OPTIMAL PROTECTION RELAY COORDINATION FOR OVERCURRENT RELAYS IN RADIAL SYSTEM

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ABSTRACT

Increase in demand on electrical power supply requires reliable and sustainable electrical system. Therefore, suitable design of power system and having a reliable and robust power system design for electrical network are crucial to minimize the possibility of any power downtime and disturbances. Unnecessary power interruption could happen in the large electrical network due to disturbances or faults that occurred far away from the healthy system. Thus, one of the mitigation is to have proper coordinated relay protection system in power network. Relay protection system is crucial to ensure equipment and system which located outside from zone of protection are protected and safe to operate continuously during fault happen in other system in the same network. The main objective of this research is to perform overcurrent relay protection coordination to obtain an optimum relay setting to minimize the operating time of overall relays in the network. The optimum value of time multiplier setting (TMS) is determined based on predefined value of tap setting (TS) and plug setting multiplier (PSM). The studies are conducted by using MATLAB software to implement the optimization method using Particle Swarm Optimization (PSO). The result from an optimization method then is compared with conventional relay coordination method for electromechanical relay as study case. The algorithm is applied for radial network. The results of the studies performed will be useful to select the best relay setting in order to optimize the design and to achieve reliable electrical network.

[OPTIMAL PROTECTION RELAY COORDINATOR FOR OVERCURRENT RELAYS IN RADIAL SYSTEM]

ABSTRAK

Permintaan yang meningkat ke atas keperluan bekalan kuasa elektrik memerlukan suatu sistem yang boleh dipercayai dan mantap. Oleh itu, rekabentuk system kuasa yang sesuai dengan keperluan serta kebolehpercayaan pada sistem adalah sangat penting untuk mengurangkan kebarangkalian putus bekalan elektrik. Ganguan bekalan elektrik yang tidak tentu boleh berlaku pada rangkaian sistem kuasa yang besar disebabkan oleh gangguan kuasa dan litar pintas yang berlaku pada sistem berada yang jauh di dalam rangkaian yang sama. Dengan itu, salh satu cara untuk mengatasi masalah ini adalah dengan menggunakan sistem peranti geganti pelindung yang sesuai dan dikoordinasikan dengan betul. Sistem peranti geganti pelindung ini adalah penting untuk memastikan alatan electrik atau rangkaian elektrik yang terletak diluar kawasan yang mengalami lintas pintas itu dilindungi dan selamat untuk terus beroperasi semasa keadaan lintar pintas berlaku di sistem yang berjauhan. Objectif utama kajian ini adalah untuk melaksanakan koordinasi geganti pelindung ke atas lebihan arus disebabkan oleh litar pintas. Hasil kajian akan memperolehi nilai tetapan geganti yang optimum dan mendapat jumlah masa yang minimum setelah semua geganti pelindung beroperasi. Nilai optimum TMS kemudian diperolehi berdasarkan kiraan nilai TS dan PMS. Kajian dijalankan dengan menggunakan perisian MATLAB untuk membuat simulasi kaedah optimum dikenali sebagai PSO. Nilai tetapan yang diperolehi daripada simulasi ini akan dibandingkan dengan hasil daripada kaedah pengiraan secara menggunakan graf gegantu pelindung. Algorithm ini diapplikasikan untuk sistem rangkaian radial. Keputusan daripada kajian ini sangat berguna untuk memilih dan mendapatkan tetapan yang terbaik seterusnya membolehkan rekaan yang lebih optimum dan mencapai rangkaian electric yang mantap.

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LIST OF SYMBOLS AND ABBREVIATIONS

A	:	Ampere
ACO	:	Ant Colony Optimization
CB	:	Circuit Breaker
CT	:	Current Transformer
CTI	:	Coordination Time Interval
EF	:	Earth Fault
EP	:	Evolutionary Programming
GA	:	Genetic Algorithm
Hz	:	Hertz
IDMT	:	Inverse Definite Minimum Time
IEC	:	International Electrotechnical Commission
kV	:	Kilo Voltage
MCCB	:	Miniature Case Circuit Breaker
OC	:	Overcurrent
OCR	:	Overcurrent Relay
PS	:	Plug Setting
PSM	:	Plus Setting Multiplier
PSO	:	Particle Swarm Optimization
SQP	:	sequential quadratic programming
TS	:	Tap Setting
TCC	:	Time Current Curves
TMS	:	Time Multiplier Setting

CHAPTER 1: INTRODUCTION

1.1 Background

Distribution network covers a large area, from high voltage transmission system as main power supply and feeding to various customers, consists of the massive quantity of electrical equipment which are connected to the electrical network. Increase in power demand requires reliable power supply and control of the overall network. Power quality become major concern for electrical engineering. Nuisance tripping will cause unnecessary disturbances and downtime to healthy circuit.

One of critical electrical system in the network to ensure continuity of electrical supply is by having proper protection coordination in particular in isolating circuit during fault happen in the system. Relays are an important integral part of any power system. Coordination schemes shall be selected based on reliability, selectivity, flexibility and relay response time to isolate the fault area. Basic information such as load flow analysis and short circuit study is required to perform protection coordination.

The impact on system reliability due to miscoordination relay cause delay in operation of the relays and increase failure index for the probability of hidden circuit breaker (CB) failure, which is depending on the magnitude and duration of the fault currents passing through the CBs (Jazaeri, Farzinfar, & Razavi, 2015). The reliability indication such as SAIDI shown that miscoordination among relays substantially reduces the reliability level of the system. The analysis also concluded that the probability of CB failure arises due to relay miscoordination.

In protection system, overcurrent relay can be operating as main protection as well as back up protection. The back up relay will initiate to trip the circuit if the main protection relay fail to isolate the fault after certain period in seconds. The important variables to obtain optimal coordination protection are the time multiplier setting (TMS) and plug setting multiplier (PSM). In the protection coordination, calculation of maximum fault current and nominal load current are factors to determine the plug setting multiplier (PSM). The significant impact to meet reliable power system is the possible loss of protection coordination. The scenario of loss of coordination happen due to uncontrolled increase in load demand led to increase in short circuit fault levels and false tripping in the network. Therefore, relay protection is required to limit the consequence of fault and reduce the risks to acceptable levels.

In conventional technique, the optimum TMS and PS setting in protection coordination is achieved by using trial-and-error approach. However, this technique consume long time to find convergence rate because of large number of iteration to obtain the suitable relay setting. Due to that, the issue of conventional techniques is mitigated by implement the optimization techniques. There are many studies are performed using several optimization techniques such as linear programming, evolutionary programming, genetic algorithm, firefly algorithm, modified PSO and lot more.

By taking advantage of the optimization techniques, the optimum values of relay setting could be determined in very short time especially when involve large distribution system. The optimum values for protection coordination setting provides an indication in getting the minimum relay operating time when applied the optimum values of TMS.

1.2 Problem Statement

Nowadays, demand on electrical power supply in the industries have increased substantially where many industrial process, automation, oil and gas and other commercial operations demand a high degree of continuity of electric power supply to avoid extensive cost of production downtime.

Protection coordination study is part of electrical power system study and fundamental requirement for relay setting and testing. The purpose of protection relay study is to determine appropriate relay setting and taking into account the coordination between relays in particular for overcurrent (OC) and earth fault (EF) relays. The product from the study is used as inputs to setting up relays. The setting values is usually verified by plotting on the Time Current Curves (TCC) for the entire interconnecting electrical network.

Isolating overcurrent faults by relay and breaker reactions at a very least period helps the equipment to experience minimum stress and losses during fault occurred. For long term, it can reduce the failure rate of the equipment. Reliability of power system is also depending on the equipment healthiness to avoid unplanned downtime due to repair works. Therefore, protection coordination is partly vital system to sustain reliable power supply in distribution system.

The assumption of electrical parameters such as electrical loads, fault current value for each bus as well as CT ratio are predefined and given which does not cover in this study.

The purpose of this research is to obtain and identify the best relay current setting and optimum TMS. It is also present a simulation solution for relay coordination protection by using MATLAB software. The simulation result is applicable only for typical relay normal inverse time curves.

Single line diagram of a 34.5kV radial system for coordination of protective relaying is shown in figure below as reference for this research.

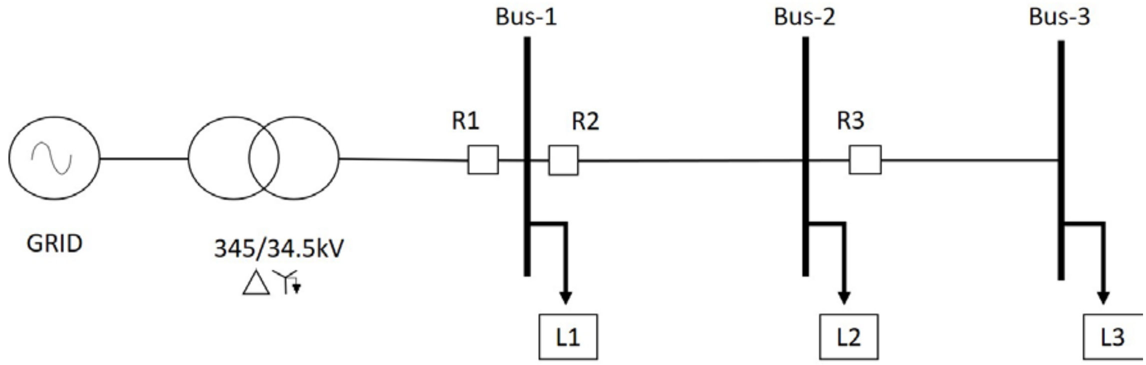

Figure 1.1 Single Line Diagram of 34.5kV Radial System (Duncan, Sarma, & Overbye, 2012)

This report is limited to relay coordination study of protective relaying for radial system. Example of three-bus system is shown in figure 1.1, where the preliminary parameters such as load capacity, three phase fault current values and CT ratio are given.

The results of this study are important to resolve the best coordination settings of overcurrent relays. The minimum operation time will provide an initial indication to protection engineers to assess their protection scheme and power system

1.3 Objectives

The main aims of this research are:

1. To perform relay protection coordination study and analyze the optimum coordination of overcurrent relays for radial distribution network.
2. To identify the best relay current setting and analyze the impacts to the optimum values of TMS and relay operating time.
3. To obtain the minimum relay operating time by using Particle Swarm Optimization (PSO).
4. To analyze relay coordination performance and responses for different setting of relay tap setting (TS) using PSO algorithm from MATLAB simulation.

1.4 Scope of research

The scope of this research will be focusing on overcurrent relay protection coordination studies for radial system. The studies is carried out by developing the concept of optimization PSO to obtain optimum TMS and minimum relay operating time. The results will be compared with the study using conventional relay coordination method (Duncan et al., 2012) for electromechanical relays setting, in term of identifying the time multiple setting values and the summation of all relays operating time. Study is also examined the affect to relay operating time by taking into account change in relay setting or also known as plus setting value. The TMS and operating are analyzed and compared for discussion. The initial parameters such as load capacity, CT ratio and short circuit fault current are provided which does not be covered in this research project.

1.5 Research project outline

This report is divided into five (5) chapters as per following:

Chapter 1: Introduction – includes the introduction on relay protection coordination and proposed optimization solution in particular the PSO. The overview of the research is discussed and the research objectives and scope are described.

