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THESIS NO: 074/MSPSE/004

A Voltage Based Optimal Relay Coordination in Distributed Generation Penetrated Distribution Network Using Particle Swarm Optimization.

by

Bharat Pokharel

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

DEPARTMENT OF ELECTRICAL ENGINEERING
LALITPUR, NEPAL

February, 2021

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ABSTRACT

The distribution system is the most visible part of the power supply chain. Most of the distribution lines are overhead in nature and thus have high chances of occurring different types of fault on the system. The distribution system (DS) has always some degree of unsafety. The proper protection in DS is one of the biggest challenges before the power engineer. Any type of fault that may occur on the DS should be cleared as soon as possible to prevent the supply outage for healthy part of the system. There are different types of safety equipment for own purposes in the distribution network. Each equipment has their assigned job. So depending upon the nature of fault, Location of fault and mode of operation of the distribution system, each equipment should operate in the right time at right condition. This becomes more complex when overcurrent based protection is used in DS having distributed generation of different topology, specifically the inverter based type.

This thesis presents the use of particle swarm optimization (PSO) technique to achieve the objective of the development of effective protection coordination in distribution system using the fault voltage as a relay actuating quantity. DIgSILENT Power Factory tool and MATLAB platform are used for fault analysis and development of coordination program respectively.

The developed program was tested for 6 node low voltage (LV) distribution network and 95 node medium voltage (MV) distribution network with injection of distributed generation at various nodes.

In addition, the coordination between line primary relays and DG unit is analyzed and conclusion is drawn for the method that can be used for the better protection coordination between them. In the research the sum of operating time for LV distribution system is found to be only 2.99 seconds for islanded mode and 4.6 seconds for grid connected mode holding the coordination time interval of 0.2 second. Similarly for MV distribution system the sum of operating time of relays is found to be 3.4919 second for islanded mode and 4.1821 second for grid connected mode. However the same for other algorithm like Firefly Algorithm (FA) is found to be 3.7789 second for islanded mode and 4.763 second for grid connected mode. Hence from this result it has been found that the PSO algorithm provides the faster operating time of the primary relays for both 6 node LV and 95 node MV DS

resulting lower value of the objective function than the other methods FA. The rate of convergence for proposed method is faster and smooth than FA method.

Hence the developed protection coordination algorithm of voltage based relay with PSO is found to be practically, the more efficient, sensitive and discriminative method for relay coordination in both low and medium voltage of distribution system. The proposed voltage based method is compared with the current based method for the Canadian Distribution Network with all the technical data same for both method. The sum of operating time of primary relays for voltage based method is found to be 7.363 seconds whereas the same for over current based method is 11. 239 seconds. Therefore, it has been found that the voltage based protection system is faster than current based protection system in distribution system with distributed generations.

ACKNOWLEDGEMENT

Firstly, I would like to express my hearty gratitude to my respected supervisor, Associate Professor Dr. Netra Prasad Gyawali, Faculty Member of Department of Electrical Engineering, Pulchowk Campus, Institute of Engineering, and Chief Executive Officer of Rastriya Grid Prasaran Company Limited, and respected co-supervisor, Assistant Professor Akhileshwar Mishra, Department of Electrical Engineering, Pulchowk Campus, for their valuable guidance throughout the entire period of this thesis work. The inspiration, invaluable support, understanding and the expertise of the supervisors have been the prominent things in completing this work. It was a great honor for me to pursue my thesis under their supervision.

I am very thankful to Professor Dr. Nava Raj Karki, Program Co-ordinator of M.Sc. in Power System Engineering, for his valuable inputs, timely coordination and the support.

I would like to thank Associate Professor Mahammad Badrudoza, Head of Department of Electrical Engineering, IOE for his valuable suggestions and support. I would also like to thank Assistant Professor Er. Khagendra Thapa, faculty members of Department of Electrical Engineering, for providing his valuable time for frequent review of this thesis article for publication on international conference.

I am very grateful to my wonderful friends and colleagues of Department of Electrical Engineering, Pulchowk Campus, for their tireless support, motivation and consultation in completing the work.

My thanks are also extended to the Department of Electrical Engineering of Pulchowk Campus, for a delightful environment, kind treatment and support.

Last but not least, I would like to express my deepest gratitude to my family members- my parents and my wife for their everlasting love and consistent support.

Bharat Pokharel

February, 2021

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LIST OF ABBREVIATION

Abbreviation	Full Form
ANN	Artificial Neural Network
ANSI	American National Standard Institute
BSP	Bulk Supply Point
CNOP	Constrained Nonlinear Optimization Problem
CTI	Coordination Time Interval
CTI_G	Coordination time interval when DS in Grid connected mode
CTI_IL	Coordination time interval when DS in Islanded mode
DERs	Distributed Energy Resources
DG	Distributed Generation
DIgSILENT	Digital Simulation of Electrical Network
DNO	Distribution Network Operator
DS	Distribution System
DUVR	Directional under Voltage Relay
EMT	Electromagnetic Transient
FA	Fire Fly Algorithm
IBDG	Inverter Based Distributed Generation
IDE	Islanding Detecting Element
IEC	International Electro-technical Commission
IEEE	Institute of Electrical and Electronic Engineering
IPM	Interior Point Method
LV	Low Voltage
MRSS	Main Receiving Sub Station
MV	Medium Voltage
OC	Over Current
OF	Objective Function
P/B	Primary/Backup Relay
PSO	Particle Swarm Optimization
PSOA	Particle Swarm Optimization Algorithm
rms	Root Mean Square
RSE	Relay Starter Element
SBDG	Synchronous Based Distributed Generation
SCADA	Supervisory Control Data Acquisition System

SCFD	Static Converter Fed Drive
S/C	Short Circuit
TDS	Time Dial Setting
VMU	Virtual Measurement Unit
W_{max}	Maximum limit of inertial weight
W_{min}	Minimum limit of inertial weight

LIST OF SYMBOL

Symbol	Name
Pu	Per Unit
V_f	Fault Voltage in p.u.
I_f	Fault Current, Ampere
D	Dimension of the decision variable in PSO
N_p	Population size
Rand()	Any random values between 0 and positive unity
t_{op}	Operating time of primary relay in second
t_{ob}	Operating time of back up relay in second
V_{sc}	Short Circuit Voltage
R_n	Relay Number
I	Current in ampere
r	Resistance per unit length in ohm
t	Time in second
x	Reactance per unit length in ohm
l	Length of the line
z	Impedance of the line in ohm
F_n	Fault number
x_p	Local best value of the particle position
x_g	Global best value of the particle position
x_i	Position of the ith particle
c_1	Personal acceleration coefficient
c_2	Social acceleration coefficient
w	Inertial weight
v_{max}	Maximum tolerable value of search direction
p	Particle
T	Iteration Number
S	Population size, N
ϵ	Tolerable value
I_{op}	Normal operational current
m_IS	‘m’ parameter value when DS in Islanded Mode
m_Grid	‘m’ parameter value when DS in Grid Connected Mode

CHAPTER 1: INTRODUCTION

1.1 Background

The electricity utilities are wondering about how reliable and quality supply of electricity can be made to the end consumers. The quality and degree of reliability of electricity supply mainly depends on the distribution system structure and coordination of safety equipment. Also, it is statutory requirements for distribution network operators (DNO) to protect persons, livestock, plant and equipment from being damaged resulting from the operation of distribution network. But in essence, protection system is installed to maintain the continuity of supply. The existing distribution network protection system design is based on the three assumptions that the fault produces a current with a magnitude that is several times larger than the system load current magnitude. Secondly, this fault current magnitude is inversely proportional to the impedance between the fault point and the source and varies accordingly with the fault location. The source mentioned here means the bulk supply point (BSP) or it can be said the main receiving sub-station (MRSS) from which the local distribution is carried out. Most of the conventional distribution systems were radial in nature so the fault current flows in unidirectional way from the BSP/MRSS to the fault points. The protection coordination between the different safety components has relatively easier concept in radial distribution system. Circuit breakers and relays or fuses are installed at several points along each branch of the radial distribution network so that when a fault is detected; the few numbers of customers is disconnected, leaving the remaining portion of the system to be continuously operating. The relay element decides whether or not to issue a trip command to the respective circuit breaker by comparing the actuating parameters. The fault level throughout the network is calculated by performing the fault analysis which is based on the advanced software packages, tools, applications. But due to the increase in penetration level of distributed generation (DG) in radial distribution system, the distribution system remains no longer in radial form. Part of the distribution system may have in interconnected/loop form and rest of the system may have in radial form. In addition the whole distribution system may be in the form of interconnected system. Therefore, in such type of restructured distribution system, the conventional type of protection system might not be valid for proper operation of the system. There might be false coordination among different type of relays. Each relay has their intended job to operate in different fault condition. Some might have to be operating as primary and other might have to be operating as backup protection for any kind of fault that occurred at particular location. The same relay must operate as primary and backup protection depending upon the location of fault. Therefore due to the DG penetration in distribution system the protection is becoming more complex due to some issues including DG interface technology, daily change of DG output and distribution system grid connected or stand-alone operational mode. Due to the DG interface technology, the DG units may make different fault current contribution. The synchronous based DG contribute more fault current in comparison to inverter based DG. The variable output of DG can make the magnitude and direction of fault current to change. The fault current magnitude in the grid connected mode is very much different from the islanded mode. Therefore in order to address such type of problem from protection point of view, several methods have been proposed. Most of the protection methods for distribution system with DG are communication based or communication assisted methods requiring fast processing units. But the communications systems are more prone to a fault which ultimately decreases the reliability of the protection system.

In order to overcome such problems, an effective protection system must be able to operate under different fault condition and mode of distribution system operation. The protection system must be reliable with suitable selectivity and stability features. This thesis presented a protection method for distribution system with DG using the local fault voltage measurement.

1.2 Problem Statement

Most of the protection methods proposed in the literature are based on the communication facilities or communication assisted for fast processing unit [2], [11]. Many number of short circuit protection coordination methods explored so far in the literature use fault current as a relay actuating signal or for making the decision to trip the respective circuit breaker [7], [8], [13], [14]. In distribution system for radial network, the relay coordination solution is found to be satisfactorily good in radial mode irrespective of their cost due to communication link.

But in DG based distribution system, the fault current is contributed by the different sources, i.e. grid and the connected DGs. So the protection coordination becomes more complex in comparison to those in radial form due to following problems.

- The synchronous based DGs integrated in DS contribute large amount of fault current thus by decreasing the fault current contribution from the grid side, making the relay at grid side to be less sensitive.

- Inverter based DGs installed in DS contribute very low fault current which may results difficulty in distinguishing whether there is fault or not for the relay at IBDG side.

In such case, over current based protection system which is generally used might not be properly sensitive.

Therefore, in order to address such problem and to make the protection system in such condition more sensitive, selective and reliable, a new relay characteristic is presented which is based on the measurement of fault voltage at relay location at the time of fault occurrence.

In addition, the performance of optimization techniques on voltage based relay coordination to get the optimal result has not found to be studied till this time. In many engineering optimization problem the performance of particle swarm optimization has found to better in-terms of handling complexities in an efficient way and requiring lower number of iterations. In over current based relay protection the performance of PSO was already done. In this research PSO is selected with the expectation of handling the complexities in solving the nonlinear type of new relay characteristics to get the global optima.

1.3 Objective and Scope of the Study

1.3.1 Objective:

The main objective of the thesis is the development of effective protection coordination algorithm using particle swarm optimization tool, taking the fault voltage at relay position. In addition, this thesis covers the following specific objectives to be met to achieve the main objective.

- The LV distribution system of utilization voltage level in which nodes are few meters away from each other, will be used to check the effectiveness of developed coordination program.
- The MV distribution system of large network in which nodes are far away from each other's, will be used to check the effectiveness of the developed coordination program in case of zone protection.
- Comparison of Voltage based relay and current based relay on the same distribution network.
- Protection coordination between line protection relay and unit protection relay

1.3.2 Scope:

The scope of this thesis is to investigate the relay operating time of primary relays for 6 node low voltage distribution system and 95 node MV distribution systems with penetration of DGs using the voltage based relay characteristics. In this study, an optimization tool called particle swarm optimization is used as a main algorithm while developing the protection coordination program. The application and performance of PSO in such system is analyzed.

Also, the thesis analyses different methods for the relay coordination between the line primary relay and backup relay at unit side for 95 node 20kV distribution system in islanded mode to arrive at a better method of coordination.

It also deals with the determination of primary relay operating time using voltage based relay characteristics and comparison is done with the result of overcurrent based protection coordination. The same distribution system with all technical parameter is used for this comparative analysis.

Since getting the faster operating time of primary relay from protection point of view is the main issue, voltage based relay with particle swarm optimization is proposed to be the better method for same in DS.

On the completion of this thesis, it is expected that the research will help to find the better solution from both safety and economic point of view.

1.4 Outline of the Thesis

This thesis report consists of the five chapters which are briefly highlighted as follows;

Chapter 1: It presents a brief knowledge about the protection system, distribution system, necessity of protection and coordination, objective/s of the presented thesis, scope and limitations.

Chapter 2 : It presents the literature review regarding the distribution system protection coordination explored so far, study of fault analysis, detail analysis of the new presented nonstandard type relay characteristic, optimization problem formulation for under voltage based directional relays.

Chapter 3: It describes about the research methodology used for development of coordination program to get the desired result/output regarding the points mentioned in the objective. It presents the particle swarm optimization (PSO) algorithm in details, some modification/repair adapted according to the nature of optimization problem.

Chapter 4: It emphasizes the main result of the thesis work. The result obtained from the program formulation is presented here. It focuses on the logical comparison of the results and detail conceptual discussion with references article.

Chapter 5: It draws the conclusion of thesis and summarizes the main task carried out in the entire thesis work. The recommendation for future research is also presented here.

CHAPTER 2: LITERATURE REVIEW

2.1 Background

Any power system or distribution system structure based on the safer and reliable operation has a natural tendency to improve the existing protection scheme. The distribution system consists of number of switches, circuit breakers and fuses which are normally closed. In recent days due to the integration of the DGs in distribution systems, their structure are changed and accordingly the protection system needs to be changed for proper coordination between various types of relay located at various points. Generally the connection of any generator to the network will lead to an increase in the fault level [9]. The additional generator creates a parallel path, lowering the effective impedance between the equivalent source and the fault, leading to an increase in fault current. But the inverter based renewable energy sources has a very low fault current capacity. Therefore if the connection of IBDG offsets conventional generation, it actually leads to a drop in fault level. In the extreme case where a network is supplied by IBDG only, the fault level can be very low so that it is hard to discern fault current from the normal load current.

A change in fault level affects the operation of the protection system by changing the jurisdictions of relays resulting in a loss of selection. This can cause the jurisdictions to overlap or leave the gaps in the coverage of the network leading to larger number of consumers on the network than necessary being disconnected or the fault going unnoticed. Moreover an increase in fault level can cause the ratings of the substation equipment to be exceeded which leads to unsafe situations and requires expensive infrastructure upgrades. The majority of relays in the distribution network is incapable of distinguishing current direction and can issue a false trip when DG fault current flows into a fault on an adjacent feeder. Each time DG is connected, protection engineers need to assess its impact on the protection system by performing a fault analysis or protection study and where necessary adjust relay settings. The protection coordination should be such that the total operating time of all the relays should be as low as possible provided the coordination time interval (CTI) among the respective relays should be properly maintained. This thesis focuses on the optimal protection coordination among various relays installed on the distribution lines. Several researches have been done on this topic. But most of them are based on the fault current. The decision variables in such type of current based protection coordination program are the time dial setting and the pickup current values. These values have to be optimally determined for relay coordination. A non-communication over current protection method based on the definite time relay is proposed in [2]. But this method may take longer time for the fault isolation in large distribution systems.

The main theme of this thesis is to optimize the relay setting. The optimal protection coordination is based on the voltage measurement at each relay. Some of the protection coordination studies based on both the measurement of current and voltage can be found in the literature [11], [5]. Using of the new relay characteristics using local voltage measurement for determination of operating time of relays is given in [4]. However any optimization technique has not been used for optimal determination of relay settings. Therefore the main theme of the thesis is the study of voltage based coordination system using the meta-heuristic algorithm called particle swarm optimization and analyzing the performance of it. One of the optimization techniques that can be used for the same is enlisted in [2].

A number of algorithm including mathematical programming, heuristic optimization methods, evolutionary algorithms such as Genetic Algorithm (GA), Artificial Neural Network (ANN), Monte Carlo Simulation, Firefly Algorithm (FA), Modified Adaptive Firefly Algorithm (MAFA) [2], Cuckoo Search Algorithm (CSA), Particle Swarm Optimization (PSO) [6], [7], [8] etc., have been proposed to select the appropriate value of the parameters of the standard characteristics of the proposed relay with the objective of minimizing total operating time of the concerned relays in the particular distribution network. The methods listed above are all the optimization tools, found to be applicable in engineering, science technology and process industry.

A vast bibliography on the optimal protection coordination problem is now available in the literature to get the best value of the relay setting.

2.2 Protection Method

The distribution network operator has a mandatory obligation to apply protection devices to every system which will, so far as is reasonably practicable, prevent any current, including leakage to earth, from flowing in any part of a system for such a period that part of the system can no longer carry that current without danger [15]. The protection system must be:

- Sensitive: It means operate correctly under the actual condition that produces the least operating tendency.
- Selective: it means protection system should be able to discriminate between conditions for which immediate, time-delayed or no action is required to ensure the

smallest number of customers is disconnected in case of an abnormal operating condition.

- Fast: it means protection system operate in the required time interval to minimize damage to the equipment (i.e. minimize energy let-through I^2t and safeguard continuity of supply.
- Stable: Protection system should be immune to all the load conditions and external faults.

The continuous measurement of the actuating quantity is necessary to make the decision on the appropriate action of the relay. The actuating quantity may be current, voltage, frequency, pressure, impedance and many others in separate form or in combination as per the nature of protection designed. The method becomes more complex when it requires voltage and current transformer, thermometers or pressure sensor. They can however be programmed to achieve high speed operation, sensitivity, selectivity and reliability.

In the distribution network, where the cost is a major factor and daily fault level fluctuations are relatively small (most of the impedance is in the form of transformer and lines), non-directional time graded over current earth fault relaying combined with fuses is the protection strategy of the choice. The proper operation of this protection strategy is based on the number of following assumptions:

- Radial network layout with unidirectional fault –current flow from MRSS to the Fault point.
- Availability of fault current level: The large thermal inertia and stored energy of conventional generators results in a large fault current contribution that has a magnitude that is typically several times larger than nominal load currents.
- Negligible variation in fault level: The dominant impedance between the fault and fault current source is in the distribution transformer and the lines, not in the source itself so changes in the connected amount of generation do not substantially alter the fault level.

2.2.1 Impact of DG on the operation of the protection system of DS

The presence of DG violates the number of the assumptions made for coordination the system algorithm applied for complete radial system feed from one source only. The connection of the DGs into an existing network leads to an increase in the fault level as it provides an additional parallel path for fault current. Fault level, generally expressed in MVA, is a measure of the fault current that is expected to flow into a fault at a particular location in the network and is limited by the system operating voltage and the equivalent impedance between the source and the fault.

