RELAY COORDINATION IN GRID WITH DISTRIBUTED GENERATION

A DISSERTATION
Submitted in partial fulfillment of the
requirements for the award of the degree
of
MASTER OF TECHNOLOGY
in
ELECTRICAL ENGINEERING
(With specialization in Instrumentation and Signal Processing)

By

PRIYAKAR PANDEY

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE - 247 667 (INDIA)
MAY, 2016

CANDIDATE'S DECLARATION

I hereby declare that this thesis report entitled **RELAY COORDINATION IN GRID WITH DISTRIBUTED GENERATION**, submitted to the Department of Electrical Engineering, Indian Institute of Technology, Roorkee, India, in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Electrical Engineering with specialization in Instrumentation and Signal Processing is an authentic record of the work carried out by me during the period June 2015 through May 2016, under the supervision of **Prof. VINOD KUMAR and Dr. C.P. GUPTA, Department of Electrical Engineering, Indian Institute of Technology, Roorkee.** The matter presented in this thesis report has not been submitted by me for the award of any other degree of this institute or any other institutes.

Date:
Place: Roorkee

Priyakar Pandey

CERTIFICATE

This is to certify that the above statement made by the candidate is true to the best of my knowledge and belief.

Dr. Vinod Kumar
Professor
Department of Electrical Engineering
Indian Institute of Technology
Roorkee, India

Dr. C.P. Gupta
Associate Professor
Department of Electrical Engineering
Indian Institute of Technology
Roorkee, India

ACKNOWLEDGEMENT

I owe my profound gratitude to **Dr. Vinod Kumar and Dr. C.P. Gupta,** Department of Electrical Engineering, Indian Institute of Technology, Roorkee, whose strengthen presence was a source of great inspiration for the successful completion of this project. Their constant guidance, useful criticism and constant help in the hours of need have been immensely useful.
I owe my deepest gratitude to my beloved parents and friends, for being a constant source of love, patience, and motivation.
I thank almighty God as a source of wisdom, knowledge and understanding.

Priyakar Pandey

Abstract

Reliability of power in modern power system is endowed by presence of distributed generation in the system. A typical power system is composed of multiplicity of elements like generators, transformers and distribution circuits, the numerous elements lead to inevitable uncertainty in the system which is manifested as failure of portion of system. In event of failure of any part of the system, it must be immediately detected and disconnected from the rest of system. So far protective relays are most commonly employed for protecting power systems owing to economic reasons. Timely removal of the faulty section of power system depends on appropriate settings of these relays under various system conditions. The modern power system which will eventually be heavily penetrated by DG, coordination of overcurrent relays will be a big challenging task for protection engineers. Addition of DG causes distribution system to experience change in the short circuit level and thus the settings chosen earlier may result in mal operation of relays. The change in system because of addition or removal of DGs will require the protection engineers to have set of relay settings pertinent to all possible system conditions. To reduce the burden of deciding the settings for numerous cases, various programming optimization techniques are frequently used to find optimal settings of overcurrent relays. In the present study Particle Swarm Optimization (PSO) technique has been implemented for solution of non-linear equation describing operation of an overcurrent relay. The optimization has been done to reduce overall time of operation of relays as well as keep them in coordination with each other. A proper combination of primary and backup relay is selected to avoid mal operation of relays and unwanted outages in healthy part of system. The study is done in two parts. In first part the mentioned optimization technique is tested on an eight bus system fault data to check consistency of obtained settings with respect to that mentioned in journal. The optimization algorithm is implemented using MATLAB software. In second part of study a standard IEEE 14 Bus system is designed on PSCAD/EMTDC software. The fault data of simulation is used to obtain optimal settings of relays for a coordinated system

Contents

Candidates Declaration…………………………………………………………..……i

Acknowledgement ii

Abstract iii

Contents iv

List of Figures v

List of Tables vi

Chapter 1 1

  1.1 Introduction 1
  1.2 Organization of Dissertation 2
Chapter 2 3

  2.1 Literature Survey 3
Chapter 3 5

  3.1 Particle Swarm Optimization 5
  3.2 Algorithm 8
  3.3 Improvements in PSO 9
  3.4 PSO parameter values used in optimization program 10
Chapter 4 11

  4.1 Relay characteristic equation 11
Chapter 5 14

  5.1 Test System 14
  8-bus network...14
  IEEE 14 Bus system...16
Chapter 6 17

  6.1 Formulation of Objective Function and Optimization Framework 17
Chapter 7 21

  7.1 Results and observations 21
  Eight bus system: 21
IEEE 14 Bus system: 30

  Observation: 39
Chapter 8 40

  8.1 Conclusion and future work 40
  References 42
Appendix A. 45

  8 Bus system 45
  IEEE 14 Bus system..46

List of Figures

Fig 4.1 Tripping time of relay with varying K..13
Figure 5.1 8-bus test system..14
Figure 5.2 14-bus test system..16
Figure 7.1: Fitness value graph (100 Iterations) 22
Figure 7.2 Fitness value graph (500 Iterations) 23
Figure 7.3 Fitness value graph (500 Iterations) 24
Figure 7.4 Fitness value graph (1000 Iterations) 25
Figure 7.5 Fitness value graph (2000 Iterations) 27
Figure 7.7 fitness value graph (Optimtool box)...28
Figure 7.8 Three phase voltage measured at relay R5 30
Figure 7.9 Three phase current measured at relay R5 30

List of Tables

Table 4.1 IEC standard values of constants K1 and K2 for overcurrent relays [20] 11

Table 5.1 Current transformer ratio specification 15

Table 5.2 Fault currents 15

Table 7.1 Optimized settings (case 4) 26

Table 7.2 Optimized relay settings (case 5) 28

Table 7.3 Optimized relay setting [11] 29

Table 7.4 Three phase fault current with no DG 31

Table 7.5 Three phase fault voltage with no DG 32

Table 7.6 Optimized relay settings [no DG] 33

Table 7.7 Optimized relay settings using modified relay equation [no DG] 33

Table 7.8 Optimized relay settings [no DG] 34

Table 7.9 Optimized relay settings using modified relay equation [no DG] 34

Table 7.10 Three phase fault current with DG connected at bus 14 35

Table 7.11 Three phase fault voltage with DG connected at bus 14 36

Table 7.12 Optimized relay settings [DG connected] 37

Table 7.13 Optimized relay settings using modified relay equation [DG connected] 37

Table 7.14 Optimized relay settings [DG connected] 38

Table 7.11 Optimized relay settings using modified relay equation [DG connected] 38

Table A.1 Line data - 8 bus system [10] 45

Table A.2 Generator data [10] 45

Table A.3 Transformer data [10] 45

Table A.4: Line data IEEE 14-bus system [22] 46

Table A.5: Bus data IEEE 14-bus system [22] 47

Table A.6: Transformer tap setting data IEEE 14-bus system [22] 47

Chapter 1

1.1 Introduction

Electric power systems of early days were designed as a pure radial networks, which have with time evolved into meshed form. Medium voltage distribution networks have been protected for long time by applying radial operations and their greatest advantage is simplicity of computation. However, improvement in power quality, system reliability and environmental problems, calls for switching to meshed networks with distributed generators as preferred option.

Along with facets of the meshed configuration and DG connection, there are also some complications such as protection coordination problems between protective devices. The reliability measure in the power system operation depends on protection relaying. Overcurrent protection principle is of basic and prime importance with the strategy of inverse time overcurrent relay employed for protection. This strategy is the backbone of all other protection schemes in the distribution networks.

In power system literature sensitivity and selectivity are the typical protection requirements. The relay operation can be delayed or, even in worst case, totally blocked because of the blinding operation, which impacts on sensitivity of system. Moreover, unnecessary tripping occurs at the feeder which is adjacent to DG. This can undesirably affect selectivity.

The settings chosen for overcurrent relay decide coordination, ensuring reliable, selective and speedy operation of relay to isolate the faulty section of the power system. The digital microprocessor based overcurrent relays have various advantages over the traditional electromechanical overcurrent relays and therefore, have wide applications to ensure efficient and safe protection. These technological developments are indispensable considering the requirement to meet the rising demand to switch over to “Smart Grids” from the traditional electric power grids [1]. The significant feature of this smart grid will be the escalating penetration of DG at distribution levels.

DG integration has manifold effects on distribution systems which includes transformation of the nature of distribution system into dynamic, increase in short circuit levels coupled with bidirectional power flow resulting in the failure of relay coordination [2].

To overcome miscoordination resulting from DG integration, new optimal relay settings need to be determined that take into account its presence. Different optimization methods, including conventional and heuristic techniques, have been applied to determine the optimum time dial and pickup current settings of the relays that guarantee coordination and minimum total relay operating times.

1.2 Organization of Dissertation

This dissertation firstly gives a brief review of studies already done in field of optimal coordination of overcurrent relay in Chapter 2, which includes the discussion on optimization techniques and novel characteristics of relay developed until now. Then Chapter 3 furnishes details of Particle Swarm Optimization which is used the entire study. Recent improvements in the technique are also highlighted. In chapter 4 the modified relay characteristic equation is discussed and its advantages over the conventional equation. Chapter 5 provides details of system under study and the simulation setup. In chapter 6 optimization problem formulation is presented with details of inclusion of constraints into objective function. Results, conclusion and scope for future work is discussed in subsequent chapters. Additional details of system under study is mentioned in appendix.

