}. The 3rd degree of freedom which is the different kinds of curves cannot be reproduced due to the reason that they are discrete values, but they are mutated discretely.

3.4.7 Mutation

Mutation changes randomly the genes of the population in small quantity. This is to prevent falling all solutions in a local optimum. Be aware that each gene is a setting of the optimization one wish to solve, so the mutation of the genes should be in such a way that the mutated value does not exceed the superior or inferior limit of the setting. This should not occur very often, because then the algorithm will in fact change to random search.

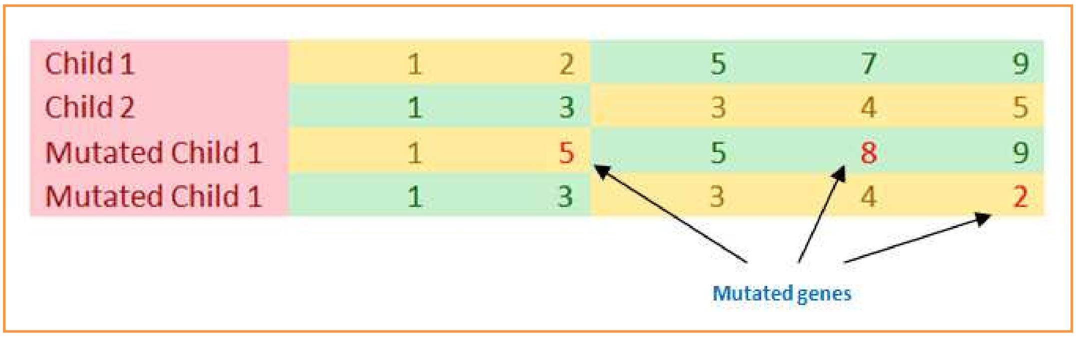


Figure 3.8: Mutation.

In this thesis, mutation is performed whenever the present global best chromosome has repeated for the past 20 iterations. Each chromosome will be affected by the massive mutation percentage 90%. It is in fact a big percentage, but this was due to the reason that the global best chromosome has repeated for the past 20 iterations, which means it might have been trapped in some point. So, by performing a massive mutation, the algorithm will have a new search space which has a greater probability in finding new optimum results or at least get out of the trapped point. This mutation percentage refers to the amount of genes that will suffer mutation and is used to generate a vector randomly which indicates the positions of the genes to be mutated. For example if the problem was to coordinate 50 relays using 3 degrees of freedom, then there will be 250 genes in each chromosome. Equation (3.9) will be used as shown:

$$number_{mutation} = NR * NV * percentage_{mutation} \tag{3.9}$$

where NR represents number of relays, NV represent number of variables. Then by substituting:

$$number_{mutation} = 50 * 5 * 0.90 = 225$$

This means that 225 genes will suffer mutation. Then generate a random vector which contains 225 values, but none of the values shall exceed the dimension of the chromosome, in this case 250. The values of this random vector are then used as the location of genes to be mutated, and the mutation is carried out. Keep in mind that each variable $dial$ and I_{pickup} has its upper and lower limits which must not be violated even in the mutation process. And for genes that represent the discrete variables of curve type $A, B\ and\ n$, they mutate all together according to the IEEE standards even if only one of the three variables was listed in the random vector.

The algorithm is also programmed to randomly carry out the mutation process with a small mutation percentage. This small mutation percentage affects only some of the chromosomes in the population. And again the selection of which chromosome to be mutated is a random process.

Apart from the massive and small mutation described above, the algorithm carries out an intelligent mutation. This intelligent mutation is a process in which only relays that are mal-coordinated suffer mutation. This is only carried out when elitism starts functioning or all chromosomes of the population are the same. In other words each chromosome has the same coordinated and mal-coordinated settings of relays as others. If a pair of coordination relays is not coordinated, the mutation will first mutate primary relay to try to decrease primary operation time, then if the pair is still not coordinated the backup relay will be mutated to increase the backup time. The mal-coordinated relays are detected by their CTI error.

3.5 Coordination of Protections using Ant Colony Algorithm

3.5.1 Introduction

Ant Colony algorithm (ACO) is part of the swarm intelligence computing, it is a metaheuristic optimization aiming to search for an optimal path in a graph, based on the behavior of ants seeking a path between their home colony and food source.

This algorithm was initially proposed by Marco Dorigo in 1992 in his PhD thesis. The original idea has since diversified to solve a wider class of numerical problems, and as a result, several problems have emerged, drawing on various aspects of the behavior of ants.

3.5.2 Basic Description of Ant Colony Algorithm

In the natural world, ants initially wander randomly until finding food. An ant-k agent runs randomly around the colony. As soon as it discovers food source, it returns to the nest, leaving in its route a trail of pheromone. If other ants encounter this route, they will stop travelling randomly but instead follow this route to the food source and return home. The route is then reinforced with more pheromone deposits. If there were different routes to reach the same food source then, in a given amount of time, the shortest one will be traveled by more ants than the longer routes. The shortest route will be increasingly enhanced, and therefore become more attractive. As time passes by, the longer routes will disappear because pheromones are volatile and eventually all the ants have “chosen” the shortest route. The idea is illustrated in Figure 3.9 (a), (b) and (c).

(a)

(b)

(c)

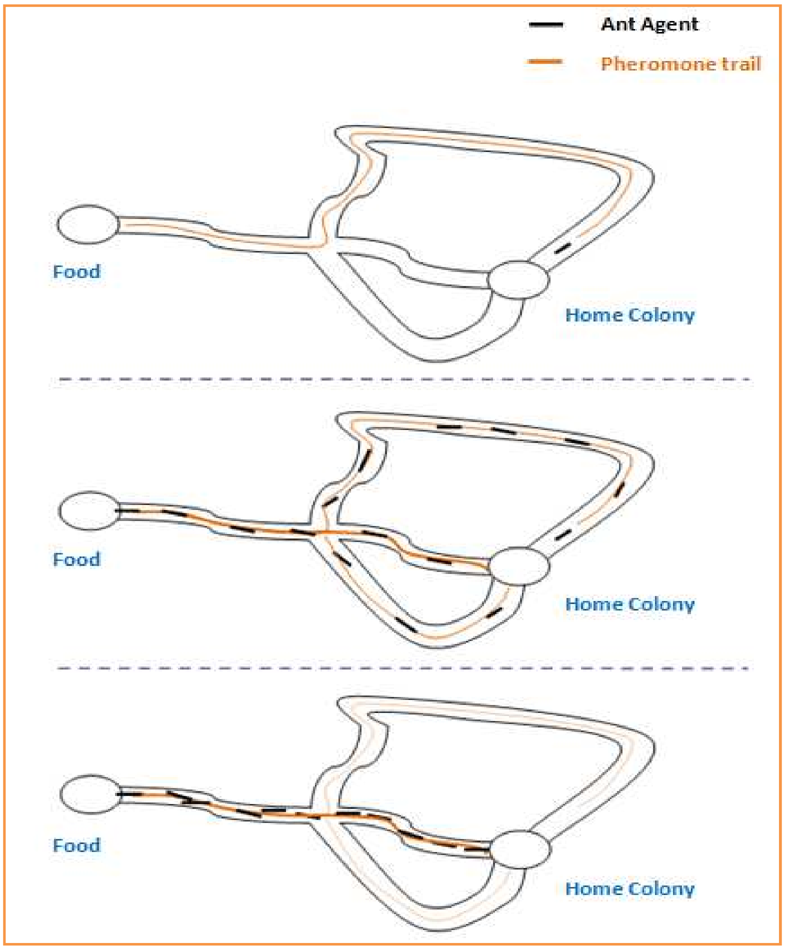


Figure 3.9: Natural behavior of Ants.

Ant agents are a number of artificial ants that build solutions to an optimization problem and exchange information on their quality through a communication scheme that is reminiscent of the one adopted by real ants [16].

The *AS-graph (search space)* is a matrix that contains discrete settings (states) of the control variables (stages) [13]. In other words, this graph or matrix contains the set of feasible solutions to the optimization problem which will be explored by the ant agents. Another matrix called pheromone matrix is created to represent the attractiveness of each discrete setting.

The *Pheromone matrix* is a matrix that contains information about the chemical pheromone deposited by ants. The matrix shows pheromone intensity of each discrete setting therefore the attractiveness of every possible route to the solution. The more intense a setting is, the more probability it has to be chosen by an ant agent as part of the solution.

The *Transition rule* is the probabilistic and stochastic mechanism that ant agents use to evaluate the pheromone intensity in order to decide which is the most attractive point to visit next.

The *Pheromone update* is the process in which pheromone intensities are increased or decreased according to the evaluated results whether the settings are good or bad solutions. This is achieved by decreasing the pheromone values through *pheromone evaporation* and increasing the pheromone levels by depositing more pheromone if it is a set of good solution.

The algorithm is started with many sets of solutions (states), together all the states form the AS-graph search space. This AS-graph is constant throughout the whole searching process hence it does not change from iteration to iteration. On the other hand, pheromone matrix is a representation of attractiveness of each discrete setting (edge) that does change not only in all iterations but in every ant tour. The settings that are good in fitness will consequently lead the ant agents to deposit more and more pheromone until all ants converge in this route (set of settings). Then the optimal solution is found.

The whole process is repeated until some condition (reached the number of maximum iterations, improvement of the best solution) is met. This is called *stopping criteria.*

The AS-graph size indicates how many states are there in the AS-graph. If there are too few states, the algorithm will have fewer possibilities to obtain the optimal solution to the problem and only a small part of the search space is explored. On the other hand, if there are too many states, the algorithm increases the possibility to encounter the optimal solution but it drastically slow down the whole process.

3.5.3 Steps of Protection Coordination using Ant Colony Algorithm

1. Generate the AS-graph (search space) that represents the discrete settings (states) of the control variables (stages). Each discrete setting is a possible solution to the problem.
2. Generate the pheromone matrix $\gamma(m, n)$ according to the size of AS-graph, where n is the number of stages and m number of states.
3. Initialize the pheromone matrix $\gamma(m, n) = \gamma_0(m, n) = \tau_{max}$. Equation (3.11) and (3.12) , in this case f_{gbest} is an initial estimation of best solution.
4. Place randomly M ants on the states of the first stage ($i = 1$).
5. Every ant must explore all stages sequentially; when ant-j is at the r-state of the $(i-1)$-stage, it will choose the s-state of the (i)-stage as the next visit according to the transition rule equation (3.13).
6. Compute primary and backup time of each relay after ant-j making its complete tour (explore all stages sequentially).
7. Execute local pheromone update of (r, s)-trail made by ant-j using equation (3.14).
8. Evaluate the fitness $f_k(x)$ of ant-j tour and save it to $f(x)$.
9. Repeat steps 5 to 8 until all ants (M) have finished their tour.
10. Execute global pheromone update of (r, s)-trail belonging to the best ant tour (f_{best}) using equation (3.17).
11. Terminate the algorithm if stopping criteria is met, if not, then continue all steps from 4 to 10.

3.5.4 AS-graph

Create the AS-graph search space with discrete settings (states) of the control variables (stages). The discrete settings are values within feasible numerical range of the corresponding setting of overcurrent relay. The control variables are the different settings of the overcurrent relay, in this particular case the degrees of freedom. The size of AS-graph is a $(m, n * NR)$ matrix where m represents number of states, n number of stages and NR number of relays. For example if a system has 10 relays with 1 degree of freedom $(dial)$, then the size of the AS-graph for 15 states will be (15,10). On the other hand, if a system has 10 relays with 2 degrees of freedom $(dial\ and\ k)$, then the size of the AS-graph for 15 states will be (15,20). But if a system has 10 relays with 3 degrees of freedom $(dial, k\ and\ A, B, n)$, then the size of the AS-graph for 15 states will be (15,30), and there will be a total of 450 discrete settings of relays. As more degrees of freedom are added to the AS-graph, the size of AS-graph increases. Bear in mind that the discrete settings A, B, n are values taken from the IEEE standard in Table 2.1 and are considered all three together as 1 degree of freedom and also as 1 variable. This is because the three together form a different curve type and not one by one. The idea of AS-graph is shown in equation (3.10) below.

$$AS = \begin{bmatrix} dial_{(1,1)} & \cdots & dial_{(1,NR)} & k_{(1,NR+1)} & \cdots & k_{(1,NR*2)} & ct_{(1,NR*2+1)} & \cdots & ct_{(1,NR*3)} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ dial_{(m,1)} & \cdots & dial_{(m,NR)} & k_{(m,NR+1)} & \cdots & k_{(m,NR*2)} & ct_{(m,NR*2+1)} & \cdots & ct_{(m,NR*3)} \end{bmatrix} \quad (3.10)$$

where *ct* represent the curve type by discrete values of 1, 2 and 3. For example 1 stands for moderate inverse (MI), 2 stands for very inverse (VI) and 3 stands for extremely inverse (EI).

In order to create the AS-graph matrix, necessary data such as upper and lower limits, steps of the control variables are needed. For example if a system has 2 relays with 2 degrees of freedom $(dial, k)$ which the range of $dial$ is [0.5, 1.4] in steps of 0.1 and the range of k is [1.4, 1.6] in steps of 0.05, then the AS-graph is constructed as shown in Figure 3.10:

$$
\begin{array}{cccc} dial_{R1} & dial_{R2} & k_{R1} & k_{R2} \end{array}
$$

$$
AS = \begin{bmatrix}
0.5 & 0.5 & 1.40 & 1.40 \\
0.6 & 0.6 & 1.45 & 1.45 \\
0.7 & 0.7 & 1.50 & 1.50 \\
0.8 & 0.8 & 1.55 & 1.55 \\
0.9 & 0.9 & 1.60 & 1.60 \\
1.0 & 1.0 & 1.60 & 1.60 \\
1.1 & 1.1 & 1.60 & 1.60 \\
1.2 & 1.2 & 1.60 & 1.60 \\
1.3 & 1.3 & 1.60 & 1.60 \\
1.4 & 1.4 & 1.60 & 1.60
\end{bmatrix}
$$

Figure 3.10: AS-graph.

Note that there are 10 values in the range of $dial$ setting including upper and lower limits, but there are only 5 values in the range of k setting including upper and lower limits. Under this circumstance, complete the rest of the matrix by repeating the upper limit of k setting as illustrated in the blue square in Figure 3.10 [16]. This is to have a sequential order.

3.5.5 Pheromone Matrix

The pheromone matrix is a matrix that contains information about the chemical pheromone deposited by ants. The matrix shows pheromone intensity of each discrete setting therefore the desirability of every possible route to the solution. The more intense a setting is, the more probability it has to be chosen by an ant agent as part of the solution.

The pheromone matrix $\gamma(m, n)$ is constructed according to the size of AS-graph, where m number of states and n is the number of stages. This matrix is initialized as presented in equation (3.11):

$$\gamma(m,n) = \gamma_0(m,n) = \tau_{max} \quad (3.11)$$

Where τ_{max} is the maximum pheromone trail and is given in equation (3.12):

$$\tau_{max} = \frac{1}{\alpha * f_{gbest}} \quad (3.12)$$

where f_{gbest} is the global best solution (best over the whole past iterations) and α is an empirical value that best suits in the range [0.88, 0.99] [13]. In the case of initializing pheromone matrix, f_{gbest} is an initial estimation of the best solution.

In this thesis, pheromone matrix was first constructed with all equal edges as presented in equation (3.11). But as it was presented in Figure 3.10, the smallest settings of relays occupy the first rows of the AS-graph, these settings are the ideal settings for coordination due to the reason that they will result minimum operation time. Hence after the pheromone matrix is constructed, the pheromones of the first rows of this matrix are increased. This was done to help the algorithm find the best time operation settings in less time, so one decide how many rows to change and in what amount. Obviously one shall not change too many rows and neither in big amount because this will significantly affect the performance of the ant's exploration. The idea is illustrated in Figure 3.11:

$$\gamma_0 = \begin{bmatrix} 2(\tau_{max}) & 2(\tau_{max}) & 2(\tau_{max}) & 2(\tau_{max}) \\ 2(\tau_{max}) & 2(\tau_{max}) & 2(\tau_{max}) & 2(\tau_{max}) \\ 2(\tau_{max}) & 2(\tau_{max}) & 2(\tau_{max}) & 2(\tau_{max}) \\ \tau_{max} & \tau_{max} & \tau_{max} & \tau_{max} \\ \tau_{max} & \tau_{max} & \tau_{max} & \tau_{max} \\ \tau_{max} & \tau_{max} & \tau_{max} & \tau_{max} \\ \tau_{max} & \tau_{max} & \tau_{max} & \tau_{max} \\ \tau_{max} & \tau_{max} & \tau_{max} & \tau_{max} \\ \tau_{max} & \tau_{max} & \tau_{max} & \tau_{max} \\ \tau_{max} & \tau_{max} & \tau_{max} & \tau_{max} \end{bmatrix}$$

Figure 3.11: Pheromone Matrix.

3.5.6 Transition Rule

Transition rule is the probabilistic and stochastic mechanism that ant agents use to evaluate the pheromone intensity in order to decide which is the most attractive point to visit next. Bear in mind that this rule can also include another factor of desirability which is the vision of the edges. For example the vision of Traveling Salesman Problem (TSP) is a symmetrical matrix that contains the inverse of the distance between each edge (city), where the main diagonal are zeros because there is zero distance for reaching the same city. A similar element would be the operation time of relays in coordination problem, but due to the reason that the relays can have many primary and backup operation times, this make the construction of the vision matrix impossible. Thus pheromone intensity will be the only factor used in the transition rule in this thesis. The advantage of having the vision matrix (as in TSP) is that the algorithm always converge in the same result while the disadvantage of not having the vision matrix is that the algorithm give different optimization result in every run. An analogy would be "An All Seen Ant" vs. "A Blind Ant".

