OPTIMAL RELAY COORDINATION WITH DISTRIBUTED GENERATION USING ARTIFICIAL INTELLIGENCE ALGORITHM

A DISSERTATION

Submitted in partial fulfilment of the requirements for the award of the degree of

MASTER OF TECHNOLOGY

in

ELECTRICAL ENGINEERING

(With specialization in Instrumentation and Signal Processing)

By

ASTHA CHAWLA

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

CANDIDATE'S DECLARATION

I, hereby, certify that the work which is being presented in the dissertation entitled " **OPTIMAL RELAY COORDINATION WITH DISTRIBUTED GENERATION USING ARTIFICIAL INTELLIGENCE ALGORITHM** " in partial fulfilment of the requirement for the award of the degree of **Master of Technology in Electrical Engineering with specialization in *Instrumentation & Signal Processing***, submitted to the Department of Electrical Engineering, Indian Institute of Technology, Roorkee, India, is an authentic record of my own work carried out during a period from May 2015 to May 2016 under the supervision of Dr. Bhavesh Bhalja and Dr. Manoj Tripathy, Department of Electrical Engineering, Indian Institute of Technology, Roorkee.

The matter presented in the dissertation has not been submitted by me for the award of any other degree of this or any other institute.

Date :

Place : Roorkee **(Astha Chawla)**

CERTIFICATE

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

(Dr. Bhavesh Bhalja)
Associate Professor
Department of Electrical Engineering
Indian Institute of Technology, Roorkee
Roorkee, 247667

(Dr. Manoj Tripathy)
Associate Professor
Department of Electrical Engineering
Indian Institute of Technology, Roorkee,
Roorkee, 247667

ACKNOWLEDGEMENTS

I owe my profound gratitude to Dr. Bhavesh Bhalja**,** Associate Professor, Department of Electrical Engineering, Indian Institute of Technology, Roorkee, for his constant guidance, valuable feedbacks and suggestions at various stages of this work and for providing relevant resources without which this thesis would not have been completed so well.

I would like to extend my sincere thanks to Dr. Manoj Tripathy**,** Associate Professor, Department of Electrical Engineering, Indian Institute of Technology, Roorkee, and Dr R. P. Maheshwari, Professor, Department of Electrical Engineering, Indian Institute of Technology, Roorkee for showing keen interest and for being helpful.

I also want to thank my parents, my grandfather, Malvika and Akshit, for being a constant source of love, patience, and motivation.

ASTHA CHAWLA

ABSTRACT

Due to dependency on Plug Setting (PS), Time Dial Setting (TDS), size of the network, more than one back-up relays for one primary relay and other technical constraints, coordination of Directional Overcurrent Relays (DOCRs) is an extremely constrained and nonlinear optimization problem. Here a new Gravitational Search (GS) based algorithm is presented for achieving optimal coordination of directional overcurrent relays. This algorithm utilizes user defined characteristic for inverse time overcurrent relays than the predefined standard curves. The user defined relay characteristic deals with constants that control the shape of the characteristics as variable adjustable values which are optimally chosen along with TDS and Plug Setting Multiplier (PSM). The performance of the proposed scheme has been evaluated for near end faults on 8-bus & 15-bus test systems and for different fault locations (near-end, far-end and middle point) on IEEE 30-bus distribution network. The time of operation of some of the primary relays at different fault locations on IEEE 30-bus distribution network is also shown. At the end, comparative evaluation of this GS based algorithm with other optimization algorithms proposed in the literature clearly indicates its effectiveness and superiority in terms of the sum of total primary relays operating time.

LIST OF FIGURES

LIST OF TABLES

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

Directional overcurrent relays are widely used for the protection of radial feeder feed from two ends, ring/mesh networks and parallel/cascaded parallel feeders. These relays are used as primary protective device at distribution and sub-transmission level and as secondary protective device at transmission level [1]- [2]. Due to restructuring of electrical power utilities and increasing share of Distributed Energy Resources (DERs), coordination of overcurrent relays is becoming quite complex and requires sophisticated programming approach [3]. The operating time of DOCRs depends on two settings namely plug setting (PS) and time dial setting (TDS). Most of the conventional DOCRs utilize IEEE standard inverse time current characteristic where the time of operation of relay is inversely proportional to the magnitude of current [4]. The modelled equation for calculating time of operation of overcurrent relay has two constants which control the current time relationship of the relay. The constant β and α represents the constants for relay characteristics and the inverse time type, respectively. In [5], set of eight different relay characteristics have been considered for overcurrent relay and the best of them have been chosen by Genetic Algorithm (GA) from the provided set of characteristics for each overcurrent relay to make the optimal coordination easier. Conversely, the proposed GS based algorithm utilizes a wide range of relay characteristics by continuously varying the values of alpha and beta within the provided bounds, making it more flexible. These values are adjusted and optimally chosen to achieve proper coordination among DOCRs [6].

In order to solve coordination problem of DOCRs, different approaches have been proposed by researchers. These approaches are based on trial and error [7], topological analysis [8]-[9] and optimization techniques. However, the first approach has not been very popular due to requirement of large number of iterations, huge computations and slow convergence rate. The topological analysis based approach requires less number of iterations and involves derivation of break points to initiate relay coordination. Nevertheless, the prime limitation of this approach is that it does not produces global optimal value of TDS & PSM and is dependent on selection of break points. An approach based on optimization technique can be classified as conventional optimization and nonconventional optimization technique. In the conventional optimization method, linear programming (LP) techniques (such as simplex, two-phase simplex, and dual simplex) and non-linear programming (NLP) optimizing techniques are very frequently used for coordination of DOCRs [10]-[11]. Though LP technique is fast and simple, it can be trapped in local minima. On the other hand, performance of NLP techniques is better than LP techniques. Afterwards, several Artificial Intelligence (AI)/nature inspired based algorithms such as genetic algorithm (GA), particle swarm optimization (PSO), teaching learning-based optimization (TLBO), ant colony optimization (ACO), bee colony optimization (BCO), differential evolution (DE), seeker optimization and biogeography-based optimization (BBO) have been successfully applied to solve the problem of optimal coordination of DOCRs [12]- [20]. Though the above approaches are able to provide global optimum, they require more computational time and have slow convergence speed. Subsequently, algorithms based on integration of various AI techniques are more complex and require high CPU time.

Here GS based algorithm is presented for optimum coordination of overcurrent relays using two different relay characteristics (standard and user defined). LINKNET structure is utilized to obtain primary- backup relay pairs whereas user developed short-circuit analysis program is used for fault calculations. The performance of the GS based algorithm has been evaluated on 8-bus, 15-bus and IEEE 30-bus distribution network at different fault locations (near-end, far-end and middle point). In addition, the time of operation of some of the primary relays at different fault locations on IEEE 30-bus distribution network is also presented. The optimal coordination of DOCRs has been carried out by implementing the proposed GS based algorithm in MATLAB 2015b software on Intel Core i3-2310M Processor. At the end, the results obtained by the proposed GS based algorithm are compared with results claimed by the existing algorithms [16], [19], [21] utilizing conventional as well as different relay characteristics incorporating some new terms/constraints [22] and they are found to be superior to the results given by the said algorithms.

CHAPTER 2

RELAY COORDINATION REVIEW

2.1 Basics of Relay Coordination

When two or more protective apparatus installed in series have characteristics that provide operating sequence, they are said to be coordinated or selective. Here the device set to operate first to isolate the fault provides primary protection while the operating device that is set to operate only when primary protection fails to operate to clear the fault, furnishes backup protection [1]. They are guided by principle that primary protection should get an adequate chance to protect the zone under its primary protection. Only if the primary protection doesn't clear the fault, the backup protection should initiate tripping [23]. Certain time interval must be maintained between operating time of various protective devices to ensure correct sequential operation of the devices. This time interval essential for maintaining selectivity between primary and backup protections is known as Coordination Time Interval (CTI) or Selective Time Interval (STI) [1].

2.2 Importance of Relay Coordination

To operate Power System appropriately, system should have a well-designed and practically coordinated protection system. Therefore, the coordination of protective relays is an important aspect of the protection system design [1].

The protection requirements of a power system must take into account the following basic principles:

Reliability: The ability of the protection to operate correctly.
Speed: Minimum operating time to clear a fault to avoid damage to equipment.

Selectivity: Maintaining continuity of supply by disconnecting the minimum section to isolate the fault.

Cost: Maximum protection at the lowest possible cost.

2.3 Difficulties in Coordination of Relays

It has been very difficult to coordinate the protective relays on transmission lines of power network because a relay operates as a primary relay (PRI) for a fault in its primary protection and same relay operates as a backup relay for some other PRIs in the system.

Thus the setting of each relay must be selected such that it not only identifies a fault in its zone of protection known as primary protection zone and act very quickly but also operates discriminately in a proper time sequence with the relays on the neighbouring lines.

But relays in different location detect greatly different currents during the same fault making relay-setting calculation difficult [1].

Moreover, Relaying Schemes and setting procedures vary from utility to utility as they reflect different company philosophies and practices. Therefore, changing a single relay setting in a system is likely to affect entire system relaying. [18]

The main problem that arises with overcurrent relaying protection is the difficulty in performing relay coordination in multiloop, multisource system. Thus, coordination of overcurrent relays in a meshed distribution system is a challenge task for the protection engineers [1].

2.4 Relay Coordination Techniques

Methods proposed for the coordination of overcurrent relays can be classified into three classes

- Trial and error.
- Topological analysis method
- Optimization method.

Trial and error method involves large number of iterations and has slow convergence. To reduce the number of iterations, topological analysis method was recommended. In this method, finding breakpoints is significant part to initiate relay coordination. Breakpoints refer to initially selected relays which are selected using graph theory approach. Relays at remote end are set first and thereafter corresponding backup relays are set from coordination protection point of view. In this way all possible paths are taken into account for optimal setting of relay parameters. Final time dial setting (TDS), plug setting multiplier (PSM) and number of iteration depends upon break points. Adequate choice of break points decreases the number of iteration needed in this approach for relay coordination but TDS and PSM obtained from this approach are not optimal.

Optimization Method

In the Optimization method, Linear and Non-Linear programming optimizing techniques are very frequently used for coordination of overcurrent relays.

Due to the complexity of nonlinear optimal programming techniques, the coordination of overcurrent relays is commonly performed by linear programming techniques. In these methods the current setting of the relays is assumed to be determined prior, and only time multiplier setting of the relays are calculated. Generally, the solution obtained is not the global optimum solution of the problem.

Presently Artificial Intelligence based techniques or nature inspired algorithms are applied for optimal co-ordination of overcurrent (OC) relays.

Comparative analysis among different Artificial Intelligence techniques used for relay coordination is given below [24]- [26].

Table 2.1 Comparison Between DE and PSO

Parameter	Differential Evolution	Particle Swarm Optimization
Accuracy	Better than PSO	Good
Convergence Speed	Faster Than PSO	Good

Table 2.2 Comparison Between DE and GA

Parameter	Differential Evolution	Genetic Algorithm
Number of Population used	Population is divided into number of subpopulations	One single population is used
Representation	Uses actual real numbers.	Uses chromosomal kind of representation
Stability	Better than GA	Good
Efficiency	Better than GA	Good

Table 2.3 Comparison Between GA and PSO

Parameter	Genetic Algorithm (GA)	Particle Swarm Optimization (PSO)
Approach	The GA employs three operators: ➢ Selection ➢ Crossover ➢ Mutation	The basic PSO algorithm consists of three steps, namely ➢ Generating particles' positions and velocities ➢ Velocity update ➢ Position update
Computational Complexity	Complex than PSO	Easy to implement
Information sharing mechanism	Chromosomes share information with each other. So the whole population moves like a one group towards an optimal area.	Only gBest (or IBest) gives out the information to others. It is a one -way information sharing mechanism
Quality of solution	Superior than PSO. Algorithm converge towards high quality solutions within a few generations	Some particles (a sub-swarm for instance) could never converge or may prematurely converge to stable point.

