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Ke Xu

University of Kentucky, xukesam@gmail.com

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Ke Xu, Student

Dr. Yuan Liao, Major Professor

Dr. Aaron Cramer, Director of Graduate Studies

INTELLIGENT METHODS FOR OPTIMUM ONLINE ADAPTIVE COORDINATION OF OVERCURRENT RELAYS

DISSERTATION

A dissertation submitted in partial fulfillment of the
requirements for the degree of Doctor of Philosophy in the
College of Engineering at the University of Kentucky

By

Ke Xu

Lexington, Kentucky

Director: Dr. Yuan Liao, Professor of Electrical and Computer Engineering

Lexington, Kentucky

2018

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ABSTRACT OF DISSERTATION

INTELLIGENT METHODS FOR OPTIMUM ONLINE ADAPTIVE COORDINATION OF OVERCURRENT RELAYS

During the operation in a modern power distribution system, some abnormal events may happen, such as over-voltage, faults, under-frequency and overloading, and so on. These abnormal events may cause a power outage in a distribution system or damages on the equipment in a distribution system. Hence these abnormal events should be identified and isolated by protection systems as quickly as possible to make sure we can maintain a stable and reliable distribution system to supply adequate electric power to the largest number of consumers as we can. To sum up, we need stable and reliable protection systems to satisfy this requirement.

Chapter 1 of the dissertation is a brief introduction to my research contents. Firstly, the background of a distribution system and the protection systems in a power system will be introduced in the first subchapter. Then there will be a review of existing methods of optimum coordination of overcurrent relays using different optimal techniques. The dissertation outline will be illustrated in the end.

Chapter 2 of the dissertation describes a novel method of optimum online adaptive coordination of overcurrent relays using the genetic algorithm. In this chapter, the basic

idea of the proposed methods will be explained in the first subchapter. It includes the genetic algorithm concepts and details about how it works as an optimal technique. Then three different types of simulation systems will be used in this part. The first one is a basic distribution system without distributed generations (DGs); the second one is similar to the first one but with load variations; the last simulation system is similar to the first one but with a distributed generation in it. Using three different simulation systems will demonstrate that the coordination of overcurrent relays is influenced by different operating conditions of distribution system.

In Chapter 3, a larger sized distribution system with more distributed generations and loads will be simulated and used for verifying the proposed method in a more realistic environment. In addition, the effects of fault location on the optimum coordination of overcurrent relays will be discussed here.

In Chapter 4, the optimal differential evolution (DE) technique will be introduced. Because of the requirement of the online adaptive function, the optimal process needs to be accomplished as soon as possible. Through the comparison between genetic algorithm and differential evolution on the optimum coordination of overcurrent relays, we found that differential evolution is much faster than the genetic algorithm, especially when the size of the distribution system grows. Therefore, the differential evolution optimal technique is more suited than the genetic algorithm to realize online adaptive function.

Chapter 5 presents the conclusion of the research work that has been done in this dissertation.

KEY WORDS: Distributed generation output and load, genetic algorithm, differential evolution, intelligent online adaptive protection, optimum coordination, overcurrent relays.

Ke Xu

September 27, 2018

INTELLIGENT METHODS FOR OPTIMUM ONLINE
ADAPTIVE COORDINATION OF OVERCURRENT RELAYS

By
Ke Xu

Dr. Yuan Liao

Director of Dissertation

Dr. Aaron Cramer

Director of Graduate Studies

November 12, 2018

Date

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Table of Contents

ACKNOWLEDGEMENTS	iii
Table of Contents	iv
List of Figures	vii
List of Tables	ix
Chapter 1 Introductions	1
1.1 Background	1
1.2 The Overcurrent Protection Systems in Power System	6
1.3 Existing Methods of Optimum Coordination of Overcurrent Relays	10
1.3.1 Fundamental Optimization Techniques	10
1.3.2 Linear Programming optimization Methods	11
1.3.3 Non- Linear Programming optimization Methods	13
1.4 Dissertation Outline	24
Chapter 2 Online Adaptive optimum coordination of overcurrent relays using the genetic algorithm (GA)	26
2.1 Introduction to the Genetic Algorithm	26
2.1.1 Basic Idea of Genetic Algorithm (GA)	26
2.1.2 The Advantages of Genetic Algorithm (GA)	28
2.2 Proposed Method of Online Adaptive Optimum Coordination of Overcurrent	

Relays – Two Steps.....	29
2.2.1 Types of Overcurrent Relays	30
2.2.2 The process of the Optimum Coordination of Overcurrent Relays	32
2.3 Implementation of the Proposed Method.....	39
2.3.1 GA Optimization Toolbox	39
2.3.2 Two-step genetic algorithm with GA solver in coding.....	48
2.4 Implementation of the Method – Single-Step Genetic Algorithm.....	52
2.5 Summary	53
Chapter 3 Intelligent Method for Online Adaptive Optimum Coordination of Overcurrent Relays for more Practical system	56
3.1 Simulation on a Large Scale Distribution System	56
3.2 Summary	62
Chapter 4 Online Adaptive Efficient Optimum Coordination of Overcurrent Relays Using Differential Evolution	64
4.1 Overview of Differential Evolution (DE) Optimization Technique	64
4.2 Overall Description of the Proposed Scheme and Simulation of Proposed Method	66
4.3 Summary	72
Chapter 5 Conclusion	74
Bibliography	77

Vita	87
------------	----

List of Figures

Figure 1.1, Modern power system model	1
Figure 1.2, 14-bus single line radial distribution system	4
Figure 1.3, A single line ring main distribution system with 8 sections.....	5
Figure 1.4, A single line inter-connected distribution system with 8 sections	5
Figure 1.5, Block and trip region of overcurrent relay	7
Figure 1.6, The relation between the primary relay operating time and backup relay operating time	9
Figure 1.7, Flowchart of a standard simplex method.....	12
Figure 1.8, Flowchart of Sequential quadratic programming (SQP)	14
Figure 1.9, Flowchart of the group search optimization (GSO) technique.....	16
Figure 1.10, Flowchart of TLBO method	18
Figure 1.11, Flowchart of ACO method	20
Figure 1.12, Brief flowchart of the SOS method	21
Figure 1.13, Flowchart of seeker algorithm.....	23
Figure 2.1, Flowchart of genetic algorithm (GA)	27
Figure 2.2, Proposed online adaptive protection system	34
Figure 2.3, Simulation distribution system with only one source.....	37
Figure 2.4, Simulation distribution system with different load level	37

Figure 2.5, Simulation distribution system with DG	38
Figure 2.6, Example simulation system in Simulink MATLAB	39
Figure 2.7, MATLAB Optimization Toolbox window.....	42
Figure 2.8, The graph of the convergence procedure of GA in proposed method by MATLAB Optimization Toolbox	47
Figure 2.9, The graph of the convergence procedure of GA in proposed method by the GA solver in coding.....	52
Figure 3.1, A large scale simulation distribution system.....	57
Figure 3.2, An example of load variation monitor in 15-minute interval in a day	58
Figure 4.1, Flowchart of differential evolution.....	66
Figure 4.2, The simulation system for the proposed method using DE.....	67
Figure 4.3, An example of DE optimization process in graph.....	72

List of Tables

Table 2.1, Operating time for different types of overcurrent relays	31
Table 2.2, The relationship of primary and backup relays	38
Table 2.3, The σi constant for relays	43
Table 2.4, The optimum TDS settings of each relay	45
Table 2.5, I_{pick} optimal values of each overcurrent relay	47
Table 2.6, Reasons that GA solver stops	49
Table 3.1, Primary and backup relays for their corresponding fault section	58
Table 3.2, The optimum settings of TDS of each relay for the middle point fault location	60
Table 3.3, Optimum of I_{pickup} of each relay for the middle point fault location.....	60
Table 3.4, The optimum settings of TDS of each relay for the near end fault location....	61
Table 3.5, Optimum of I_{pickup} of each relay for the near end fault location	61
Table 4.1, Fault Sections and their Corresponding Primary And Backup Relays	67
Table 4.2, TDS settingsfor the fault occurs at the 30% length from the left end point of any faulted section	69
Table 4.3, Pickup current settings for the fault occurs at the 30% length from the left end point of any faulted section.....	69
Table 4.4, TDS for the fault occurs at the 50% length from the left end point of any faulted section	70

Table 4.5, Pickup current settings for the fault occurs at the 50% length from the left end point of any faulted section.....	70
---	----

Table 4.6, TDS for the fault occurs at the 80% length from the left end point of any faulted section	71
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Table 4.7, Pickup current settings for the fault occurs at the 80% length from the left end point of any faulted section.....	71
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Chapter 1 Introductions

Section 1 will present a brief introduction to the electric power distribution system and its protection systems. Then a review of existing protection methods of optimum coordination of overcurrent relays using different optimization techniques will be discussed. In the end, the dissertation outline will be illustrated.

1.1 Background

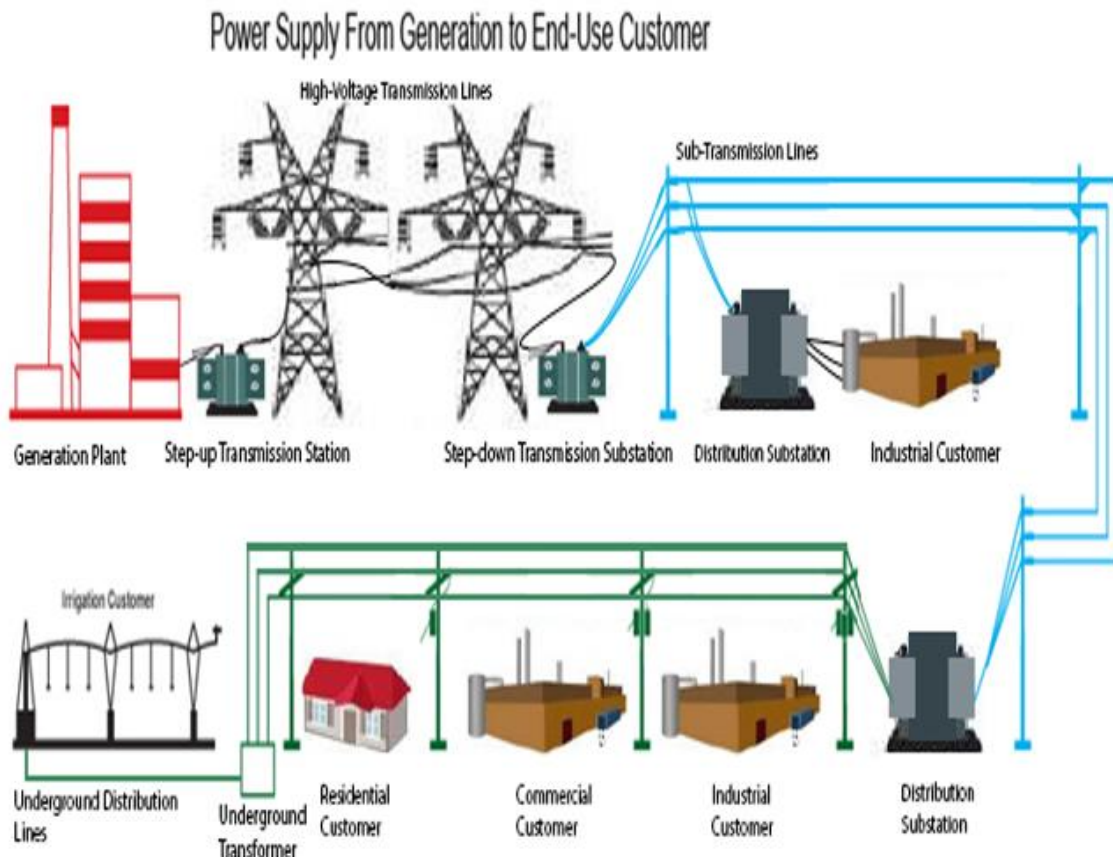


Figure 1.1, Modern power system model

In the power systems, there are two main parts: the power transmission systems and power distribution systems. The transmission systems are used for transferring electric power over long distance. It transfers the electric power from electric generation plants to local substations through high voltage and three-phase alternating current because of the lower energy loss. Distribution systems will deliver electric power from substations to electric consumers at a lower voltage level.

Figure 1.1 illustrates a modern power system [1]. In the figure, the part in red is the electric power generation plant. The part in blue is the transmission system which includes high-voltage transmission lines, step-down transmission substation and sub-transmission lines. The part in green is the distribution system that consists of the distribution substation, local distribution lines, industrial customers, commercial customers, residential customers and underground transformer.

Electric power distribution systems became very important after the 1880s when electricity began being generated at power stations. Before the 1880s, the electricity was mainly generated where it was used. The typical distribution systems mainly consist of the following parts [2]:

- Distribution substation
- Feeders
- Distribution transformers
- Distributor
- Service mains
- Switches
- Protection equipment

- Measurement equipment

The distribution substation is located near the consumer area. It receives the electric power from the transmission system. The high voltage electric power from transmission lines will be stepped down to the primary distribution level voltage power by the step-down transformer. The most common primary distribution level voltage is 11kV, but there are some other values of primary distribution level voltage in the range from 2.4 kV to 33 kV based on the need of consumers.

The distribution feeder conductors are used to transfer the stepped-down voltage power to the distribution transformers, which means it connects the substation to the electric power distributed area.

The distribution transformer, also called service transformer, is a step-down three-phase transformer to perform the final voltage transformation in the power distribution system.

The distributor is used for carrying the output from the distribution transformers. It is a conductor from which tappings are taken to supply power to the consumers.

The service mains is a cable that connects the distributor to the electricity users.

Also the power distribution system can be classified into three types:

- Radial system
- Ring main system
- Inter-connected system

The radial system is the distribution system with separate feeders radiating from a single substation and feed the distributors at one end only. It is the easiest type with the

lowest building cost. At the same time, the radial electrical power distribution system has a major disadvantage as the related consumers would have a power outage without any alternative path to the power source if there is a feeder failure. Figure 1.2 is an example of a single line radial distribution system. In Figure 1.2, it contains only one source and 14 buses.

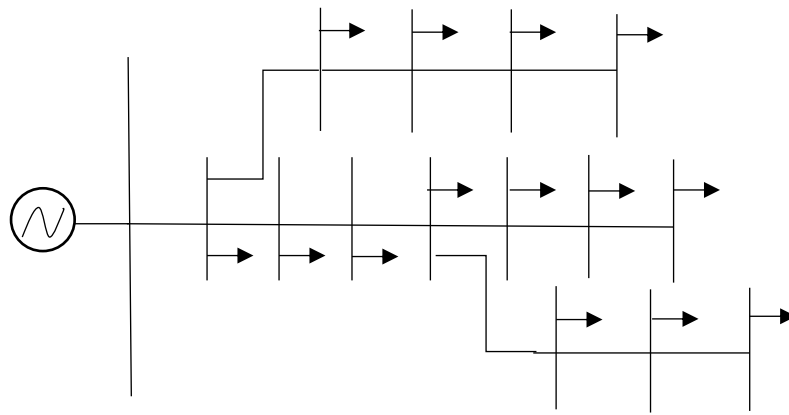


Figure 1.2, 14-bus single line radial distribution system

Because of the major drawback of a radial electric power distribution system, the ring main electric power distribution system is introduced to solve this drawback. In the ring main distribution system, each distributor is not only fed by one feeder. Therefore, the distributor still can be powered by another feeder if one of its feeders is under maintenance or fault. In addition, the ring main system can be divided into several sections. If a fault occurs in any section, that section can be isolated with a little influence on other sections.

Figure 1.3 is an example of a single line ring main distribution system with 8 sections.

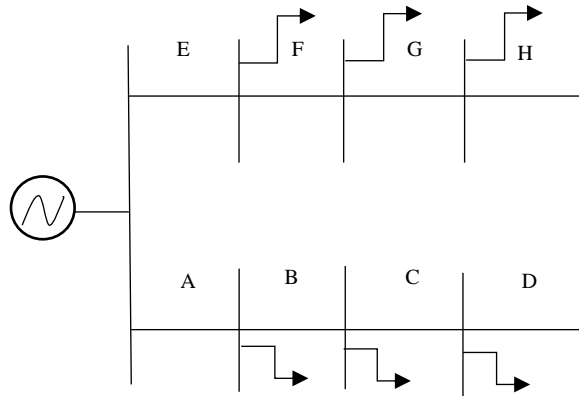


Figure 1.3, A single line ring main distribution system with 8 sections

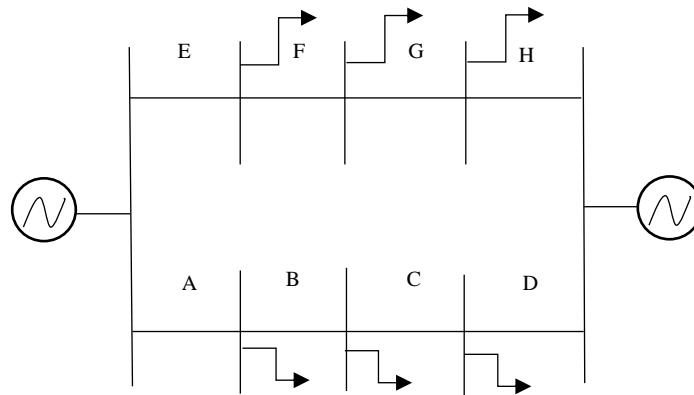


Figure 1.4, A single line inter-connected distribution system with 8 sections

Compared with the ring main electric power distribution system, the inter-connected distribution system is a ring main distribution system that is energized by more than two sources. Also, the interconnected distribution system has higher service reliability

and higher efficiency because it has more sources to feed to the system. Figure 1.4 is an example of a single line inter-connected distribution system with eight sections.

