Optimal Coordination of Directional Overcurrent Relay using Water Evaporation Optimization Algorithm

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DECLARATION

I hereby certify that the work which is presented in dissertation entitled, "**Optimal Coordination of Directional Overcurrent Relay using Water Evaporation Optimization Algorithm**", in partial fulfillment of the requirements for the award of the degree of **Master of Engineering in Power Systems**, submitted to Electrical & Instrumentation Engineering Department of Thapar Institute of Engineering & Technology (Deemed to be University) is as authentic record of my own work carried under the supervision of **Dr. S.K. Jain** and **Dr. Nitin Narang**. It refers others researcher's work which are duly listed in the reference section. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other degree to any other university or institute except as reported in text and references.

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ABSTRACT

In modern power system, protection devices play an important role. The protection in the network is provided by combined operation of relays, breakers etc. Two types of relays, primary and backup relays are installed for increasing the reliability of power system which should have a coordinated operation time to provide a reliable protection and to avoid unnecessary tripping of relays thereby reducing the total operational time of relays.. The relay operation requires TMS, PSM and pickup current settings.

The aim of optimal coordination of Directional Overcurrent Relays is to maintain a certain time gap called coordinated time interval between the operation of primary and backup relays for preventing any malfunction and unnecessary tripping of relays and to obtain the optimal settings of relays so that the overall tripping time of all the primary relays is minimized.

Thus, obtaining the Time Multiplier Setting (TMS), Plug Setting Multiplier (PSM) and pickup current settings for minimizing the operating time of relays while adhering to various boundary constraints and coordination become a highly constrained problem. The water evaporation optimization algorithm uses the water molecules as the algorithm individuals which gives the fast and more accurate results due to its global and local search ability in two different phases of evaporation.

The mentioned formulation is proposed to be realized with the water evaporation optimization technique. The problem formulation is divided into two sections: (1) Continuous settings optimization and (2) discrete settings optimization. This problem of continuous and discrete coordination of directional overcurrent relay is validated by implementing through the standard IEEE 8 bus and 9 bus systems.

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NOMENCLATURE

To_i : operating time of i^{th} relay.

w_i : allocated weight.

CTI : coordination time interval.

TMS_i : time multiplier setting of the i^{th} relay.

PSM^i : plug setting multiplier of the i^{th} relay.

I_F^i : fault current passing through i^{th} relay.

I_P^i : pickup current magnitude passing through i^{th} relay.

J : evaporation flux.

P_E : water molecule escape probability.

P_O, J_O : constant parameter of diameter and volume of molecules.

$P_G(\theta)$: water molecule probability on liquid gas surface with contact angle θ.

DEP : droplet evaporation probability.

MEP : monolayer evaporation probability.

A, B, C : coefficients of time inverse characteristics.

$CTratio^i$: current transformer ratio of the i^{th} relay.

CHAPTER 1

INTRODUCTION

1.1. OVERVIEW

The electrical protection system aims to isolate that part of the power network which is faulted due to the several power outages or faults in the power system. Due to various physical issues the condition of short circuit can arise at any time in any part of the network unexpectedly .Thus the faulted system must be segregated as soon as possible so that the large amount of fault current through the system apparatus does not flow and the remaining healthy sections of the network continue to work in the normal conditions [1].

The bad parts from any electrical circuit are removed by a primary device fuse. Breakers simplicity and meanness is the best advantage in security utilization. But fuse is not that capable to regulate the duration of the outing and hence the issues related to primary-backup matching action arises. But its biggest disadvantage is that it has to be replaced each time whenever faults occur and it melts. Thus, the remote action need to be implemented [2].

In practical, circuit breaker does this action of preventing the network of power system. For imbalanced conditions, CBs on receiving the tripping pulse from the protective relays open the circuit. Since we yet do not have the method to stop the imbalance or transients arising in the network we had to remove the faulty section.

Relays are the very integral part of protection for the reliable operation of the power system. And regarded as the brain of power system protection and thus also termed as a fault sensor in power system.

Thus, there is an introduction of an overcurrent relay. Overcurrent relays are used for heavily meshed as well as multi source power network by providing both primary and backup protection. The maximum load current handled by the load during the faults and minimum fault current (a CT ratio is being used to step down the current) is sensed by a relay decides the pickup value of an overcurrent relay that is the reference value for which the relay start operating. This proportion of current with the pickup value is defined as plug setting multiplier.