2.5 Approach for Optimal Relay Coordination

Relay Coordination involves following approach

- LINKNET structure is formed for storing network configuration in system
- Primary-Backup pairs of relays are calculated using LINKNET structure. Refer [1] for algorithm.
- Load Flow and Short Circuit analysis is done.
- Optimization of Settings using Artificial Intelligence Algorithm (here Gravitational Search Algorithm is used).

Primary-Backup relay pairs along with their corresponding fault currents for 8-bus system, 15 bus system and IEEE 30 bus distribution system in tabular format are given in Appendix.

CHAPTER 3

OPTIMAL RELAY COORDINATION PROBLEM FORMULATION

The directional overcurrent relay operates only when the current flowing through the relay is more than its plug setting and also the current flows through the relay in its correct (operative) direction. Most of the conventional DOCRs (electromechanical type) use standard inverse time current characteristic. Different types of characteristics are obtained by changing constants of the characteristic equation. In this study, IEEE standard C37.112 inverse time current characteristic is used for conventional DOCRs [4]. In addition, digital/numerical based DOCRs are used which provide a chance to utilize user defined characteristic to change constants (α and β) of the characteristic equation as per user requirements. The optimal coordination of DOCRs involves calculation of optimal relay settings. Here, LINKNET structure is used to store information of network configuration. Using this structure, primary-backup pairs of the relay have been calculated [1]. Afterwards, user developed short-circuit analysis program is used for calculation of three phase fault currents. Finally, settings of all the relays are calculated and optimized to avoid miscoordination.

3.1. Objective Function

The goal of objective function is to minimize the sum of primary relays' operating time. This is achieved by optimizing relay settings without violating the conditions of protection coordination with conventional/user defined characteristic using GS algorithm. The objective function, as given in equation (3.1), is the summation of operating time of all the primary overcurrent relays located at the end of different lines [17]-[18]..

$$Min(Z) = \sum_{i=1}^{n} w_i \times t_{i,k} \qquad (3.1)$$

Where, n is the number of relays, $t_{i,k}$ is the operating time of the i^{th} relay for fault in zone k, and w_i is the weight assigned for operating time of i^{th} relay. It represents the probability of a given fault that may occur at each location of the protective zones (w_i=1 for distribution feeders having same length). For conventional standard inverse time-current characteristics, the operating time of DOCR is given by equation (3.2).

$$t_{i,k} = \left[\frac{\beta \times TDS_i}{(M_i)^{\alpha}-1}\right] + L \tag{3.2}$$

Where, TDS_i and M_i is the time dial setting and plug setting multiplier for the i^{th} relay, respectively. PSM indicates the severity of fault as seen by the relay in terms of multiple of pick-up current whereas *TDS* corresponds to the distance travelled by the relay contacts for final closing. M depends on the magnitude of fault current and pickup setting of the relay and is given by equation (3.3).

$$M = \frac{I_{fault}}{I_{pickup}} \tag{3.3}$$

$$M = \frac{I_{fault}}{PS_i \times \text{ Rated Secondary current of} CT} \tag{3.4}$$

Where, I_{fault} is the short-circuit current measured at the secondary winding of the current transformer (CT) while I_{pickup} is the minimum value of current above which the relay starts to operate. PS_i represents Plug Setting of the i^{th} relay. As per IEC and ANSI/IEEE Standards, β and α are two constants which control the time/current relation of the relay; β represents the constant for relay characteristics and α represents the inverse time type. For standard Inverse Definite Minimum Time (IDMT) characteristic, relay constants α, β and L are taken as 0.02, 0.14 and 0, respectively [4]. The values of α, β and L for various standard overcurrent types of relay is given in Table 3.1 [4]. User defined characteristic allows the relay to operate within different time current characteristics (not limited to the standard ones) by considering continuous variable values of β and α along with *TDS* and *PS*. Thus, coordination problem now involves four settings to be optimized and the operating time of DOCR is now given by equation (3.5).

$$t_{i,k} = \left[\frac{\beta_i \times TDS_i}{(M)^{\alpha i}-1}\right] + L \tag{3.5}$$

Table 3.1: Values of α, β and L for different Standard Characteristics of OCRs

Relay type	Standard	Alpha(α)	Beta (β)	L
Moderately inverse	IEEE	0.02	0.0515	0.114
Very inverse	IEEE	2	19.61	0.491
Extremely inverse	IEEE	2	28.2	0.1217
Standard inverse	IEC	0.02	0.14	0
Very inverse	IEC	1	13.5	0

3.2. Normal Coordination Constraints

The constraints of the said optimization problem are given as under.

3.2.1 Limits on Problem Variables

The relay manufacturer provides bounds on *TDS* of each relay. This is given by equation (3.6).

$$TDS_i^{min} \leq TDS \leq TDS_i^{max} \tag{3.6}$$

Where, TDS_i^{min} and TDS_i^{max} are the minimum and the maximum value of *TDS* of i^{th} relay, respectively. The value of *TDS* generally varies from 0.1 to 1.0 [16].

Moreover, bounds on pickup setting (PS) of each relay are given by equation (3.7). The value of *PS* depends on full load current and short circuit level of the system.

$$PS_i^{min} \leq PS \leq PS_i^{max} \tag{3.7}$$

Where, PS_i^{min} and PS_i^{max} is the minimum and the maximum value of PS of the i^{th} relay, respectively. It is taken as 0.5 and 2.5, respectively [16].

Furthermore, bounds on constants of the user defined relay characteristic is given by equation (3.8).

$$\beta_i^{min} \leq \beta_i \leq \beta_i^{max}$$

$$\alpha_i^{min} \leq \alpha \leq \alpha_i^{max} \tag{3.8}$$

Where, β_i^{min} & β_i^{max} and α_i^{min} & α_i^{max} are taken as 0.14 & 13.5 and 0.02 & 1.0, respectively [4].

3.2.2 Limits on Primary Relay Operating Time

It is worthwhile to note that the primary operation time with reference to each possible fault location should be less than the maximum allowed time delay. At the same time, it is also more than some minimum predefined time considering transient conditions [11]. The minimum operation time depends on the relay manufacturer while the critical clearing time is required to prevent equipment damage as well as to preserve system stability.

3.2.3 Coordination Criteria (Selectivity Constraint)

It is to be noted that the primary as well as the secondary relay senses the fault at the same time. Therefore, it is universal practice to adjust operating time of backup relay such that it operates only after primary relay fails to operate. If R_j is the primary relay for fault at k, and R_i is backup relay for the same fault, then the coordination constraint is given by equation (3.9).

$$t_{j,k} - t_{i,k} = \Delta t \tag{3.9}$$

Where, $t_{j,k}$ and $t_{i,k}$ is the operating time of primary relay (R_j) and back relay (R_i), respectively, for fault at k. Δt is the Coordination Time Interval (CTI). It is generally taken as 0.2 sec to 0.3 sec [16].

CHAPTER 4

REVIEW OF GRAVITATIONAL SEARCH ALGORITHM AND ITS IMPLEMENTATION TO RELAY COORDINATION PROBLEM

The Gravitational Search Algorithm (GSA) was developed in 2009. It is based on the Newtonian gravity: "Every particle in the universe attracts every other particle with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between them" [27]. Detailed information about algorithm is available in [27]. Srivastava *et. al* [28] proposed hybrid PSO-GS based algorithm for optimal coordination of DOCRs. However, applicability of this algorithm has been tested on small radial test system only. Moreover, the use of hybrid PSO-GS based algorithm increases complexity. Fig. 4.1 shows flowchart of the GS based algorithm for optimal coordination of DOCRs. Initially, number of agents (population) in defined search space (dim) that are to be optimized are defined in the algorithm. Here, agents are variables that need to be optimized. Afterward, maximum and minimum allowable range of the variables are defined which are used to randomly generate the values of these variables in defined search space. The performance (quality) of possible solutions of the problem is determined by the masses of agents. The masses of objects are calculated based on fitness value/objective function which refers to sum of time of operation of all primary relays.

