DEVELOPMENT OF NON-STANDARD CHARACTERISTICS FOR DIRECTIONAL OVERCURRENT RELAYS USING HEURISTIC OPTIMIZATION METHODS

DUAL DEGREE PROJECT THESIS

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By

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CERTIFICATE

This is to certify that the project work entitled "DEVELOPMENT OF NON-STANDARD CHARACTERISTICS FOR DIRECTIONAL OVERCURRENT RELAYS USING OPTIMIZATION METHODS" submitted by **Vasukumar Bhimani**, EE14B109, to **Indian Institute of Technology Madras** in partial fulfillment of the requirements for the award of degree of **Master of Technology**, is a bonafide record of work carried out by him. The contents of this report, in full or part have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

KEYWORDS: Distribution networks, Protection coordination, Directional overcurrent relays, nonlinear programming, heuristic programming, hybrid heuristic programming, optimization

Electrical power networks are prone to disturbances due to short circuit faults caused by various unintended phenomena involving or without involving human intervention. The immediate effect of a short-circuit fault is the sudden rise of fault current which, if exceeds the nominal operating limit of the electrical equipment, could cause accountable damage to it. Hence, it is extremely necessary to provide proactive protection schemes to detect and dislocate the short-circuit in time before the current results to the damaging level of the equipment. In sub-transmission or distribution line protection, each line is equipped with necessary primary and backup protection devices to ensure multi-tier protection for isolating the fault. However, to ensure the reliable performance of the protection, the primary and backup protection devices are to be properly coordinated such that the fault is cleared in time before the disturbance expands further.

For sub-transmission and distribution systems, directional overcurrent protection becomes more feasible and economical compared to distance protection. The coordination of directional overcurrent relays (DOR) can be formulated as a numerical optimization problem with an objective to minimize the overall DOR operating times, subject to coordination and other operating constraints. In the past literature, the DOR coordination problem is solved by using many traditional, heuristic and hybrid heuristic optimization techniques. However, the past techniques though work fairly effective, they do not provide the best relay operating times due to the behavior of the inverse characteristic or the operational constraints posed in the coordination problem. This work addresses the DOR coordination with a non-standard characteristics which are generated by varying the characteristic coefficients along with DOR settings. The proposed non-standard characteristic model is formulated as a quadratically constrained quadratic programming (QCQP) problem, to which the current settings of the DOR is provided, by heuristically generating the CPS using particle swarm optimization (PSO). This proposed hybrid QCQP technique works better than the past methods in providing the best DOR settings, and minimum DOR operating times as well. The proposed technique is evaluated on various standard benchmark test systems and results are found to be satisfactory.

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ABBREVIATIONS

LP	Linear Programming
NLP	Non-Linear Programming
DOR	Directional Overcurrent Relay
DOR-PCP	Directional Overcurrent Relay Protection Coordination Problem
QCQP	Quadratically Constrained Quadratic Programming
GA	Genetic Algorithm
GSA	Gravitational Search Algorithm
IWO	Invasive Weed Optimization
PSO	Particle Swarm Optimization

NOTATION

t_{op}	operating time of the relay
I	relay number
t_i	operating time for i^{th} relay
TDS_i^{min}	minimum time dial setting for i^{th} relay
TDS_i^{max}	minimum time dial setting for i^{th} relay
CPS_i^{min}	minimum current plug setting for i^{th} relay
CPS_i^{max}	minimum current plug setting for i^{th} relay
t_i^k	operating time of k^{th} backup relay for i^{th} primary relay
OF	objective function
A_i, B_i, C_i	characteristics coefficients

CHAPTER 1

INTRODUCTION

1.1 Background

Distribution networks mainly rely on overcurrent protection schemes. Transmission and sub-transmission systems use distance protection as the primary protection [1]. The distribution overcurrent protection uses either inverse or the definite time-based relay characteristics to sense an issue the trip. Getting adequate relay coordination between primary and backup relays for the relays satisfying all operational constraints about different system conditions is a complex task. With day-by-day increasing load demand, the protection of expanding meshed distribution networks has become a challenging issue. Obtaining the best relay settings for such networks remains an active research challenge.

This thesis emphasizes the statistical evaluation of heuristic, hybrid-heuristics and traditional optimization-based methods for finding the solution to the directional overcurrent relay coordination problem.

1.2 Literature review

Initially, most of the distribution networks were radial. In the radial system, the fault current is being fed only from one direction. Later on, with expanding of distribution networks, meshed systems started dominating in which fault current is fed from various paths. Relay coordination problem in radial systems, formulated as a linear programming (LP) model [2] [3] which is the simplest form of convex optimization, can be easily solved and will give always one fixed solution. Where in meshed systems, conventional trial and error, breakpoint method and various traditional methods are used in literature to tackle the coordination issue. In the breakpoint method, we analyze the graph by breaking down it into simple loops using breakpoints. The optimal breakpoint should be obtained to find proper relay coordination which is time-consuming and does not always give the best results. Similarly, the trial and error method is also sluggish due to the huge number of iterations required to converge and get the solution.

Nowadays, optimization-based methods are popular due to their simple formulation. In directional over-current relays (DORs), optimal relay coordination is a highly constrained non-convex nonlinear optimization problem.

Some of the solution techniques based on linear programming (LP), nonlinear programming (NLP) and quadratically constrained quadratic programming (QCQP) [4] formulations are available in the literature. LP problem, in which time dial setting(TDS) and current plug setting(CPS) of the DOR are fixed, can be solved using simplex and dual simplex methods. Whereas, in NLP, CPS and TDS are taken as variables and the problem is solved using methods like sequential quadratic programming (SQP) are used to get the solution.

Nowadays, various heuristics and hybrid heuristic methods are used to solve the coordination problem. They are more efficient and faster than traditional methods. Various heuristics methods like genetic algorithms (GA), particle swarm optimization (PSO), gravitational search (GSA) [5], invasive weed optimization (IWO), etc have been statistically evaluated in this work to find the optimal DOR settings.

Heuristic optimization techniques, sometimes do not fetch the global optimum and do not converge to feasible solutions because there is no specific algorithm exists that can achieve the best solution for a particular optimization problem. This disadvantage can be overcome by applying hybrid optimization techniques that combine both heuristic and conventional optimization techniques [6].

1.3 Objectives and scope

The objectives of this work are:

1) Statistical evaluation of heuristics and hybrid heuristics methods used for solving the directional overcurrent relay coordination problem

2) Development of quadratically constrained quadratic programming (QCQP) based non-standard DOR characteristics using hybrid PSO-QCQP (Particle swarm optimization-QCQP)

The scope of this work are:

1) The work is limited to directional overcurrent relay protection with standard and non-standard inverse characteristics and the same is considered for the evaluation of heuristic algorithms.

2) Computational performance of the coordination algorithms presented in this work has not been evaluated because the algorithms are assumed to be offline.

1.4 Organization of thesis

This thesis is organized into 5 chapters.

Chapter 2 provides information on overcurrent relay protection and overcurrent characteristics. Directional overcurrent relay coordination problem and its formulation is discussed along with a description on how to select limits of various parameters in coordination problem

In *Chapter 3,* various heuristics and hybrid heuristic algorithms are statistically evaluated on 3, 8 and 15 bus systems in order to find a better method for minimizing relay operating time for primary and backup relays. The development of non-standard characteristics for relay coordination is encouraged in the end.

In *Chapter 4,* a new hybrid algorithm with a combination of particle swarm optimization and quadratically constrained quadratic programming is proposed to solve the directional overcurrent relay problem. The proposed algorithm is tested on 3, 8 and 15 bus system and the results are discussed.

Chapter 5 concludes the thesis then the future scope of the work is discussed.

CHAPTER 2

DIRECTIONAL OVERCURRENT RELAY PROTECTION

2.1 Introduction

Overcurrent protection is one of the most widely used protection techniques. In sub-transmission and transmission systems, overcurrent protection is preferred over distance protection [7]. Overcurrent relays are the nucleus of the whole overcurrent protection model. Learning about the working and characteristics of an overcurrent protection relay is very important to proceed further. Various parameters like current plug settings and time dial settings and the constraints on them play a major role in the formulation of directional overcurrent relay protection coordination problem.

2.2 Overcurrent relay protection

There are various types of overcurrent protection devices as shown in figure 2.1. Fuse is has a metal strip or wire that melts when current flowing exceeds a certain limit and thus stops the flow of current to prevent potential damage. Fuse once operated, it must be replaced or rewired. Thermal relay has a bimetallic strip with two metals of different coefficients of expansion, and a heating coil attached to it. When overcurrent flows through the heating coil, it heats up the bimetallic strip and the strip bends towards the metal with a low coefficient of expansion. As a result, relay contacts are closed which energizes the circuit breaker for tripping. An overcurrent relay is a protection device that operates when sensed current goes above the threshold current setting. There are two decision variables in an overcurrent relay viz. Time Dial Settings (TDS) and Current Plug Settings (CPS). TDS is fixed by setting a dial scaled for the time in seconds, and CPS is fixed by placing a shorting plug in the plug setting bridge so that the number of turns of the operating coil is changed to fix the pickup. Overcurrent relays were initially mechanical having fixed and moving components. Later on, microprocessor-based relaying came into the picture. A digital overcurrent relay model is shown in the figure 2.2. The current flowing is sensed by a current transformer (CT), and after step-down, it is sent to the DOR. The sensed current is compared with the CPS, and if the current is greater than the CPS, the timer starts counting. For directionality check of the fault current, the angle between fault current and the line voltage is measured. If the measured angle is greater than a predefined angle and if the time counted by the time counter reaches TDS, the trip command is issued to the circuit breaker. An overview of the digital relay is shown in figure 2.2.