When ant-j is at the r-state of the $(i-1)$-stage, it will choose the s-state of the (i)-stage as the next visit according to the transition rule presented in equation (3.13):

$$p(r,s) = \frac{\gamma(r,s)}{\sum_l \gamma(r,l)} \quad s,l \in N_r^j \tag{3.13}$$

Where N_r^j is a memory tabu list of ant- j that defines the set of points still to be visited when it is at point *r*. For TSP N_r^j is very important because every ant agent jumps non-sequentially from stage to stage whereas every ant agent explore all stages sequentially for the coordination problem as it was designed in this thesis. Thus N_r^j was omitted due to its unnecessary existence. The pheromone of the next possible visit of (i)-stage currently under evaluation is $\gamma(r,s)$ and $\sum_l \gamma(r,l)$ is the pheromone sum of the entire column of the (i)-stage under evaluation. The idea is illustrated in Figure 3.12 (a), (b) and (c):

$$\gamma = \begin{bmatrix} 0.8 & 1.5 & 0.7 & 0.5 \\ 0.6 & 0.9 & 0.6 & 0.9 \\ 0.7 & 0.7 & 0.9 & 0.7 \\ 0.8 & 0.9 & 0.8 & 0.3 \\ 0.9 & 1.1 & 1.2 & 0.3 \\ 0.1 & 0.3 & 0.3 & 0.4 \\ 0.4 & 0.1 & 0.5 & 0.1 \\ 0.5 & 0.4 & 0.2 & 0.3 \\ 0.8 & 0.5 & 0.1 & 0.3 \\ 0.2 & 0.2 & 0.1 & 0.5 \end{bmatrix}$$

(a)

$$\gamma = \begin{bmatrix} 0.8 & 1.5 & 0.7 & 0.5 \\ 0.6 & 0.9 & 0.6 & 0.9 \\ 0.7 & 0.7 & 0.9 & 0.7 \\ 0.8 & 0.9 & 0.8 & 0.3 \\ 0.9 & 1.1 & 1.2 & 0.3 \\ 0.1 & 0.3 & 0.3 & 0.4 \\ 0.4 & 0.1 & 0.5 & 0.1 \\ 0.5 & 0.4 & 0.2 & 0.3 \\ 0.8 & 0.5 & 0.1 & 0.3 \\ 0.2 & 0.2 & 0.1 & 0.5 \end{bmatrix}$$

(b)

$$\gamma = \begin{bmatrix} 0.8 & 1.5 & 0.7 & 0.5 \\ 0.6 & 0.9 & 0.6 & 0.9 \\ 0.7 & 0.7 & 0.9 & 0.7 \\ 0.8 & 0.9 & 0.8 & 0.3 \\ 0.9 & 1.1 & 1.2 & 0.3 \\ 0.1 & 0.3 & 0.3 & 0.4 \\ 0.4 & 0.1 & 0.5 & 0.1 \\ 0.5 & 0.4 & 0.2 & 0.3 \\ 0.8 & 0.5 & 0.1 & 0.3 \\ 0.2 & 0.2 & 0.1 & 0.5 \end{bmatrix}$$

(c)

Figure 3.12: Transition Rule

In Figure 3.12, the green colors represent the r-state of the $(i-1)$-stage and the yellow colors represent the s-state of the (i)-stage. This is the illustration of an ant- j agent completing its tour according to the transition rule, therefore the set of settings of this ant- j agent tour in the current iteration, referring to the example of Figure 3.10 are [0.7 0.5 1.60 1.45]. Note that the ant-j agent did not start on the most intense pheromone edge in column one because it was placed randomly on the first stage, this is carried out at the beginning of each iteration.

3.5.7 Pheromone Updates

Pheromone update is the process in which pheromone intensities are increased or decreased according to the evaluated results whether the settings are good or bad solutions. This is achieved by decreasing the pheromone values through *pheromone evaporation* and increasing the pheromone levels by depositing more pheromone if it is a set of good solution.

3.5.7.1 Local Pheromone Update

The pheromone trail on each edge of an ant-j tour is updated immediately as the ant-k agent finishes its tour. This is given in the equation (3.14):

$$\gamma(r,s) = \alpha * \gamma(r,s) + \Delta\gamma^{j}(r,s) \tag{3.14}$$

$$0 < \alpha < 1 \tag{3.15}$$

$$\Delta\gamma^{j}(r,s) = \frac{1}{Q * f} \tag{3.16}$$

where α is the persistence of the pheromone trail, $(1-\alpha)$ represent the pheromone trail evaporation and $\Delta\gamma^{j}(r,s)$ is the amount of pheromone that ant-j puts on edge (r,s). The desirability of the edge (r,s) is represented by $\Delta\gamma^{j}$, such as shorter distance, better performance, and in this case less operation time. The objective function evaluation of the settings of ant-j tour is represented by f and Q is a positive constant. It is observed from equation (3.16) that as constant Q increases, the contribution of pheromone an ant deposits decreases. Here Q was chosen to be 100.

3.5.7.2 Global Pheromone Update

After all ant agents have completed their tours in the iteration, primary and backup operation times are computed. The objective function is evaluated for each ant tour and all pheromone edges (r, s) of the best ant tour (ant tour with best fitness value) are updated according to equation (3.17):

$$\gamma(r,s) = \alpha * \gamma(r,s) + \frac{R}{f_{best}} \quad r,s \in J_{best}^{j} \tag{3.17}$$

where f_{best} is the best solution of this iteration, R is a positive constant and J_{best}^{j} is the location list of the best ant tour that records the state of each stage when ant-j moves from one stage to another. It is observed from equation (3.17) that as constant R increases, the contribution of pheromone an ant deposits increases. Here R was chosen to be 5.

In this thesis, the global pheromone update was not performed as described in the previous paragraph. This was due to the reason that updating only the best ant tour leads to premature convergence, thus the global pheromone update was performed by updating a percentage of the best ant tours. For example, 30% of the ant tours that ranked the best were updated.

Apart from the change presented in the previous paragraph, the algorithm was programmed to perform global update randomly in some iteration. This was done also to avoid premature convergence and at the same time this makes the ant agents explore the AS-graph better. After the program has executed certain iterations, specific iterations were selected to perform the global update randomly. This idea is similar to the mutation process in the Genetic Algorithm.

Empirical tests have shown that the ACO converges faster when both Q and R are arbitrarily large numbers and almost equal to one another. Studies in the literatures might use $Q = R = 1{,}000{,}000$ for other problems, but such large constant is not very suitable to use here because the algorithm converges around 30 iterations, leaving many coordination pairs uncoordinated. This is the reason for choosing $Q = 100$ and $R = 5$. They were chosen empirically but can work for any network.

3.5.8 Intelligent Exploration

Intelligent exploration of the AS-graph consists of exploring setting $(dial)$ of specific relays after a pre-specified amount of iterations. This was programmed to help coordinating all coordination pairs. The $dial$ setting was chosen because it has more influence in the relay operation time.

First, detect the coordination pairs that are not coordinated. Select a pair to start with. Then get the setting of this specific relay (primary) from the best ant tour and use it as the upper limit. Next, equation (3.17) is applied again but with a little modification as given in equation (3.18).

$$\gamma(r,s) = \alpha * \gamma(ran1,s) + \frac{R}{f_{best}} \quad r,s \in J_{best}^{j} \tag{3.18}$$

where $ran1$ is a random number selected from the interval $[1{:}r]$. Pheromone is then deposited on this edge. Note that r represent the upper limit (state) and s represent the specific relay (stage). Depositing pheromone on this specific edge will lead the ant agents to explore the corresponding setting from the AS-graph. And because it has an upper limit, the newly explored edge will correspond to a smaller setting in the AS-graph, leading to a reduction of primary operation time.

Now get the setting of the specific relay (backup) from the best ant tour of the same coordination pair that was selected previously and use it as the lower limit. Then equation (3.17) is applied again but with a little modification as given in equation (3.19).

$$\gamma(r,s) = \alpha * \gamma(ran2,s) + \frac{R}{f_{best}} \quad r,s \in J_{best}^{j} \tag{3.19}$$

where $ran2$ is a random number selected from the interval $[r: end\ of\ state]$. The Pheromone is then deposited on this edge. Note that r represent the lower limit (state) and s represent the specific relay (stage). Depositing pheromone on this specific edge will lead the ant agents to explore the corresponding setting from the AS-graph. Because it has a lower limit, the newly explored edge will correspond to a bigger setting in the AS-graph, leading to an increment of backup operation time.

If all coordination pairs were coordinated then detect coordination pairs that have a greater CTI than the pre-specified and try to reduce them. Choose a coordination pair to start with and get the settings of both relays (primary and backup) from the best ant tour and use them as the upper limit. Then, equation (3.18) is applied again, this time, for both primary and backup relay. Note that r represent the upper limit (state) and s represent the specific relay (stage). By doing so, pheromone trails are deposited on these specific edges (both primary and backup). This will lead ant agents to explore the corresponding settings from the AS-graph which due to the reason that they have upper limit, the newly explored edges will correspond to a smaller setting in the AS-graph, hence reduction of both primary and backup operation time.

3.6 Coordination of Protections using Differential Evolution Algorithm

3.6.1 Introduction

Differential Evolution algorithm (DE) is a part of the evolutionary algorithms; it is a metaheuristic search algorithm based on evolutionary ideas of natural selection of genes.

The idea of evolutionary computing was introduced in the 1960s by I. Rechenberg in his work "Evolution Strategies". His idea was then developed by other researchers. Differential Evolution Algorithm (DE) was first reported as a written article by R. Storn and K. V. Price in 1995.

3.6.2 Basic Description of Differential Evolution Algorithm

The Differential Evolution algorithm operates through similar computational steps as employed by a standard evolutionary algorithm (EA). However, unlike traditional evolutionary algorithms, the differential evolution algorithm perturbs the current generation population members with the scaled differences of randomly selected and distinct population members. Therefore, no separate probability distribution has to be used for generating the offspring. This characteristic made the algorithm has less mathematical operations, hence less execution time compared to other algorithms.

Main stages of the DE algorithm are presented in Figure 3.13:

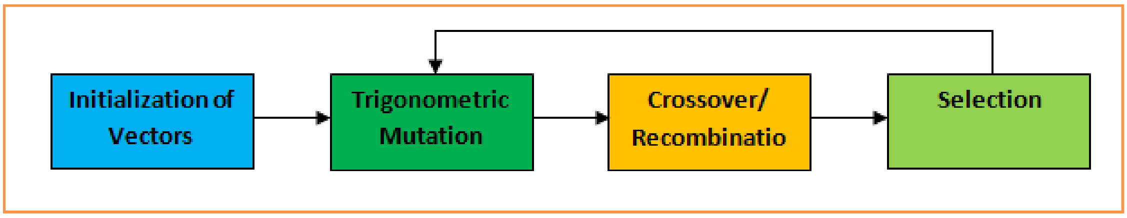


Figure 3.13: Main stages of the DE algorithm.

In the Differential Evolution community, the individual trial solutions (which constitute the population) are called parameter vectors or genomes. Each *parameter vector* contains a set of possible solution information.

Crossover is a recombination (or reproduction). Sons or new individuals are formed by the recombination of the genes of certain parameter vectors called parents or *target vectors*. The newly formed individuals (sons) are called *trial vectors.*

Mutation is a sudden change or perturbation with a random element. A mutant or *donor vector* is formed for each target vector.

Selection is the process that keep the population size constant over the subsequent generations by determine whether the target or trial vector survives to the next generation.

Search space is the space of all feasible solutions. Each point in the search space represents a feasible solution and each feasible solution can be marked by its fitness value for the problem. This feasible solution is then a maximum or a minimum.

The algorithm is started with many sets of solutions, together all the parameter vectors form a population. Solutions from one population are taken and used to form a new population. And by employing the selection process, it guarantees the population to either get better (with respect to the minimization of the objective function) or to remain the same in fitness status, but never deteriorates.

The whole process is repeated until some condition (reached the number of maximum iterations, improvement of the best solution) is met. This is called *stopping criteria.*

The population size (NP) indicates how many parameter vectors are there in the population (in one generation). If there are too few parameter vectors, the algorithm will have very few possibilities to perform crossover and only a small part of the search space is explored. On the other hand, if there are too many parameter vectors, the algorithm will explore more variety of feasible solutions but the execution time is increased.

The three major control parameters in DE are F, Cr and NP. They are fixed values in this thesis, but there are reported in the literatures to be able to make the DE algorithm become more efficient in both time and quality result aspect when using them in dynamic way. This is considered as future work.

3.6.3 Steps of Protection Coordination using Differential Evolution Algorithm

1. Generate the initial population randomly of n parameter vectors in which each gene is a possible solution to the problem.
2. Select randomly 3 mutually exclusive parameter vectors from the current population for each target vector.
3. Trigonometric Mutation:

a. Evaluate the fitness $f(x)$ of the 3 parameter vectors selected for each target vector.
b. Calculate the 3 weighting coefficients according to equation (3.22).
c. Create the donor vector for each target vector according to equation (3.26) and (3.27).

4. Reproduction:
   a. Perform binomial crossover according to equation (3.28) to form trial vectors.
5. Selection:
   a. Evaluate the fitness $f(x)$ of both target and trial vectors.
   b. Generate the new population of each iteration by performing selection according to equation (3.29).
6. Evaluate the fitness $f(x)$ of the new population
7. Execute the algorithm again using the new population.
8. Terminate the algorithm if stopping criteria is met, if not, then continue all steps from 3 to 7.

3.6.4 Initial Population

Create a new population randomly with reasonable genes. That is to create a new population which all genes of all parameter vectors are initialized somewhere in their feasible numerical range of the corresponding setting of overcurrent relay. Each row is an individual and each column is a gene/variable/setting of a relay. The size of the population is $(NP, D * NR)$ where NP represents number of parameter vectors, D number of control variables and NR number of relays. For example if a system has 10 relays with 1 degree of freedom $(dial)$, then the size of the population for 10 individuals will be (10,10). On the other hand, if a system has 10 relays with 2 degrees of freedom $(dial\ and\ k)$, then the size of the population for 10 individuals will be (10,20). But if a system has 10 relays with 3 degrees of freedom $(dial, k\ and\ A, B, n)$, then the size of the population for 10 individuals will be (10,30), and there will be a total of 300 genes or settings of relays. As more degrees of freedom are added to the population, the population size increases. Bear in mind that the discrete settings A, B, n are values taken from the IEEE standard in Table 2.1 and are considered all three together as 1 degree of freedom. This is because the three together form a different curve type and not one by one. The idea of population is shown in equation (3.20) below.

$$P=\begin{bmatrix} dial_{(1,1)} & \cdots & dial_{(1,NR)} & k_{(1,NR+1)} & \cdots & k_{(1,NR*2)} & ct_{(1,NR*2+1)} & \cdots & ct_{(1,NR*3)} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ dial_{(NP,1)} & \cdots & dial_{(NP,NR)} & k_{(NP,NR+1)} & \cdots & k_{(NP,NR*2)} & ct_{(NP,NR*2+1)} & \cdots & ct_{(NP,NR*3)} \end{bmatrix} \quad (3.20)$$

where *ct* represent the curve type by discrete values of 1, 2 and 3. For example 1 stands for moderate inverse (MI), 2 stands for very inverse (VI) and 3 stands for extremely inverse (EI).

First create the population randomly with values between 0 and 1 then the equation (3.21) is applied as presented below in order to let the narrow the initial random population to be within its superior and inferior limits.

$$P(p,q) = limit_{lower} + \left(limit_{upper} - limit_{lower}\right) * P(p,q)_{random} \quad (3.21)$$

3.6.5 Trigonometric Mutation

Biologically, "mutation" means a sudden change in the gene characteristics of a chromosome. In the context of the evolutionary computing paradigm, however, mutation is also seen as a change or perturbation with a random element. In DE-literature, a parent vector from the current generation is called target vector, a mutant vector obtained through the trigonometric mutation operation is known as donor vector and finally an offspring formed by recombining the donor with the target vector is called trial vector. Unlike the GA, mutation in DE is performed to all target vectors (individuals) in every iteration.

The trigonometric mutation operator was proposed by Fan and Lampinen to speed up the performance of the differential evolution algorithm. To implement the scheme, for each target vector, three distinct vectors are randomly selected from the DE population. Suppose for the i-th target vector $\vec{X}_{i,G}$, the selected population members are $\vec{X}_{r_1,G}$, $\vec{X}_{r_2,G}$, $\vec{X}_{r_3,G}$. The indices r_1, r_2 and r_3 are mutually exclusive integers randomly chosen from the range [1,NP], which are also different from the index i, these indices are generated only once for each mutant vector. Now three weighting coefficients are formed according to the following equations (3.23), (3.24) and (3.25):

$$p' = \left|f(\vec{X}_{r_1})\right| + \left|f(\vec{X}_{r_2})\right| + \left|f(\vec{X}_{r_3})\right| \tag{3.22}$$

$$p_1 = \left|f(\vec{X}_{r_1})\right|/p' \tag{3.23}$$

$$p_2 = \left|f(\vec{X}_{r_2})\right|/p' \tag{3.24}$$

$$p_3 = \left|f(\vec{X}_{r_3})\right|/p' \tag{3.25}$$

where $f()$ is the function to be minimized. Let Γ be the trigonometric mutation rate in the interval (0,1). Then the trigonometric mutation scheme may now be expressed as equations (3.26) and (3.27):

$$\vec{V}_{i,G+1} = \frac{\vec{X}_{r_1} + \vec{X}_{r_2} + \vec{X}_{r_3}}{3} + (p_2 - p_1) * \left(\vec{X}_{r_1} - \vec{X}_{r_2}\right) + (p_3 - p_2) * \left(\vec{X}_{r_2} - \vec{X}_{r_3}\right) + (p_1 - p_3) * \left(\vec{X}_{r_3} - \vec{X}_{r_1}\right) \quad \text{if rand}[0,1] \leq \Gamma \tag{3.26}$$

$$\vec{V}_{i,G+1} = \vec{X}_{r_1} + F\left(\vec{X}_{r_2} - \vec{X}_{r_3}\right) \quad \text{else} \tag{3.27}$$

where F is a scalar number that typically lies in the interval [0.4,1]. Both parameters Γ and F are selected as 0.5 and 0.8 respectively in this thesis.

3.6.6 Binomial Crossover/Recombination

To enhance the potential diversity of the population, a crossover operation comes into play after generating the donor vector through mutation. The donor vector exchanges its components with the target vector $\vec{X}_{i,G}$ under this operation to form the trial vector $\vec{U}_{i,G} = [\, u_{1,i,G},\, u_{2,i,G},\, u_{3,i,G}, \dots,\, u_{D,i,G}]$. The DE family of algorithms can use two kinds of crossover methods: *exponential* (or two-point modulo) and *binomial* (or uniform).