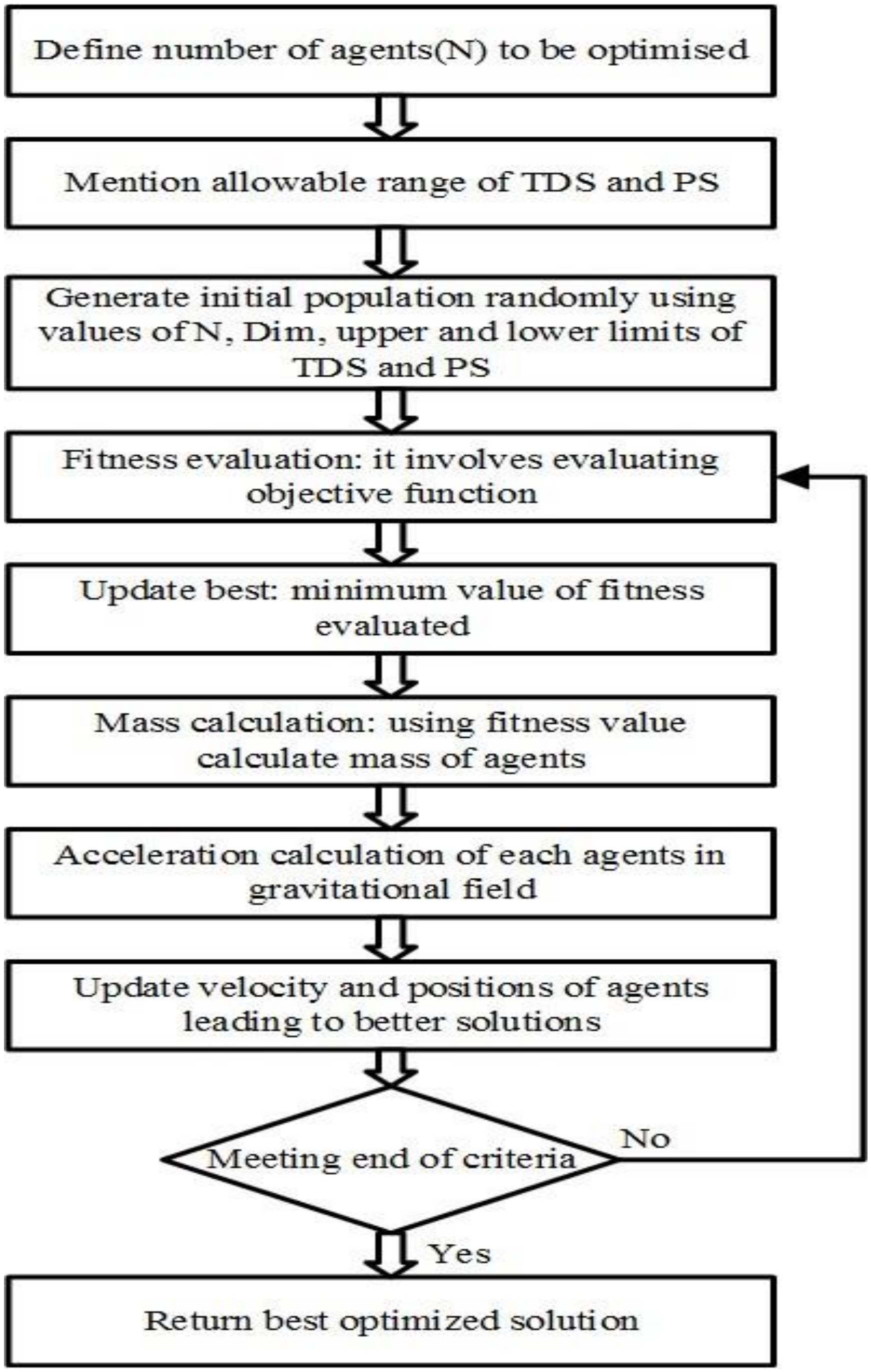

Fig. 4.1 Flowchart of the proposed GS based algorithm

Fig. 4.2 shows flowchart for calculation of fitness value. With reference to relay coordination problem, evaluation of fitness value requires information about primary-backup relay pairs which are calculated using LINKNET structure. Fault data are generated using user developed short circuit analysis program. With this information, time of operation of all primary- backup relay pairs and CTI are calculated. Based on violation in CTI constraint, penalty factor is taken into account. When the penalty factor becomes very small (close to zero), sum of primary relay operating time is obtained. The minimum fitness value so obtained is considered as the best while the maximum one as the worst. Mass of agents/variables is then evaluated from the fitness values. This is followed by calculating the force experienced by each mass in search space due to other masses present and calculation of acceleration of masses. Finally, the velocity and position of masses are updated with every iteration to give more optimum solutions as described in Fig. 4.1. The updated positions of masses (optimized values of variables) represent the final solutions of the problem.

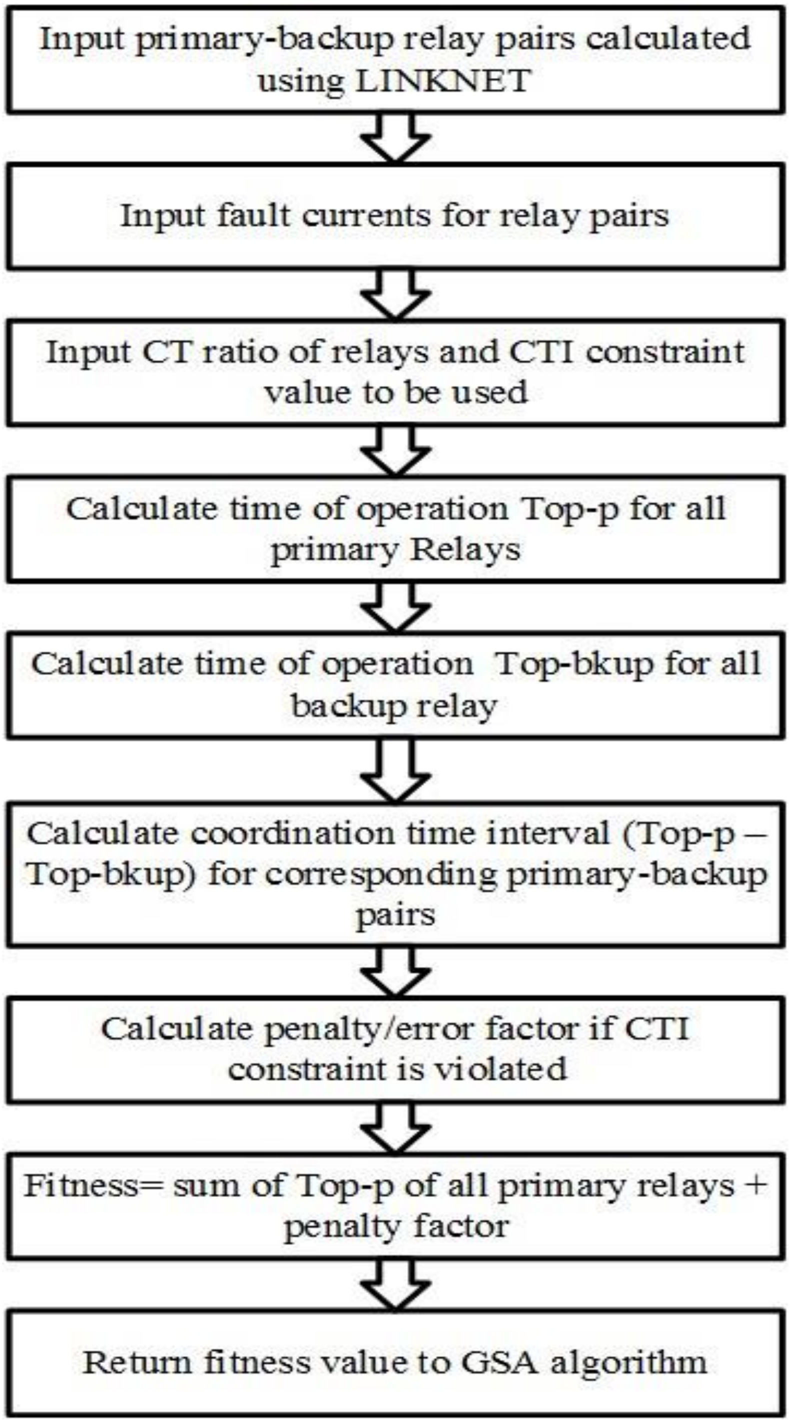

Fig. 4.2 Flowchart for calculation of fitness value

CHAPTER-5

RESULTS AND DISCUSSIONS

5.1. Performance of GS based Algorithm for 8-bus Network

Fig. 5.1 shows the single line diagram of 8-bus meshed distribution system which contains 14 relays. As shown in Fig. 5.1, there is also a link to another network at bus-4 modelled by a short circuit power of 400 MVA [16]. The short-circuit data for three phase faults and primary back-up relay pairs are obtained using user developed short-circuit program and LINKNET structure, respectively [16]. The CT ratio of 800/5 A is used for relays 3, 7, 9, 14 whereas 1200/5 A CT ratio is considered for rest of the relays. The population size is taken as 100 while the CTI is taken as 0.2 [16].

The structure of solution vector is given as follows:

- With Conventional Characteristic: 14 optimization parameters
  TDS_1 to TDS_{14} for all 14 relays in system
- With user defined characteristic: 42 optimization parameters
  TDS_1 to TDS_{14}, β_1 to β_{14} and α_1 to α_{14} for all 14 relays in system

Table 5.1: Structure of solution vector for 8 bus system with user defined characteristic

TDS	Beta (β)	Alpha (α)
TDS_1……………TDS_{14}	β_1 ………………. β_{14}	α_1 ………………. α_{14}

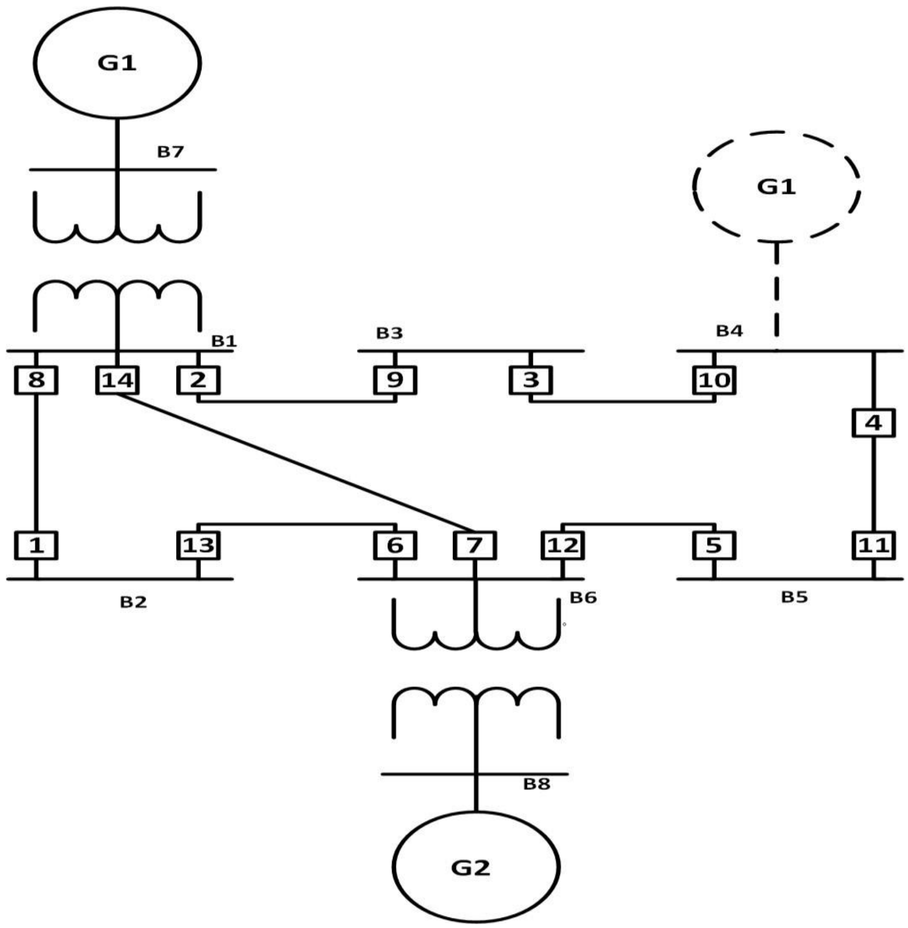

Fig.5.1 Single line diagram of 8-bus meshed distribution system

Table 5.2 shows comparative evaluation of the existing algorithms [16], [19] and GS based algorithm for near end fault location. The results in terms of PS, TDS and total operating time for primary relays given by the two recently proposed schemes in the literature [16], [19] are shown in the first two columns of Table 5.2. In the last two columns of the same table, results obtained from the GS based algorithm using conventional standard relay characteristic and user defined relay characteristic (along with optimal values of β and α) are shown. It is to be noted that the sum of primary relays' operating time given by the GS based algorithm using conventional characteristic is 8.0814 sec while it is 2.5718 by utilizing user defined relay characteristic which is considerably lower than the values given by existing algorithms [15], [18]. Moreover, in Table

5.3, optimal relay setting, optimal relay characteristic constants and time of operation of primary relays calculated using proposed user defined characteristic is also compared with the already existing results in [22] (Table 12: case 1 with parameter values as α_1 =1, α_2 = 2, β_2 =100) where optimal coordination of overcurrent relays has been carried out by incorporating some new terms/constraints. It has been observed from Table 5.3 that the sum of time of operation of primary relays given by the proposed scheme is 2.8041 sec which is much lower than 10.6944 sec claimed in [22]. This clearly indicates superiority of this method. Fig 5.2 shows the convergence curve of this system with GS based algorithm with user defined characteristic.

The performance of the proposed scheme has also been evaluated for far end fault location and the results are shown in Table 5.4. Table 5.4 shows the optimized values of relay settings and characteristics constants for far-end fault location with increased time of operation. Time of operation of all primary relays (T_{pri}) for the obtained optimal settings is also depicted in Table 5.4. It has been observed from Table 5.4 that the sum of the relays' operating time given by this scheme based on GS based algorithm is 21.4531 sec. Though this time is higher than the sum of the relays' operating time obtained in case of near end fault location, this scheme works perfectly without any miscoordination between primary backup relay pairs.