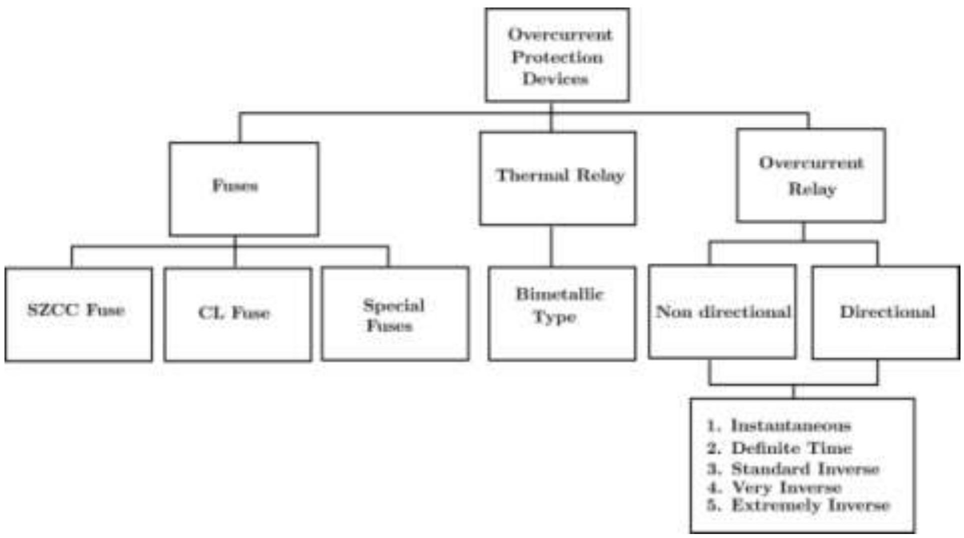

Figure 2.1 Relay coordination methods for protection

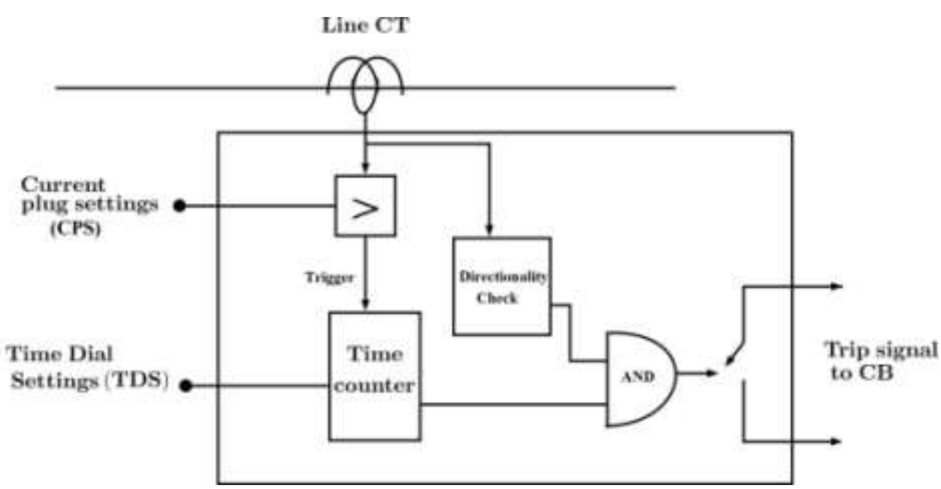

Figure 2.2 Overview of digital DOR

2.3 Overcurrent protection characteristics

According to the IEEE/ANSI standards, inverse relay coordination characteristics and the mathematical expression for the relay operating time is given by,

$$t_{op} = \left(\frac{a}{\left(\frac{I^{max}}{CPS}\right)^{b} - 1} + c \right) TDS \tag{2.1}$$

where, a, b, c - constants, TDS - time dial setting, CPS- current plug setting

Depending on the time of operation, the overcurrent relay is categorized into instantaneous, definite time, standard inverse, very and extremely inverse.

In **instantaneous** overcurrent characteristics, there is no intentional time delay, so it does not have any time setting (TDS) and operates only on the CPS.

Definite time overcurrent characteristic has a fixed CPS and TDS which are adjustable.

The **very inverse** overcurrent characteristics, because of their inverted curve shape, are best suited for places where there the magnitude of the short-circuit current falls rapidly because of the large distance from the source.

Extremely inverse overcurrent characteristics are used to provide the right coordination margin between the primary and backup relays where there is an accountable drop in fault current from one relay location to another.

The **Standard inverse** overcurrent characteristics embed the feature of both definite time and inverse characteristics.

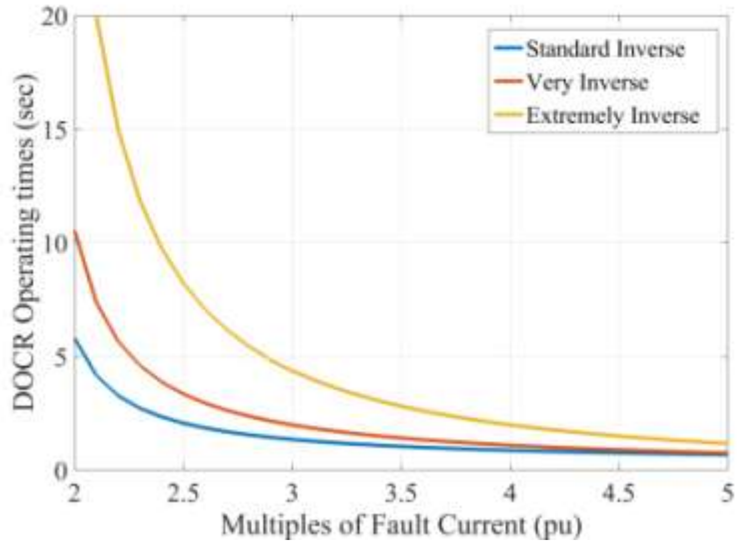

Figure 2.3 Standard inverse characteristics of DOR

2.4 Directional overcurrent relay (DOR) coordination

Most of the relay tripping is due to poor relay settings than because of actual fault. It is essential to decide the sequence of relays and fix the settings to adequately detect and give the trip command for a particular fault. Hence, optimal relay coordination study is an important part of protection design.

The closest relays in direction to the fault current are supposed to operate first and thus called primary relays. When primary relays fail to operate, the second most closest relays, called backup relays, will operate. To minimize the fault isolation time and properly coordinate relays, their CPS and TDS should be optimally set. This DOR protection problem (DOR-PCP) can be solved by writing it as a mathematical optimization problem constrained with limit and coordination constraints [10]. The final aim is to minimize the DOR operating time.

2.5 DOR-PCP formulation

According to IEEE/ANSI standards, inverse characteristics time-current equation is given by,

$$t_i = \frac{a(TDS_i)}{\left(\frac{I_i}{CPS_i}\right)^b - 1} \forall\, i \in N_r \tag{2.2}$$

t_i - operating time of i^{th} primary relay, I_i is fault current flowing through i^{th} relay, CPS_i and TDS_i time delay and current plug settings of i^{th} DOR, (a, b) - constants, N_r - number of DORs. The mathematical formulation of DOR-PCP is given by,

$$\min OF = \sum_{f=1}^{F} \sum_{i=1}^{N_r} \left(t_i + \sum_{k=1}^{K} t_i^k \right) \quad \forall\, i \in N_r, k \in K_i \tag{2.3}$$

$$t_i^k - t_i \geq CTI \forall\, i \in N_r, k \in K_i \tag{2.4}$$

The necessary constraints on TDS, CPS and operating time are,

$$TDS_i^{min} \leq TDS_i \leq TDS_i^{max} \tag{2.5}$$

$$CPS_i^{min} \leq CPS_i \leq CPS_i^{max} \tag{2.6}$$

$$t_i^{min} \leq t_i, t_i^k \leq t_i^{max} \tag{2.7}$$

where, t_i^k - operating time of k^{th} backup relay, K_i - number of backup relays for i^{th} primary DOR. The primary relay should operate first and before the backup relay when a fault occurs. Therefore, the backup relay is constrained to operate after a time gap called the coordination time interval (CTI).

2.6 Selection of CPS limits for the DOR

The minimum CPS limit is kept considering a nominal of 30-50 % overload (OL) on the line. So, the relay is not supposed to pick up till the line current is 1.3-1.5 times of the load current I_L

$$CPS^{min} = OL \times I_L \tag{2.8}$$

Similarly, according to the main principle of the relay, it should sense even the smallest magnitude of the fault current. So,

$$CPS^{max} = I_{fault}^{min} \tag{2.9}$$

2.7 Selection of TDS limits for the DOR

This margin between primary and backup relay operating times is created by the TDS setting which is used to adjust the inverse curves of primary and backup relays in the time-current plane appropriately such that the primary relay time curve lies below the backup relay time curve by a sufficient time margin. Typically TDS is set between 0.01 and 2.5.

2.8 Selecting relay time limits

When a fault occurs, the primary relay is given enough time to operate. The backup relay is set to operate after a time gap (CTI) in case the primary relay fails to operate. Relay is given time (t_r) to sense the fault and time taken by the circuit breaker to operate is (t_{cb}), so, minimum operating time for primary relay (t_p^{min}) is given by,

$$t_p^{min} = t_r + t_{cb} \tag{2.10}$$

In the case of digital relays, the sensing time is very less and is almost negligible. The primary relay and the backup relay are differed by a time margin (CTI) which is set between 0.2 to 0.5. Therefore, minimum operating time of the backup relay (t_b^{min}) is given by,

$$t_b^{min} = t_p^{min} + CTI \tag{2.11}$$

Similarly, the maximum operating time of the relay is set considering relay should not be too sluggish in responding to the fault.

2.9 Summary

In this chapter, overcurrent relay protection and its characteristics have been discussed. Formulation of directional overcurrent relay protection coordination problem using various relay parameters is done with appropriate constraints on those parameters. Selection of the current plug settings and time dial settings limit values and formulation of the constraints are discussed. Relay operating time has been broken down as the sum of the fault sensing time and circuit breaker operating time.