Bidirectional fault –current flows:

With the penetration of distributed generation (DG), the MRSS is no longer the only source of fault-current and thus the flow of fault current is altered. Let us consider a situation illustrated in the Figure 2.1, which shows a MRSS, supplying two overcurrent protected HV feeders through the transformer. The DG is connected to the feeder B at point 'X'. In case of the fault occurred in the feeder A, say at point 'Y', fault currents will flow from the gird (solid line) as well as from the DG (dashed line) on the feeder B. the non-directional relay system will operate here at breaker A and trips, removing the faulty section from the system.

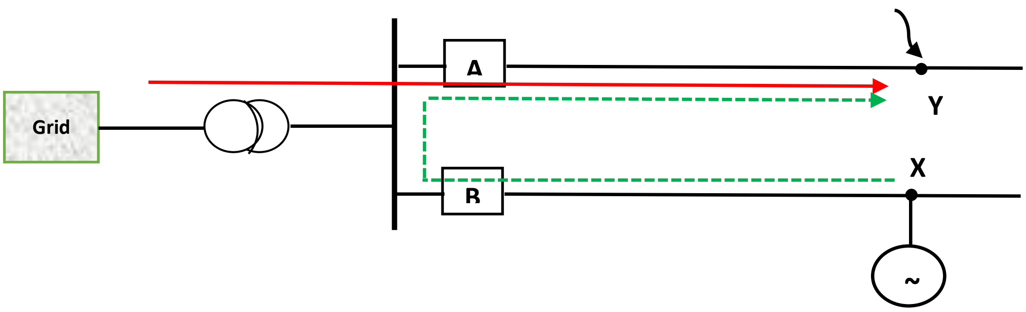

Figure 2.1: DG on Adjacent Feeder

However, with the DG connected on feeder B, the non-directional relay at breaker B will pick up on the DG distribution on the fault current. In the Figure 2.2, the fault is occurred in between the grid source and the DG source, then the fault current will flow in reverse direction through the relay B, which if it is of the non-directional type, will pick up and possibly trip.

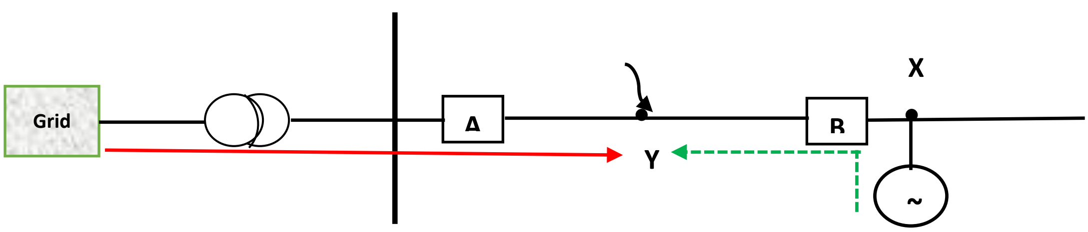

Figure 2.2: DG on the Downstream Feeder

2.3 Coordination Problem and Formulation

The main objective of the thesis is to optimize the protection coordination of relays installed at various location of the distribution line. In this thesis the location where the possible DG is connected is taken as the individual node/bus bar. At each node the Directional under Voltage Relays (DUVR) are considered to be installed.

For the coordination problem, the main task is to calculate the TDSs and constant parameter ‘m’ which would minimize the operating times of the relays. Therefore, the total operating (tripping) time of all relays for particular distribution network in any operating mode should be an optimally minimum as given by equation (2.1)

$$\text{i.e. Objective Function, } OF = \min \sum_{j=1}^{n} t_j \quad (2.1)$$

This objective function shows that it consists of the relays characteristics of the ‘n’ number of primary relays for the calculation of the relay operating time and this should be minimum as far as possible with not violating the possible constrained imposed in the relay characteristics. The possible constraints that apply in relay coordination in this study are as follows:

2.3.1 Coordination Criteria

It is a general practice that every primary protection has at least one backup protection for operating that system when the first system that has to be operated, fails. So there must be logical time difference in operating the two protective systems. When a predefined time difference between primary protection and backup protection lapses, then the backup protection operate. This time difference chosen so far is called the coordination time interval, (CTI) which is represented by equation (2.2)

The CTI depends up on the type of relays i.e. weather it is electromechanical based or it is micro-processor based. It also depends upon the speed of the circuit breaker designed for and in many others system parameter. The relay system used in this thesis research is micro-processor based. The typical value of CTI for micro-processor based relays found in literature lies in between 0.1 to 0.2 second as the speed of micro-processor based relay is very fast due to the absence of moving part in the system.

$$t_{j+1,m} - t_{j,m} \geq CTI \quad (2.2)$$

Where $t_{j+1,m}$ is the operating time of first backup relay when fault occurs at point ‘m’ in the system, $t_{j,m}$ is the operating time of primary relay when fault occurs at point ‘m’ in the system.

Mathematically, this constraint is inequality constraint for solving the optimization problem.

2.3.2 Relay Operational Characteristics

The proposed relay is based on the fault voltage measurement. The relay operating time is the function of faulted voltage at relay position. Independent of the DG type and fault condition, closer a bus to a fault has lower magnitude and voltage magnitude rises by increasing the distance from the fault location. A simple distribution system with penetration of distributed generation is given in Figure 2.3.

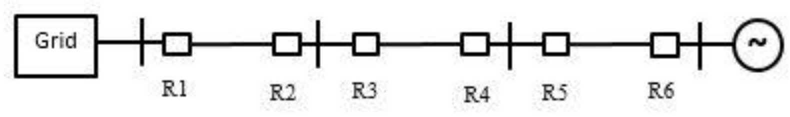

Figure 2.3: A Simple Radial Distribution Line with DG at the End

The first term deduced for the relay characteristic is the 'k' term which is given by equation (2.3)

$$k = \left(\frac{v_{sc}}{2} * \left(1 - \frac{v_{sc}}{2} \right) \right)^m \tag{2.3}$$

Where, v_{sc} is the fault voltage measured at any nodes whose value is taken in per unit basis. For constant value of m, the effect of variation of fault voltage in k-term is given by Figure 2.4

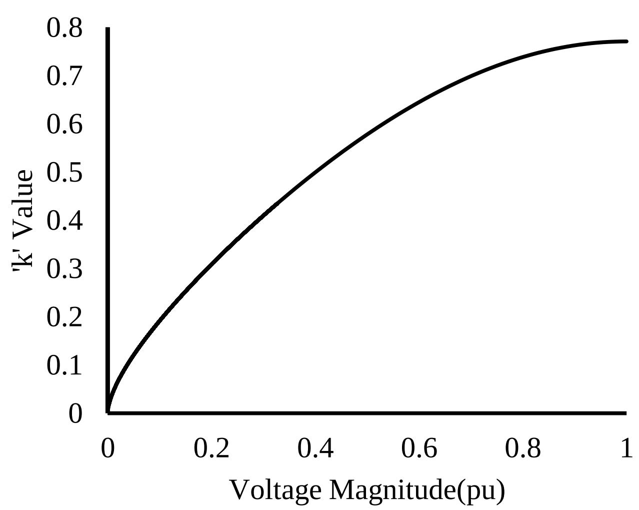

Figure 2.4: k-term of Relay Characteristics with Voltage

During the fault, the variation of fault voltage at measured position may be from 0 to 1.73 per unit depending upon the short circuit fault types and mode of grounding in the system. So from Figure 2.4, it is seen that the 'k' value increases as the voltage increases for constant value of 'm'. From the equation 2.3, it is seen that for 0 value of 'm' the resulting value of 'k' would be 1. That means there would be no meaning of taking the fault voltage. So from this concept it can be said that, to take the effect of fault voltage to determine the relay operating time, the value of the 'm' cannot be zero. Similarly, the value of 'k' can never be 1. It will be always less than 1.

The effect of variation of 'm' parameter in k-term is given in Figure 2.5. Here, as the value of m increases the k-term decreases.

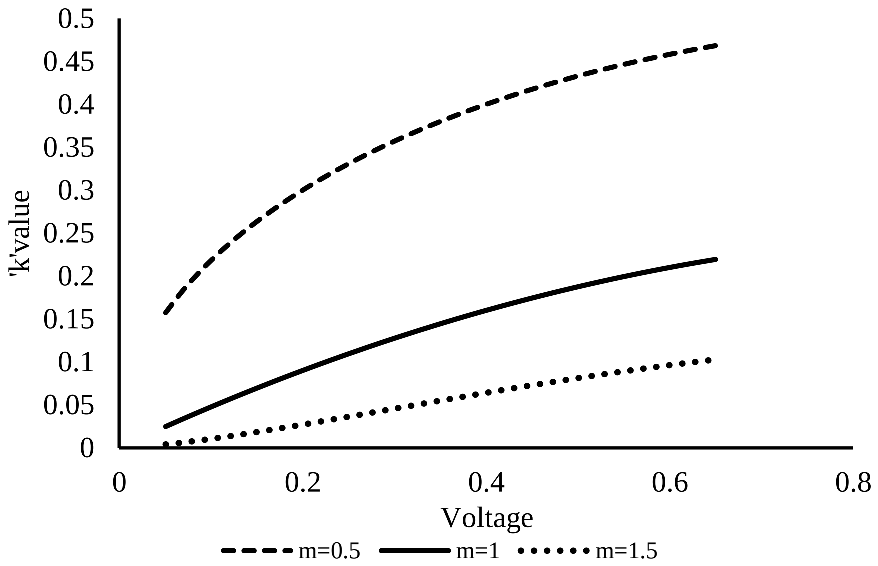

Figure 2.5: k-term Variation with Different Values of 'm' Parameter

A voltage based characteristics can be found that can respond to small changes in the voltage magnitude during a fault, then it can be used for relay coordination.

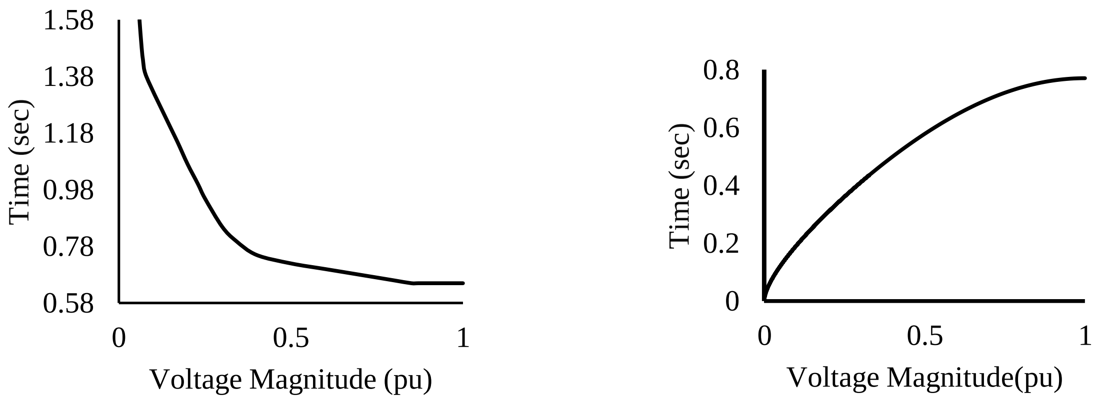

Figure 2.6: IEC Characteristics Curves of Voltage and Time

The presented characteristics is in the form of product of the standard characteristics IEC standard time current characteristics and the standard logarithmic overcurrent characteristics commonly used for fuses. The difference is that instead of current the inverse per unit voltage is used. The IEC characteristics curve with $(1/v_{sc})$ instead of Isc is shown in the Figure 2.6. In Figure 2.3, if a fault occurs in the line R3-R4 then the relay R3 will operate as primary protection. If R3 fails relay R1 will operate as backup protection. Here the relays R1, R3, R5 are forward relay and relays R2, R4 and R6 are reverse relay. So the voltage at each relay position is continuously measured and the relay operating time will be calculated at each relay such that for fault in between R3-R4 , the relay R3 will have faster operating time than relay R1. It can be seen that slope in the first curve of Figure 2.6 is positive low at low voltage. Also the characteristics of fuse with respect of $(1/v_{sc})$ given in second curve has very high negative slop at low voltage.

Now by multiplying the two curves given in Figure 2.6, a new curve will be obtained which represents the relay characteristics of the novel voltage based relay. The graphical comparison between the conventional over current relay characteristic and the presented novel voltage based relay characteristic is given in Figure 2.7 and Figure 2.8 respectively.

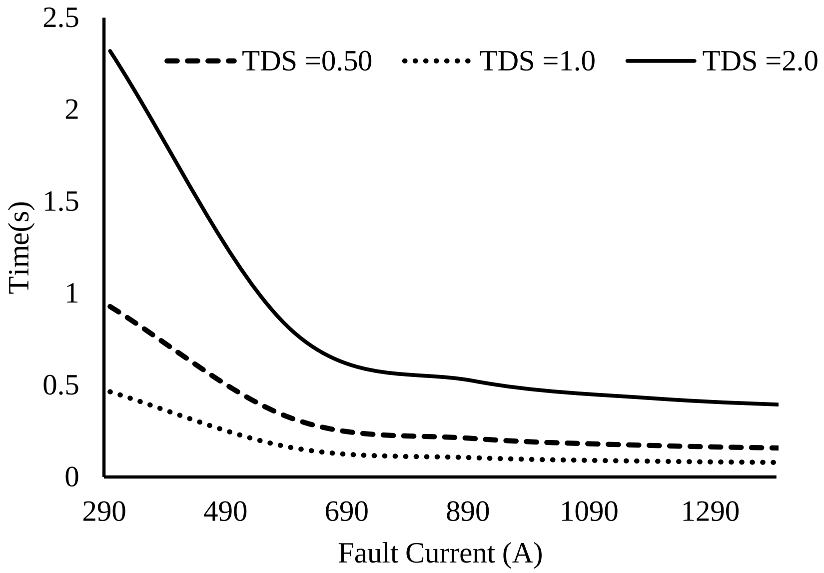

Figure 2.7: Inverse Current Based Relay Characteristics

Now if the two relay characteristics are compared the relay operating time depends upon the fault current and the time decreases as the fault current increases in the conventional relay system as shown in Figure 2.7. However, in voltage based relay, the relay operating depends upon the fault voltage and higher the amount of fault voltage drop faster will be the relay response to operate as shown in Figure 2.8.

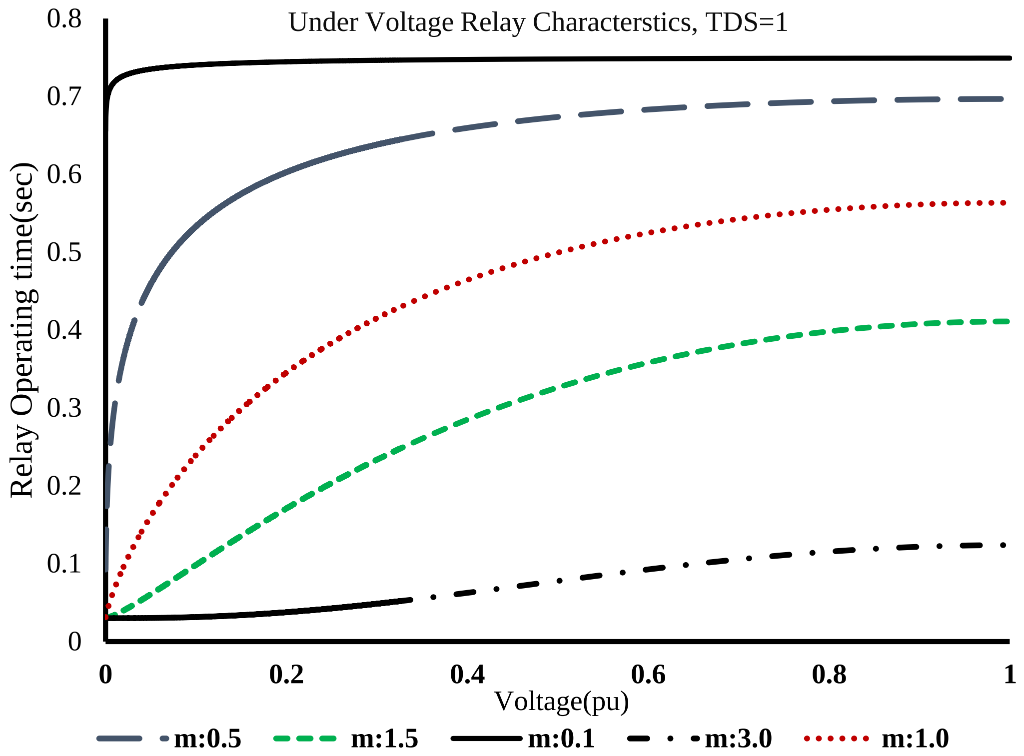

Figure 2.8: Voltage Based Non-Standard Relay Characteristic

From these two graphs it is seen that during the protection coordination the large current in the order of kilo ampere should be dealt with for calculating the relay operating time. However in voltage based relay, only the voltage magnitude of 0 to 1.0 pu for calculating relay operating time. This is found to be logical as the relay near to the fault location has very low voltage and there is good time discrimination even for small voltage difference.

The nature and slope of the curve at low voltage depends upon the value of k and relay setting parameter TDS. So the best value of k and TDS for each relay has to be determined to minimize the total tripping time of relays.

$$t = TDS * \frac{A}{\left(\frac{1}{k}\right)^{p} - 1} * \log_{2}\left(\frac{1}{k}\right) * \left(\frac{1}{k}\right) + D \tag{2.4}$$

Where, ‘A’ and ‘p’ are the constant parameters

The equation (2.4) is the final relay characteristics for under voltage based relay used for relay coordination in distribution network. The equation mentioned above is the non-linear equation. In the domain of study, the entire relay is assumed to be identical representing this relay characteristic. In this equation time dial setting (TDS) and the constant parameter ‘m’ are the decision variables whose values has to be optimally determined. Therefore each relay consists of two decision variables.

There are operational and designed constraints on this equation while solving the coordination problem. Therefore the problem is constrained non-linear optimization problem (CNOP). The key issue in the constrained optimization problem is to deal with the constraints.

In the above equation, 'A' and 'p' are the constant parameters. The value of 'p' is taken equal to 2 according to IEC extremely inverse characteristic. Here the constant parameter 'A' is directly multiplied with the equation, that means it has direct impact on the TDS. Therefore for the sake of simplicity, its value is taken 1. Here 'D' value is taken as 0.03 for the consideration of at least the operation time of circuit breaker.

2.3.3 Bounds on Time Dial Setting (TDS)

The relay characteristic chosen here so far is the static relay. So the values of TDS obtained from the optimization solution are on the continuous basis, not a discrete type. The values of time dial setting should be such that it should be limited to lower bound if it calculates the relay operating time below the lower limit or it should be limited to upper bound if it calculates the relay operating time above the upper limit as given by equation (2.5). The range of time dial setting, set in this thesis work is 0.001 to 3.

$$TDS_{\min} \le TDS \le TDS_{\max} \qquad (2.5)$$

Where, $TDS_{\min}$ is the time dial setting for lower limit.

$TDS_{\max}$ is the time dial setting for upper limit.