Table 5.2: Optimal Relay Settings obtained from GS based algorithm
for 8 bus meshed distribution system

Relay number	Results obtained from existing algorithm [16]		Results obtained from existing algorithm [19]		Results obtained from GS based algorithm using conventional standard characteristic		Results obtained from GS based algorithm using user defined characteristic			
	PS	TDS	PS	TDS	PS	TDS	PS	TDS	Beta (β)	Alpha (α)
1	2	0.113	2.5	0.1	2	0.1188	2	0.1003	5.2834	0.9756
2	2.5	0.26	2	0.30329	2.5	0.2305	2.5	0.2161	10.2649	0.9986
3	2.5	0.225	2.5	0.23571	2.5	0.213	2.5	0.1946	9.1432	0.9560
4	2.5	0.16	1.5	0.22043	2.5	0.1619	2.5	0.1274	7.6544	0.9738
5	2.5	0.1	2.5	0.1	2.5	0.1	2.5	0.1229	2.8901	0.9115
6	2.5	0.173	2.5	0.1734	2.5	0.2239	2.5	0.1864	7.2805	0.9903
7	2.5	0.243	2.5	0.25321	2.5	0.2515	2.5	0.3226	7.4430	1.0000
8	2.5	0.17	0.5	0.34805	2.5	0.1431	2.5	0.1615	7.7485	0.9797
9	2.5	0.147	2.5	0.14866	2.5	0.1251	2.5	0.1031	6.8741	0.9603
10	2.5	0.176	2	0.20519	2.5	0.1659	2.5	0.2279	4.7174	0.9826
11	2.5	0.187	2.5	0.19198	2.5	0.175	2.5	0.3987	2.9661	0.9723
12	2.5	0.266	2.5	0.27146	2.5	0.2441	2.5	0.2526	9.0811	0.9995
13	2	0.114	2	0.1154	2	0.1013	2	0.1101	4.2382	0.9448
14	2.5	0.246	2.5	0.24928	2.5	0.2229	2.5	0.2617	7.7661	0.9652
Sum of Relays' Operating Time	8.427 sec		8.7559 sec		8.0814 sec		2.5718 sec			

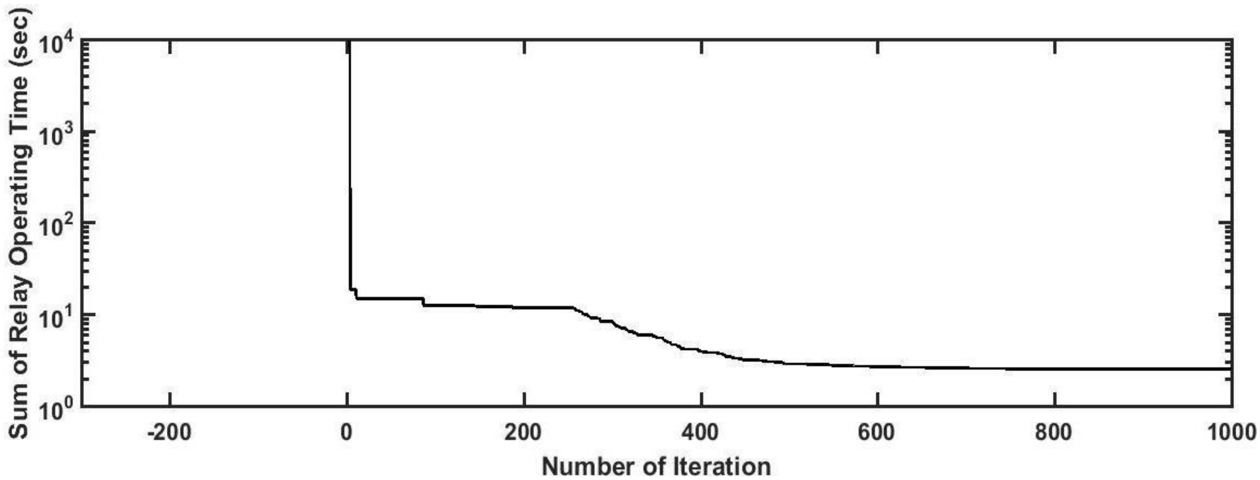

Fig. 5.2 Convergence curve of the 8-bus system under study with GS based algorithm with user defined characteristic

Table 5.3: Comparison of the results from GS based algorithm with existing method involving new terms/constraints

Relay Number	Results obtained from existing algorithm [22]		Results obtained from GS based algorithm using user defined characteristic			
	TDS (α_1 =1, α_2 = 2, β_2 =100)	Time of operation of primary relays	TDS	Beta (β)	Alpha (α)	Time of operation of primary relays
1	0.15	0.5894	0.101	4.6074	0.9258	0.11934
2	0.35	1.2173	0.205	9.8600	0.9827	0.26625
3	0.25	0.9621	0.276	6.1696	0.9929	0.23618
4	0.1	0.6636	0.168	2.3681	0.9608	0.15692
5	0.1	0.766	0.105	1.1265	0.8721	0.11497
6	0.25	0.7623	0.256	5.7582	0.9394	0.23436
7	0.2	0.7059	0.162	10.4068	0.9793	0.18597
8	0.25	0.7625	0.208	5.1233	0.9019	0.18624
9	0.05	0.3479	0.200	1.1735	0.9464	0.09890
10	0.15	0.6883	0.100	4.2493	0.9194	0.17085

11	0.25	0.9835	0.247	5.0385	0.9717	0.27537
12	0.4	1.1847	0.497	6.1191	0.9929	0.38977
13	0.1	0.4665	0.100	4.9438	0.9238	0.13850
14	0.15	0.5944	0.252	8.4910	0.9875	0.23051
Sum of Relays' Operating Time	10.6944 sec		2.8041 sec			

Table 5.4: Performance evaluation of the GS based scheme for far-end fault location

Relay Number	Results obtained from GS based method			
	TDS	Beta (β)	Alpha (α)	T_{pri} (sec)
1	0.1104	6.113	0.8523	1.067
2	0.3918	7.3748	0.8824	0.762
3	0.3205	7.3409	0.817	0.98
4	0.1751	2.0223	0.7159	0.632
5	0.3002	0.6793	0.785	7.822
6	0.1019	6.4226	0.9782	0.193
7	0.1483	8.6852	0.7213	0.746
8	0.11	6.2147	0.8759	0.271
9	0.1	4.3136	0.9015	3.851
10	0.2231	3.2211	0.7585	1.047
11	0.1994	6.0634	0.8749	0.46
12	0.4323	11.2013	0.783	1.543
13	0.1592	4.3832	0.8138	1.173
14	0.2429	9.0813	0.8872	0.906
Sum of relays' operating time	21.4531 sec			

5.2 Performance of GS based Algorithm for 15-bus Network

The performance of the GS based algorithm has been evaluated on 15-bus meshed distribution network as shown in Fig. 5.3. This network contains 42 relays and 82 backup-primary relay pairs. In addition, it also includes many synchronous based Distributed Energy Resources (DERs). The synchronous reactance of each DER is 15% with 15 MVA and 20 kV ratings whereas the short circuit capacity of the external grid is 200 MVA [16]. The system parameters as well as the short circuit currents for near-end faults have been given in [16]. These are considered as per IEC standards. Moreover, appropriate CT ratio has been used for each relay and is given in Appendix. The population size is taken as 120 and 200 with conventional and user defined characteristic, respectively. Furthermore, CTI is taken as 0.2 and the structure of solution vector is given as follows:

- With conventional characteristic: 42 optimization parameters
  TDS_1 to TDS_{42} for 42 relays in system
- With user defined characteristic: 126 optimization parameters
  TDS_1 to TDS_{42} , β_1 to β_{42} and α_1 to α_{42} for all 42 relays in system

Table 5.5: Structure of solution vector for 15 bus system with user defined characteristic

TDS	Beta (β)	Alpha (α)
TDS_1……………TDS_{42}	β_1 ………………. B_{42}	α_1 ………………. α_{42}

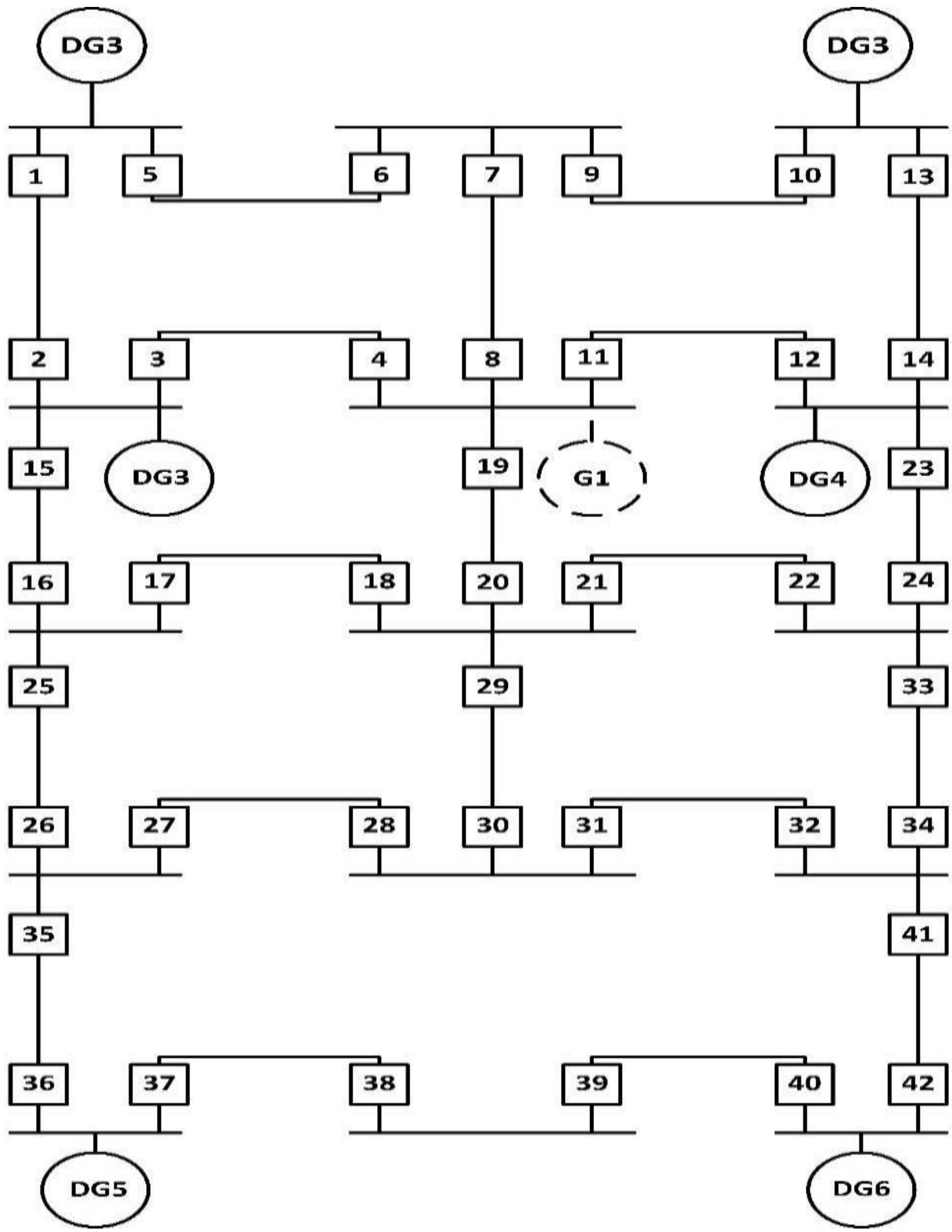

Fig. 5.3 Single line diagram of 15-bus distribution network

Table 5.6 depicts the optimal values of PS, TDS and sum of relays' operating time for existing algorithms [16], [21]. Moreover, the results given by the GS based algorithm with conventional and user defined characteristic are also given in Table 5.6. It has been observed from Table 5.6 that the optimal value of sum of relays' operating time given by the existing algorithms is 12.22 sec [16] and 15.002 sec [21], respectively. Conversely, the proposed GS based algorithm with conventional and user defined characteristic gives the optimal value of sum of relays' operating time of the order of 12.23 sec and 8.4184 sec, respectively. These values are considerably lower than the values given by the existing algorithms. Fig. 5.4 shows the convergence curve of the 15 bus system under study with user defined characteristics using GS based Algorithm.