Binomial crossover is performed on each of the D variables whenever a randomly generated number between 0 and 1 is less than or equal to the Cr value. In this case, the number of parameters inherited from the donor has a (nearly) binomial distribution. The scheme may be outlined as equation (3.28):

$$u_{j,i,G} = \begin{cases} v_{j,i,G} & \text{if } \left(rand_{i,j}[0,1] \leq Cr \text{ or } j = j_{rand}\right) \\ x_{j,i,G} & \text{otherwise} \end{cases} \tag{3.28}$$

where $rand_{i,j}[0,1]$ is an uniformly distributed random number, which is called anew for each j-th component of the i-th parameter vector. $j_{rand} \in [1, 2, \dots, D]$ is a randomly chosen index, which ensures that $\vec{U}_{i,G}$ gets at least one component form $\vec{V}_{i,G}$. It is instantiated once for each vector per generation. We note that for this additional demand, Cr is only approximating the true probability p_{Cr} of the event that a component of the trial vector will be inherited from the donor.

The Cr parameter is selected to be 0.5 in this thesis.

3.6.7 Selection

To keep the population size constant over subsequent generations, the next step of the algorithm calls for *selection* to determine whether the target or the trial vector survives to the next generation, for example at $G = G + 1$. The selection operation is presented in equation (3.29):

$$\vec{X}_{i,G+1} = \begin{cases} \vec{U}_{i,G} & \text{if } f(\vec{U}_{i,G}) \leq f(\vec{X}_{i,G}) \\ \vec{X}_{i,G} & \text{if } f(\vec{U}_{i,G}) > f(\vec{X}_{i,G}) \end{cases} \tag{3.29}$$

where $f(\vec{X})$ is the objective function to be minimized. Therefore, if the new trial vector yields an equal or lower value of the objective function, it replaces the corresponding target vector in the next generation; otherwise the target is retained in the population. Hence, the population either gets better (with respect to the minimization of the objective function) or remains the same in fitness status, but never deteriorates.

3.7 Conclusion

The real time algorithm shall work in different network topologies, and different n-1 contingencies. This algorithm is the most important stage in the online coordination process because the optimization algorithms can be of any type, as long as it is fast, accurate, robust etc. Although the real time algorithm consists of different methods (incident method, block construction method, Newton Raphson method, symmetrical components etc...), it is the brilliant idea that makes it shine, the union of all above methods made it possible to accomplish the objective. These methods that were used in this algorithm are not obligatory; one can use other methods accomplishing the same objective. It is the idea that is unique.

The GA is an old algorithm very easy to employ. It is robust up to certain point, meaning that it is very easy to adapt to function in different areas not only for protection use. It is the most well know algorithm due to simplicity over the decades. On the contrary ACO and DE are newly developed algorithms which are not as popular as GA now, however they have started to gain popularity due to their outstanding performance compared to GA. In the near future, GA will become obsolete; ACO, DE and other more efficient algorithms shall replace it. ACO and DE have never been implemented in the protection area; but they are indeed robust to be able to adapt the coordination problem.

CHAPTER 4 EVALUATION AND COMPARISON AMONG THE ALGORITHMS IN IEEE TEST SYSTEMS

4.1 Introduction

Different algorithms are implemented to coordinate the overcurrent relays, but there will always be some performance advantages that one algorithm has over another. Due to this purpose, three algorithms are programmed and compared in this thesis. The GA is used as benchmark reference (because it is the most widely known in the protection area), then both ACO and DE are programmed and compared with the GA. The ACO and DE were chosen because they are reported to have outstanding performance in different literatures and had never been implemented in the protection field. These two major reasons made them candidates in this thesis.

4.2 Real Time Coordination and Comparison of Algorithms: GA, ACO and DE

The performance of each algorithm is tested in this section using the IEEE 14-bus test system, advantages and disadvantages of each algorithm are highlighted. Their performance is based on the execution time, result quality, robustness and convergence ability of each algorithm.

4.2.1 Parameter Settings and Test System Data

4.2.1.1 Parameter Settings

Parameters	GA	ACO	DE
CTI	0.3	0.3	0.3
dial	[0.5:2.0]	[0.5:2.0]	[0.5:2.0]
k	[1.4:1.6]	[1.4:1.6]	[1.4:1.6]
dial step	continuous	0.05	continuous
k step	continuous	0.01	continuous
Q	--	100	--
R	--	5	--
r	--	--	0.5
F	--	--	0.8
Cr	--	--	0.5
individual-ants	500	500	500
iterations	1000	1000	1000

Table 4.1: Parameter settings of GA, ACO and DE.

The range of dial was selected by running the particular test system several times and by observing the results, one concludes the range where the results are located, and hence narrow the search space for obtaining better results and speeding up the algorithm convergence.

Both GA and DE have continuous dial and k settings, while ACO has discrete settings. Bear in mind that the AS-graph is constructed by the discrete step settings, as the step size becomes more continuous (smaller), the size of AS-graph increases and therefore the execution time increases. So for real time coordination the step size (dial and k) were chosen as presented in Table 4.1, not too big (will cause bad quality result) and not too small (will cause long execution time).

The influence of parameters Q, R, F, Cr and ρ have all been presented in chapter 3.

The only stopping criterion is to stop when the algorithms have reached the maximum iteration of 1,000. Although each algorithm has its own stopping criteria, they were disabled in order to be comparable between them. This maximum iteration number was selected due to the minimum improvement that the algorithms contribute after 1,000 iterations when 3,000 and 5,000 were established as maximum simulation iteration.

Both GA and DE are simulated with 500 individuals and ACO is simulated with 500 ant agents. The number of individuals and ant agents were selected due to the need of speed.

4.2.1.2 Test System Data

The IEEE 14-bus test system was chosen to test and compare the performance of the three algorithms. The system is shown in Figure 4.1. The system consists of 32 relays and they are located as shown in Figure 4.1. The voltages were selected to be 34.5 kV for buses at high voltage side of transformers and 22 kV for buses at low voltage side of transformers. All relays are considered to have very inverse time characteristic curve as was presented in Table 2.1.

The relay names are not assigned as a number as was done conventionally, but generated automatically by the real time algorithm as a string of numbers. These relay names (string of numbers) consist of 3 digits. The first digit is the name of the nearby bus. The second digit is the name of the remote bus and the third digit represents the number of the lines (parallel lines) between two buses. For example, the relays between buses 1 and 2 that are nearby bus 1 are assigned as [1 2 1], [1 2 2] while the relays that are nearby bus 2 are assigned as [2 1 1] and [2 1 2] respectively.

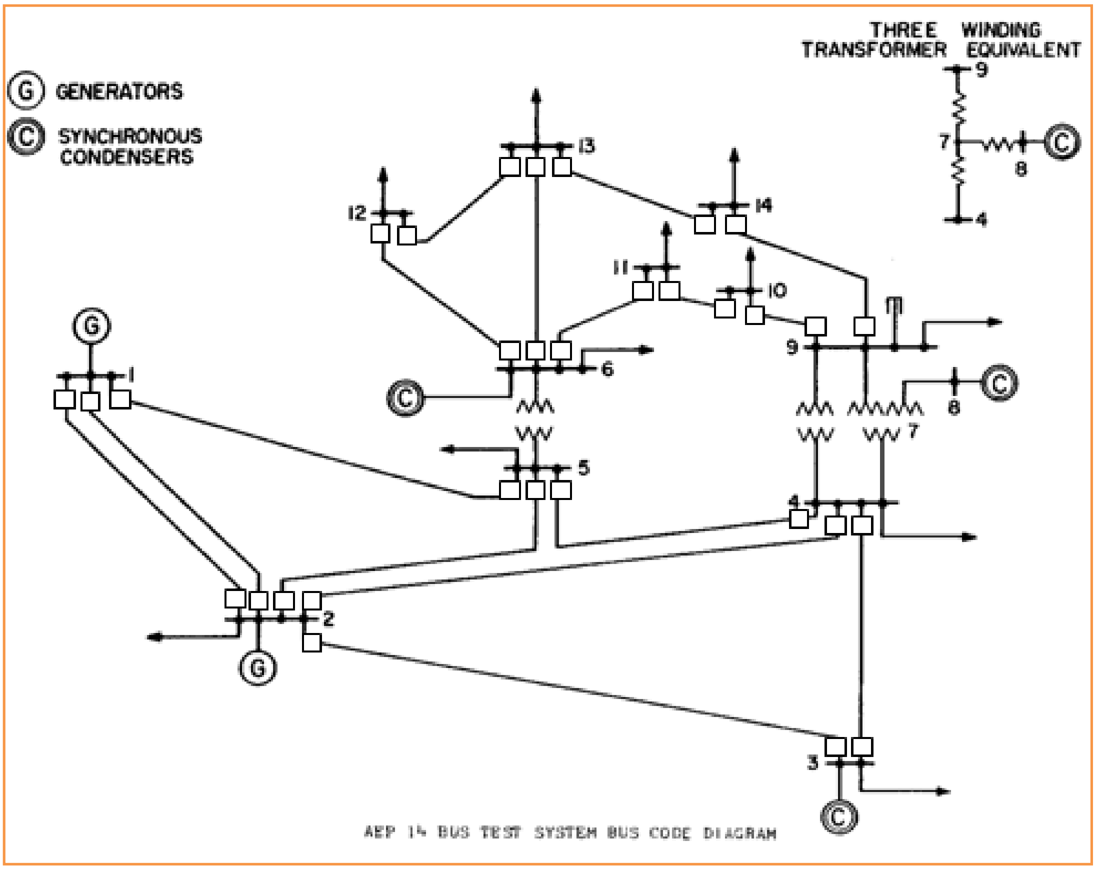


Figure 4.1: IEEE 14 bus test system.

The two lines between buses 1 and 2 have the same impedance value. Therefore the relays [1 2 1], [1 2 2], [2 1 1] and [2 1 2] sense the same amount of maximum load currents of 815 A, but due to the n-1 contingency analysis described in section 3.2.3, the maximum load currents of these relays are 1,849 A. The current values are based on minimum load operation.

The fault currents are calculated with the remote end opened. This was done due to two considerations, to obtain the maximum fault current that the relay senses and the very small probability for the remote end relay to mal-operate. Bear in mind that as elements' operation or network topology changes, load flow and fault analysis must be computed again through real time algorithm.

The data Xd for the generators one and two are 0.01 and 0.3 respectively.

The maximum load is the same as the original 14 bus load data while the minimum load is the 70% of the 14 bus load data.

4.2.2 Results and Comparison

The 14 bus test system consists of 62 relay coordination pairs before sensitivity filter. But this varies accordingly to the variation of load demand.

4.2.2.1 Case 1

The 14 bus test system is simulated using GA, ACO and DE with the corresponding parameters presented in previous section at maximum load. There are a total of 39 relay coordination pairs after the sensitivity filter. All three algorithms were simulated ten times. The convergence of each algorithm was averaged using the best fitness of each iteration of the ten simulations. This is presented in Figure 4.2 for comparison.

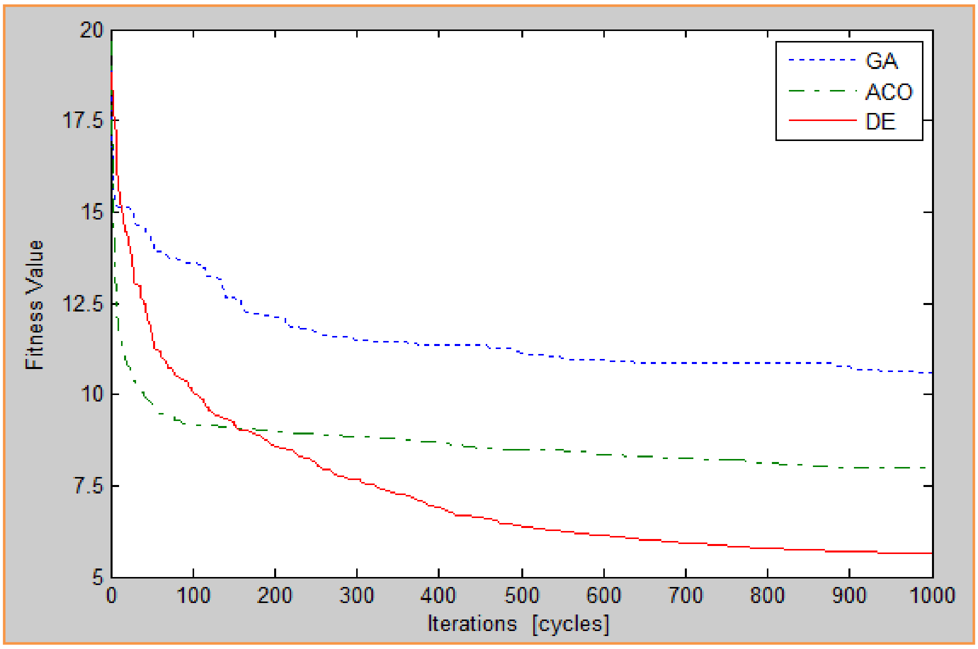


Figure 4.2: Averaged fitness convergence of the 14 bus test system of GA, ACO and DE in ten simulations operating at maximum load.

The averaged number of violation of coordination constraints, averaged fitness convergence and averaged time of GA, ACO and DE are presented in Table 4.2.

Parameters	GA	ACO	DE
NV	0.1	0	0
Fitness	10.611	7.994	5.598
Time (sec)	5507	441	89

Table 4.2: Comparison of averaged results of GA, ACO and DE at maximum load.

From these results, it is concluded that both ACO and DE have less violation of coordination constraint, better convergence and faster performance than GA. Note that in ACO and DE all coordination pairs are coordinated for the ten simulations. On the contrary, some of the ten GA simulations do not have all coordination pairs coordinated. The DE shows an outstanding performance.

The averaged relay settings and operation time, as well as CTI and sensitivity of the ten averaged GA, ACO and DE simulations are presented in Table 4.3.

Algorithm	Dial	K	Backup time	Primary time	CTI	Sensitivity
GA	1.1324	1.4952	3.1425	1.1817	1.9650	3.12005
ACO	0.9875	1.5004	2.3968	1.0383	1.3584	3.12624
DE	0.7374	1.4289	1.7015	0.7346	0.9669	3.29381

Table 4.3: Averaged relay settings, operation time, CTI and sensitivity of GA, ACO and DE for 14 bus test system at maximum load.

Although it is observed from Table 4.3 that the averaged dial is near 1, there are many relays that use the minimum dial value which leads to less operation time, some uses a dial near minimum, and the rest uses bigger dials due to the necessity for coordination purpose. All relays uses small k which leads to greater sensitivity. This observation goes for GA, ACO and DE.

4.2.2.2 Case 2

The 14 bus test system is simulated again using GA, ACO and DE with the corresponding parameters presented in previous section at minimum load. There are a total of 48 relay coordination pairs after the sensitivity filter. All three algorithms were simulated ten times. The convergence of each algorithm was averaged using the best fitness of each iteration of the ten simulations. This is presented in Figure 4.3 for comparison.

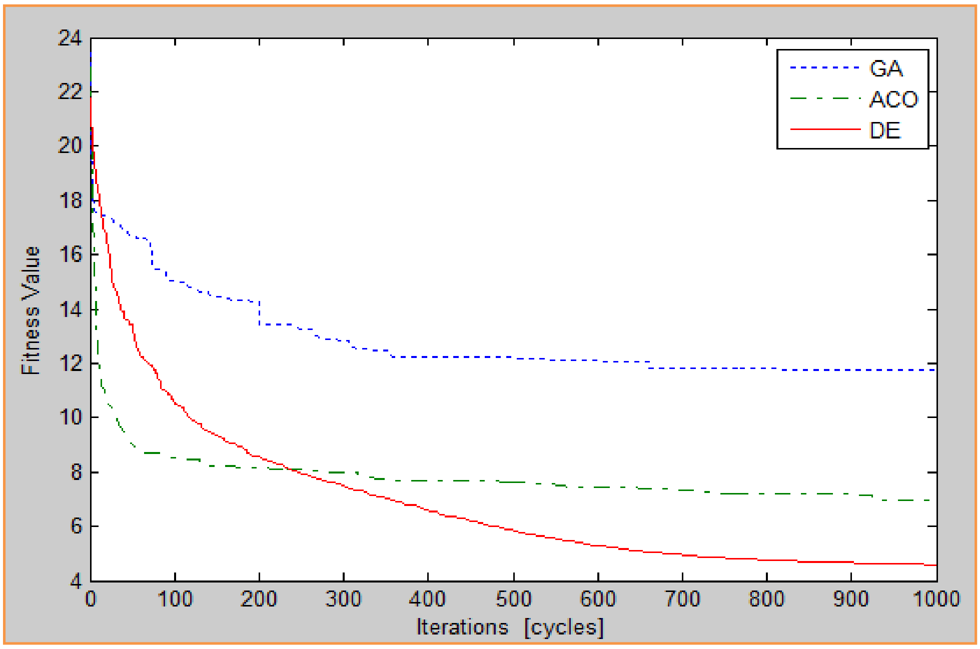


Figure 4.3: Averaged fitness convergence of the 14 bus test system of GA, ACO and DE in ten simulations operating at minimum load.

The averaged number of violation of coordination constraints, averaged fitness convergence and averaged time of GA, ACO and DE are presented in Table 4.4.

Parameters	GA	ACO	DE
NV	1.4	0	0
Fitness	11.748	6.968	4.612
Time (sec)	5825	438	94

Table 4.4: Comparison of averaged results of GA, ACO and DE at minimum load.

From these results, it is concluded that both ACO and DE have less violation of coordination constraint, better convergence and faster performance than GA. Note that in ACO and DE all coordination pairs are coordinated for the ten simulations. On the contrary, some of the ten GA simulations do not have all coordination pairs coordinated. The DE shows an outstanding performance.

The averaged relay settings and operation time, as well as CTI and sensitivity of the ten averaged GA, ACO and DE simulations are presented in Table 4.5.

Algorithm	Dial	K	Backup time	Primary time	CTI	Sensitivity
GA	1.1336	1.4903	2.7546	0.8511	1.9266	4.03250
ACO	1.1165	1.4434	2.1331	0.7974	1.3357	4.17205
DE	0.7863	1.4324	1.4938	0.5297	0.9641	4.18241

Table 4.5: Averaged relay settings, operation time, CTI and sensitivity of GA, ACO and DE for 14 bus test system at minimum load.

4.2.2.3 Case 3

Even though other type of protection principle is used for transformers, overcurrent relays are implemented here for the purpose of coordination study in this section. This increased the number of coordination pairs. The single line diagram of 14 bus test system is presented in Figure 4.4.