1.2 The Overcurrent Protection Systems in Power System

The overcurrent protection system is the simplest way to protect the distribution system, which mainly consists of three basic components [3]:

- Instrument transformers
- Protective overcurrent relays
- Circuit breakers

There are two basic types of instrument transformers: voltage transformers (VTs) or potential transformers (PTs), and current transformers (CTs). Both voltage transformers and current transformers are used to reduce the primary voltage and current values to meet the suitable value levels of overcurrent relays.

In the real power distribution system, the protective overcurrent relays (OC) are widely used for the protection system. The protective overcurrent relays are used to detect abnormal activities that may happen in the distribution system, and initiate appropriate system action to eliminate these abnormal activities. The overcurrent relays are widely used for protection because they are an efficient and cost-effective way to protect feeders.

There are six common types of overcurrent relays [4]:

- Normally inverse overcurrent relay
- Very inverse overcurrent relay
- Extremely inverse relay
- RI-type relay
- RXIDG-type relay

- Long time inverse relay

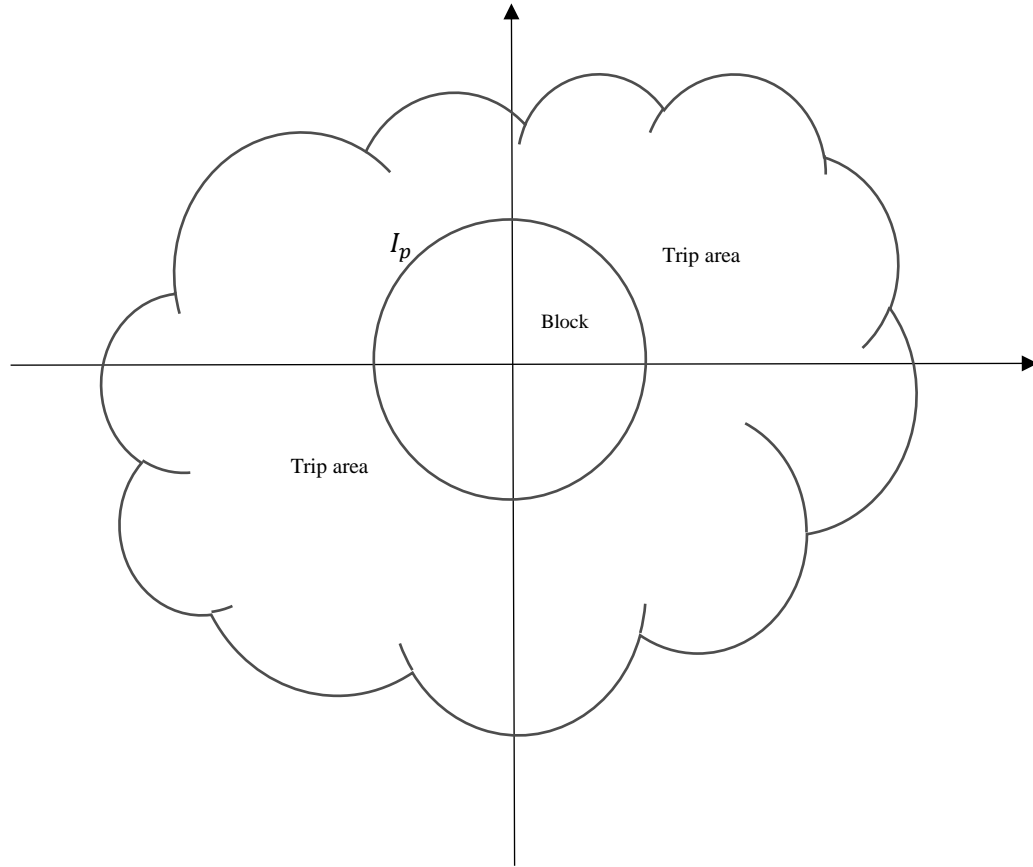


Figure 1.5, Block and trip region of overcurrent relay

Figure 1.5 shows how overcurrent relay works. I_p is the pickup current of overcurrent relay. When the magnitude of fault current I_f seen by overcurrent relay exceeds I_p , the relay contacts close instantaneously to trigger the breaker trip coil. If the magnitude of fault current I_f that overcurrent relay meets is less than the I_p , the overcurrent relay contacts will open to block the breaker coil. For the different types of overcurrent relays, the operating

time of overcurrent relay will be calculated differently and the details will be discussed in latter chapters.

The protective overcurrent relays act as a brain to sense the abnormal activities in the distribution systems, but they cannot isolate the problem section from the whole distribution system. Therefore, circuit breakers are needed to perform fault isolation. Thus, protective overcurrent relays and circuit breakers work together to sense the fault section and isolate it from the distribution system.

The objective of power system protection is to sense the fault and isolate the faulted sections caused by abnormal events, which minimizes the impacts on the rest of the sections of power system in-service. There are several requirements for the protection system design criteria [5]:

- Reliability
- Selectivity
- Speed
- Economic
- Simplicity

The requirement of reliability means making sure the protection system will operate correctly. There are two aspects in this requirement: dependability and security. Dependability means how certainly the overcurrent relays work correctly. Security means the ability of relays to never trip for a fault that occurs outside its protected sections.

The requirement of selectivity is also known as the relay coordination. It is a process of applying and setting the overcurrent relays so that they operate as fast as possible within their primary protected sections with delayed action within the backup sections. In

this process, the overcurrent relays are classified into two types: primary and backup relays. When a fault happens in the distribution system, the primary relays for this faulted section will react first. If the primary relays fail to react, the backup relays should take over quickly to ensure the stability of the distribution system. Figure 1.6 shows the relation between the primary relay operating time and backup relay operating time [6].

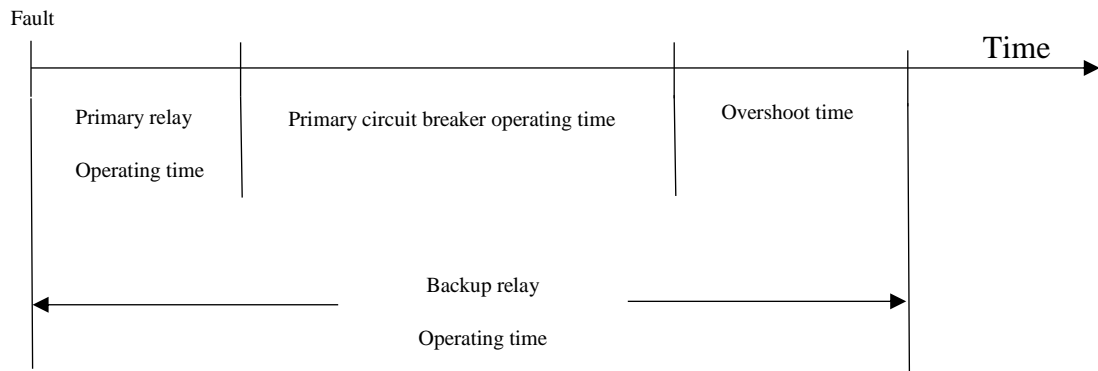


Figure 1.6, The relation between the primary relay operating time and backup relay operating time

The requirement of speed is to isolate the faulted sections as rapidly as possible. Also, the overcurrent relays associated with the healthy sections in the distribution system should not act faster than the overcurrent relays of the problem section.

It is very important to keep the maximum protection with the minimum cost, because the cost of the protection system is a major factor.

The requirement of simplicity is to keep the protection system as simple and

straightforward as possible. We should use caution when adding some additional components that may enhance the protection system functions, but will increase complexity.

1.3 Existing Methods of Optimum Coordination of Overcurrent Relays

No matter which type the overcurrent relay is, each overcurrent relay has two settings: current tap setting and time-dial setting. Current tap setting is the pickup current (I_p) of overcurrent relay in amperes; it defines the minimum value of fault current that the overcurrent relay will act on for the fault. Time-dial setting is the adjustable amount of time delay (TDS); it defines the operation time of the overcurrent relay for different fault current values [7]. The overall protection coordination of overcurrent relays is a challenging problem. The objective of overcurrent relays coordination is to calculate the most appropriate settings of each overcurrent relay for different faults that may happen in a distribution system by minimizing the sum of the operation time of each overcurrent relay.

1.3.1 Fundamental Optimization Techniques

There are many existing methods of optimum coordination of overcurrent relays so far in the modern distribution system. In earlier times, the simple and fundamental optimization techniques are utilized to realize the optimum coordination of overcurrent relays:

- Curve-fitting [8]
- Graph-theoretical method [9]

- The method of trial and error [10]
- Analytical method [11, 12, 13, 14, 15, 16].

The cur-fitting method is only good for the handwork but not when applied to the computer calculations; it means it is not good for a distribution system with a big amount of overcurrent relays.

The limitation of the graph-theoretical method is that sometimes it will not calculate the optimal settings for the overcurrent relays; the settings it optimizes are the best alternative settings, which are not the most appropriate settings for the coordination.

The method of trial and error is the simplest optimization technique that is very time consuming; it has a very slow rate of convergence for the final optimal settings values.

1.3.2 Linear Programming optimization Methods

Next, the optimization methods with objective function and constraints are applied in the optimum coordination of overcurrent relays. For these methods of optimization, they are classified into two types: linear programming and non-linear programming methods. The linear programming methods have less complexity than the non-linear ones because only the time-dial settings are optimized with the preset fixed current tap settings. The common linear optimization techniques used for optimum coordination of overcurrent relays are:

- Simplex method [17]
- Dual simplex [18]
- Two-phase simplex [19]

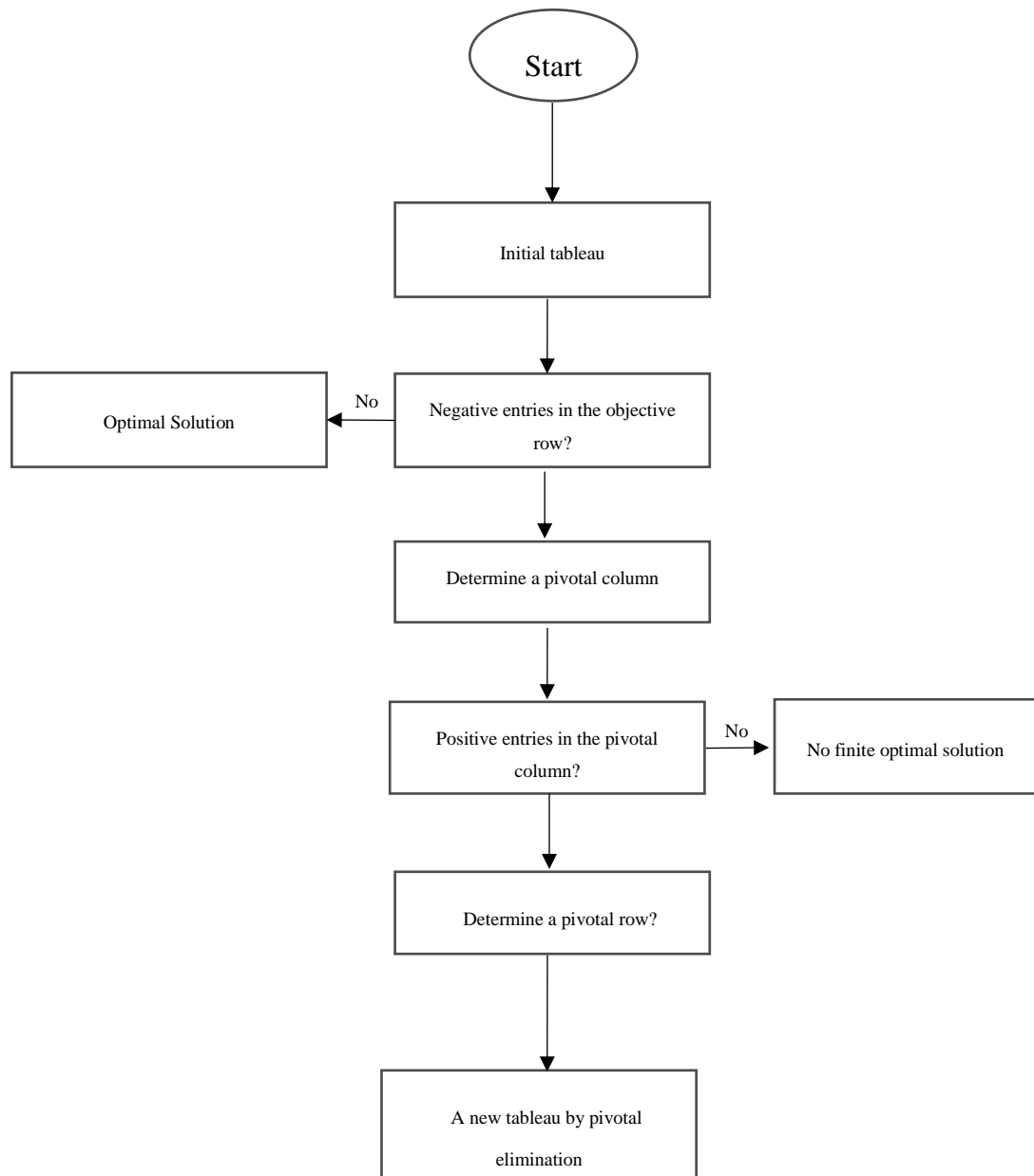


Figure 1.7, Flowchart of a standard simplex method

The simplex method is most widely used for solving linear problems. This method is

created by George Dantzig in 1947, and it is one of the earliest important applications of the revolutionary. The simplex method is very efficient, although it has exponential worst-case complexity; it generally takes 2 to 3 times the amount of equality constraints iterations to optimize the results [20]. Figure 1.7 is a flowchart of the standard simplex method.

For the method of two-phase simplex, the simplex method is divided into two phases.

- Phase I: finding a feasible solution with valid constraints.
- Phase II: finding the optimal relay settings.

In Phase I, moving takes place from the initial extreme point to the feasible region. In Phase II, pivoting is done from the initial extreme point to an optimal extreme point. All the constraints will be checked for whether they are valid in phase I, and then the invalid constraints will be excluded in phase II. Therefore, the two-phase simplex method is much more efficient than the original standard simplex method.

1.3.3 Non- Linear Programming optimization Methods

The non-linear optimization methods are also applied in the optimum coordination of overcurrent relays. In the non-linear optimization methods, both the time-dial settings and the current tap settings will be optimized. There are many non-linear programming techniques have been proposed for the optimum coordination of overcurrent relays [21]:

- Sequential quadratic programming (SQP) [22]
- Group search optimization algorithm (GSO) [23]

The sequential quadratic programming method is a nonlinear iterative optimization technique for constrained problems. The SQP method can be used in line search and trust-region frameworks. Also the SQP is the generalization of Newton's optimization method.

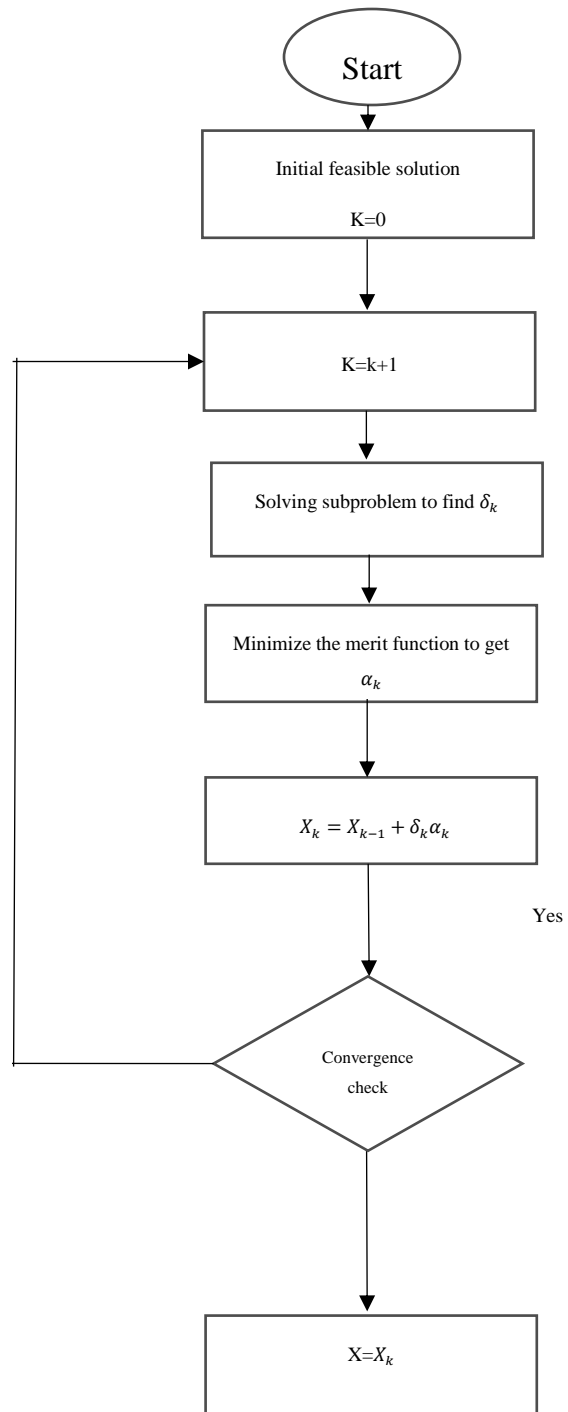


Figure 1.8, Flowchart of Sequential quadratic programming (SQP)

The SQP method finds a solution of a sequence of quadratic programming (QP) sub-problems in which a quadratic model of the objective function is minimized with the linearized constraints [24].