Chapter 2: Literature Review – a review on research materials in relation to relay protection coordination studies as well as application of PSO algorithm would be summarized and discussed.

Chapter 3 – Methodology - describes the technique of simulation being modeled using MATLAB software is explained. The process flow and application of PSO will be summarized. Standard generic system parameters will be shown as a basis for the simulation and the scenarios of the simulations performed for each study will be explained.

Chapter 4: Results & Discussions – the results obtained on optimize relay operating time from the relay protection coordination studies in radial system will be discussed.

Chapter 5: Conclusion – the overall research will be concluded with some recommendation for future research.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

A power system consists of substantial number of equipment and associated devices including circuit breakers and relays as part of electrical system. Reliability is defined as the probability of equipment operating under specified conditions will perform satisfactorily for a given period of time. One of the major considerations in design of a power system is to achieve an adequate and appropriate control of short circuits current in the event of electrical faults occurred in electrical system. Short circuit current flows in the electrical system can cause damage and shorten the life of the electrical equipment and could led to fire damage and danger to people, environment, asset and subsequently the reputation of the power industry.

Therefore, isolation of electrical circuit from the faults current is necessary to protect the equipment as well as safety of people. Nonetheless, the isolation of affected circuits will lead to power outage. Interruption in power supply is causing major impact to the industrial which experience production downtime and associated inconvenience such as interruption of essential facilities.

2.2 Electrical Power System

Power system in utilities, industrial, commercial, or residential, have the common purpose of delivering reliable and economics electric energy to the electrical equipment. The importance of feasibility, reliability and safety considerations are relying on type of overall electrical network system. The different type of system may have different basis of design intent in relation to customer requirement, economics and criticality of the electrical system.

Nowadays, electrical power system requires to deliver large power in meeting power demand for the operation of the plants and buildings. Important industries demands higher requirement in terms of safety and reliability of power supply. Therefore, fulfillment of certain criteria are necessary including the best selection of generation system, distribution configuration, protection system and use of adequately rated equipment.

Apart of power system analysis, the calculation of short circuit current is important to select adequate ratings of all the air circuit breakers prior to further investigate the protection system of electrical network (Glover, Sarma, & Overbye, 2012). Fault protective devices were used to ensure proper relay coordination throughout the system can be achieved. These devices have to be selected and set according to appropriate protection system study. Therefore, the nearest device to the fault is opened to clear the fault without affecting other interconnecting system which farthest from the source of fault.

A reliable electrical system design requires an optimum power system studies such as short circuit analysis, load flow analysis, largest motor starting analysis and protection coordination studies to be performed. The power system studies are conducted due to different configuration of every facility which will be having its own maximum demand and load characteristics such as transformers and asynchronous motors.

The required type of power system studies depends on the size scale and scope of the project requirement. Typically, the power system analysis consist of four (4) power system studies:

i. Load Flow Study
ii. Short Circuit Study

iii. Largest Motor Starting Study

iv. Relay Protection Coordination Study

2.3 Relay Protection System

Protection system is a complete arrangement of protection equipment with associated devices required to obtain a specific function based on protection principal. A collection of protection devices such as relays, fuses are called protection equipment. Protection scheme consist of protection function definition and including all equipment in protection system to complete the scheme works such as relays, current transformer, voltage transformers, circuit breakers, contactors and batteries.

Relay protection is required to limit the consequence of fault and reduce the risks to acceptable levels while maintaining the disruption to operation of the power system. The result of ac short circuit currents is fundamental for the selection of protective devices and equipment rating in power systems. The calculation of short circuit current is usually conducted as part of power system analysis.

Protective relays are used to detect any abnormal condition such as fault current, and to operate the selected circuit breakers in order to disconnect only the faulty equipment from the system as quickly as possible. The relays in the power system are to be coordinated accordingly in order to avoid malfunction and hence to avoid the unnecessary outage of healthy part of the system. The overcurrent relays are the major protection devices in a distribution system. With relay protection in place, it could minimize the trouble and damage to the equipment causing destruction and fire. Unclear faults due to improper relay setting will result in equipment overheating and destruction, reduce instability margin, malfunction operation of equipment and explosions (Hernanda, Kartinisari, Asfani, & Fahmi, 2014).

Clearly, the fault must be quickly removed from the power system, and this is mitigated by having the protective device, the circuit breakers and/or fusible switches. To meet this requirement, the protective device must have the ability to interrupt the maximum short-circuit current for worst case scenario of bolted three phase fault.

Protection study is important to ensure relay are properly coordinated and operating when fault happen within its zone of protection. Unable to isolate the fault within specific time can lead to damage to the equipment causing destruction and fire, equipment overheating, causing under voltages or over voltages in the area of the fault in the system, blocking power flow, causing reduction instability margins, causing improper operation of equipment due to system unbalance and causing the system to become unbalanced and lose synchronism by an event.

In many cases, it is not feasible to protect against all hazards with a relay that response to a single power system quantity. An arrangement using several quantities is required.

The operating characteristics of relay depends on the energizing quantities fed to it:

- Current
- Voltage
- Combination of current and voltage

From the current and voltage information, various types of relays have been developed. There are several methods or parameters required to operate certain protection in electrical system. Table below shows the type of protection and methods to detect the faults.

Table 2.1 Type of protection and methods of detection

No.	Type of Protection	Methods of detecting Faults
1.	Overcurrent protection	Magnitude of current
2.	Earth fault protection	Magnitude of current
3.	Directional fault protection	Magnitude and phase angle of current
4.	Directional Earth Fault Protection.	Magnitude and phase angle of current in earth or neutral
5.	Impedance protection	Voltage-Current ratio
6.	Differential protection	Difference between 2 or more currents
7.	Phase comparison protection	Difference between phase angles of 2 currents
8.	Over- or under- voltage protection	Magnitude of voltage
9.	Over or under-frequency protection	Magnitude of Frequency
10.	Thermal protection	Temperature

In protection system, zone protection is important criteria while considering protection study. Figure below shows the examples of zones of protection coverage. The power system is divided into protection zones and relays are used to measure the system current and voltage parameters to assist in clearing the disturbances. If fault occurs inside the protection zone, the relay will operate to isolate the faulted system which usually downstream of relay from the rest of the power system.

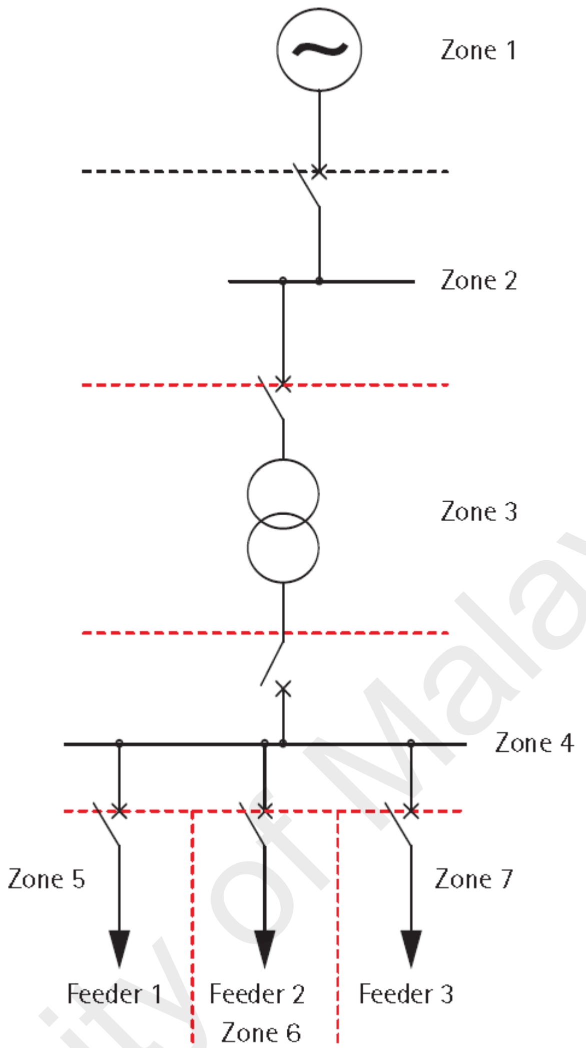

Figure 2.1: Zones of protection

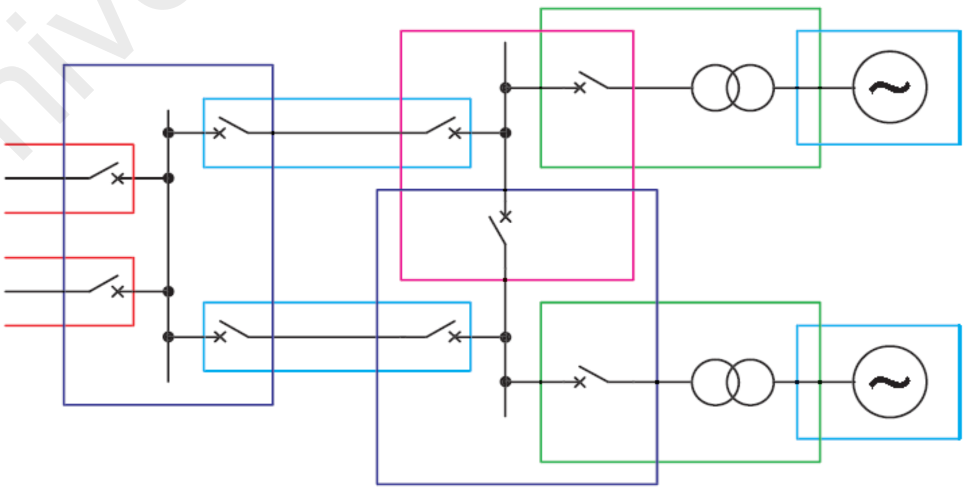

Figure 2.2: Overlapping of zones

Figure 2.2 shows the overlapping zones to achieve a reliable and stable protection design. It is important to have more than one primary protection system operating in parallel. In the event of failure or non-availability of the primary protection, some other means of fault isolation is required. This secondary system is referred to as back-up protection (Brown, 2008; Paithankar & Bhide, 2011).

In the event of fault, both the main and backup protection system will detect the fault simultaneously. However, the operation of backup protection must be deferred to specific interval time to ensure that the primary protection clears the fault first.

2.3.1 Overcurrent protection

Overcurrent (OC) protection is a protection against excessive current occurs in the system or above acceptance rating of equipment. One of type of overcurrent is short circuit. There are several types of protection devices use for overcurrent protection such as fuse, molded case circuit breaker (MCCB) and overcurrent relay. This research will only focus on normal inverse definite minimum time (IDMT) overcurrent relay principals of grading. The most common type of curve used in IEC type. IEC type of curve consists of 4 main curves namely IEC curve A for normal inverse, IEC Curve B for very inverse, IEC Curve C for extremely inverse.

Comparison for some other type of curves are shown in table below. Different international standard refer to different identifications for similar curve.