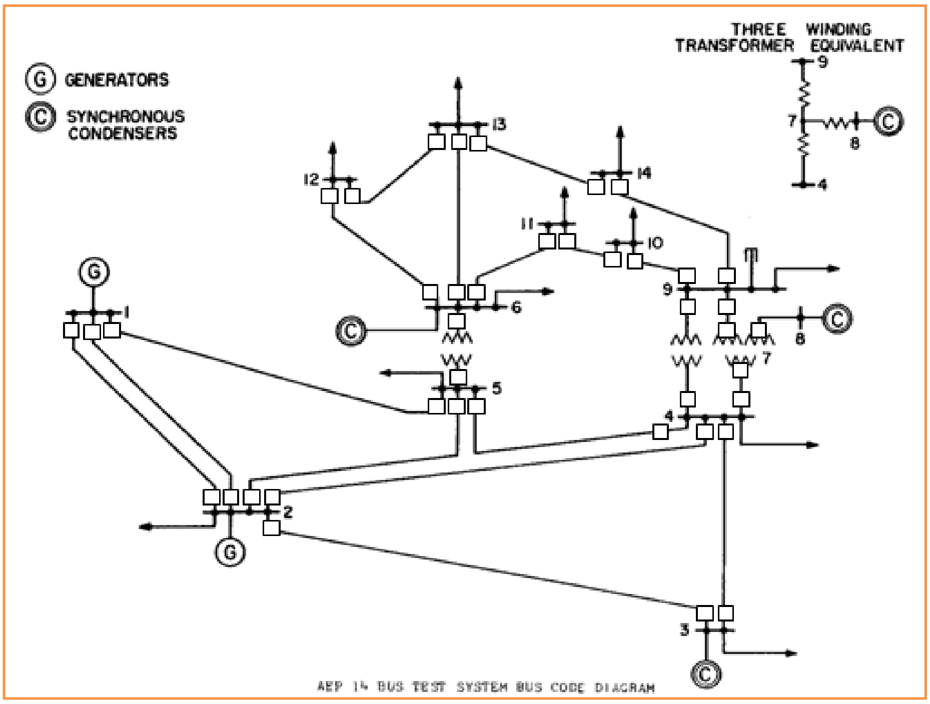


Figure 4.4: IEEE 14 bus test system. Considering DOCRs as protections for transformers.

The system is simulated using GA, ACO and DE with the corresponding parameters presented in previous section at minimum load. There are a total of 102 relay coordination pairs before sensitivity filter and 73 after. All three algorithms were simulated ten times. The convergence of each algorithm was averaged using the best fitness of each iteration of the ten simulations. This is presented in Figure 4.5 for comparison.

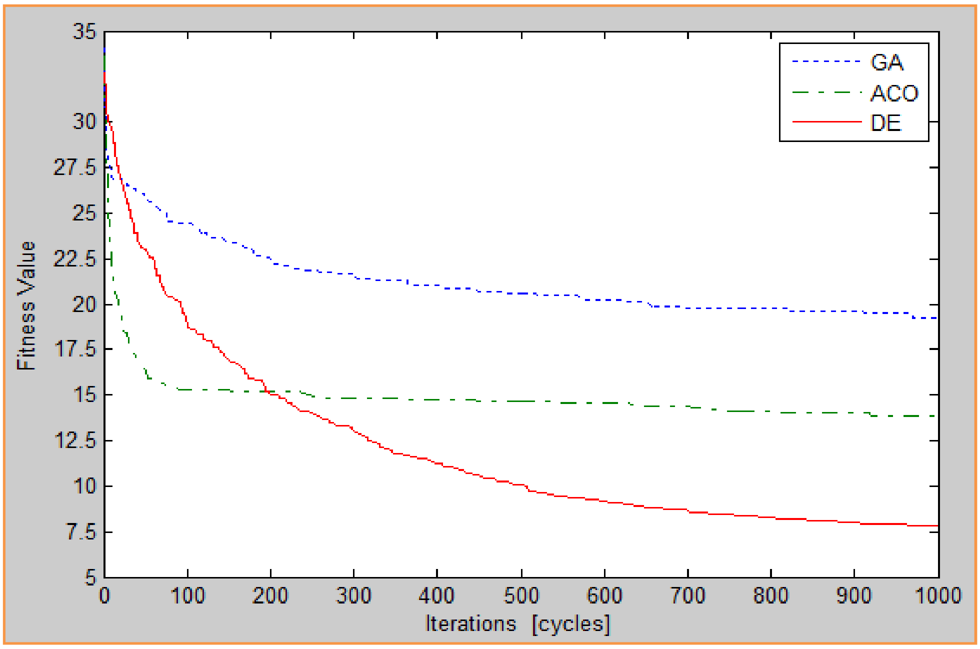


Figure 4.5: Averaged fitness convergence of the 14 bus test system of GA, ACO and DE in ten simulations operating at minimum load, considering DOCRs as protections for transformers.

The averaged number of violation of coordination constraints, averaged fitness convergence and averaged time of GA, ACO and DE are presented in Table 4.6.

Parameters	GA	ACO	DE
NV	3.2	1.3	0.8
Fitness	19.225	13.813	7.849
Time (sec)	10259	467	120

Table 4.6: Comparison of averaged results of GA, ACO and DE at minimum load, considering DOCRs as protections for transformers.

From these results, it is concluded that both ACO and DE have less violation of coordination constraint, better convergence and faster performance than GA. The DE shows an outstanding performance.

The averaged relay settings and operation time, as well as CTI and sensitivity of the ten averaged GA, ACO and DE simulations are presented in Table 4.7.

Algorithm	Dial	K	Backup time	Primary time	CTI	Sensitivity
GA	1.1832	1.4970	2.7396	0.9894	1.8516	3.91388
ACO	1.1707	1.5172	2.3805	0.9477	1.4661	3.88585
DE	0.9347	1.4600	1.6853	0.7581	0.9543	4.03123

Table 4.7: Averaged relay settings, operation time, CTI and sensitivity of GA, ACO and DE for 14 bus test system at minimum load, considering DOCRs as protections for transformers.

4.2.2.4 Case 4

In this case, the 14 bus test system is simulated at minimum load. Overcurrent relays are not considered as protection for transformers in this case. The new idea in this section is the open range of dial parameter in the coordination process. So limits of dial, iterations are modified for studying the algorithms behaviors as presented in Table 4.8.

Parameters	GA	ACO	DE
CTI	0.3	0.3	0.3
dial	[0.5:10.0]	[0.5:10.0]	[0.5:10.0]
k	[1.4:1.6]	[1.4:1.6]	[1.4:1.6]
dial step	continuous	0.05	continuous
k step	continuous	0.01	continuous
Q	--	100	--
R	--	5	--
Γ	--	--	0.5
F	--	--	0.8
Cr	--	--	0.5
individual-ants	500	500	500
iterations	5000	5000	5000

Table 4.8: Parameter settings of GA, ACO and DE. Open range search.

There are a total of 48 relay coordination pairs after the sensitivity filter. All three algorithms were simulated five times. The convergence of each algorithm was averaged using the best fitness of each iteration of the five simulations. This is presented in Figure 4.6 for comparison.

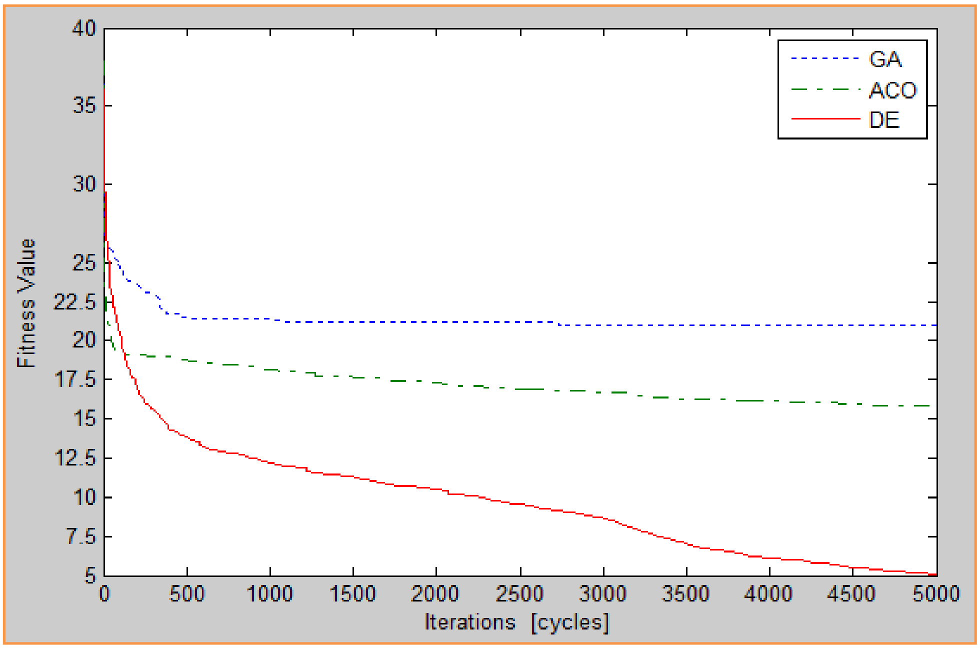


Figure 4.6: Averaged fitness convergence of the 14 bus test system of GA, ACO and DE in five simulations operating at minimum load. Open range dial simulation.

The averaged number of violation of coordination constraints, averaged fitness convergence and averaged time of GA, ACO and DE are presented in Table 4.9.

Parameters	GA	ACO	DE
NV	0	0	0
Fitness	20.980	15.808	5.054
Time (sec)	20687	4075	515

Table 4.9: Comparison of averaged results of GA, ACO and DE at minimum load. Open range dial simulation.

It is observed that there are zero violation of coordination constraints in all three algorithms. But the fitness value of GA and ACO are very far from the fitness values of Case 2. The fitness value of DE is very close to the value in Case 2. The DE shows an outstanding performance.

The averaged relay settings and operation time, as well as CTI and sensitivity of the ten averaged GA, ACO and DE simulations are presented in Table 4.10.

Algorithm	Dial	K	Backup time	Primary time	CTI	Sensitivity
GA	3.8181	1.4977	7.3595	2.6492	4.7102	4.00712
ACO	2.7053	1.5815	4.9068	1.8311	3.0757	3.79766
DE	0.9475	1.4330	1.6429	0.6255	1.0174	4.18542

Table 4.10: Averaged relay settings, operation time, CTI and sensitivity of GA, ACO and DE for 14 bus test system at minimum load. Open range dial simulation.

4.2.2.5 Comparison and Conclusion

The comparison purpose of cases 1 and 2 is to observe the speed and result quality of the algorithms. The DE outperformed GA and ACO.

Case 3 evaluated the robustness of the three algorithms by increasing the number of coordination pairs and maintaining the same initial settings as presented in Table 4.1. The DE outperformed GA and ACO.

Case 4 evaluated the convergence ability of the three algorithms by using an open range of dial as search space with no prior elimination. The settings are as presented in Table 4.8. The DE outperformed GA and ACO. DE found good quality results in reasonable amount of computational time.

These can be observed from the averaged results of the 4 cases in Table 4.11, Table 4.12, Table 4.13 and Figure 4.7.

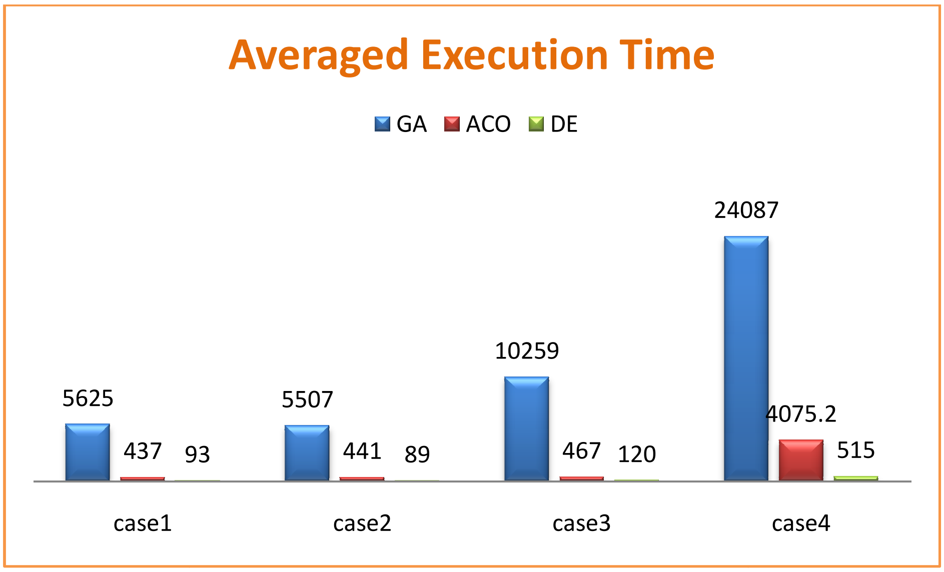


Table 4.11: Averaged execution time of GA, ACO and DE for the 4 cases.

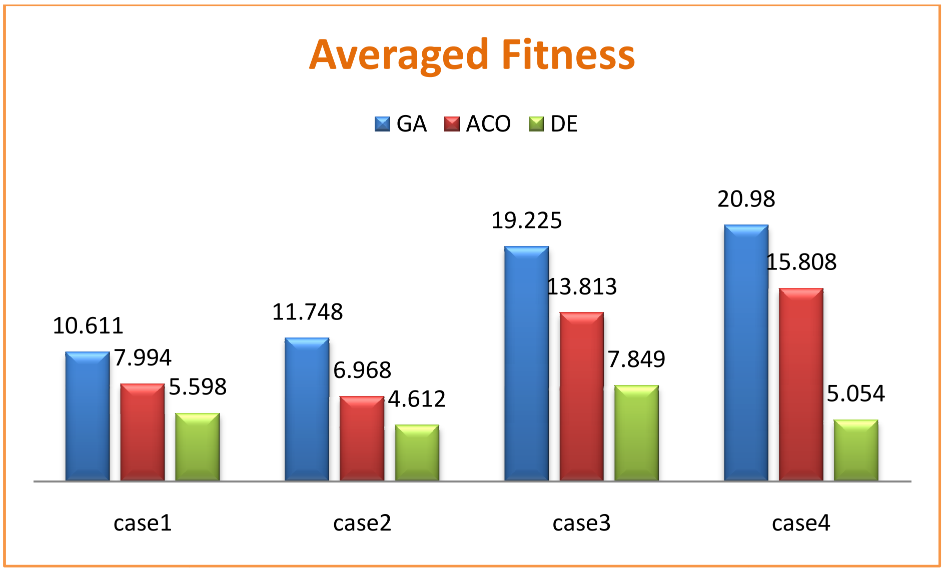


Table 4.12: Averaged fitness of GA, ACO and DE for the 4 cases.

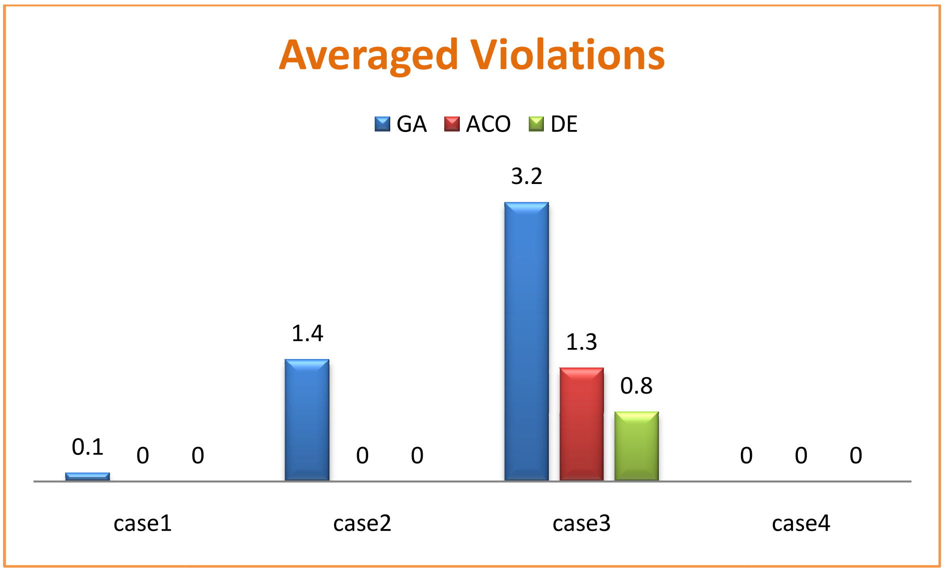


Table 4.13: Averaged number of violations of GA, ACO and DE for the 4 cases.

The overall performances (result quality, robustness, and convergence) of the three algorithms of all four cases are averaged and presented in Figure 4.7.

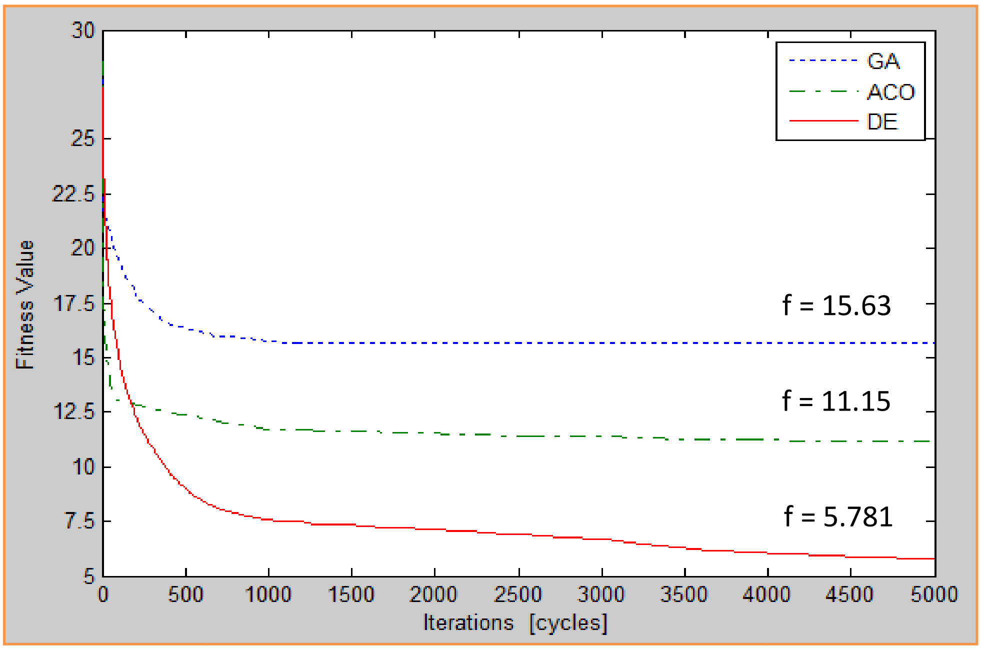


Figure 4.7: Overall performance of GA, ACO and DE.