In Figure 1.8, it illustrates how SQP works to optimize the problems [25]. α_k is a scalar obtained by the line search for the kth iteration, δ_k is a search direction for the kth iteration. The SQP method can be summarized in 7 steps [26]:

1. Initialize the first feasible solution.
2. Compute the constraint matrices.
3. Solve the QP problem.
4. Compute the scalar which is obtained by the line search.
5. Set $X_k = X_{k-1} + \delta_k \alpha_k$
6. If the decrease in the objective function value is not huge, we get $X = X_k$ and stop.
7. Return to Step 2.

The group search optimization (GSO) technique is a swarm intelligent mechanism which is inspired by animal searching behaviors and the scrounging strategies of house sparrows [27]. It was created in 2006 by He [28]. The GSO technique has an obviously superior performance to other optimization methods in terms of accuracy and convergence speed. Figure 1.9 is a flowchart of the group search optimization (GSO) technique.

In the above non-linear programming methods, the complexity of coordination will increase dramatically if using the binary variables. Also the most important drawback of these methods is the initial guess selection. The inappropriate initial guess may fail to converge.

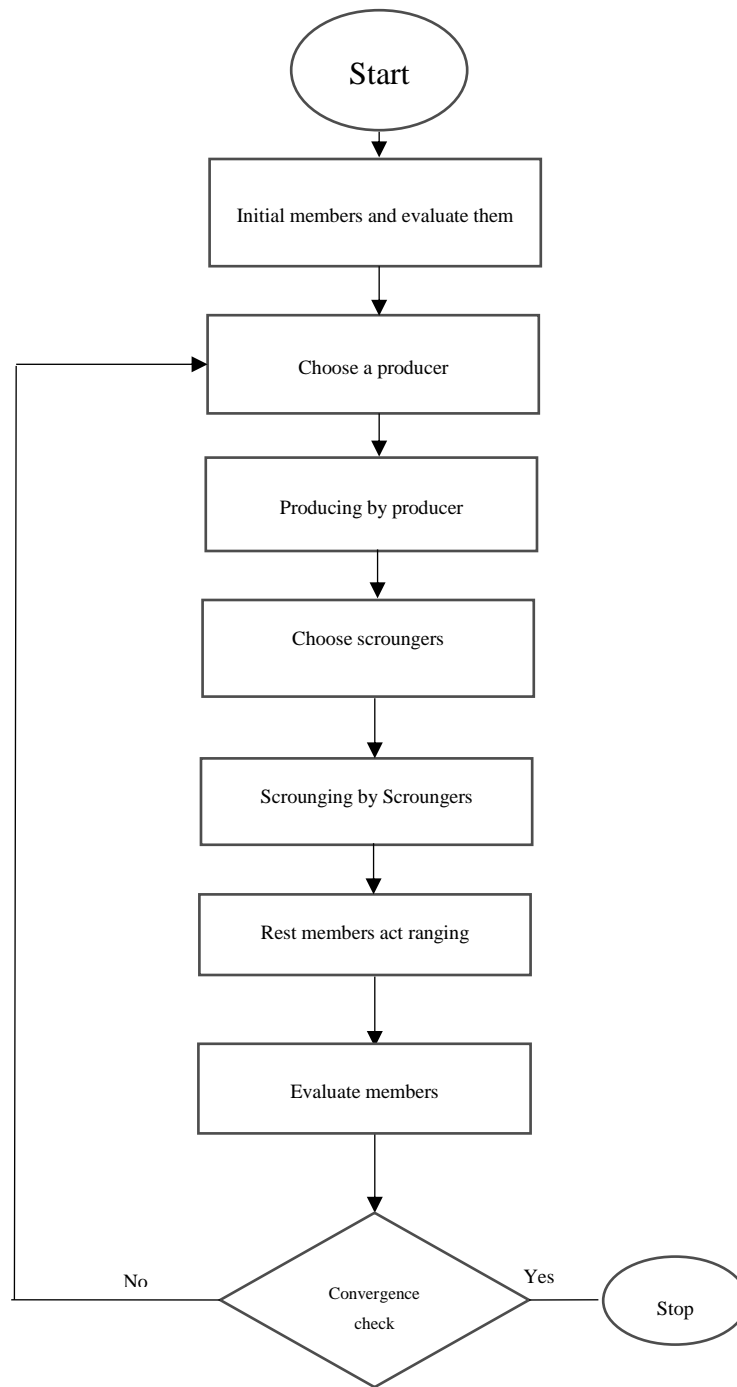


Figure 1.9, Flowchart of the group search optimization (GSO) technique

For the non-linear programming methods, the heuristic and evolutionary computation based techniques are introduced in the optimum coordination of overcurrent relays. In the past couples of decades, the development of efficient stochastic optimization methods was fast. The heuristic and evolutionary optimization methods detect the optimization results through the population. The followings are several heuristic and evolutionary methods:

- Particle swarm optimization (PSO) [29]
- Teaching learning-based optimization (TLBO) [30]
- Ant colony optimization (ACO) [31]
- Symbiotic organism Search optimization technique (SOS) [32]
- Seeker Algorithm [33]

The Particle swarm optimization (PSO) was created by Kennedy and Eberhart. PSO is inspired from animal swarming behavior. PSO is a population-based algorithm that searches a population of individuals in the promising area. In the PSO method, swarm is the population and the particles are the individuals. With the development of the past decade, PSO has been found to have several advantages [34]:

- Fast convergence.
- Finding global optimal result, although some local optimal results exist.
- Simple programming.

The PSO method consists of three major steps, and the PSO method will repeat these three steps until the optimal results come out or the stopping conditions are met:

1. Evaluate the fitness value of each particle (individual).
2. Find and update individual and global bests.

3. Find and update the velocity and position of each particle (individual).

Figure 1.10 is a flowchart of TLBO method.

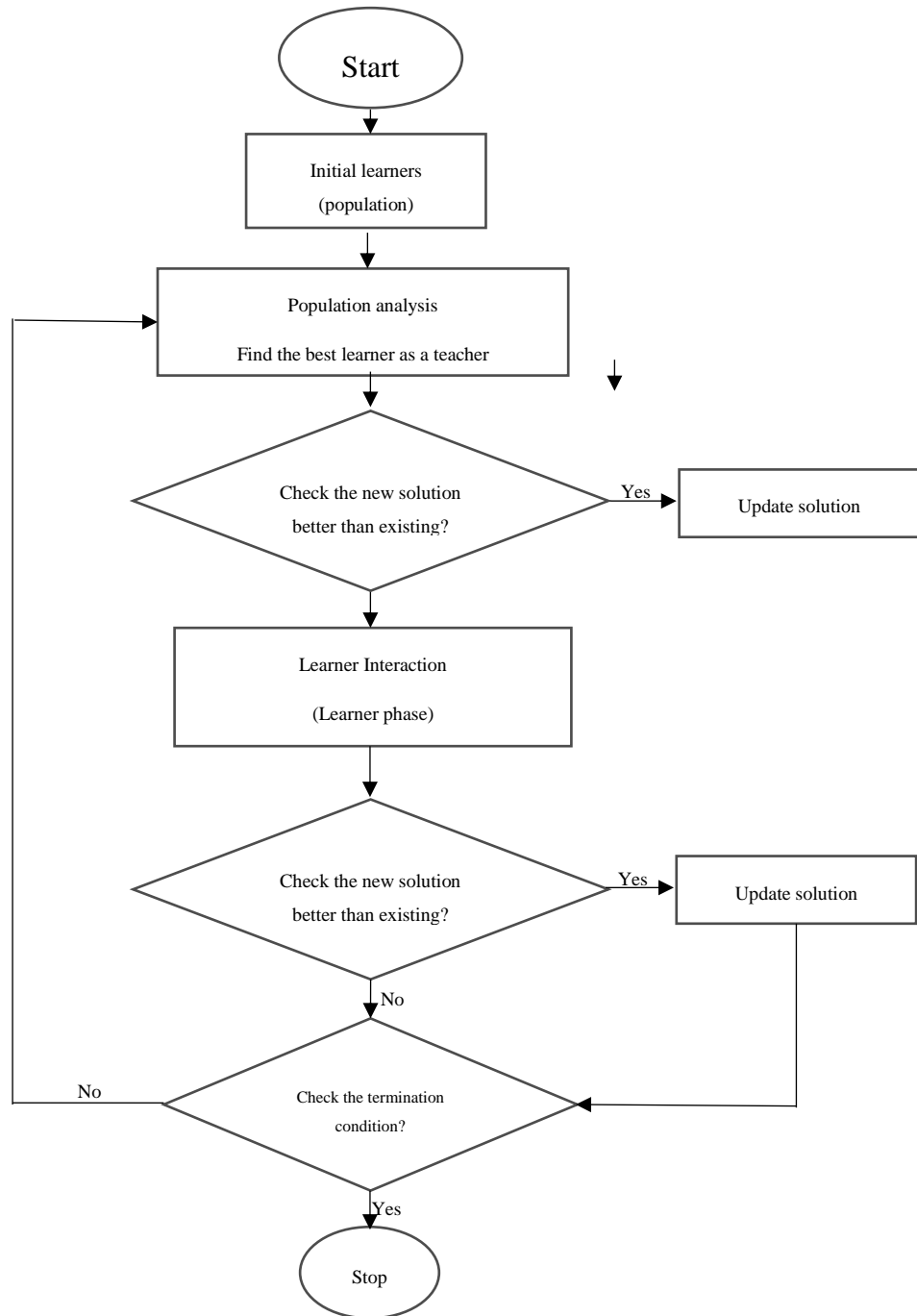


Figure 1.10, Flowchart of TLBO method

The Teaching learning-based optimization (TLBO) method is also a population-based one that proposes a population of solutions and then proceeds to the global optimal values. The TLBO works on the influence of a teacher on learners. In the TLBO method, the learners are the population. Through the tests of many constrained benchmark problems, TLBO has been proved that it is more effective and efficient than other optimization methods for the mechanical design optimization problems [35]. In addition, TLBO doesn't require any algorithm specific parameters, it only needs the population size and the number of generation. Therefore, TLBO is also a specific parameter less algorithm. There are two important phases in TLBO:

1. Teacher Phase.
2. Learners phase.

In phase 1, TLBO simulates the process of learners learning from teachers. During this phase, a teacher teaches all learners knowledge to increase the mean results of whole learners. In phase 2, TLBO simulates the study process that learners interact with other learners.

The ACO method was proposed in 1992 by Marco Dorigo. It is one of the meta-heuristic methods which is based on the ants' collective behavior when searching for food sources. During the food search, ants use their pheromones to mark their searching path, although the pheromones will evaporate over time. Also, ants always travel the shortest path back to their nest, so the shortest path has a higher concentration of pheromones. Therefore, all ants will choose to follow this shortest path because of the pheromones [36].

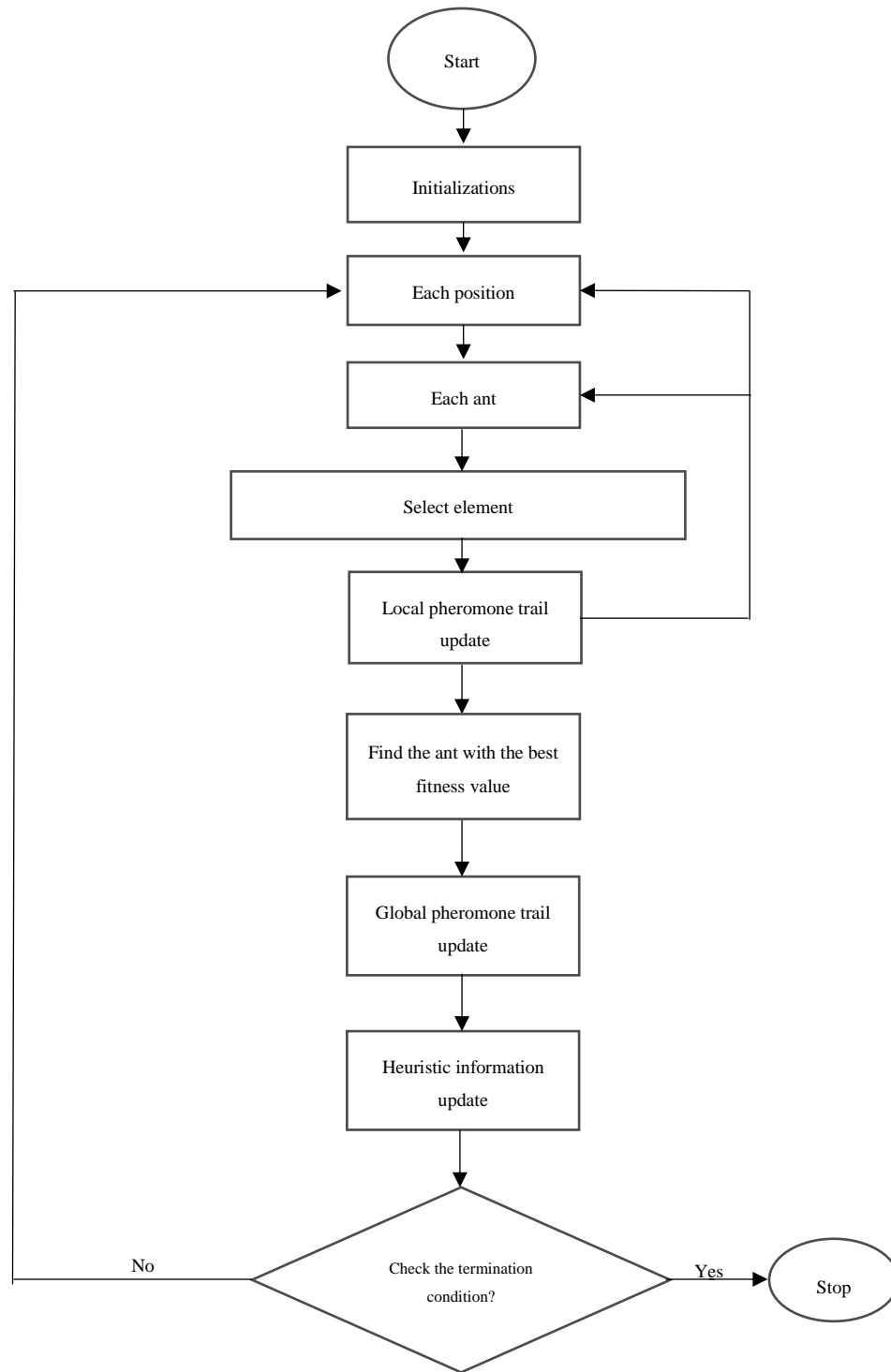


Figure 1.11, Flowchart of ACO method

The ACO has been reported to be a powerful optimization method to solve the complicated

problems in different areas. A significant advantage of ACO is that it uses the pheromone matrix as a global memory which makes the optimization process have a faster and better convergence. In Figure 1.11, it is a flowchart of the Ant colony optimization (ACO) method [37].