2.3.4 Bounds on the Relay Operating Time

When the fault is detected then it takes certain time for detecting, measuring, processing, deciding and sending command from the relay controller to the respective circuit breaker intended to operate. Also there is a minimum time for the operation of circuit breaker. Therefore, while designing the relay coordination these factors should be considered. It has been found that at least 30 millisecond is required for such type of delay work. It means the proposed relay operating time should be at least 30 milliseconds.

The maximum relay operating time that can be set depends upon the safe guard concept of every electrical equipment and component that will be imposed on the fault current. Every electrical component is designed to withstand the fault current in a certain period of time. If the fault is not cleared in the specified period of time then the electrical components may get damaged. If the fault current is higher the operating time of relay should be lower and if the fault current is relatively lower then slow response of relay may not damage the equipment. The damaging of electrical equipment from short circuit is the basis of Joule's law of Heating given by equation (2.6).

$$\text{Energy Dissipated, } E = I^2 * r * t \quad (2.6)$$

It means higher the fault current, higher may be the chance of damaging the equipment. At that time the relay operating time should be as fast as possible in order to save from being damaged. So the relay maximum operating time should be such that every electrical system should not be damaged for that magnitude of fault current under that time period.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 General

The outline of this thesis work begin from the literature review of the protection system, in which the method of protection in distribution system explored so far, their advantages and disadvantages, their scope, reliability of protection, degree of sensitivity and selectivity are studied. At the review stage, the impact of distributed energy resources (DERs) on the protection system of distribution network was investigated, the methodologies for the protection system study was sought, relevant research for the same was analyzed and the new aspect of the same has been tried to explore for the betterment of the protection system.

Line data, lump load data, generator static and dynamic data are collected from the various research papers for the purpose of testing the system under proposed. The various distribution line data with DG parameters are searched from the research paper published in popular technical professional organization like IEEE, IET, Science direct, and Research Gate etc.

At the preliminary stage, the proposed voltage based protection system has been tried to compare with the performance of the over current based protection system. For this the Canadian Distribution Network [4] is taken for the comparative analysis.

With the conclusion of preliminary study of the protection system that the voltage based protection system is far better than the over current based protection system in DS, the research has been moved forward to check the performance of PSO as optimization method on the same.

The short circuit analysis is done on the simulation tool and the required data are prepared for use in the coordination program. The PSO program has been coded in the MATLAB simulation tool, necessary debugging and testing were done, the result were compared, analyzed and finally came to stage of report preparation with acceptable conclusion.

3.2 Baseline in Moving to Voltage Based Method

Before moving to the performance analysis of PSO algorithm on voltage based protection method, as already mentioned above, one particular test feeder has been taken whose optimal protection coordination from over current based method was already done in [4]. Same feeder was used here but with the voltage based method. The Canadian Urban Benchmark 9 bus feeder distribution system of 12.47 kV feed by grid system of 500MVA and X/R equals to 6 is taken for the testing purpose. Here 4 DGs of capacity equals to 5 MVA each are connected at various nodes as shown in Figure 3.1. It consists of 16 directional relays which will be under voltage based in this study. The result of the work is compared with the result that was obtained from the over current based relay characteristics as in [4]. Here each line is considered to be 500 meter long.

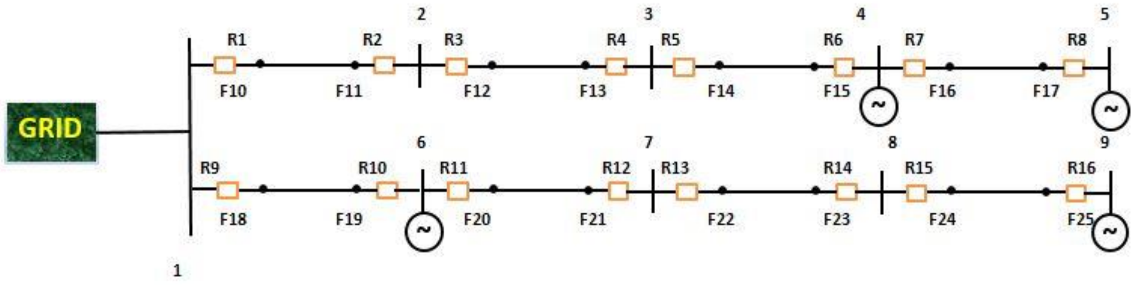

Figure 3.1: Canadian Distribution Network with Penetration of DG [4]

3.3 Fault Analysis

For the reliable coordination between the relays installed on the particular distribution network, the fault analysis should be carried out in an accurate manner. False analysis and taking of data may lead to mis-coordination between the relays. In this thesis research, since the protection system is based on the local fault voltage measurement on the relay location, the reliable preparation of fault voltages at various locations in the distribution network is necessary. The two distribution systems are modeled in a simulation tools for the study of effectiveness of the proposed relay system in relay coordination. The first system consists of 6 buses/nodes of low voltage distribution structure i.e.230/400 volt system. The distance between the buses is very close, in the order of meter.

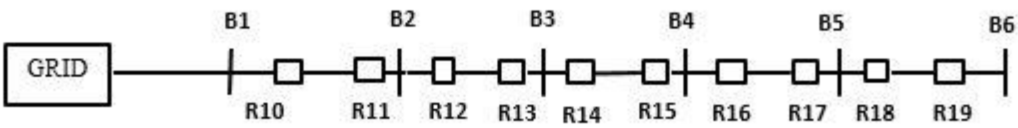

Figure 3. 2: SLD of Low Distribution with Six Nodes

At each node two relays are connected, forward relay and reverse relay. In the Figure 3.2, the relays R10, R12, R14, R16 and R18 are the forward relays as seen from the grid side and the relays R11, R13, R15, R17 and R19 are the reverse relays as seen from the end of the feeder. Now if the fault occurs, say, in line section B3-B4, then R14 will be forward primary relay and for this relay, R12 and R10 will be the backup relays. Similarly R15 will be the reverse primary relay and R17 and R19 will be backup relays for R15 if DG is connected at the end of the feeders. The system is simulated on DigSILENT Power Factory Tool and fault voltage data are prepared for the protection coordination. The fault voltages data are presented in the Annex (C). In this system the DGs are connected at each node and protection coordination is evaluated.

The second system consists of 95 nodes of MV distribution structure of 20kV. Figure 3.3 shows the reduced diagram of 95 nodes MV distribution system in which the line section between each node consists of multiple number of junction. The distance between the nodes in Figure 3.3 is in the order of kilometer. That means the protection system will be similar to zonal protection system holding the selectivity among the installed relays.

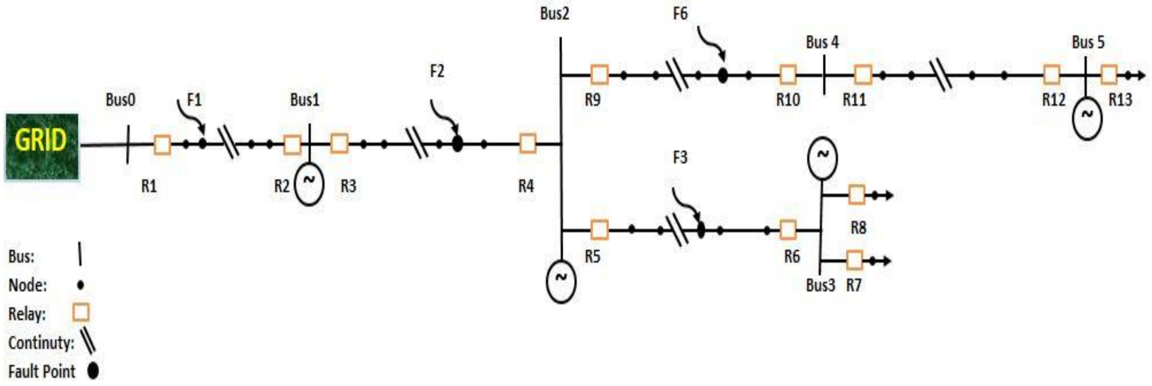

Figure 3.3: MV Distribution System with DG Penetration

One scenario of having the distributed generation connected at 5 nodes has been studied to check the effectiveness the presented relay characteristics using the met heuristic algorithm. Here the node at which distributed generation shall be connected are taken as bus as mentioned in the above figure. Both the synchronous based distributed generation (SBDG) and inverter based distributed generation (IBDG) are connected in the system.

The main idea in taking the fault voltage in the presented relay characteristic is based on the fact that under any fault condition, the bus closer to the fault location has lower fault magnitude and as the distance of fault location from the bus increases the fault voltage measured at that bus increases. This nature of fault voltage apply for all DS irrespective of fault type, fault location, fault nature, operating mode of distribution system, DG type, size and their location. This explanation is illustrated by Figure 3.4. In this figure the fault voltage variation is given according to the fault location variation from the particular buses. It has shown the fault voltage of two neighboring buses/nodes. It can be seen that two buses have very small fault voltage differences. This small fault voltage difference is used to calculate the operating time of the respective relay maintaining the selecting time interval between them.

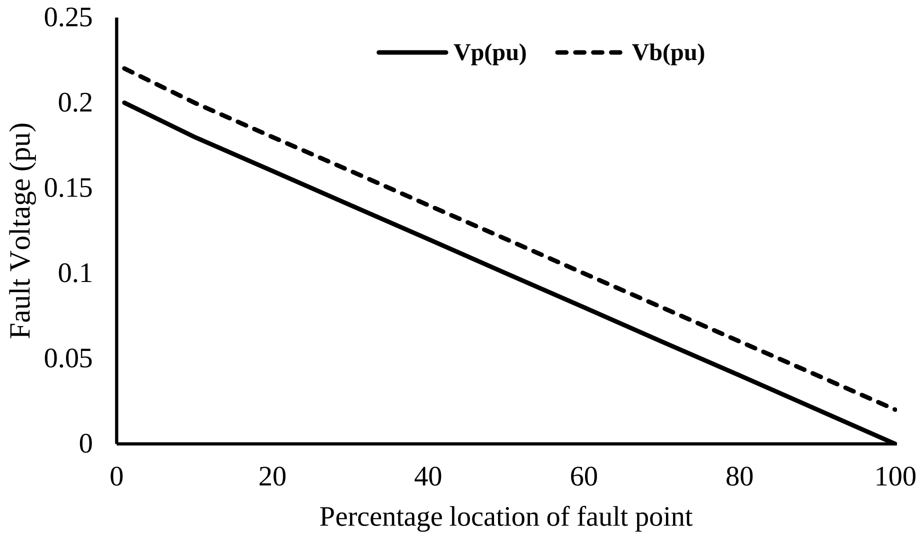

Figure 3.4: Variation of Fault Voltage of Simple Distribution System with the Length of any Line

The concept of preparing the fault data for optimal relay coordination is similar to the over current (OC) relays. In OC relay based system the TDS are determined for network operating condition producing the maximum fault current. However in this system the worst case scenario for the network is for producing the maximum voltage drop. In order to have the maximum voltage drop the distribution system should be in islanded mode, it should be supplied by the inverter based DG and the fault nature should be bold (solid) type. Therefor for determining the TDS of forward relay, the grid source is removed and at that point IBDG is connected. Similarly for determining the reverse relay TDS, the IBDG is connected at the end of the distribution system with grid source disconnected. The IBDG is capacity is chosen to supply all the loads in the DS.

The three phase short circuit fault with zero fault impedance is used for the preparation of fault data with the assumption that it will produces the maximum fault voltage drop in the system in comparison to other type of fault. The impact of load on the fault contribution is neglected here. The fault are created at near end and far end of each line section for low voltage distribution system and at near point and far point of each section for MV distribution system. The respective fault voltages for the relays are studied, analyzed and prepared for the coordination program.

The system will be checked for all types of fault including three phase bolted fault, single line to ground fault, double line to ground fault at any location of the network under study.

3.3.1 Short Circuit Analysis

Power system structure is designed not only for supplying of electrical loads safely and reliably, but also for adequate handling of short- circuits for intended period of time. After the definite time the components and structure of the system may get damaged. So, timely prevention of fault or isolation of fault from the healthy system is necessary. This brings out the concept of protection system.

To know the status of the power system, the information of value of current and voltage is needed. The nature, direction and magnitude of these two parameters determines whether the system is healthy or under the abnormal condition. Therefore the actual value of the real time current and voltage is necessary to protect the system under the fault condition. The value of current/voltage are the actuating quantity which determines which relay and at what time it has to be operated for safer operation of the system. Therefore short circuit analysis should be carried out on the system for designing the protection system of the power network before going in the implementation phase.

3.3.1.1 Assumption made on short circuit Analysis

The main simplifications of the method are as follows:

- Load currents are neglected, $I_{op} = 0$
- Nominal conditions are assumed for the whole network
- Loads are not considered in positive and negative sequence network
- To ensure that the results are conservatively estimated, a correction factor, c, is applied to the voltage at the faulted bus bar. This factor differs for the calculation of the maximum and minimum short circuit currents of the network.

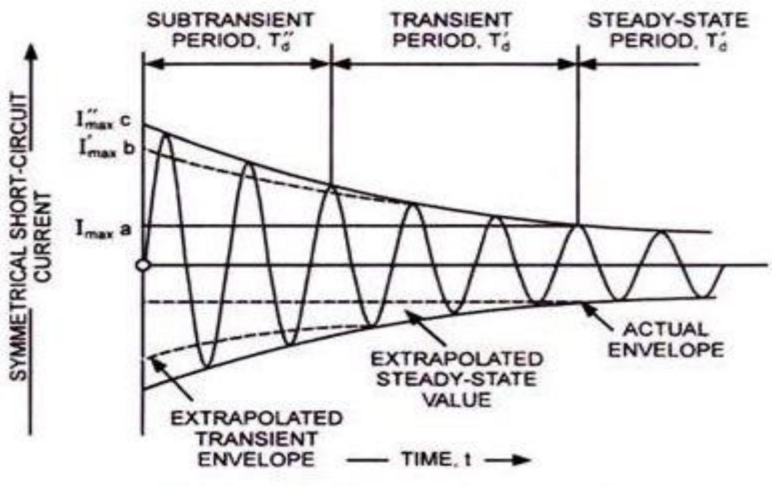

Figure 3.5: Oscillogram of symmetrical short circuit current [21]

The method mentioned here can be used for all type of short circuit analysis which include three phase short circuit, three phase to ground short circuit, single line to ground short circuit, double line to ground short circuit, single line to neutral short circuit and many more.

3.3.1.2 Equivalent Voltage Source Method

The current If flowing into a fault is essentially calculated using traditional circuit analysis by considering an equivalent network consisting of the Thevenin equivalent impedance Z_{th} of the utility grid, the fault impedance Z_f and the pre-fault line-to-earth rms voltage V_0 at the fault location as shown in figure below.

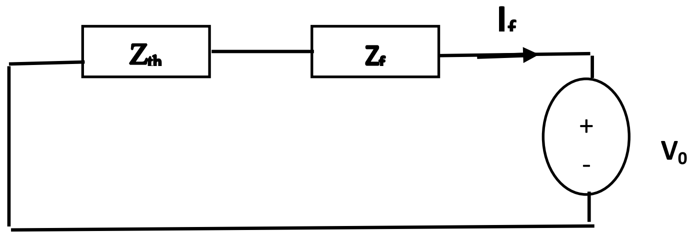

Figure 3.6: Equivalent Circuit of Faulty Network

From the resulting equivalent network, the rms fault-current can be calculated as per equation (3.1):

$$I_f = \frac{v_o}{(z_{th} + z_f)} \tag{3.1}$$

The network equivalent impedance z_{th} is the total equivalent impedance between the fault location and the common reference node, which in most cases is earth.

In transmission network fault studies, line resistance is sometimes neglected but normally the ratio of reactance to resistance X/R is used to determine the peak asymmetric fault-current. The X/R ratio can be found from the complex Thevenin equivalent impedance $Z_{th} = R_{th} + jX_{th}$ as the fraction of a circuit equivalent reactance X_{th} into its equivalent resistance Rth. Transmission networks typically exhibit high X/R ratios due to the inductive nature of transmission lines whereas distribution networks tend to have a much lower X/R ratio.

3.4 Block Diagram of Research Methodology

As explained clearly in section 3.2, the voltage based protection system is compared with over current based method in distribution protection system with DG. After the logical comparison, the work is carried out on solving the coordination problem optimization using the particle swarm optimization, a Meta heuristic technique for the determination of optimal relay setting parameters of the proposed relay characteristics. The obtained data will be logically compared with the literature data. To accomplish such task, the following is the overall task/methods that need to be proceeds.

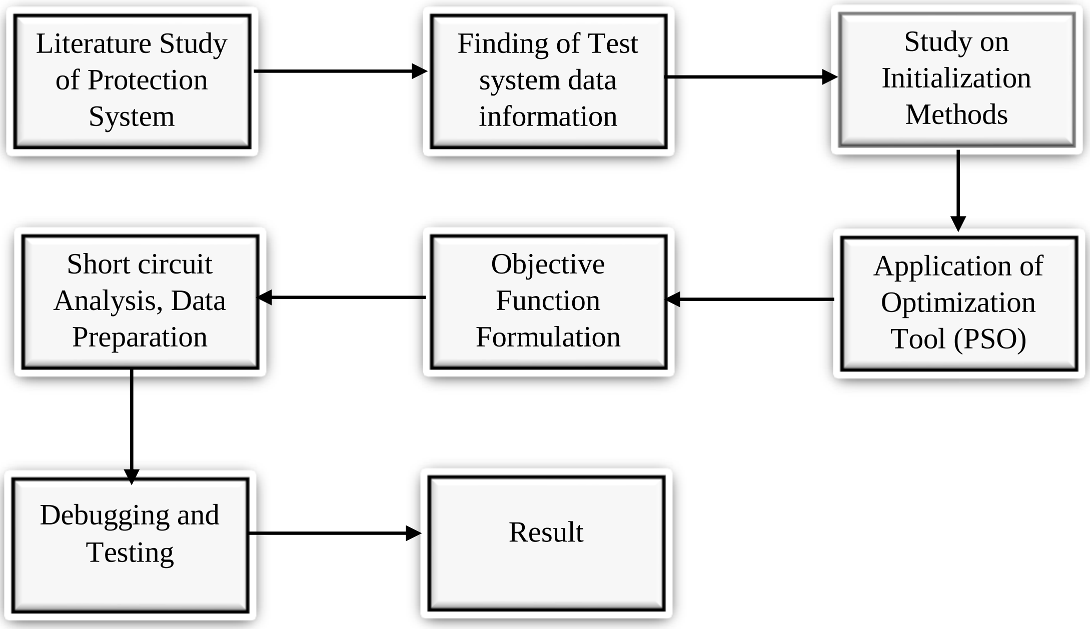

Figure 3.7: Block Diagram of Methodology

3.5 Simulation Tool

DigSILENT Power Factory (Digital Simulation of Electrical NeTworks) is a computer based engineering tool for the analysis of transmission, distribution and industrial electrical power network systems [26]. It is an interactive and advanced integrated software tool for electrical engineers and researchers for the planning of the power system and for the operation optimization. It consists of various function related to electrical engineering like integrated interactive single line graphic and data case handling, line and machine parameter calculation based on geometrical or nameplate information, power system network analysis with interactive or online SCADA access, generic interface for computer based mapping systems, eg. MATLAB, and many more.