From Table 4.11 it is observed that the execution time of GA increased almost double in case 3 due to the increment of coordination pairs, and almost 5 times in case 4 due to the increment of iterations compared to cases 1 and 2. On the other hand, both ACO and DE did not increase significantly in case 3 (are not affected significantly) due to the increment of coordination pairs. But in case 4, ACO increased more than 5 times compared to cases 1 and 2, this is because the open dial search increased the size of AS-graph, therefore decreased the speed of the algorithm dramatically. The DE increased reasonably in case 4 compared to cases 1 and 2.

From Table 4.12 it is observed that as there are more coordination pairs in the system, the fitness values increases. Case 3 > Case 1 > Case 2. This is reasonable because as there are more coordination pairs, there are more coordination constraints and therefore more difficult to coordinate. GA and ACO seem not to be as robust as DE in case 3 due to the increment of coordination pairs. In case 4, it is observed that DE tends to have much better convergence ability than GA and ACO because it's fitness value approaches the fitness of case 2.

From Table 4.13 it is observed that as coordination pairs increases the number of violation increases as well. This can be easily observed from case 3 compared to cases 1 and 2. The number of violations increased for all three algorithms because the number of coordination pairs was increased but the number of individuals/ant agents or number of iterations was not increased.

From Figure 4.7 it is observed that the overall performance of DE outstand GA and ACO. DE tends to converge to the minimum during the 5000 iterations, on the contrary, GA and ACO tends to converge to a fixed result and maintained throughout the 5000 iterations.

4.3 Real Time Coordination using DE

DE was chosen to coordinate DOCRs on more cases of Real Time coordination because it was demonstrated to be the best out of the three algorithms. The IEEE 30 bus test system is selected to study the behavior of the system under dynamic changes. These consequences of changes are presented in Table 2.2 described in section 2.5 "The Need of Real Time Coordination of DOCRs". Different cases are planned and studied to see whether or not the hypothesis is correct.

4.3.1 Parameter Settings and Test System Data

4.3.1.1 Parameter Settings

Parameters	DE
CTI	0.3
dial	[0.5:4.0]
k	[1.4:1.6]
dial step	continuous
k step	continuous
r	0.5
F	0.8
Cr	0.5
individual-ants	500
iterations	5000

Table 4.14: Parameter settings of DE.

The range of dial was selected by running the particular test system several times and by observing the results, one concludes the range where the results are located, and hence narrow the search space for obtaining better results and speeding up the algorithm convergence.

The only stopping criterion is to stop when the algorithm has reached the maximum iteration of 5,000. Although the contribution of results have minimum improvement after 1,000 iterations, this maximum iteration number was selected due to the reason that the most important issue on a real time basis analysis at this very moment is the result quality among the different cases and not the speed. This is to proof whether or not the hypothesis is correct with more accuracy than using just 1,000 iterations.

Now DE is simulated with 500 individuals due to the need of speed. Besides, the number 500 is tested and empirically seems to be a very suitable number of individuals in searching quality results in a reasonable computational time.

4.3.1.2 Test System Data

The IEEE 30-bus test system was chosen to test and analyze the dynamic operations in the system. The system is shown in Figure 4.8. The system consists of 72 relays not considering DOCRs as protections for transformers. There are a total of 141 coordination pairs before the sensitivity filter. The voltages were selected to be 34.5 kV for buses at high voltage side of transformers and 22 kV and 13.8 kV for buses at low voltage side of transformers. All relays are considered to have very inverse time characteristic curve as was presented in Table 2.1.

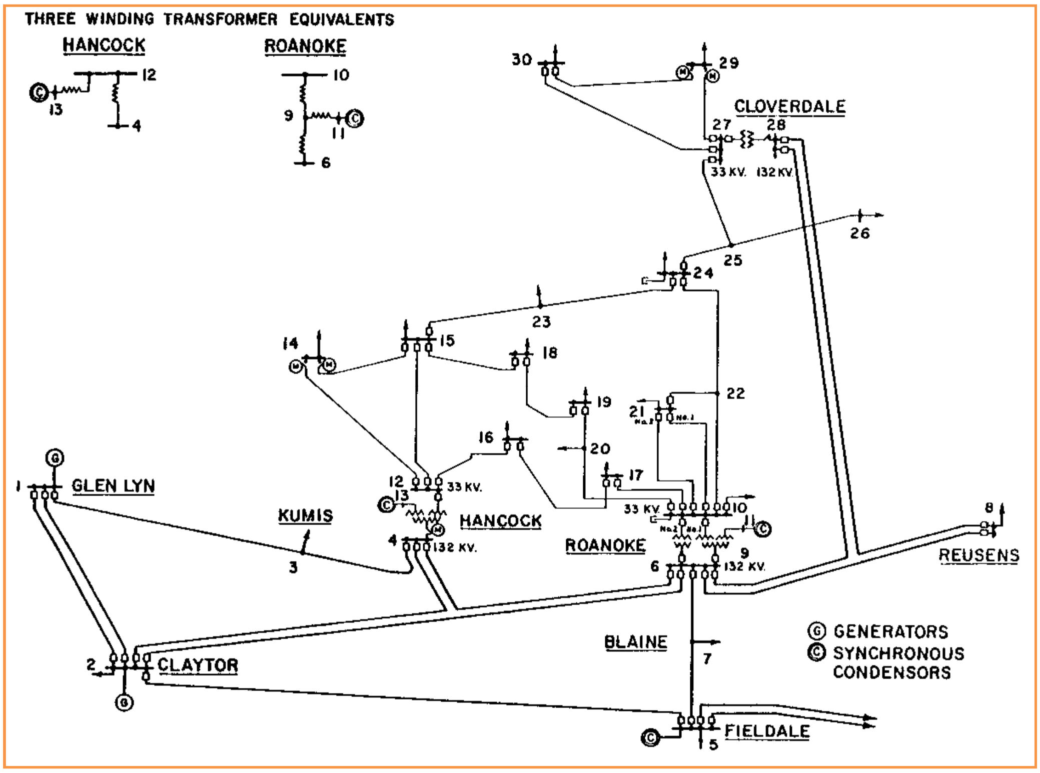


Figure 4.8: IEEE 30 bus test system.

The two lines between buses 1 and 2 have the same impedance value. Therefore the relays [1 2 1], [1 2 2], [2 1 1] and [2 1 2] sense the same amount of maximum load currents of 929 A, but due to the n-1 contingency analysis described in section 3.2.3, the maximum load currents of these relays are 2,002 A. The current values are based on minimum load operation.

The fault currents are calculated with the remote end opened. This was done due to two considerations, to obtain the maximum fault current that the relay senses and the very small probability for the remote end relay to mal-operate. Bear in mind that as elements' operation or network topology changes, load flow and fault analysis must be computed again through real time algorithm.

The data Xd for the generators one and two are 0.01 and 0.03 respectively.

The maximum load is the same as the original 30 bus load data while the minimum load is the 70% of the 30 bus load data.

4.3.2 Results and Analysis

4.3.2.1 Case 1

The 30 bus test system is simulated with the corresponding parameters presented in previous section at maximum load. There are a total of 99 relay coordination pairs after the sensitivity filter. The convergence is presented in Figure 4.9.

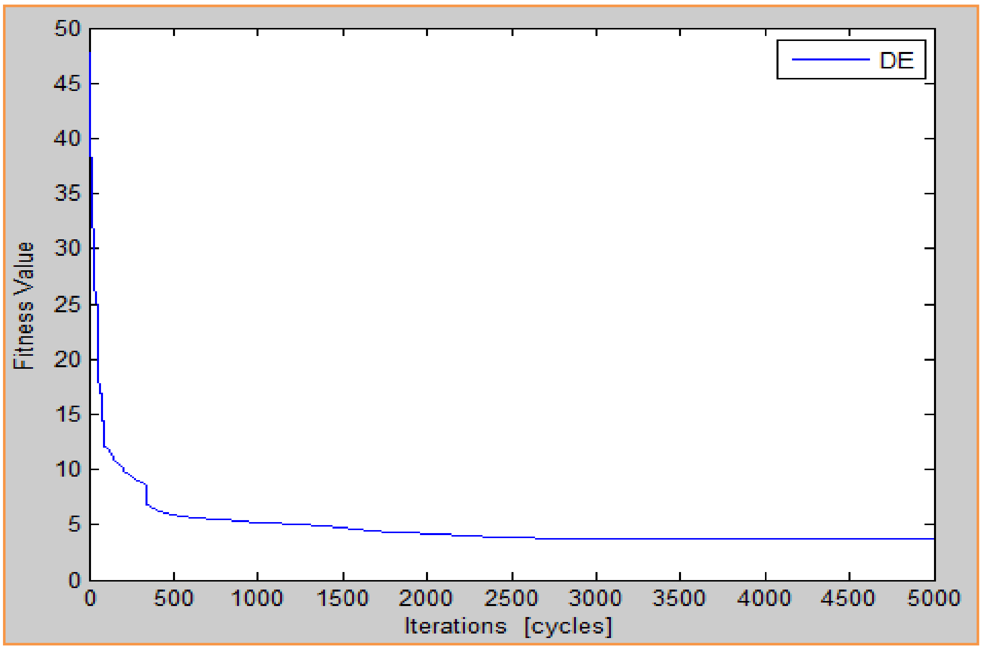


Figure 4.9: Fitness convergence of the 30 bus test system of DE operating at maximum load.

The number of violation of coordination constraints, fitness convergence and time of DE are presented in Table 4.2.

Parameters	DE
NV	0
Fitness	3.682
Time (sec)	1143

Table 4.15: Simulation result of DE of IEEE 30 bus system operating at maximum load.

The averaged relay settings and operation time, as well as CTI and sensitivity of DE are presented in Table 4.16.

Algorithm	Dial	K	Backup time	Primary time	CTI	Sensitivity
DE	0.9765	1.4069	1.5959	0.7833	0.8126	4.2722

Table 4.16: Averaged relay settings, operation time, CTI and sensitivity of DE for 30 bus test system at maximum load.

4.3.2.2 Case 2

The 30 bus test system is simulated with the corresponding parameters presented in previous section at minimum load. There are a total of 107 relay coordination pairs after the sensitivity filter. The convergence is presented in Figure 4.10.

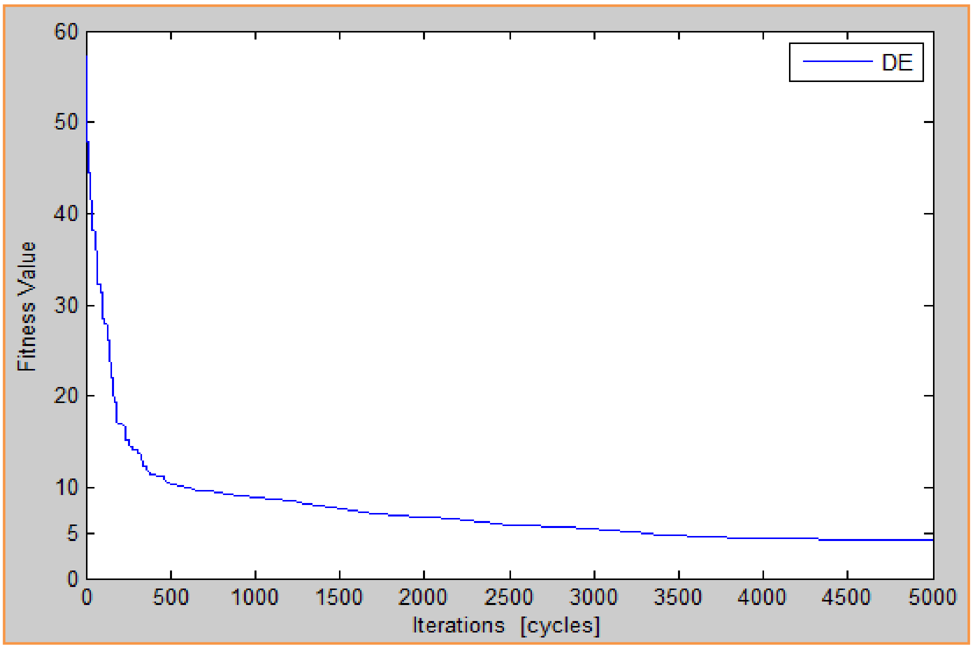


Figure 4.10: Fitness convergence of the 30 bus test system of DE operating at minimum load.

The number of violation of coordination constraints, fitness convergence and time of DE are presented in Table 4.17.

Parameters	DE
NV	0
Fitness	4.202
Time (sec)	1168

Table 4.17: Simulation result of DE of IEEE 30 bus system operating at minimum load.

The averaged relay settings and operation time, as well as CTI and sensitivity of DE are presented in Table 4.18.

Algorithm	Dial	K	Backup time	Primary time	CTI	Sensitivity
DE	1.152	1.4155	1.3300	0.7361	0.5939	5.8048

Table 4.18: Averaged relay settings, operation time, CTI and sensitivity of DE for 30 bus test system at minimum load.

4.3.2.3 Case 3

The 30 bus test system is simulated with the corresponding parameters presented in previous section at minimum load with outage of line [1 2 2]. There are a total of 97 relay coordination pairs after the sensitivity filter. The convergence is presented in Figure 4.11.

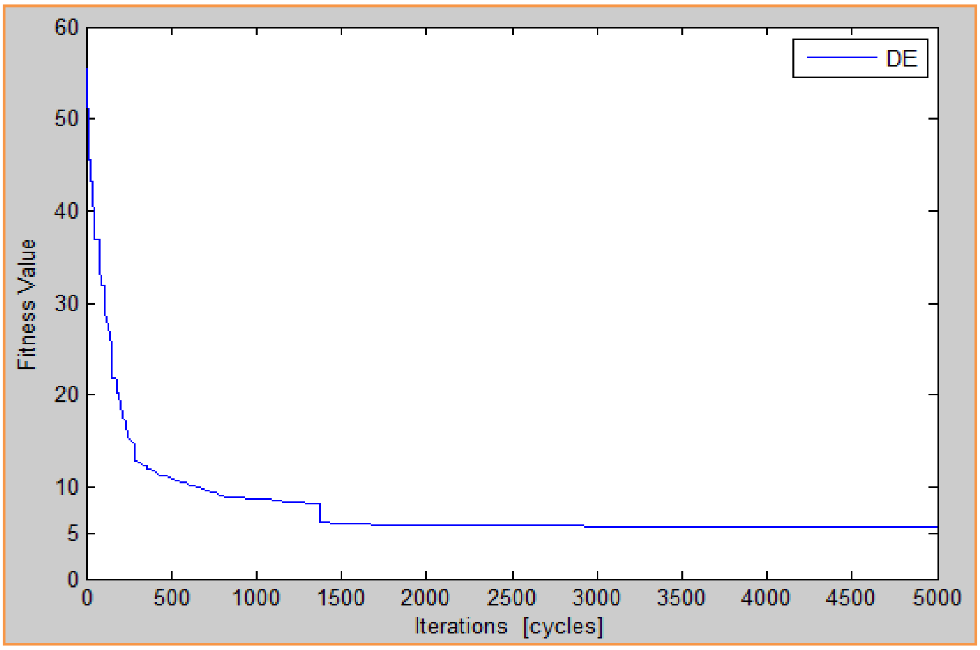


Figure 4.11: Fitness convergence of the 30 bus test system of DE operating at minimum load with n-1 contingency of line [1 2 2].

The number of violation of coordination constraints, fitness convergence and time of DE are presented in Table 4.19.

Parameters	DE
NV	0
Fitness	5.584
Time (sec)	1141

Table 4.19: Simulation result of DE of IEEE 30 bus system operating at minimum load with n-1 contingency of line [1 2 2].

The averaged relay settings and operation time, as well as CTI and sensitivity of DE are presented in Table 4.20.

Algorithm	Dial	K	Backup time	Primary time	CTI	Sensitivity
DE	1.2365	1.4479	1.7195	0.9321	0.7874	5.3651

Table 4.20: Averaged relay settings, operation time, CTI and sensitivity of DE for 30 bus test system at minimum load.

4.3.2.4 Case 4

The 30 bus test system is simulated with the corresponding parameters presented in previous section at minimum load with outage of G2 and an entrance of G3 located at bus 5. There are a total of 121 relay coordination pairs after the sensitivity filter. The convergence is presented in Figure 4.12.

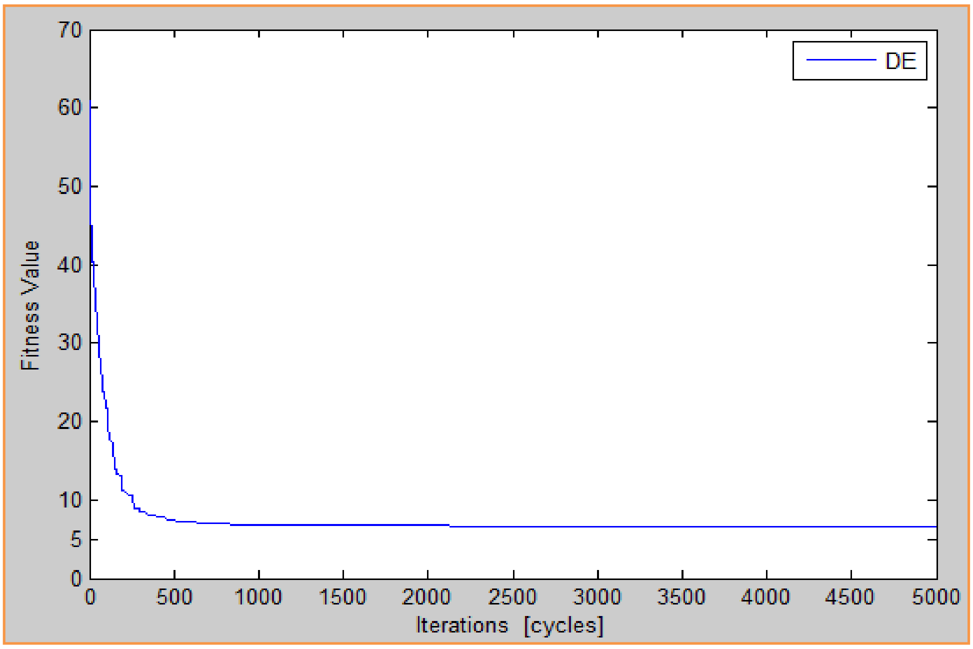


Figure 4.12: Fitness convergence of the 30 bus test system of DE operating at minimum load with output of G2 and input of G3.