Table 2.2 Type of time curve

IEEE	IEC	GE TYPE IAC	OTHER
IEEE Extremely Inverse	IEC Curve A	IAC Extremely Inverse	I^2t
IEEE Very Inverse	IEC Curve B	IAC Very Inverse	FlexCurves A,B,C and D
IEEE Moderately Inverse	IEC Curve C	IAC Inverse	Recloser Curves
	IEC Short Inverse	IAC Short Inverse	Definite Time

IDMT operation is time base operation and inversely proportional to the fault current value. The curve characteristic is a function of time and current where the time is plotted on vertical axis of the TCC and current is plotted on horizontal axis. The closest relay to the source will be the fastest relay to operate in the event of fault current occurred in between two end of distribution feeder. The fault current level is the highest at the power source. IDMT is a solution to the weakness of grading only by time or grading by current. Figure 2.3 shows the characteristic of IDMT relay which depict the IDMT and instantaneous curve.

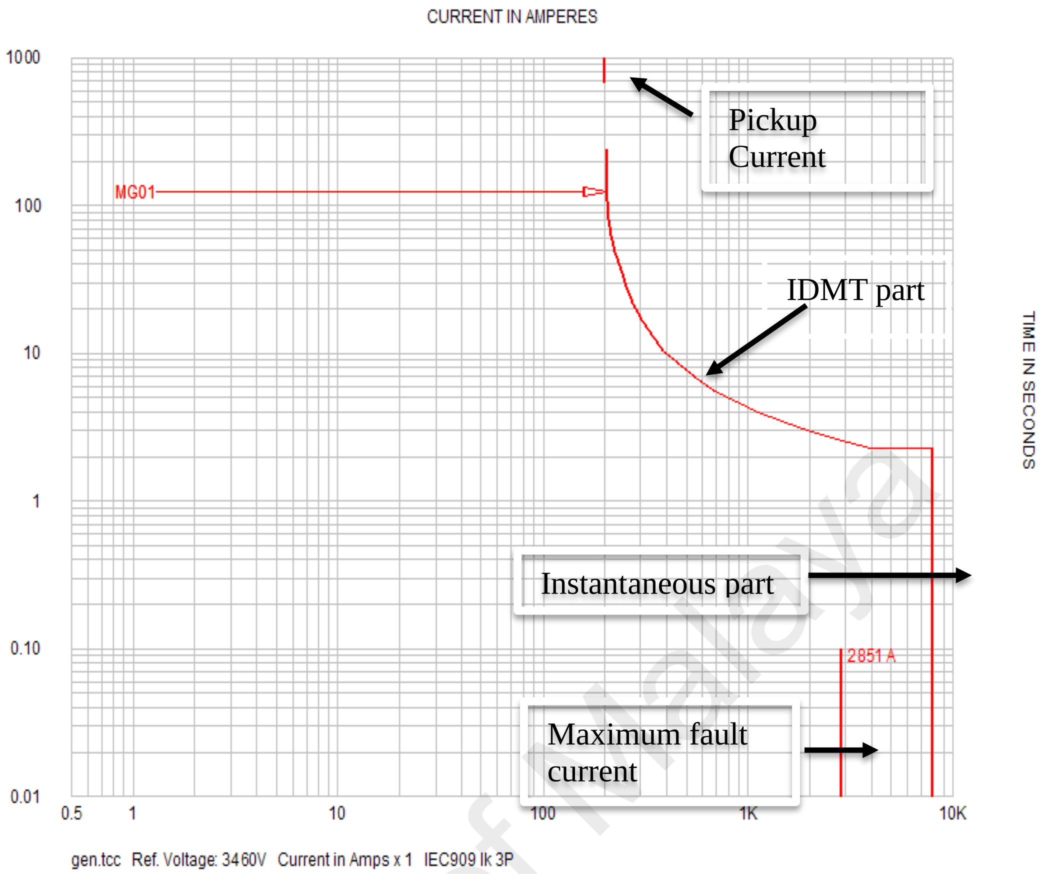

Figure 2.3: IDMT relay characteristics

Principle of Discrimination/Coordination are based on:

I. The nearest relay to the fault shall operate to isolate fault in the shortest time possible.

II. This is achieved by making each upstream relay slower than its downstream relay.

III. The margin between two successive relays usually between 0.3 seconds and 0.5 seconds.

The time for a relay to operate or trip depends on:

I. Magnitude of fault current – the amount of current, sensed by the CT, is compared to the setting of plug setting multiplier (PSM).

II. Plug or current setting (PS): A value of current at relay input which is referring to maximum load current where the relay starts to pick up.

III. Time multiplier setting (TMS): Controls the tripping process (time) and time of relay operation.

2.4 Optimization method

There are many studies performed on analyzing the optimum values for the overcurrent relays coordination by using simulation of optimization methods (A. Alipour & M. Pacis, 2016; Prashant P Bedekar, Sudhir R Bhide, & Vijay S Kale, 2009; Gholinezhad, Mazlumi, & Farhang, 2011; Pragati N Korde & Prashant P Bedekar, 2016; Srinivas & Swarup, 2017; Tjahjono et al., 2017; Zeineldin, El-Saadany, & Salama, 2006). Different algorithms have been applied for most of the previous methods in relation with radial distribution systems, mode of operation (Chaudhari, Upadhyay, & Ahemedabad, 2011; Jenkins, Khincha, Shivakumar, & Dash, 1992; Salem, Abdallah, & Abbasy, 2017; Singh, Panigrahi, & Abhyankar, 2011).

Direction overcurrent relay also have been considered by using optimization method (Amir Alipour & Michael Pacis, 2016; Mansour, Mekhamer, & El-Kharbawe, 2007; Radosavljević & Jevtić, 2016; Urdaneta, Nadira, & Jimenez, 1988; Zeineldin et al., 2006)

There are many objectives or problems needs more than one solution. Evolutionary computation is an iterative process in which a population is obtained in a guided random search. The computation is using parallel processing to obtain the desired result which inspired by biological mechanisms of evolution (Jazaeri et al., 2015).

In general, there are several conventional Evolutionary Algorithms, such as Swarm Intelligence, Differential Evolution, Genetic & Evolutionary programming, Genetic Algorithm and Evolutionary Strategy. In particular for Swarm Intelligence, the computational study is based on the collective intelligence such as schools of fish, flocks of birds and colonies of ants. Swarm Intelligence are considered adaptive strategies to search and optimize domains. The evolutionary algorithm divided into Ant Colony Optimization (ACO) and Particle Swarm Optimization (PSO). ACO is performed from probabilistic algorithms inspired by the foraging behavior of ants, however the PSO algorithm inspired by the birds flocking and fish schooling.

PSO, does not like Genetic Algorithm, has no evolution operators such as crossover and mutation. The potential solutions namely, particles, fly into the problem space by following the current optimum particles. Each particle is associated with the best solution, called fitness or *pbest*, on its coordinate is kept track in the coordinates in the problem space. The best value obtained by compared the values between the best solutions for each particle and then choose the best value from the neighbour of the particle called *gbest*. Then, the velocity, *v*, of each particle is updated close to its *pbes*t and *gbest* locations. Weight for the acceleration is randomly selected, with separation random numbers being generated for acceleration close to *pbest* and *gbest* locations (Banerjee, Narayanasamy, & Swathika, 2017).

Protection coordination is the process of determining the primary protective device that is responsible for clearing the fault as quickly as possible. For each fault location, taking into account in the event that any of these devices fail, each should be backed up by another protective device (A. Alipour & M. Pacis, 2016). Each protection relay in the power system needs to be coordinated with the relays protecting the adjacent equipment. One of the most commonly used relays in a power system is the overcurrent relay.

In overcurrent relay coordination method, discrimination can be achieved by grading of time, grading of current or based on principle of current-time grading. The solution for OC protection coordination is a highly constrained domain and is subject to the user preference such as time-grading, current-grading and minimum operating time grading (So, Li, Lai, & Fung, 1997). Three case studies were performed to show the effect on different type of grading. The current grading were achieved by changing the Time Multiplier setting. For the current grading became the main consideration for discrimination coordination. Lastly, the time-current grading emphasized on minimum total operating time which provided better solution. The solution is using Genetic Algorithm optimization methods, the effect on population size and number of generations indicated better results with faster relay operating time towards the source and smaller grading margin and applicable for ring network.

The overcurrent relay coordination in radial distribution networks is among typically constrained optimization problem. Therefore, an optimum relay setting was determined by affecting the plug setting multiplier (PSM) and result of minimize the time of relay operating was obtained to avoid the malfunction of relays. This report used linear programming technique for optimum coordination for a ring fed distribution system (P. P. Bedekar, S. R. Bhide, & V. S. Kale, 2009).

On other optimization method, Dual Simplex and Genetic Algorithms (GA) on a radial network was used and identified the TMS of the relay to maintain the time interval between relays during faults (Madhumitha, Sharma, Mewara, Swathika, & Hemamalini, 2015). The optimum solution of TMS was found for 2-bus and 4-bus radial system with the bounds on relay operating time became the constraint.

Another optimization method for optimum coordination in distribution system is using nonlinear programming method namely sequential quadratic programming (SQP) method to calculate the TMS and PS for overcurrent relay. The result was compared with other optimization method, in this case, the Genetic Algorithm and found that SQP method is more superior than GA method (P. N. Korde & P. P. Bedekar, 2016).

Tripping time is set at appropriate time grading for fault located far from the actual location of the fault especially in radial distribution network. The optimization methods of Two Phase Simplex and Particle Swarm Optimization (PSO) algorithm were implemented for 2-bus system (Banerjee et al., 2017). The optimum TMS and minimum relay operating time were obtained to maintain coordination time interval among relays. The result showed that the PSO algorithm provided higher accuracy and the best result for complex network compared to two phase simplex even though require more iterations to run the programming.

2.5 Summary

In this chapter, the theory of relay protection system is described. Focusing in overcurrent IDMT normal inverse relay has been discussed. Issues on miscoordination of overcurrent relay in the system cause significant impact to the overall electrical network as well as stress to the equipment especially the switchgears and breakers. Stress to equipment could led to unexpected equipment failure for long term. Selection of optimum time multiplier setting is important to obtain minimum operating time of relays in the system. It helps the system which experience faults to be isolated as quick as possible.

Other healthy system operates continuously and avoid unnecessary tripping due to remote fault. Minimum time to clear the fault during overcurrent situation helps the equipment to feel minimum effects and reduce the failure rate of the equipment. Optimization methods are used to determine the minimum operating time of relay as a result of getting the optimum value of TMS for normal inverse IDMT relay. However, there are still a lot of improvement to explore using optimization methods to get the best relay setting for other complex electrical configuration and parallel with increase in power demand.

CHAPTER 3: METHODOLOGY

3.1 Overview

Improper selection of overcurrent setting for relay protection will cause unnecessary tripping of power supply on healthy circuit, burden on the system and severe effect on system efficiency or furthermore could lead to fire or damage the equipment. Failure in power system due to fault will cause extensive losses and cost of production especially to critical industry such as automation industrial. Electrical power interruption or losses can be minimized or contained within zone protection by setting the protection overcurrent relay at optimum time to clear the fault. To address this issues, relay coordination needs to be selected properly to prevent unwanted tripping by relay protection due to fault happen far away from the circuit.

This chapter presents methodology adopted in the research to obtain optimal time multiplier setting based on plug setting. From the optimum TMS values from optimization method will determine the minimum relay operating time.