This thesis is basically related to protection of the relays. So the load flow section, short circuit analysis section and protection section will be quite helpful to generate the intended data for the optimal coordination of the relays in distribution networks.

The reliable data required for the thesis purpose is the fault voltage at the relay position. So, DigSILENT Power Factory is especially used for the short circuit analysis purpose in this thesis. It is necessary to prepare the fault data from this tool. Therefore the learning of short-circuit analysis part is one of the important work in the thesis. The reliable and good data for the intended distribution network is must for better determination of the time dial setting.

The DigSILENT power factory has the provision of short circuit analysis. Some of the standards that are available in DigSILENT power factory for short circuit analysis include IEC 60909/VDE 0102, ANSI, IEC61363 and many more. The short circuit calculation in this tools is able to simulate the single faults as well as multiple faults of almost unlimited complexity. The short circuit analysis can be done in both system operation and system planning.

During the planning condition the simplified methods that the DigSILENT power factory employs are the IEC and ANSI standards. The method is based on the equivalent voltage source at the fault location. It will calculate the various parameters of the short circuit current. The initial symmetrical short-circuit current (rms) will be used for analysis purposes. And the respective fault voltage at that duration will be used for the relay coordination.

The IEC 60909 method is used in this thesis for the fault analysis purpose which uses an equivalent voltage source at the faulted bus and is a simplification of the superposition method. The aim of the method is to accomplish a close to reality short circuit calculation without the need for the preceding load flow calculation and the associated definition of actual operating conditions.

3.5.1 Reporting and Interpreting the Results

In the simulation tools, there is the facility of creating the fault at any point in the network i.e. it may be in any node/bur bar/junction and at any point in each line section. The fault parameters can be displayed in both the numeric values as well as in the graphical form. The software tools have the facility of Virtual Measurement Unit (VMU) through which any fault parameter for the analysis purposes can be obtained. The fault can be done in different way. That means it may be group fault or single fault. Electromagnetic simulation as well as rms simulation both can be carried out in this tool. That’s why the transient behavior of the fault at any points can be seen.

The result of load flow or short circuit of any simulated network can be taken out in the form of report. It will help in easy documentation. The detailed data of the network components can also be get in the standard format. Various parameters in bar chart format also can be obtained. Lots of variable are available in the tools for getting the result. The software tools is very informative and user friendly for electrical network simulation studies.

3.6 Requirement of Data

Technical data are required while performing the short circuit analysis. In this study, the simulation tool requires the following data for short circuit analysis.

3.6.1 Distribution Line Parameter

The technical data regarding each line section, node, bus, and transformer are needed to be specified in the editor option of the simulation tool. These data are required for steady state analysis and transient analysis. It must include:

- Branch Z, R, X, X/R values and corresponding units, tolerance and temperature if applicable.
- Transformer rated kV, kVA/MVA, OLTC, transient reactance, No load loss etc.
- Length of each line section and units
- Type and kV of each node/bus bar.

3.6.2 Synchronous Generator Data

The data required for normal load flow and short circuit analysis, in case of synchronous generator data are:

- Rated kV
- Dynamics data e.g. transient, sub transient data for S/C analysis.
- MW and MVar Loading of generator
- Operating mode of generator (swing, voltage control or MVAR control).
- %V, MW loading, and MVar limits (Qmax & Qmin) for voltage control mode of operation.
- %V and angle for swing mode of operation.

3.6.3 Invertor Based Generator Data

The following data are required for normal load flow and short circuit analysis, in case of IBDG;

- Rated kV, MW
- Dispatch mode, Bus type
- Active power operation limit

- Sub transient short circuit level

Here the static converter fed drive (SCFD) is selected for the contribution of fault.

3.6.4 Static Load Data

The data required for load flow and transient calculations for static loads includes:

- Static load ID
- Rated kVA/MVA and kV
- Power factor
- Loading category ID and % loading
- Equipment cable data

3.7 Optimization Method

The introduction of distributed generations to the distribution network and the recent drive towards the smart grid makes it to transform the radial distributed networks into a meshed structured resembling somehow the interconnected system. The occurrence of fault on such system will cause the bidirectional flow of fault currents. This might makes the coordination among the respective relay to be failed. As the size of such distribution network increases, the coordination problem might be even more complex.

One of the most popular methods for solving such kind of problem found in the literature is the use of optimization methods. The optimization methods are the mathematical solution technique that can either maximize or minimize the value of objective functions. In relay coordination problem, off course it will be the minimization of objective function satisfying the possible constrained imposed on the operation phase of the system. Therefore the main objective is to achieve the minimum possible tripping times of all the primary relays by obtaining the optimal settings of each directional relay elements. In our scope the directional relay element is the voltage based directional relay (DUVR). Many number of algorithm including mathematical programming, meta-heuristic optimization technique, such as particle swarm optimization (PSO), evolutionary algorithm such as genetic algorithm (GA) , artificial neural network (ANN), Monte Carlo simulation, firefly algorithm (FA), modified adaptive firefly algorithm (MAFA), Cuckoo search algorithm (CSA) and many evolutionary methods have been proposed to solve the complex protection coordination problems.

3.7.1. Particle Swarm Optimization

Particle swarm optimization (PSO) is a population based stochastic optimization technique developed by Dr. Jamesh Knnedey (Social-psychologist) and Dr. Russell Eberhert (electrical engineer) in 1995, inspired by social behavior of bird flocking or fish schooling. It is based on the movement and intelligence of swarm. One of the main advantages of PSO is that it needs no gradient information derived from the objective function.

The main idea of PSO algorithm is to maintain a population of particles, referred to as swarm where each particle represents a potential solution to the objective function under the consideration. Each particle in the swarm memorizes its current position that is determined by evaluation of the objective function.

3.7.2 The Particle Swarm Optimization for Unconstrained Optimization

Initially the algorithm is developed and tested for the unconstrained mathematical optimization problem. During the execution time i.e. iterations in the optimization context, each particle possesses a velocity vector that is a stochastic combination of its previous velocity and the distances of its current position to its own best ever position and to the best ever swarm position. The weight of the two directives are monitored and controlled by the special parameters. They are called the cognitive parameter and social parameter.

The PSOA belongs to the class of stochastic algorithm for global optimization and its main advantages are the easily parallelization and simplicity. It seems to perform the genetic algorithm for some difficult programming classes, usually the unconstrained global optimization problems. Besides these advantages, the algorithm has some drawbacks. It mainly depends on the parameters used in the algorithm and the slow convergence rate in the vicinity of the global minimum.

As already discussed, the algorithm preferred here is a population based optimization algorithm each particle is associated with the velocity that indicates in which direction the particle is travelling.

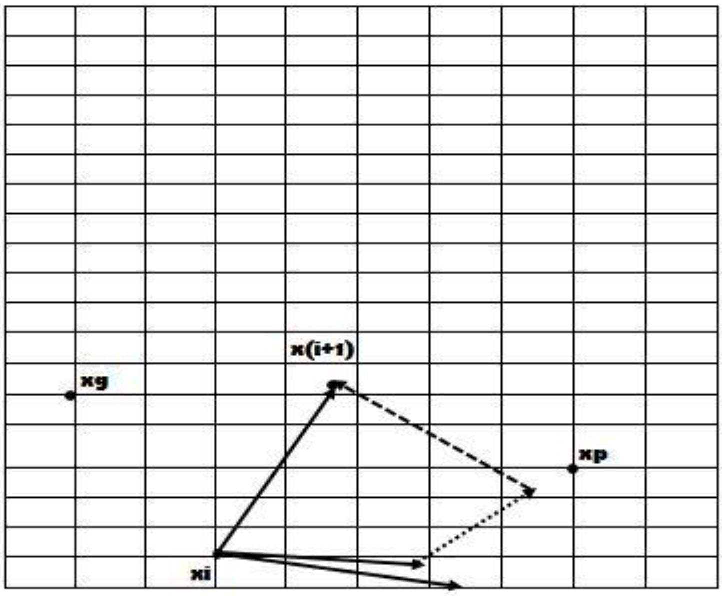

Figure 3.8: Vector Representation of How the Particle Position are Updated

Suppose t be a time moment, the new particle position is computed by adding the velocity vector to the current position of the particle given by equation (3.2).

$$X^{p}(t+1) = X^{p}(t) + V^{p}(t+1), \qquad (3.2)$$

Where, $X^{p}(t)$ is the current position of particle p. The p ranges from 1 to s at a time instant t, $V^{p}(t+1)$ is the new velocity at time t+1 with which the particle ‘p’ is travelling, s is the population size and $X^{p}(t+1)$ is the new updated position of the particle at time t+1. The velocity updates equation i.e. the second term in right hand side of the equation (3.2) is given by equation (3.3)

$$V^{p}(t+1) = W * V^{p}(t) + C_1 * rand() * \left(pbest - X^{p}(t)\right) + C_2 * rand() * \left(gbest - X^{p}(t)\right) \qquad (3.3)$$

where the first term in equation (3.3) represents the inertia of the particle. The value of ‘W’determines how fast the solution is converged to the final values and result the more accurate values. It simply determines the velocity factor of each particle. Higher values and lower value of ‘W’has its own benefits and drawbacks. The function given by equation (3.4) is usually used for the determination of ‘W’.

$$W = W_{\max} - \left(\frac{W_{\max} - W_{\min}}{Iter_{\max}}\right) * iter \qquad (3.4)$$

where W_{max} and W_{min} are the maximum and minimum weight values constants, iter is the iteration number whose value increases as the number of iteration increases, $Iter_{max}$ is the maximum number of iteration allowed for the execution of program.

The value of W regulates the tradeoff between the global and local exploration. A large inertial weight facilitates exploration while the small values tend to facilitate exploitation (fine turning) of the current position. A better value of the inertial weight provides a balance between the global and local exploration. From the equation (3.4) it can be seen that the value of inertial weight decreases as the number of iteration increases. It indicates that in the initial period of execution higher velocity is used to come close to the optimal values and during the last period velocity becomes smaller which helps in getting the more accurate optimal values. But the values of 'W' can be set as a constant value during the entire execution period of the optimization algorithm. It depends upon the nature of optimization problem that is going to be solved. So the value of 'W'

- Can be a constant value
- Multiplied with damping ratio in each iteration.
- Linearly decreased between W_{max} to W_{min}
- Set using constriction coefficient

The damping ratio W_{max} and W_{min} are user defined. Random value in equation (3.3) can be any value between 0 and 1.

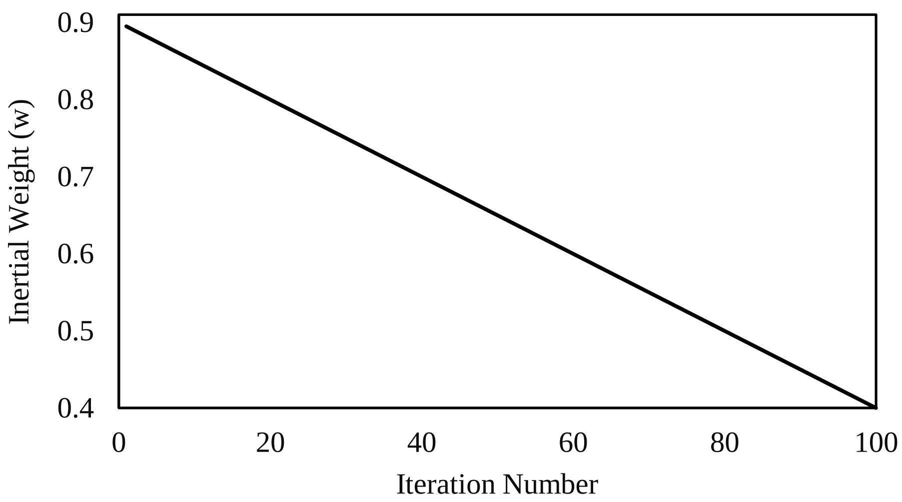

Figure 3.9: Variation of Inertial Weight (W) with Iteration Number

In some of the cases, during the velocity update process, the boundary condition on the velocity can be set as per equation (3.5);

$$|V(t+1)| << V_{max} \tag{3.5}$$

This equation represents the resolution with which the searching process will be done within the feasible region. It ensures not to escape from the boundary of feasible region. Choosing the higher values of V_{max} may make the particles to fly away from the optimal solutions. On the other hand, lower value V_{max} of may make the particle not to explore in a sufficient way which may cause the particle to stick in local optimal values.

In the equation (3.3), the second term represents the memory of the individual particles and the third term represents the social coordination between the particles. The second term determines the deviation factor of the position of the particle with its previous position and the third term determines the deviation factor of the position of the particle with respect to global best position of any particle. The constant C_1 and C_2 in this equation represent the acceleration rate that pulls each particle towards its local best and global best values. To get the optimal values, values of C_1 and C_2 has to be best determined. Clerk and Kennedy in 2002 AD define these parameters constriction coefficient as given by the equations (3.6) and (3.7).

$$\chi = \frac{2*k}{\left|2-\varphi-\sqrt{\varphi^2-4*\varphi}\right|} \tag{3.6}$$

Where, $0 < k < 1$, the value of k is commonly set to 1.

$$\varphi = \varphi_1 + \varphi_2 \geq 4 \tag{3.7}$$

Generally the values of φ_1 and φ_2 taken are 2.05 each.

The constriction coefficient rules tells that, $W = \chi, C_1 = \chi * \varphi_1$ and $C_2 = \chi * \varphi_2$. Various values of C_1 and C_2 and their impacts on the convergence and getting of optima can be summarized as follows;

S.N.	Parameter values	Output status
1	$C_1 = C_2 = 0$	The particle travel through its initial direction only until the boundary is reached.
2	$C_1 = 0$; $C_2 > 0$	The particle projected into one value and all particles converges to the single value which might not be optimal.

3	$C_2 = 0;\ C_1 > 0$	The particle projected in its own best value only in a search space.
4	$C_1 = C_2$	The particle is attracted towards average pbest and gbest
5	$C_1 >> C_2$	The particle attracted towards its pbest which results in excessive wandering.
6	$C_1 << C_2$	The particle attracted towards gbest and cause premature convergence towards optima.
7	Low values of C_1 and C_2	Smooth particles trajectories
8	High values of C_1 and C_2	Abrupt movements

The nature of velocity factor in graphical form can be represented as follows;

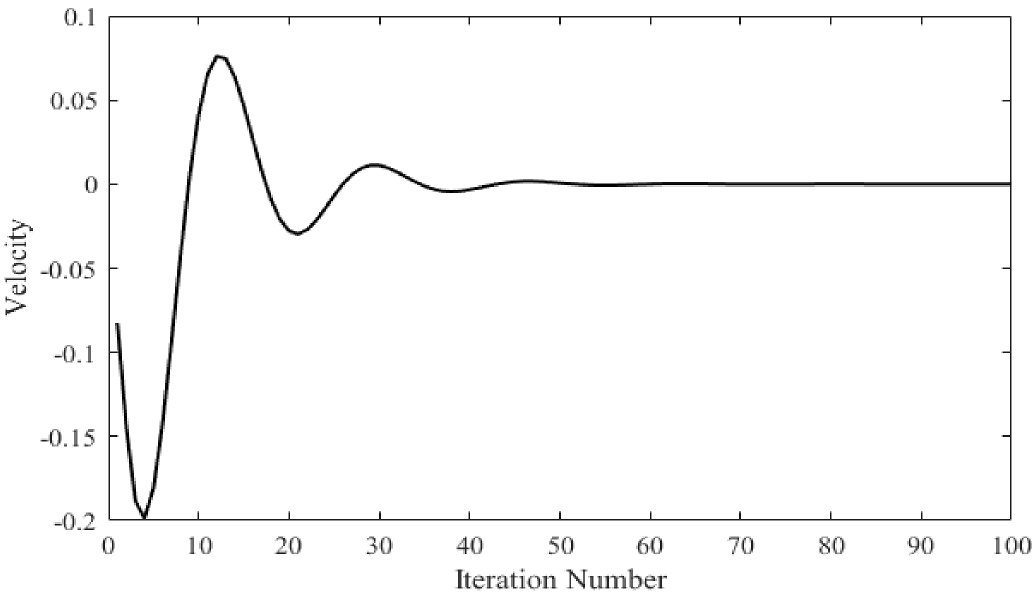

Figure 3.10: Nature of Updated Velocity in PSO with Respect to Iteration Number

The input to the algorithm is objective function, bounds on the decision variables from the problem statements. The others inputs are the parameter inputs of the PSO algorithm. The algorithm that can be used in the PSO can be presented as follows;

1. Randomly initialize the particle position, $X = \{x^1(0), x^2(0), x^3(0), \ldots\ldots\ldots x^s(0)\}$
2. Randomly initialize the particle velocity, $V = \{V^1(0), V^2(0), V^3(0), \ldots, \ldots V^s(0)\}$
3. Initialize the population size, generation number, $W_{\min}$, $W_{\max}$, C_1, C_2 and others parameters if any

4. Let at initial time $t = 0, y^p(t) = x^p(t), p = 1,\ldots,\ldots s$
5. For all p in {1, … … … … … , s}

   Calculate $f\left(x^p(t)\right)$
6. Do comparison with previous values for all p as;

   If $f\left(x^p(t)\right) < f\left(y^p(t)\right)$, then $y^p(t+1) = x^p(t)$

   Else set $y^p(t+1) = y^p(t)$
7. For all p in {1, … … … … … , s}

   Compute $v^p(t+1)$ and $x^p(t+1)$ using the equations (2.3) and (2.2)
8. If the stopping criteria are met then stop, otherwise set $t = t+1$ and go to step number 5.

The particle position may have number of components according to the objective function. The numbers of decision variable determining the value of objective function are treated as the component of particle positions. If $x_1, x_2, x_3, \ldots\ldots x_n$ are the decision variable of the objective function whose value has to be best determined, then n-Dimension of the decision variable exists with the vector size of 1xn. Suppose the population size in PSO as N_p, then the position vector for all the particles is given by (3.8);

$$\begin{bmatrix} x_{1,1} & \ldots\ldots & x_{1,n} \\ \ldots & \ldots\ldots & \ldots \\ x_{N_p,1} & \ldots\ldots & x_{N_p,n} \end{bmatrix} \tag{3.8}$$

The size of this vector will be N_p X n

The size of velocity vector of the swarm is also N_p X n.

For N_p number of population size, the objective function is given by (3.9)

$$\begin{bmatrix} f\left(x_{1,1}\right) & \ldots\ldots & f\left(x_{1,n}\right) \\ \ldots & \ldots\ldots & \ldots \\ f\left(x_{N_p,1}\right) & \ldots\ldots & f\left(x_{N_p,n}\right) \end{bmatrix} \tag{3.9}$$

The size of this matrix will be N_p X 1.

The global best value of the objective function is the minimum value of the matrix given by equation (3.9). The global best values of the particle position will be the value of decision variable in matrix (3.8) corresponding to the minimum value of matrix (3.9).

For T number of iteration selected for the algorithm, the number of times the objective function value will be determined $= N_p + T * N_p$

For same number of iteration, the number of times for which position component of particle updated $= T$

The stopping criteria generally used in PSO is related to the function value at global best solution. The algorithm stops if the maximum number of iteration allowed is reached or the value of objective function is now becoming very close to each other at every iteration satisfying the tolerable value. However the particles position governed by the equations (3.2) and (3.3) has no any guarantee that it will converges to its local or global optimum. This is because the global optimum is not known in advance and the stopping algorithm with maximum number of iteration reached may causes premature or too late termination.