The number of violation of coordination constraints, fitness convergence and time of DE are presented in Table 4.21.

Parameters	DE
NV	0
Fitness	6.656
Time (sec)	996

Table 4.21: Simulation result of DE of IEEE 30 bus system operating at minimum load with output of G2 and input of G3.

The averaged relay settings and operation time, as well as CTI and sensitivity of DE are presented in Table 4.22.

Algorithm	Dial	K	Backup time	Primary time	CTI	Sensitivity
DE	1.7463	1.4801	1.8883	1.0058	0.8826	5.7999

Table 4.22: Averaged relay settings, operation time, CTI and sensitivity of DE for 30 bus test system at minimum load with output of G2 and input of G3.

4.3.2.5 Case 5

The 30 bus test system is simulated with the corresponding parameters presented in previous section at maximum load referring to case 1 with increment of load on bus 30 of 15MW. There are a total of 93 relay coordination pairs after the sensitivity filter. The convergence is presented in Figure 4.13.

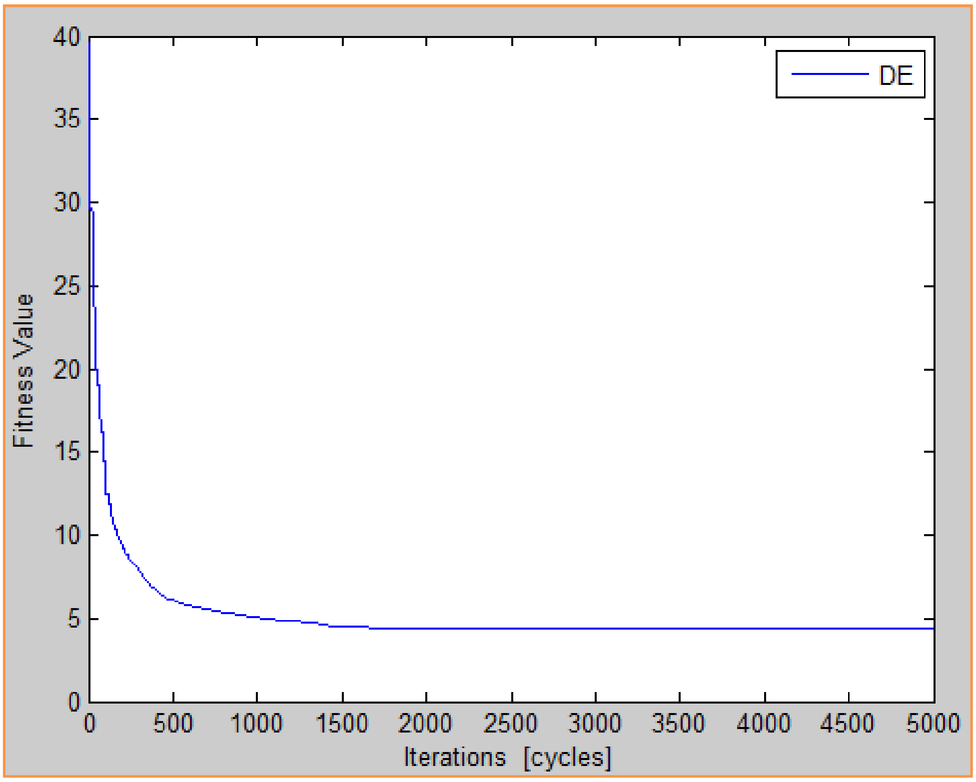


Figure 4.13: Fitness convergence of the 30 bus test system of DE operating at maximum load with increment of load on bus 30 of 15MW.

The number of violation of coordination constraints, fitness convergence and time of DE are presented in Table 4.23.

Parameters	DE
NV	0
Fitness	4.375
Time (sec)	867

Table 4.23: Simulation result of DE of IEEE 30 bus system operating at maximum load with increment of load on bus 30 of 15MW.

The averaged relay settings and operation time, as well as CTI and sensitivity of DE are presented in Table 4.24.

Algorithm	Dial	K	Backup time	Primary time	CTI	Sensitivity
DE	0.9364	1.4124	1.9378	0.7884	1.1494	3.6476

Table 4.24: Averaged relay settings, operation time, CTI and sensitivity of DE for 30 bus test system at maximum load with increment of load on bus 30 of 15MW.

4.3.2.6 Case 6

The 30 bus test system is simulated with the corresponding parameters presented in previous section at maximum load referring to case 1 with increment of line between buses 1 and 3. There are a total of 151 relay coordination pairs before the sensitivity filter and 106 after. The convergence is presented in Figure 4.14.

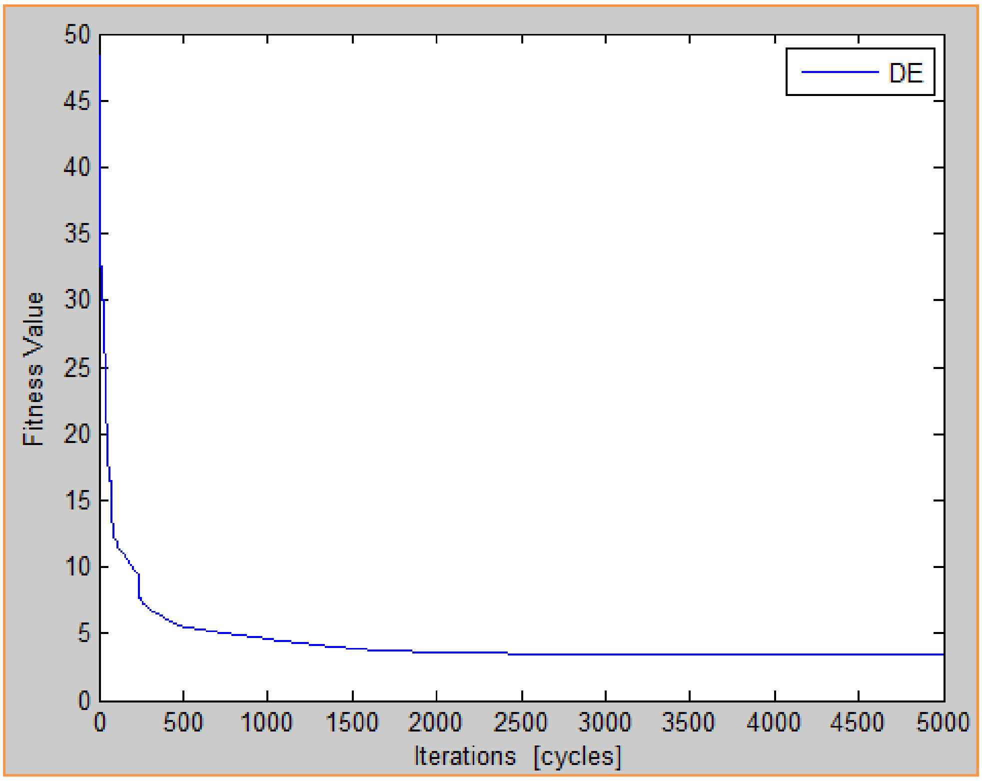


Figure 4.14: Fitness convergence of the 30 bus test system of DE operating at maximum load with increment of line between buses 1 and 3.

The number of violation of coordination constraints, fitness convergence and time of DE are presented in Table 4.25.

Parameters	DE
NV	0
Fitness	3.459
Time (sec)	1139

Table 4.25: Simulation result of DE of IEEE 30 bus system operating at maximum load with increment of line between buses 1 and 3.

The averaged relay settings and operation time, as well as CTI and sensitivity of DE are presented in Table 4.26.

Algorithm	Dial	K	Backup time	Primary time	CTI	Sensitivity
DE	0.9187	1.4060	1.4733	0.7028	0.7704	4.2994

Table 4.26: Averaged relay settings, operation time, CTI and sensitivity of DE for 30 bus test system at maximum load with increment of line between buses 1 and 3.

4.3.2.7 Analysis and Conclusion

The six cases above are analyzed to see whether the hypothesis is right or wrong. Case 1 and case 2 are compared, mainly their relay operation time and sensitivity.

The purpose of case 3 is simply a demonstration of the real time algorithm when there is a network topology change. The newly coordinated system has the ability to withstand one contingency as well, after the occurrence of the previous contingency.

Case 4 demonstrates the ability of the real time algorithm to coordinate the DOCRs when a new generator is considered in the network. This case has no reference to be compared.

Case 5 demonstrates the inappropriate relay operations (inappropriate operation), if real time coordination is not implemented.

Case 6 demonstrates the possible improvements of sensitivity, if real time coordination is implemented.

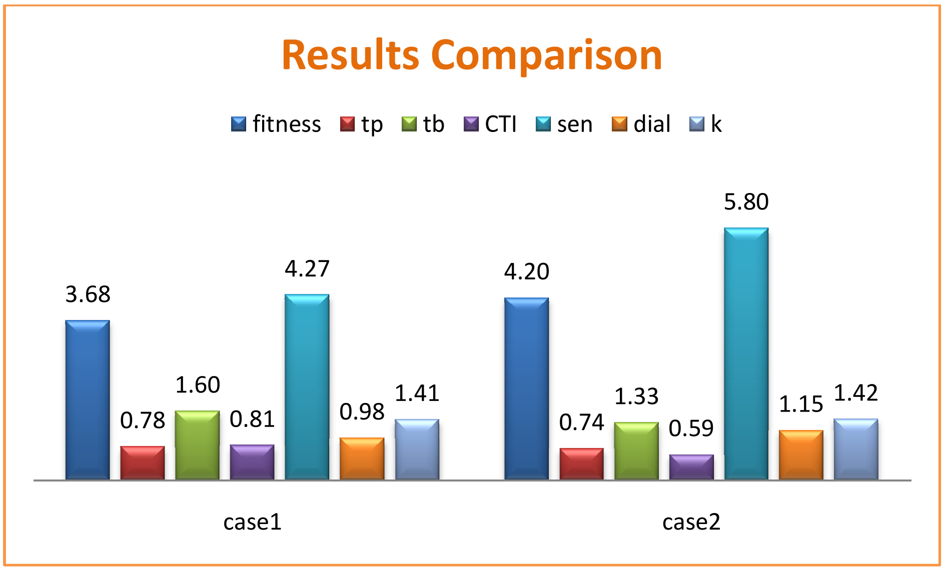


Table 4.27: Results comparison of the 30 bus test system of DE operating at maximum (case 1) and minimum (case 2) load.

It is observed from Table 4.27 that even though case1 has smaller fitness value than case 2 the averaged relay operation time (primary and backup) and CTI of case 2 are smaller than case 1. This demonstrates that the real time coordination does enhance the relay operation time.

Another observation is the increment of sensitivity in case 2. This also demonstrates that the real time coordination does enhance the relays sensitivities. Not only are the sensitivities of relays increased but the number of coordination pairs are also increased due to the increase of sensitivity as presented in Table 4.28:

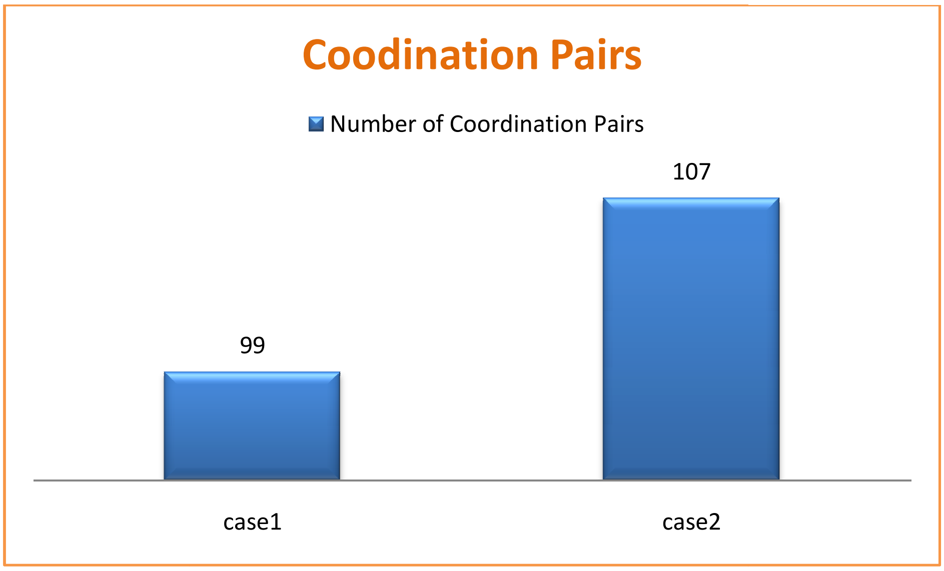


Table 4.28: Comparison of number of coordination pairs.

A very important observation from Table 4.27 is the increment of averaged dial in case 2. So even though case 2 has greater dial than case 1, the averaged relay operation time are smaller than case 1. In other words, dial is not the only parameter that can manipulate relay operation time, but also the pickup current. Therefore, as the pickup current decreases, the relay operation time decreases as well.

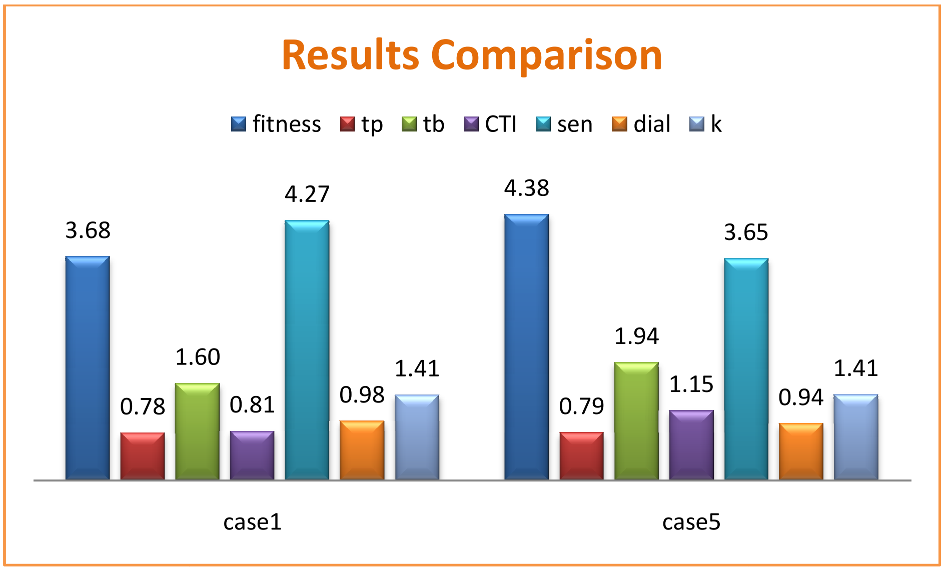


Table 4.29: Results comparison of the 30 bus test system of DE operating at maximum load (case 1) with increment of load at bus 30 of +15MW.

From Table 4.29 it is observed that after the re-coordination of the system due to the increment of load at bus 30 as presented in case 5, there is greater averaged relay operation time (primary and backup), greater CTI and smaller sensitivity. Apparently, the real time coordination did no good, but made things worse. Let's take a closer view of the effect of this increment of load by analyzing the load current. As the increment was located at bus 30, we analyze the nearby relays, since they are the most affected by this change.

Relay Name	Ipickup
27 30 1	358.16
30 27 1	358.16

Table 4.30: Pickup current with contingency analysis before the increment of load at bus 30.

Relay Name	Load current
27 30 1	438.34
30 27 1	438.34

Table 4.31: Load current without contingency analysis after the increment of load at bus 30.

From all the relays it was observed that these two relays [27 30 1] and [30 27 1] as shown in Table 4.30 and Table 4.31 have an increase of load current without contingency analysis after the increment of load at bus 30 which is greater than the maximum pickup current calculated considering contingency analysis before this increment of load. In other words, as the load at bus 30 is increased, these two relays will operate inappropriately because the actual load current is greater than de pickup current.

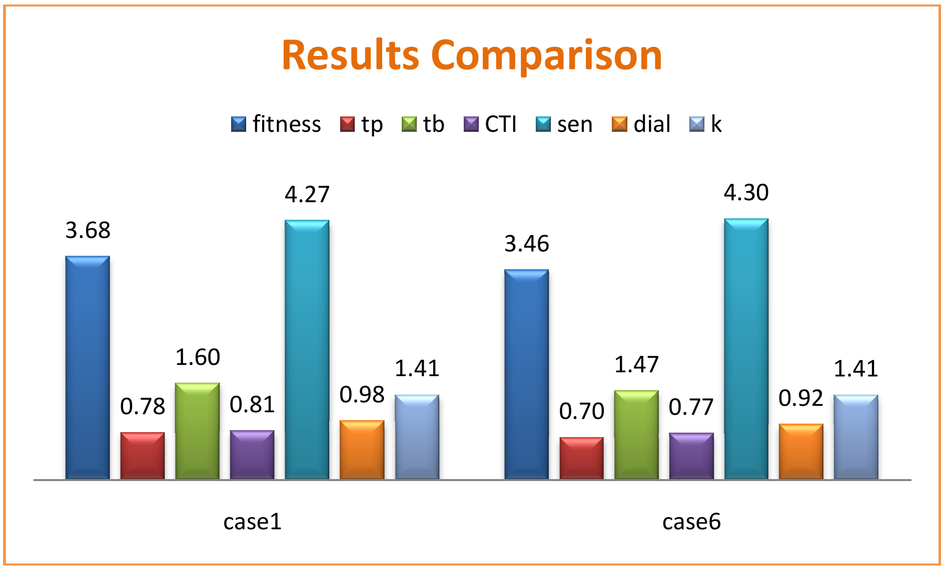


Table 4.32: Results comparison of the 30 bus test system of DE operating at maximum load (case 1) with increment of line between buses 1 and 3.