Chapter 2

2.1 Literature Survey

Various approaches have been proposed over period of time to solve the problem of directional overcurrent coordination. Broadly, two different methodologies are adopted. The first approach relies on topological analysis, which includes functional dependencies and graph theoretic techniques. The concept of breakpoint has been utilized in graph theoretic methods [3]- [4]. In [3], all simple loops of the network have been identified and analysed in both directions by employing the concept of linear graph theory, taking into account the minimum set of breakpoints and all pairs of primary and backup relay. In functional dependencies method, which is essentially a systematic topological analysis technique, the constraints on the relay settings are formulized by a set of functional dependencies [5].

The second category lists optimization techniques, wherein coordination problem is formulated as a linear or nonlinear mathematical function. Solution of this function determines values of TDSs and PSs via linear or nonlinear programming solvers keeping the pickup settings fixed [6].

Analytic methods (e.g., Simplex method) [6]- [8] or evolutionary techniques [9]– [18] are utilized to solve optimization problem. While in the linear programming approach, only TDS is optimized, to enhance the degree of freedom time dial and pickup current settings can be optimized simultaneously, this will result in a nonlinear optimization problem. Non-linear problem requires heuristic techniques to obtain optimal solutions. Research done in the field show utilization of evolutionary techniques like Genetic Algorithm [9]- [14], and the particle swarm optimization (PSO) algorithm [15]- [18].

The major weakness of the mathematical methods, and some of genetic algorithms is the likely hood of being trapped in local minima or maxima (depending on type of objective function). This difficulty is countered by searching for solutions randomly at start so that entire expanse of solution set is visited. This will ensure chances of reaching the optimum solution. In PSO this is achieved by using random function in algorithm that is used to create and update solution set in each generation.

Chapter 3

3.1 Particle Swarm Optimization

3.1.1 Introduction

It is an evolutionary method of optimization. Particle Swarm Optimization (PSO) is a population based stochastic optimization technique. It is used to explore the search space of a given problem to find possible solutions to minimize or maximize a particular objective. Invention of the technique is owed to James Kennedy and Russell C. Eberhart who developed it in year 1995. Inspiration of this evolutionary technique is the interactions observed in social groups such as bird flocks, fish schools, or human societies.

The particle swarm optimization algorithm imitates the behavioral pattern of these social organisms. The word particle refers to, for example, a bee in a colony or a bird in a flock. Each individual or particle in a swarm behaves in a certain fashion using its own intellect and the intelligence of group or swarm. So, if a particle discovers a path to food, then by nature the rest of swarm will also follow the path instantly even if their location is far away in the swarm. The algorithm has been designed such that solutions to an objective problem follow the same behavior so as to lead to an optimum solution.

3.1.2 Terminology of PSO

Particle: Each possible solution is called a "particle" in the search space. It is subjected to movement in a multidimensional space that represents the solution space. Particles possess memory, which helps them retain part of their previous state.

Search space: It is the N-dimensional space consisting of allowable solutions. A particle is allowed to roam in this space to search for best solution. This space is defined by selecting the range within which the particle can attain any value. In present case the range of solutions is defined by allowable values of TDS, PS and *K* (modified relay characteristic).

Swarm: It is the group of particles which can also be understood as feasible solutions.

Fitness function: A particular type of objective function that is used to summarize, as a single figure of merit, how close a design solution is in achieving set aims.

Generation: Each iteration is known as a generation.

Position: In every iteration the designed solution is a set of N-dimensional coordinates which can also be visualized as a positions in solution space.

pbest (Personal best): Each particle keeps track of its coordinates in the solution space which produced the best solution (fitness) it has achieved so far. This value is stored as *pbest*.

gbest (Global best**):** Another "best" value that is tracked is a global one. This is the best value achieved by any particle in any generation. This location is called *gbest*.

Both pbest and gbest have significant role in terms of routing the particles to optimum solution.

V_{max}: The maximum velocity, or the rate at which next designed solution can move in a particular direction.

3.1.3 Velocity and Position Update

Following factors decide the velocity and position of each particle in the swarm as they are updated:

- Previous velocity of the particle.
- The personal best position of the particle (pbest).
- The global best position of the particle (gbest).

Velocity is updated as:

$$vel_k(iter+1) = w * vel_k(iter) + c_1 * r_1\big(pbest_k(iter) - x_k(iter)\big) + c_2 * r_2(gbest(iter) - x_k(iter)) \qquad (3.1)$$

The position is updated by the following expression:

$$x_k(iter+1) = vel_k(iter+1) + x_k(iter) \qquad (3.2)$$

Where,

x_k: particles position

vel_k: particle's velocity

r_1 and r_2 are uniform random numbers between 0 and 1, generated independently for each particle in each generation (in MATLAB these random numbers are generated using 'rand' command).

c_1 and c_2 are learning factors controlling the importance of the best solution ever found by the kth particle and the best solution found by the swarm, respectively.

$iter$: iteration number

w: inertia weight

3.2 Algorithm

Step 1: Initialization of particles

The adjustable PSO parameters are assigned some values and particles are initialized in terms of initial velocity and position.

Step 2: Evaluation of fitness function

Values corresponding to each particle are placed in the fitness function and it is evaluated thereafter.

Step 3: Updating best solutions

In this step pbest for each particle is determined and gbest from entire swarm is selected. This update is subjected to superiority of solutions of present generation.

Step 4: Shifting to the new position

Every particle advances to fresh position as per particle update equation.

Step 5: Feasibility check

In case a particle goes beyond the permissible range it is moved back to its previous position.

Step 6: Verifying the termination criterion

In event of termination criteria being satisfied, which in this study is completion of total number of iterations, gbest is noted as optimal solution.

Otherwise, steps 2– 5 are repeated.

3.3 Improvements in PSO

3.3.1 Concept of Velocity clamping [19]:

It is observed that many particles tend to depart from the feasible region of the space at the outset of the optimization process. To tackle this problem, and to clamp the excessive wandering of particles, concept of velocity clamping is introduced by the following relation:

$$vel_k(iter+1) = \begin{cases} {v_k}^{max} & if\ vel_k(iter+1) > {v_k}^{max} \\ -{v_k}^{max} & if\ vel_k(iter+1) < \ -{v_k}^{max} \\ vel_k(iter+1) & otherwise \end{cases}$$

(3.3)

3.3.2 Linear weight updation in PSO

In original PSO velocity update equation, a factor of linearly decreasing weight has been introduced to enhance the performance of algorithm. The advanced version is called as linearly decreasing weight particle swarm optimization (LDWPSO). This has significant improvement over the original PSO because LDWPSO is to balance out the global and local search capabilities of the swarm effectively. In LDWPSO, W_{ldw} linearly decreases from 0.9 to 0.4 through the search process denotes the inertia weight. The equation describing linearly decreased weight is:

$$W_{ldw} = (W_{max} - W_{min}) * \left(\frac{Total\ Iteration - Current\ Iteration}{Total\ Iteration}\right) + W_{min}$$

(3.4)

W_{ldw} : updated weight

W_{max} : Maximum value of weight

W_{min} : Minimum value of weight

3.4 PSO parameter values used in optimization program

PSO has been implemented for both the systems mentioned with following parameter values.

Number of birds, N=200

$c_1 = c_2 = 2$

weight

min: .4

max: .9

Velocity clamping factor: 2

Chapter 4

4.1 Relay characteristic equation

Characteristic equation of a typical inverse time overcurrent relay is:

$$\text{Time of operation (S)} = \frac{\mathrm{K1} * \mathrm{TDS}}{\left(\frac{If}{PS * CTRatio}\right)^{\mathrm{K2}} - 1}$$

(4.1)

Where;

If : Fault current magnitude

PS: Plug setting (used to vary no. of turns of actuating coil so as to alter value of actuating current)

$CTRatio$: Current transformer turns ratio

TDS: Time dial setting (adjusts position of moving contact of relay to vary its time of operation)

K1: constant (value depends on type of relay)

K2: constant (value depends on type of relay

Table 4.1 IEC standard values of constants K1 and K2 for overcurrent relays [20]

Type of relay	K1	K2
I.E.C. Class A - Standard inverse	0.14	0.02
I.E.C. Class B – Very inverse	13.5	2.00
I.E.C. Class C – Extremely inverse	80.0	2.00
I.E.C Long-time inverse	120.0	2.00

Modified characteristics [21], which has been implemented on IEEE 14-Bus system is provided as under:

$$\text{Time of operation (S)} = \left(\frac{1}{e^{(1-Vf)}}\right)^{K} \frac{K1*TDS}{\left(\frac{If}{PS*CTRatio}\right)^{K2}-1}$$

(4.2)

Vf: Per unit fault voltage (phase) measured at DOCR terminal

The novel characteristic used, integrates the fault voltage magnitude as another element to the traditional time current characteristic that ensures enhanced degree of freedom to the conventional tripping characteristics which sets and optimizes by employing only three setting values. The characteristic of the new directional overcurrent relay (DOCR) comprise of two parts in cascade. The first part comprises of the conventional inverse characteristic equation for DOCR operation, which confirms for the maintenance of inverse time–current relation. The other part in the DOCR characteristic signifies the fault voltage magnitude as an exponential function. An exponential function fulfills following conditions:

a) The characteristic depends on the fault voltage measurement. Fault voltage in the system depends on the distance between the location of fault and that of the particular DOCR where measurement is performed. For a solid fault, the measurement can reach zero value at the VT terminal of DOCR nearest to the fault. Typical operating time of a DOCR is about 16–20 milliseconds, the exponential function safeguards against zero operation time in event of a bolted fault occurring near DOCR.

b) The time of operation is formulated to be in proportion to the drop in voltage observed during a fault. Occurrence of large voltage drop indicated that fault occurs somewhere near to the relay demanding speedy operation. Therefore, the reciprocal of the exponential is dealt with, and ($1 - V_f$) is taken as the exponential superscript.

c) Fault voltage effect is nullified by setting constant K to zero which makes modified equation again as conventional time–current characteristic equation, this also provides flexibility.

d) Moreover, the effect of TDS and I_p on characteristic of relay is unaltered.