Another logic for stopping the execution of algorithm may be checking of the magnitude of search direction i.e. velocity vector. It can be easily said that when the magnitude of search direction is approximately zero then further progress in the solution will not be possible. So when all the search direction is zero then the algorithm stops. Mathematically the algorithm execution stops if equation (3.10) becomes valid.

$$Max_{p\in\{1,\ldots\ldots,s\}}\left|V^{p}(t+1)\right| \leq \in \quad (3.10)$$

3.7.3 Particle Swarm Optimization for Constrained Optimization Problem

In the above algorithm, only the objective function is used to see if the new particle position is more favorable than previous one or not. That means it only focus on the minimization of the objective function whatever be the value of decision variable. But off course there are some bounds on the values of decision variable, some operational constraints imposed on the system. These constrained has to be addressed on the optimization problem to get the feasible solution in addition to get the optimum value of objective functions. In case of constrained nonlinear optimization problems (CNOP), it is the main issue to deal with constraints. During the initialization process of PSO, only the solutions that are within the feasible search space are used to initialize the PSO algorithm. So, initially interior point method (IPM) from the MATLAB tool can be used to get the initial feasible solution for large complex system having many numbers of variables. This is done by setting the ‘m’ parameter in the characteristics equation of relay randomly. In doing so, the problem now becomes linear and the TDS values are calculated using IPM. Then these initial feasible solutions are applied to PSO algorithm.

The second problem that may occur in the optimization of CNOP is that during the updating process of the particle position, the resultant position could be outside the feasible search space. This reduces the possibility of finding the optimal values or close to the optimal values.

To overcome from this type of problem, another modification on the algorithm can be made. The position of the particles is updated one after another, instead of updating the entire particle position in all D- dimensions at the same time.

3.7.4 Flow chart of PSOA

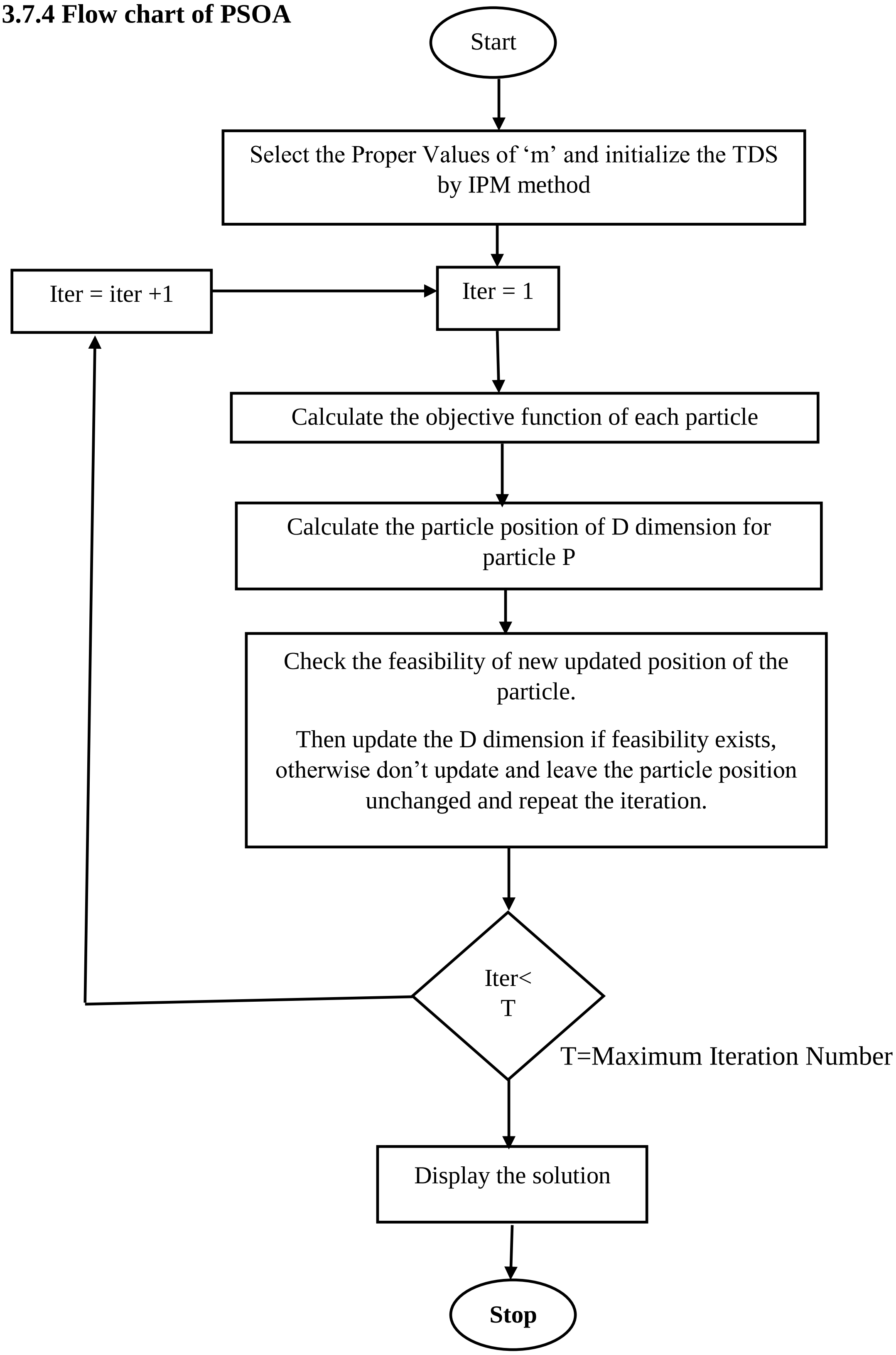

Figure 3.11: General Flowchart of PSO Algorithm for Coordination Problem

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Overview

This chapter gives the insight about the results and analysis of this thesis. As mentioned in chapter three, the particle swarm optimization algorithm is used as an optimization tool for relay coordination using the proposed new non-standard type voltage based relay characteristic. The general outlines of the result section are as follows;

- Result of over current based relay and voltage based relay coordination in the same distribution network is analyzed.
- The relay coordination program using the particle swarm optimization algorithm is developed.
- The effectiveness of the developed coordination program is checked on LV distribution system having 6 nodes with penetration of various types of DGs using the voltage based relay characteristics.
- Same PSO concept is applied on MV distribution system having 95 nodes with penetration of various types of DGs using the voltage based relay characteristics.
- Performance of optimization tool in relay coordination is analyzed.
- Finally the relay coordination between line primary relay and the backup relay at unit side is formulated.

Both the 6 node and 95 node distribution systems are modeled in the DIgSILENT simulation tool for fault voltage analysis. For each system, the required fault voltage data are prepared which are used, later in relay coordination program. Simulation is done for both islanded mode of operation and grid connected mode of operation. The optimal relay parameters and hence the relay operating times are determined for both mode of operation in each system.

The overall simulation study takes into account the some assumptions that are done in many research articles related to the optimal coordination of the relay. The assumption includes:

- ➢ Directional under Voltage Relay (DUVR) are placed at each end of each line section of the DS
- ➢ Network topologies are fixed; any contingencies including line outage, generator unit outage, transformer outage and utility outage are not considered. The main available network is considered unchanged for this study.

➢ Since the relay coordination optimization process is the offline assessment, the fault voltages for the primary relays and backup relays are predetermined. Far end fault, near end fault and middle point fault are usually taken for relay coordination. The three phase fault with zero impedance at the far end of each section is considered for LV and MV distribution system protection coordination for the sake of ease to compare with the literature.

4.2 Comparison of Over Current Based and Voltage Based Method

The single line diagram (SLD) of Figure 3.1 is modeled in DigSILENT Power Factory 15.1 version for the fault voltage analysis. The relay pair coordination for the same distribution network for near end fault case in each line section is shown in the Figure 4.1. It can be noticed that the coordination time interval of 0.2 second is holding for each primary and backup relay pair.

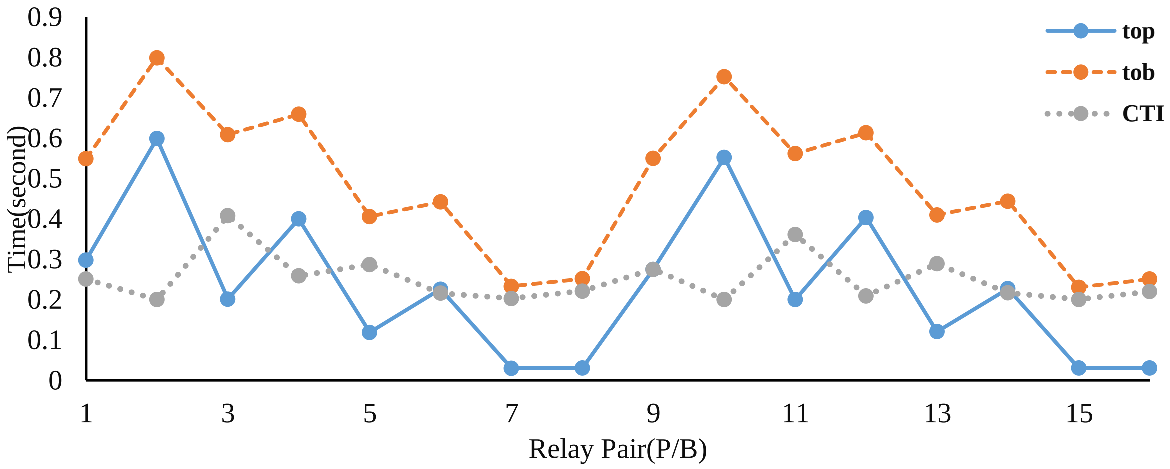

Figure 4. 1: Coordination of Relay Pair in Canadian Distribution Network

For the same distribution network with all technical data same, the sum of operating time of primary relays for near end fault not considering any contingencies in line/unit is equals to 11.239 seconds for over current based method of optimization [4]. The comparison for two methods is pictorially shown in the following bar chart, Figure 4.2.

From this method it is clear that the operating time for voltage based protection system is faster than the current based protection system in distribution network. For the faulty system, faster the relay operating time better is the protection system and hence less chances of any hazardous consequences in livestock and electrical components used in the distribution network. So the voltage based protection system is more preferable to use in the recent distribution system having penetration of distributed generation.

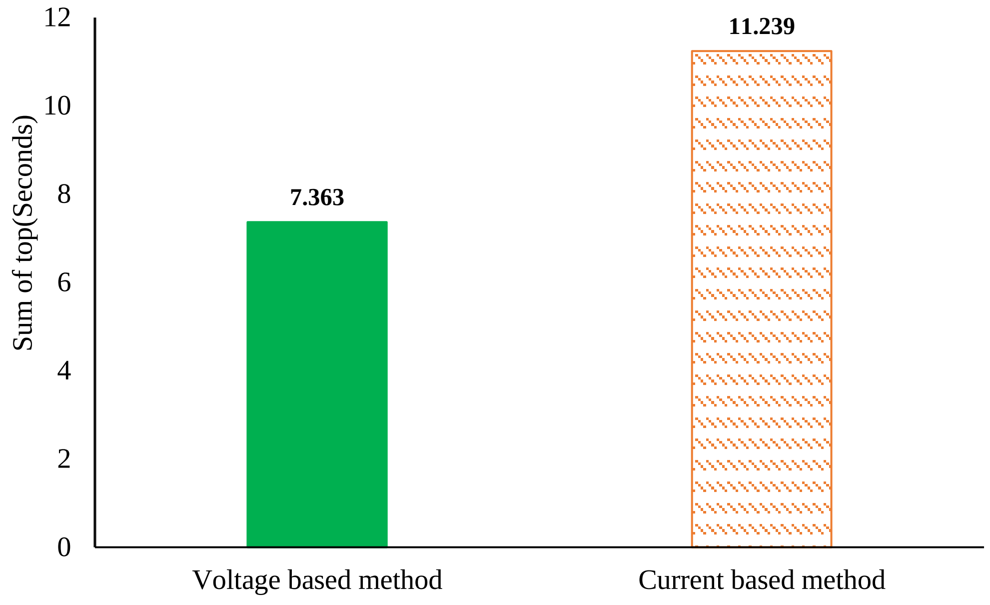

Figure 4. 2: Comparison of Voltage Based and Current Based Protection Method

4.3 Voltage Based Relay Coordination in LV Distribution System Using PSO

In this section, the PSO algorithm is applied to low voltage distribution system of 230/400 volt for relay coordination using the presented new relay characteristic. Here the distributed generation is penetrated at each node and the line distance from node to node is in the range of few meters. The data for the line are taken from [1] and PSO is applied to get the optimal value of the parameters of relay characteristics. The optimally obtained parameters are then used to determine the operating time of relays and the obtained data are analyzed. The modeling of low voltage distribution network with penetration of various DGs as shown in Figure 4.3 is done in DigSILENT Power Factory 15.1 for fault analysis.

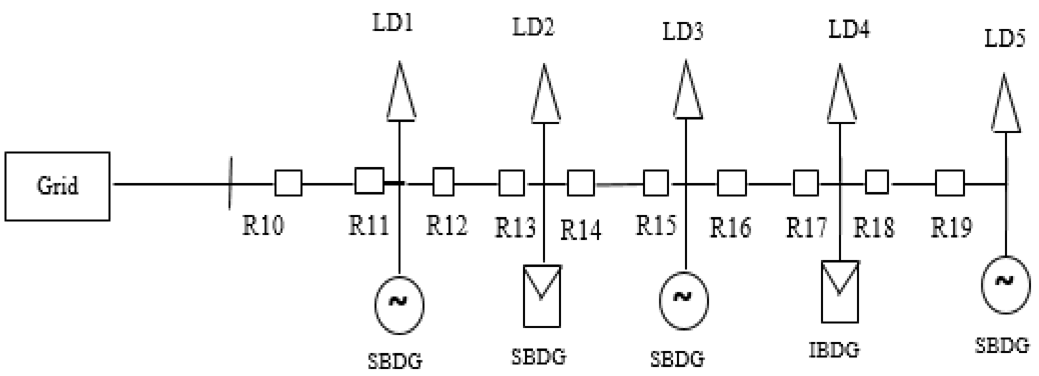

Figure 4.3: A Six Node LV Distribution Network with Penetration of DGs.

The primary relay operating time, backup up relay operating time and their coordination interval in two modes of operation for the low voltage distribution system are tabulated as follows.

Table 4.1: PSO Result of Relay Operating Time of LV Distribution System

Islanded Mode						Grid Connected Mode		
Line Section	Fault type	Relay	Tpri (sec)	Tbackup (sec)	CTI_IL (sec)	Tpri (sec)	Tbackup (sec)	CTI_G (sec)
L2, Midpoint	LLL	R13	0.1674	0.36938	0.20198	0.1620	0.38360	0.2216
		R12	0.2927	-		0.2300	0.50000	0.2700
	LLG	R13	0.1710	0.37654	0.20554	0.1570	0.35700	0.2000
		R12	0.5227	-		0.1600	0.49000	0.3300
	LG	R13	0.1680	0.37660	0.20860	0.1640	0.36560	0.2016
		R12	0.4600	-		0.1530	0.49000	0.3370
L3, Midpoint	LLL	R15	0.2197	0.43010	0.21042	0.2190	0.43000	0.2110
		R14	0.2903	0.52660	0.23630	0.1500	0.40000	0.2500
	LLG	R15	0.2351	0.44280	0.20772	0.2544	0.49000	0.2356
		R14	0.4097	0.73600	0.32633	0.1345	0.35400	0.2195
	LG	R15	0.2350	0.45000	0.21500	0.2780	0.53800	0.2600
		R14	0.3614	0.64500	0.28360	0.1848	0.38800	0.2032
L5, Midpoint	LLL	R19	0.3257	-		0.2900	-	-
		R18	0.0304	0.28663	0.25627	0.0308	0.25000	0.2192
	LLG	R19	0.3245	-		0.3370	-	-
		R18	0.0305	0.34880	0.31834	0.0308	0.24780	0.2170
	LG	R19	0.3258	-		0.0309		
		R18	0.0305	0.32400	0.29355	0.0304	0.28800	0.2576
PSO Result			4.6002	5.31400		2.9966	5.97200	

From the Table 4.1 it is seen that the coordination time interval holds the minimum limit of CTI for both mode of operating condition. Two mode of operating condition i.e. Grid connected mode and islanding mode are tested for the optimal values of relay parameters. The graphical representation of the relay coordination as in Figure 4.4 shows the clear pictorial view for better understanding.

The optimal values of relay parameters determined from the PSOA are presented in the Table 4.2.

Here the value of ‘m’ parameter for all the reverse relay is same which is equal to 0.5 and when the distribution system is operated for islanded mode the value of ‘m’ parameter is same for the entire relay. Similarly the TDS value is same for all relay irrespective of operating mode of relay. The value of ‘m’ parameter differs for forward relay when it is operated in grid connected mode.

Table 4.2: Optimal Values of TDS and m of LV Distribution Network

Relay	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19
TDS	1.6	0.002	2.1422	0.7391	1.6509	1.1278	0.894	1.7397	0.002	2.506
m_IS	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
m_Grid	1.779	0.500	1.3837	0.500	1.2757	0.500	1.0825	0.500	0.500	0.500

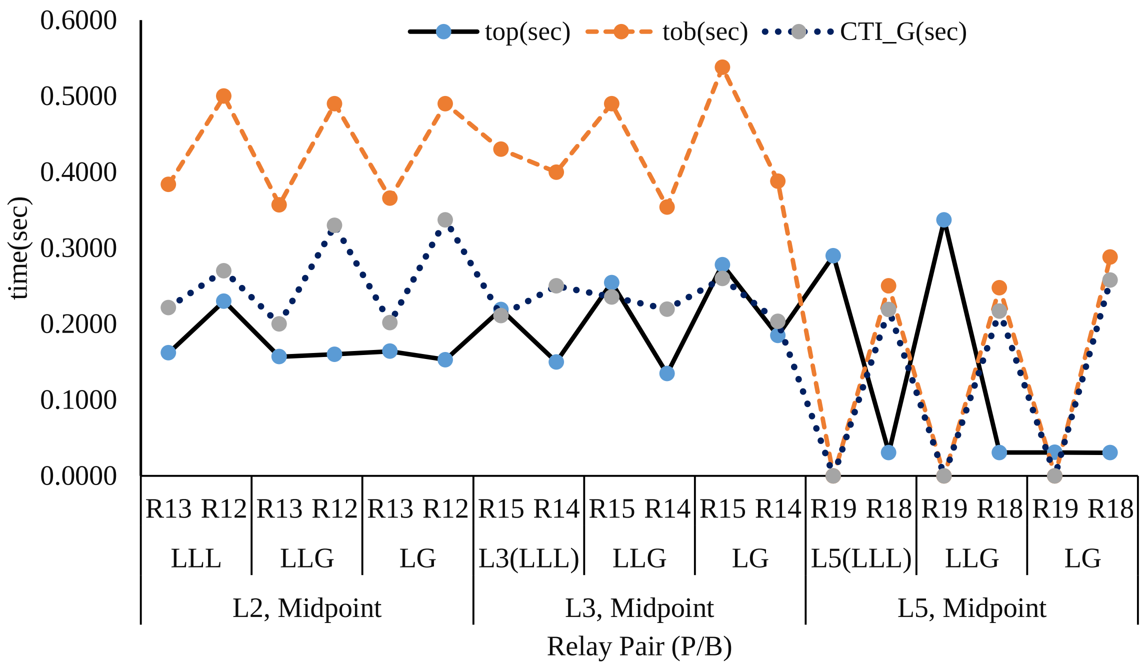

Figure 4.4: Relay Coordination for LV Tested Feeder in Grid Connected Mode

The PSO algorithm determines the sum of the operating time of primary relays for the fault location as mentioned in Table 4.1. It is equal to 4.6002 second for islanded mode of operation. Similarly, for grid connected mode of operation, the PSO algorithm gives the sum of primary relay time equals to 2.9966 seconds. So for LV distribution system of utilization voltage level, the voltage based protection with PSO algorithm gives the better result in relay coordination.