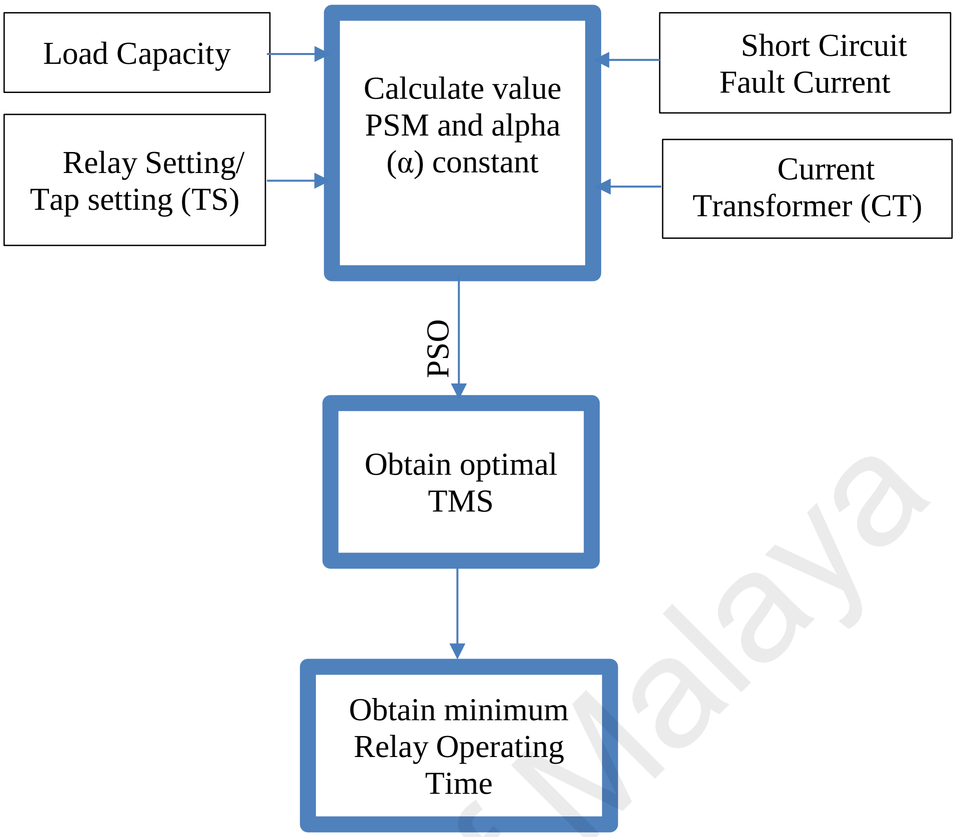

Figure 3.1 Research Methodology

3.2 Overview of Optimization Technique

Evolutionary algorithm is developed to resolve complex and large network of nonlinear engineering problems. Among the optimization technique are like Artificial Neural Networks, Genetic Algorithm (GA), Evolutionary Programming (EP) and Particle Swarm Optimization (PSO). The main reason in developing an algorithm is to find the global best solution in very short time and satisfying all constraints.

In this report, optimal overcurrent relay coordination study is performed by using optimization technique of PSO method. PSO is among the most popular evolutionary algorithm used for optimization study. It is a population based optimization technique. The basic concept and application of PSO algorithm in various power system study is explained in (Ho, Yang, Ni, Lo, & Wong, 2005; Shi & Eberhart, 1999). They presented the variants involved in PSO and also described on the fitness functions.

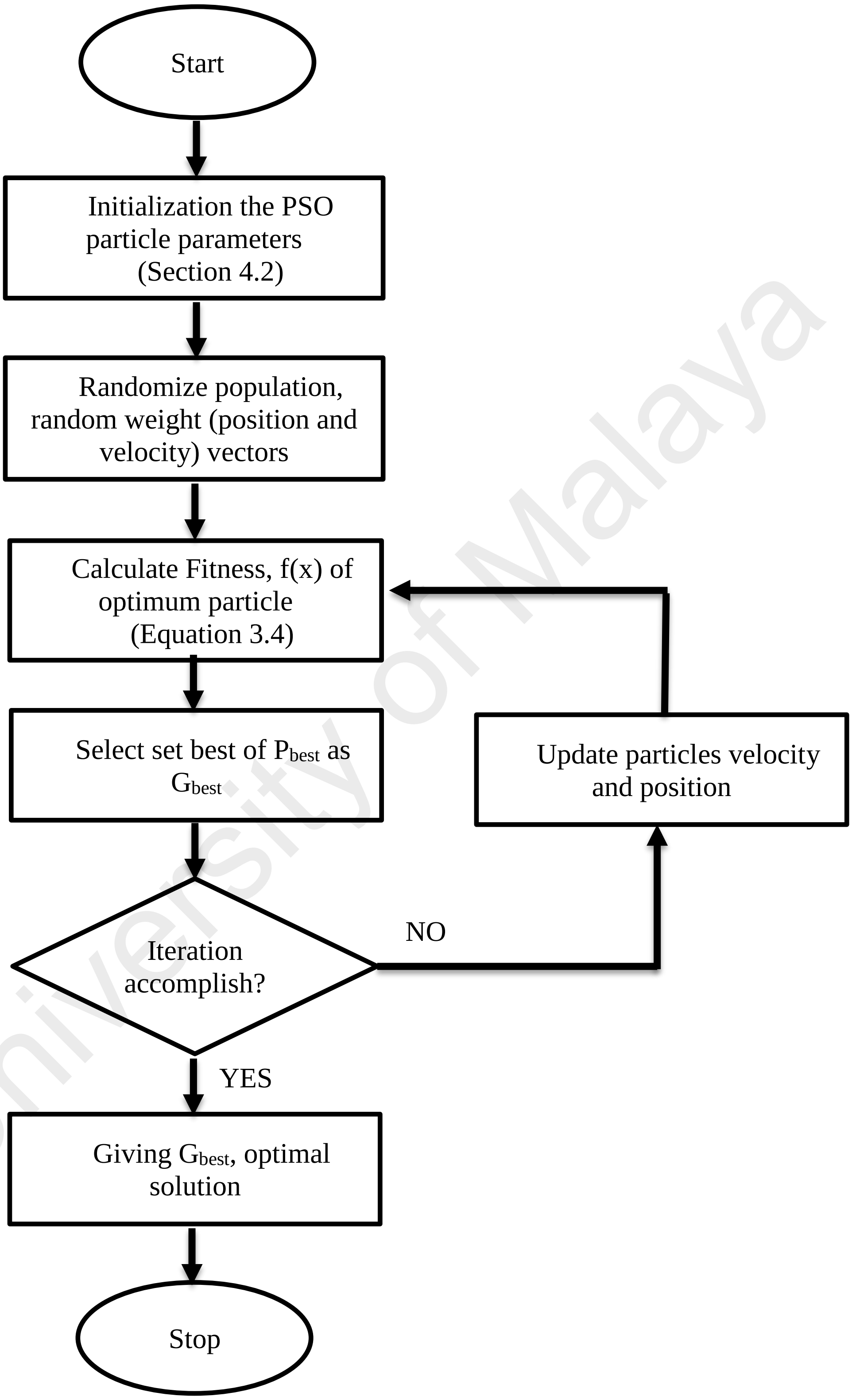

Figure 3.2 Flow Chart for PSO Algorithm

3.3 Problem Formulation

Important parameters in getting the optimum overcurrent relay coordination are the time multiplier setting (TMS) and the plug setting (PS). Optimum TMS value for each relay determines the operating time of the relay for optimum coordination of overcurrent relay (OCR) and the relay operation is influenced by PS selection. Therefore, minimum relay operating time are minimized by getting the optimum TMS value using PSO to obtain the optimum relay coordination.

3.3.1 Objective Function

The objective function shows an optimization problem, which it is defined as below:

$$Min\ z = \sum_{n=1} t_{op\ n} \tag{3.1}$$

Where;

z	:	Minimum total relay operating time
$t_{op\ n}$	:	Operating time of relay
n	:	Number of bus

3.3.2 Constraints

The total operating times of relays are reduced by minimizing their constraints in relay coordination objective function. Among the constraints are coordination criteria, relay operating time, limit on TMS of each relay, limit on PS value of each relay and relay characteristics. The constraints are described as follows:

3.3.2.1 Coordination Criteria

Coordination criteria is usually known as coordination time interval (CTI). The CTI is period of relay operating time between the upstream relay and downstream relay. Factors to define the minimum different time between upstream and downstream relays are based on operating time of main relay, circuit breaker operating time as well as the overshoot time. Both relays will sense and initiate during fault condition at the same time. Operationally, the backup relay will operate to trip the circuit breaker if the primary relay fails to operate after specified time interval.

The basis for CTI for this research purpose is 300ms.

3.3.2.2 Limit on Relay Operating Time

Constraint happens on the operating time of OCRs because Relays require certain duration to operate. Therefore, minimum and maximum time of relay operation become one of the constraint. In the study, limitation on relay operating time is not define. The total relay operating time is calculated and summarized based on the optimize TMS values.

The relay operating time is defined as follow (Mousavi Motlagh & Mazlumi, 2014):

$$t_{op\ n} = \frac{TMS \times \lambda}{PSM^{\gamma} - 1} \tag{3.2}$$

Where;

The constant values for normal inverse IDMT relay are as follow:

$$\lambda = 0.14,\ \gamma = 0.02$$

The operating time, t_{op} is simplified with function of alpha, α as follow (Madhumitha et al., 2015):

$$\alpha = \frac{\lambda}{PSM^{\gamma} - 1} \tag{3.3}$$

Therefore, the function of fitness is

$$t_{op\ n} = \alpha \times TMS \tag{3.4}$$

3.3.2.3 Limit on the TMS value for each relay

The TMS affects the operating time of relays in the optimum coordination. In this study, the TMS is bounded between 0 and 1. The TMS limit is stated as follow:

$$0 < TMS_n < 1$$

Where, TMS_n, is minimum value of TMS of relay n.

3.3.2.4 Limit on PSM of each relay

PSM is simply referring to ratio of fault current-to-maximum current of the system. PSM can be calculated as below:

$$PSM = \frac{I_{fault}}{CT_{ratio} \times TS} \tag{3.5}$$

Where

I_{fault}	:	Maximum fault current
CT_{ratio}	:	CT ratio for each relay
TS	:	Tap setting (Relay Setting)

Tap setting (TS) or also known as relay setting is usually determined based on the maximum load current measured at secondary CT output. This is to ensure that the relay does not operate at maximum load current.

3.3.2.5 Relay operating time characteristic

Relay operating time for main protection (or primary protection) shall be operated instantaneously to isolate the faults. The instantaneous time is usually assumed to be within 0.05s.

3.4 Base case study

The case study is taken from typical radial system as reference. The study is used to show comparison result between the simulation of optimization method and the relay coordination study for electromechanical relay.

The parameters of initial value is provided in the study which does not cover in this study. The output from the MATLAB simulation by using optimization method is compared for both optimum value of TMS of each relay and total relays operating time for the radial system.

From figure 1.1 shows the three-bus radial system (Duncan et al., 2012) which the current transformers are located at incoming of bus-1 (R1) and outgoing of feeder bus-1 (R2) and bus-2 (R3), respectively.

The single line diagram depicts the 345/34.5kV, 60Hz radial system. The information of maximum loads and maximum fault current are given in Table 3.1 and the CT ratio for each relay are given in Table 3.2.