Variation observed in relay tripping time with reference to variation in fault voltage (V_f) is regulated by changing value of K (as shown in Fig. 4.1). To solve the problem of coordination, K is studied as an additional relay setting and is also considered as optimization variable in the objective function in order to achieve optimal settings for every relay. In figure below $\frac{\text{If}}{\text{PS}*\text{CTRatio}} = 1.5$ *and TDS*= 0.1 is considered.

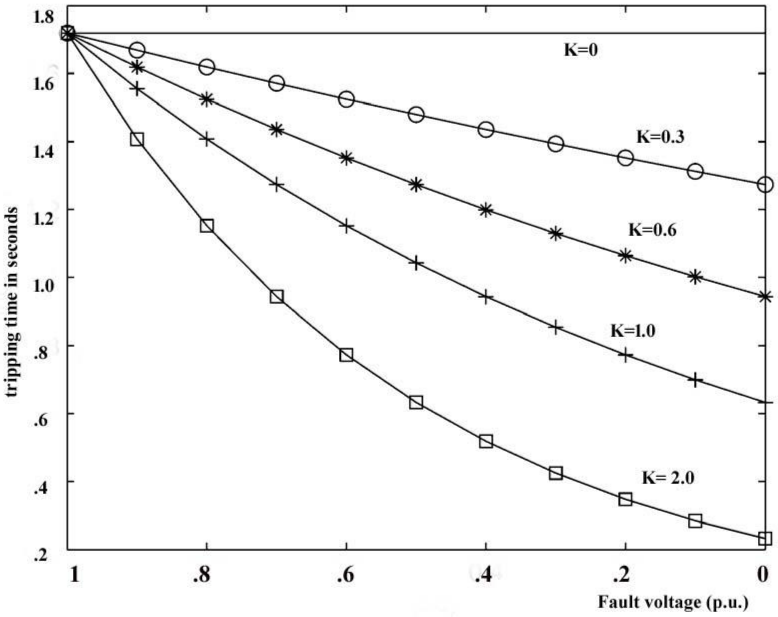

Fig 4.1 Tripping time of relay with varying K

Chapter 5

5.1 Test System

The PSO algorithm is applied to 8-Bus network and IEEE 14-Bus network.

8-bus network

The single line diagram of 8 bus network [22] is as shown below in Fig. 5.1. In this power system network, Bus- 3 is connected to another network via a link which has been represented with the help of an equivalent generator of 400 MVA. Both the generators G1(connected at Bus- 7) and G2(connected at Bus- 8) have their rated capacity of 150 MVA. Line, transformer and generator data are provided in appendix A.

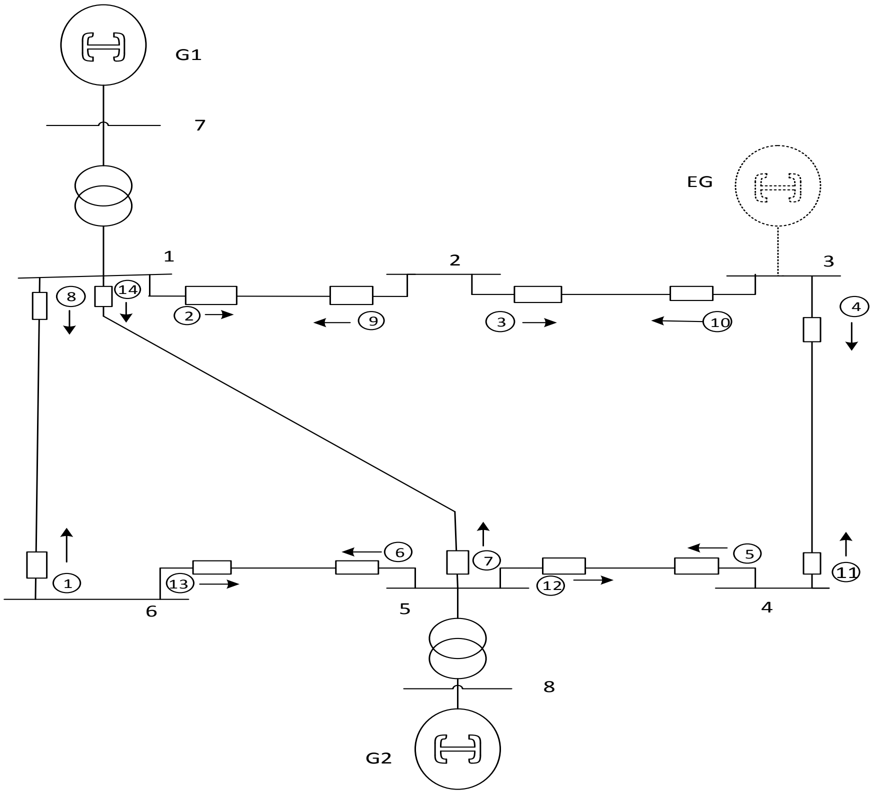

Figure 5.1 8-bus test system

The test case has 14 relays, the value of **TDSs** of each of which varies continuously from **0.1 to 1.1**. The **pick up tap settings** vary from **.5 to 2.5**.

Table 5.1 Current transformer ratio specification

Relay No.	CT Ratio	Relay No.	CT Ratio
1	1200:5	8	1200:5
2	1200:5	9	800:5
3	800:5	10	1200:5
4	1200:5	11	1200:5
5	1200:5	12	1200:5
6	1200:5	13	1200:5
7	800:5	14	800:5

Table 5.2 Fault currents

Primary relay	Fault Current (A)	Backup 1	Fault Current (A)	Backup2	Fault Current (A)
1	3232	6	3232	0	0
2	5924	1	996	7	1890
3	3556	2	3556	0	0
4	3783	3	2244	0	0
5	2401	4	2401	0	0
6	6109	5	1197	14	1874
7	5223	5	1197	13	987
8	6093	7	1890	9	1165
9	2484	10	2484	0	0
10	3883	11	2344	0	0
11	3707	12	3707	0	0
12	5899	13	987	14	1874
13	2991	8	2991	0	0
14	5199	1	996	9	1165

Zero value denote absence of a backup relay and corresponding fault current is mentioned as zero

IEEE 14 Bus system

The system shown below is standard IEEE 14-Bus system with G1 having 430 MVA capacity. Other specifications of system related to line, loads and transformer tap settings is listed in appendix A.