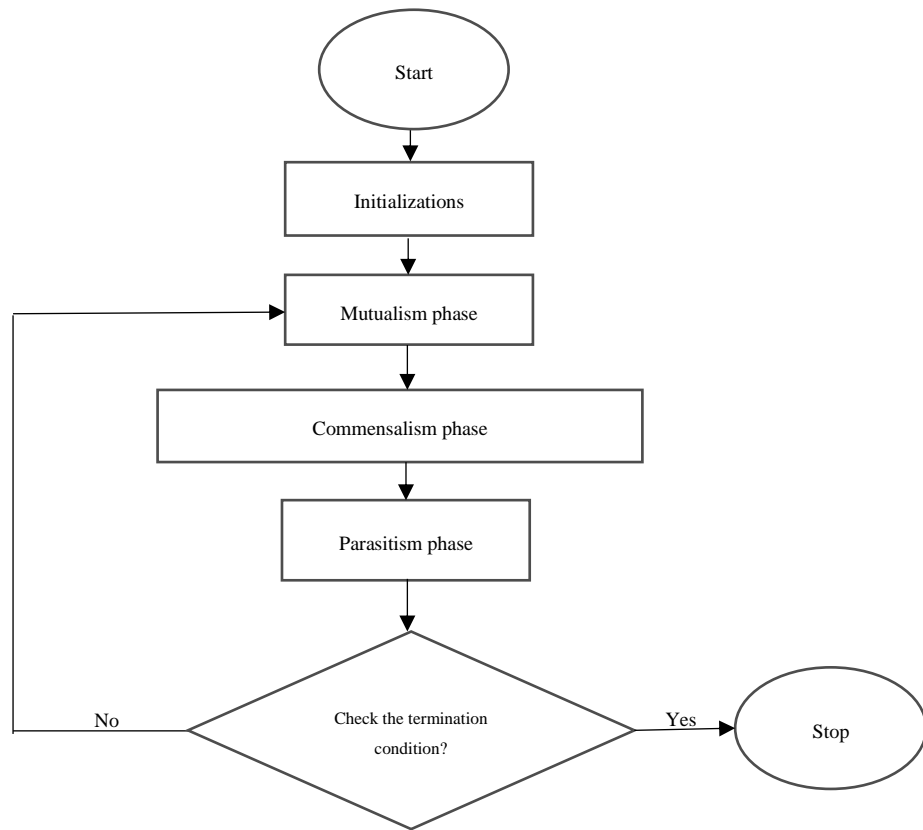


Figure 1.12, the flowchart of the SOS method

The symbiotic organism Search optimization technique (SOS) is a significant influential metaheuristic algorithm. Figure 1.12 is a brief flowchart of the SOS method.

The SOS method simulates the symbiotic interactions of organisms in the nature for finding the fittest generation in the following three phases [38]:

- Mutualism phase
- Commensalism phase
- Parasitism phase

In all three phases, each organism interacts with each other randomly. In the mutualism phase, both sides get benefits because of the interactions. A similar example for this phase in the natural environment can be found: the plover birds will clean the teeth of a crocodile, and the plover birds can take the leftover food on crocodile's teeth as their food source. Therefore, this is beneficial for both sides and the mutualistic behavior is simulated in this phase. The commensalism phase can be illustrated as one side benefits from the other side which is in neutral, such as the egg collection from chickens which is harmless to both sides. In the parasitism phase, one side benefits while the other side is harmed. In the natural world, there is a similar example of it: mosquitoes suck blood from human beings or animals and spread diseases to them without any benefits [38].

The seeker optimization algorithm is a computational optimization algorithm that simulates the human searching behaviors that are based on memory, experience and social learning. In this method, each individual of the population is called a seeker. Also, the search space and population can be divided into subpopulations and all subpopulations share their information to avoid the local optimal values. The most important two parts of the seeker optimization method are:

- Search direction
- Search step length

These two aspects are determined by the values of the objective function and its constraints.

For the search direction, it has three sub aspects:

1. Personal direction
2. Local and global directions
3. Historical direction

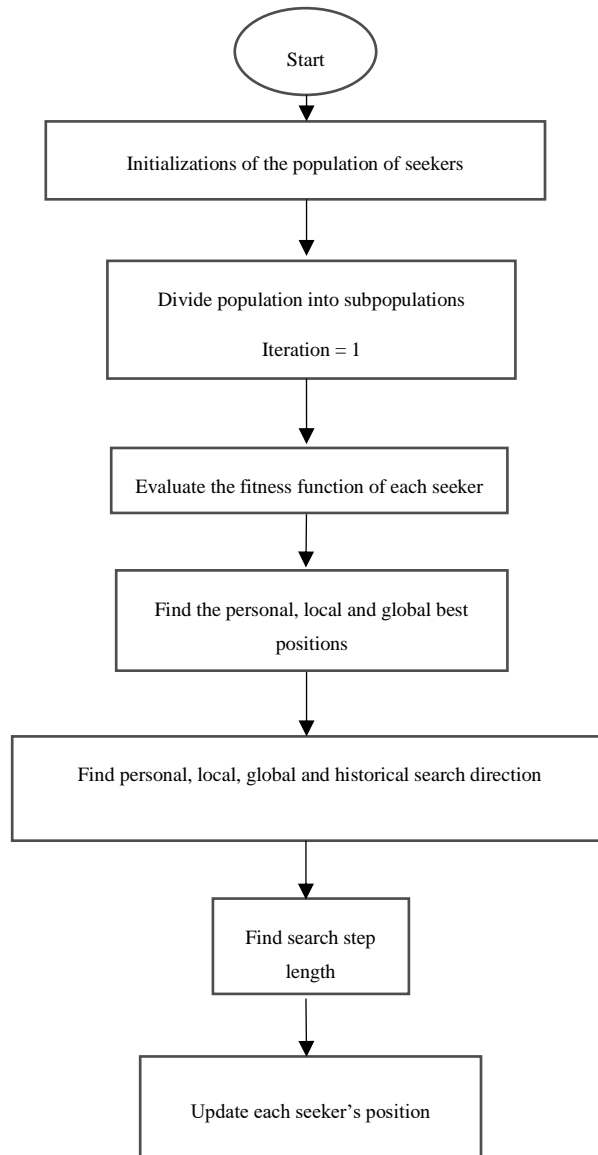


Figure 1.13, Flowchart of seeker algorithm

For the personal direction, it means each seeker has its own direction that guides it to its best position; the local and global directions are based on the social behaviors of agents which lead each seeker to its local and global best positions. The local best position is the best position among the subpopulation and the global best position is the best position among all the seekers. For the historical direction, it means each seeker has its own existing experience which can lead it to its best position among the whole searching space.

For the step length, the fuzzy judgment will be used to determine the step length. Figure 1.13 is a basic flowchart of the seeker optimization method. Therefore, the above techniques are some existing common optimization methods have been applied in the optimum coordination of overcurrent relays.

1.4 Dissertation Outline

In this dissertation, Chapter 2 will describe a novel method of optimum online adaptive optimum coordination of overcurrent relays using the genetic algorithm. In this chapter, the basic idea of the proposed method will be discussed first. It includes the details of genetic algorithm concepts. Then a comparison between three different types of simulation systems will be discussed. The first one is a basic distribution system without distributed generations (DGs). The second one is similar to the first one but with load variations. The last simulation system is similar to the first one but with a distributed generation in it. The reason to make a comparison between three simulation systems is to prove the coordination of overcurrent relays is influenced when there is a variation condition in the distribution system.

In Chapter 3, a large size simulation distribution system with more distributed generations and loads will be discussed. This proposed method should work with the real distribution system with much more distributed generations and loads, which is more practical. In addition, the effects of fault location on the optimum coordination of overcurrent relays will be discussed here.

In Chapter 4, the optimal technique differential evolution (DE) will be introduced. Because of the requirement of online adaptive function, the optimal process need to be accomplished as soon as possible. Through the comparison between the genetic algorithm and differential evolution on the optimum coordination of overcurrent relays, we found that differential evolution is much faster than genetic algorithm, especially when the size of the distribution system is growing. Therefore, the differential evolution optimization technique is much better than the genetic algorithm in the proposed method to achieve the online adaptive function.

Finally, a conclusion is made in Chapter 5 to talk about the study of the optimum coordination of overcurrent relays in this dissertation.

Chapter 2 Online Adaptive optimum coordination of overcurrent relays using the genetic algorithm (GA)

This chapter discusses the details of the proposed method presented in [39], and Chapter 2 is organized as follows: Subchapter 2.1 is an introduction about the genetic algorithm (GA) and the details about how it works. Subchapter 2.2 discusses the problem of online adaptive optimum coordination of overcurrent relays. In this subchapter, the features of overcurrent relays and the detailed process of online adaptive optimum coordination of overcurrent relays will be illustrated. Subchapter 2.3 is discussing the detailed simulations process and the comparison between three different distribution systems. At last, there is a conclusion for Chapter 2.

2.1 Introduction to the Genetic Algorithm

2.1.1 Basic Idea of Genetic Algorithm (GA)

Genetic algorithm (GA) is one of the heuristic and evolutionary algorithms that is inspired by Charles Darwin's theory of natural evolution. This algorithm is based on natural selection, the idea that individuals with the best fitness value are selected to produce the next generation, and this process is repeated again and again until the generation with fittest individuals are found [40] [41].

The genetic algorithm (GA) mainly consists of three parts [39]:

- Initialization
- Fitness evaluation
- Crossover and mutation

Initialization is when the population is created based on a random process and empirical

knowledge. Fitness evaluation is used to check the fitness value, which is used to describe the optimality of individuals in each generation. Crossover and mutation are the ways to generate the next generation; crossover exchanges partial bits between chromosomes, and mutation toggles certain bits of a chromosome. Figure 2.1 is a flowchart of the genetic algorithm (GA).

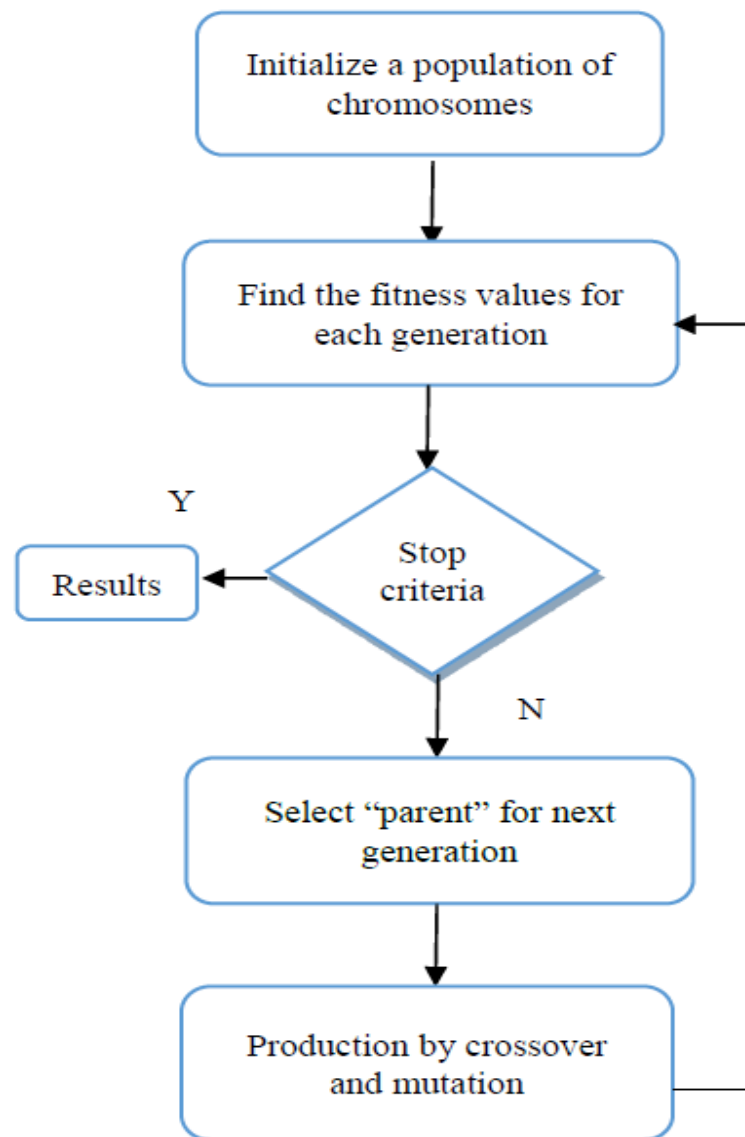


Figure 2.1, Flowchart of genetic algorithm (GA)

2.1.2 The Advantages of Genetic Algorithm (GA)

As discussed in the last chapter, there are many existing heuristic evolution methods that have been applied for the optimum coordination of overcurrent relays. However we chose the genetic algorithm as the optimization technique in the proposed methods; the reasons are as follows:

- GA is one of oldest and most used heuristic evolution optimization algorithms. Also, its effectiveness has been examined by many optimization applications and experiments before.
- In the problem of optimum coordination of overcurrent relays, the most desirable coordination is only based on the current tap setting and time-dial setting of each relay. Hence, the problem of optimum coordination of overcurrent relays belongs to the type of value advantage problems. The value advantage problems are the problems that contain the advantage derived from values of design variables. Also in the paper [42], it proves that GA is good at the value advantage problems with a significant convergence.
- Genetic Algorithm (GA) is able to handle a huge amount of variables to be optimized, which means it works with a distribution system with a large number of overcurrent relays. With the deeper research in our proposed method, more and more variables need to be optimized, hence this advantage of the genetic algorithm is very important for future work.

2.2 Proposed Method of Online Adaptive Optimum Coordination of Overcurrent Relays – Two Steps

During the operation of a modern distribution power system, some abnormal conditions like faults and over-voltage may occur. These abnormal conditions may cause power outage and damage on the equipment connected to the power system. To minimize the damage, the faulted components must be identified and isolated as quickly as possible. Therefore, a reliable protective system is needed. To ensure the reliability of protection system, a back-up protective scheme should act in case of the failure of the primary protection. To sum up, the coordination of relays is very important in the protection system in distribution systems [39].

Due to the soaring usage of distributed generations and the load increase in the modern distribution system, the existing optimum coordination of overcurrent relays based on intelligent algorithms are not able to satisfy the requirements of a protection system in a distribution system. These are reliability, selectivity, speed, economic, simplicity, which we discussed in the last chapter because the variation of load and distributed generations may cause some effects on protection schemes. In other words, the protective coordination of overcurrent relays applied in distribution systems with distributed generations becomes very difficult to implement, because it lacks the flexibility of adaptive relay settings for the changes in modern distribution system. Also, in some others' previous research papers, the sensitivity of overcurrent relays was downgraded by the high concentration of distributed generations [43] [44] [45] [46] [47] [48]. Therefore, the design of protective coordination of overcurrent relays should also consider the location and capacity of distributed generations. In addition, the variation of direction and magnitude of the fault current seen

by the overcurrent relays also affects the optimum coordination of overcurrent relays [49].

Therefore, there are some optimization algorithms that have been applied in the optimum coordination of overcurrent relays, but all these methods are not good for the distribution systems with varying distributed generations output and load variation. All these methods are only valid for the static conditions of distribution systems, which means they only work for the fixed load value and distributed generations output. They are not able to offer the most appropriate settings of overcurrent relays to keep the protective coordination of overcurrent relays in normal working condition.

Here is a question; why do the varying distributed generations output and load variation affect the original optimum coordination of overcurrent relays? Because the maximum allowable DG output which is determined at the peak demand is not suitable for the lower system demand which actually occurs most of the time in a day. It means that the distributed generations output is always dynamic and is based on the load level. Also, the presence of distributed generations may increase the feeder loss dramatically [50]. It means the distributed generations change the short circuit data like the fault current, which may thereby affect the protective coordination of overcurrent relays. All above reasons require that an online adaptive optimum coordination of overcurrent relays is necessary for the modern distribution systems.

2.2.1 Types of Overcurrent Relays

As we discussed above, there are six different common types of overcurrent relays in the market. Each different type of overcurrent relay has a different equation to calculate the operating time. The operating time of overcurrent relay is a definite time when the fault exceeds the pickup current value of that overcurrent relay. The operating times for the

different types of overcurrent relays are listed in Table 2.1 [51] . In Table 2.1, TDS and I_{pick} are the settings of each overcurrent relay, time dial setting and pick up current setting. I_{fault} is the fault current seen by the relay.