Table 5.6: Optimal Relay Settings obtained from the GS based algorithm for 15-bus test network

Relay number	Results obtained from existing algorithm [16]		Results obtained from existing algorithm [21]		Results obtained from GS based algorithm using conventional standard characteristic		Results obtained from GS based algorithm using user defined characteristic			
	PS	TDS	PS	TDS	PS	TDS	PS	TDS	Beta (β)	Alpha (α)
1	1	0.118	2.12	0.1	1	0.11811	1	0.2805	8.4414	0.9725
2	1	0.101	1.61	0.1	1	0.10083	1	0.4263	6.7965	0.9986
3	2	0.105	2.23	0.126	2	0.1052	2	0.3870	5.7989	0.9822
4	1	0.115	2.29	0.1	1	0.11529	1	0.4318	5.6664	0.9218
5	2	0.109	1.79	0.158	2	0.10856	2	0.3494	6.5231	0.9885
6	2	0.108	2.1	0.136	2	0.10858	2	0.3948	6.2131	0.9970
7	2	0.106	2.49	0.12	2	0.10554	2	0.1836	8.2104	0.9553
8	1.5	0.108	2.45	0.1	1.5	0.10764	1.5	0.2249	7.8719	0.9716
9	2	0.106	2	0.128	2	0.10624	2	0.2852	6.0238	0.9989
10	1.5	0.112	2.4	0.106	1.5	0.11242	1.5	0.5657	7.4220	0.9999
11	1.5	0.1	1.47	0.12	1.5	0.10005	1.5	0.3231	6.5240	0.9975
12	1.5	0.1	2.12	0.1	1.5	0.1	1.5	0.2595	6.2375	0.9911
13	2	0.107	2.47	0.1	2	0.10734	2	0.3113	6.2058	0.9879
14	1	0.111	1.61	0.1	1	0.11154	1	0.4751	6.6399	0.9614
15	1	0.103	1.93	0.1	1	0.10346	1	0.5277	7.2699	0.9850
16	1.5	0.1	2.21	0.1	1.5	0.10004	1.5	0.2088	7.1637	0.9712
17	2	0.1	2.25	0.102	2	0.10055	2	0.2767	6.5295	0.9959

18	1	0.105	1.52	0.1	1	0.10508	1	0.2858	8.2498	0.9354
19	2	0.102	2.18	0.117	2	0.10166	2	0.2691	6.1923	0.8740
20	1.5	0.1	1.99	0.1	1.5	0.10016	1.5	0.3589	6.5055	0.9906
21	0.5	0.166	1.81	0.1	0.5	0.16582	0.5	0.6625	7.6653	0.9711
22	1.5	0.109	2.47	0.1	1.5	0.10921	1.5	0.2672	7.7309	0.9800
23	1	0.109	1.76	0.1	1	0.10945	1	0.5073	7.0022	0.9796
24	1.5	0.1	2.07	0.1	1.5	0.1	1.5	0.3275	8.5668	0.9999
25	2	0.103	2.5	0.117	2	0.10273	2	0.3257	5.9431	0.9933
26	1.5	0.112	1.56	0.142	1.5	0.11233	1.5	0.4351	5.5460	0.9999
27	2	0.104	2.47	0.116	2	0.10408	2	0.3240	5.9382	0.9993
28	2.5	0.105	2.5	0.146	2.5	0.1051	2.5	0.4366	5.7954	0.9914
29	1.5	0.104	2.45	0.1	1.5	0.10421	1.5	0.3720	6.8598	0.9766
30	2	0.101	2.5	0.102	2	0.10114	2	0.2944	5.4491	0.9646
31	2	0.1	2.29	0.117	2	0.10012	2	0.2737	6.7353	0.9612
32	1.5	0.105	2.43	0.1	1.5	0.10549	1.5	0.2914	6.1903	0.9418
33	2.5	0.1	2.38	0.152	2.5	0.10029	2.5	0.1894	6.9198	0.9692
34	2.5	0.107	2.45	0.141	2.5	0.10726	2.5	0.2975	6.3421	0.9928
35	2	0.103	2.5	0.122	2	0.1031	2	0.2927	4.9626	0.9755
36	2	0.1	2.5	0.105	2	0.10011	2	0.2486	6.0817	0.9767
37	2.5	0.103	2.5	0.143	2.5	0.10295	2.5	0.2226	6.6731	0.9827
38	2.5	0.106	1.86	0.167	2.5	0.10631	2.5	0.2760	6.3519	1.0000
39	2.5	0.1023	2.14	0.146	2.5	0.10254	2.5	0.4587	4.7531	1.0000
40	2.5	0.104	2.5	0.147	2.5	0.10432	2.5	0.1717	7.8823	0.9989
41	2.5	0.104	2.49	0.15	2.5	0.10416	2.5	0.1765	6.7782	0.9884
42	1.5	0.104	2.24	0.1	1.5	0.10431	1.5	0.3918	5.7433	0.9641
Sum of Relays' Operating Time	12.22 sec		15.002 sec		12.23 sec		8.4184 sec			

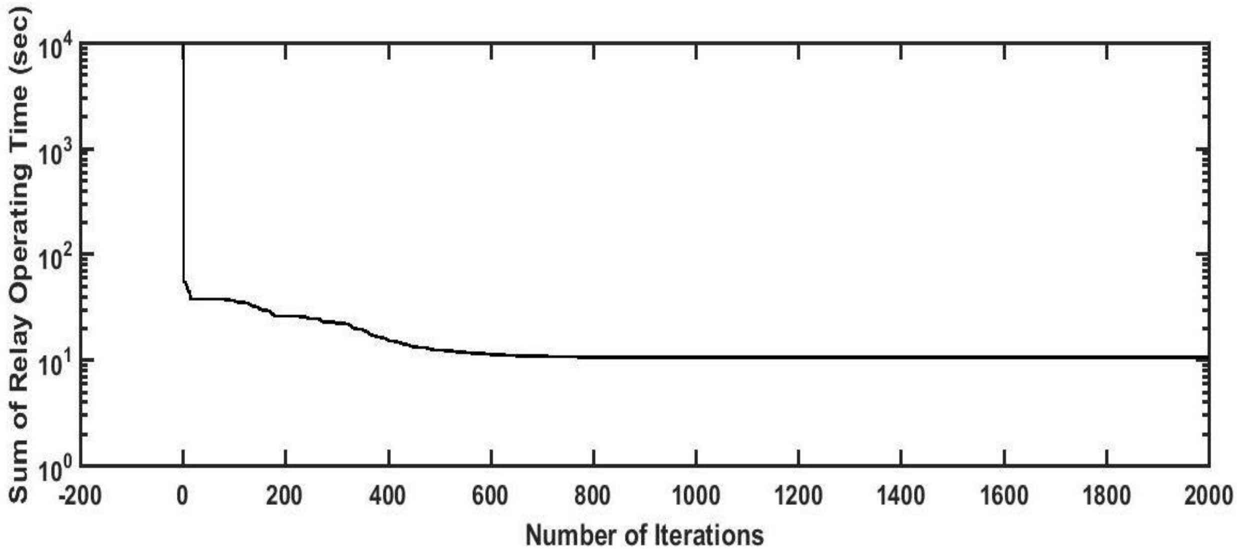

Fig. 5.4 Convergence curve of the 15-bus system under study with user defined characteristics

5.3 Performance of GS based Algorithm for IEEE 30-bus Distribution Network

Performance of the GS based algorithm has also been evaluated on IEEE 30-bus distribution network. The single line diagram of this network is shown in Fig. 5.5. The system is fed through three 50 MVA, 132 kV/33 kV transformers connected at buses 1, 6, and 15, respectively. The detailed information about the system is available in [18], [29].

Table 5.8 shows the optimal values of relay settings in terms of TDS and PS obtained from existing algorithm [18]. In the last two columns of the same table, optimal relay settings (TDS, PS, β and α) resulted from the GS based algorithm for conventional and user defined characteristics are also given. The range of TDS is from 0.01 to 1.0 and PS varies between 0.5 to 2.5. Faults are generated at different locations which includes near end and far end of buses and middle point of lines. The CT ratio for each relay is considered as 500/1 A. The population size and CTI is same as that used for 15-bus test system. The structure of solution vector is given as follows:

- With conventional characteristic: 84 optimization parameters
  TDS_1 to TDS_{42} and PS_1 to PS_{42} for 42 relays in system
- With user defined characteristic: 168 optimization parameters
  TDS_1 to TDS_{42}, PS_1 to PS_{42}, β_1 to β_{42} and α_1 to α_{42} for all 42 relays in system

Table 5.7: Structure of solution vector for IEEE 30 bus Distribution system with user defined characteristic

TDS	PS	Beta (β)	Alpha (α)
TDS_1………… TDS_{42}	PS………. PS_{42}	β_1 ………….… β_{42}	α_1 ……...……. α_{42}

It has been observed from Table 5.8 that the sum of primary relays' operating time obtained from standard characteristic and user defined characteristics is 44.1229 sec and 19.8098 sec respectively. Conversely, the sum of primary relays' operating time given by the existing algorithm is 65.4245 sec [18]. Table 5.9 and Table 5.10 shows the optimized settings given by the GS based algorithm using both conventional and user defined relay characteristics for faults at middle point and far- end, respectively. It has been observed from Table 5.9 and Table 5.10 that the sum of Relays' operating time given by the proposed algorithm using both conventional and user defined relay characteristics is 69.3512 sec & 39.2981 sec and 146.5081 sec & 82.5050 sec, respectively, for faults at middle-point and far-end. It is clear from both these tables that though the sum of Relay's operating time is higher in case of middle-point fault location and the highest during far-end fault location as compared to near-end fault location, the proposed scheme works perfectly without any miscoordination between primary backup relay pair.

In addition, the optimal time of operation given by the GS based algorithm for few relays at near end, middle-point and far-end fault locations are also shown in Table 5.11. It is to be noted from Table 5.11 that the time of operation of primary relays increases as the location of fault moves from near- end to far-end of the distribution feeders.

These results clearly indicate that the proposed scheme is superior to the existing algorithm in terms of estimating optimal relay settings of DOCRs. This is also verified by observing Fig. 5.6 which shows the convergence curve of the GS based algorithm utilizing user defined characteristic for IEEE 30-bus distribution system. It has been observed from Fig. 5.6 that the convergence of this algorithm is very fast.