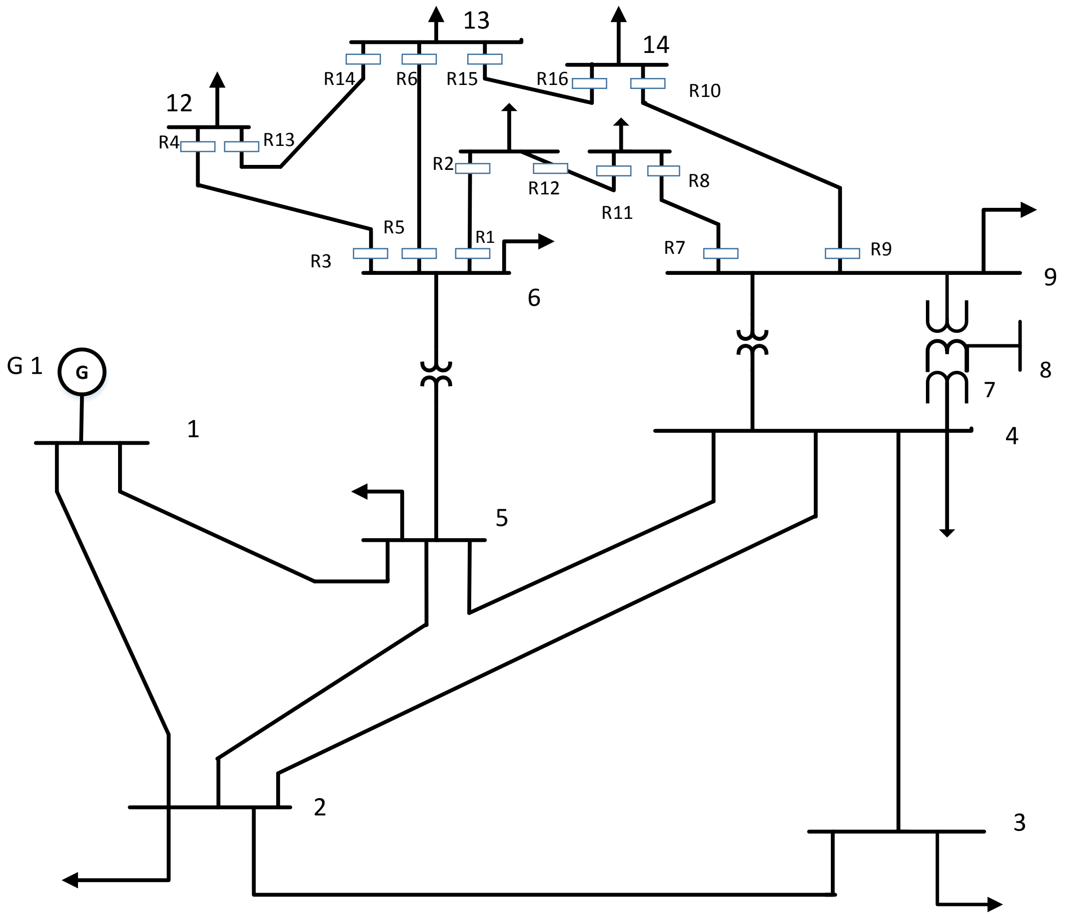

Figure 5.2 14-bus test system

Chapter 6

6.1 Formulation of Objective Function and Optimization Framework

6.1.1 Objective Function Formation

The relay coordination is expressed as a constrained optimization problem. The objective function and the constraints of the optimization problem are specified as:

6.1.2 Objective function

The prime purpose of the objective function is the minimization in total time of operation of the relays when subjected to a fault in their vicinity making them as primary protective relay.

$$\mathrm{F} = \min\{\textstyle\sum_{q=1}^{NR}(tq)\}$$

(6.1)

where, $'tq'$ represents, the time of operation of the relay q, NR represents the total number of relays in the power system of interest. For each protective relay the time of operation $'tq'$ is defined as follows:

$$tq = \frac{K1 * TDS}{\frac{I}{CTRatio * Ip}^{K2} - 1}$$

(6.2)

The variables in formula have already been explained in chapter on relay equation.

6.1.3 Optimization constraints

In the process of optimization of mentioned objective function it is subjected to below mentioned constraints which ensures that the relays settings are chosen such that they remain in coordinated state.

6.1.3.1 Coordination Time Interval (CTI)

The coordination between the primary and the backup relays must be ascertained to guarantee selectivity. This is done as shown below.

$$t_{backup} - t_{primary} \geq \text{CTI} \tag{6.3}$$

where, t_{backup} and $t_{primary}$ denote time of operation for backup and primary relay respectively, CTI signifies the minimum coordination time interval that should be maintained between every primary and backup relay pair. CTI generally varies between 200 to 800 milliseconds.

6.1.3.2 Plug setting

They are discrete settings used to tap specific portions of actuating coil so as to alter the value of actuating current. It is also defined as the ratio of pickup current to CT ratio and has typical range of .5 to 2.5. So plug setting * CT ratio is equal to pickup current. Instead to pickup current, PS has been selected for optimization in present study. This constraint is a device constraint, as it is an attribute of electromagnetic overcurrent relay.

$$t = \frac{K1 * TDS}{\left(\frac{If}{PS * CT\ Ratio}\right)^{K2} - 1} \tag{6.4}$$

6.1.3.3 Time Dial Setting (TDS)

The function of *TDS* (Time Dial Setting) is to regulate the time delay that occurs after magnitude of fault current becomes equal to or more than the pickup current value.

$$TDS_{min} \leq TDS \leq TDS_{max} \tag{6.5}$$

where, TDS_{min} is the minimum limit and TDS_{max}, the corresponding maximum limit of TDS.

6.1.3.4 Minimum operating time

In order to avoid false tripping due to initial current of loads and transient faults every relay must operate only after a certain threshold time. Here, the minimum time for any relay to operate has been set as 0.2 seconds.

6.1.5 Constraints violation handling

The coordination constraint given in equations 6.3,6.5 and that of minimum time of operation tends to get violated at times, during the process of optimization. In such an event, the penalty function (PF) is imposed in conjugation of total time of operation to yield the modified objective function. Minimization of such a function would yield no coordination violations.

$$F_{1penalized} = F_1 + PF \tag{6.6}$$

Where, F_1 is the objective function presented in (6.1) without penalization; and *PF* refers to the penalty function mentioned below:

$$PF=\sum_{i=1}^{N} Penalty(i) \tag{6.7}$$

N : Total number of primary backup pairs in system

The *Penalty* parameter is calculated as shown below:

- Set *Penalty* [1: N] = 0

- For a particular set of backup relay *j* and primary relay *i*

In the event of any violation of coordination, that when time interval between relay pairs is less than 300 milliseconds, the penalty is computed as:

$$\text{“}1*e^{5}*(\text{abs}(\ ((\text{CTI\_1}(i))-\text{CTI})\ )\ -\ ((\text{CTI\_1}(i))-\text{CTI}))\text{”} \qquad (6.8)$$

in optimization program, where CTI_1(i) is difference in time of operation of primary relay i with its first backup. The best solution is one which has least value of objective function with no violations.

Penalty on violation of minimum operating of primary relay is imposed by assigning it a large value.

Chapter 7

7.1 Results and Observations

Particle Swarm Optimization algorithm has been implemented on fault data of both eight bus and IEEE 14-bus system using MATLAB software to optimize objective function. In case of IEEE 14-Bus system, modified relay characteristics in addition to conventional relay characteristic has been used to compute time of operation with distributed generator installed in grid.

Eight bus system:

The test system data is input to the algorithm and time of operation obtained is compared with that provided in the journal consulted for the system.

<u>Case 1:</u>

Iterations: 100

Penalty: No

Objective function value: 28.38

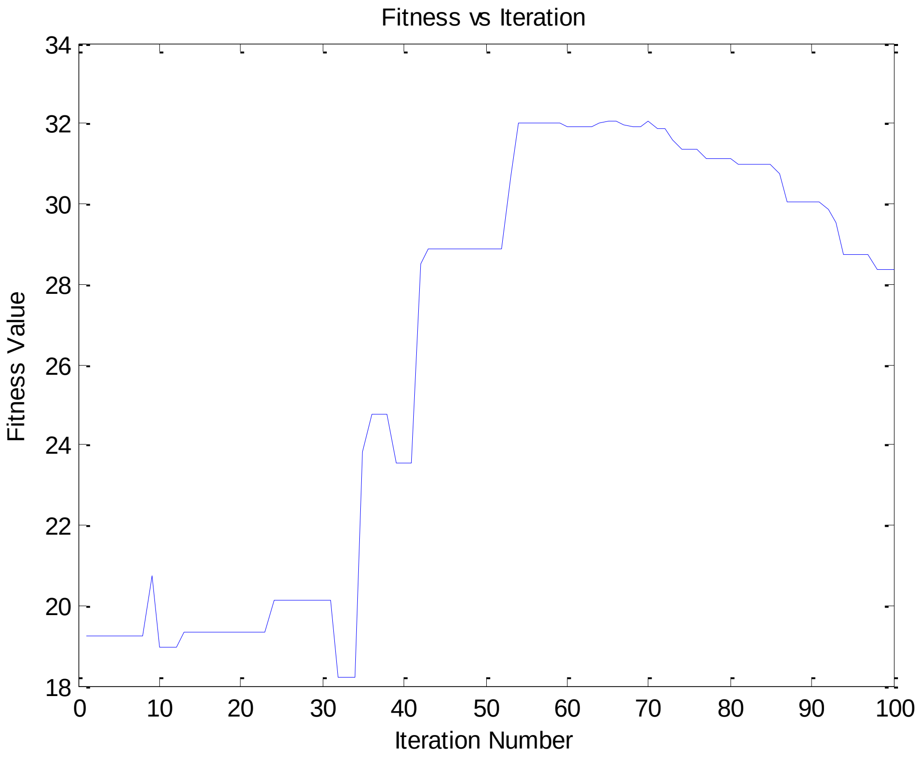

Figure 7.1: Fitness value graph (100 Iterations)

Objective function value of 28.38 is obtained after 100 iterations. Initially graph shows lower values and for later iterations shows a jump suggesting non violated objective function will have higher value than that observed in the launch iterations. This observation is supported by final value of objective function with no violations. The graph shape though suggests that function value could further reduce with more iterations.