4.4 Voltage Based Relay Coordination in MV Distribution System Using PSO

In this section, the PSO algorithm is applied for the MV distribution system using the proposed new non-standard type microprocessor based relay for the relay coordination between the primary relay and backup relay of the line. Different types of DGs are penetrated at different location of the distribution system. The 20kV Iranian distribution system having the 95 nodes is taken for the testing of PSO algorithm for easy to compare with the data and result with [1] and other optimization tools. The modeling of the 95 node MV distribution system is done in DigSILENT Power Factory 15.1 for short circuit analysis purpose as in Figure 4.5 and to prepare the fault voltage data which are required for relay coordination program. The fault voltage measurement data for relay coordination of the various relay is provided in Annex (C). The line data and load data are provided in Annex (B). The coordination time interval between primary and backup relay, CTI is considered as 0.2 second. The value of 'm' parameter for all relays in islanded mode and for reverse relay in grid connected mode is selected properly to be 0.5. The population size N_p is chosen 5 and the maximum number of iteration, T is chosen to be 100. The test system consists of 13 directional relays, all having the same proposed relay characteristics. It has 16 number of primary backup relay coordination pair. For PSO algorithm, the summary of program parameter set is given in the Table 4.3.

Table 4.3: Tuning Parameters of PSO

S.N.	**Set Parameters**	**Values**
1	Inertial Weight, W	0.9
2	Personal acceleration factor, C_1	2.0
3	Social acceleration factor, C_2	2.5
4	Population size, N_p	5
5	Maximum Iteration Number, T	100

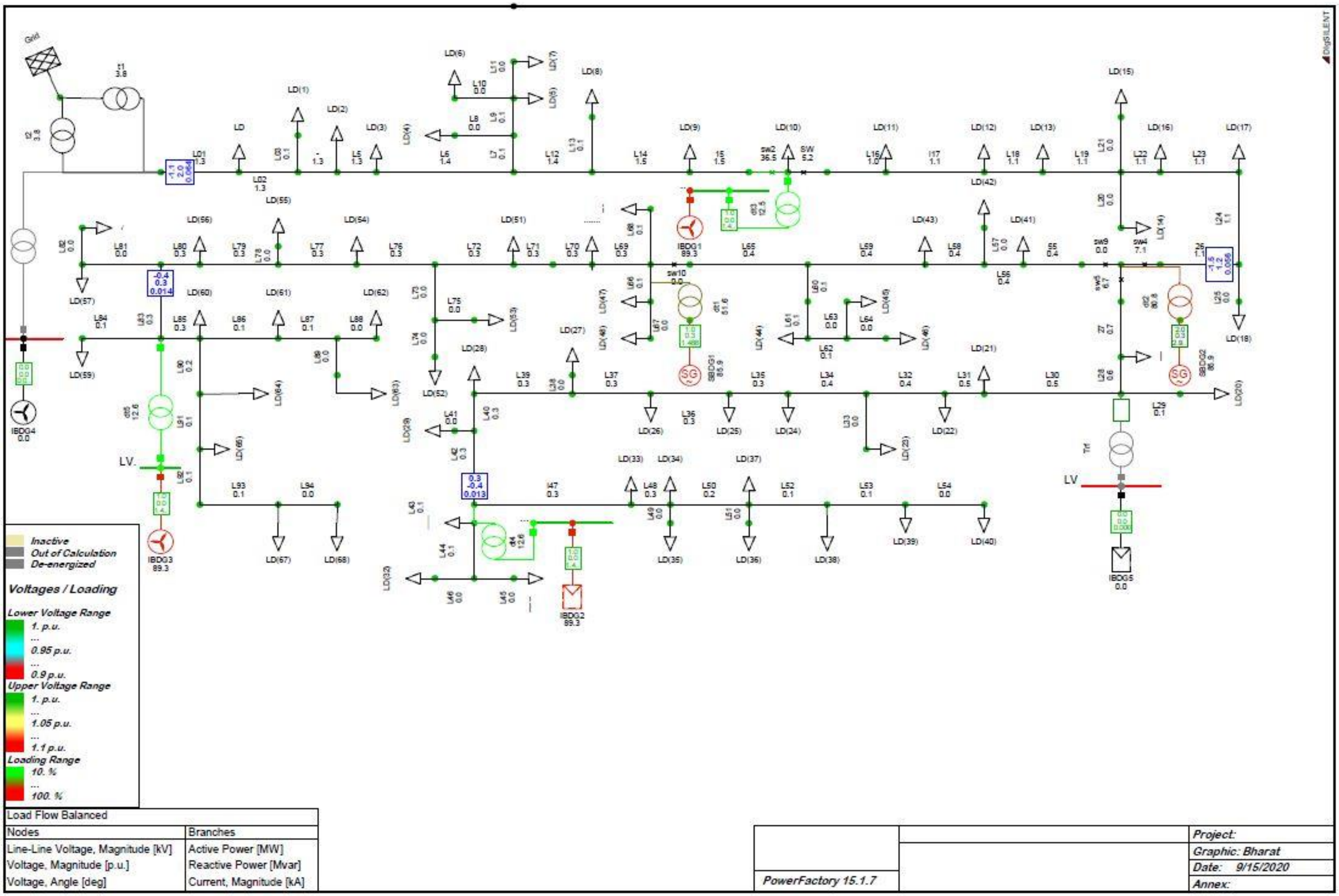

Figure 4.5: Modeling of 95 Node 20kV Iranian Distribution Network in DigSILENT Power Factory 15.1 for Fault Analysis

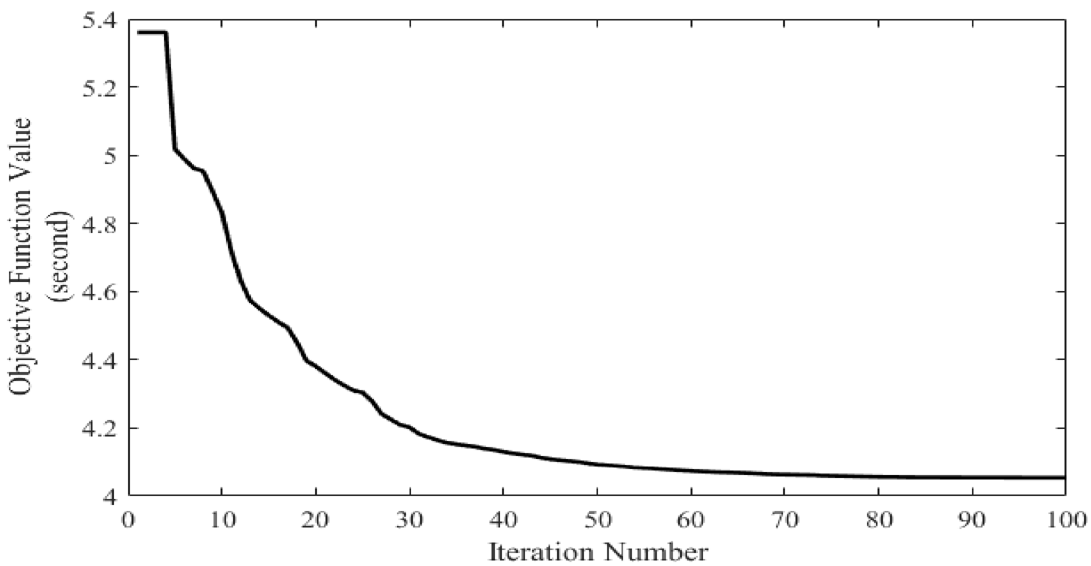

Figure 4.6: Objective Function Convergence Graph with PSO Algorithm

The Figure 4.6 shows the convergence of the objective function value of the PSO program. It is actually the sum of operating time of the entire primary relay for the particle which possesses this minimum value.

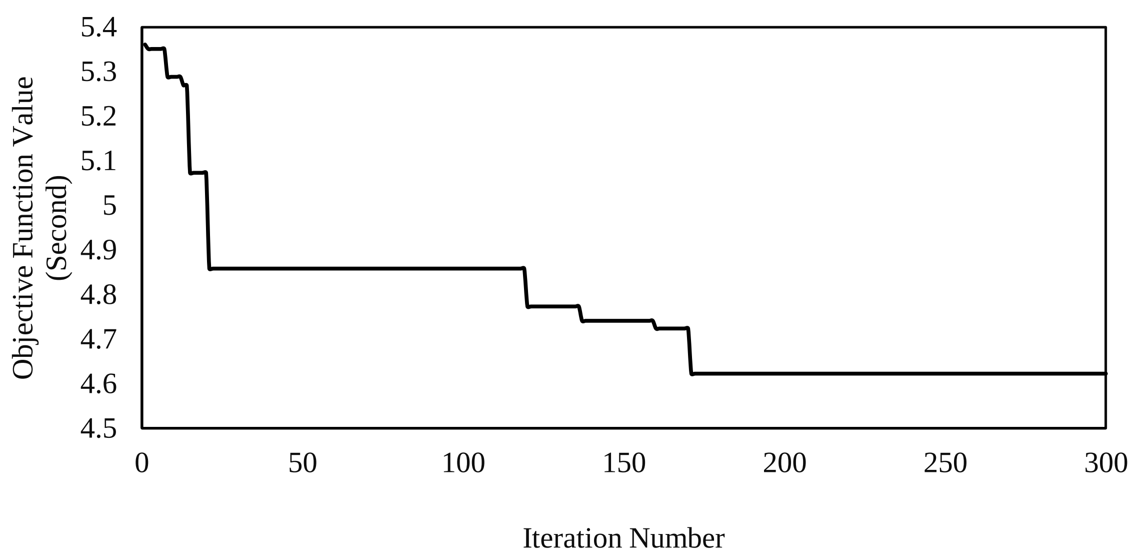

Figure 4.7: Objective Function Convergence Graph with FA Algorithm

The Figure 4.7 shows the convergence graph of objective function using Firefly algorithm (FA). The value is converges to the final value with almost zero error in the last consecutive iterations. From Figure 4.6 and Figure 4.7, it is clear that the objective function converges for

PSO algorithm is very smooth and converges to final value with less than 100 iterations. However, for FA algorithm the objective value is converges to final value after the 190 iterations. The second point to be noted here is that the final convergence value is less than 4.2 second with low number of iteration for PSO algorithm and the same for FA is more than 4.6 second with larger number of iterations. So the convergence rate for this type of system is fast for PSO in comparison to FA.

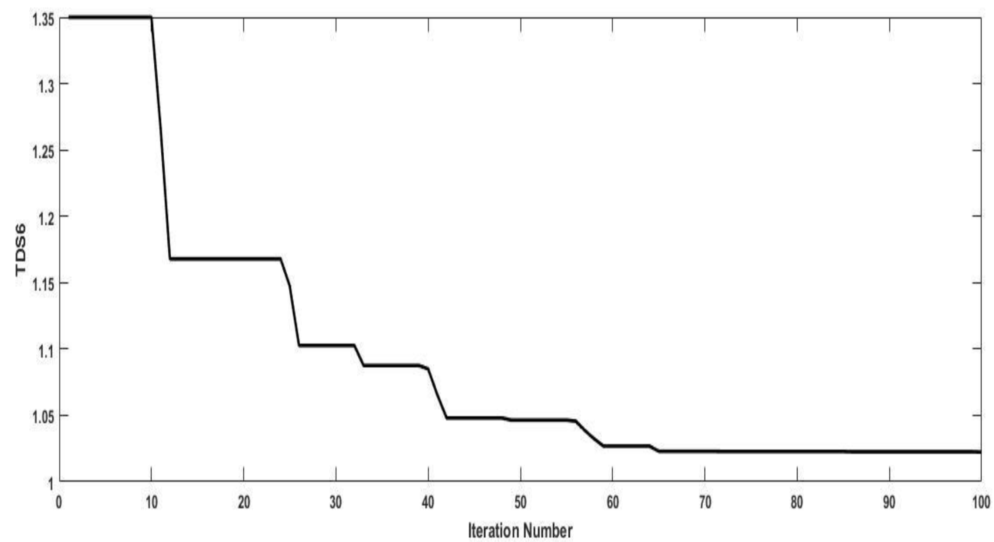

Figure 4.8: TDS Value Convergence with Iteration

Figure 4.8 shows the convergence of time dial setting of reverse relay number 6 of 95 nodes MV distribution System. From the figure, it is seen that TDS value converges to the final value in less than 70 iterations.

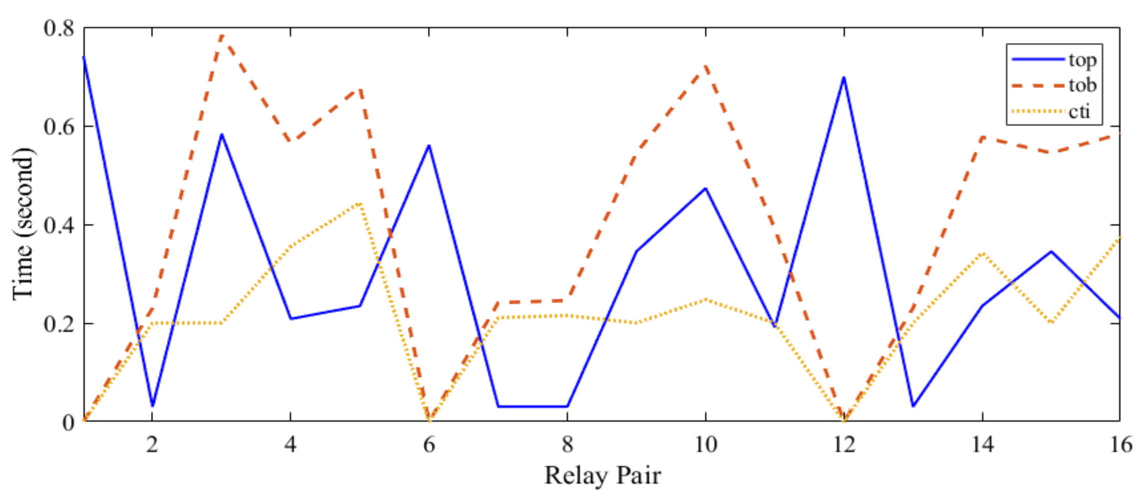

Figure 4.9: Relay Coordination of P/B relay pair

Figure 4.9 shows the relay coordination between the primary relay and backup relay. Here the coordination time interval of 0.20 seconds holds for every relay pair. The relay number point 1, 6, and 12 do not have any backup relay due to network configuration.

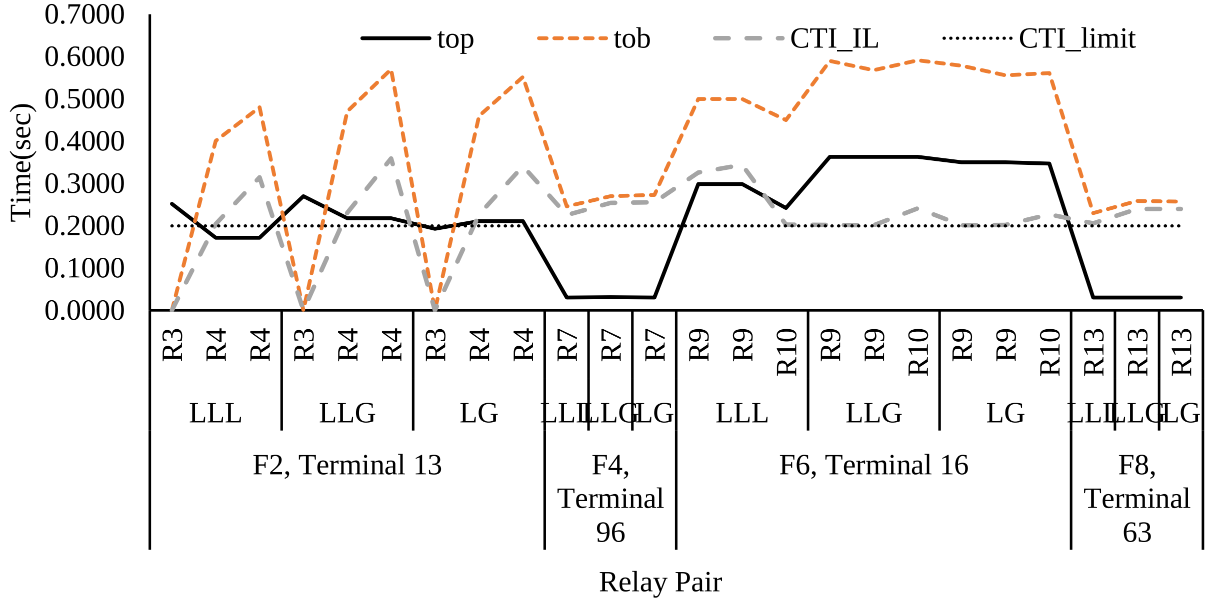

Figure 4.10: Relay Coordination of MV DS for Various Fault Condition when in Islanded Mode

Figure 4.10 shows the relay coordination in MV distribution for indicated fault location point. Here LLL, LLG and LG fault are created and tested to check whether the coordination between the relay is achieved or not. The result from the Figure 4.10 illustrates that for every relay pair and for every fault type, the coordination time interval holds the minimum limit. The relay number 3 does not have backup relay in islanded mode of operation.