CHAPTER 3

STATISTICAL EVALUATION OF HEURISTICS AND HYBRID HEURISTICS ALGORITHMS

3.1 Introduction

In this chapter, various heuristics and hybrid heuristics optimization techniques have been statistically evaluated. We try to analyze various techniques and results to see which gives optimal solution for relay coordination. Genetic algorithm (GA), gravitational search algorithm (GSA), particle swarm algorithm (PSO) and invasive weed optimization (IWO) are four techniques used here. Moreover, we also analyze hybrid NLP models of all these techniques viz. GA-NLP, GSA-NLP, PSO-NLP and IWO-NLP.

3.2 Overview of Heuristic Programming

Heuristic methods are a faster way to get solutions for a complex nonconvex problem where traditional methods take a huge amount of time. In relay DOR-PCP, along with the nonlinear nonconvex nature of the problem, we have many coordination constraints. Heuristic programming serves as a powerful tool to solve such problems.

3.2.1 Genetic algorithm (GA)

The genetic algorithm repeatedly modifies a population of individual solutions. At each step, the genetic algorithm selects individuals at random from the current population to be parents and uses them to produce the children for the next generation. Over successive generations, the population "evolves" toward an optimal solution. The parameters of GA used for solving the problem are shown in table 3.1.

Table 3.1 GA parameters

Crossover probability	0.5
Mutation probability	0.1
Population count	100
No. of bits	8

3.2.2 Particle swarm optimization (PSO)

The particle swarm algorithm begins by creating the initial particles and assigning them initial velocities It evaluates the objective function at each particle location, and determines the best (lowest) function value and the best location. It chooses new velocities, based on the current velocity, the particles' individual best locations, and the best locations of their neighbors. It then iteratively updates the particle locations (the new location is the old one plus the velocity, modified to keep particles within bounds), velocities, and neighbors. Iterations proceed until the algorithm reaches a stopping criterion. The parameters of PSO used for solving the problem are shown in table 3.2.

Table 3.2 PSO parameters

Initial velocity	0.1
Swarm count	100
ω_{min} & ω_{max}	0.9 & 0.4
c_1 & c_2	0.4 & 0.2

3.2.3 Gravitational search algorithm (GSA)

GSA is an algorithm inspired by Newton's famous law of gravity and law of motion. Each agent is considered as the objects and all objects move towards other objects with heavier mass due to gravity force. The best solution is the one with the heavier mass. The parameters of GSA used for solving the problem are shown in table 3.3.

Table 3.3 GSA parameters

α	20
G_o	100
Number of agents	50
Iterations	400

3.2.4 Invasive weed optimization (IWO)

The IWO is a population-based evolutionary optimization method inspired by the behavior of the weed colonies. Weed is the unwanted plant that looks for optimality and finds the best environment for life and quickly adapts itself to environmental conditions. Weeds produce seeds and dispose into their neighborhood which develops into another weed plant and the process continues until the resources to reproduce are over. The parameters of IWO used for solving the problem are shown in table 3.4.

Table 3.4 IWO parameters

Population size	200
Minimum no. of seeds	5
Maximum no. of seeds	15
Maximum no. of iterations	1×10^3
Maximum SD	0.5
Minimum SD	0.0001
Non-linear modulation index	3

3.3Hybrid heuristics programming

One of the disadvantages of conventional heuristics methods is that they don't always guarantee convergence. Many times heuristics have the tendencies to converge towards local optimum and some arbitrary points rather than the desired global optimum. Also, heuristics do not scale well with complexity such as NLP problems.

To address this problem we have evaluated hybrid heuristics models of each GA, PSO, GSA and IWO methods viz. GA-NLP, PSO-NLP, GSA-NLP and IWO-NLP. To increase the computational efficiency of the relay coordination problem, it is beneficial to hybridize heuristics with non-linear programming.

In hybrid heuristics, DOR-PCP is decomposed into two sub-problems, solving the NLP problem and updating the fitness function at each iteration if required. The flow chart of the GA-NLP is shown in the figure 3.1 which gives an idea on how all the hybrid heuristic methods work.

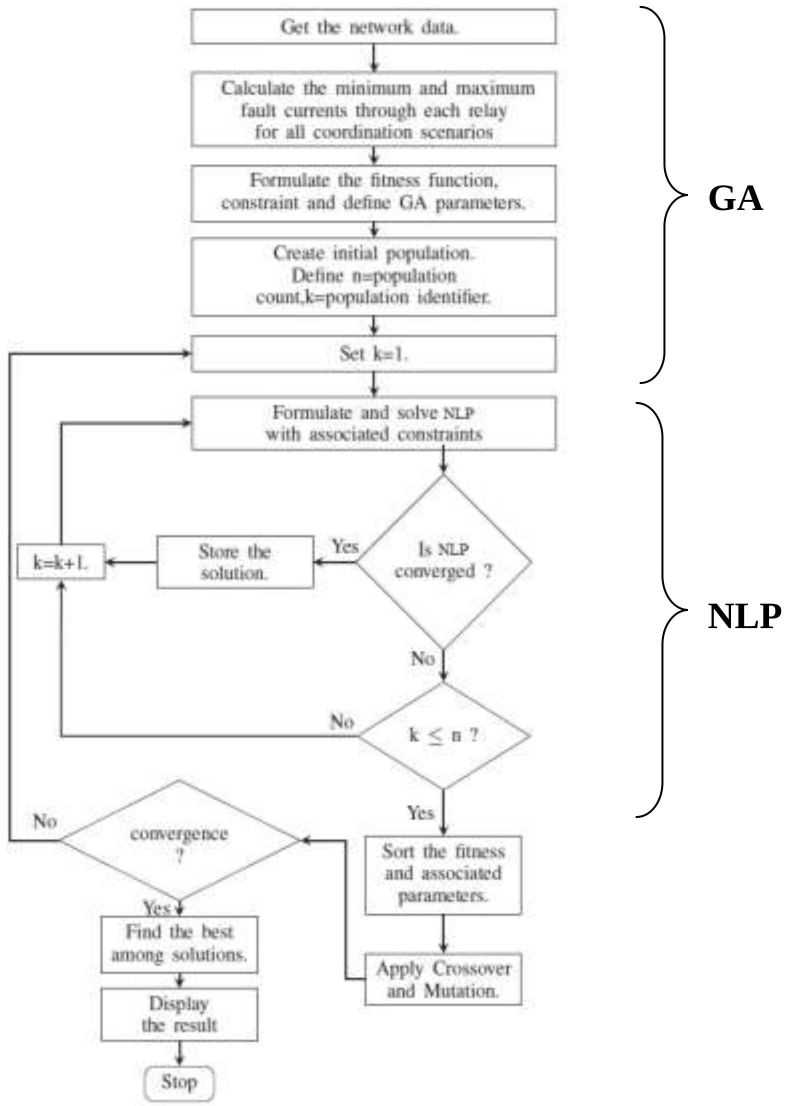

Figure 3.1 Flowchart of hybrid GA-NLP method

3.4 Test systems and results

The DOR coordination problem is evaluated using GA, GSA, PSO, IWO, GA-NLP and PSO-NLP by testing it against benchmark 3, 8 and 15 bus systems as shown in figure 3.2, 3.3 and 3.4. The fault current data for all the systems is taken from [8].