Case 2:

Iterations: 500

Penalty: Yes

Objective function value: 9.99

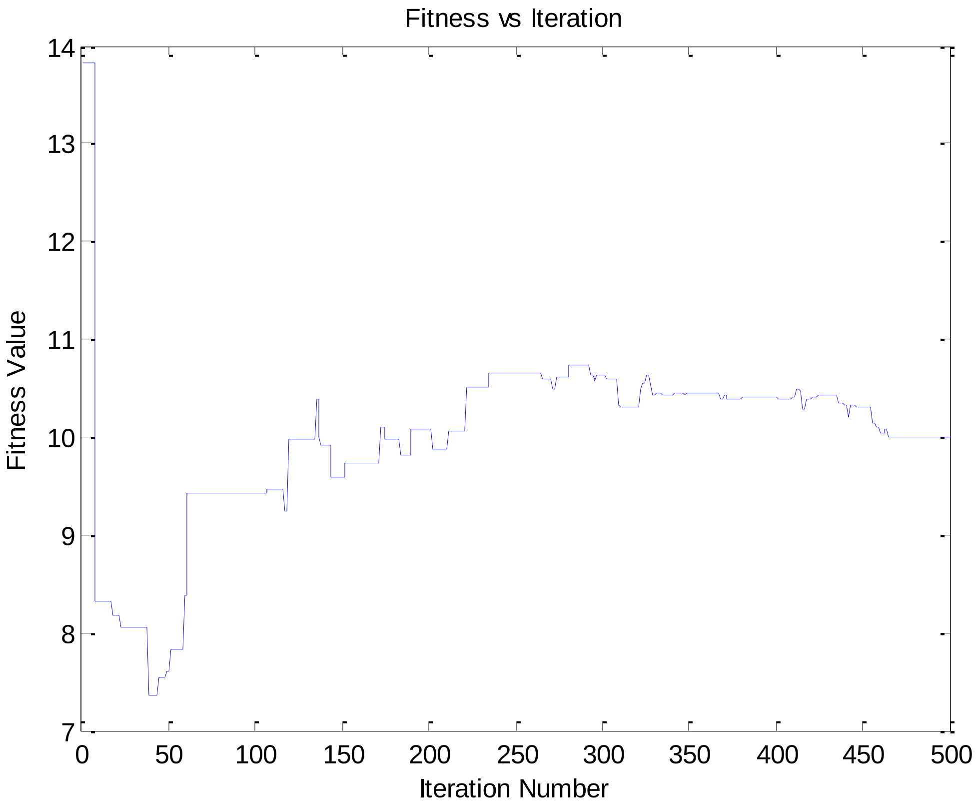

Figure 7.2 Fitness value graph (500 Iterations)

Above is lowest value achieved by algorithm, but it does not ensure coordination as it has violated the constraints imposed. Objective function value in this case is more or less settled after initial iterations.

Case 3:

Iterations: 500

Penalty: No

Objective function value: 25.19

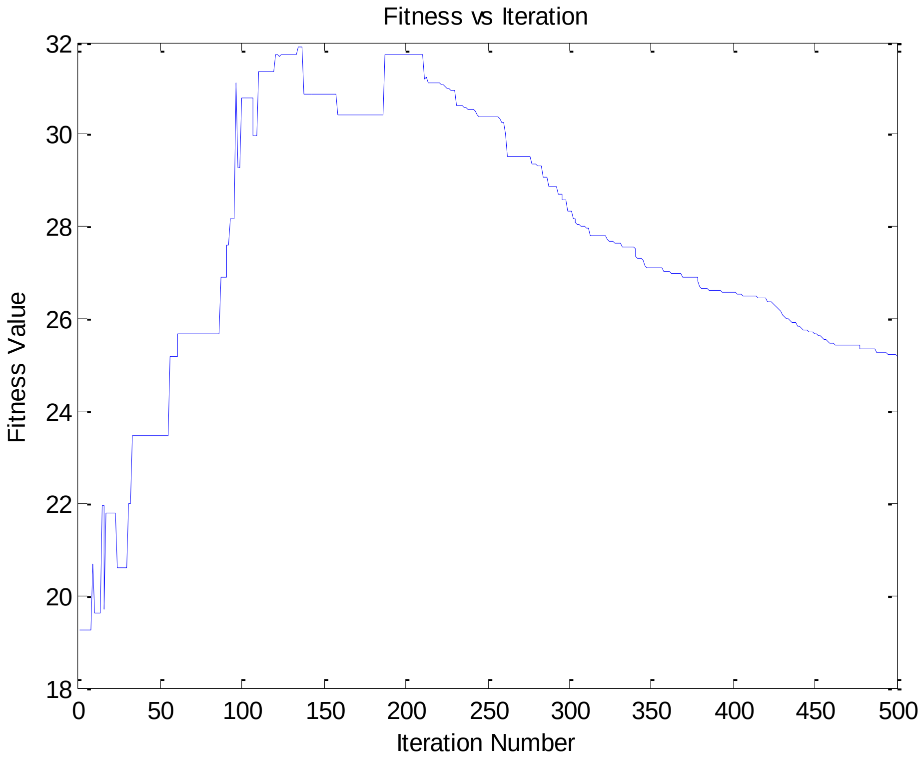

Figure 7.3 Fitness value graph (500 Iterations)

When algorithm code is executed again with same number of iterations as in previous case the function is found to achieve value of 25.19 with no violations. This value is lower than 100 iterations case and hence there is motivation to still perform greater number of iterations till the value settles for a larger part of iterations.

Case 4:

Iterations: 1000

Penalty: No

Objective function value: 23.12

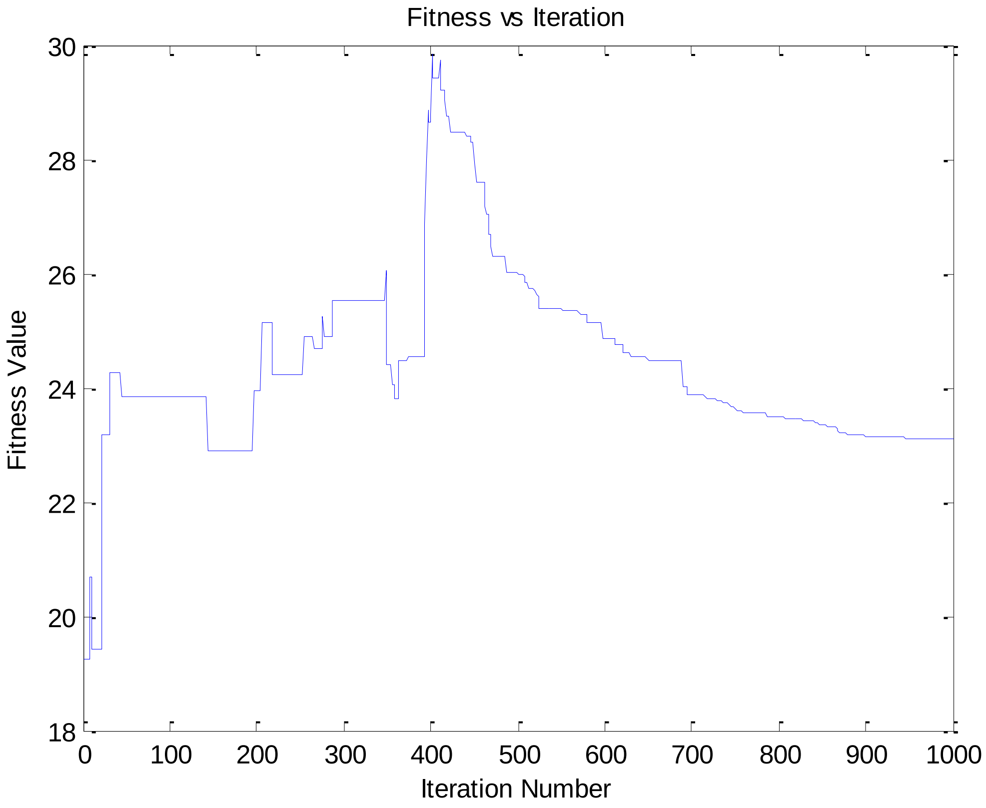

Figure 7.4 Fitness value graph (1000 Iterations)

Upon performing more iterations, the graph does show significant change in shape in comparison to previous graphs in that, it has a settled value for significant number of iterations.

Table 7.1 shows optimized values of TDS and PS for the case 4.

Table 7.1 Optimized settings

Relay	TDS	PS	Relay	TDS	PS
1	0.629756	0.5	8	0.620596	0.5
2	0.577948	2.5	9	0.432893	2.5
3	0.615582	2.5	10	0.534209	1.546596
4	1.1	0.5	11	1.1	0.5
5	0.734235	0.5	12	0.654073	2.5
6	1.1	0.5	13	0.273421	1.930253
7	0.527808	2.5	14	0.630553	2.5

Case 5:

Iterations: 2000

Penalty: No

Objective function value: 26.49

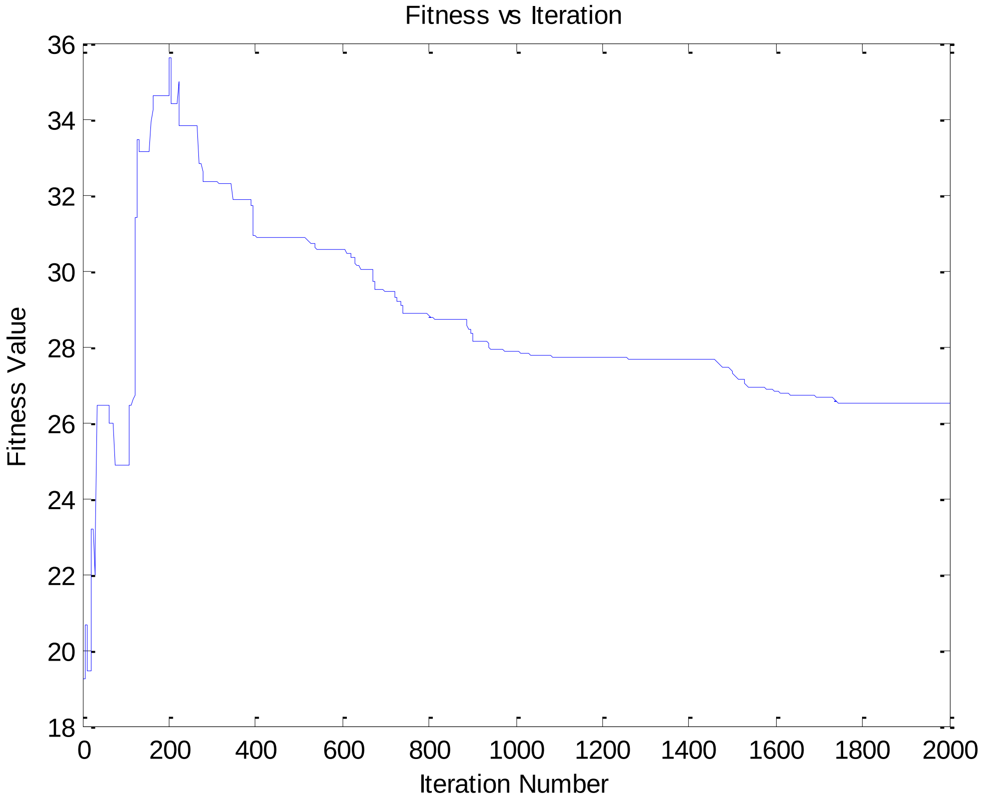

Figure 7.5 Fitness value graph (2000 Iterations)

When still more iterations were performed the graph depicts a shape similar to that of case 4 in the initial part. In this case the value settled for even larger part of iterations. It also suggests that for particular problem 1000 iterations are enough to attain reasonably good value.

Table 7.1 shows optimized values of TDS and PS for the case 4.

Table 7.2 Optimized relay settings (case 5)

Relay	TDS	PS	Relay	TDS	PS
1	0.160036	2.5	8	1.1	0.5
2	1.1	0.5	9	1.1	0.5
3	0.362098	2.5	10	0.507489	2.5
4	0.583928	0.5	11	0.427727	2.5
5	0.205535	2.5	12	0.618736	1.689999
6	0.233434	2.5	13	0.152749	2.458315
7	1.1	0.5	14	0.880272	0.5

The objective function is also optimized using optimization tool box of MATLAB for checking consistency with PSO results. The mentioned MATLAB solver computed value of 27.12, which is nearer to that of obtained using PSO

Solver used: fmincon

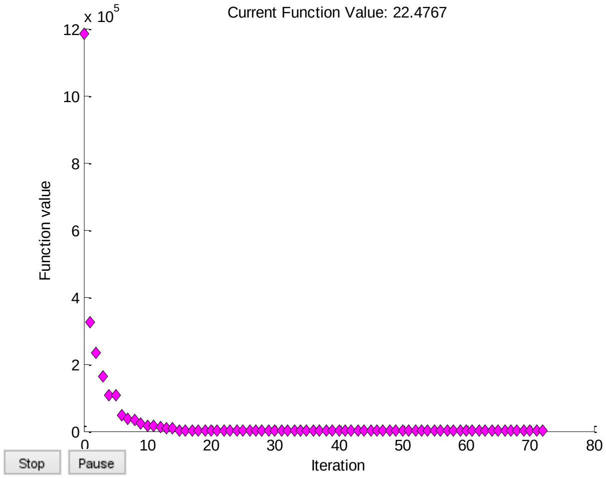

Figure 7.7 fitness value graph (Optimtool box)

The table below shows optimized results from consulted journal [11].

Table 7.3 Optimized relay setting [11]

Relay	TDS	PS	Relay	TDS	PS
1	0.29	1	8	0.24	2.5
2	0.31	2.5	9	0.17	2
3	0.26	2.5	10	0.19	2.5
4	0.19	2.5	11	0.21	2.5
5	0.18	1.5	12	0.36	2.5
6	0.26	2.5	13	0.23	1.5
7	0.54	0.5	14	0.51	0.5

Observation:

The algorithm worked satisfactorily on the fault data the system, and after zero violation the system can be assured to be in coordinated state with minimum time of operation feasible. It was however observed that upon execution of program with same number of iterations multiple times, the algorithm at times produced results with violations, this suggest the randomness of the technique.

The journal paper from which data set was sought had a lower objective function value of 11.01 seconds but with violations. The optimum settings mentioned in the paper was tested in the designed program and it did produce same value (with violations). This reassured that program was coded correctly.

IEEE 14 Bus system:

Following graphs show three phase voltage and current measured at relay R5.

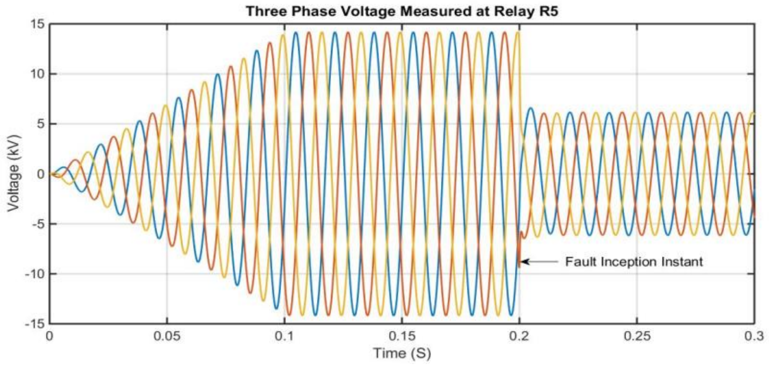

Figure 7.8 Three phase voltage measured at relay R5

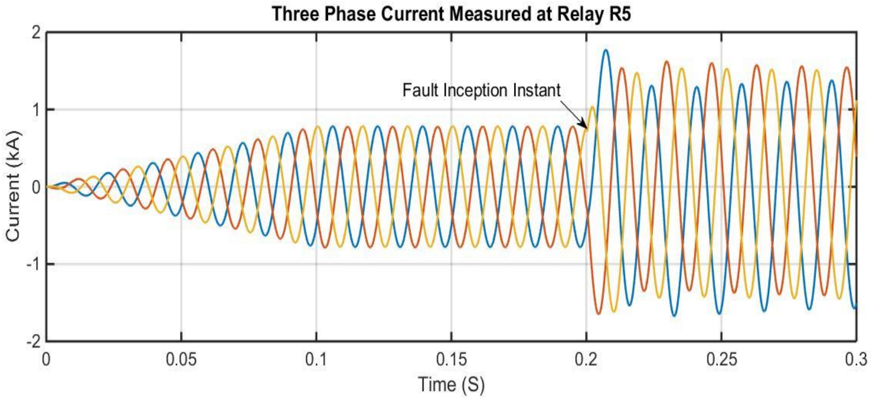

Figure 7.9 Three phase current measured at relay R5

Generator takes .1 seconds to buildup voltage when simulation is initiated.

Dip in voltage level with simultaneous increase in current is observed at relay R5 when three phase fault is introduced at .2 seconds.

Following tables shows three phase midpoint fault data when no DG is connected in the system.

Table 7.4 Three phase fault current with no DG

Primary relay	**Fault Current (A)**	**Backup 1**	**Fault Current (A)**	**Backup2**	**Fault Current (A)**
1	10392	4	172	6	754
2	4869	11	4833	0	0
3	10028	2	2104	6	1255
4	2919	14	2875	0	0
5	11989	2	2412	4	1050
6	3857	13	1038	16	2671
7	13961	10	1581	0	0
8	4220	12	4035	0	0
9	10248	8	1447	0	0
10	3596	15	3566	0	0
11	8396	7	8341	0	0
12	5994	1	5960	0	0
13	4289	3	4287	0	0
14	7358	5	5175	16	2239
15	6864	5	5524	13	1389
16	4822	9	4806	0	0

Table below shows phase voltage corresponding to various fault locations.

Table 7.5 Three phase fault voltage with no DG

Primary relay	**Voltage (p.u.)**	**Backup 1**	**Voltage (p.u.)**	**Backup2**	**Voltage (p.u.)**
1	0.258592	4	0.267324	6	0.281549
2	0.120986	11	0.349859	0	0
3	0.321127	2	0.426127	6	0.283803
4	0.092817	14	0.283803	0	0
5	0.197394	2	0.315986	4	0.13007
6	0.062042	13	0.13007	16	0.296479
7	0.13838	10	0.246408	0	0
8	0.041901	12	0.232887	0	0
9	0.346268	8	0.375704	0	0
10	0.119648	15	0.429648	0	0
11	0.197183	7	0.367746	0	0
12	0.141549	1	0.440282	0	0
13	0.145423	3	0.415563	0	0
14	0.249366	5	0.415986	16	0.438592
15	0.301338	5	0.486338	13	0.393732
16	0.210845	9	0.538944	0	0

Following tables show optimized relay settings in scenario of no DG connected to the system and CT ratio of 500:1.