Table 2.1, Operating time for different types of overcurrent relays

Relay Type	Operating time
Normally inverse	$T = \frac{0.14 * TDS}{(\frac{I_{fault}}{I_{pick}})^{0.02} - 1}$
Very inverse	$T = \frac{13.5 * TDS}{(\frac{I_{fault}}{I_{pick}})^1 - 1}$
Extremely inverse	$T = \frac{80 * TDS}{(\frac{I_{fault}}{I_{pick}})^2 - 1}$
RI-type	$T = \frac{TDS}{0.339 - 0.236 * (\frac{I_{pick}}{I_{fault}})^1}$
RXIDG-type	$T = 5.8 - 1.35 * \ln(\frac{I_{fault}}{TDS * I_{pick}})$
Long time inverse	$T = \frac{120 * TDS}{(\frac{I_{fault}}{I_{pick}})^1 - 1}$

In the proposed method, all overcurrent relays used are all normally inverse relays, which is convenient for the optimization. Hence, the operating time of each primary and backup relays in the proposed method is:

$$T = \frac{0.14 * TDS}{(\frac{I_{fault}}{I_{pick}})^{0.02} - 1} \quad (2.1)$$

2.2.2 The process of the Optimum Coordination of Overcurrent Relays

The objective of the proposed method is to find the online adaptive optimum coordination of all overcurrent relays in the distribution system using genetic algorithm. To reach this objective, we minimized the sum of the operating time of all primary and backup relays for each faulted section. This is a constrained nonlinear optimization problem and the objective function of this optimization problem can be written as:

$$\text{Min } \sum_{i=1}^n (T_{primary_j} + T_{backup_j}) \quad (2.2)$$

In this objective function, n means the total amount of faulted sections in the simulation distribution system, $T_{primary_j}$ is the operating time of primary relays for faulted section j and T_{backup_j} is the operating time of the backup relays for faulted section j . Also there are four constraints for this optimization problem; all final optimized settings should follow these constraints:

$$T_{i,min} \leq T_i \leq T_{i,max} \quad (2.3)$$

$$TDS_{min} \leq TDS_i \leq TDS_{max} \quad (2.4)$$

$$I_{pick_{min}} \leq I_{pick} \leq I_{pick_{max}} \quad (2.5)$$

$$T_{backup_j} - T_{primary_j} \geq CTI \quad (2.6)$$

The equation 2.3 is the boundary of the operating time of each relay, no matter whether it is primary relay or a backup relay for a faulted section. The range is from 0.1 seconds to 1.1 seconds. The lower limit is used for avoiding false tripping of circuit breakers due to switching transients and overshoots [52]. Equation 2.4 is the range of time dial setting (TDS) of each relay, which is from 0.025 to 1.2. The equation 2.5 is the boundary of the pickup current setting of each overcurrent relay. The lower bound value is set as 1.3 times the maximum load current in the system, and the upper bound value is equal to the minimum fault current seen by the relay in the distribution system [53]. The equation 2.6 is the constraint that used to make sure the backup relays are not able to react before the reaction of the primary relays, they only work after the primary relays fail to work for a faulted section. CTI in this equation means the coordination time interval; it is the minimum time interval between the primary relay reaction and backup relay reaction for the same faulted section. CTI is set as 0.3 seconds in the proposed method [54].

In Figure 2.2, there is an overall description of the proposed online adaptive optimum coordination of overcurrent relays. In the proposed method, the system is divided into two major subsystems. The one is the subsystem that consists of the Supervisory Control and Data Acquisition (SCADA) system with Advanced Meter Infrastructure (AMI) embedded within the wireless communication system. This system is used to achieve the

online adaptive function of the proposed method. The other one is the optimization system to take care of the optimum coordination of overcurrent relays.

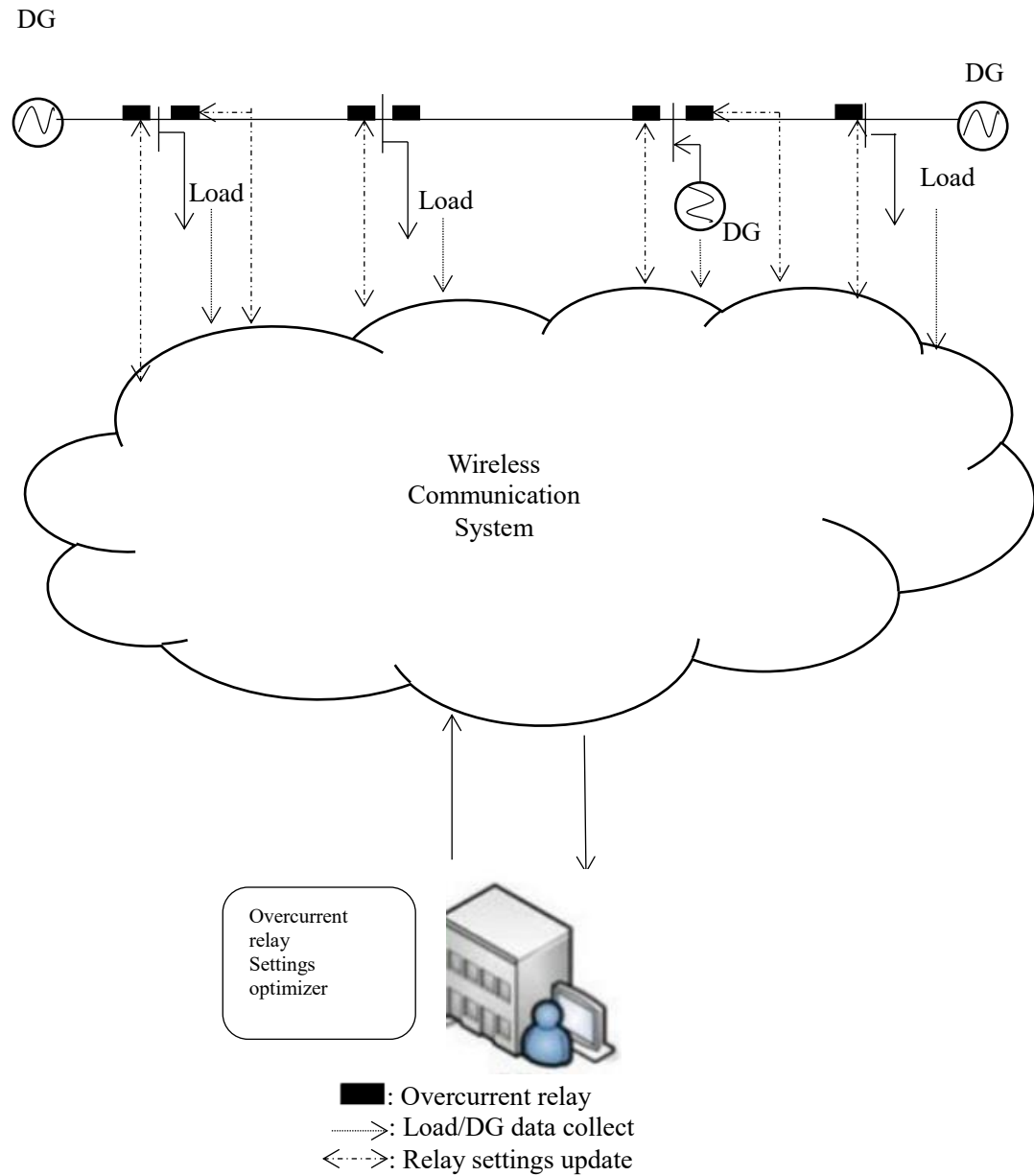


Figure 2.2, Proposed online adaptive protection system

SCADA systems are defined as a collection of equipment that will provide an operator at a remote location with provided information to determine the status of particular equipment that cause actions to take place. There are two main parts in the SCADA implementation: the first is the data acquisition or monitoring of a process or equipment, the other part is the supervisory control of the process. The features of SCADA systems can achieve complete automation. Automating the monitoring part translates into an operator in a control room, and the remote process can be seen in the control room with all the acquired information displayed and updated at an appropriate time intervals [55].

In the first subsystem, the Supervisory Control and Data Acquisition (SCADA) system is used to obtain essential measurements including distributed generations output in the distribution systems, and the Advanced Meter Infrastructure (AMI) is used to gather the current and load values from each relay and load. The data is acquired from the distribution system and is then transferred to the main control center in the second subsystem through the wireless communication system. Also, AMI is the deployment of a metering solution with two-way communications to enable time stamping of meter data, outage reporting, communication into the customer premise, service connect/disconnect, on-request reads, and other functions. The AMI systems have the ability to gather more information on voltage, current, power, and outages from the distribution systems to enable other applications [56]. Besides this, wireless communication technologies will be used in the proposed method because GPRS, 3G or 4G and other wireless communication networks are very common in the United States.

The other subsystem is for the coordination optimization of overcurrent relays. In this subsystem, the settings of each overcurrent relay will be optimized based on the data

transferred from the first subsystem. In this subsystem, the Genetic Algorithm (GA) is applied for the optimization because Genetic Algorithm (GA) has many advantages which are very appropriate for this optimization problem.

In order to prove that the distributed generations and load variations will affect the original coordination of overcurrent relays in distribution system, there are three simulation systems created for the proposed method. The first one is a basic distribution system without distributed generations (DGs). The second one is similar to the first one but with load variations. The last simulation system is similar to the first one but with a distributed generation in it. The same fault was placed at the same location in all three simulation systems, and then the fault current values seen by the relays will be measured. The optimum coordination of overcurrent relays will be simulated on the system without DG in this chapter. In addition to this comparison, two different ways of genetic algorithm (GA) have been applied in the proposed method.

1. Two-step GA algorithm with MATLAB Toolbox.
2. Two-step genetic algorithm with GA solver in coding.

All three simulation systems are divided into four faulted sections A-D. There are four loads and eight overcurrent relays in each simulation distribution systems. For each faulted section, there are two primary relays and two corresponding backup relays. The relationship of primary and backup relays is listed in the above table, and Figure 2.6 is an example simulation system in Simulink MATLAB. Figure 2.3, Figure 2.4 and Figure 2.5 are the three simulation systems we discussed above,

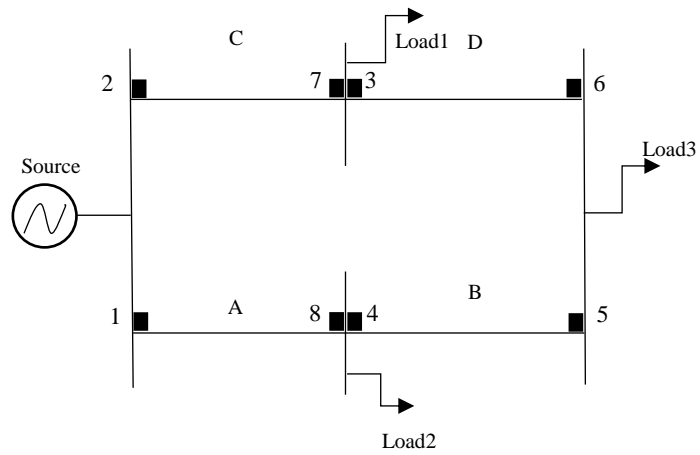


Figure 2.3, Simulation distribution system with only one source

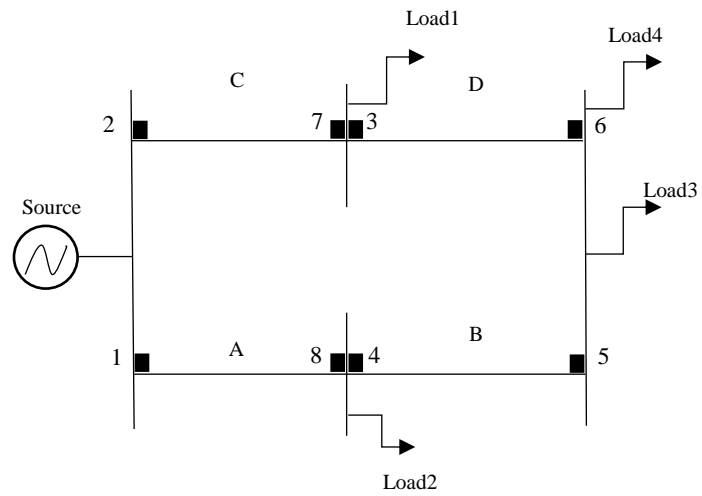


Figure 2.4, Similar simulation distribution system with different load level

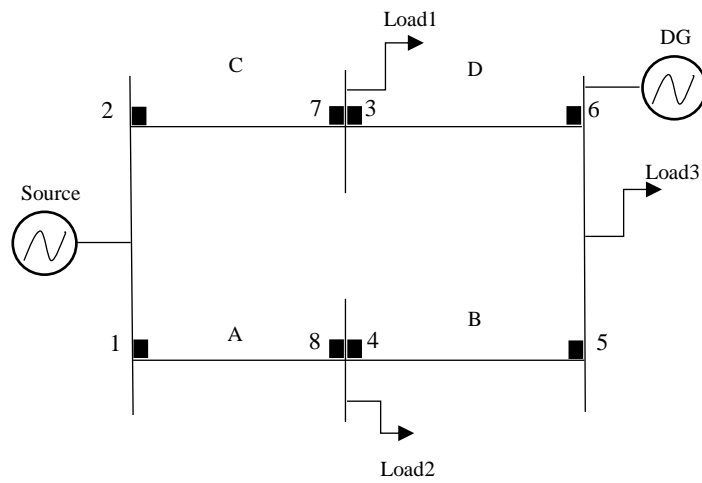


Figure 2.5, Similar Simulation distribution system with DG

Table 2.2, The relationship of primary and backup relays

Fault section	Primary relay	Backup relay
A	1	7
	8	5
B	4	1
	5	3
C	2	8
	7	6
D	3	2
	6	4

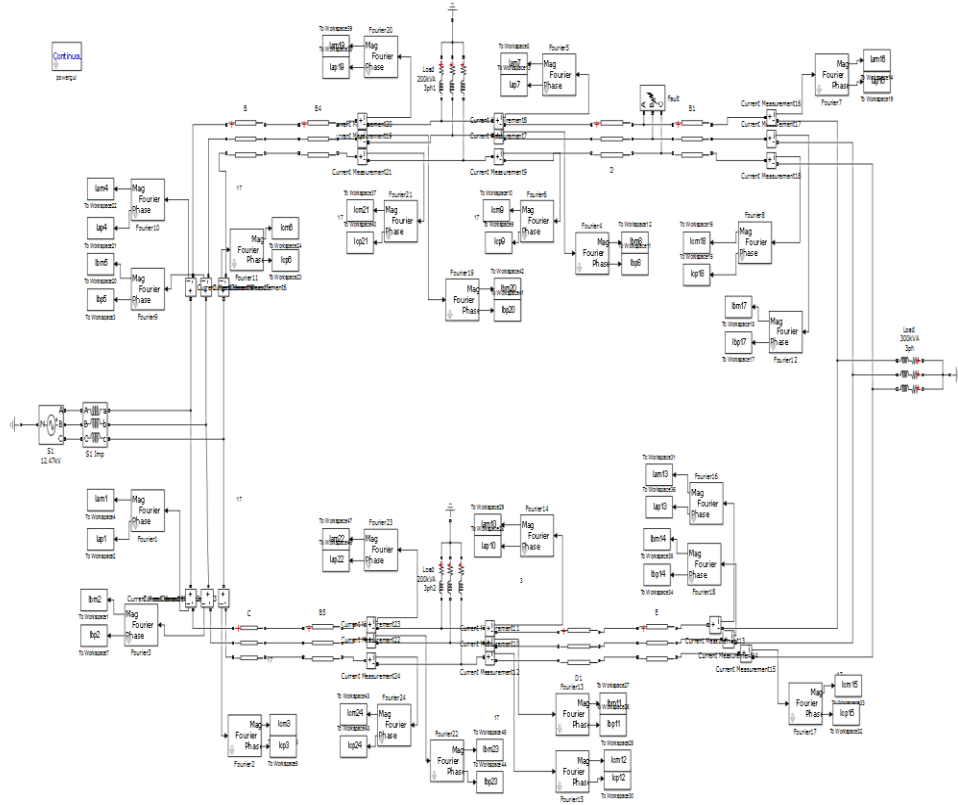


Figure 2.6, Example simulation system in Simulink MATLAB

2.3 Implementation of the Proposed Method

As discussed above, two different ways of applying genetic algorithm have been applied in the study. The details of these two methods are discussed in this subchapter.

2.3.1 GA Optimization Toolbox

At the very beginning of the simulation, the GA Optimization Toolbox was applied to the optimum coordination of overcurrent relays. The Optimization Toolbox is a collection of optimization functions in the MATLAB numeric computing modules. It provides functions for finding optimal solutions that minimize or maximize continuous and

discrete objective problems under constraints. The Optimization Toolbox can be applied to many types of optimization problems, for examples [57]:

- Linear programming problems (LP)
- Mixed-integer linear programming problems (MILP)
- Unconstrained or constrained nonlinear minimization problems (NLP)
- Minimax and semi-infinite minimization problems
- Quadratic and linear programming (QP)
- Constrained Least squares problems
- Nonlinear least squares problems
- Sparse and structured large-scale problems
- Nonlinear equations problems
- Graphical monitoring of optimization process
- Gradient estimation acceleration

The MATLAB Optimization Toolbox provides a flexible way for solving optimization problems and requires users to provide input parameters and constraints through a user interface.

Figure 2.7 is an example of the MATLAB Optimization Toolbox window. In the window, the first part on the left-hand side is the optimization solver choice. MATLAB optimization Toolbox offers many optimization solvers besides genetic algorithm (GA). The second part is the details of the optimization problem. It consists of the objective fitness function and the number of variables in the fitness function. For the proposed method, the fitness function is equation 2.2, the sum of the operating time of all primary and backup relays for each faulted section. Also there are eight overcurrent relays in the simulation system and

each relay has two settings. Therefore, there should be 16 variables $x_1 \sim x_{16}$ to be optimized in the proposed case. The variables $x_1 \sim x_8$ are the TDS of each overcurrent relay, and variables $x_9 \sim x_{16}$ are the pickup current setting of each overcurrent relay. The third part is the constraints part. This part includes linear inequalities, linear equalities, bounds and nonlinear constraint functions. Equation 2.3 belongs to the linear inequalities constraints, which should be written in the form of

$$A * x \leq B \quad (2.7)$$

The equations 2.4 and 2.5 belong to the bounds constraints because they are the bounds of 16 variables in the objective fitness function. The blank marked as lower is the lower limit of all 16 variables, and the blank marked as upper is the upper limit of all 16 variables in the objective fitness function. The equation 2.6 belongs to the nonlinear constraints part, this type of constraint was written as a separate M file because it is more complicated than both the linear inequalities constraints and the bounds constraints. The option part on the right-hand side is the part of where the optimization parameters can be set. In the proposed simulation, we used the default settings for each parameter.