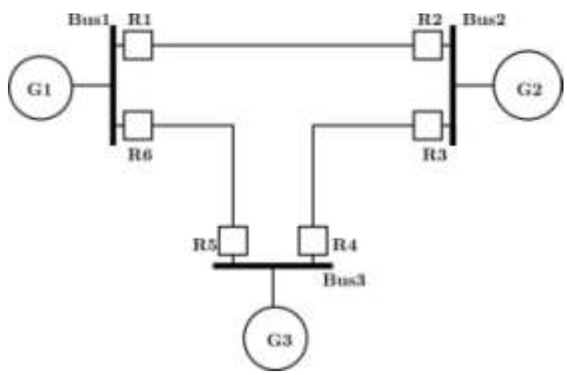

Figure 3.2 Three Bus system

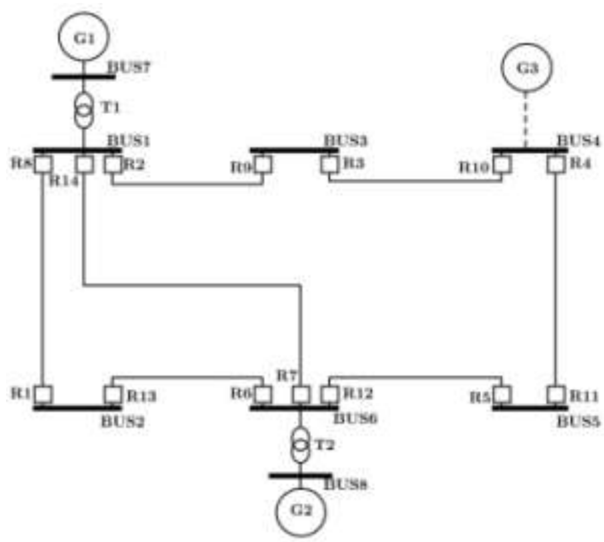

Figure 3.3 Eight Bus system

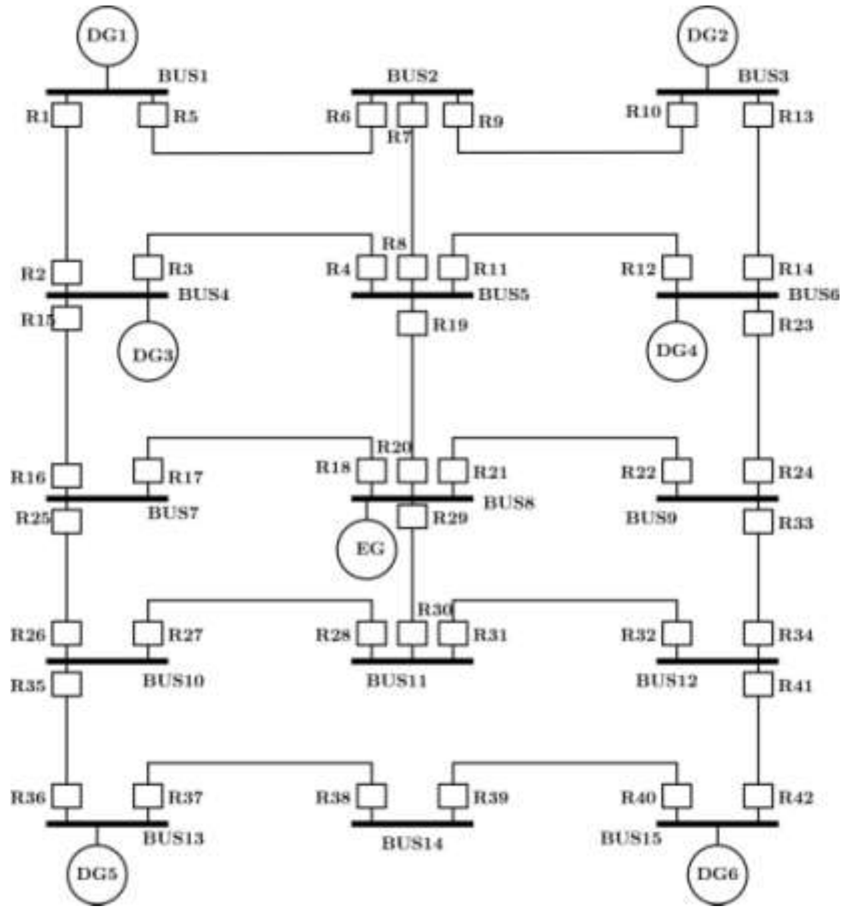

Figure 3.4 Fifteen Bus system

To evaluate the capability of heuristic algorithms to find the optimum for the protection coordination problem, each heuristic program is run for 50 trial runs over 10^4 iterations. The convergence results of heuristic and hybrid heuristic programs are shown in the figures 3.5-3.15. The convergence charts provided in those figures are the best of all the trials runs. The respective mean and standard deviation values among all the trial runs are provided in tables 3.5-3.10.

3.4.1 GA and GA-NLP results

Table 3.5 GA data

	Mean_1000 (sec)	Mean_5000 (sec)	Mean_10000 (sec)	SD_1000	SD_5000	SD_10000	Best Value (sec)	Worst Value (sec)
3 Bus	5.12283554	5.09007211	5.057252463	0.055702	0.0452	0.032019	5.03179	5.142406554
8 Bus	1137.89045	1137.86771	1137.846525	18.28479	18.208	18.208	18.208001	2016.94957
15 Bus	2023.22291	2022.51822	2022.470838	66.22246	65.67316	65.67316	39176.55	47153.516

Table 3.6 GA-NLP data

	Mean_50 (sec)	Mean_250 (sec)	Mean_500 (sec)	SD_50	SD_250	SD_500	Best Value (sec)	Worst Value (sec)
3 Bus	5.03178995	5.03178995	5.031789951	4.49E-15	4.49E-15	4.49E-15	5.03179	5.031789951
8 Bus	117.01988	17.0198797	17.01987974	303.0458	5.24E-13	2.99E-13	17.01988	17.01987974
15 Bus	1990.0875	1990.0875	1990.0875	1990.088	1990.088	1990.088	1990.0875	1990.0875

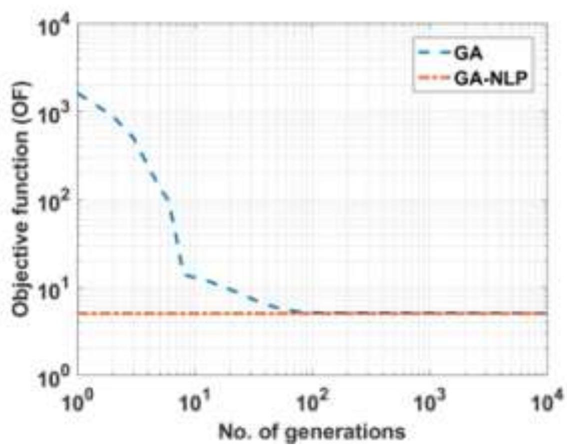

Figure 3.5 Convergence chart for 3 Bus system

In figure 3.5, convergence is achieved at 5.03179 sec for both GA and GA-NLP but the GA-NLP converges and gives solution much earlier.

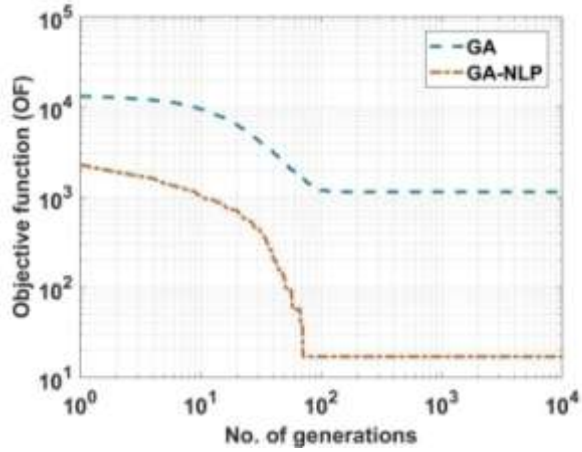

Figure 3.6 Convergence chart for 8 Bus system

In figure 3.6, For GA, the value at the end of 10000th iteration is 1137 sec which shows that with penalty factor being 1000, there is a violation of one constraint and thus it is not a favorable result. However, in the case of GA-NLP, after 500 iterations, the graph is converging at 17.0198 sec which is the best result and is achieved much faster.

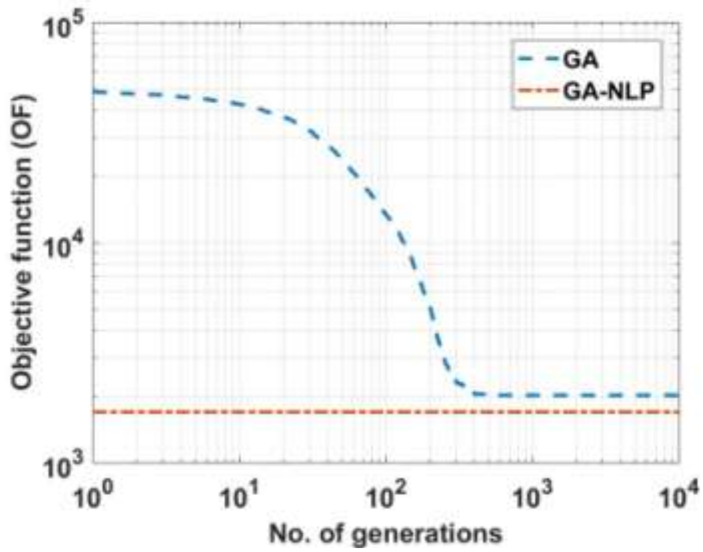

Figure 3.7 Convergence chart for 15 Bus system

In figure 3.7, both GA and GA-NLP violate constraints, two in case of GA and one is case of GA-NLP, as seen from their final values 2022.470838 and 1990.0875. It shows that as the complexity of the system increases, these methods are not reliable.

3.4.2 PSO and PSO NLP results

Table 3.7 PSO data

	Mean_1000 (sec)	Mean_5000 (sec)	Mean_10000 (sec)	SD_1000	SD_5000	SD_10000	Best Value (sec)	Worst Value (sec)
3 Bus	5.07791025	5.07791025	5.077910251	0.090164	0.090164	0.090164	5.03179	5.388665653
8 Bus	3299.99856	3239.92367	3239.905971	1358.501	1406.598	1406.602	1019.0328	6032.639755
15 Bus	10655.0894	9849.51707	9467.373532	3548.726	3651.67	3524.907	3068.6287	18064.60823

Table 3.8 PSO-NLP data

	Mean_50 (sec)	Mean_250 (sec)	Mean_500 (sec)	SD_50	SD_250	SD_500	Best Value (sec)	Worst Value (sec)
3 Bus	5.03178995	5.03178995	5.031789951	4.49E-15	4.49E-15	4.49E-15	5.03179	5.031789951
8 Bus	497.01988	137.01988	77.01987974	579.9367	385.4496	239.8979	17.01988	1017.01988
15 Bus	5402.36434	4562.36434	4402.364343	700	585.9465	637.7042	3042.3643	5042.364343

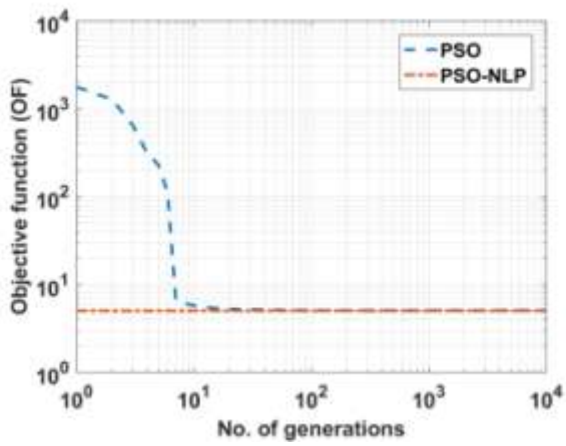

Figure 3.8 Convergence chart for 3 Bus system

In figure 3.8, convergence is achieved at 5.0777791 and 5.03179 sec for GA and GA-NLP but the GA-NLP converges and gives solution much earlier.

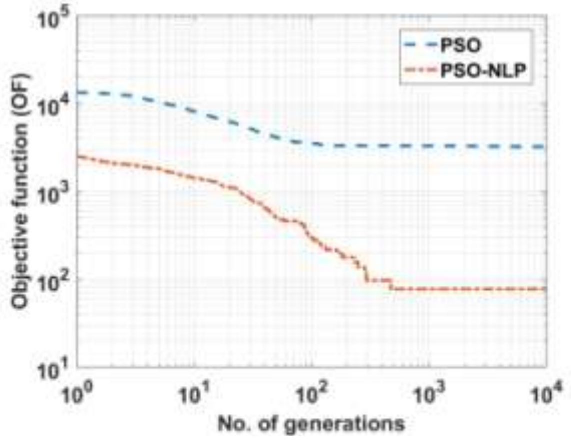

Figure 3.9 Convergence chart for 8 Bus system

In figure 3.9, PSO gives 3239.9060 sec after 10000th iteration which implies 3 constraints violation with penalty factor being 1000. PSO gives 77.0199 sec after 10000th iteration which implies no constraints violation but the solution is not good compared to the GA-NLP solution which was 17.0198 sec.