Table 3.1 Maximum Load and Fault Current Level

Bus	Maximum Load Capacity		Symmetrical fault current
	Load, S (MVA)	Lagging Power Factor	Maximum Fault Current based on bolted 3-phase fault) (A)
1	11.0	0.95	3000
2	4.0	0.95	2000
3	6.0	0.95	1000

Table 3.2 Information on breaker and current transformer for each relay based on IDMT relay

Breaker	Breaker Operating Time	CT Ratio
R1	5 cycles (0.083 sec)	400:5
R2	5 cycles	200:5
R3	5 cycles	200:5

For a main case study, the protection coordination for radial system is considering a fault occur at P1 and P2. The fault, P1, is happen downstream of bus-2 and fault, P2, is happen at between bus-1 and bus-2.

To achieve proper coordination, during fault at P1, the closest relay at circuit breaker, R3, shall open while circuit breakers, R2 and R1 remains closed. Load L3 is interrupted as a result of tripping of circuit breaker, R3. To ensure coordination between two relays, relay setting is set at longer time delay for the relay at R2, so that relay at R3 to operate first. Thus, for any fault to the downstream of circuit breaker, R3, the main protection shall be protected by circuit breaker, R3. Therefore, circuit breaker, R2, provides as backup protection in the event if R3 fails to open after specific time delay.

Similarly, for a case where consider a fault at P2, the circuit breaker, R2, shall open while R1 remains closed. Loads at L2 and L3 are interrupted as a result of tripping of circuit breaker, R2. In this case, the fault current is higher than the previous fault, P1 because the fault, P2, is closer to the power source. At this time, relay at circuit breaker, R2, senses higher fault current and initiate R2 to open even faster than previous fault, P1. To ensure the coordination, a longer time delay is set for relay at circuit breaker R1 compared to relay setting for R2.

Since the fault is closer to the source, the fault current will be larger than for the previous fault considered. R2, set to open for the previous, smaller fault current after time delay, will open more rapidly for this fault. The R1 relay is selected with a longer time delay than R2, so that R2 opens first. Thus, R2 provides primary protection for faults between R2 and R3, as well as backup protection for faults to the right of R3. Similarly, R1 provides primary protection for faults between R1 and R2, as well as backup protection for further downstream faults

3.5 Protection Coordination Method for Electromechanical Relay

For electromechanical relay, the protection coordination method is based on typical time curve for normal inverse IDMT curve. The TS is selected based on maximum load current and the nearest tap setting available for electromechanical relay.

The TMS for each relay are selected to satisfy with the fastest time to isolate the fault from the system for main relay and compliance with CTI and breaker operating time for backup relay.

The relay operating time for main protection is determined with a basis to clear the faults as rapid as possible. In this case, the relay operating time for main protection is limit to 0.05s.

Table 3.3 Tap setting (TS) values for each relay/breaker

Breaker (Relay)	Total load, S (MVA)	Maximum load current, I (A)	CT Ratio	Maximum load current, I (A), at CT secondary	Tap setting (TS) for each
R1	(11 + 4 + 6) = 21	351.4	400/5	4.39	**5**
R2	(4 + 6) = 10	167.3	200/5	4.18	**5**
R3	6	100.4	200/5	2.51	**3**

The maximum load current and TS values for each relay are summarized in table 3.3. The TS value is depending on maximum load current measured at secondary CT.

Table 3.4 Relay coordination result with CTI=0.3s

Breaker (Relay)	Tap setting (TS) for each	Plug Setting Multiplier (PSM)	Relay operating time (s)	Time Multiplier Setting (TMS)
R1	5	7.5	0.76	**3**
R2	5	10.0	0.43	**2**
R3	3	16.7	0.133	**0.5**

The solution of protection coordination for faults current is tabulated in table 3.4. For main protection, the TMS value is selected to achieve instantaneous tripping during fault. Relay operating time is calculated based on normal inverse curve and to take into account the breaker operating time, 0.083 seconds.

The approximate total relay operating time, t_{op} for this case is calculated as below:

$$(0.133 + 0.43 + 0.76) \text{ seconds} = 1.323 \text{ seconds}$$

As a base case study, the same values of TS and PSM as shown in table 3.4 are used to perform the optimal coordination of overcurrent relay protection study using optimization PSO method.

3.6 Solving Optimum TMS and Minimum Relay Operating Time using PSO

The optimum solution for relay coordination is performed based on different cases to compare the result from conventional method as well as analyze the effect to relay coordination for different initial values.

For all cases, the objective function of minimum relay operating time is defined as per equation (3.1) is used to obtain the optimum value of TMS and total relay operating time.

Then the operating time, t_{op} for each relay is obtained from equation (3.2). For calculation purpose, equation (3.2) is simplified with function of alpha,α as per equation (3.3). Therefore, the function of fitness is defined as per equation (3.4)

The flow of calculation method to generate the objective function is shown in below figure. The calculation initially determines the TS value which calculated from maximum load current measured at secondary of CT. The TS value is selected for each relay connected to respectively bus.

Value of maximum fault current is used to find the PSM value which is also known as ratio of fault current-to-maximum load current.

3.7 Summary

This chapter presents the methodology approached on the study case to obtain the optimum values of TMS and minimum relay operating time. Both parameters are formulated as objective function. PSO is used as optimization tools to get the optimum solution. Three case studies are simulated as proposed methodology and the result and discussion points are presented in the section 4.

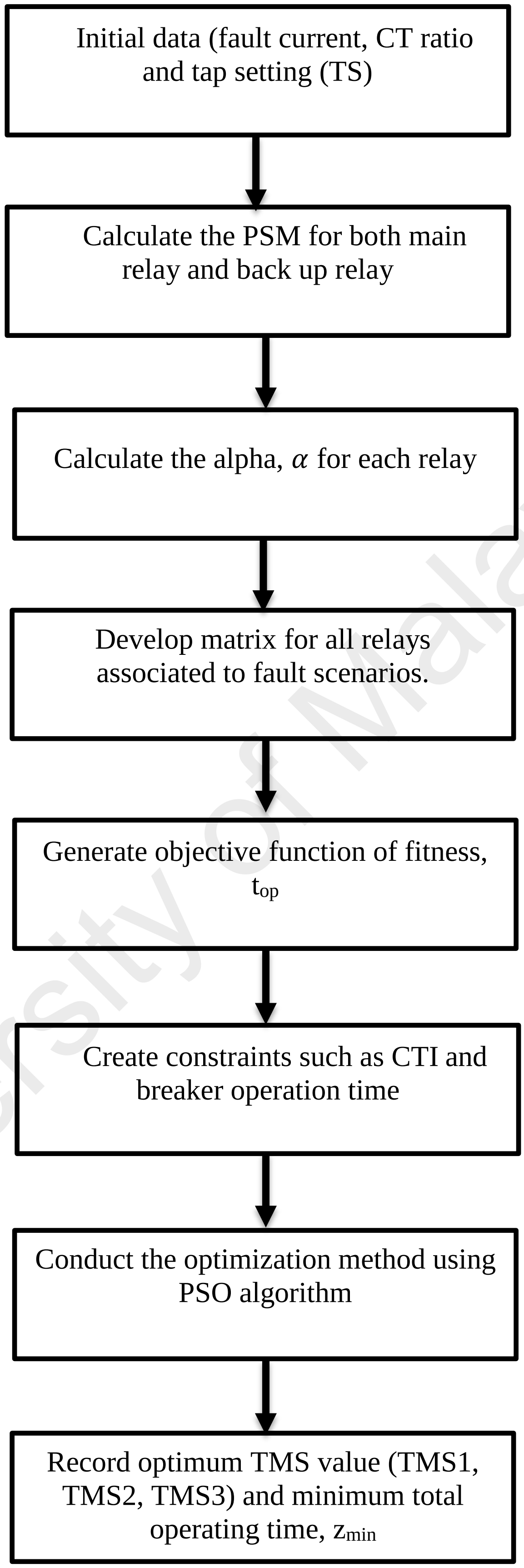

Figure 3.3 Methodology to obtain the optimum TMS and minimum total

CHAPTER 4: RESULTS AND DISCUSSION

This chapter explains in detail all the results and discussions that has been achieved for relay protection coordination study for radial system. The objective function of the relay operating time for typical three bus radial system is compared and different cases are simulated as explained in previous chapter.

In this report, an optimization methodology is presented to solve the problem of coordinating the overcurrent relays in a radial network of power system. Most of the previous algorithms were discussed on getting the time multiplier setting of all relays where the current settings of relays are known. In this report, the current setting and plug setting multiplier of all relays were considered and result were compared with the conventional method of overcurrent relay setting for electromechanical relay by using the relay time-current curve. The study only considers normal inverse for all relays. The proposed PSO algorithm is used to obtain the optimal value of setting of overcurrent relays. Three case studies based on three-bus radial system are performed and effects of the total operating time for different setting of TS are analyzed. The case study is also concluded with comparison of TMS result between PSO and other optimization method which was studied for different bus radial configuration and parameters (Madhumitha et al., 2015)

The scenarios for case study are as below:

Study Case-1: Selection of TS is using similar values as used in electromechanical relay coordination method.

Study Case-2: Selection of TS is based on exact calculated value of current setting. The current setting is equal to maximum load current where TS is set at 100%.

Study Case-3: Change in tap setting initial value. The selection of TS is based on relay setting at 125% of maximum load current.

Study Case-4: Comparison of optimization method result between PSO with Dual Simplex and Genetic Algorithm

4.1 Formulation of base case study

From figure 1.1, the single line diagram shows a three-bus system with three (3) relays with associated breakers are located at certain bus for radial network. The preliminary information given for above system are tabulated in Table 3.1 and Table 3.2. In power system study, the information provided below are obtained from load flow study and short circuit study which do not covered in this research.

The same information is used in simulation using PSO and comparison of the result from simulation are discussed.

The relay operating time for main protection is determined with a basis to clear the faults as rapid as possible. In this case, the relay operating time for main protection is limit to 0.05s.

Based on maximum load current, the TS value is selected for each relay. The calculated and selected TS values are summarized in Table 3.3. The maximum load current is calculated based on total connected load close to each relay or breaker at particular bus. Thus, selection of TS value is depending on maximum load current measured at secondary CT. For electromechanical relay, the TS value is selected to the nearest round up value of calculated TS.

Both main protection relay and back up protection relay pick up the excessive current which above TS preset value, at the same time. The main protection shall be the first relay to isolate the fault by initiating to trip the associated breaker instantaneously. For this case study, the instantaneous time is assumed as 0.05sec. At the same time, the backup relay will take over to clear the fault in case of main relay fail to operate after certain interval time. In this case study, to meet the coordination requirement for both main and back up relays, the CTI is set at 0.3 seconds.

On top of relay initialization time, relay operating time of protection system is also taking into consideration of circuit breaker reaction operating time. Assumption for breaker operating time is about 5 cycles which is equal to 0.083 seconds, for 60 Hz system.