In addition, because the objective fitness function is a nonlinear equation and has 16 variables, it may be time consuming to optimize all 16 variables at the same time. Two-step genetic algorithm is introduced here to speed up the optimization process. This method was introduced in [6] [58]. This method is to set one type of variables as fixed when optimizing the other variables, and then the variables fixed in the first step are re-optimized, which means just half amount of variables will be optimized in each step. This is discussed in the author's paper [39]. Therefore, the genetic algorithm here is divided into two steps:

1. Set I_{pick} as constants to find optimal TDS.

2. Find optimal I_{pick} .

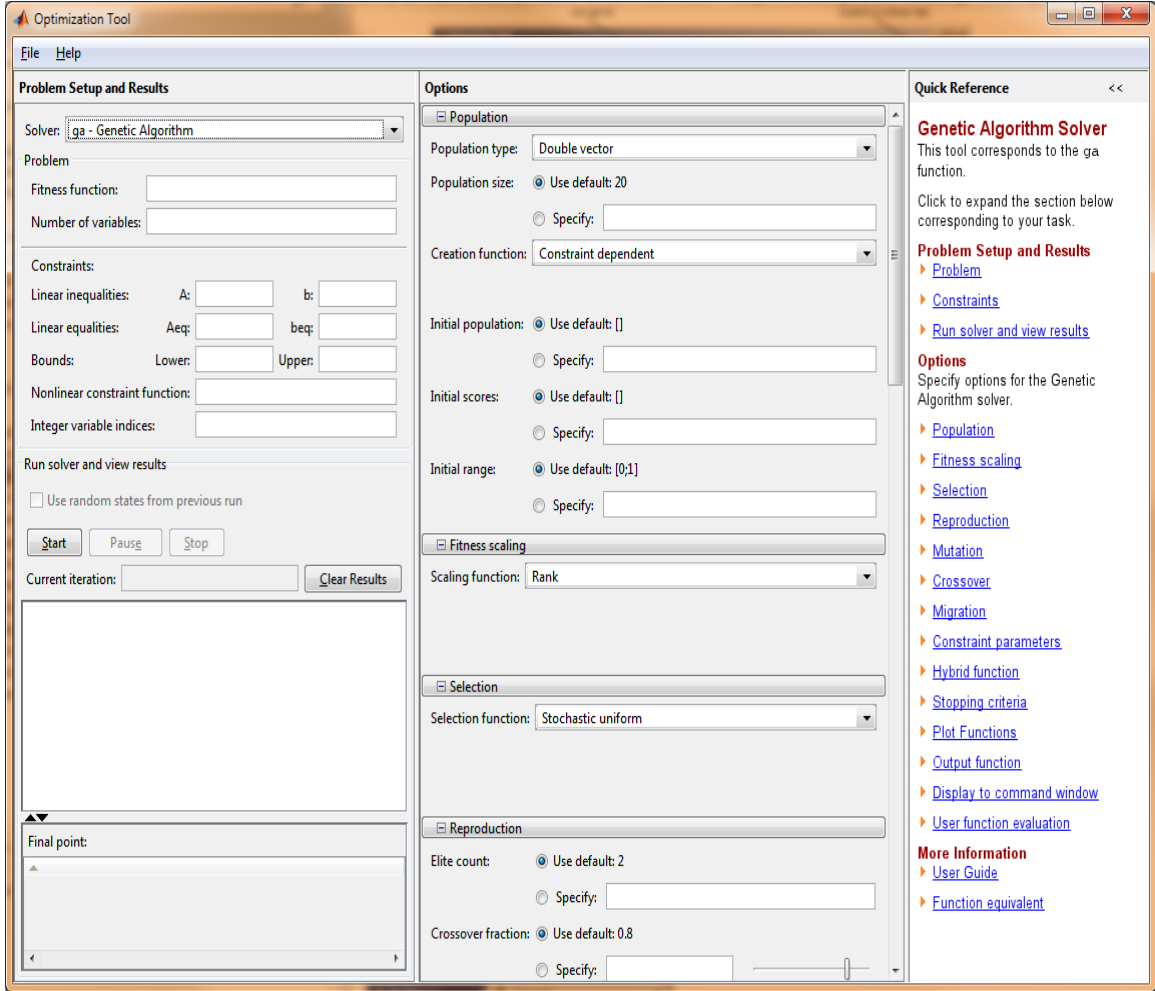


Figure 2.7, MATLAB Optimization Toolbox window

Step I – Set I_{pick} as constants to find the optimal TDS

The objective function for the step I is

$$\text{Min } \sum_{i=1}^n \left[\left(\frac{0.14(\text{TDS})}{P_{SM}^{0.02} - 1} \right)_{pj} + \left(\frac{0.14(\text{TDS})}{P_{SM}^{0.02} - 1} \right)_{bj} \right] \quad (2.8)$$

Where

$$PSM = \frac{I_{fault}}{I_{pick}} \quad (2.9)$$

The linear equation is formulated in terms of TDS by taking I_{pick} as a constant value. In step 1, the I_{pick} is set to be a constant equal to 1.5 times the maximum load current in the simulated distribution system to get the optimum setting of TDS for each relay. Then the object function can be written as:

$$\text{Min } \sum_{i=1}^n \sigma_i (TDS_{pi} + TDS_{bi})$$

This is a linear equation where i is the identifier number of the relay and σ_i is the constant $\frac{0.14}{PSM^{0.02} - 1}$, which can be calculated easily for each relay. Then the objective function and the minimum operating time including all primary and backup relays becomes a linear equation containing eight unknowns, which can be optimized by GA easily. The following Table 2.3 shows σ_i of primary and backup relays for each fault area.

Table 2.3, The σ_i constant for relays

Fault point		Relay							
		1	2	3	4	5	6	7	8
A	σ_i	1.6813	-	-	-	3.2428	-	3.1787	3.2436
B	σ_i	2.1903	-	2.6029	2.1936	2.6112	-	-	-
C	σ_i	-	1.5442	-	-	-	3.5618	3.5640	3.4929
D	σ_i	-	2.0970	2.1002	2.6958	-	2.6983	-	-

Then the objective function, minimum the operating time of all primary and backup relays becomes this linear function:

$$\begin{aligned} \text{Min } [& 3.8716(TDS_1) + 3.6412(TDS_2) + 4.7031(TDS_3) + 4.8894(TDS_4) + \\ & 5.5840(TDS_5) + 6.2601(TDS_6) + 6.7427(TDS_7) + 6.7365(TDS_8)] \end{aligned}$$

Subject to the constraints

$$1.1 \geq 1.6813(TDS_1) \geq 0.1; \quad 1.1 \geq 1.5442(TDS_2) \geq 0.1;$$

$$1.1 \geq 2.1002(TDS_3) \geq 0.1; \quad 1.1 \geq 2.1936(TDS_4) \geq 0.1;$$

$$1.1 \geq 2.6112(TDS_5) \geq 0.1; \quad 1.1 \geq 2.6983(TDS_6) \geq 0.1;$$

$$1.1 \geq 3.1787(TDS_7) \geq 0.1; \quad 1.1 \geq 3.2436(TDS_8) \geq 0.1;$$

And

$$0.025 \leq TDS_1 \leq 1.2; \quad 0.025 \leq TDS_2 \leq 1.2;$$

$$0.025 \leq TDS_3 \leq 1.2; \quad 0.025 \leq TDS_4 \leq 1.2;$$

$$0.025 \leq TDS_5 \leq 1.2; \quad 0.025 \leq TDS_6 \leq 1.2;$$

$$0.025 \leq TDS_7 \leq 1.2; \quad 0.025 \leq TDS_8 \leq 1.2;$$

$$3.1787(TDS_7) - 1.6813(TDS_1) \geq 0.3; \quad 3.2428(TDS_5) - 3.2436(TDS_8) \geq 0.3;$$

$$2.1903(TDS_1) - 2.1936(TDS_4) \geq 0.3; \quad 2.6029(TDS_3) - 2.6112(TDS_5) \geq 0.3;$$

$$3.4929(TDS_8) - 1.5442(TDS_2) \geq 0.3; \quad 3.5618(TDS_6) - 3.5640(TDS_7) \geq 0.3;$$

$$2.0970(TDS_2) - 2.1002(TDS_3) \geq 0.3; \quad 2.6958(TDS_4) - 2.6983(TDS_6) \geq 0.3;$$

Then the MATLAB Optimization Toolbox is used to optimize this objective function to find out the optimum TDS for each relay. Because the genetic algorithm is used to optimize the relays coordination, the solver here is chosen as “ga-Genetic Algorithm.” In the problem section, the fitness function is filled with the above linear objective function, and also the number of variables is eight because just TDS of each overcurrent relay will be optimized in this step.

In the constraints section, the first part of constraints about the operating time limit is filled in the blank of linear inequalities. The second part of constraints is filled in the blanks of bounds, and the last part of constraints is filled into the blank of nonlinear constraints.

Then running the Toolbox and the TDS of each relay can be optimized by the genetic algorithm. The optimum TDS settings of each relay are listed in Table 2.4.

Table 2.4, The optimum TDS settings of each relay

Relay	1	2	3	4
TDS	0.908	0.785	0.642	0.770
Relay	5	6	7	8
TDS	0.525	0.658	0.574	0.433

Step II – Set TDS as constants to find the optimal I_{pick}

In this step, we set TDS of each relay as constants which have been optimized in step I. Then we use the GA solver in the MATLAB Optimization Toolbox to optimize the I_{pick} of each overcurrent relay based on the constraints of pickup current. Its lower bound value is set as 1.3 times the maximum load current in the system, and the upper bound value is equal to the minimum fault current seen by the relay in the distribution system. The objective fitness function will become a non-linear function:

$$\text{Min } \sum_{i=1}^n \left[\left(\frac{0.14(\text{TDS})}{P_{SM}^{0.02-1}} \right)_{pj} + \left(\frac{0.14(\text{TDS})}{P_{SM}^{0.02-1}} \right)_{bj} \right]$$

Substitute the TDS from step I and the fault current values seen by each overcurrent relay into the objective fitness function:

It becomes:

$$\begin{aligned} \text{Min } [& \frac{0.14 \cdot 0.908}{(\frac{1421.4}{I_{pick_1}})^{0.02-1}} + \frac{0.14 \cdot 0.908}{(\frac{577.18}{I_{pick_1}})^{0.02-1}} + \frac{0.14 \cdot 0.785}{(\frac{1997.2}{I_{pick_2}})^{0.02-1}} + \frac{0.14 \cdot 0.785}{(\frac{659.57}{I_{pick_2}})^{0.02-1}} + \frac{0.14 \cdot 0.642}{(\frac{357.71}{I_{pick_3}})^{0.02-1}} + \\ & \frac{0.14 \cdot 0.642}{(\frac{656.46}{I_{pick_3}})^{0.02-1}} + \frac{0.14 \cdot 0.770}{(\frac{574.6}{I_{pick_4}})^{0.02-1}} + \frac{0.14 \cdot 0.770}{(\frac{327.56}{I_{pick_4}})^{0.02-1}} + \frac{0.14 \cdot 0.525}{(\frac{215.63}{I_{pick_5}})^{0.02-1}} + \frac{0.14 \cdot 0.525}{(\frac{354.79}{I_{pick_5}})^{0.02-1}} + \\ & \frac{0.14 \cdot 0.658}{(\frac{179.09}{I_{pick_6}})^{0.02-1}} + \frac{0.14 \cdot 0.658}{(\frac{326.82}{I_{pick_6}})^{0.02-1}} + \frac{0.14 \cdot 0.574}{(\frac{224.81}{I_{pick_7}})^{0.02-1}} + \frac{0.14 \cdot 0.574}{(\frac{178.88}{I_{pick_7}})^{0.02-1}} + \frac{0.14 \cdot 0.433}{(\frac{215.51}{I_{pick_8}})^{0.02-1}} \\ & + \frac{0.14 \cdot 0.433}{(\frac{185.48}{I_{pick_8}})^{0.02-1}} ; \end{aligned}$$

The optimal values of I_{pick} were calculated by the genetic algorithm in the MATLAB Optimization Toolbox. The optimal results are displayed in the

Table 2.5.

Table 2.5, I_{pick} optimal values of each overcurrent relay

Relay	1	2	3	4
I_{pick}	26.159	26.195	26.094	26.165
Relay	5	6	7	8
I_{pick}	26.109	26.194	26.164	26.042

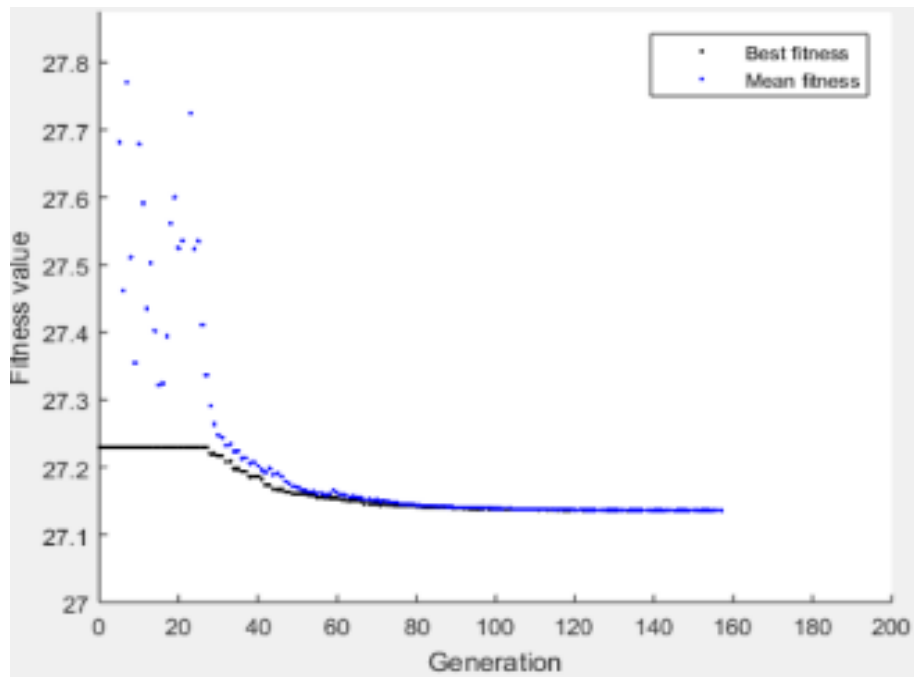


Figure 2.8, The graph of the convergence procedure of GA in the proposed method by

MATLAB Optimization Toolbox

Figure 2.8 depicts the convergence locus of the GA optimization process for the proposed method. It is shown that the whole optimization procedure takes around 160 generations to reach the final optimal results.

2.3.2 Two-step genetic algorithm with GA solver in coding.

From the many tests for the proposed methods using the MATLAB Optimization Toolbox, we found that although the MATLAB Optimization Toolbox is very easy and convenient for us to get the optimization results and the graph of the optimization procedure. However, the constraints and measured fault current values should be input manually when there is a change in the distribution system. It is complicated to input the updated constraints and fault currents automatically. Therefore, the MATLAB Optimization Toolbox is only good for the one-time optimization, but not really good at the online adaptive optimum coordination of overcurrent relays because the conditions of the distribution system are dynamic. In order to achieve the online adaptive feature of the optimum coordination of overcurrent relays, we tried the genetic algorithm (GA) solver in coding to reach this objective.

The GA solver in MATLAB is represented in the form of:

```
[x,fval,exitflag,output,population]=ga(fun,nvars,A,b,Aeq,beq,lb,ub,nonlcon,IntCon,options)
```

On the left-hand side of the syntax of GA solver, x is the final optimal results optimized by GA solver; fval is objective function value at the solution, it should be a real number; exitflag is an integer which means the reason why GA algorithm stops, it consists nine reasons, which is listed in Table 2.6.

Table 2.6, Reasons that GA solver stops

Exit flag	Meaning
1	Value of the fitness function over defined maximum generations is less than defined tolerance, and the constraint violation is less than the defined tolerance of constraints
3	Value of the fitness function did not change in the maximum generations and the constraint violation is less than the defined tolerance of constraints
4	Magnitude of step is smaller than the machine precision and the constraint violation is less than the defined tolerance of constraints
5	Minimum fitness limit reached the constraint violation is less than the defined tolerance of constraints
0	Maximum number of generations exceeded.
-1	Optimization terminated by an output function or plot function.
-2	No feasible point found.
-4	Stall time limit exceeded.
-5	Time limit exceeded.