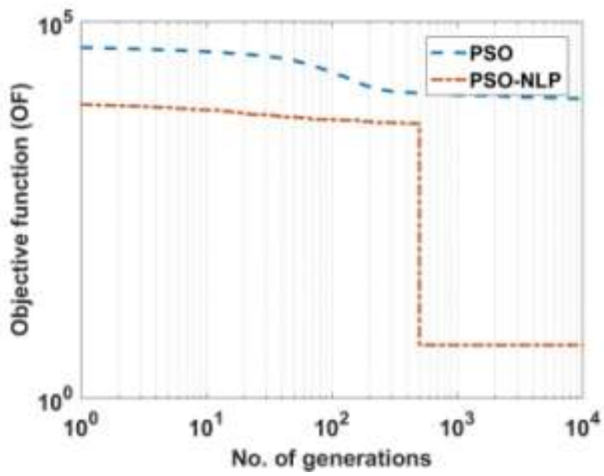

Figure 3.10 Convergence chart for 15 Bus system

In figure 3.10, PSO and PSO-NLP give 9467.3735 and 4402.3643 as final solutions which have 9 and 4 constraints violations respectively with penalty factor being 1000.

3.4.3 IWO results

Table 3.9 IWO data

	Mean_1000 (sec)	Mean_5000 (sec)	Mean_10000 (sec)	SD_1000	SD_5000	SD_10000	Best Value (sec)	Worst Value (sec)
3 Bus	1433.69118	1219.41733	1219.417328	365.9186	21.06896	21.06896	1176.3495	1291.519929
8 Bus	753.402359	127.362105	127.251427	605.4491	300.5436	300.4082	19.066806	1025.57959
15 Bus	22872.1846	4019.13066	3876.50728	4360.339	1797.742	1639.903	2048.3407	9065.401421

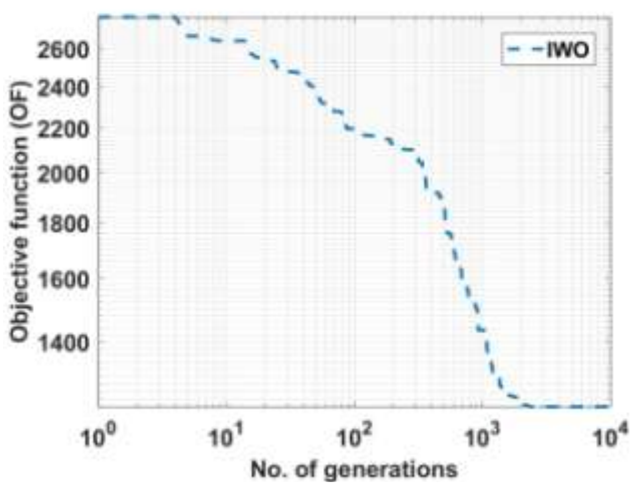

Figure 3.11 Convergence chart for 3 Bus system

In figure 3.11, the final solution is 1219.4173 sec which implies 1 constraint violation with penalty factor being 1000.

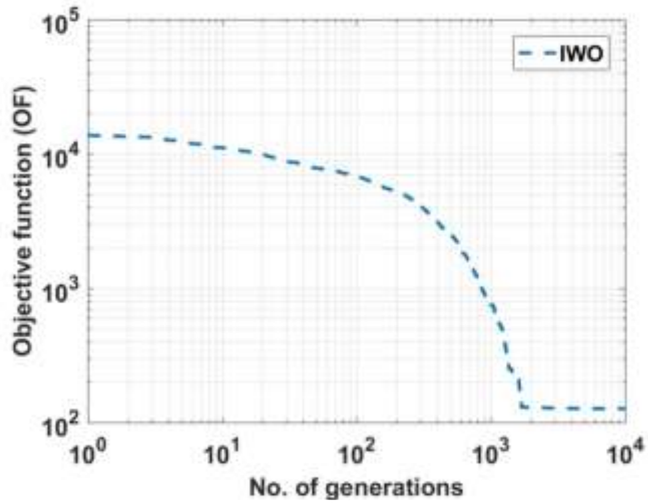

Figure 3.12 Convergence chart for 8 Bus system

In figure 3.12, there are no constraint violations but the value is 127.2514 sec which is very high compared to the results of GA-NLP for 8 bus system which is 17.0198 sec.

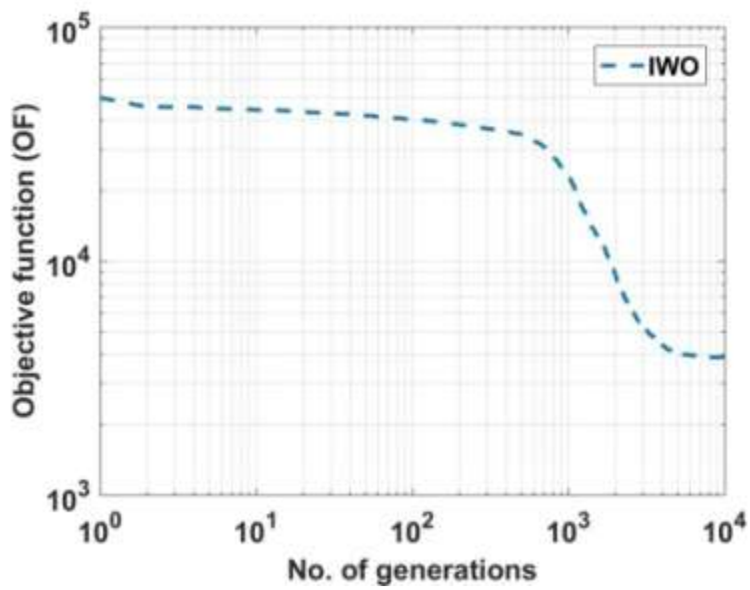

Figure 3.13 Convergence chart for 15 Bus system

In figure 3.13, the final solution is 3876.5073 sec which implies 3 constraints violation with penalty factor being 1000.

3.4.4 GSA results

Table 3.10 GSA data

	Mean_1000 (sec)	Mean_5000 (sec)	Mean_10000 (sec)	SD_1000	SD_5000	SD_10000	Best Value (sec)	Worst Value (sec)
3 Bus	1433.69118	1219.41733	1219.417328	365.9186	21.06896	21.06896	1176.3495	1291.519929
8 Bus	753.402359	127.362105	127.251427	605.4491	300.5436	300.4082	19.066806	1025.57959
15 Bus	22872.1846	4019.13066	3876.50728	4360.339	1797.742	1639.903	2048.3407	9065.401421

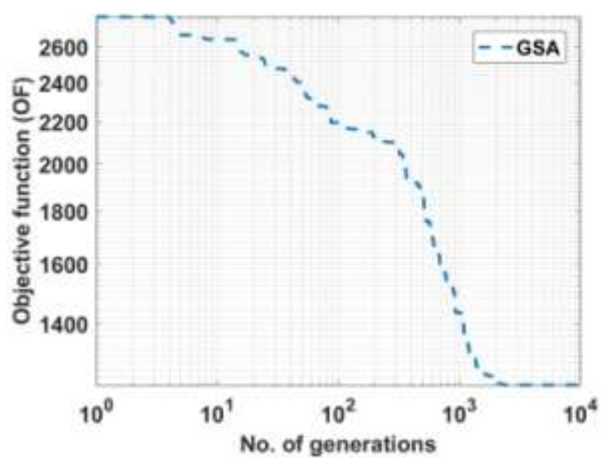

Figure 1.14 Convergence chart for 3 bus system

In figure 3.14, the final solution is 1219.4173 sec which implies 1 constraint violation with penalty factor being 1000.

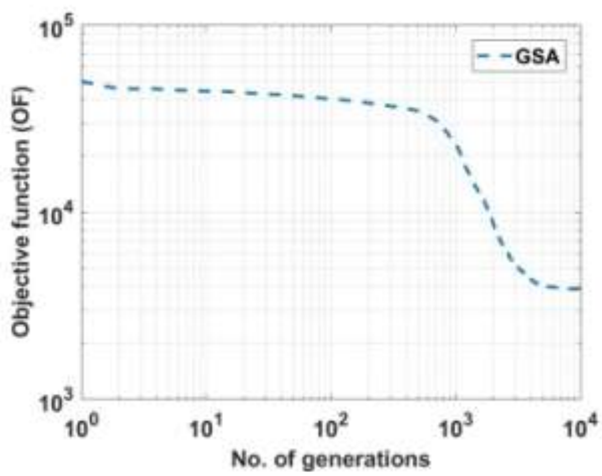

Figure 3.15 Convergence chart for 15 bus system

In figure 3.15, the final solution is 3876.5073 sec which implies 3 constraints violation with penalty factor being 1000.

By considering all the results from figure 3.5-3.15, there are no. of constraints violations in solutions of many methods for various systems. It can be understood that GA has achieved better mean and standard deviation as compared with other heuristic programs, while GSA and IWO have shown least promising results. However, the hybrid heuristic programs of all the tests algorithms have found to be equally on par with each other. However, one major setback of hybrid heuristics as compared with heuristic programs is that the convergence time per iteration is very very high for hybrid heuristics. But performance wise, hybrid heuristics are more promising as compared with heuristic programs. The best fitness value of the objective function for the 3 bus system is achieved to be 5.0318 sec, which is the global optimum [QCQP]. Similarly, the best fitness values for 8 bus system and 15 bus system are 17.0198 sec and 18.148 respectively (for both heuristic and hybrid heuristic methods).

3.5 Summary

After statistically evaluating various hybrid and hybrid heuristic methods, it is evident that heuristic methods don't always converge to the global optimum and hybrid heuristic methods need an initial solution and take a huge amount of time to reach to the global optimum. Moreover, as the complexity of systems increases, these methods are not suitable to give the best solutions.