In protection study, the fault-to-pickup current ratio (PSM) is calculated for both main and back up relay. Starting with the most downstream relay, the PSM is determined based on the maximum fault occurred close to the relay. In this case study, relay (breaker), R3 is located close to bus-2 will become the main protection. The maximum bolted 3-phase fault at bus-2 is 2000A. Therefore, the PSM of R3 for main protection is calculated as below:

$$PSM3 = \frac{2000}{(200/5) \times 3} = 16.7$$

Then, the TMS is selected from the time-current curve of electromechanical relay (Figure 4.2) based on PSM3 value and requirement to trip instantaneously. Therefore, time for R3 to trip is set at 0.05 seconds and the TMS is 0.5.

For same fault location, the R2 relay is become back up protection. The PSM for back up relay (PSM2B) is:

$$PSM2B = \frac{2000}{(200/5)\ \times\ 5} = 10.0$$

The TMS value for back up relay now is coordinated by taking into consideration the CTI and breaker operation time. Therefore, R2 operates at time:

$$T2 = T3 +\ T_b + CTI = 0.05s + 0.083s + 0.3s = 0.43s$$

From above PSM2B and T2 values, the TMS for back up relay is 2.0, measured from the time-current curve (Figure 4.2).

The same method is repeated for a case of fault at bus-1, where R2 and R1 is the main protection and back up protection, respectively. The solution of protection coordination for the base case study is summarized in table 4.4 below.

From above basis, the TMS value for electromechanical relay was determined by referring to typical electromechanical relay time-current curve in relation to PSM and required tripping time.

Table 4.1 Relay coordination for electromechanical relay with CTI=0.3s

Breaker (Relay)	Tap setting (TS) for each	Plug Setting Multiplier (PSM)	Relay operating time, T	Time Multiplier Setting (TMS)
B1 (R1)	5	7.5	0.76	3
B2 (R2)	5	10.0	0.43	2
B3 (R3)	3	16.7	0.133	0.5

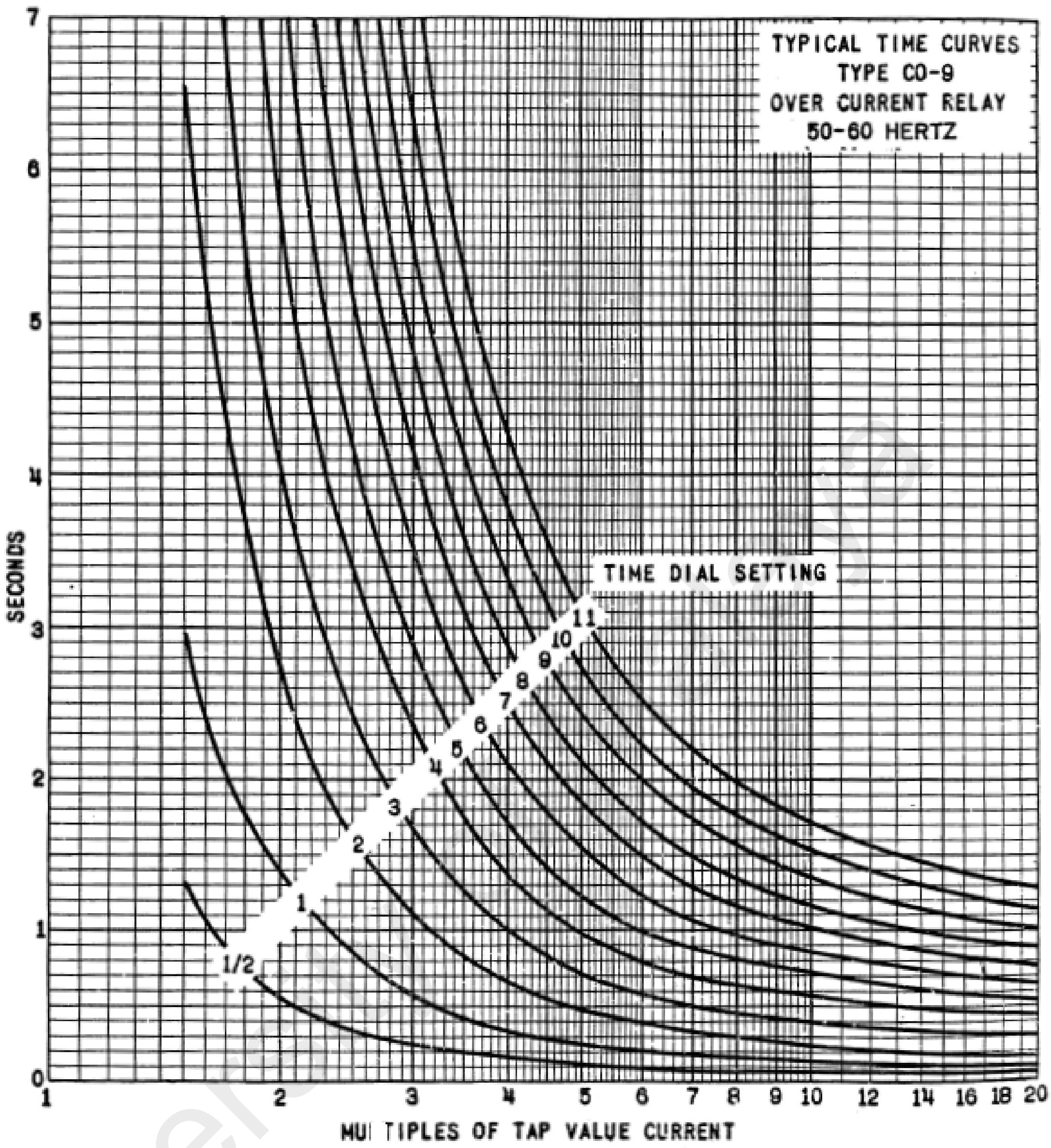

Figure 4.1 Typical Time-Current Curve (Duncan et al., 2012)

The TMS for main protection is selected to achieve instantaneous tripping during fault and relay operating time is calculated by taking into account the breaker operating time (0.083s). Therefore, the approximate total relay operating time is

$$t_{op} = (0.133 + 0.43 + 0.76)s = 1.323s$$

4.2 Particle Swarm Optimization Algorithm Parameter Setting

PSO is used as optimization method to obtain the optimum result of TMS for overcurrent protection coordination.

The PSO parameters declared in this study are initialized are as follows:

Maximum inertia weight	=	0.9
Minimum inertia weight	=	0.4
Acceleration factor, C1 and C2	=	2.0
Population size (number of particles)	=	100
Maximum Iteration	=	200

4.3 Simulation Result

Simulation results of optimum TMS and relay operating time was obtained using MATLAB software based on PSO method of optimization. The simulation for PSO was performed by using the initial parameters as described above. The convergence graph for each case study is also presented.

4.3.1 Case Study -1: Simulation using same TS value as per base case study.

In this case, the simulation was performed based on exact values of TS as per base case study where the TS is selected based on time-current curve used for electromechanical relay.

Table 4.2 Initial parameters used in the simulation (for Case Study-1)

Breaker (Relay)	Total maximum connected load (MVA)	CT Ratio	Bolted 3-phase fault current	Tap setting (TS)
R1	21	400:5	3000	5
R2	10	200:5	3000	5
R3	6	200:5	2000	3

The PSM and constant alpha, α, values are calculated using equation (4.1) and (4.2), respectively. The values of PSM and constant α are derived from the initial parameters to generate the objective function for the base case.

$$PSM = \frac{I_{fault}}{CT_{ratio} \times TS} \tag{4.1}$$

$$\alpha = \frac{\lambda}{PSM^{\gamma} - 1} \tag{4.2}$$

The calculated values of PSM and α are summarized as below:

Table 4.3 Values of PSM and α (for Case Study-1)

Fault location	Circuit Breakers (Relays)		
	B1 (R1)	B2 (R2)	B3 (R3)
Just beyond R1:			
PSM	7.5	-	-
α	3.40	-	-
Just beyond R2:			
PSM	7.5	15.0	-
α	3.40	2.52	-
Just beyond R3:			
PSM	-	10.0	16.7
α	-	2.97	2.42

Therefore, the objective function can be stated as:

$$Min\ z = \sum_{n=1} t_{op\ n}$$

$$\sum_{n=1} t_{op\ n} = 3.40(TMS1) + 2.52(TMS2) + 2.42(TMS3)$$

The boundary of lower and upper of TMS value for all relays is assumed to be between 0 and 1.

Minimum operating breaker is considered as 0.083 seconds and the CTI is taken as 0.3 seconds. Above objective function is limited with the constraints that are subject to CTI and breaker operating time as follow:

$$3.40(TMS1) - 2.52(TMS2) > 0.3\ seconds$$

$$2.97(TMS2) - 2.42(TMS3) > 0.3\ seconds$$

$$3.40(TMS1) > 0.083\ seconds$$

$$2.52(TMS2) > 0.083\ seconds$$

$$2.42(TMS3) > 0.083\ seconds$$

The result of TMS value and total minimum relay operating time using PSO is as shown in below table.

Table 4.4 TMS value and minimum relay operating time using PSO (Case Study-1)

TMS of relays	PSO algorithm	α value	Relay operating time (seconds)
TMS1 (R1)	0.20	3.40	0.680
TMS2 (R2)	0.15	2.52	0.378
TMS3 (R3)	0.04	2.42	0.097
		Total minimum relay operating time	1.155

Result from the optimization shows that optimum TMS values are obtained using PSO and meeting all constraints. The time operating of each relay is calculated by multiplying optimum TMS values and constant α value. Total minimum relay operating time obtained from the PSO is 1.155 seconds.

The convergence graph of result of relay operating time from PSO optimization is shown as below. The convergence occurred before the maximum iteration. In this case, the result was converged after more than 100 iterations.

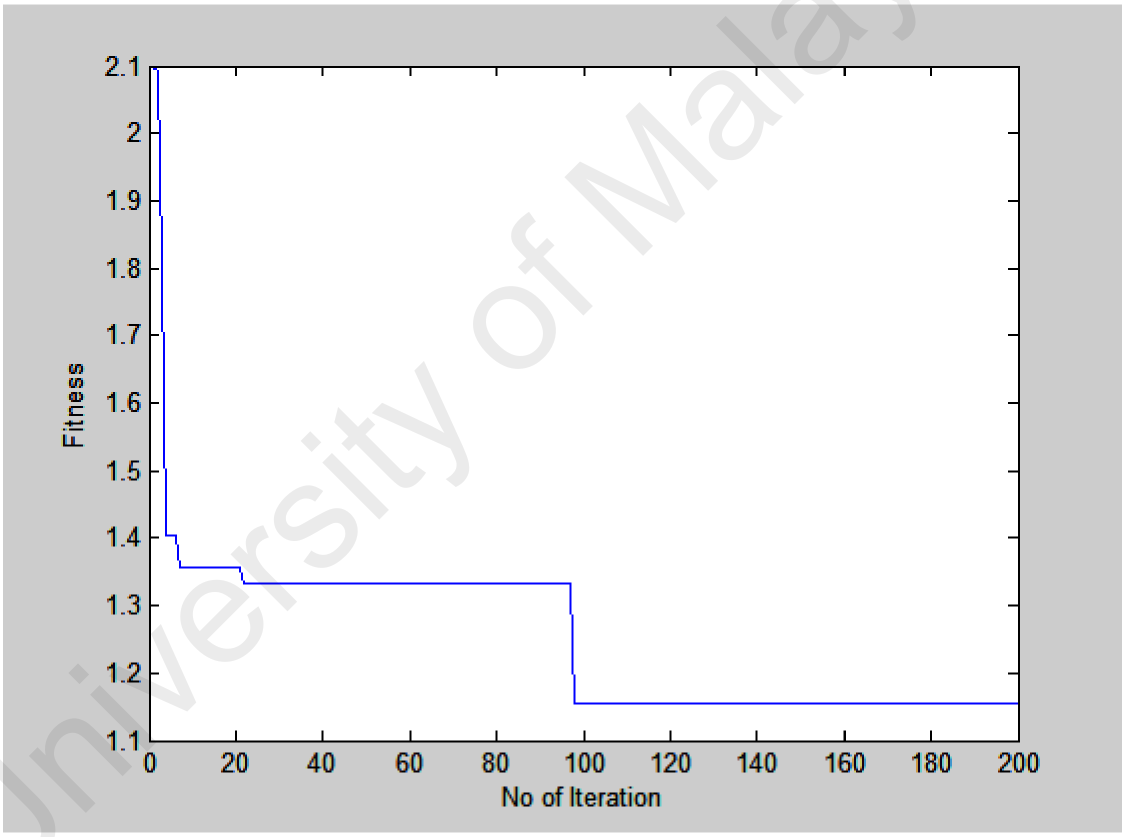

Figure 4.2 Convergence graph of minimum relay operating time (Case Study-1)

The comparison results of TMS value and total minimum relay operating time using PSO and conventional method is as shown in below table.