Output is the information about the optimization process; it contains the number of generations computed, the number of evaluations of the fitness function, the reason that algorithm stopped and the maximum constraint violation. Population is the final population, which is a matrix with the size of the population times the number of variables. Also, the rows of the matrix are the individuals in the optimization.

The right-hand side of the syntax of GA solver in coding is to minimize the fitness function with the defined parameters in the options. The fun means the objective fitness function. Nvars is a positive integer which means the number of variables in the objective fitness function; A and b represent the linear inequality constraints, A is a real matrix and b is a real vector, it is in a form of:

$$A * x \leq B$$

Aeq and beq are the linear equality constraints. Aeq is a real matrix and beq is a real vector. They are represented in the form of:

$$Aeq * x = beq$$

lb and ub are the lower bounds and the upper bounds of the variables in the objective fitness function; they are both real vectors of array. Nonlcon is the nonlinear constraints; it is a function that contains c(x) and ceq(x), where c(x) is an array of nonlinear inequality constraints at x and ceq(x) is an array of nonlinear equality constraints at x:

$$c(x) \leq 0$$

$$ceq(x) = 0$$

Options are the optimization options, where all the parameters of optimization can be set.

The most important advantage of the genetic algorithm solver in coding is that all data information measured from distribution systems can be applied to the GA solver automatically, and this process is very simple and convenient. Therefore, it is better than the GA in the MATLAB Optimization Toolbox for the online adaptive coordination of overcurrent relays. From simulation of the optimum coordination of overcurrent relays using GA solver in coding, the optimal settings of overcurrent relays are very close to the

results we got from the MATLAB Optimization Toolbox. Figure 2.9 is a graph of the convergence procedure of GA in the proposed method by the GA solver in coding.

Then to prove the distributed generations output and load variations will affect the original optimum coordination of overcurrent relays, the same fault was placed at the same location in Figure 2.3, Figure 2.4 and Figure 2.5. The measured fault current seen by the relays in the last two simulation distribution systems are different from the measured ones in the first distribution system. According to the ([43]- [49]) and the equation 2.1,

$$T = \frac{0.14 * TDS}{\left(\frac{I_{fault}}{I_{pick}}\right)^{0.02} - 1}$$

We can see that the values of the operating time of overcurrent relays will change when the value of fault current seen by that overcurrent relay changes. Therefore, the objective fitness function 2.2

$$\text{Min } \sum_{i=1}^n (T_{primary_j} + T_{backup_j})$$

may change, which means the TDS and the pickup current settings may change. Hence, the original overcurrent relays settings are not appropriate anymore and an online adaptive coordination of overcurrent relays are necessary when there are variations of load or distributed generations output.

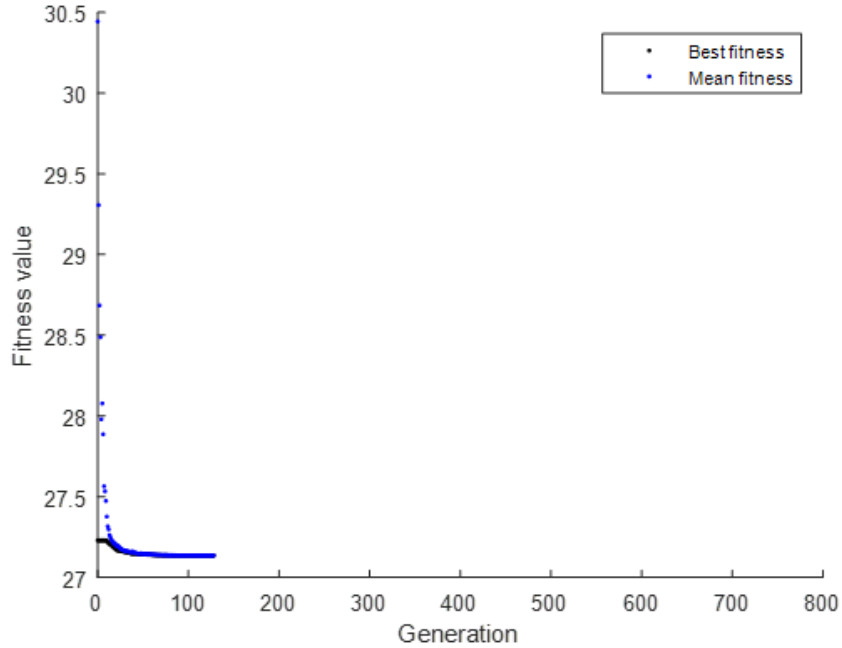


Figure 2.9, The graph of the convergence procedure of GA in the proposed method by the GA solver in coding

2.4 Implementation of the Method – Single-Step Genetic Algorithm

For the proposed method, the single-step genetic algorithm is also considered originally. In the single-step genetic algorithm, both settings of each overcurrent relay will be optimized in one step. Theoretically, optimization results from the single-step genetic algorithm would be more appropriate than the ones from the two-step genetic algorithm because all results would be optimized at the same time. However, we found that the process of the optimization by the single-step genetic algorithm is more time consuming than the two-step genetic algorithm sometimes. This result may be caused by the non-linear objective function with all 16 variables at the same time. Hence the single-step genetic

algorithm may not satisfy the time requirement of the online adaptive function of the proposed method. In addition, the optimization results from the single-step genetic algorithm are not much different from the ones optimized from two-step genetic algorithm. Therefore, the two-step genetic algorithms are used in the proposed method.

2.5 Summary

According to the discussion above, the existing optimum coordination methods are designed under the conditions of fixed DG output and load in the distribution system. In other words, the methods only consider the static conditions of the distribution system. When there is a variation of load or distributed generations in the distribution system, the optimum coordination methods may not provide the most desirable coordination of overcurrent relays in the distribution system

Also, load changes during the day and the allowable DG output power is different at each load level. The DG output power would decrease with the decrease of the load. In addition, the allowable DG output power varies with the load level in an approximately linear form. It concludes that the appropriate DG output should be determined by the system demand to reduce feeder loss. Therefore, protective coordination of overcurrent relays applied in distribution systems with DGs becomes very difficult to achieve because it lacks the flexibility of adaptive relay schemes by harnessing prevailing conditions of the distribution system. Also, this point has been proved by the comparison between three different types of simulation systems which are discussed above.

This chapter presents the overall picture of the proposed online and adaptive overcurrent relay coordination setting scheme considering variation in load and DG in the distribution

system using the genetic algorithm. To realize the function of online and adaptive optimum coordination of overcurrent relays, one important aspect is the collection of required data of distribution system and the communication between the central control office and the data collecting points. The proposed system will take advantage of the SCADA (Supervisory Control and Data Acquisition) system, AMI (Advanced Meter Infrastructure), and 3G 4G wireless communication technologies to achieve the online adaptive function for the optimum coordination of overcurrent relays.

Also based on the advantages of genetic algorithm (GA), a genetic algorithm is used as the optimization technique in the proposed method. With the comparison between two different genetic algorithms:

1. Two-step GA algorithm with MATLAB Toolbox.
2. Two-step genetic algorithm with GA solver in coding.

The two-step genetic algorithm with GA solver in coding is more appropriate for the online adaptive optimum coordination of overcurrent relays because it can realize the information input automatically which meets the requirement of online adaptive function.

To make the proposed online scheme practical, more research is needed. A fast optimization method including GA considering dynamic crossover and mutation rate will be explored to speed up convergence. In order to make the coordination more computationally efficient, we will try to find an appropriate threshold for the variation of load and DG. The optimum coordination function would be triggered only if the variation exceeds the threshold. Otherwise, the adaptive optimum coordination procedure would not

be triggered. Other optimization techniques such as differential evolution may be tried for improved performance.

Chapter 3 Intelligent Method for Online Adaptive Optimum Coordination of Overcurrent Relays for more Practical system

In this chapter, a large size simulation distribution system with more distributed generations and loads will be discussed. Because this proposed method should work with the real distribution system with much more distributed generations and loads, which is more practical. We just considered the effects of variations of distributed generations output and load values on the optimum coordination of overcurrent relays, and in this chapter, the effects of fault locations on the optimum coordination of overcurrent relays will be discussed.

3.1 Simulation on a Large Scale Distribution System

Although the GA optimization algorithm has been applied in the proposed method in the last chapter, there is still much work that can be done in this field. The original simulation system is a simple one with only eight overcurrent relays and four faulted sections. In this chapter, we tried the two-step genetic algorithm with GA solver in coding in a large scale simulation distribution system to make sure it is still valid for a more practical distribution system. Therefore, this proposed method is an improved one which is based on the one in the last chapter. In addition, the proposed method should also meet the following requirements:

1. Meet the requirements of the protection system which have been mentioned in the above introduction: sensitivity, selectivity, reliability and speed.
2. Be able to determine the most desirable settings of overcurrent relays for intelligent online adaptive coordination on time to reduce the effects of the variations of load

value and distributed generations output on the protection system in distribution systems as much as possible.

3. It is very important to ensure that this method satisfies the cybersecurity requirements because the overcurrent relay setting data is security sensitive, although it is beyond the scope of this research field.

Figure 3.1 shows the new studied power distribution system. In the simulated distribution system, there are 16 overcurrent relays and A-H, 8 fault sections. In

Table 3.1, it shows the primary and backup relays for their corresponding faulted sections. In order to check the effects of the fault locations on overcurrent relays coordination, different fault locations are examined in the proposed method.

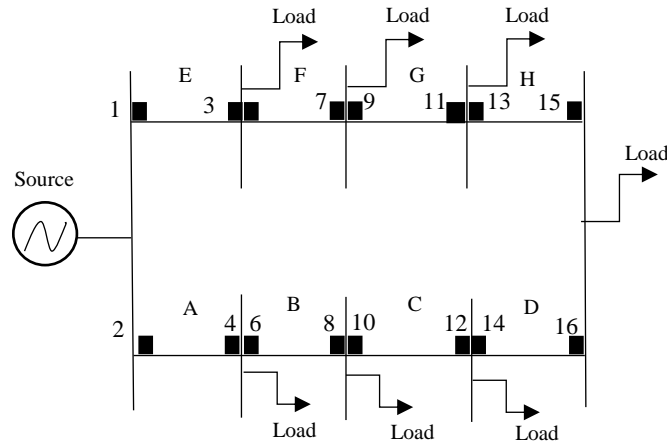


Figure 3.1, A large-scale simulation distribution system

Table 3.1, Primary and backup relays for their corresponding fault section

Fault Section	Primary Relay	Backup Relay	Fault Section	Primary Relay	Backup Relay
A	2	3	E	1	4
	4	8		3	7
B	6	2	F	5	1
	8	12		7	11
C	10	6	G	9	5
	12	16		11	15
D	14	10	H	13	9
	16	13		15	14

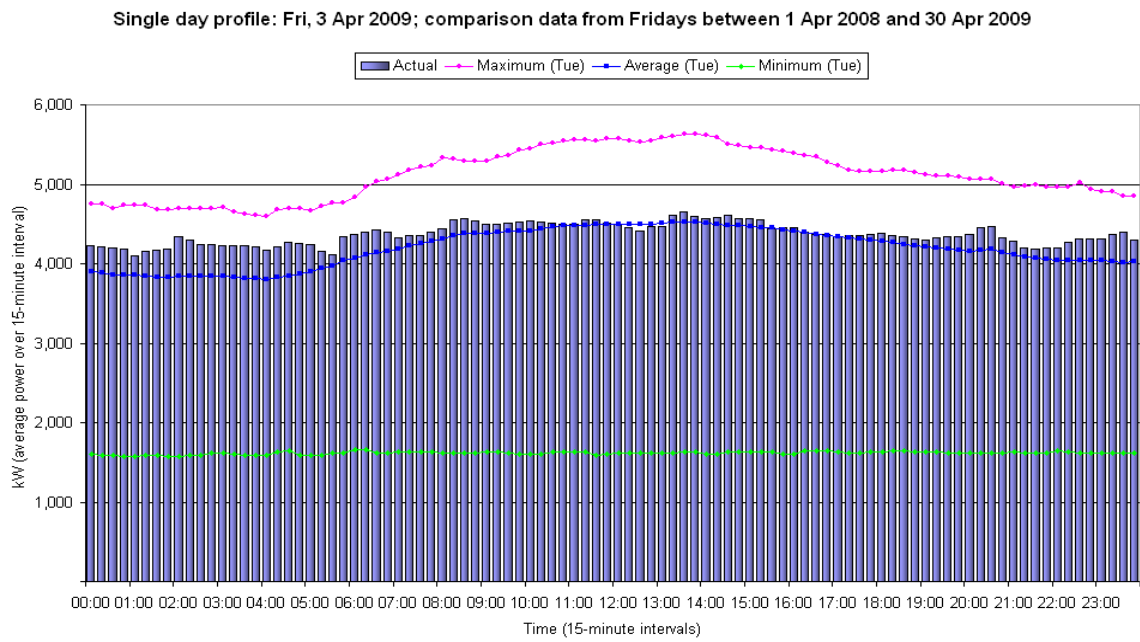


Figure 3.2, An example of a load variation monitor in the 15-minute interval in a day

According to the report from the U.S. Energy Information Administration, there are over 40 million AMI meters in the 15-min interval that are installed across the U.S. The 15-minute load monitoring is the most common in distribution systems. Therefore, the proposed method will perform an online adaptive coordination of overcurrent relays in a 15-min interval based on the system variations. The Supervisory Control and Data Acquisition (SCADA) system is used to obtain essential measurements including distributed generations output in the distribution systems, and Advanced Meter Infrastructure (AMI) is used to gather the current and load values from each relay and load every 15 minutes. The data is acquired from the distribution system and then transferred to the main control center through the wireless communication system. Then the optimum coordination of overcurrent relays is performed at a 15-minute interval. In Figure 3.2, there is an example of a load variation monitor in a 15-minute interval in a day [59].

Also in order to check the effects of the fault locations on overcurrent relays coordination, faults with different locations are examined in the proposed method. In the first optimization of overcurrent relays coordination, the fault was located at the middle point of each fault section. Table 3.2 and Table 3.3 list the optimized settings of each relay in the simulated distribution system for the middle point fault location. Table 3.4 and Table 3.5 list the optimized settings of each relay in the simulated distribution system for the near end fault location. From the comparison of optimized settings for two different locations, it can be seen that they are different when faults happen at the different locations. So, in practice, it might be appropriate to form a combined objective function considering near end faults, middle point faults and far end faults, so that the estimation results will be optimal for general cases.

Table 3.2, The optimum settings of TDS of each relay for the middle point fault location

Relay	1	2	3	4
TDS	0.6206	0.8385	0,1549	0.1345
Relay	5	6	7	8
TDS	0.5890	0.8788	0.3834	0.2827
Relay	9	10	11	12
TDS	0.6132	0.8902	0.6611	0.4257
Relay	13	14	15	16
TDS	0.7374	0.9606	0.8216	0.6436

Table 3.3, Optimum of I_pickup of each relay for the middle point fault location

Relay	1	2	3	4
I_pickup	62.1295	50.2900	62.4168	50.6632
Relay	5	6	7	8
I_pickup	43.0700	31.3449	43.4908	31.9416
Relay	9	10	11	12
I_pickup	24.2837	22.3433	24.6960	22.7573
Relay	13	14	15	16
I_pickup	15.1266	13.1830	15.5510	13.6298

Table 3.4, The optimum settings of TDS of each relay for the near end fault location

Relay	1	2	3	4
TDS	0.5377	1.2000	0.0250	0.8622
Relay	5	6	7	8
TDS	0.3188	0.0451	0.0250	0.3426
Relay	9	10	11	12
TDS	1.2000	1.2000	0.0283	1.2000
Relay	13	14	15	16
TDS	0.7254	0.0443	0.7147	0.0408

Table 3.5, Optimum of I_pickup of each relay for the near end fault location

Relay	1	2	3	4
I_pickup	53.9280	43.8025	54.1795	44.1294
Relay	5	6	7	8
I_pickup	37.4114	27.3780	37.7768	27.9089
Relay	9	10	11	12
I_pickup	21.1306	19.5833	21.4933	19.9565
Relay	13	14	15	16
I_pickup	13.1998	11.6521	13.5589	12.0584

3.2 Summary

Although the two-step GA optimization algorithm has been applied in the proposed method and discussed in the last chapter, there is still much work that can be done in this field. The original simulation system is a simple distribution system with only eight overcurrent relays and four faulted sections, and we were not sure whether it still works when the size of the distribution system is growing. Therefore in this chapter, we tried the two-step genetic algorithm with GA solver in coding in a large scale simulation distribution system to make sure it is still valid for a more practical distribution system. Therefore, the proposed method illustrated in this chapter is an improved one which is based on the one in the last chapter. In addition, the proposed method should also satisfy the following requirements:

1. Meet the requirements of the protection system.
2. Be able to find the most desirable settings of overcurrent relays for intelligent online adaptive coordination on time so that reduce the effects of the variations of load value and distributed generations output on the protection system.
3. It is very important to ensure that this method should satisfy the cybersecurity requirements because the overcurrent relay setting data is security sensitive, although it is beyond the scope of this research field.