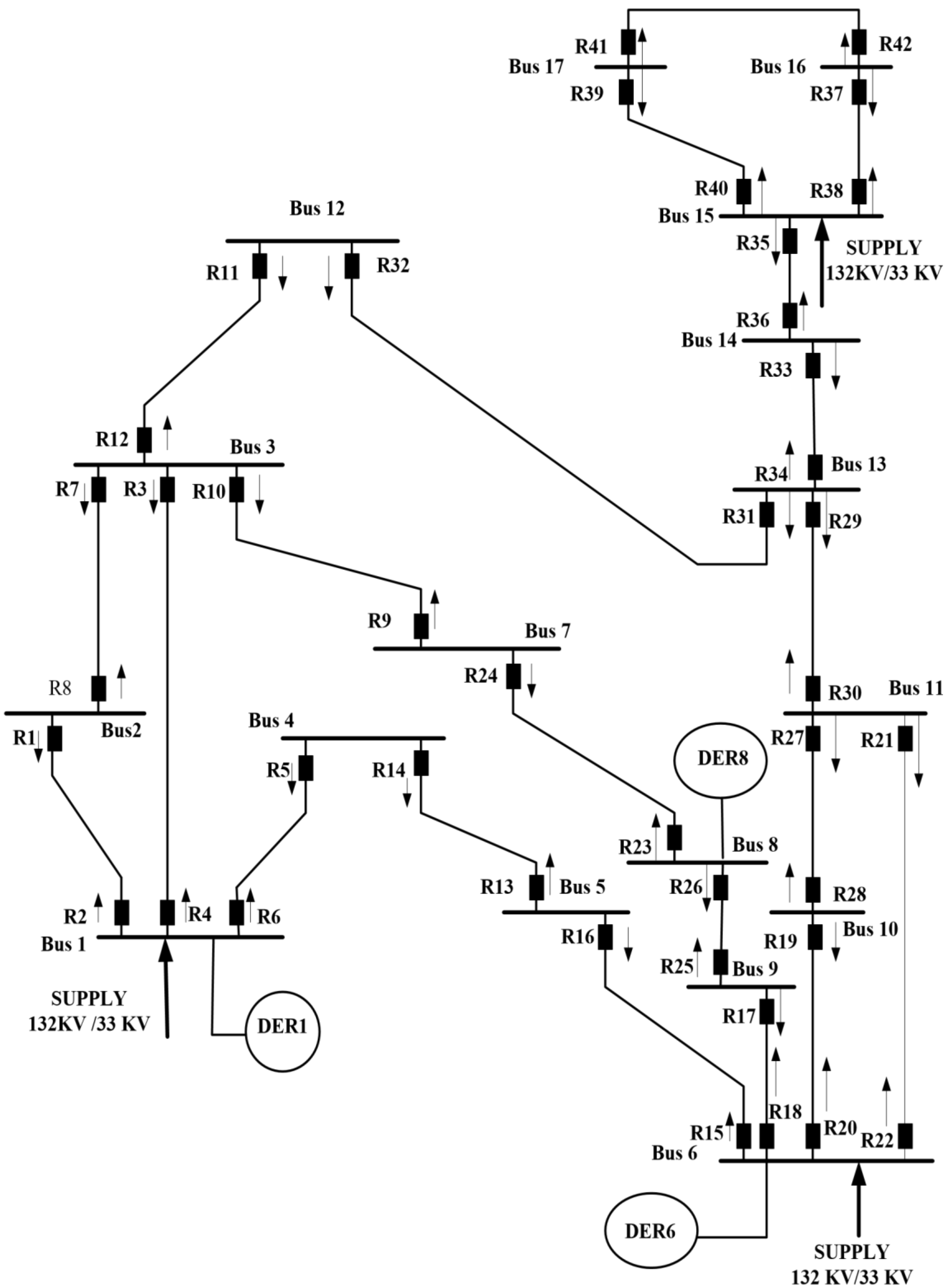

Fig. 5.5 Single line diagram of IEEE 30-bus distribution network

Table 5.8 Performance of the GS based algorithm for IEEE 30-bus distribution network at near-end fault location

Relay Number	Results obtained from existing Algorithm [18]		Results obtained from GS based algorithm using conventional standard characteristic		Results obtained from GS based algorithm using user defined Characteristic			
	TDS	PS	TDS	PS	TDS	PS	Beta(β)	Alpha (α)
1	0.271	1.43	0.0437	1.0089	0.0407	0.9737	5.4256	0.8585
2	0.962	1.04	0.3773	1.3196	0.4558	1.6475	7.8553	0.9401
3	0.413	1.6	0.2705	1.3240	0.3665	1.5577	6.3530	0.9334
4	0.57	2.15	0.5229	1.6692	0.5628	1.5351	8.5806	0.9383
5	0.193	2.38	0.2628	1.5464	0.4336	1.0955	5.1016	0.9167
6	0.545	1.09	0.5617	1.4050	0.5268	1.6638	9.0018	0.9600
7	0.357	1.81	0.2443	1.4494	0.3482	1.3315	8.4732	0.8960
8	0.898	1.12	0.1704	1.2951	0.2346	1.3691	4.9769	0.8925
9	0.489	1.41	0.2277	0.9510	0.2373	1.1444	5.9409	0.9376
10	0.421	1.95	0.4610	1.7952	0.5641	1.7277	7.9219	0.9771
11	0.413	2.5	0.2042	1.8786	0.2165	1.2963	6.2190	0.8459
12	1.142	0.62	0.0827	1.5352	0.1496	1.6203	5.9415	0.8220
13	0.774	0.51	0.4431	1.3826	0.3780	1.6297	8.9478	0.9656
14	0.256	2.47	0.3978	1.4920	0.3939	1.2766	8.3705	0.9726
15	0.497	1.84	0.5787	1.9024	0.6072	1.3903	7.6297	0.7939
16	0.223	1.26	0.2219	1.5769	0.3064	1.1883	5.0766	0.9545
17	0.234	0.77	0.0892	1.4961	0.1360	1.1337	5.0813	0.9017
18	0.582	1.12	0.6348	1.9909	0.5142	1.4323	8.8058	0.8254
19	0.353	0.51	0.2024	1.2776	0.1113	1.6294	5.1359	0.8198
20	0.857	0.5	0.6328	1.8524	0.5745	1.5417	8.0567	0.7902
21	0.555	0.5	0.0992	1.5214	0.3229	1.3023	4.9959	0.8314
22	0.696	0.74	0.4830	1.2809	0.5407	1.6484	7.6589	0.9186
23	0.587	1.19	0.3120	1.4113	0.5304	1.2344	5.7129	0.9233
24	0.338	1.8	0.4343	1.3900	0.4414	1.4609	7.8374	0.9963
25	0.698	0.83	0.4329	1.4549	0.4866	1.4000	8.6059	0.9794
26	0.151	1.84	0.1542	1.3434	0.3326	1.1470	5.5838	0.9270
27	0.392	1.64	0.3472	1.4002	0.4338	1.1230	7.8642	0.9279
28	0.67	1.56	0.4867	1.7556	0.4540	1.5565	7.5453	0.9167
29	0.353	1.88	0.2563	1.5512	0.2871	1.1059	8.6535	0.9394

30	0.423	1.84	0.4446	1.7191	0.4752	1.6555	7.4552	0.9572
31	0.652	1.18	0.4074	1.9615	0.4254	1.7769	7.3974	0.9531
32	0.865	0.5	0.5106	1.7094	0.6211	1.5979	6.7801	0.4422
33	0.426	1.69	0.3185	1.7130	0.3663	1.5469	8.0330	0.9456
34	0.598	0.51	0.4689	1.1532	0.3988	1.5276	6.6317	0.9339
35	0.812	1.21	0.2402	1.6516	0.4902	1.1671	6.7938	0.9740
36	0.283	1.79	0.4264	1.7501	0.5113	1.2488	8.8033	0.9802
37	0.042	1.07	0.0101	0.6676	0.0100	0.6354	4.6139	0.7768
38	0.492	2.14	0.2270	1.2755	0.2786	1.4588	8.9578	0.9193
39	0.333	0.52	0.0100	0.7584	0.0100	0.7345	5.9871	0.7759
40	0.192	2.5	0.1214	1.7289	0.2806	1.5508	6.3203	0.9127
41	0.147	0.5	0.0110	1.3046	0.0272	1.1613	4.3109	0.7850
42	0.497	0.94	0.0440	1.3277	0.1890	1.0539	5.2534	0.8803
Sum of Relays' Operating Time	65.4245 sec		44.1229 sec		19.8098 sec			

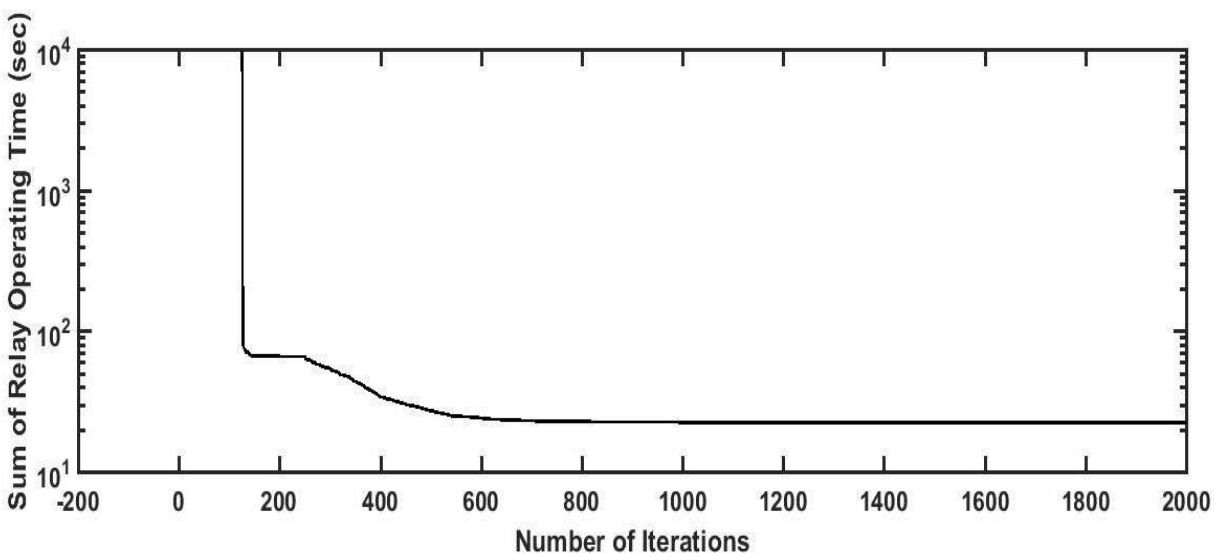

Fig. 5.6 Convergence curve of the IEEE 30-bus distribution system with user defined characteristics.