Table 4.5 Comparison results of TMS and relay operating time (PSO vs Conventional method)

Breakers (Relays)	Conventional method (Base Case)		PSO algorithm (Study Case-1)	
	TMS	Relay operating time (seconds)	TMS	Relay operating time (seconds)
B1(R1)	3	0.76	0.20	0.715
B2 (R2)	2	0.43	0.15	0.352
B3 (R3)	0.5	0.133	0.04	0.097
$\boldsymbol{Min\ z = \sum_{n=1} t_{op\ n}}$	**-**	**1.323**	**-**	**1.155**

From table 4.6, the comparison shows the optimum TMS values from PSO are meeting all constraints and boundary limit between 0 and 1.

As a result of optimum TMS, the relay operating time for each relay is faster than conventional method. Subsequently, the reduce the total minimum relay operating time from 1.323 seconds to 1.155 seconds, which is 0.168 seconds earlier.

4.3.2 Case Study-2: Selection of tap setting is based on actual TS value.

This case study is to analyze the result from the exact TS value calculated from the maximum load current. The tap setting is equal to maximum load current where TS is set at 100% of the maximum load capacity.

From table 4.3, new TS values for this case study are calculated and summarized as below:

Table 4.6 New setting of TS value (for Case Study-2)

Breaker (Relay)	Total load, S (MVA)	Maximum load current, I (A)	CT Ratio	Maximum load current, I (A), at CT secondary	New tap setting (TS) for each relay (Case Study-2)
R1	(11 + 4 + 6) = 21	351.4	400/5	4.39	**4.39**
R2	(4 + 6) = 10	167.3	200/5	4.18	**4.18**
R3	6	100.4	200/5	2.51	**2.51**

The values of PSM and α are calculated and summarized by using new TS are shown in Table 4.8 below.

Table 4.7 Values of PSM and α (for Case Study-2)

Fault location	Circuit Breakers (Relays)		
	B1 (R1)	B2 (R2)	B3 (R3)
Just beyond R1: PSM α	 8.5421 3.1939	 - -	 - -
Just beyond R2: PSM α	 8.5421 3.1939	 17.9426 2.3552	 - -
Just beyond R3: PSM α	 - -	 11.9617 2.7512	 19.9203 2.2705

Therefore, the objective function can be stated as:

$$Min\ z = \sum_{n=1} t_{op\ n}$$

$$\sum_{n=1} t_{op\ n} = 3.19(TMS1) + 2.36(TMS2) + 2.27(TMS3)$$

Minimum operating breaker is considered as 0.083 seconds and the CTI is taken as 0.3 seconds. Above objective function is limited with the constraints that are subject to CTI and breaker operating time as follow:

$$3.19(TMS1) - 2.36(TMS2) \quad > \quad 0.3\ seconds$$

$$2.75(TMS2) - 2.27(TMS3) \quad > \quad 0.3\ seconds$$

$$3.19(TMS1) \quad > \quad 0.083\ seconds$$

$$2.36(TMS2) \quad > \quad 0.083\ seconds$$

$$2.27(TMS3) \quad > \quad 0.083\ seconds$$

The result of TMS value and total minimum relay operating time using PSO is as shown in below table.

Table 4.8 TMS value and minimum relay operating time using PSO (Case Study-2)

TMS of relays	PSO algorithm	α value	Relay operating time (seconds)
TMS1 (R1)	0.23	3.19	0.734
TMS2 (R2)	0.16	2.36	0.377
TMS3 (R3)	0.04	2.27	0.091
Total minimum relay operating time			1.202

From result above, it shows that optimum TMS values are obtained using PSO and meeting all constraints. The time operating of each relay is calculated by multiplying optimum TMS values and respective constant α value. Total minimum relay operating time obtained from the PSO is 1.202 seconds.

The convergence graph of result of relay operating time from PSO optimization is shown as below. The convergence occurred before the maximum iteration. In this case, the result was converged after more than 70 iterations.

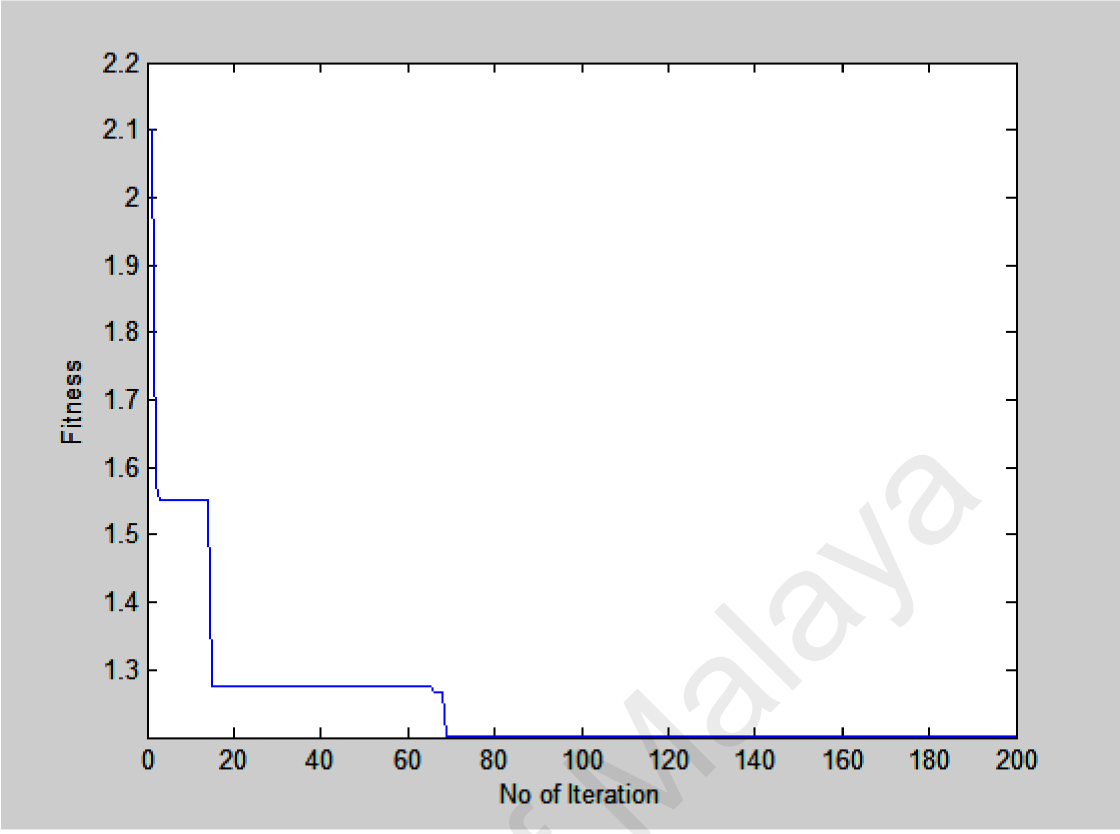

Figure 4.3 Convergence graph of minimum relay operating time (Case Study-2)

4.3.3 Case Study-3: Change in tap setting (TS) to maximum factor of relay setting at maximum setting of 125%.

The same simulation was performed for study case-3 where the result was analyzed based on the TS value set at protection setting of 125% of the maximum load capacity.

From table 4.3, new TS values for this case study are calculated and summarized as below:

Table 4.9 New setting of TS value (for Case Study-3)

Breaker (Relay)	Total load, S (MVA)	Maximum load current, I (A)	CT Ratio	Maximum load current, I (A), at CT secondary	New tap setting (TS) for each relay (125%) (Case Study-3)
R1	(11 + 4 + 6) = 21	351.4	400/5	4.39	**5.49**
R2	(4 + 6) = 10	167.3	200/5	4.18	**5.23**
R3	6	100.4	200/5	2.51	**3.14**

The values of PSM and α are re-calculated and summarized by using new TS values are shown as below.

Table 4.10 Values of PSM and α (for Case Study-3)

Fault location	Circuit Breakers (Relays)		
	B1 (R1)	B2 (R2)	B3 (R3)
Just beyond R1:			
PSM	6.8306	-	-
α	3.5736	-	-
Just beyond R2:			
PSM	6.8306	14.3403	-
α	3.5736	2.5592	-
Just beyond R3:			
PSM	-	9.5602	15.9236
α	-	3.0311	2.4597

Therefore, the objective function can be stated as:

$$Min\ z = \sum_{n=1} t_{op\ n}$$

$$\sum_{n=1} t_{op\ n} = 3.57(TMS1) + 2.56(TMS2) + 2.46(TMS3)$$

Minimum operating breaker is considered as 0.083 seconds and the CTI is taken as 0.3 seconds. Above objective function is limited with the constraints that are subject to CTI and breaker operating time as follow:

$$3.57(TMS1) - 2.56(TMS2) \quad > \quad 0.3\ seconds$$

$$3.03(TMS2) - 2.46(TMS3) \quad > \quad 0.3\ seconds$$

$$3.57(TMS1) \quad > \quad 0.083\ seconds$$

$$2.56(TMS2) \quad > \quad 0.083\ seconds$$

$$2.46(TMS3) \quad > \quad 0.083\ seconds$$

The result of TMS value and total minimum relay operating time using PSO is as shown in below table.

Table 4.11 TMS value and minimum relay operating time using PSO (Case Study-3)

TMS of relays	PSO algorithm	α value	Relay operating time (seconds)
TMS1 (R1)	0.20	3.57	0.714
TMS2 (R2)	0.15	2.56	0.384
TMS3 (R3)	0.04	2.46	0.098
		Total minimum relay operating time	1.196

From result above, it shows that optimum TMS values are obtained using PSO and meeting all constraints. The time operating of each relay is calculated by multiplying optimum TMS values and respective constant α value. Total minimum relay operating time obtained from the PSO is 1.196 seconds.

The convergence graph of result of relay operating time from PSO optimization is shown as below. The convergence occurred before the maximum iteration. In this case, the result was converged after more than 55 iterations.