There is usually an alternative protection network that is the backup relay to the each individual primary relay. The time of operation of primary relays should be earlier than the backup relays execution so that the smooth operation of breaking of the faulty section can take place. A fixed interval of time (as a constraint) is required for the starting operation of backup relays. This particular time gap is must and it is known as 'Coordination Time Interval'.

The principle followed by the directional overcurrent relay is whenever the fault current flows in a particular direction into a relay, the relay actuates and the relay will not operate if the power flows in the opposite direction. The DOCR predicts the direction in which fault occurs based on the relative location of the relay unlike conventional overcurrent relay which operates for fault current in any direction and as such unnecessarily operation of other relays is avoided.

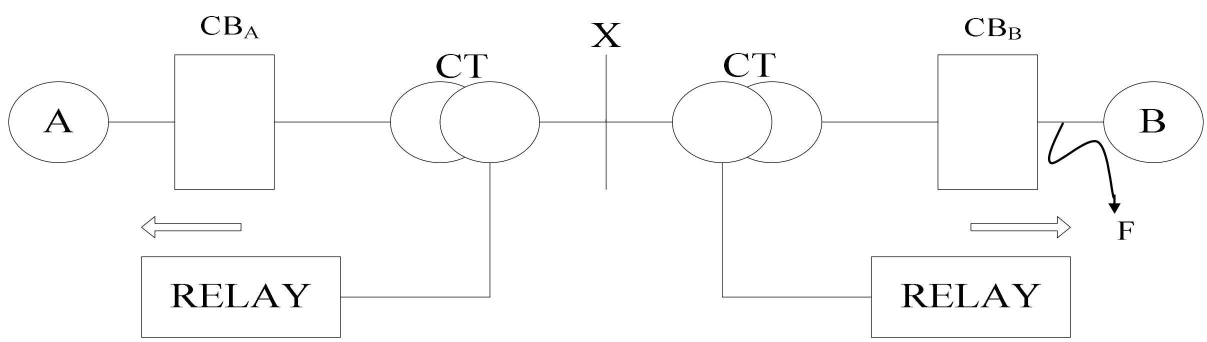

Fig 1.1: Single line diagram representing operation of DOCR

Let us assume a feeder XY as shown in the fig 1.1. If a fault F occurs in XB feeder which is provided by a directional relay, then it will trip only the circuit breaker CB_B as the direction of fault current will be in the XB direction only and the unnecessarily tripping of circuit breaker CB_A is avoided which leads to the removal of only the faulty section of the network. Since the operation of primary relays is to isolate only faulted section of the power system network, and that of backup relays to disconnect the healthy sections as well as the faulted section, the proper coordination of both primary relays as well as backup relays is important to ensure the system reliability. Thus the TMS, PSM and pickup current has to be optimized to ensure the relay coordination.

The relays coordination aims to secure the power network effectively by instantly isolating bad areas to maintain power supply in other healthy areas.

Over the last 40 years, there had been a great development and progress in the use of relays for providing the power system protection. The directional overcurrent relays is being applied as an alternative economical design for the primary and backup protection of power system network

[3].DOCRs are being used mainly to provide the primary protection in the distribution networks as well as in the sub transmission networks and to provide backup protection in transmission networks [4].

The primary and backup relay coordination comes under the optimization problem. The CTI as a constraint is being used to avoid the simultaneous working of relays. Thus the optimization for minimization of tripping time for primary relay, having the constraints related to boundaries for interval of tripping for each relay and related to CTI is to be done.

Many techniques are developed for the optimization problem stated above. The limitations of conventional optimization approaches are the pre mature convergence which leads to ineffectiveness in their operation. The models of conventional optimization are infeasible and not accurate when the problems are more complex and of non linear type. The conventional optimization methods are preferable where the fast rate of operation is required in comparison to the accuracy of obtained solution thereby minimizing its drawbacks.

Global optimization techniques are more effective and robust as it tries to find the best possible solution. In such type of real world application, global optimization modes are preferred as the solution that is obtained from global optimization techniques are preferable and accurate as well. Water evaporation algorithm is one of the best available techniques, which provides the global optimized results. Furthermore, adjustment of parameters gives fast convergence of output.