Table 7.6 Optimized relay settings [no DG]

Relay	TDS	PS	Relay	TDS	PS
1	1.1	0.5	9	1.1	2.5
2	0.479563	0.512943	10	0.115565	2.5
3	0.089228	2.5	11	0.276745	2.5
4	1.1	0.5	12	0.313112	0.5
5	0.384707	2.5	13	0.035666	2.5
6	1.1	0.5	14	0.402813	2.5
7	1.1	2.5	15	0.160049	2.5
8	0.081875	2.5	16	0.427226	2.015244

Table 7.7 Optimized relay settings using modified relay equation [no DG]

Relay	TDS	PS	K	Relay	TDS	PS	K
1	1.1	2.5	2	9	1.1	0.5	2
2	0.290186	2.5	2	10	1.1	0.5	2
3	1.1	2.5	2	11	1.1	2.5	2
4	0.149981	2.5	2	12	0.281819	0.5	0
5	0.403657	2.5	2	13	1.1	0.5	2
6	0.212502	2.5	2	14	0.251292	2.5	2
7	1.072923	2.5	2	15	0.370975	2.5	2
8	1.1	0.5	2	16	1.1	0.5	2

Following tables show optimized relay settings in scenario of no DG connected to the system and CT ratio of 1000:1.

Table 7.8 Optimized relay settings [no DG]

Relay	TDS	PS	Relay	TDS	PS
1	1.1	0.5	9	0.204559	0.588922
2	0.019181	2.5	10	1.1	0.5
3	1.1	0.5	11	1.1	0.5
4	0.01	2.5	12	0.152563	0.5
5	1.1	0.5	13	0.015571	2.5
6	0.012503	2.495245	14	0.031354	2.5
7	0.514601	2.499988	15	0.210124	2.5
8	0.015082	2.5	16	0.121742	0.5

Table 7.9 Optimized relay settings using modified relay equation [no DG]

Relay	TDS	PS	K	Relay	TDS	PS	K
1	1.1	0.5	2	9	0.151134	2.5	2
2	0.111223	2.5	2	10	1.1	0.5	2
3	1.1	0.5	2	11	1.1	0.5	2
4	1.1	0.5	2	12	1.1	0.5	2
5	1.1	0.5	2	13	0.196923	1.250731	2
6	1.1	0.5	2	14	1.1	0.5	2
7	1.1	2.5	2	15	1.1	0.5	2
8	0.423067	0.5	2	16	0.091567	2.5	2

Below is shown three phase midpoint fault data for the case when DG is connected to Bus 14.

Table 7.10 Three phase fault current with DG connected at Bus 14

Primary relay	**Fault Current (A)**	**Backup 1**	**Fault Current (A)**	**Backup2**	**Fault Current (A)**
1	14973	4	1279	6	5151
2	7656	11	7612	0	0
3	13659	2	3463	6	2055
4	5077	14	5049	0	0
5	14928	2	4623	4	649
6	11180	13	682	16	10602
7	23877	10	12976	0	0
8	6426	12	6224	0	0
9	12026	8	3342	0	0
10	3080	15	3222	0	0
11	12979	7	12949	0	0
12	8499	1	8468	0	0
13	5669	3	5660	0	0
14	12145	5	4106	16	8401
15	8460	5	6816	13	1714
16	25197	9	4044	0	0

Table 7.11 Three phase fault voltage with DG connected at Bus 14

Primary relay	**Voltage (p.u.)**	**Backup 1**	**Voltage (p.u.)**	**Backup2**	**Voltage (p.u.)**
1	0.327698	4	0.395883	6	0.476482
2	0.169183	11	0.489582	0	0
3	0.389707	2	0.537492	6	0.440799
4	0.144167	14	0.440362	0	0
5	0.217031	2	0.418403	4	0.185028
6	0.163631	13	0.183968	16	0.995571
7	0.21335	10	0.995571	0	0
8	0.057143	12	0.318777	0	0
9	0.360699	8	0.417405	0	0
10	0.984841	15	0.768497	0	0
11	0.271678	7	0.506862	0	0
12	0.178291	1	0.554648	0	0
13	0.170119	3	0.485714	0	0
14	0.365253	5	0.485714	16	0.993575
15	0.329507	5	0.531129	13	0.430381
16	0.986588	9	0.787087	0	0

Following tables show optimized relay settings in scenario of DG connected to Bus 14 and CT ratio of 500:1.

Table 7.12 Optimized relay settings [DG connected]

Relay	TDS	PS	Relay	TDS	PS
1	1.1	0.5	9	1.1	0.5
2	1.1	0.777665	10	1.1	1.111518
3	1.1	2.5	11	0.755777	2.499108
4	0.04071	2.5	12	0.769131	0.5
5	1.1	0.906385	13	1.1	0.5
6	1.1	0.5	14	1.1	0.5
7	1.1	1.315882	15	0.726992	2.229997
8	0.314134	2.5	16	0.703394	2.5

Table 7.13 Optimized relay settings using modified relay equation [DG connected]

Relay	TDS	PS	K	Relay	TDS	PS	K
1	0.553629	0.5	0	9	0.757097	0.5	0
2	1.1	1.020498	2	10	0.311239	2.5	2
3	1.1	1.327342	2	11	0.416799	0.5	0
4	1.1	0.5	2	12	1.1	2.5	2
5	1.1	0.5	1.118611	13	1.1	2.5	2
6	1.1	0.5	1.36248	14	1.1	0.5	2
7	1.1	0.5	1.254334	15	1.1	2.5	2
8	0.733951	2.5	1.997122	16	1.1	0.5	2

Following tables show optimized relay settings in scenario of DG connected to Bus 14 and CT ratio of 1000:1.

Table 7.14 Optimized relay settings [DG connected]

Relay	TDS	PS	Relay	TDS	PS
1	1.1	0.664802	9	1.1	0.5
2	1.1	0.5	10	1.1	0.500013
3	1.1	0.5	11	0.490637	2.5
4	0.020792	2.5	12	1.1	0.5
5	1.1	0.5	13	0.220973	0.5
6	1.1	0.5	14	0.172123	0.5
7	1.1	0.551339	15	0.162751	2.5
8	0.11059	2.5	16	1.1	0.666908

Table 7.11 Optimized relay settings using modified relay equation [DG connected]

Relay	TDS	PS	K	Relay	TDS	PS	K
1	0.257356	2.5	2	9	1.006715	0.5	2
2	0.372196	2.5	2	10	0.48319	0.5	2
3	0.300763	2.5	2	11	0.338536	2.5	2
4	0.119194	2.5	2	12	0.259272	2.5	2
5	0.475424	0.5	0	13	1.1	0.5	2
6	0.059681	2.5	0	14	0.767199	2.5	2
7	1.1	2.5	2	15	1.1	0.5	2
8	0.181732	2.5	2	16	1.1	0.5	2

Observation:

For the first scenario when no DG is connected in the system the total time of operation of primary relays is obtained as 24.22 seconds and 26.80 seconds, when CT ratio of 500:1 and 1000:1 is used respectively. This result is obtained when conventional relay characteristics is used in formulation of objective function. The time of operation however reduced to 7.58 seconds (CT ratio 500:1) and 7.78 seconds (CT ratio 1000:1) when modified relay equation is employed in objective function. Both of the cases had no violations in operation timings between primary and backup relay pairs. The optimization program converged in 1000 iterations.

In second case a DG of 10 MVA capacity is installed at Bus number 14 without any change in the rest of system. It is observed from line current measurement of generators of the entire bus system that there is a reduction in loading of transmission network generator and that the difference is supplied by DG installed at bus 14. The shift in loading of generator manifests itself as overall increase in fault current magnitude as can be seen from fault current data table. Results of optimizations show 33.48 seconds (CT ratio 500:1) and 30.12 seconds (CT ratio 1000:1) seconds as overall time of operation when conventional characteristic is used. It reduces to 14.25 seconds (CT ratio 500:1) and 10.43 seconds (CT ratio 1000:1) when modified characteristics is used. Also, it is evident that total time of operation increases when DG is introduced in the system.

It also noticed that TDS and PS are generally large valued for relays with higher fault current. This helps to increase time of operation for these relays in order to avoid the violation of minimum time of operation.

Further, the drastic reduction in total time of operation in case of using modified relay characteristic equation is owed to larger number of relays having optimized value of K as 2. This significantly reduces time operation of any relay in comparison to that when conventional characteristic is used.

Chapter 8

8.1 Conclusion and future work

8.1.1 Conclusion

First part of study focuses on development of an optimization algorithm to obtain relay settings with the constraint of keeping system in coordinated state which is mathematically put into perspective by checking for difference in time of operation of primary and its backup relay. The developed algorithm is tested on simulation results of journal paper [22]. The algorithm is found to optimize objective function successfully for most of the cases, expect for a few occasions when penalty is observed for the cases which yielded none in other instances. This is attributed to randomness of technique. This prime facie appears to be short coming of the method, but it is this attribute of the technique which saves it from being trapped in local minima. What must be emphasized here is that a higher value objective function must be acceptable rather than getting a lower value with violations, as it can lead to erroneous tripping.

In the next phase of study IEEE 14-bus system is designed using PSCAD/EMTDC software. The fault data obtained from simulation is put in the program code developed in the earlier phase. Two scenarios of generations are considered, one with no DG connected and other with a DG. Both of the scenarios are optimized using two different relay characteristics and different CT ratios. It can be concluded from observation of both the scenarios that modified relay characteristic is efficient in reducing overall time of operation of relays keeping the system in coordination. CT ratio change results in variation of time of operation in various scenarios studied, it is an important factor to consider when dealing with DGs in grid which cause increase in fault current magnitude. Abnormally high value of fault current beyond a certain interval of time (depending on fault current magnitude) may result in CT getting saturated. So studying effect of CT ratio on time of operation is pertinent in respect of future expansion of a system or establishment of a new one.