CHAPTER 4

DEVELOPMENT OF NON-STANDARD DIRECTIONAL OVERCURRENT RELAY CHARACTERISTICS

4.1 Introduction

We have mostly seen in previous chapters that DOR coordination dealt with standard inverse characteristics. In LP, CPS is fixed and TDS is taken as a decision variable whereas, in NPL, both are taken as decision variables. At the end of chapter 3, we've seen that hybrid NLP heuristics methods are the most effective till now. However, the hybrid NLP heuristic methods take a huge amount of time because they are solving NLP at each iteration to give better results. In some cases, hybrid NLP heuristic methods don't even converge to the global optimum. Our final aim is to minimize the operating times of the primary and backup relays and isolating the fault as soon as possible.

One of the methods we are going to use in the chapter is to formulate the DOR-PCP into a quadratically constrained quadratic programming (QCQP) by heuristically choosing the CPS value as well as the values of the constants a, b, c and developing non-standard characteristics for DOR-PCP. i.e. taking a, b, c as variables and solving the problem. The problem is solved using the MATLAB programming and the algorithm is tested on 3Bus, 8 Bus and 15 Bus systems similarly as in chapter 3.

4.2 Formulation of QCQP for DOR-PCP

Operating time of a DOR is given by IEEE standard as,

$$t_i = \left(\frac{A_i}{\left(\frac{I_i^{max}}{CPS_i}\right)^{C_i} - 1} + B_i \right)(TDS_i) \tag{4.1}$$

and if the DOR is acting as a backup relay then,

$$t_i^k = \left(\frac{A_i}{\left(\frac{I_i^{min}}{CPS_i}\right)^{C_i} - 1} + B_i \right) (TDS_i) \quad (4.2)$$

where, t_i - operating time of the i^{th} DOR, t_i^k - operating time of kth backup DOR of ith primary DOR. I_i^{max} and I_i^{min} are the maximum and the minimum fault currents seen by i^{th} DOR. (TDS_i) and CPS_i are time dial settings and current plug settings of i^{th} DOR. A_i, B_i and C_i are the coefficients of the inverse characteristics.

4.3 Impact of coefficients A, B and C on DOR inverse characteristics

The DORs are typically governed by standard inverse characteristics given by (4.1) and (4.2). A_i, B_i and C_i affect the position and steepness of the curve [9]. Typical values of these coefficients are given in the table.

Table 4.1 Coefficient values for various inverse curves

Characteristics	A_i	B_i	C_i
Standard inverse	0.14	0	0.02
Very inverse	13.5	0	1
Extremely inverse	80	0	2

The variation of DOR operating times with respect to the fault current ratio $\left(\frac{I_{i,f}^{min}}{CPS_i}\right)$ for various values of A_i, B_i and C_i are shown in the figures

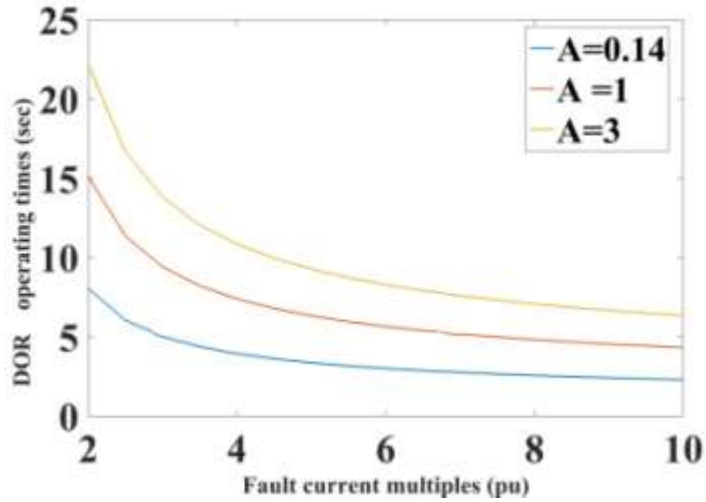

Figure 4.1 DOR characteristics with variation in A

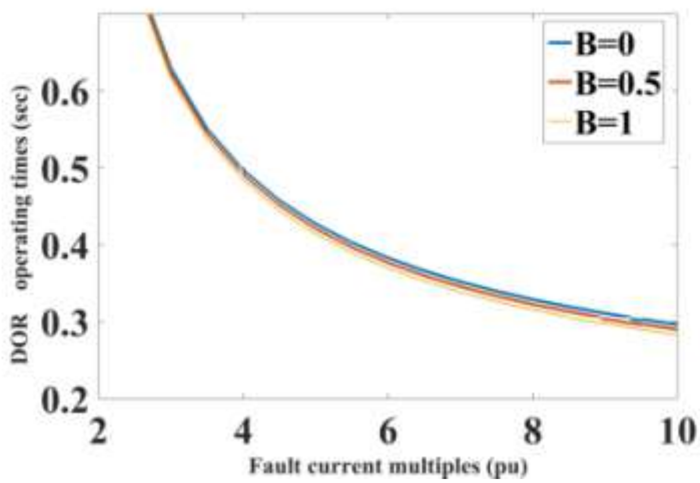

Figure 4.2 DOR characteristics with variation in B

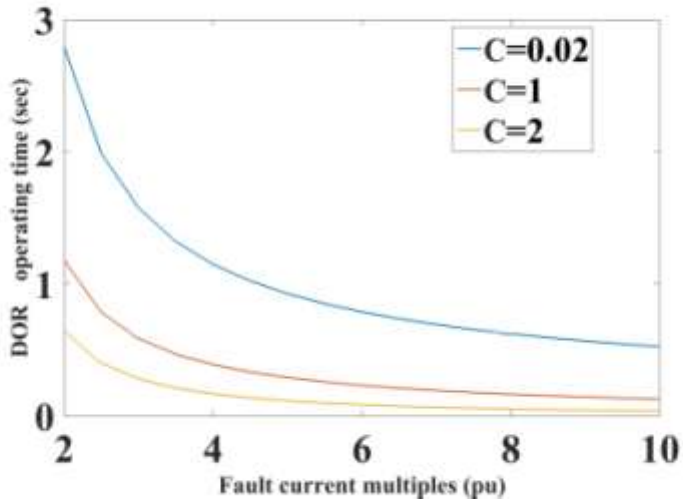

Figure 4.3 DOR characteristics with variation in C

4.4 Formulation of PSO

The main objective of the DOR-PCP is to minimize the overall operating times of primary and backup relays. Therefore the objective function is given by

$$\min OF = \sum_{i=1}^{N_r} \left(t_i + \sum_{k=1}^{K} t_i^k \right) \tag{4.3}$$

The constraints of DOR are given as,

$$t_{i,f}^k - t_{i,f} \geq CTI \tag{4.4}$$

$$TDS_i^{min} \leq TDS_i \leq TDS_i^{max} \tag{4.5}$$

$$CPS_i^{min} \leq CPS_i \leq CPS_i^{max} \tag{4.6}$$

$$t_i^{min} \leq t_i, t_i^k \leq t_i^{max} \tag{4.7}$$

$$A_i^{min} \leq A_i \leq A_i^{max} \tag{4.8}$$

$$B_i^{min} \leq B_i \leq B_i^{max} \tag{4.9}$$

$$C_i^{min} \leq C_i \leq C_i^{max} \tag{4.10}$$

Now let's define two variables, a_i and a_{ik} as,

$$a_i = \left(\frac{I_i^{max}}{CPS_i}\right)^{C_i} - 1 \tag{4.11}$$

$$a_{ik} = \left(\frac{I_i^{min}}{CPS_i}\right)^{C_i} - 1 \tag{4.12}$$

then (4.1) and (4.2) can be written as,

$$t_i = \frac{1}{a_i} A_i TDS_i + B_i TDS_i \tag{4.13}$$

$$t_i^k = \frac{1}{a_{ik}} A_i TDS_i + B_i TDS_i \tag{4.14}$$

With the assumption that values of CPS_i and C_i are known a priori, the standard non-linear DOR equation can be transformed into quadratic equations as a function of A_i, B_i and TDS_i. A QCQP based problem can be defined as,

$$\min OF = X^T QX + C^T X \tag{4.15}$$

constrained to, $$X^T Q_i X + L_1^T X \leq b_i \ \ \forall\, i \in IN \tag{4.16}$$

$$X^T Q_i X + L_2^T X = b_i \ \ \forall\, i \in EQ \tag{4.17}$$

where, *X*, *C*, *L1* and *L2* are n x 1 real vectors, and *Q*, Q_i are n x n real symmetric matrices. C is the coefficient vector and *X* is the decision variable vector. In (4.16) and (4.17), *IN* and *EQ* are inequality and equality constraint sets respectively. For DOR coordination in present study, X = [$t_{i,f}$, $t_{i,f}^k$, TDS_i, A_i, B_i]. Though QCQP problems are nonconvex, smooth Np - hard, they tend to give the global solution when *Qi*, *Q* becomes positive semi-definite for i ∈ *IN* and Q_i = 0 for i ∈ *EQ*. However, in the proposed QCQP defined by () - (), Q = 0, Q_i = 0 i ∈ IN , and L2 = 0, bi =0 i ∈ EQ, which makes the proposed QCQP to be a nonconvex optimization problem. The proposed QCQP is solved to get the global solution using a non-commercially available "scip" solver of the OPTI optimization toolbox [12].

4.5 PSO-QCQP algorithm

Previously we've seen that the QCQP formulation of DOR-PCP is based on the assumption that CPS_i and C_i are known a priori. From section 4.3 we understand that C_i defines steepness of the DOR characteristics and is an important parameter to define coordination between primary and backup relays. So, instead of randomly generating and fixing the values of CPS_i and C_i, it would be meaningful to use evolutionary programming resulting in meaningful convergence. In each iteration, each generated population of CPS_i and C_i by the evolutionary program are fed to the QCQP algorithm to find the fitness . The pupils those fetching infeasible solutions are penalized according to the no. of constraints violations. Thus, while sorting, the pupils with better solutions are preserved over the generations.