1.2. LITERATURE REVIEW

In the recent few years, for solving the coordination problem of directional overcurrent relay various methods of optimization have been adopted. Initially, when the era of computers were not there, the computation of optimization problems were done manually by using very large and complex calculations which not only increases the time but also increases the inaccuracy. Some of the metaheuristic approaches now have been adopted, which makes the solution more reliable and accurate. To achieve the reliable operation of electrical power network the operating time of relay is to be minimized. This requirement led researchers to work on this purpose.

The first approach basically includes graph theory technique and function developments. The solution for different settings of relays has been tried so as to design an electrical network layout [5]. Using the computer system tools researchers has estimated the P/B relay pairs, settings for directional OC and distance relays and a procedure was proposed by utilizing the digital computer aided interface for complex calculation [6].

Some computational efforts based linear functions are used by classical linear methods. The linear formulation has been done in a network where small level of variation takes place which need less time for computation and as such change in settings is not desired [7]. A new proposed method is adopted based on linear and non linear programming model for the coordination of overcurrent (OC) relays only on the basis of constraints which initially assume lower values of settings and then iteratively increases the values [8].

The other classical approaches that have been adopted coordination problem are Evolutionary Algorithms (EA) and Covariance Matrix Adaptation Evolution Strategy (CMA-ES). Also the combination of evolutionary as well as linear schemes is presented for a meshed circuit DOCR problem considering current and time multiplier factors [9]. The effects of using distant faults and multiplication constants on the results of coordination problems give a moderate result [10]. The output does not change much but little accuracy of coordination constraint is lost and thus the results are not much feasible.

The non-linear formulation methods are also developed for minimizing the trip time for relays. A hybrid EA and linear programming (LP) approach to perform the coordination optimization problems give more promising results where a partial solution is obtained neglecting particular constraints to obtain a feasible solution thus, researchers developed a tripping curve for time, current and voltage for decrease in the execution time of relays established in the hybrid distributed generation networks [11]. A mixed integer linear programming was adopted to overcome the drawback of trapping of local minima while using heuristics approaches and gave better approach to deal with a non linear and non convex optimization problem [12].

The global optimization finds the optimal value of a required objective function among all the possible number of solutions. Genetic algorithm (GA) and its various variants first started the global optimization discussion[13]. The solution approach based on the GA that contains the system properties and adjusting factors and is used to optimize the discrete and continuous time settings of a relay is done by the improved GA formulation [14]. The hybrid scheme of GA-NLP is proposed for solving the limitations of GA and non-linear programming (NLP) for DOCRs problem ,that is, GA has a drawback of converging to the values which may not be optimum, and NLP have a limitation of converging to local optimum values, if the local optimum is nearer to the initial choice [15]. And considering more practical problem, the conversion from bounded crossover and mutation to the real coded GA is adopted [16].Further with the help of NSGA-II, the time delay from backup relays to primary relays is minimized for the directional overcurrent relay system [17].

PSO and their variants are a powerful mechanism for solving the relay problems for both types of decision variables using quantized approach that is the best search from the swarm is chosen. The randomized value of velocity is used with the each solution which is obtained by the implementation of PSO based on its own and the flying experiences of neighbor. The different solutions thus obtained are then flown through search space. PSO gained a lot of interest for its simplicity, robustness, and easy implementation. A new method of the conventional PSO for relay coordination due to its easy implementation is proposed [18]. PSO has a good memory due to which all particle stores the good solutions unlike GA where previous value is destroyed as the population changes. The original PSO need to be modified as it is capable to find optimal solution only for unconstrained problem [19]. And further improving the diversity of the swarm a superior approach is presented [20].

For larger and complex coordination problem, an evolutionary PSO algorithm is used to coordinate the directional relays [21]. Some researchers have found that differential evolution (DE) approach has provided a new scope in the problem of relay coordination. DE comes out to be better in all algorithm techniques when a comparison has been done on various solution strategy such as GA, PSO, and DE on DOCRs problem[22]. The another approach for traditional DE is well illustrated by five different methods where instead of using constant scaling function the Laplace distribution function is considered [23]. To obtain the suitable discrete time and plug settings a new technique is also developed based on DE as it is a non-linear problem[24]. The use of LINKNET structure was proposed to upgrade the reclustering scheme of DE for relay coordination problem [25].