In addition, we also considered the effects of fault location on the optimum coordination of overcurrent relays. So the middle point fault and near then end fault are tested in this chapter, we found that the fault location also affects the optimum coordination settings of each overcurrent relay. At last, we think we may find another optimization

technique which is faster than the two-step genetic algorithm in coding tested in this chapter, so we can achieve the online adaptive function of the coordination of overcurrent relays better. Therefore, this will be discussed in Chapter 4.

Chapter 4 Online Adaptive Efficient Optimum Coordination of Overcurrent Relays Using Differential Evolution

As the summary in the last chapter stated, we tested another optimization technique instead of the genetic algorithm optimization technique for the proposed method, hence the differential evolution (DE) will be introduced. Because the requirement of online adaptive function, the optimal process need to be accomplished as soon as possible. Through the comparison between genetic algorithm and differential evolution on the optimum coordination of overcurrent relays, we found that differential evolution is much faster than genetic algorithm especially the size of distribution system grows. Therefore, the differential evolution optimal technique is much better than the genetic algorithm in the proposed method to realize online adaptive function.

4.1 Overview of Differential Evolution (DE) Optimization Technique

The differential evolution (DE) is an evolutionary optimization method. It has all the evolutionary components: gene, chromosome, individual, population and evolution process. It also has a good reputation as an efficient and robust optimizer. Compared with the genetic algorithm (GA), DE executes mutation, crossover and selection in each evolution loop. But DE only accepts a child when it dominates its direct mother, which is different from GA.

Also, DE has a similar process like GA, it includes 4 main steps:

1. Initialization

2. Mutation
3. Crossover
4. Selection

For the DE, three main parameters affect its performance [60]:

- Population size
- Scaling factor
- Crossover rate

The population size is the size of initialization at the very beginning of optimization. Scaling factor is the mutation intensity, which is used in the step of mutation. Crossover rate is used in the step of crossover. It is very good at searching for the global optimal values in a continuous domain. It has two advantages: high rate of convergence and very simple algorithm construction.

In the proposed method, the differential evolution will be used to optimize the coordination of overcurrent relays. The reasons are:

- DE has a good reputation as an efficient and robust optimizer.
- DE is good at searching for the global optimal values in a continuous domain.
- Compared with the genetic algorithm (GA), we found that DE converges more quickly than GA when we increased the number of relays, which means more variables need to be optimized in the fitness function.

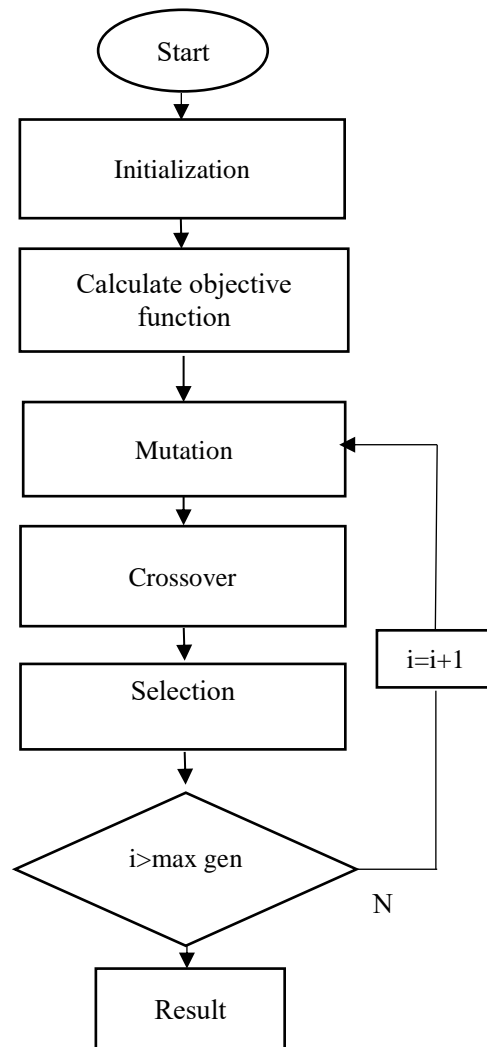


Figure 4.1, Flowchart of differential evolution

4.2 Overall Description of the Proposed Scheme and Simulation of Proposed Method

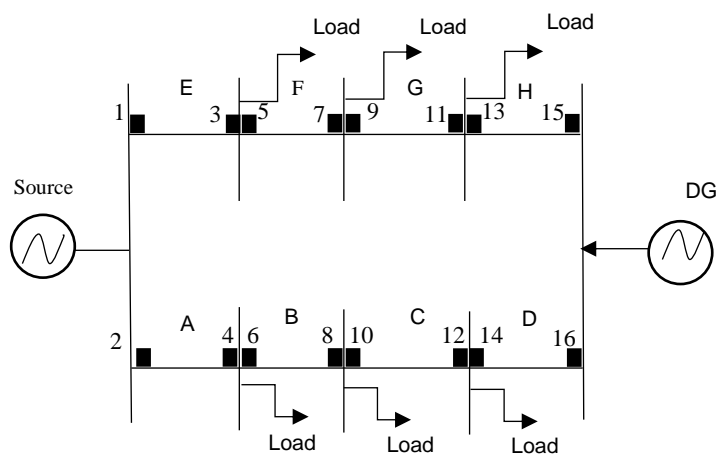


Figure 4.2, The simulation system for the proposed method using DE

Table 4.1, Fault Sections and their Corresponding Primary And Backup Relays

Fault Section	Primary Relay	Backup Relay	Fault Section	Primary Relay	Backup Relay
A	2	3	E	1	4
	4	8		3	7
B	6	2	F	5	1
	8	12		7	11
C	10	6	G	9	5
	12	16		11	15
D	14	10	H	13	9
	16	13		15	14

The simulation system has 16 overcurrent relays and 8 faulted sections. Each faulted section has two primary relays located at both ends of the faulted section and two backup relays which correspond to the primary ones. Figure 4.2 is the simulation system used to test the proposed method. Table 4.1 shows each faulted section and its corresponding primary and backup relays. Also, there is one power source on the left-hand side, one distributed generation on the right-hand side and six loads in the simulation system. As the proposed method introduced in Chapter 2, we still optimized the objective fitness function 2.2 based on the constraints 2.3~2.6.

$$\text{Min } \sum_{i=1}^n (T_{\text{primary}_j} + T_{\text{backup}_j})$$

Then the DE optimization technique is used to optimize the coordination of overcurrent relays in the simulation system. Table 4.2 ~ Table 4.7 show the optimization results of TDS and pickup current of each overcurrent relay for different fault locations in the simulation system. Table 4.2 and Table 4.3 show the optimization results of TDS and pickup current settings for the fault occurs at the 30% length from the left end-point of any faulted section; Table 4.4 and Table 4.5 show the optimization results of TDS and pickup current settings for the fault occurs at the 50% length from the left end-point of any faulted section; Table 4.6 and Table 4.7 show the optimization results of TDS and pickup current settings for the fault occurs at the 80% length from the left end-point of any faulted section. Figure 4.3 is an example of the DE optimization process.

Table 4.2, TDS settings for the fault occurs at the 30% length from the left end-point of
any faulted section

Relay	1	2	3	4
TDS	0.1885	0.0250	0.1593	0.0328
Relay	5	6	7	8
TDS	0.3077	0.8646	0.2357	0.1708
Relay	9	10	11	12
TDS	0.8590	0.8435	1.2000	1.1595
Relay	13	14	15	16
TDS	0.6156	0.4538	0.9201	0.6051

Table 4.3, Pickup current settings for the fault occurs at the 30% length from the left
end-point of any faulted section

Relay	1	2	3	4
I_pickup	125.2933	653.5352	54.7990	57.8577
Relay	5	6	7	8
I_pickup	284.4852	93.1077	37.7768	40.8740
Relay	9	10	11	12
I_pickup	21.1306	19.5833	35.9252	19.9565
Relay	13	14	15	16
I_pickup	13.1998	11.6251	29.2098	109.5697

Table 4.4, TDS for the fault occurs at the 50% length from the left end-point of any faulted section

Relay	1	2	3	4
TDS	0.5750	0.7025	0.3392	0.0617
Relay	5	6	7	8
TDS	0.4998	1.2000	0.8163	0.1021
Relay	9	10	11	12
TDS	0.8189	0.1184	0.5771	0.4017
Relay	13	14	15	16
TDS	0.8880	0.1170	0.0250	1.2000

Table 4.5, Pickup current settings for the fault occurs at the 50% length from the left end point of any faulted section

Relay	1	2	3	4
I_pickup	595.1166	321.6192	54.0945	43.9081
Relay	5	6	7	8
I_pickup	37.3273	27.1656	37.6920	61.1355
Relay	9	10	11	12
I_pickup	23.9169	138.6250	21.4032	59.6108
Relay	13	14	15	16
I_pickup	45.7164	59.9893	65.9587	50.4231

Table 4.6, TDS for the fault occurs at the 80% length from the left end point of any faulted section

Relay	1	2	3	4
TDS	1.2000	1.2000	0.5528	0.0360
Relay	5	6	7	8
TDS	0.0326	1.2000	0.1456	0.4485
Relay	9	10	11	12
TDS	0.2227	0.7244	0.3666	0.7220
Relay	13	14	15	16
TDS	1.2000	0.0824	1.2000	1.0894

Table 4.7, Pickup current settings for the fault occurs at the 80% length from the left end point of any faulted section

Relay	1	2	3	4
I_pickup	53.8455	154.3670	64.5359	51.4162
Relay	5	6	7	8
I_pickup	113.2943	27.1656	58.6781	44.2885
Relay	9	10	11	12
I_pickup	24.1344	35.0019	21.4032	30.3840
Relay	13	14	15	16
I_pickup	13.1097	84.3808	15.9738	78.9810

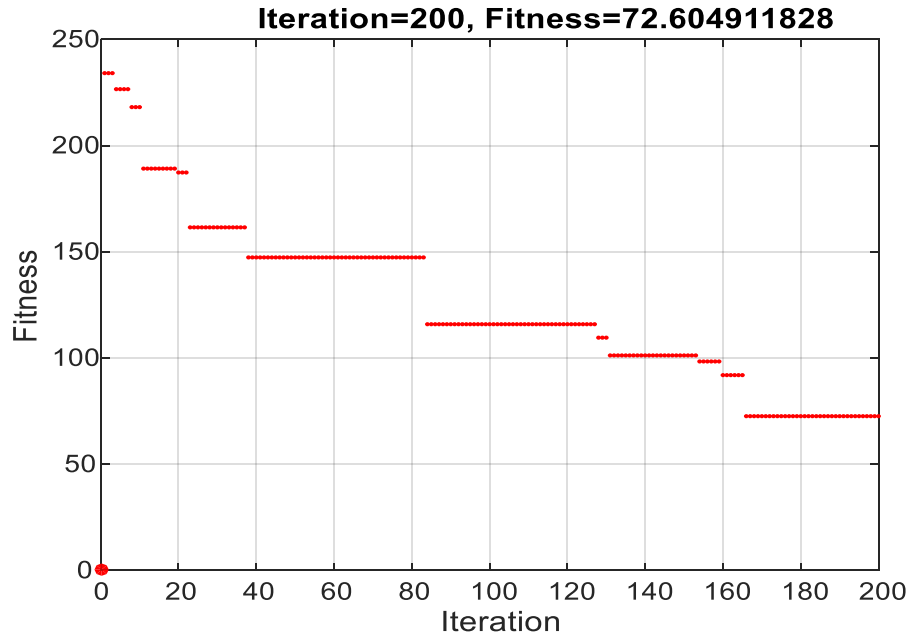


Figure 4.3, An example of the DE optimization process

Through the comparison between the genetic algorithm (GA) and the differential evolution (DE), we found that the DE is more computationally efficient than the GA when they are used to optimize the same system. More computation time can be saved for a larger system with DE method. Therefore, DE can provide a better optimization than GA to satisfy the time requirement of online adaptive optimum coordination of overcurrent relays.

4.3 Summary

In this chapter, we tested the differential evolution optimization technique instead of the genetic algorithm optimization technique for the proposed method. Because the requirement of online adaptive function, the optimal process need to be accomplished as

fast as possible. Through the comparison between the genetic algorithm and the differential evolution on the optimum coordination of overcurrent relays, we found that differential evolution is much faster than the genetic algorithm, especially when the size of the distribution system is growing. In addition, differential evolution has other advantages: it is an efficient and robust optimizer; it is good at searching for the global optimal values in a continuous domain. Therefore, the differential evolution optimization technique is much better than the genetic algorithm for the proposed method to realize online adaptive function.

Chapter 5 Conclusion

During the operation of a modern distribution power system, some abnormal conditions like faults and over-voltage can frequently occur. These abnormal conditions may cause power outage and damage on the equipment connected to the power system. To minimize the damage, the faulted components must be identified and isolated as quickly as possible. Therefore, a reliable protective system is needed. Also, the protection system should follow the requirements of sensitivity, selectivity, reliability and speed. In the power distribution system, the overcurrent relays are widely used for protection because they are an efficient and cost-effective way to protect feeders. The core part of the protection system is the problem of overcurrent relays coordination, which is to select the appropriate settings of each overcurrent relay to make sure the backup relays take over as quickly as possible when the primary relays fail. Therefore, the coordination of relays is very important in the protection system in distribution systems. So far, there are some existing optimum coordination methods for the coordination of overcurrent relays. However, these methods are usually based on the conditions of fixed distributed generations output and constant load in the distribution system, which is a static condition for the distribution system. When there is a variation of distributed generations output or load in distribution system, these existing optimum coordination methods may not offer the most appropriate settings for overcurrent relays anymore. Therefore, the proposed method is a solution to solve this problem via an online adaptive optimum coordination of overcurrent relays.

Two different genetic algorithms for the online adaptive optimum coordination of overcurrent relays are proposed in Chapter 2. The first is the two-step GA algorithm with the MATLAB Toolbox, and the other one is two-step genetic algorithm with GA solver in

coding. Through the comparison of two types of genetic algorithms, it was found that the second one is more appropriate for the online adaptive optimum coordination of overcurrent relays because of the automatic input of the measured data in the distribution system. Also, the effects of the variations of load value level and distributed generations output have been proved through the simulations on the similar distribution systems with different load levels or different amount of distributed generation in the simulation systems.

Then to make sure the proposed method of online adaptive coordination of overcurrent relays using two-step genetic algorithm with GA solver is more practical in the distribution system, a large-scale distribution system is introduced in Chapter 3. The updated simulation distribution system is almost twice as big as the original one, and the proposed two-step genetic algorithm with GA solver also satisfied the requirements of online adaptive optimum coordination of overcurrent relays which is operated on a 15-minute interval. Also, faults at different locations are tested for the optimum coordination of overcurrent relays. Therefore, it might be appropriate to form a combined objective function considering near end faults, middle point faults and other fault locations so that the estimation results will be optimal for universal cases.

Due to the time requirement of online adaptive optimum coordination of overcurrent relays, the optimization process needs to be accomplished as soon as possible, so another optimal technique is discussed in Chapter 4. Through the comparison between the genetic algorithm and the differential evolution on the optimum coordination of overcurrent relays, differential evolution is much faster than genetic algorithm, especially when the size of distribution system grows. Therefore, the differential evolution optimal technique is much better than the genetic algorithm in the proposed method to realize

online adaptive optimization. Also, relay settings under three different fault locations are optimized by the differential evolution algorithm, and the results provide setting guidance for general cases.

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Vita

Ke Xu

Education

01/2015—present

Ph. D. Student

Department of Electrical and Computer Engineering, University of Kentucky,

Lexington, Kentucky, USA

08/2012—08/2014

Master of Science in Electrical Engineering

Department of Electrical and Computer Engineering, University of Kentucky,

Lexington, Kentucky, USA

08/2009—12/2011

Bachelor of Science in Electrical Engineering

Department of Electrical and Computer Engineering, University of Kentucky,

Lexington, Kentucky, USA

Awards

01/2015—12/2018

Teaching Assistant, University of Kentucky, Lexington, KY, USA

10/2013

Pass the FE exam (Fundamental Engineering), and get the EIT certificate.

08/2012—05/2013

PEIK Scholarship sponsored by United States Department of Energy.

05/2011

The second place of senior design project competition, Department of Electrical Engineering, University of Kentucky, Lexington, KY, USA

08/2009—12/2011

2010, 2011 International Transfer scholarship—College of Engineering, University of Kentucky, Lexington, KY, USA

05/2010

UK International Student Scholarship, University of Kentucky, Lexington, KY, USA

08/2009—12/2011

Dean's List for five semesters in a row, University of Kentucky, KY, USA