Table 5.9: Performance of the GS based algorithm for IEEE 30-bus distribution network for fault at middle point

Relay Number	Results obtained from GS based algorithm using conventional standard relay characteristic		Results obtained from GS based algorithm using user defined Characteristic			
	TDS	PS	TDS	PS	Beta (β)	Alpha (α)
1	0.1104	1.0464	0.1941	1.0056	5.7041	0.8736
2	0.5525	1.6586	0.5370	1.3657	6.7201	0.8021
3	0.0206	1.6384	0.2492	1.3665	6.1838	0.8268
4	0.5379	1.8167	0.6392	1.3706	6.2873	0.7289
5	0.3563	0.8475	0.1425	1.5584	5.4359	0.8232
6	0.5892	1.7186	0.5205	1.3643	8.1149	0.7733
7	0.4475	1.6507	0.3085	1.4048	9.1573	0.9221
8	0.0613	1.3687	0.2387	1.2253	5.9127	0.8686
9	0.3948	0.7953	0.2599	1.0128	6.4525	0.8275
10	0.6381	1.5710	0.5242	1.9785	8.5501	0.9296
11	0.2063	1.2292	0.3193	1.4934	4.6666	0.8740
12	0.4269	1.7024	0.5864	1.2701	7.2689	0.8507
13	0.4329	1.4298	0.5196	1.6810	6.2708	0.9036
14	0.4999	1.2097	0.4083	1.5679	6.3569	0.9491
15	0.7266	1.7096	0.5192	1.3818	9.0361	0.7263
16	0.3684	1.0525	0.3478	1.3273	4.7968	0.8840
17	0.0695	1.2990	0.2290	1.0724	5.5764	0.8758
18	0.7454	1.8667	0.5992	1.7448	8.0644	0.8348
19	0.0286	1.5094	0.1214	1.3017	3.4395	0.6910
20	0.7575	1.5536	0.4976	1.5303	8.3386	0.6319
21	0.2848	1.2831	0.3698	1.2958	4.2215	0.7679
22	0.4827	1.7000	0.5102	1.6773	5.2511	0.7461
23	0.4838	1.2168	0.5169	1.4280	6.5051	0.9344
24	0.3438	1.8337	0.5619	1.5800	6.9523	0.9658
25	0.6282	1.3241	0.5993	1.5757	9.0752	0.9534
26	0.3859	1.2484	0.3216	1.3501	5.2895	0.8485
27	0.5727	1.4039	0.4407	1.3722	8.2276	0.8951
28	0.5187	1.7723	0.6834	1.6627	7.3790	0.9473
29	0.3781	1.6625	0.3685	1.4941	6.5192	0.9360
30	0.4375	1.6449	0.6026	1.5911	8.0097	0.9572
31	0.5510	1.1706	0.3445	1.5662	8.1101	0.8627
32	0.1725	1.8180	0.2862	1.4459	6.0394	0.8913

33	0.3963	1.1316	0.4408	1.1084	6.4412	0.8751
34	0.5628	1.1426	0.4000	1.5883	7.2762	0.9111
35	0.5594	1.8696	0.6144	1.2953	8.5147	0.8899
36	0.3155	1.0755	0.3670	1.0690	5.9647	0.9006
37	0.2347	0.5100	0.2127	0.5001	7.6511	0.8652
38	0.2851	1.6640	0.2348	1.3356	8.7636	0.8680
39	0.2449	0.5558	0.1004	0.5480	7.4233	0.7979
40	0.1673	1.6140	0.3009	1.5725	7.0613	0.9661
41	0.0100	1.3837	0.0100	1.4274	3.3373	0.7289
42	0.0169	1.3956	0.0987	1.5719	2.4635	0.7782
Sum of Relays' Operating Time	69.3512 sec		39.2981 sec			

Table 5.10: Performance of the GS based algorithm for IEEE 30-bus distribution network for far-end fault location

Relay Number	Results obtained from GS based algorithm using conventional standard relay characteristic		Results obtained from GS based algorithm using user defined characteristic			
	TDS	PS	TDS	PS	Beta (β)	Alpha (α)
1	0.5415	1.6762	0.5450	1.7601	6.7372	0.4846
2	0.6022	1.6905	0.3107	1.6049	7.2403	0.6766
3	0.4530	1.3723	0.2235	1.0683	6.4705	0.7310
4	0.7539	1.6907	0.6962	1.7209	6.0932	0.6239
5	0.4904	1.3114	0.4932	0.9896	6.5371	0.7504
6	0.6937	1.7592	0.5793	1.6606	7.7078	0.7031
7	0.5908	0.8675	0.3665	0.8678	6.5646	0.7796
8I	0.5847	1.2013	0.2759	0.9389	4.9861	0.7769
9	0.3488	1.1517	0.3643	1.0079	4.7042	0.7150
10	0.6699	1.9757	0.5680	1.6238	8.9151	0.6624
11	0.6530	1.1932	0.4923	1.0823	6.1564	0.8320
12	0.6340	1.2036	0.4048	1.4263	6.3140	0.7672
13	0.4789	1.9833	0.5849	1.7369	8.3100	0.8346
14	0.4703	1.8389	0.4779	1.5528	6.6343	0.7984
15	0.7260	1.7647	0.5799	1.5621	8.1373	0.5526
16	0.5783	1.0578	0.4549	1.1446	5.2377	0.7949

17	0.4703	0.9051	0.3825	0.7278	4.9167	0.7787
18	0.8476	1.8267	0.7037	1.4557	7.8675	0.5878
19	0.8560	1.1487	0.5605	0.6634	8.0275	0.4506
20	0.5274	1.9254	0.6061	1.8036	6.1942	0.7294
21	0.6748	0.6990	0.6220	0.5860	6.0790	0.5559
22	0.5337	1.1510	0.6125	1.2064	7.1905	0.8756
23	0.5869	1.2255	0.5996	1.3466	6.1125	0.8099
24	0.6223	1.5208	0.6235	1.4008	6.6651	0.8096
25	0.7587	1.4583	0.6297	1.5843	7.6296	0.7415
26	0.4545	1.3341	0.5189	1.5017	4.0323	0.7944
27	0.4777	1.7862	0.2684	2.0982	6.2557	0.7795
28	0.4775	1.5941	0.4353	2.0287	6.2267	0.8569
29	0.8200	1.8848	0.7084	2.0195	6.4046	0.7538
30	0.5643	1.5065	0.4974	1.8082	6.6777	0.8111
31	0.6815	1.8741	0.5027	1.6910	7.5820	0.8350
32	0.5361	1.6089	0.5032	1.3784	6.3792	0.5121
33	0.7360	1.6209	0.5085	1.9392	7.4929	0.8384
34	0.5467	1.6016	0.5395	1.4400	6.9038	0.8064
35	0.4263	1.5774	0.4114	1.2980	8.5457	0.8275
36	0.6301	1.8200	0.5091	1.5335	7.6594	0.7629
37	0.5902	1.8106	0.6056	1.7211	6.8568	0.4385
38	0.4370	1.5667	0.1585	1.6042	7.8883	0.7931
39	0.4636	1.5697	0.5003	1.7038	5.5845	0.5842
40	0.5684	1.7726	0.1976	1.3995	6.4289	0.7531
41	0.3045	1.1825	0.1443	0.7525	5.2070	0.7233
42	0.4004	1.0716	0.1373	0.8586	5.4135	0.5788
Sum of Relays' Operating Time	146.5081 sec		82.5050 sec			

Table 5.11: Optimal time of operation given by the GS based algorithm for few relays at different fault locations

Relay Number	Near-end fault		Fault at middle point		Far-end Fault	
	(T_{op}) Using conventional Characteristic (sec)	(T_{op}) Using userdefined characteristic (sec)	(T_{op}) Using conventional Characteristic (sec)	(T_{op}) Using userdefined characteristic (sec)	(T_{op}) Using conventional Characteristic (sec)	(T_{op}) Using userdefined characteristic (sec)
2	0.9227	0.3539	2.0827	0.8923	3.0524	1.4025
4	1.4745	0.5080	1.9489	1.0333	3.1788	2.4385
6	1.4804	0.5156	2.1651	1.0365	3.1722	2.2254
7	0.7176	0.3837	1.9205	0.6894	2.2321	0.7689
9	0.9292	0.4566	1.7021	0.8096	2.5461	1.4651
10	1.5332	0.6587	2.5291	1.4687	3.8373	3.3013
12	0.2578	0.1844	1.7495	0.9789	2.5019	1.0905
13	1.3353	0.5091	1.6242	0.9252	2.6986	2.3027
14	1.6370	0.6702	2.1784	1.0355	3.6403	2.3640
18	1.7756	0.5116	2.7072	1.1700	3.7616	2.9978
21	0.3106	0.2684	1.1865	0.6169	6.8528	6.1610
22	1.1297	0.3961	1.7353	0.8372	2.2437	1.4550
23	1.3342	0.7561	2.1162	1.2217	2.8246	1.8709
24	1.9200	0.9889	2.1584	1.6627	3.7170	2.4013
25	1.6723	0.8485	2.4662	1.5527	3.3123	2.3656
26	0.8310	0.6632	2.1180	0.9866	2.7731	1.6853
29	1.0524	0.4406	2.2016	1.0179	6.4495	5.3637
30	1.4095	0.4919	1.6846	1.0262	2.4812	1.6008
31	1.5558	0.6158	2.1195	1.0601	4.5051	2.3616
33	1.2422	0.6087	1.9009	1.0982	4.8390	3.5243
34	1.4307	0.5039	2.1941	1.0797	3.5082	2.3263
35	1.2414	0.8018	2.5256	1.1906	2.9037	2.0364
40	0.4256	0.3171	0.9254	0.8742	7.3447	1.6029
42	0.2711	0.4327	0.1450	0.3434	4.1087	1.0891

CHAPTER-6

CONCLUSION

Here Gravitational Search based algorithm is used for optimal coordination of DOCRs which utilizes user defined characteristic for inverse time overcurrent relays along with the predefined standard characteristic. By utilizing variable values of constants, the shape of the relay characteristic has been controlled which yields optimal coordination of DOCRs. The performance of the GS based algorithm has been evaluated by calculating optimal settings of DOCRs for 8-bus & 15-bus test systems as well as IEEE 30-bus distribution network. The sum of primary relays' operating time obtained from the user defined characteristic for 8-bus and 15-bus systems are 2.5718 sec and 8.4184 sec respectively. Faults at different locations is generated on IEEE 30-bus distribution system and the sum of primary relays' operating time is found to be 19.8098 sec, 39.2981 sec and 82.5050 sec for faults at near-end, middle point and far-end respectively with user defined characteristics. It is observed that the time of operation of primary relays increases as the location of fault moves from near- end to far-end of the distribution feeders.

Moreover, comparative evaluation of the GS based algorithm with the existing algorithms utilizing standard characteristic clearly indicates noticeable reduction in the sum of primary relays' operating time.

CHAPTER-7

FUTURE WORK

- Settings of Directional overcurrent relays (DOCRs) can be optimally obtained from some new Artificial Intelligence Algorithm which can further minimize or improve the value of objective function (sum of time of operation of all primary relays) along with avoiding the instances of miscoordination.
- Problem of sympathetic/nuisance trippings is observed in power grids. To eliminate sympathetic/nuisance tripping in an interconnected distribution system, some additional constraints can be incorporated in over current relay coordination problem.

REFERENCES

[1] Bhavesh Bhalja, R.P. Maheshwari and Nilesh G. Chothani, "Protection and Switchgear,"*Oxford University Press, New Delhi, India*, 2011.

[2] Bhavesh Bhalja, B. A. Oza and P. H. Shah, "Coordination of overcurrent relays for cascaded parallel feeder," *In Proceedings of International Conference on Advances in Power System Control, Operation and Management, Hong Kong,* pp. 1-4, 30th October – 2nd November, 2006.

[3] Khaled A. Saleh, H. H. Zeineldin, A. al-Hinai and Ehab F. El-Saadany, "Optimal Coordination of Directional Overcurrent Relays Using a New Time-Current-Voltage Characteristic," *IEEE Transactions on Power Delivery*, vol. 30, no. 2, pp. 537-544, April 2015.