4.5 Test systems and results

The proposed PSO-QCQP algorithm is tested on 3,8 and 15 bus systems as given in chapter 3. The fitness value of each swarm agent generated from PSO is feed to QCQP and fitness value is obtained. The swarm agents which are giving infeasible solutions are penalized with a penalty factor which makes the solution less preferred one. It is handled as OF = OF + (nvc) x Penalty factor, where OF is objective value function from (4.3) and nvc is no. of violated constraints. The power of PSO-QCQP is assessed by comparisons with PSO and sequential quadratic programming (SQP) [11]. The PSO and QCQP parameter values are given in the table

Table 4.2 Limits variation for the test systems

Parameter	3 Bus	8 Bus	15 Bus
Swarm population	50	150	250
t_i^{min}, t_i^{max} (sec)	[0.1, 1.1]	[0.1, 1.1]	[0.2, 1.1]
C_i^{min}, C_i^{max}	[1.5, 5]	[1.5, 5]	[0.5, 2.5]
TDS_i^{min}, TDS_i^{max} (sec)	[0.1, 1.1]	[0.1, 1.1]	[0.1, 1.1]
A_i^{min}, A_i^{max}	[0.14, 13.5]	[0.14, 13.5]	[0.14, 13.5]
B_i^{min}, B_i^{max}	[0, 1]	[0, 1]	[0, 1]
C_i^{min}, C_i^{max}	[0.02, 1]	[0.02, 1]	[0.02, 1]
CTI (sec)	[0.3]	[0.3]	[0.2]

1) 3 Bus system

Table 4.3 DOR settings for 3 bus system

Relay	PSO					SQP					PSO-QCQP				
	A	B	C	TDS	CPS	A	B	C	TDS	CPS	A	B	C	TDS	CPS
R1	1.556	0.222	1	0.269	4.97	7.77	0.008	0.99	0.133	2.829	0.272	0.463	0.148	0.173	2.411
R2	0.14	0.467	0.695	0.225	3.247	3.597	0.75	0.921	0.106	1.556	1.144	0.157	0.597	0.193	3.17
R3	10.56	0.425	0.932	0.1	2.704	7.922	0.155	0.911	0.14	2.136	0.168	0.724	0.07	0.129	3.124
R4	5.291	0.889	0.929	0.127	2.589	7.56	0.012	0.987	0.159	2.225	0.655	0.124	0.31	0.179	1.503
R5	0.14	0.594	0.771	0.301	3.682	2.321	0.515	0.686	0.118	1.852	0.651	0.151	0.315	0.181	1.615
R6	1.237	0.545	0.391	0.1	3.194	6.467	0.132	0.965	0.144	1.622	0.212	0.582	0.109	0.159	4.402
OF			3.781					3.005					3.000		

Table 4.4 Best DOR operating times for 3 bus system

Primary relay	Backup relay	t_i (sec)	t_i^k (sec)
1	5	0.100	0.400
2	4	0.100	0.400
3	1	0.100	0.400
4	6	0.100	0.400
5	3	0.100	0.400
6	2	0.100	0.400

2) 8 Bus system

Table 4.5 DOR settings for 8 bus system

Relay	PSO					SQP					PSO-QCQP				
	A	B	C	TDS	CPS	A	B	C	TDS	CPS	A	B	C	TDS	CPS
R1	2.358	0.00	0.665	0.224	0.877	1.591	0.00	0.546	0.209	1.543	1.627	0.00	0.861	0.212	2.42
R2	0.140	1.000	0.989	0.42	0.771	0.192	0.764	0.136	0.240	1.831	0.731	0.209	0.383	0.189	2.288
R3	1.054	0.00	0.583	0.376	2.212	1.558	0.00	0.777	0.199	1.385	0.199	0.580	0.078	0.147	1.994
R4	1.245	0.00	0.347	0.265	0.866	0.192	0.560	0.083	0.139	1.221	1.532	0.00	0.694	0.211	2.032
R5	0.140	1.000	0.889	0.545	0.738	0.140	0.906	0.037	0.100	1.482	1.662	0.00	0.922	0.222	2.234
R6	1.466	0.00	0.501	0.309	1.367	0.230	0.633	0.117	0.198	1.622	0.864	0.170	0.397	0.189	2.402
R7	2.095	0.00	0.582	0.221	1.652	0.409	0.498	0.219	0.231	2.452	0.515	0.233	0.261	0.181	1.618
R8	0.676	0.141	0.326	0.181	1.636	1.915	0.00	0.971	0.203	1.584	1.201	0.02	0.553	0.182	2.273
R9	0.140	1.000	0.930	0.403	0.641	1.592	0.00	0.622	0.238	1.869	0.511	0.092	0.227	0.170	1.033
R10	3.045	0.00	0.827	0.215	1.092	1.193	0.00	0.609	0.257	2.304	0.386	0.282	0.192	0.175	1.329
R11	0.539	0.00	0.116	0.193	0.996	1.229	0.00	0.780	0.275	1.864	1.319	0.296	0.862	0.219	2.366
R12	1.074	0.00	0.498	0.187	1.260	1.195	0.00	0.888	0.358	1.688	0.140	0.748	0.034	0.100	0.555
R13	0.921	0.109	0.303	0.184	2.124	0.716	0.109	0.241	0.179	1.598	0.469	0.295	0.252	0.185	1.917
R14	0.758	0.00	0.374	0.312	1.441	1.933	0.00	0.978	0.280	1.752	0.335	0.333	0.169	0.173	1.357
OF			14.046					9.5685					7.506		

Table 4.6 Best DOR operating times for 8 bus system

Primary Relay	Backup Relay	t_i	t_i^k
1	6	0.142	0.442
2	1	0.100	0.400
2	7	0.100	0.400
3	2	0.100	0.400
4	3	0.159	0.459
5	4	0.165	0.465
6	5	0.100	0.400
6	14	0.100	0.400
7	5	0.100	0.400
7	13	0.100	0.400
8	7	0.100	0.400
8	9	0.100	0.400
9	10	0.100	0.400
10	11	0.100	0.400
11	12	0.187	0.487
12	13	0.100	0.400
12	14	0.100	0.400
13	8	0.100	0.400
14	1	0.100	0.400
14	9	0.100	0.400

3) 15 Bus system

Table 4.7 DOR settings for 15 bus system

Relay	PSO					SQP					QCQP				
	A	B	C	TDS	CPS	A	B	C	TDS	CPS	A	B	C	TDS	CPS
R1	11.208	0.374	0.727	0.101	1.387	6.425	0.718	0.853	0.213	0.671	0.336	0.463	0.189	0.194	1.949
R2	11.120	0.100	1.000	0.100	1.728	6.400	0.810	0.894	0.210	0.601	0.270	0.628	0.387	0.242	2.101
R3	2.139	0.525	0.566	0.333	1.440	6.601	0.412	0.774	0.230	1.016	0.730	0.036	0.223	0.179	2.457
R4	5.168	0.683	0.922	0.100	2.072	6.511	0.609	0.806	0.211	0.743	0.362	0.357	0.195	0.178	2.500
R5	7.540	0.441	0.389	0.100	1.633	6.616	0.549	0.767	0.236	0.910	5.656	0.231	1.000	0.330	1.291
R6	13.50	0.017	1.000	0.100	2.500	6.672	0.428	0.771	0.230	1.073	5.059	0.207	1.000	0.284	1.968
R7	11.681	0.658	1.000	0.223	1.243	6.650	0.427	0.773	0.228	1.043	4.900	0.233	0.991	0.293	1.714
R8	3.951	0.331	0.694	0.162	2.500	6.540	0.524	0.786	0.215	0.832	0.725	0.328	0.356	0.211	2.213
R9	0.140	0.649	1.000	0.721	2.25	6.510	0.618	0.800	0.247	0.799	2.593	0.400	1.000	0.306	2.176
R10	7.597	0.162	0.999	0.806	0.535	6.508	0.619	0.800	0.233	0.772	1.953	0.313	0.563	0.239	1.419
R11	0.140	0.364	0.516	0.755	1.174	6.512	0.605	0.805	0.211	0.745	0.985	0.440	0.708	0.265	2.445
R12	2.847	0.298	0.986	0.619	0.885	6.537	0.523	0.793	0.204	0.807	0.768	0.360	0.474	0.239	2.308
R13	11.397	0.942	0.750	0.100	1.250	6.482	0.634	0.815	0.222	0.745	1.147	0.464	0.828	0.286	2.500
R14	5.212	0.376	1.000	0.146	1.831	6.429	0.719	0.848	0.210	0.666	0.354	0.539	0.414	0.249	2.448
R15	3.852	0.00	0.934	0.441	1.016	6.357	0.835	0.907	0.211	0.588	0.248	0.648	0.494	0.254	2.500
R16	3.934	0.707	1.000	0.359	1.181	6.478	0.704	0.833	0.225	0.683	0.562	0.392	0.360	0.216	2.500
R17	2.177	0.807	0.681	0.245	1.462	6.473	0.686	0.831	0.242	0.721	1.326	0.376	0.639	0.265	2.229
R18	5.009	0.248	1.000	0.150	2.228	6.303	0.845	0.908	0.215	0.582	0.752	0.467	0.397	0.264	1.057
R19	2.417	0.139	1.000	0.397	2.499	6.552	0.534	0.784	0.231	0.874	1.475	0.260	0.488	0.222	2.174
R20	6.377	0.694	1.000	0.163	1.884	6.416	0.692	0.842	0.218	0.700	0.919	0.515	1.000	0.322	2.500
R21	3.502	0.017	0.750	0.530	0.535	6.311	0.839	0.906	0.215	0.587	0.150	0.944	0.192	0.166	2.500
R22	6.823	0.212	1.000	0.523	1.492	6.491	0.665	0.821	0.246	0.745	7.192	0.202	0.841	0.411	0.500
R23	5.569	0.698	1.000	0.111	2.007	6.354	0.834	0.906	0.212	0.590	0.488	0.053	0.105	0.171	0.644
R24	1.756	0.036	0.598	0.460	1.195	6.464	0.716	0.841	0.230	0.678	1.572	0.395	0.749	0.275	1.865
R25	7.176	1.000	0.942	0.247	1.507	6.618	0.444	0.776	0.219	0.970	4.811	0.248	0.898	0.302	1.134
R26	4.503	0.180	0.998	0.648	1.281	6.550	0.545	0.779	0.230	0.841	1.714	0.301	0.652	0.231	2.250
R27	8.095	0.831	1.000	0.216	1.904	6.724	0.262	0.818	0.220	1.322	3.579	0.198	1.000	0.242	2.500
R28	10.635	0.589	0.998	0.231	1.441	6.752	0.260	0.806	0.240	1.353	3.205	0.166	0.803	0.229	2.500
R29	4.387	0.234	0.395	0.100	1.637	6.421	0.670	0.831	0.223	0.724	2.365	0.464	1.000	0.338	1.331
R30	11.297	0.346	0.932	0.183	1.086	6.559	0.581	0.787	0.234	0.825	5.130	0.251	0.936	0.320	1.224
R31	0.436	0.498	1.000	0.852	2.500	6.465	0.664	0.816	0.246	0.744	1.265	0.470	0.930	0.309	2.500
R32	10.933	0.786	0.657	0.107	0.87	6.432	0.738	0.847	0.236	0.666	1.428	0.408	0.781	0.286	1.854
R33	9.562	0.00	1.000	0.650	0.872	6.803	0.176	0.852	0.238	1.568	3.688	0.101	0.837	0.218	2.500
R34	7.867	0.212	1.000	0.299	2.083	6.859	0.142	0.858	0.281	1.632	5.790	0.00	1.000	0.266	2.500
R35	8.470	0.011	1.000	0.499	1.064	6.642	0.390	0.780	0.220	1.049	2.126	0.344	0.912	0.257	2.500
R36	2.856	0.588	0.504	0.222	1.483	6.585	0.458	0.779	0.216	0.915	2.742	0.417	1.000	0.297	1.755
R37	6.880	0.510	0.758	0.337	0.983	6.697	0.363	0.775	0.239	1.178	3.257	0.251	0.895	0.243	2.472
R38	1.013	1.000	0.589	0.374	1.768	6.737	0.341	0.782	0.239	1.245	5.254	0.00	1.000	0.260	2.500