From Table 4.32 it is observed that after a new line is constructed, the averaged relay operation time (primary and backup), CTI decreased. The sensitivity increased.

These changes may not be very notable on the averaged value, but it is has a great impact on the DOCR [1 3 1] which functions as backup for relay [3 4 1]. These are relays that originally exist in the system. This is presented in Table 4.33 and Table 4.34:

Coordination Pair	Sensitivity
1 3 1 3 4 1	2.8420

Table 4.33: Sensitivity before the newly constructed line between buses 1 and 3.

Coordination Pair	Sensitivity
1 3 1 3 4 1	3.6050

Table 4.34: Sensitivity after the newly constructed line between buses 1 and 3.

4.3.2.8 Implementation Criteria

As the different sceneries are presented, one can easily understand the effect of intermittent source. For example wind, solar, hydraulic powers are very dynamic in the aspect of energy generation. They connect to the system when they have energy and disconnect from the system when they don't. Therefore, in order to avoid inappropriate relay operations, their generations are considered in the coordination. But this causes the DOCRs to become less sensitive when these intermittent sources are not connected on to the system. So as a conclusion, an online coordination will become very effective for this case.

Actually, the effect of distributed generation (wind, solar, hydraulic etc) is seemed as a normal energy injection. The intermittent characteristic is the major factor of these sources. Therefore, the benefits of real time coordination can be easily understood, since the intermittent source can suddenly reach maximum generation because there is a lot of wind and also reach minimum generation because there is no wind, the load flow changes drastically. Hence, the criteria of including the distributed generation are critical.

The distributed generations of small capacity (solar) can simply be omitted from the analysis, since their fault contribution and generation are very small compared to the fault contribution and generation of the entire system. They are insignificant.

The distributed generations of big capacity (wind, hydraulic etc) will be considered to have maximum fault (as if they are generating at maximum to have maximum fault); and at the same time considered to have minimum generation (as if there is almost no wind or almost no water). These considerations are to avoid the loss of coordination for DOCRs that are located on the distributed generator bus which offer backup for relays on adjacent lines; and DOCRs of the system.

The considerations of distributed generators of big capacity cannot follow or base on prognostic data, since the nature is unpredictable. Therefore, boarder conditions are planned; the worst conditions that can occur are included; the purpose of these considerations is to avoid the loss of coordination of DOCRs that are to be coordinated.

4.4 Conclusion

All three algorithms showed the ability to encounter reasonable results for the tested system. But due to the need of speed in real time coordination, the number of individuals and ant agents were reduced to only 500 for the complicated problem. This lead to bad results for GA, but at the same time also showed the outstanding performance of DE. DE encountered the best results with 500 individuals out of the three algorithms, and is also the fastest. DE is the most suitable candidate for real time coordination.

The real time coordination surely increased the sensitivity of DOCRs in some cases and at the same time reduced the sensitivity of DOCRs in other cases. Also, relay operation time are reduced in some cases and increased in other cases. These are all due to the operation of the network. But despite of the reduction of sensitivity or increment of relay operation time, these are due to the latest network operation condition. Therefore, the system is prepared for another unknown contingency. This made the system to stay strong at all time.

CHAPTER 5 CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

5.1 Introduction

In this chapter, important ideas are summarized and highlighted. As well as good practice recommendation, contribution and future works.

5.2 Summary and General Conclusion

From the comparison results of the three algorithms, it was observed that GA has the worst result, slowest and the most affected in execution time when the number of coordination pairs increased. On the contrary, both ACO and DE are faster and obtain better results than GA, and are almost not affected by the increment of coordination pairs. The execution time in this thesis is a very important factor as well as the result quality, robustness and convergence ability. DE has the global best performance over the other algorithms studied in this thesis.

The Real Time Coordination really did satisfy the hypothesis. The relay operation time reduced, the sensitivity increased and the system is prepared for another contingency.

5.3 Good Coordination Practice and Highlighted Experiences

<u>Manual Coordination</u>

1. In a radial system, start the coordination process from the furthest DOCR from the source. Eventually, the last DOCR to be coordinated is the one nearest to the source.

2. In a mesh system, choose a starting point and coordinate the system. If the DOCRs are not coordinated when closing the ring system, then choose another starting point and coordinate again. Repeat until the mesh system is coordinated.

Computational Coordination

1. GA -- use as many chromosomes as possible to get quality results, but bear in mind that for every chromosome increased in the population, the execution time increases as well.

2. ACO -- as the step sizes are made more continuous, the AS-graph matrix increases and the execution time increases, but this does not guarantee a better result than choosing a bigger step size. In fact, this can lead to poor quality result as the ant agents cannot explore all settings or will need to increase the amount of ant agents to do so, but the execution time will increase. On the contrary, choosing a big step size may speed up the coordination process but simultaneously lead to poor quality result. The empirical test showed that a good step size of dial which will not increase the execution time significantly and at the same time offering a good result is 0.05. Q and R shall not be close values for coordination problems, because they can cause a premature convergence.

3. DE -- the classic DE (simplest version) mutation with difference vectors, DE mutation using arithmetic recombination are not suitable for protection coordination. They are very fast in execution time, but return very poor results. On the other hand, DE using trigonometric mutation outstand the above mentioned versions for coordination purpose. Good quality results were found in reasonable computational time.

4. Both GA and ACO need to narrow down the search space in order to obtain quality results.

5. DE does not necessarily need a narrowed search space to obtain quality results. Unlike GA and ACO which significantly suffer premature convergence, quality results can be obtained as iteration increases.

6. Perform sensitivity filtration of the coordination pairs before coordinating them. To insure that the optimization algorithm will not spend extra time on trying to find settings for those insensitive pairs of relays which per se have no settings that will suit them.

<u>Other ideas</u>

1. The pickup current must not be selected accordingly to the power flow analysis, but according to an n-1 contingency analysis. This ensures the obtained coordination settings to be able to function properly when there is a presence of one contingency (element outage).

2. Even though dial is the major factor that affects the DOCRs operation time; the parameter dial's primordial function is not to reduce the operation time of relays but the freedom parameter to keep the coordination pairs coordinated. So the principal usage/objective of dial is not fast operation time, but the zero violation of coordination constraints. i.e.: The IEEE 14 and 30 bus systems were both simulated considering and not considering DOCRs as transformer protections and it was observed that as more coordination pairs were added, the averaged dial increased to satisfy all coordination constraints.

   Ps.--> If use very small dial to get small time but sacrificed the fulfillment of coordination constraints, leading to violation of constraints. Then this set of relay settings are of no use, because the DOCRs are not coordinated!

3. Another factor that affects the averaged size of dial is the load demand. As the IEEE 14 and 30 bus systems were simulated operating at maximum and

minimum load; it was observed that the averaged dial for the two systems at maximum load are smaller than the averaged dial for the two systems at minimum load. This might not be reasonable but it is indeed correct. As was presented in the previous point, dial is the major parameter that is used to satisfy the coordination constraints by adjusting the operation time; therefore, as load current decreases the relay operation time decreases (faster operation) as well, so the dial increases to maintain coordination. On the contrary, if the load current increases the dial decreases.

4. According to fault analysis for different protection scheme, different reactance will be used in the study. The X''d is used in the study of instantaneous overcurrent relay (sub-transmission and distribution) because a fault extinction time of 1-2 cycles is required. The X'd is used in the study of distance relay (transmission) because a fault extinction time of 2-8 cycles is required to avoid stability problems and also avoid unnecessary operation due to temporary power swing of generators. And the Xd or Xs is used in the study of inverse time overcurrent relays (sub-transmission and distribution), the averaged fault extinction time in sub-transmission system is around 30-60 cycles.

5.4 Contributions

1. Improvement of objective function by normalizing the fitness value so that it can be compared among systems of different size.
2. Improvement of GA for the coordination problem; intelligent mutation.
3. Formulate the coordination problem using ACO, and also the improvement of ACO for this specific problem; intelligent exploration.
4. Empirically adjust the constants *Q* and *R* for ACO; and also the original idea of percentage global update instead of best global update.

5. Formulate the coordination problem using DE. Three versions of DE were tested: mutation with difference vectors, trigonometric mutation and arithmetic recombination; the best was chosen.

6. Three algorithms GA, ACO and DE are studied, applied in protection and compared. Their performance: execution time, quality result, robustness, convergence ability are reported and documented. The best was chosen.

7. The concept of "Real Time Coordination" was introduced. This online coordination enhanced the operation time of DOCRs, sensitivity of DOCRs, the number of coordination pairs due to sensitivity and the ability to withstand another contingency.

5.5 Recommendations for Future Work

1. Add the third freedom parameter, type of curves. In order to reduce even more the operation time of relays. Fourth or fifth freedom parameters may be added as well, to guarantee minimum operation time.

2. Improve the penalization by monitoring each of the penalized elements separately (penalization by index), which should lead to better and faster convergence.

3. Explore, test, study and analyze a dynamic objective function. That the weighting values α, β, δ changes throughout the execution of the algorithms.

4. Upgrade of DE; by making the DE more efficient in speed and result quality using automatic re-adjustment of parameters NP, Cr and F as the algorithm runs.

5. Explore, test, study and analyze other versions of DE. Three versions of DE are tested in this thesis, yet there are many other versions that worth a try.

6. Explore, test, study and analyze parallel DE. Many calculations may be carried out simultaneously based on the principle that large problems can often be divided into smaller ones; coordination may be solved in parallel. This will enhance significantly the execution time of DE.

7. Explore, test, study and analyze the performance of CMA-ES. Compare it with DE to see which is more suitable for coordination.

8. Develop hybrid methods.

9. Reduce the coordination pairs before coordination. If a DOCR shall offer backup for more than one primary relay, choose the slowest primary relay to coordinate with this backup. The idea is to simplify the number of coordination constraints in the optimization algorithm, so the pairs that are reduced due to faster primary relay operation are not really eliminated. At the end these pairs need to be evaluated (operation time) when the relay settings are calculated. So it is just a temporary reduction, not elimination (filter) of coordination pairs. This can be done by observing the Isc.

BIBLIOGRAPHY

[1] Carlos J. Zapata and German E. Mejia “Coordinacion de reles de sobrecorriente en sistemas enmallados utilizando programacion lineal”, 2003.

[2] A. J. Urdaneta, R. Nadira, and L. G. Perez, "Optimal coordination of directional overcurrent relays in interconnected power systems", *IEEE Transactions on Power Delivery*, vol. 3, No. 3, pp. 903-911, July.1988.

[3] A. J. Urdaneta, H. Restrepo, S. Marquez, and J. Sanchez "Coordination of directional overcurrent relay timimg using linear programming", *IEEE Transactions on Power Delivery*, vol. 11, No.1, pp. 122-129, January 1996.

[4] B. Chattopadhyay, M. S. Sachdev, T. S. Sidhu "An on-line relay coordination algorithm for adaptive protection using linear programming technique", *IEEE Transactions on Power Delivery*, vol. 11, No.1, pp. 165-173, January 1996.

[5] Mohamed M. Mansour, Said F. Mekhamer, and Nehad El-Sherif El-Kharbawe, "A modified particle swarm optimizer for the coordination of directional overcurrent relays", *IEEE Transactions on Power Delivery*, vol. 22, No.3, pp. 1400-1410, July 2007.

[6] Reza Mohammadi, Hossein Askarian Abyaneh, Farzad Razavi, Majid Al-Dabbagh, Seyed H. H. Sadeghi, "Optimal relays coordination efficient method in interconnected power systems", *journal of Electrical Engineering*, vol. 61, No. 2, pp. 75-83, 2010.

[7] Manohar Singh, B. K. Panigrahi, "Optimal overcurrent relay coordination in distribution system", *IEEE*, 2011.

[8] Dharmendra Kumar Singh and S. Gupta, "Optimal coordination of directional overcurrent relays: A genetic algorithm approach", *IEEE Students' Conference on Electrical, Electronics and Computer Science*, 2012.

[9] Dusit Uthitsunthorn and Thanatchai Kulworawanichpong, "Optimal overcurrent relay coordination using genetic algorithms", *International Conference on Advances in Energy Engineering*, 2010.

[10] Abbas Saberi Noghabi, Javad Sadeh, and Habib Rajabi Mashhadi, "Considering different network topologies in optimal overcurrent relay coordination using a hybrid GA", *IEEE Transactions on Power Delivery*, vol. 24, No.4, pp. 1857-1863, Octuber 2009.

[11] A. Motie Girjandi, M. Pourfallah, "Optimal coordination of overcurrent relays by mixed genetic and particle swarm optimization algorithm and comparison of both", *International Conference on Signal, Image Processing and Applications*, vol. 21, 2011 IACSIT Press, Singapore.

[12] J. Lewis Blackburn, and Thomas J. Domin, "Protective relaying, principles and applications", 3rd edition, 2006.

[13] Kwang Y. Lee, and John G. Vlachogiannis, "Optimization of power systems based on ant colony system algorithms: an overview", ISAP, 2005.

[14] Yun-He Hou, Yao-Wu Wu, Li-Juan Lu, Xin-Yin Xiong "Generalized ant colony optimization for economic dispatch of power systems", IEEE, 2002.

[15] Shyh-Jier Huang, "Enhancement of hydroelectric generation scheduling using ant colony system based optimization approaches", *IEEE Transactions on Energy Conversion*, vol. 16, No. 3, September 2001.

[16] Marco Dorigo, mauro Birattari, and Thomas Stutzle, "Ant colony optimization: artificial ants as a computational intelligence technique", *IEEE Computational Intelligence Magazine*, November 2006.

[17] Swagatam Das and Ponnuthurai Nagaratnam Suganthan, "Differential Evolution: A Survey of the State of the Art", *IEEE Transactions on the Evolutionary Computation*, vol. 15, No. 1, February 2011.

[18] Hadi Saadat "Power system analysis", 1999.

[19] John Horak "Directional Overcurrent Relaying (67) Concepts", Basler Electric Company.

[20] Jarm-Long Chung, Ying Lu, Wen-Shiow Kao and Chih-Ju Chou, "Study of Solving the Coordination Curve Intersection of Inverse-Time Overcurrent Relays in Sub-

transmission Systems", *IEEE Transactions on Power Delivery*, Vol.23, No.4, October 2008.

[21] A. J. Urdaneta, L. G. Perez, and H. Restrepo, "Optimal coordination of directional overcurrent relays considering dynamic changes in the network topology", *IEEE Transactions on Power Delivery*, vol. 12, No. 4, pp. 1458-1464, October.1997.

[22] Abbas Saberi Noghabi, Javad Sadeh, and Habib Rajabi Mashhadi, "Optimal coordination of directional overcurrent relays considering different network topologies using interval linear programming", *IEEE Transactions on Power Delivery*, vol. 25, No.3, pp. 1348-1345, July 2010.

[23] http://www.businessdictionary.com/definition/optimization.html

[24] Javier Otamendi "The Importance of the Objective Function Definition and Evaluation in the Performance of the Search Algorithms", 16th European Simulation Symposium, 2004.

[25] IEEE Std. C37.113-1999, Guide for protective relay applications to transmission lines, Sept 1999.

APPENDIX A

Radial Coordination

The radial system that was illustrated in Figure 2.7 will be studied as an example of coordination. Consider $k = 1.5$ and $CTI = 0.3$. Note that the purpose of this example is to show the process of manual coordination; therefore, contingency analysis is not considered.

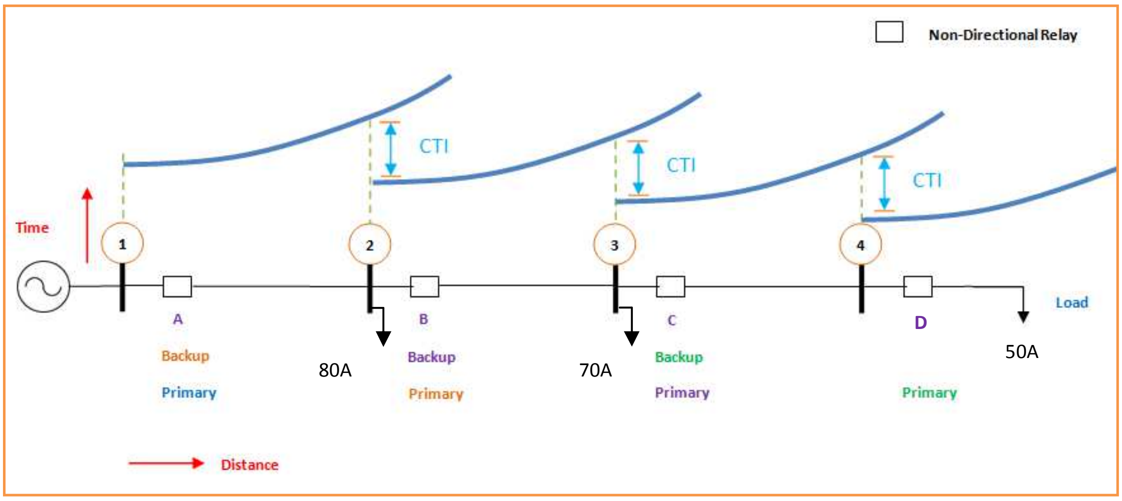


Figure 2.7: Coordination of DOCRs in a radial system.

The short circuit data of each bus are given:

Bus	Isc 3ph Primary
1	2000
2	1500
3	1000
4	500

The load and short circuit current data of each relay are given:

Relay	Isc 3ph Primary	Isc 3ph Backup	Iload	Ipickup
A	2000	1500	80+70+50	300
B	1500	1000	70+50	180
C	1000	500	50	75
D	500	--	50	75

The three phase backup current of the relays are also called coordination current. The pickup current is the product of load current times the factor *k*.

Now the system shown in Figure 2.7 is manually coordinated as presented in section 2.4.1.

1. Select one of the IEEE conventional curves

The very inverse (VI) curve is selected. The constants A, B and n are as presented in Table 2.1 which are 19.61, 0.491 and 2 respectively.