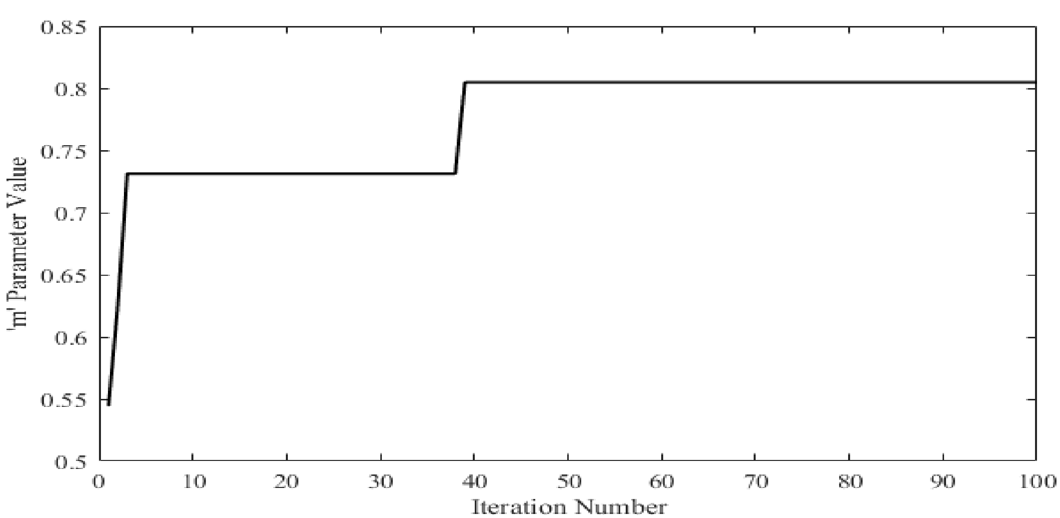

Figure 4.11: Convergence of 'm' Parameter of R9 when in Grid Connected Mode

Figure 4.11 shows the convergence of 'm' parameter of the relay number 9 when MV distribution system operated in gird connected mode. Here the value converges to the final value in less than 50 iterations.

Figure 4.12 shows the sum of operating time of primary relays for the indicated fault point [1] for 95 node 20kV distribution network when it is operated in islanded mode and grid connected mode. At first the relay characteristics parameters are determined optimally. Then, these parameters are used to calculate the operating time of primary relay for the indicated fault point. From the figure, the sum of operating time for the indicated fault location, in case of PSOA for islanded mode is 3.4919 seconds. Similarly, for FA method, sum of operating time of relay for indicated fault location is 3.7789 seconds. Also when the DS is operated in grid connected mode, the sum of operating time of primary relay for PSOA is 4.1821 seconds and that for FA is 4.76399 seconds.

The value of the objective function obtained above is less for PSOA method. The PSOA converges to the final value with just the population size of 5. The execution time of such program for this particular case is less than two seconds. The final values are obtained in less than 100 iterations.

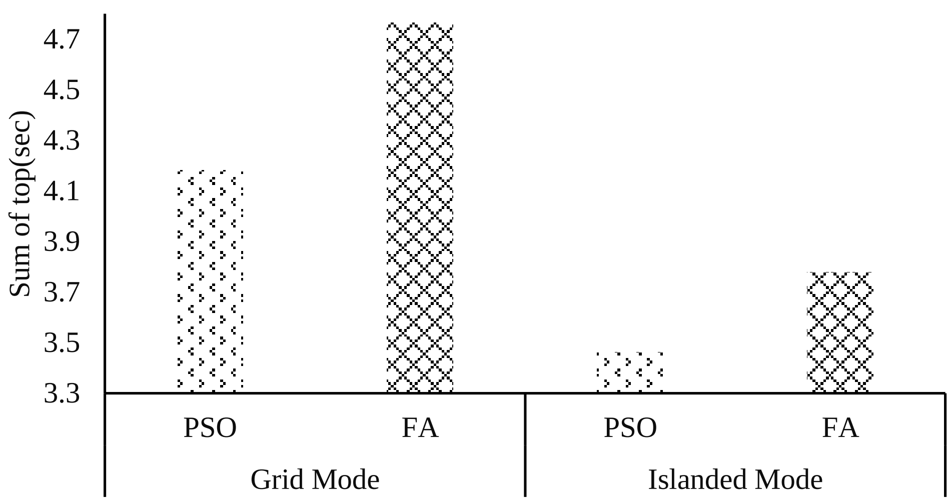

Figure 4.12: Comparison of Two Methods with Respect to Operating Time of Relay

4.5 Protection Coordination between Line Primary Relay and DG unit.

If primary relay of the line protection fails to operate, secondary line relay as a backup protection should operate. In addition if there is DG in between primary line protection relay and backup line protection relay, the relay corresponding to the DG should also operate with faster time than the line backup relay, or at the same time if primary relay fails to operate. The DG will have to feed all the fault current if the above mentioned condition is not satisfied. This might create the serious problem in DG unit and its auxiliary components. So weather the line relay is reverse or forward, it should be coordinated with unit relay as well as line relay. Two methods are analyzed here for the determination of the coordination among the line relay and unit relay.

4.4.1 Determination of TDS and 'm' Parameter using optimization method

In this case, the relay corresponding to the DG is also considered for coordination optimization. Five DGs of different types are connected at 95 node MV distribution system as given in Table 4.4. To check the coordination between the line primary relay and unit backup relay, the PSO is applied taking the DS in islanded mode. Here the optimum value of the TDS of the line relay which would act as primary relay, is taken in this case. Also for the preparation of fault data, the near end fault of 5 percentage distance from each node is considered.

Table 4.4: DG Data Connected at Various Nodes

S.N.	DG Type	Capacity	Connected Node
1	Inverter Based DG	1.12MVA	Terminal 8
2	Synchronous Based DG	1.2MVA	Terminal 14
3	Synchronous Based DG	1.2MVA	Terminal 19
4	Inverter Based DG	1.12MVA	Terminal 51
5	Inverter Based DG	1.12MVA	Terminal 84

The fault voltage data are given in Annex (C). The Table 4.5 shows the optimum values of TDS of the unit relay as backup relay when DS is in the islanded mode.

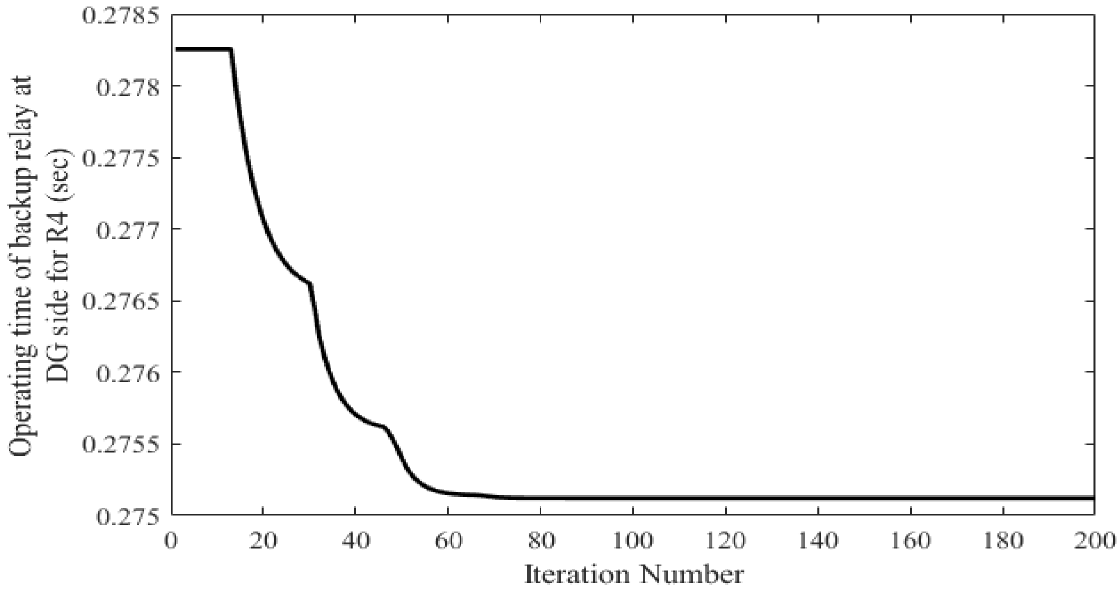

Figure 4.13: Operating Time Variation of Backup Relay at Unit Side with Iteration Number

Figure 4.13 shows the convergence nature of operating time of a particular relay at unit side as back up. The operating time is decreasing with the iteration number with holding the pre specified coordination time interval. In other way it can be said that this is the convergence of time dial setting of that particular relay during the relay coordination.

Table 4.5: TDS value of Backup relay at unit side

Relay-backup	R_{g1}	R_{g2}	R_{g3}	R_{g4}	R_{g5}
TDS	7.899	3.8419	3.705	5.5105	3.0663

The above values in Table 4.5 are obtained from the optimization technique in which population size of 5, C_1:2.5, C_2:2.5 are taken and inertial weight varies from 0.9 to 0.4 with the iteration Number. 200 iteration numbers is taken in the execution of algorithm

Figure 4.14 shows the relay coordination between the line primary relays and backup relay at unit side. Here it is seen that the relay coordination of 0.2 second holds for every relay pair. But the important things to be noticed here is that the relay operating time for backup at DG side is very large for some of the relays pair. This is because same relay has to co-operate with two line relays. If one line relay holds CTI of minimum, then with others have high value of CTI with same values of relay parameters. Here same value of relay parameters for backup relay at unit side for both the line primary relays is taken.

The second point in getting such a high time for backup relay in DG side is that, the actuating quantity, i.e. fault voltage for both line primary relay and line backup relay at DG side is same. So to get the considerable time difference between those relay, the value of TDS for backup relay at DG side for same value of ‘m’ parameter has to be set at high value. This is illustrated from the values given in Table 4.5.

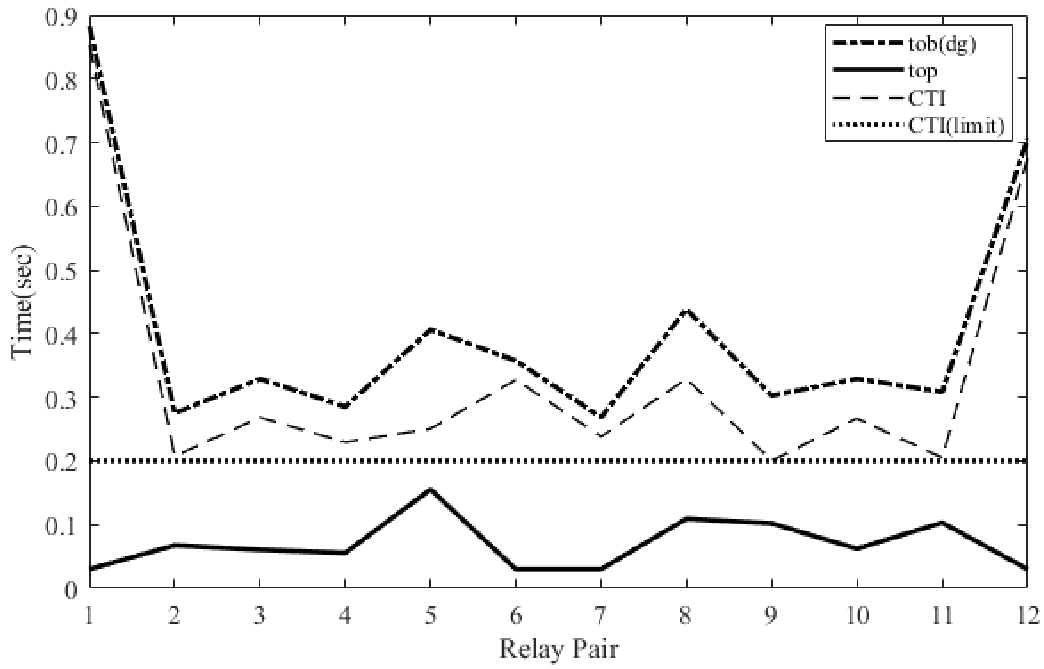

Figure 4.14: Relay Coordination between Line Primary Relay and Back up at Unit Side

Figure 2.8 shows that for same values of fault voltage, there must be either m value changed or TDS value changed. If the ‘m’ value is changed then accordingly the backup relay at DG side must consists of two relays for different side fault location. However for same value of ‘m’, TDS needs to be set high

The third point to be noted here is that, since the relay characteristic is the nonlinear function of fault voltage, higher the fault voltage, higher will be the CTI for same TDS and ‘m’ values. This might happens for the far end fault. Since the above Figure 4.14 is optimized for near end fault location, the same relay parameter will result high value of operating time when far end faults are taken which is shown in Figure 4.15.

If coordination is carried out with the objective of getting the optimal relay operating time with minimization of backup operating time for far end faults, then obviously it will not hold the CTI limit for near end fault.

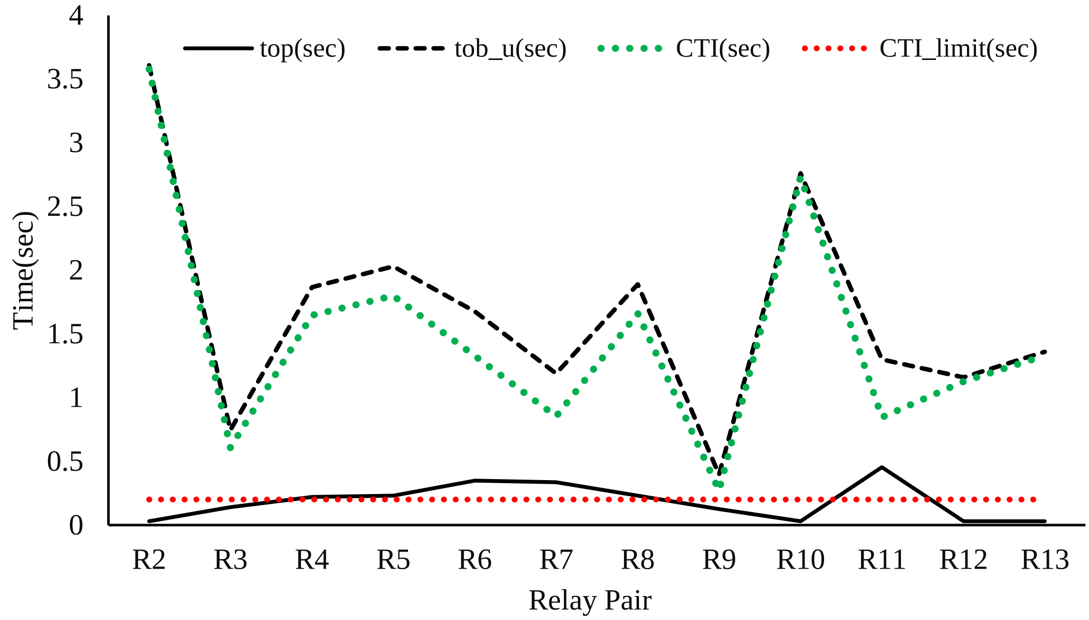

Figure 4.15: Line Relay and Backup Relay at Unit Side Coordination in case of Far End Fault

4.4.2. Trip Command Sending to Master Trip Relay (86) of Generator Circuit Breaker

At any junction or bus bar point where the DG is synchronized to the distribution system, the relay block will be the same for line relays which includes the characteristics curve of both the reverse relay and forward relay. As the relay model is microprocessor based, the relay characteristics can be coded within the system and depending upon the site where the fault occurs in the line section, the corresponding curve will be activated and will generate the operating time for primary relay.

In addition to the operating time for the primary relay, the operating time can be calculated as backup in the same relay block for DG side circuit breaker to trip. And if, the primary fails to operate, after the predefined coordination time interval the trip signal will be sent to the Master Trip Relay of the DG protection system to isolate the faulty path and protect the DG from continuously feeding the fault.

Since these all works can be done on the same relay model and the same bus bar system, this method is quite suitable for the primary relay of the line and the backup relay for the DG protection in comparison to the previous method since larger operating time result in the previous method for back up relay at DG side.

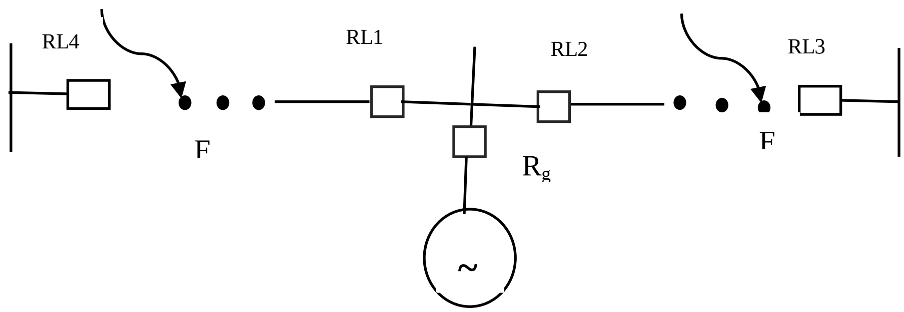

Figure 4.16: Conceptual Figure for Line Primary and Backup at DG side Coordination

In the above Figure 4.16, if fault occurs at F1, then RL1 has to operate as primary line relay and RL3 as backup line relay. Since DG is connected at node, R_g has to be operated as backup relay for the protection of DG unit.

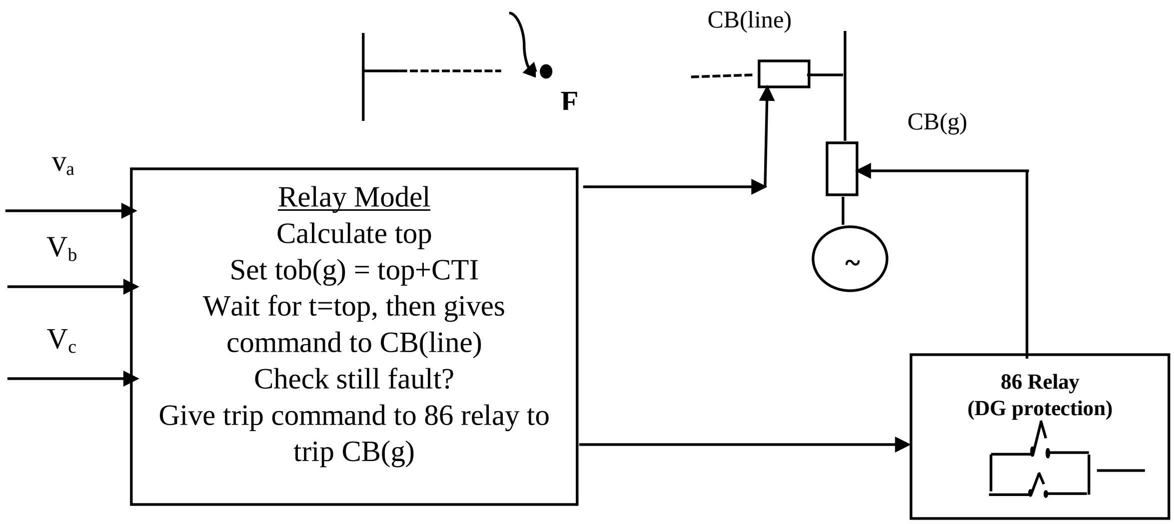

Figure 4.17: An example of Relay Coordination block

In such condition for better protection system operating time of R_g should be at least equal to or less than the operating time of RL3. Otherwise for some period of time Rg has to supply the entire fault current solely. Same applies if fault occurs at other side, i.e. at F2.