R39	3.250	0.639	0.969	0.512	1.207	6.738	0.340	0.783	0.237	1.244	5.313	0.00	1.000	0.262	2.500
R40	2.705	0.739	0.618	0.348	1.643	6.687	0.379	0.771	0.240	1.151	3.532	0.272	1.000	0.254	2.500
R41	9.482	0.791	0.616	0.144	1.473	6.622	0.464	0.760	0.250	1.017	2.552	0.382	1.000	0.303	2.500
R42	0.965	0.478	1.000	0.433	2.5	6.525	0.564	0.794	0.211	0.780	0.295	0.510	0.203	0.188	2.500

Table 4.8 Best DOR operating times for 15 bus system

PR	BR	t_i	t_i^k	PR	BR	t_i	t_i^k	PR	BR	t_i	t_i^k	PR	BR	t_i	t_i^k
1	6	0.2	0.4	11	20	0.2	0.4	21	17	0.2	0.4	30	32	0.2	0.4
2	4	0.2	0.4	12	13	0.2	0.4	21	19	0.2	0.4	31	27	0.2	0.4
2	16	0.2	0.4	12	24	0.2	0.4	21	30	0.2	0.4	31	29	0.2	0.4
3	1	0.2	0.4	13	9	0.2	0.4	22	23	0.2	0.4	32	33	0.203	0.403
3	16	0.2	0.4	14	11	0.2	0.4	22	34	0.2	0.4	32	42	0.203	0.403
4	7	0.2	0.4	14	24	0.2	0.4	23	11	0.2	0.4	33	21	0.2	0.4
4	12	0.2	0.4	15	1	0.2	0.4	23	13	0.2	0.4	33	23	0.2	0.4
4	20	0.2	0.4	15	4	0.2	0.4	24	21	0.2	0.4	34	31	0.203	0.403
5	2	0.2	0.4	16	18	0.2	0.4	24	34	0.2	0.4	34	42	0.203	0.403
6	8	0.2	0.4	16	26	0.2	0.4	25	15	0.2	0.4	35	25	0.2	0.4
6	10	0.2	0.4	17	15	0.2	0.4	25	18	0.2	0.4	35	28	0.2	0.4
7	5	0.2	0.4	17	26	0.2	0.4	26	28	0.2	0.4	36	38	0.2	0.4
7	10	0.2	0.4	18	19	0.2	0.4	26	36	0.2	0.4	37	35	0.2	0.4
8	3	0.2	0.4	18	22	0.2	0.4	27	25	0.2	0.4	38	40	0.227	0.427
8	12	0.2	0.4	18	30	0.2	0.4	27	36	0.2	0.4	39	37	0.226	0.426
8	20	0.2	0.4	19	3	0.2	0.4	28	29	0.2	0.4	40	41	0.2	0.4
9	5	0.2	0.4	19	7	0.2	0.4	28	32	0.2	0.4	41	31	0.203	0.403
9	8	0.2	0.4	19	12	0.2	0.4	29	17	0.2	0.4	41	33	0.203	0.403
10	14	0.2	0.4	20	17	0.2	0.4	29	19	0.2	0.4	42	39	0.2	0.4
11	3	0.2	0.4	20	22	0.2	0.4	29	22	0.2	0.4	PR : Primary Relay			
11	7	0.2	0.4	20	30	0.2	0.4	30	27	0.2	0.4	BR : Backup Relay			

4.6 Summary

In this chapter, a new method is proposed to develop non-standard characteristics for DOR. Quadratically constrained quadratic programming (QCQP) problem, unlike NLP, does not require an initial point to solve and can be solved much faster using the "scip" solver available. PSO is an evolutionary programming method that is used to generate the coefficient values required to solve the QCQP. The results obtained by this method, by testing it against benchmark 3,8 and 15 bus systems are found to be way better than other heuristic or hybrid heuristic methods.

CHAPTER 5

CONCLUSION AND FUTURE SCOPE

5.1 Conclusion

Protection coordination of Directional overcurrent relays with non-standard inverse characteristics has been presented in this thesis. The protection relay coordination problem is defined as a nonlinear nonconvex optimization problem, which is initially evaluated on heuristic methods like GA, PSO, GSA, IWO and hybrid heuristic methods like GA-NLP, PSO-NLP. From the statistical results, it has been observed that the heuristic and hybrid heuristic techniques, though fairly effective, could not fetch the best relay operating times. For this reason, non-standard relay characteristics are developed by making the coefficients of the characteristic as variables. The protection coordination problem is formulated as a quadratically constrained quadratic problem, by fixing CPS and C. However, to obtain the global optimum, the values of CPS and C are heuristically generated using the PSO algorithm. The proposed technique is evaluated on standard benchmark test systems and results are found to be satisfactory.

5.2 Future Scope

Nonstandard characteristic protection relays based on overcurrent protection has been discussed in this thesis. In the view of microgrids and smartgrids where inverter based distributed generation are predominant, the directional overcurrent protection is a complex task as the fault current contribution is not prominent. Hence, other network parameters like voltage, fault impedance seen by the relay have to be incorporated into the protection relay characteristics for providing better relay sensitivity. Besides, adaptive and online protection models based on communication has to be developed to better address the fault detection problem for smartgrids.

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APPENDIX

1) 3 Bus fault current data

Table 1 Fault data for 3 bus

Primary Relay	Fault Current(A)	Backup Relay	Fault Current(A)
Normal Configuration			
1	1978.90	5	175.00
2	1525.70	4	545.00
3	1683.90	1	617.22
4	1815.40	6	466.17
5	1499.66	3	384.00
6	1766.30	2	145.34

2) 8 Bus fault current data

Table 2 Fault data for 8 bus

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

3) 15 Bus fault current data

Table 3 Fault data for 15 bus

Primary	I(A)	Backup	I(A)	Primary	I(A)	Backup	I(A)
1	3621	6	1233	20	7662	30	681
2	4597	4	1477	21	8384	17	599
2	4597	16	743	21	8384	19	1372
3	3984	1	853	21	8384	30	681
3	3984	16	743	22	1950	23	979
4	4382	7	1111	22	1950	34	970
4	4382	12	1463	23	4910	11	1475
4	4382	20	1808	23	4910	13	1053
5	3319	2	922	24	2296	21	175
6	2647	8	1548	24	2296	34	970
6	2647	10	1100	25	2289	15	969
7	2497	5	1397	25	2289	18	1320
7	2497	10	1100	26	2300	28	1192
8	4695	3	1424	26	2300	36	1109
8	4695	12	1463	27	2011	25	903
8	4695	20	1808	27	2011	36	1109
9	2943	5	1397	28	2525	29	1828
9	2943	8	1548	28	2525	32	697
10	3568	14	1175	29	8346	17	599
11	4342	3	1424	29	8346	19	1372
11	4342	7	1111	29	8346	22	642
11	4342	20	1808	30	1736	27	1039
12	4195	13	1503	30	1736	32	697
12	4195	24	753	31	2867	27	1039
13	3402	9	1009	31	2867	29	1828
14	4606	11	1475	32	2069	33	1162
14	4606	24	753	32	2069	42	907
15	4712	1	853	33	2305	21	1326
15	4712	4	1477	33	2305	23	979
16	2225	18	1320	34	1715	31	809
16	2225	26	905	34	1715	42	907
17	1875	15	969	35	2095	25	903
17	1875	26	905	35	2095	28	1192
18	8426	19	1372	36	3283	38	882
18	8426	22	642	37	3301	35	910
18	8426	30	681	38	1403	40	1403
19	3998	3	1424	39	1434	37	1434
19	3998	7	1111	40	3140	41	745
19	3998	12	1463	41	1971	31	809
20	7662	17	599	41	1971	33	1162
20	7662	22	642	42	3295	39	896