2. Propose a dial for the first primary relay

$$dial_{R_D} = 0.5$$

3. Calculate operation time of relay D

$$t_{R_D} = \left[\frac{A}{\left(\frac{I_{sc3\emptyset_{R_D}}}{I_{pickup_{R_D}}}\right)^n - 1} + B\right] * dial_{R_D} = \left[\frac{19.61}{\left(\frac{500}{75}\right)^2 - 1} + 0.491\right] * 0.5 = 0.4712$$

4. Calculate operation time of backup relay

$$t_{R_C} = t_{R_D} + CTI = 0.4712 + 0.3 = 0.7712$$

5. Calculate dial of backup relay

$$dial_{R_C} = \frac{t_{R_C}}{\left[\frac{A}{\left(\frac{I_{sc3\emptyset_{RC}}}{I_{pickup_{R_C}}}\right)^n - 1} + B\right]} = \frac{0.7712}{\left[\frac{19.61}{\left(\frac{500}{75}\right)^2 - 1} + 0.491\right]} = 0.8273$$

6. Calculate primary operation time of relay C

$$t_{R_C} = \left[\frac{A}{\left(\frac{I_{sc3\emptyset_{RC}}}{I_{pickup_{R_C}}}\right)^n - 1} + B\right] * dial_{R_C} = \left[\frac{19.61}{\left(\frac{1000}{75}\right)^2 - 1} + 0.491\right] * 0.8273 = 0.4980$$

7. Calculate operation time of backup relay

$$t_{R_B} = t_{R_C} + CTI = 0.4980 + 0.3 = 0.7980$$

8. Calculate dial of backup relay

$$dial_{R_B} = \frac{t_{R_B}}{\left[\frac{A}{\left(\frac{I_{sc3\emptyset_{RB}}}{I_{pickup_{R_B}}}\right)^n - 1} + B\right]} = \frac{0.7980}{\left[\frac{19.61}{\left(\frac{1000}{180}\right)^2 - 1} + 0.491\right]} = 0.6953$$

9. Calculate primary operation time of relay B

$$t_{R_B} = \left[\frac{A}{\left(\frac{I_{sc3\emptyset_{R_B}}}{I_{pickup_{R_B}}} \right)^n - 1} + B \right] * dial_{R_B} = \left[\frac{19.61}{\left(\frac{1500}{180} \right)^2 - 1} + 0.491 \right] * 0.6953 = 0.5406$$

10. Calculate operation time of backup relay

$$t_{R_A} = t_{R_B} + CTI = 0.5406 + 0.3 = 0.8406$$

11. Calculate dial of backup relay

$$dial_{R_A} = \frac{t_{R_A}}{\left[\frac{A}{\left(\frac{I_{sc3\emptyset_{R_A}}}{I_{pickup_{R_A}}} \right)^n - 1} + B \right]} = \frac{0.8406}{\left[\frac{19.61}{\left(\frac{1500}{300} \right)^2 - 1} + 0.491 \right]} = 0.6426$$

12. Calculate primary operation time of relay A

$$t_{R_A} = \left[\frac{A}{\left(\frac{I_{sc3\emptyset_{R_A}}}{I_{pickup_{R_A}}} \right)^n - 1} + B \right] * dial_{R_A} = \left[\frac{19.61}{\left(\frac{2000}{300} \right)^2 - 1} + 0.491 \right] * 0.6426 = 0.6056$$

The primary and backup operation time of relays are shown:

Relay	tp	tb	dial
A	0.6056	0.8406	0.6426
B	0.5406	0.7980	0.6953
C	0.4980	0.7712	0.8273
D	0.4712	--	0.5

Mesh Coordination

The mesh system that was illustrated in Figure 2.8 will be studied as an example of coordination. Consider *k = 1.5* and *CTI = 0.3.* The X'd of generators 1 and 2 are 1 and 1 respectively. Note that the purpose of this example is to show the process of manual coordination; therefore, contingency analysis is not considered.

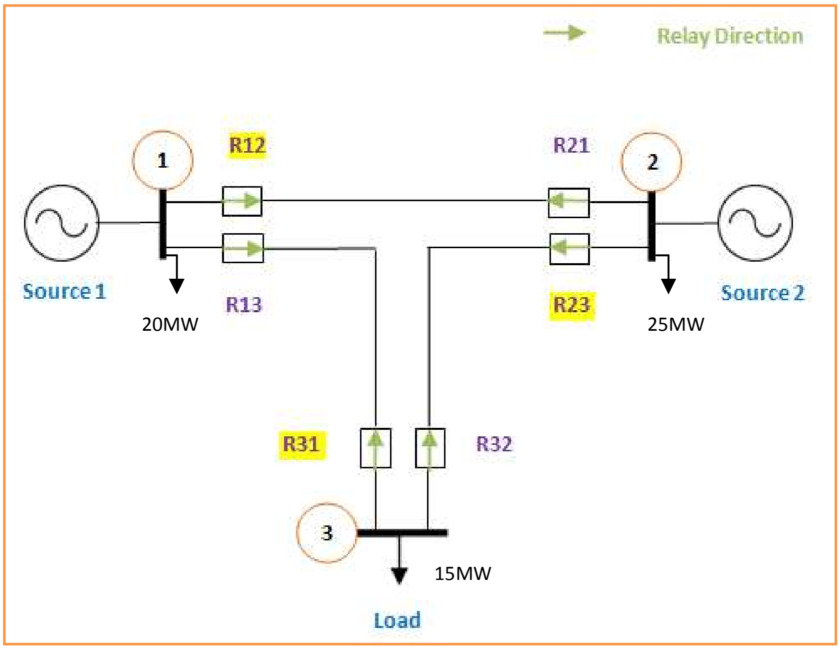


Figure 2.8: Coordination of DOCRs in a ring fed system.

The load and short circuit current data of each relay are given:

Relay	Isc 3ph Primary	Isc 3ph Backup	Iload	Ipickup
1 2	8051	4020	589	883
2 1	8072	4088	589	883
2 3	8515	5716	255	382
3 2	7957	3582	255	382
1 3	8508	7723	826	1239
3 1	5934	3664	826	1239

The three phase backup current of the relays are also called coordination current. The pickup current is the product of load current times the factor *k*.

Now the system shown in Figure 2.8 is manually coordinated as presented in section 2.4.1.

1. Select one of the IEEE conventional curves

The very inverse (VI) curve is selected. The constants A, B and n are as presented in Table 2.1 which are 19.61, 0.491 and 2 respectively.

<u>Clockwise coordination:</u>

2. Propose a dial for the first primary relay

$$dial_{R_{31}} = 0.5$$

3. Calculate primary operation time of relay R_{31}

$$t_{R_{31}} = \left[\frac{A}{\left(\frac{I_{sc3\emptyset_{R_{31}}}}{I_{pickup_{R_{31}}}} \right)^n - 1} + B \right] * dial_{R_{31}} = \left[\frac{19.61}{\left(\frac{5934}{1239} \right)^2 - 1} + 0.491 \right] * 0.5 = 0.6924$$

4. Calculate operation time of backup relay

$$t_{R_{23}} = t_{R_{31}} + CTI = 0.6924 + 0.3 = 0.9924$$

5. Calculate dial of backup relay

$$dial_{R_{23}} = \frac{t_{R_{23}}}{\left[\frac{A}{\left(\frac{I_{sc3\emptyset_{R_{23}}}}{I_{pickup_{R_{23}}}} \right)^n - 1} + B \right]} = \frac{0.9924}{\left[\frac{19.61}{\left(\frac{5716}{382} \right)^2 - 1} + 0.491 \right]} = 1.714$$

6. Calculate primary operation time of relay R_{23}

$$t_{R_{23}} = \left[\frac{A}{\left(\frac{I_{sc3\emptyset_{R_{23}}}}{I_{pickup_{R_{23}}}} \right)^n - 1} + B \right] * dial_{R_{23}} = \left[\frac{19.61}{\left(\frac{8515}{382} \right)^2 - 1} + 0.491 \right] * 1.714 = 0.9094$$

7. Calculate operation time of backup relay

$$t_{R_{12}} = t_{R_{23}} + CTI = 0.9094 + 0.3 = 1.2094$$

8. Calculate dial of backup relay

$$dial_{R_{12}} = \frac{t_{R_{12}}}{\left[\frac{A}{\left(\frac{I_{sc3\emptyset_{R_{12}}}}{I_{pickup_{R_{12}}}}\right)^n - 1} + B\right]} = \frac{1.2094}{\left[\frac{19.61}{\left(\frac{4020}{883}\right)^2 - 1} + 0.491\right]} = 0.8143$$

9. Calculate primary operation time of relay R_{12}

$$t_{R_{12}} = \left[\frac{A}{\left(\frac{I_{sc3\emptyset_{R_{12}}}}{I_{pickup_{R_{12}}}}\right)^n - 1} + B\right] * dial_{R_{12}} = \left[\frac{19.61}{\left(\frac{8051}{883}\right)^2 - 1} + 0.491\right] * 0.8143 = 0.5942$$

10. Calculate backup operation time of relay R_{31}

$$t_{R_{31}} = \left[\frac{A}{\left(\frac{I_{sc3\emptyset_{R_{31}}}}{I_{pickup_{R_{31}}}}\right)^n - 1} + B\right] * dial_{R_{31}} = \left[\frac{19.61}{\left(\frac{3664}{1239}\right)^2 - 1} + 0.491\right] * 0.5 = 1.5115$$

Anticlockwise coordination:

11. Propose a dial for the first primary relay

$$dial_{R_{21}} = 0.8094$$

12. Calculate primary operation time of relay R_{21}

$$t_{R_{21}} = \left[\frac{A}{\left(\frac{I_{sc3\emptyset_{R_{21}}}}{I_{pickup_{R_{21}}}}\right)^n - 1} + B\right] * dial_{R_{21}} = \left[\frac{19.61}{\left(\frac{8072}{883}\right)^2 - 1} + 0.491\right] * 0.8094 = 0.5896$$

13. Calculate operation time of backup relay

$$t_{R_{32}} = t_{R_{21}} + CTI = 0.5896 + 0.3 = 0.8896$$

14. Calculate dial of backup relay

$$dial_{R_{32}} = \frac{t_{R_{32}}}{\left[\frac{A}{\left(\frac{I_{sc3\emptyset_{R_{32}}}}{I_{pickup_{R_{32}}}}\right)^{n} - 1} + B\right]} = \frac{0.8896}{\left[\frac{19.61}{\left(\frac{3582}{382}\right)^{2} - 1} + 0.491\right]} = 1.241$$

15. Calculate primary operation time of relay R_{32}

$$t_{R_{32}} = \left[\frac{A}{\left(\frac{I_{sc3\emptyset_{R_{32}}}}{I_{pickup_{R_{32}}}}\right)^{n} - 1} + B\right] * dial_{R_{32}} = \left[\frac{19.61}{\left(\frac{7957}{382}\right)^{2} - 1} + 0.491\right] * 1.241 = 0.6655$$

16. Calculate operation time of backup relay

$$t_{R_{13}} = t_{R_{32}} + CTI = 0.6655 + 0.3 = 0.9655$$

17. Calculate dial of backup relay

$$dial_{R_{13}} = \frac{t_{R_{13}}}{\left[\frac{A}{\left(\frac{I_{sc3\emptyset_{R_{13}}}}{I_{pickup_{R_{13}}}}\right)^{n} - 1} + B\right]} = \frac{0.9655}{\left[\frac{19.61}{\left(\frac{7723}{1239}\right)^{2} - 1} + 0.491\right]} = 0.9568$$

18. Calculate primary operation time of relay R_{13}

$$t_{R_{13}} = \left[\frac{A}{\left(\frac{I_{sc3\emptyset_{R_{13}}}}{I_{pickup_{R_{13}}}} \right)^n - 1} + B \right] * dial_{R_{13}} = \left[\frac{19.61}{\left(\frac{8508}{1239} \right)^2 - 1} + 0.491 \right] * 0.9568 = 0.8763$$

19. Calculate backup operation time of relay R_{21}

$$t_{R_{21}} = \left[\frac{A}{\left(\frac{I_{sc3\emptyset_{R_{21}}}}{I_{pickup_{R_{21}}}} \right)^n - 1} + B \right] * dial_{R_{21}} = \left[\frac{19.61}{\left(\frac{4088}{883} \right)^2 - 1} + 0.491 \right] * 0.8094 = 1.1742$$

The primary and backup operation time of relays are shown:

Relay	tp	tb	dial
1 2	0.5942	1.2094	0.8143
2 1	0.5896	1.1742	0.8094
2 3	0.9094	0.9924	1.7140
3 2	0.6655	0.8896	1.2410
1 3	0.8763	0.9655	0.9568
3 1	0.6924	1.5115	0.5000

These results are obtained simulating DE in matlab. Hence the reason why all relays are coordinated at the first try. The coordination pairs and the CTIs of DOCRs are shown:

Coordination pairs	tp	tb	CTI
[1 2] [2 3]	0.9094	1.2094	0.3000
[2 1] [1 3]	0.8763	1.1742	0.3000
[2 3] [3 1]	0.6924	0.9924	0.3000

[3 2] [2 1]	0.5896	0.8896	0.3000
[1 3] [3 2]	0.6655	0.9655	0.3000
[3 1] [1 2]	0.5942	1.5115	0.9173

The Need of Contingency Analysis

The *n-1* contingency analysis is very important. The study with and without contingency analysis will be discussed here. A parallel line is an easy and effective way to show the importance of contingency analysis. The IEEE 14 bus test system is used as an example for this discussion. The discussion will be focused on the parallel lines between buses 1 and 2. Both lines between buses 1 and 2 have the same impedance value. Consider that $k = 1.5$.

The relay names are not assigned as a number as was done conventionally, but generated automatically by the real time algorithm as a string of numbers. These relay names (string of numbers) consist of 3 digits. The first digit is the name of the nearby bus. The second digit is the name of the remote bus and the third digit represents the number of the lines (parallel lines) between two buses. For example, the relays between buses 1 and 2 that are nearby bus 1 are assigned as [1 2 1], [1 2 2] while the relays that are nearby bus 2 are assigned as [2 1 1] and [2 1 2] respectively.

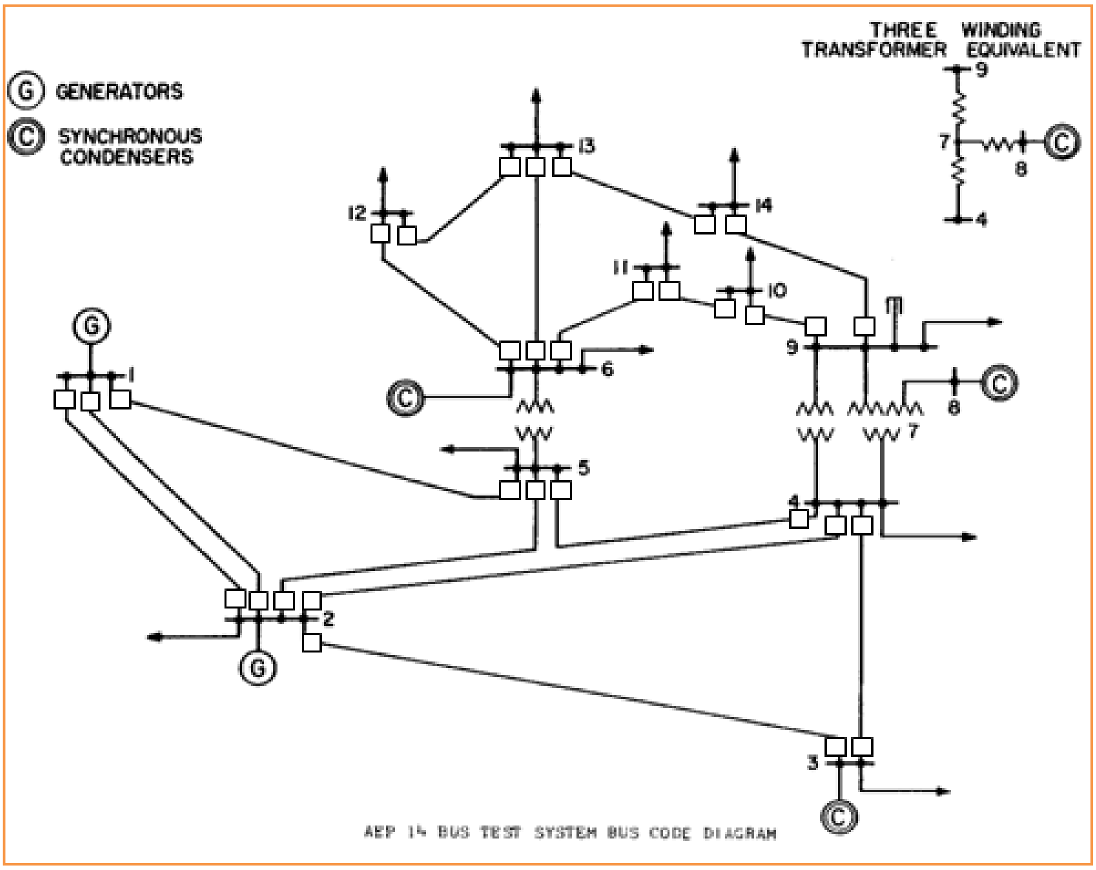


Figure 4.1: IEEE 14 bus test system.

The load and pickup currents of the relays between buses 1 and 2 are shown:

Relay	Iload	Ipickup	Iload	Ipickup
1 2 1	815	1,223	1,849	2,774
1 2 2	815	1,223	1,849	2,774
2 1 1	815	1,223	1,849	2,774
2 1 2	815	1,223	1,849	2,774

The first two columns are load flow results without considering contingency analysis while the last two columns consider contingency analysis. These are load flow results based on minimum load operation.

Suppose that the DOCRs were coordinated without considering the contingency analysis. Then the pickup currents of the relays [1 2 1], [1 2 2], [2 1 1] and [2 1 2] will be 1,223 A. If the line [1 2 2] is out of service due to maintenance, then relays [1 2 2] and [2 1 2] will no longer exist in the new network topology; and the load flow that was travelling on line [1 2 2] will now travel on line [1 2 1]. This makes a sum of 1,630 A which relays [1 2 1] and [2 1 1] will need to sense. As a result, relays [1 2 1] and [2 1 1] will mal-operate because the actual load current is greater than the pickup current; 1,630 A > 1,223 A.

The mal-operation of relays wouldn't have happened if contingency analysis was considered. It can be proved by comparing the actual load current when line [1 2 2] is out of service with the pickup current considering contingency analysis. The relay will be held steady and still and no mal-operation will take place because the actual load current is smaller than the pickup current; 1,630 A < 2,774 A. Therefore, the *n-1* contingency analysis is very important because it makes the system become more robust, in other words, the system can withstand at least 1 unaccounted contingency without coordination loss.