[4] IEEE Standard Inverse-Time Characteristic Equations for Overcurrent Relays, IEEE Standard C37.112-1996, July 1999.

[5] Reza Mohammadi Chabanloo, Hossein Askarian Abyaneh, Somayeh Sadat Hashemi Kamangar, and Farzad Razavi "Optimal Combined Overcurrent and Distance Relays Coordination Incorporating Intelligent Overcurrent Relays Characteristic Selection" *IEEE Transactions on Power Delivery*, vol. 26, no. 3, pp. 1381-1391, July 2011.

[6] Hebatallah Mohamed Sharaf, H.H. Zeineldin, Doaa Khalil Ibrahim and Essam EL-Din Abou EL-Zahab, "A proposed coordination strategy for meshed distribution systems with DG considering user-defined characteristics of directional inverse time overcurrent relays," *International Journal of Electrical Power and Energy Systems*, vol. 65, pp. 49-58, February 2015.

[7] M.J. Damborg, R. Ramaswami, S.S. Venkata and J.M. Postforoosh, "Computer aided transmission protection system design," *IEEE Transactions on Power Apparatus Systems*, vol. 103, no. 1, pp. 51–59, 1984.

[8] A.J. Urdaneta, Nadira Ramon and Luis G.P. Jimenez, "Optimal coordination of directional relays in interconnected power system," *IEEE Transactions on Power Delivery*, vol. 3, no. 3, pp. 903–911, 1988.

[9] A. J. Urdaneta, H. Restrepo, S. Marquez, and J. Sanchez, “Coordination of directional relay timing using linear programming,” *IEEE Transactions on Power Delivery*, vol. 11, no. 1, pp. 122– 129, January 1996.

[10] D. Birla, R. P. Maheshwari, and H. O. Gupta, “Time-overcurrent relay coordination: A review,” *International Journal of Emerging Electrical Power Systems*, vol. 2, no. 2, pp. 1–13, April 2005.

[11] D. Birla, R.P. Maheshwari and H.O. Gupta “A new nonlinear directional overcurrent relay coordination technique and banes and boons of near-end faults based approach,” *IEEE Transactions on Power Delivery*, vol. 21, no. 3, pp. 1176–1182, June 2006.

[12] H. A. Abhyaneh, M. Al-Dabbagh, H. K. Karegar, S. H. H. Sadeghi, and R. A. J. Khan,“A new optimal approach for coordination of directional overcurrent relays in interconnected power system,” *IEEE Transactions on Power Delivery*, vol. 18, no. 2, pp. 430–435, April 2003.

[13] M.M.H.A. Mansour and S.F. Mekhamer, “A modified particle swarm optimizer for the coordination of directional overcurrent relays,” *IEEE Transactions on Power Delivery*, vol. 22, no. 3, pp. 1400–1410, July 2007.

[14] F. Razavi, H.A. Abyaneha, M. Al-Dabbaghb, R. Mohammadia and H. Torkaman, “A new comprehensive genetic algorithm method for optimal overcurrent relays coordination,” *Electric Power Systems Research*, vol. 78, no. 4, pp. 713–720, April 2008.

[15] P. Bedekar and S. Bhide, “Optimum coordination of directional overcurrent relays using the hybrid GA-NLP approach,” *IEEE Transactions On Power Delivery*, vol. 26, no. 1, pp. 109–119, January 2011.

[16] T. Amraee, "Coordination of directional overcurrent relays using seeker algorithm," *IEEE Transactions on Power Delivery*, vol. 27, no. 3, pp. 1415-1422, July 2012.

[17] Manohar Singh, B.K. Panigrahi and A.R. Abhyankara,“Optimal coordination of directional over-current relays using Teaching Learning-Based Optimization (TLBO) algorithm,” *International Journal of Electrical Power and Energy Systems*, vol. 50, no. 2, pp. 269-276, September 2013.

[18] Manohar Singh, B.K. Panigrahi, A.R. Abhyankara and Swagatam Das, “Optimal coordination of directional over-current relays using informative differential evolution algorithm,” *Journal of Computational Science*, vol. 5, no. 2, pp. 269-276, March 2014.

[19] Fadhel A. Albasri, Ali R. Alroomi and Jawad H. Talaq, “Optimal Coordination of Directional Overcurrent Relays Using Biogeography-Based Optimization Algorithm,” *IEEE Transactions on Power Delivery*, vol. 30, no. 4, pp. 1810-1820, August 2015.

[20] Meng Yen Shih, Carlos Alberto Castillo Salazar and Arturo Conde Enríquez, “Adaptive directional overcurrent relay coordination using ant colony optimization,” *IET Generation, Transmission & Distribution*, vol. 9, Issue 14, pp. 2040-2049, 2015.

[21] V. A. Papaspiliotopoulos, T. S. Kurashvili adn G. N. Korres, “Optimal Coordination of Directional Overcurrent Relays for Distribution Systems with Distributed Generation based on a Hybrid PSO-LP Algorithm,” *In Proceedings of 9th Mediterranean Conference on Power Generation, Transmission Distribution and Energy Conversion, Athens, Greece*, November 2014.

[22] F. Razavi, H. Askarian Abyaneh, M. Al-Dabbagh, R. Mohammadi, and H.Torkaman,“A new comprehensive genetic algorithm method for Overcurrent relays coordination,” *Electrical Power System Research*, vol. 92, no. 9, pp. 713-720, Apr. 2008.

[23] Manohar Singh, B. K. Panigrahi and A. R. Abhyankar “Optimal Overcurrent Relay Coordination in Distribution System”, *In Proceedings of IEEE International Conference on Energy, Automation, and Signal (ICEAS)*, pp. 1-6, 2011

[24] Brian Hegerty, Chih-Cheng Hung, and Kristen Kasprak “A Comparative Study on Differential Evolution and Genetic Algorithms for Some Combinatorial Problems”, *In Proceedings of 8th Mexican International Conference on Artificial Intelligence*, pp. 9-13, Nov. 2009

[25] PSO Tutorial, URL: http://www.swarmintelligence.org/tutorials.php

[26] Difference between PSO and GA, URL:http://www.researchgate.net/

[27] Esmat Rashedi, Hossein Nezamabadi-pour and Saeid Saryazdi, "GSA: A Gravitational Search Algorithm," *Journal Information Sciences*, vol. 179, no. 13, pp. 2232–2248, 2009.

[28] Adhishree Srivastava, Jayant Mani Tripathi, Soumya R. Mohanty and Bhagabat Panda, "Optimal Over-Current Relay Coordination with Distributed Generation Using Hybrid Particle Swarm Optimization–Gravitational Search Algorithm," *Electric Power Components and Systems*, Early Access, pp. 1-12, 2016

[29] R. Christie, Power System Test Cases Available [Online]: www.ee.washington.edu/research/pstca, August 1993.

APPENDIX

Table I: Primary-Backup Relay pairs and Near-end fault Data for 8 bus System

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

Table II: CT Ratios of relays of 15 bus system

Relay Number	CT Ratio
18,20,21,29	1600/5
2,4,8,11,12,14,15,23	1200/5
1, 3, 5, 10,13,19,36,37,40,42	800/5
6,7,9,16,24,25,26,27,28,31,32,33,35	600/5
17,22,30,34,38,39,41	400/5

Table III: Primary-Backup Relay pairs and Near-end fault Data for 15 bus System

Primary Relay	Primary Relay Fault Current	Backup Relay	Backup Relay Fault Current	Backup Relay	Backup Relay Fault Current	Backup Relay	Backup Relay Fault Current
1	3621	6	1233	-	-	-	-
2	4597	4	1477	16	743	-	-
3	3948	1	853	16	743	-	-
4	4382	7	1111	12	1463	20	1808
5	3319	2	922	-	-	-	-
6	2647	8	1548	10	1100	-	-
7	2497	5	1397	10	1100	-	-
8	4695	3	1424	12	1463	20	1808
9	2943	5	1397	8	1548	-	-
10	3568	14	1175	-	-	-	-
11	4342	3	1424	7	1111	20	1808
12	4195	13	1503	24	753	-	-
13	3402	9	1009	-	-	-	-
14	4606	11	1475	24	753	-	-
15	4712	1	853	4	1477	-	-
16	2225	18	1320	26	905	-	-
17	1875	15	969	26	905	-	-
18	8426	19	1372	22	642	30	681
19	3998	3	1424	7	1111	12	1463
20	7662	17	599	22	642	30	681
21	8384	17	599	19	1372	30	681
22	1950	23	979	34	970	-	-
23	4910	11	1475	13	1053	-	-
24	2296	21	175	34	970	-	-
25	2289	15	969	18	1320	-	-
26	2300	28	1192	36	1109	-	-
27	2011	25	903	36	1109	-	-
28	2525	29	1829	32	697	-	-
29	8346	17	599	19	1372	22	642

30	1736	27	1039	32	697	-	-
31	2867	27	1039	29	1828	-	-
32	2069	33	1162	42	907	-	-
33	2305	21	1326	23	979	-	-
34	1715	31	809	42	907	-	-
35	2095	25	903	28	1192	-	-
36	3283	38	882	-	-	-	-
37	3301	35	910	-	-	-	-
38	1403	40	1403	-	-	-	-
39	1434	37	1434	-	-	-	-
40	3140	41	745	-	-	-	-
41	1971	31	809	33	1162	-	-
42	3295	39	896	-	-	-	-

Table IV: Primary-Backup Relay Pairs and Near-End Fault Data for IEEE 30 bus Distribution Network

Primary Relay	Primary Relay Fault Current	Backup Relay	Backup Relay Fault Current	Backup Relay	Backup Relay Fault Current	Backup Relay	Backup Relay Fault Current
1	2595	7	2675	-	-	-	-
2	10675	5	1765	3	1697	-	-
3	4216	11	1641	9	1489	8	1109
4	9412	5	1765	1	435	-	-
5	3383	13	3383	-	-	-	-
6	9345	3	1697	1	435	-	-
7	7435	11	1641	9	1489	4	4328
8	3221	2	3301	-	-	-	-
9	2569	23	2570	-	-	-	-
10	7055	11	1641	8	1109	4	4328
11	2671	31	2672	-	-	-	-
12	6902	9	1489	8	1109	4	4328
13	6696	15	6702	-	-	-	-
14	3973	6	3973	-	-	-	-
15	10830	21	693	19	1060	17	965

16	2247	14	2253	-	-	-	-
17	2071	26	2074	-	-	-	-
18	11444	21	693	19	1060	16	1579
19	4157	27	4169	-	-	-	-
20	11349	21	693	16	1579	17	965
21	6775	29	2277	28	4531	-	-
22	11716	19	1060	16	1579	17	965
23	3533	25	3534	-	-	-	-
24	3304	10	3304	-	-	-	-
25	4313	18	4316	-	-	-	-
26	2421	24	2422	-	-	-	-
27	5205	29	2277	22	2961	-	-
28	5604	20	5616	-	-	-	-
29	4147	33	2324	32	1824	-	-
30	7459	28	4531	22	2961	-	-
31	5934	33	2324	30	3611	-	-
33	4995	35	2181	-	-	-	-
34	5433	32	1824	30	3611	-	-
35	3142	39	-	37	-	-	-
36	5169	34	2356	-	-	-	-
37	803	41	803	-	-	-	-
38	6123	13	3212	36	2981	-	-
39	1055	42	1055	-	-	-	-
40	6123	36	2981	-	-	-	-
41	1519	40	1519	-	-	-	-
42	2042	38	2042	-	-	-	-