5.1.2 Future work

It is observed that addition of DG increased fault current levels in the system. In the present study the system settings were recalculated for the scenario with DG installed. These settings will have to be reevaluated for every possible scenarios considering the impact of DG capacity on fault currents. The problem is just not limited to relay settings computation, the power flow in the system changes with different points of installation of DG. Hence a prudent decision has to be taken during installation of current transformers which is generally a onetime investment and does not have flexibility like a digital relay. Future study on this topic should take into consideration above mentioned problems and suggest allowable DG capacity and points of installation so that capital investment made sustains itself for future expansion.

References

[1] G. P. Baber, P. G. Beaumont, K. Fukushima, T. Miyoshi, T. Shono, M. Ookubo, T. Tanaka. K. Abe, S. Umeda, F. Kawano, "Intelligent protection relay system for smart grid," in *10th IET International Conference Developments in Power System Protection (DPSP 2010). Managing the Change*, Manchester, 2010.

[2] K. K. Li, K. P. Wong, Hui Wan, "An adaptive multiagent approach to protection," *IEEE Transactions on Industry Applications,* vol. 46, no. 5, pp. 2118 - 2124, September 2010.

[3] M. Damborg, R. Ramaswami, S. Venkata, and J. Postforoosh, “Computer aided transmission protection system design part I: Alcorithms,” *IEEE Trans. Power App. Syst.*, vol. PAS-103, no. 1, pp. 51–59, Jan. 1984.

[4] M. H. Dwarakanath and L. Nowitz, “An application of linear graph theory for coordination of directional overcurrent relays,” in *Proc. Elect. Power Problems—Math. Challenge Conf.*, Seattle, WA, 1980, no. 1, pp. 104–114, SIAM

[5] L. Jenkins, H. Khincha, S. Shivakumar, and P. Dash, “An application of functional dependencies to the topological analysis of protection schemes,” *IEEE Trans. Power Del.*, vol. 7, no. 1, pp. 77–83, Jan. 1992.

[6] A. Urdaneta, R. Nadira, and L. P. Jimenez "Optimal coordination of directional overcurrent relays in interconnected power systems," *IEEE Trans. Power Del.*, vol. 3, no. 3, pp. 903–911, Jul. 1988.

[7] B. Chattopadhyay, M. Sachdev, and T. Sidhu, “An online relay coordination algorithm for adaptive protection using linear programming technique,” *IEEE Trans. Power Del.* , vol. 11, no. 1, pp. 165–173, Jan. 1996.

[8] H. Abyaneh, M. Al-Dabbagh, H. Karegar, S. Sadeghi, and R. Khan, “A new optimal approach for coordination of overcurrent relays in inter- connected power systems,” *IEEE Trans. Power Del.*, vol. 18, no. 2, pp. 430–435, Apr. 2003.

[9] F. Razavi, H. A. Abyaneh, M. Al-Dabbagh, R. Mohammadi, and H. Torkaman, "A new comprehensive genetic algorithm method for optimal overcurrent relays coordination," *Elect. Power Syst. Res.*, vol. 78, no. 4, pp. 713–720, 2008.

[10] P. Bedekar and S. Bhide, "Optimum coordination of directional overcurrent relays using the hybrid GA-NLP approach," *IEEE Trans. Power Del.*, vol. 26, no. 1, pp. 109–119, Jan. 2011.

[11] A. Noghabi, J. Sadeh, and H. Mashhadi, "Considering different network topologies in optimal overcurrent relay coordination using a hybrid GA," *IEEE Trans. Power Del*, vol. 24, no. 4, pp. 1857–1863, Oct. 2009.

[12] Adhishree, Ram Krishan, Jyant Mani Tripathi, "Optimal coordination of overcurrent relays using gravitational search algorithm with DG penetration," in *Power India International Conference (PIICON)*, Delhi,2014

[13] P. Bedekar, S. Bhide, and V. Kale, "Optimum coordination of overcurrent relays in distribution system using genetic algorithm," in *Proc. Int. Conf. Power Syst.*, Dec. 2009, pp. 1–6.

[14] C. W. So and K. K. Li, "Time coordination method for power system protection by evolutionary algorithm," *IEEE Trans. Ind. Appl.*, vol. 36, no. 5, pp. 1235–1240, Sep. 2000.

[15] T. A. Kurashvili, G. N. Korres, V. A. Papaspiliotopoulos, "Optimal coordination of directional overcurrent relays in distribution systems with distributed generation based on a hybrid PSO-LP algorithm," in *MedPower 2014*, Athens, 2014.

[16] H. Zeineldin, E. El-Saadany, and M. Salama, "Optimal coordination of overcurrent relays using a modified particle swarm optimization," *Elect. Power Syst. Res.*, vol. 76, no. 11, pp. 988–995, 2006.

[17] M. Mansour, S. F.Mekhamer, and E.-S. N. El-Kharbawe, "A modified particle swarm optimizer for the coordination of directional overcurrent relays," *IEEE Trans. Power Del.*, vol. 22, no. 3, pp. 1400–1410, Jul. 2007.

[18] J. Sadeh, H. Rajabi Mashhadi and M. Taghizadeh, "A new hybrid particle swarm optimization for optimal coordination of over current relay," in *International Conference on Power System Technology*, Hangzhou, 2010.

[19] Peyman Ayubi and Mohammad Hoseein Mojarrad, "Particle swarm optimization with chaotic velocity clamping (CVC-PSO)," in *7th Conference on Information and Knowledge Technology*, Urmia, 2015.

[20] Schneider Electric, "Standard Inverse Time (SIT and SIT-A) 3000 TC," LaVergne, TN, USA, 2008.

[21] H. H. Zeineldin, A. Al Hinai, Ehab F. El-Saadany and Khaled A. Saleh, "Optimal coordination of directional overcurrent relays using a new Time–Current–Voltage characteristic," *IEEE Trans. Power Del.,* vol. 30, no. 2, pp. 537- 544, 2015

[22] T. Amraee, "Coordination of directional overcurrent relays using seeker algorithm," *IEEE Trans. Power Del.,* vol. 27, pp. 1415-1422, 2012.

[23] Univ. Washington, Seattle, WA, USA, “Power systems test case archive,” Tech Rep., 2006. [Online]. Available: http://www.ee.washington.edu/research/pstca

Appendix A.

8 Bus system

Table A.1 Line data - 8 bus system [22]

Nodes	*R* (Q/km)	*X* (Q/km)	*Y* (S/km)	Length
1–2	0.004	0.05	0.0	100
1–3	0.0057	0.0714	0.0	70
3–4	0.005	0.0563	0.0	80
4–5	0.005	0.045	0.0	100
5–6	0.0045	0.0409	0.0	110
2–6	0.0044	0.05	0.0	90
1–6	0.005	0.05	0.0	100

Table A.2 Generator data [22]

Node	MVA	*V*p (kV)	*x* (%)
7	150	10	15
8	150	10	15

Table A.3 Transformer data [22]

Node	MVA	*V*p (kV)	*V*s (kV)	*x* (%)
7–1	150	10	150	4
8–6	150	10	150	4

IEEE 14 Bus system

The data shown in the following tables is provided on 100MVA base.

Table A.4: Line data IEEE 14-bus system [23]

Line Number	From bus	To bus	Line impedance (*p.u.*)		Half line charging susceptance (*p.u.*)
			Resistance	Reactance	
1	1	2	0.01938	0.05917	0.02640
2	1	5	0.05403	0.22304	0.02190
3	2	3	0.04699	0.19797	0.01870
4	2	4	0.05811	0.17632	0.02460
5	2	5	0.05695	0.17388	0.01700
6	3	4	0.06701	0.17103	0.01730
7	4	5	0.01335	0.04211	0.00640
8	4	7	0	0.20912	0
9	4	9	0	0.55618	0
10	5	6	0	0.25202	0
11	6	11	0.09498	0.1989	0
12	6	12	0.12291	0.25581	0
13	6	13	0.06615	0.13027	0
14	7	8	0	0.17615	0
15	7	9	0	0.11001	0
16	9	10	0.03181	0.0845	0
17	9	14	0.12711	0.27038	0
18	10	11	0.08205	0.19207	0
19	12	13	0.22092	0.19988	0
20	13	14	0.17093	0.34802	0

Table A.5: Bus data IEEE 14-bus system [23]

Bus number	Load	
	Real Power (MW)	Reactive Power (MVAR)
1	0	0
2	21.7	12.7
3	94.2	19.1
4	47.8	-3.9
5	7.6	1.6
6	11.2	7.5
7	0	0
8	0	0
9	29.5	16.6
10	9.0	5.8
11	3.5	1.8
12	6.1	1.6
13	13.8	5.8
14	14.9	5.0

Table A.6: Transformer tap setting data IEEE 14-bus system [23]

From bus	To bus	Tap setting value (*p.u.*)
4	7	0.978
4	9	0.969
5	6	0.932