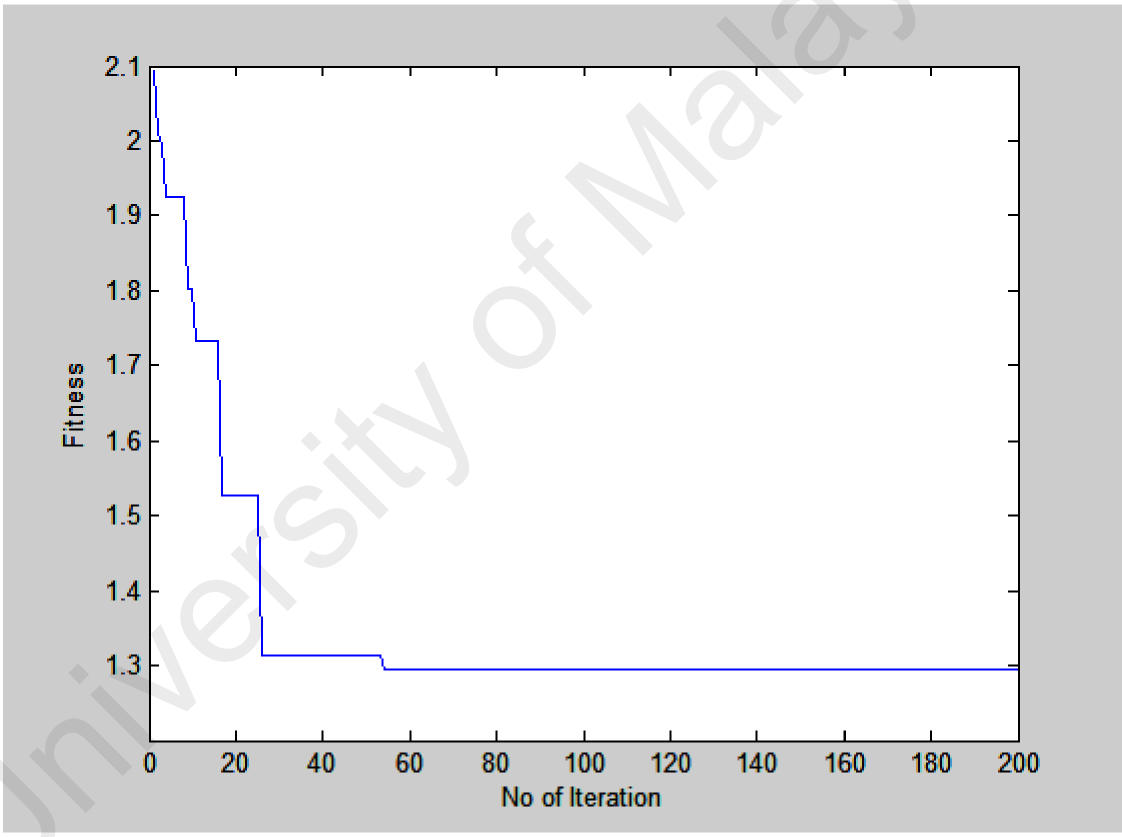

Figure 4.4 Convergence graph of minimum relay operating time (Case Study-3)

4.3.4 Study Case-4: Comparison of optimization method result between PSO with Dual Simplex and Genetic Algorithm

The result of TMS from PSO is compared based on other optimization method study for radial system such as Dual Simplex and Genetic Algorithm. The study was conducted for 4-bus and 2-bus radial system (Madhumitha et al., 2015).

The values of PSM and α, for both 4-bus and 2-bus system are tabulated in table 4.12 and 4.13, respectively.

Minimum operating breaker is considered as 0.20 seconds and the CTI is taken as 0.57 seconds.

Table 4.12 Values of PSM and α for 4-bus system

Fault location	Circuit Breakers (Relays)			
	R1	R2	R3	R4
Just beyond R1: PSM α	 14.924 2.520	 - -	 - -	 - -
Just beyond R2: PSM α	 11.376 2.809	 12.052 2.742	 - -	 - -
Just beyond R3: PSM α	 - -	 7.14 3.4915	 7.276 3.4577	 - -
Just beyond R4: PSM α	 - -	 - -	 6.708 3.6083	 6.74 3.5991

Table 4.13 Values of PSM and α for 2-bus system

Fault location	Circuit Breakers (Relays)	
	R1	R2
Just beyond R1:		
PSM	8.432	-
α	3.21	-
Just beyond R2:		
PSM	2.556	6.812
α	7.38	3.57

Therefore, the objective functions are form as below:

For 4-bus system,

$$\sum_{n=1} t_{op\,n} = 2.52(TMS1) + 2.74(TMS2) + 3.46(TMS3) + 3.59(TMS4)$$

Above objective function is limited with the constraints that are subject to CTI and breaker operating time as follow:

$$2.81(TMS1) - 2.74(TMS2) \quad > \quad 0.57\ seconds$$

$$3.49(TMS2) - 2.46(TMS3) \quad > \quad 0.57\ seconds$$

$$3.61(TMS3) - 3.59(TMS4) \quad > \quad 0.57\ seconds$$

$$2.52(TMS1) \quad > \quad 0.2\ seconds$$

$$2.74(TMS2) \quad > \quad 0.2\ seconds$$

$$3.46(TMS3) \quad > \quad 0.2\ seconds$$

$$3.59(TMS4) \quad > \quad 0.2\ seconds$$

Therefore, the result of TMS values are obtained by using PSO are shown below.

Table 4.14 TMS value for 4-bus system

Optimization Method	TMS1	TMS2	TMS3	TMS4
PSO	0.597	0.393	0.224	0.057

For 2-bus system,

$$\sum_{n=1} t_{op\ n} = 3.21(TMS1) + 3.57(TMS2)$$

Above objective function is limited with the constraints that are subject to CTI and breaker operating time as follow:

$$7.38(TMS1) - 3.57(TMS2) \quad > \quad 0.57\ seconds$$

$$3.21(TMS1) \quad > \quad 0.2\ seconds$$

$$3.57(TMS2) \quad > \quad 0.2\ seconds$$

Therefore, the result of TMS values are obtained by using PSO is shown below.

Table 4.15 TMS value for 2-bus system

Optimization Method	TMS1	TMS2
PSO	0.105	0.057

4.4 Comparison results of all case studies

Three (3) case studies are performed with a basis of selecting different tap setting for overcurrent relay coordination. All results from all three (3) case studies are analyzed and summarized are as follow:

Table 4.16 Comparison of results for 3 case studies

Relays	Conventional method			Particle Swarm Optimization								
	Base Case			Case Study-1 (TS=base case)			Case Study-2 (TS=100%)			Case Study-3 (TS=125%)		
	TS	TMS	t_{op}	TS	TMS	t_{op}	TS	TMS	t_{op}	TS	TMS	t_{op}
R1	5	3	0.76	5	0.20	0.680	4.4	0.23	0.734	5.5	0.20	0.714
R2	5	2	0.43	5	0.15	0.378	4.2	0.16	0.377	5.2	0.15	0.384
R3	3	0.5	0.133	3	0.04	0.097	2.5	0.04	0.091	3.1	0.04	0.098
$\sum t_{op}$	1.323			1.155			1.202			1.196		

The TMS values are only slightly different for each case when changes in tap setting. Changes in tap setting (TS) will change the problem statement or objective function of the relay operating time with constant α value is proportional to TS value.

TMS value obtained from PSO optimization method reduces the relay operating time to clear the fault. This result in lower total minimum relay operating time to approximately between 0.15 to 0.2 seconds.

From optimization approach, the total relay operating time is almost the same period for all cases.

Observation from the case studies, it can be concluded that the overcurrent relay coordination between main and backup relay is achieved with selective optimum TMS values from PSO method. The results show the minimum operating time is also attained with optimum TMS value.

For comparison study with other result from others optimization method are summarized as below.

Table 4.17 Comparison of TMS Values for 4-bus radial system

Optimization Method	TMS1	TMS2	TMS3	TMS4
Dual Simplex	0.568	0.375	0.213	0.055
Genetic Algorithm	0.577	0.379	0.213	0.056
PSO	**0.597**	**0.393**	**0.224**	**0.057**

Table 4.18 Comparison of TMS Values for 2-bus radial system

Optimization Method	TMS1	TMS2
Dual Simplex	0.104	0.056
Genetic Algorithm	0.104	0.056
PSO	**0.105**	**0.057**

From the above result, it shows that PSO is like genetic algorithm are more effective for large population and when minimum data is known and less variables is to be obtained. However, PSO is time consuming when increase in variables and data to be handled.

4.5 Summary

In this chapter, simulation results of different tap setting is performed using PSO optimization tool. All results and findings are discussed. Different in tap setting only shows very slight different in term of TMS value. However, the operating time for each relay will experience bit different values. Therefore, the total relay operating time is also affected. However, the different operating time is very minimum. It also shows that changing in time selecting will impact the operating time of each relay. Increase in tap setting value, will decrease the PSM value and subsequently increase the relay operating time. Longer operating time can affect the equipment thermal withstand capability and reduce equipment life span. Therefore, lower setting of TS or close to the maximum load capacity shall be considered in order to get the best optimal overcurrent time multiplier setting with very minimum overall relay operating time.

CHAPTER 5: CONCLUSION

5.1 Conclusion

In this work, the optimum time multiplier setting (TMS) and minimum relay operating time have been proposed based on Particle Swarm Optimization method. The results then was compared with conventional method of coordination study used for electromechanical relay. The optimization method was further implemented for different initial value set for tap setting (TS) or also known as relay setting. The different initial value of TS was based on 100% and 125% of maximum load current.

The optimum TMS value and operating time was recorded and compared with previous result. The result showed that by using optimization method, in particular the PSO, the optimum result of TMS can easily be determined within few seconds. Besides that, the minimum operating time is still achieved if the value of TS which determined the PSM values, is set between 100% and 125% of maximum load current.

In conclusion, parameters for setting up the relays is very crucial in order to achieve suitable sensitivity, selectivity and stability of relay operation. Coordination of overcurrent relay is important to ensure protect the electrical network from unnecessary tripping and reduce stress on the equipment itself during faults condition. The result from proposed optimization technique can improve the performance and reliability of overcurrent protection system. Subsequently, it helps the engineers and designers to develop more reliable electrical network as well as improve the failure rate of electrical equipment. Indirectly, improvement in relay coordination study can optimize the design to meet minimum standard requirement and also reducing the cost of maintenance with minimum system interruption.

Using optimization method like PSO, enhance the result by obtaining the best values of TMS and subsequently improve the total operating time of overall relay in very short time for small scale power system. The PSO method is utilizing the best value from random initial values and the result will converge after many iterations even and could obtain less than predefined number of iteration. Nonetheless, the time consume to obtain the optimum result is proportionate with number of variables which is high for PSO if number of variables is more and lead to less optimum result.

5.2 Recommendations

Future works that can be recommended from this research work are:

1. To consider using the same optimization method for different type of network configuration such as ring network.
2. To explore further on different objective function for different type of IEC relay such as very inverse or extremely inverse relay.
3. To take into account other constraints in the optimization calculation such as thermal withstand capacity and equipment damage curve into objective function.
4. To convert the simulation and result from PSO or other algorithm into graphical interface

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