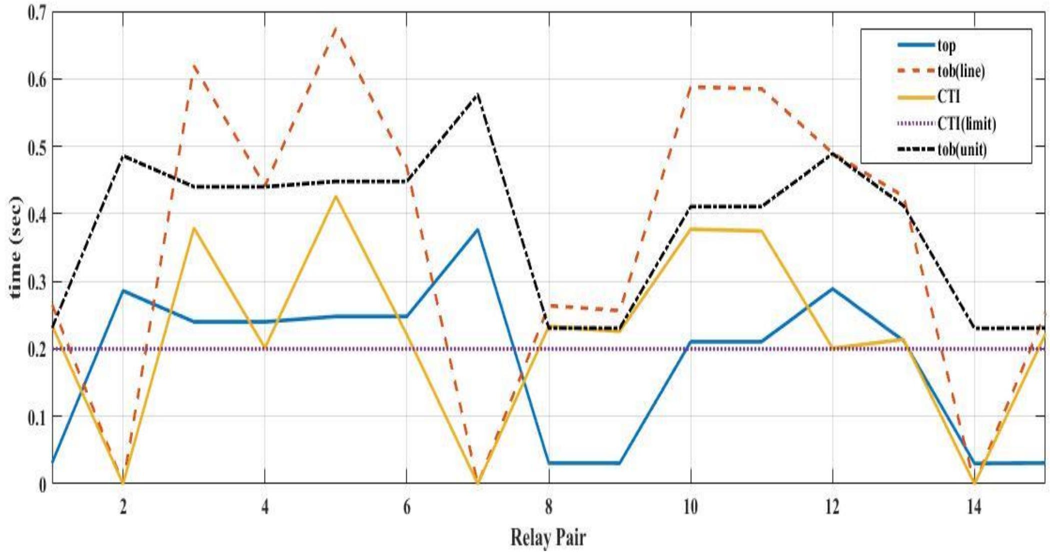

Figure 4. 18: Coordination Graph with Line primary relay, Line backup relay and Backup Relay at Unit Side

This is the case of islanding mode of operation of 95 node 20kV distribution networks in which there exists a total of 15 relays pair as primary and backup line relay with the line coordination. For the same number of 15 primary relay there exists another 15 pair of relay coordination with backup relay at unit side. This is because of the connection of distributed generation at all the relay position except R1 as shown in Figure 4.5.

The graph generated from MATLAB as shown in Figure 4.18 is relay coordination graph for far end fault condition in which the optimally determined relay parameters are used for the calculation of operating time of those relays which must be responsible for acting as primary and backup relay as per the location of fault. In the Figure 4.18 the relay pair number 2, 7, 14 do not have line backup relay as they are the last relay point in the network as per the structure of the distribution network. In addition to this, the noticing point from Figure 4.18 that as per the concept of 4.4.2, there exists a defined coordination time interval between primary line relay and backup relay at unit side. This means the operating time of backup relay at unit side is less than or equal to operating time of line back up relay. In this situation there would not be the case of feeding the fault from DG only, thus protected from severe hazardous accident.

4.5 Summary

The developed relay coordination program using particle swarm optimization technique is found to be effective in distribution system protection using the voltage based relay characteristics.

The low voltage Canadian distribution system with penetration of DGs at various nodes was taken to determine the relay parameter optimally using the presented relay characteristics with particle swarm optimization algorithm. It provides the faster operating time of primary relays in comparison to overcurrent based protection system in the same network. In addition, the coordination time interval limit holds for every relay pair.

The low voltage distribution system in which each node were few meters apart, modeled in DIgSILENT power factory tool was used for testing of the proposed PSO algorithm. Different types of DGs were connected at different node. The tests were carried out for both mode of operation, i.e. islanded and grid connected mode of operation. It has been found that the convergence rate of the algorithm for the above mentioned tuning parameter is very fast. That means it converges with less than 100 iterations. Hence the voltage based protection coordination with PSO can be used in low powered low voltage distribution system in an effective way.

The MV distribution system with 95 nodes, 20kV, modeled in DIgSILENT power factory tool was used as second case for the testing of the algorithm for zonal type protection. In this modeled system, it can be realized that each nodes are very far i.e. in the range of kilometers and protective relays are located at DG points. So each relay pairs has some zone of DS to protect. As in LVDS, tests were carried out for both mode of operation. In this system also, the convergence rate is fast.

The same MV distribution system was taken to make the coordination between line relay and DGs in islanded mode. It is found that the coordination can be hold between the relays but it might result larger operating time for some relays to trip DGs. The reason behind this is the relay actuating quantity for both primary and backup relay is same. However this can be easily solved by adding proper delay time as it is a microprocessor based relay.

CHAPTER 5: CONCLUSION AND FUTURE WORK

5.1 Conclusion

The radial distribution system with no DGs is easy from the over current protection coordination point of view as there is unidirectional flow of fault current which is contributed from one source only. However due to penetration of DGs at various location of conventional radial distribution system, it makes over current protection coordination less sensitive as the fault current contribution from main source to the fault point decreases due to supply of some part of fault current from connected DGs. This thesis identifies the voltage based algorithm with PSO as the better solution to this problem. The PSO based algorithm is developed taking the relay characteristics which uses fault voltage as an actuating quantity. A 6-bus LV distribution system and 95-bus MV distribution system are simulated in DIgSILENT Power Factory tool and the prepared fault data are used in the coordination program.

The following conclusion can be drawn from this study:

- From the results as discussed in chapter 4, it can be seen that the developed coordination program using PSO with voltage based relay is quite effective. The rate of convergence for the algorithm is fast. The PSO based algorithm for such type of relay provides the faster operating time of primary relay holding the pre-defined coordination time interval. The results show that this methods of protection coordination can be used in low voltage distribution network in which the local consumer have their own distributed generator (few kW) feeding the grid in case of surplus power. In addition, the algorithm seems to be very effective in MV distribution network in which large scale distributed generators (few MW) are penetrated in the gird system.
- The presented algorithm with the new relay characteristics is very suitable for the DS with higher penetration level of inverter based distributed generation. The DOCR based protection system is not sensitive in such type of DS.
- The proposed protection system requires only one set of potential transformer at the junction of DS, no matter how much branching is going out from that junction point. Hence the proposed algorithm is economical too. Unlike in DOCR based relay, it is

not necessary to deal with large amount of fault current. Only the per unit fault voltage is needed. This is one of the advantages from the point of memory in numerical relay.

So, the algorithm is applicable/ practicable in distribution protection system with penetration of DGs. When there is sufficient level of penetration level of renewable energy resources in distribution system, then the voltage based protection would be much better for protection system coordination in distribution system.

5.2 Future work

This research can be further extended to meet the limitations that are realized while carrying out this thesis. The idea of detecting the mode of operation of the distribution system is not considered in this thesis. Though the relay TDS have same value whether it is operated in islanded mode or grid connected mode, the 'm' parameter of the forward relay is different for grid connected mode. So, island detecting methods may be explored. Islanding detection techniques, for example passive detection, active detection etc. can be the part of the study [25].

The optimization of protection system with presented relay characteristics can be done using other optimization techniques and may make the comparison with the result of the above PSO technique.

Since this thesis considered the fixed topology under the study, the protection coordination with the voltage based characteristics considering the variable network topology by incorporating the multiple number of constraints as per the type of contingencies can be the future work.

PUBLICATION

B. Pokharel, N.P. Gyawali, K. Thapa, A. Mishra, N. R. Karki, “A Voltage Based Optimal Relay Coordination using PSO in Distributed Generation Penetrated Distribution System”, International Conference on Role of Energy for Sustainable Social Development in ‘New Normal’ Era, *IEEE Power and Energy Society Nepal Chapter*, 28th-29th December 2020.

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Annex A

Table A.1: TDS of Canadian DS for Voltage Based Method, m: 0.5

Relay Number	Time Dial Setting		Relay Number	Time Dial Setting
1	1.0682		9	0.9801
2	1.3113		10	1.3955
3	0.7085		11	0.7094
4	1.5301		12	1.7311
5	0.3833		13	0.3799
6	1.7245		14	1.9946
7	0.002		15	0.002
8	2.0548		16	2.1712

Table A.2: Relay Operating Time for Canadian DS for Near End Fault & Far End Fault

Fault	For Near End			For Far End		
	Primary relay,p1(sec)	Backup relay,b1(sec)	CTI (sec)	Primary relay,p1(sec)	Backup relay,b1(sec)	CTI (sec)
F10	0.2980	0.5490	0.2510	0.5100	0.7110	0.2010
F11	0.5988	0.7990	0.2002	0.2148	0.6140	0.3992
F12	0.2010	0.6090	0.4078	0.5980	0.7990	0.2010
F13	0.4000	0.6590	0.2590	0.2470	0.6880	0.4410
F14	0.1190	0.4060	0.2870	0.6756	0.8890	0.2134
F15	0.2258	0.4419	0.2161	0.2810	0.6854	0.4040
F16	0.0302	0.2330	0.2028	0.6620	-	-
F17	0.0305	0.2517	0.2212	0.2620	-	-
F18	0.2750	0.5500	0.2750	0.5486	0.7486	0.2000
F19	0.5520	0.7520	0.2000	0.2280	0.5821	0.3541
F20	0.2000	0.5616	0.3616	0.5590	0.7801	0.2210
F21	0.4035	0.6130	0.2095	0.2240	0.6610	0.4370
F22	0.1210	0.4100	0.2890	0.6428	0.8495	0.2067
F23	0.2270	0.4440	0.2170	0.2540	0.7189	0.4649
F24	0.0304	0.2308	0.2004	0.6984	-	-
F25	0.0310	0.2510	0.2200	0.2750	-	-

Annex B

Table B.1: Line and Load data of Iranian Practical Test Distribution Network.

Line Name	Fuse at Line	Resistance (Ω)	Reactance(Ω)	Load(kVA)
L01	-	0.1130	0.1440	84.00
L02	-	0.1260	0.1610	0.000
L03	-	0.0300	0.0240	154.0
L04	-	0.0890	0.1140	213.0
L05	-	0.0490	0.0620	151.0
L06	-	0.0980	0.1250	0.000
L07	F07	0.7450	0.6050	0.000
L08	-	0.1010	0.0820	19.00
L09	-	0.0670	0.0540	150.0
L10	-	0.1090	0.0890	19.00
L11	-	0.1860	0.1510	19.00
L12	-	0.0490	0.0620	0.000
L13	-	0.0250	0.0210	236.0
L14	-	0.0660	0.0840	19.00
L15	-	0.1620	0.2070	19.00
L16	-	0.1340	0.1710	188.0
L17	-	0.2600	0.3320	75.00
L18	-	0.1090	0.1390	19.00
L19	-	0.1660	0.2120	0.000
L20	-	0.0690	0.0560	75.00
L21	F21	0.1750	0.1420	19.00
L22	-	0.0270	0.0350	38.00
L23	-	0.0800	0.1020	38.00
L24	-	0.1070	0.1370	0.000
L25	-	0.0520	0.0420	19.00
L26	-	0.0670	0.0860	0.000
L27	-	0.0490	0.0620	150.0
L28	-	0.0340	0.0430	0.000
L29	F29	0.3090	0.2510	120.0
L30	-	0.1940	0.2470	150.0
L31	-	0.1170	0.1490	75.00
L32	-	0.0500	0.0640	0.000
L33	F33	0.2630	0.2140	75.00
L34	-	0.1760	0.2250	150.0
L35	-	0.1930	0.2460	75.00
L36	-	0.1650	0.2110	150.0
L37	-	0.1760	0.2250	0.000
L38	-	0.0330	0.0420	75.00
L39	-	0.1900	0.2420	75.00

Line Name	Fuse at Line	Resistance (Ω)	Reactance(Ω)	Load(kVA)
L40	-	0.0540	0.0690	0.000
L41	-	0.0450	0.0370	75.00
L42	-	0.1360	0.1730	0.000
L43	F43	0.0900	0.0740	75.00
L44	-	0.0680	0.0550	0.000
L45	-	0.2720	0.2210	75.00
L46	-	0.2270	0.1850	75.00
L47	F47	0.2040	0.1660	75.00
L48	-	0.0450	0.0370	38.00
L49	-	0.1180	0.0960	75.00
L50	-	0.1140	0.0920	75.00
L51	-	0.0910	0.0740	75.00
L52	-	0.1590	0.1290	75.00
L53	-	0.1910	0.1550	75.00
L54	-	0.2000	0.1620	75.00
L55	-	0.1820	0.2320	19.00
L56	-	0.1790	0.2280	0.000
L57	-	0.1110	0.0900	38.00
L58	-	0.0940	0.1190	150.0
L59	-	0.0140	0.0170	0.000
L60	F60	0.1430	0.1160	0.000
L61	-	0.0320	0.0260	75.00
L62	-	0.0230	0.0180	0.000
L63	-	0.0360	0.0300	75.00
L64	-	0.0980	0.0800	19.00
L65	-	0.2200	0.2800	0.000
L66	F66	0.0050	0.0040	188.0
L67	-	0.1310	0.1060	19.00
L68	-	0.0680	0.0550	150.0
L69	-	0.0770	0.0990	75.00
L70	-	0.0290	0.0370	0.000
L71	-	0.0540	0.0690	19.00
L72	-	0.0820	0.1040	0.000
L73	F73	0.0400	0.0330	0.000
L74	-	0.1100	0.0890	38.00
L75	-	0.0660	0.0540	38.00
L76	-	0.0680	0.0870	38.00
L77	-	0.0540	0.0690	0.000
L78	F78	0.1570	0.1270	75.00
L79	-	0.0600	0.0770	120.0
L80	-	0.0340	0.0440	0.000
L81	F81	0.0260	0.0330	38.00

Line Name	**Fuse at Line**	**Resistance (Ω)**	**Reactance(Ω)**	**Load(kVA)**
L82	-	0.1400	0.1780	38.00
L83	-	0.0270	0.0350	0.000
L84	F84	0.2830	0.2300	150.0
L85	-	0.2440	0.3110	75.00
L86	F86	0.2470	0.2010	75.00
L87	F87	0.0910	0.0740	0.000
L88	-	0.0690	0.0560	75.00
L89	-	0.0810	0.0660	75.00
L90	F90	0.1310	0.1670	75.00
L91	-	0.1220	0.1560	75.00
L92	-	0.1080	0.1380	38.00
L93	-	0.0130	0.0160	75.00
L94	-	0.5420	0.6920	38.00

Table B.2: Synchronous Generator Parameter as in [4]

Electrical parameters of DGs		
Parameters	**Value**	**Remarks**
S (MVA)	1.300	
Vn (kV)	0.400	
PF	0.800	
Xd (p.u.)	2.170	
Xq (p.u.)	3.620	
Xd' (p.u.)	0.160	
Xq' (p.u.)	0.201	
Xd'' (p.u.)	0.136	
Xq'' (p.u.)	0.142	

Table B.3: Line Data for LV Distribution Network

Line	**L12**	**L23**	**L34**	**L45**	**L56**
Length, meter	90	18	17	22	14
Conductor type	Aluminum, 150 mm^2	Aluminum, 150 mm^2	Aluminum, 150 mm^2	Aluminum, 150 mm^2	Aluminum, 150 mm^2
Resistance, Ω/km	0.207+j.072	0.207+j.072	0.207+j.072	0.207+j.072	0.207+j.072

Annex C

C.1 Fault Voltage Data for LV Distribution System Protection Coordination

Table C.1: Fault Voltage Data for LV system

P/B relay pair No.	Primary Relay No.	Backup Relay No.	Primary Fault Voltage, P.U.	Backup Fault Voltage, P.U.
1	R11	R13	0.02600	0.03200
2	R13	R15	0.00530	0.01040
3	R15	R17	0.00510	0.01100
4	R17	R19	0.00670	0.01080
5	R19	-	0.00420	-
6	R18	R16	0.00410	0.01065
7	R16	R14	0.00650	0.01150
8	R14	R12	0.00500	0.01040
9	R12	R10	0.00530	0.03200
10	R10	-	0.02688	-

C.2. Fault Voltage Data for MV Distribution System Protection Coordination in Islanded Mode

Table C.2: Fault Voltage Data for MV system

P/B relay pair No.	Primary Relay No.	Backup Relay No.	Primary Fault Voltage, P.U.	Backup Fault Voltage, P.U.
1	R11	-	0.0890	-
2	R2	R4	0.0488	0.1105
3	R4	R6	0.0630	0.1640
4	R4	R10	0.0642	0.1107
5	R6	-	0.1170	-
6	R10	R12	0.0489	0.0490
7	R12	-	.04320	-
8	R13	R11	0.0710	0.1000
9	R11	R9	0.0400	0.0840
10	R9	R3	0.0466	0.1090
11	R9	R6	0.0470	0.1501
12	R3	R1	0.0657	0.1177
13	R7	R5	0.0215	0.1170
14	R8	R5	0.0447	0.1380
15	R5	R3	0.0977	0.1580
16	R5	R10	0.1000	0.1455

C.3. Fault Voltage Data for Canadian Distribution System Protection Coordination

Table C.3: Fault Voltage Data for Comparison of O/C and Voltage Based Method

P/B Relay Pair No.	Primary Relay No.	Backup Relay No.	Primary Fault Voltage, P.U.	Backup Fault Voltage, P.U.
For Near End Fault Condition				
1	R1	R10	0.007890	0.03800
2	R3	R1	0.006980	0.14670
3	R5	R3	0.006250	0.13100
4	R7	R5	0.006400	0.12000
5	R9	R2	0.007800	0.03700
6	R11	R9	0.007000	0.14660
7	R13	R11	0.006800	0.14360
8	R15	R13	0.006100	0.12800
9	R2	R4	0.001500	0.13200
10	R4	R6	0.001500	0.03200
11	R6	R8	0.001600	0.01700
12	R8	-	0.100800	-
13	R10	R12	0.001500	0.01700
14	R12	R14	0.000789	0.01654
15	R14	R16	0.007900	0.01670
16	R16	-	0.000800	-
For Far End Fault Condition				
1	R1	R10	0.1343	0.1610
2	R3	R1	0.1200	0.2400
3	R5	R3	0.1080	0.2200
4	R7	R5	0.1100	0.2130
5	R9	R2	0.1330	0.1600
6	R11	R9	0.1310	0.2560
7	R13	R11	0.1170	0.2400
8	R15	R13	0.1060	0.2180
9	R2	R4	0.0284	0.0583
10	R4	R6	0.0290	0.0590
11	R6	R8	0.0298	0.0454
12	R8	-	0.0151	-
13	R10	R12	0.0290	0.0440
14	R12	R14	0.0148	0.0304
15	R14	R16	0.0150	0.0307
16	R16	-	0.0151	-

C.4. Fault Voltage Data for LVDS for the Calculation ‘m’ in Grid Connected Mode

Table C.4: Fault Voltage Data to Calculate 'm' Parameter for LVDS

P/B Relay Pair No.	Primary Relay No.	Backup Relay No.	Primary Fault Voltage, P.U.	Backup Fault Voltage, P.U.
1	R10	-	0.8434	-
2	R12	R10	0.1460	0.870
3	R14	R12	0.1230	0.253
4	R16	R14	0.1400	0.248
5	R18	R16	0.0832	0.213

C.5. Fault Voltage Data for MVDS for the Calculation ‘m’ in Grid Connected mode

Table C.5: Fault Voltage Data to Calculate 'm' Parameter for MVDS

P/B Relay Pair No.	Primary Relay No.	Backup Relay No.	Primary Fault Voltage, P.U.	Backup Fault Voltage, P.U.
1	R13	R11	0.298	0.420
2	R11	R09	0.207	0.426
3	R09	R3	0.277	0.610
4	R3	R1	0.432	0.592
5	R1	-	0.720	-
6	R7	R5	0.276	0.412
7	R8	R5	0.265	0.395
8	R5	R3	0.230	0.560