The modified DE for small area search is now discussed which calculates the time and plug settings for relays [26]. It can be gained by expansion of nearby space of best result obtained. A detailed study on different DE approaches regarding optimal coordination is done and a comparison based upon their time, sensitivity, power quality, life time and fast detection of faults is provided. The main advantages of using DE is that it can handle large-scale and expensive optimization problems very easily compared to many other evolutionary algorithms such as EA. The accuracy, convergence speed, and robustness are high and the number of control parameters is very low. Moreover it requires very less storage for computation [27].

The other approach used by few researchers is gravitational search algorithms (GS). The algorithm based on hybrid combination of GS and sequential quadratic programming (SQP) where GS is used as a global optimizer and SQP as a local optimizer is proposed to get the feasible solution [28]. Another hybrid scheme that was presented was PSO and GS where the variation in environmental factors affecting the relay settings is discussed and the proposed method gives the better results [29]. Hybridized symbiotic organism search algorithm is another method used for such a highly constrained coordination problem [30].

Application of Teaching Learning-Based Optimization (TLBO) is also developed which gives more promising result as compared to other artificial algorithms by the utilization of TLBO approach for Directional Overcurrent relays problem in a meshed electrical network [31]. An improvised TLBO with the help of variable range of TMS and constant PSM The range for PSM is kept constant [32]. The hybrid structure of biogeography based optimization algorithm with linear programming is also proposed for the minimization of operational time of directional overcurrent relay [33]. The more improved mathematical formulation was proposed by using GA for far and near end faults in coordination of primary and backup relays [34].

In recent few years, area of machine learning has grabbed the attention of my researchers and thus encouraged some peoples to get focused in the area of protection system like coordination problem of relays. Some estimated the non-linear constrained optimization problem of OC relays with the help of extended discrete Artificial Bee Colony (ABC) technique for the electro-mechanical relays application[35].

The Artificial Neural Network is also utilized for DOCRs problem of very large looped power systems as it gives better results in comparison with differential evolution and as a result the hybrid approach of genetic algorithm and artificial neural network is used [36]. Some more meta-heuristics are also implemented for achieving the coordination of relays like improved group search algorithm is proposed to enhance the convergence rate [37]. The researchers have prescribed more advanced techniques based on the electromagnetic field optimization to achieve better convergence [38]. Other techniques include the seeker algorithm for mixed integer DOCR problem [39] and the optimal coordination of relay for distributed generation by using back tracking search algorithm [40]. Bat algorithm and its improved algorithm is one of the metaheuristic technique used for the DOCR coordination problem [41], [42]. The researchers have adopted another technique called most valuable player algorithm to deal with such a highly constrained coordination problem [43].

Newly, motivated by the shallow water theory, for solving global optimization problem researchers have proposed Water Evaporation Optimization (WEO) algorithm[44]. The WEO algorithm is simple and easy to implement. The WEO algorithmic searches both globally as well as locally. Thus the proposed algorithm is competitive with other efficient well-known meta-heuristics.

Apart from the various algorithms developed early, the water evaporation optimization algorithm is selected for the problem of directional overcurrent relay coordination. The prime reason to choose this algorithm for the DOCRs coordination problem is the accuracy and fast response due to global and local search ability of the algorithm. WEO uses the concept of water evaporation where the water molecules are considered as algorithm individuals and the search space is defined by the variable wettability of the surface [45]. The probability of evaporated water molecules are updated based upon the rate of evaporation flux. This give rise to the two phases of the algorithm, till the one half of the maximum iterations monolayer evaporation phase (MEP) is used to update the water molecules and for the next half iterations the droplet evaporation phase (DEP) is considered to update the water molecules. The fine balance of global and local search of the two phases of the algorithm helps in achieving the well converged solution.

Researcher Wang has developed a Molecular Dynamics (MD) simulations on the evaporation of water from a solid substrate with different surface wettability [46] .Thus a fine analogy can be found between such phenomena of water evaporation and a population based meta-heuristic algorithm. This analogy led us to utilize the basic WEO algorithm.

1.3. SCOPE OF WORK AND OBJECTIVES

- Efficient protection coordination by minimizing the total operating time of directional overcurrent relay by using WEO algorithm.
- WEO algorithm is applied to solve the DOCRs coordination problem in two categories. Firstly, where both the decision variables are continuous that is, time multiplier settings and pickup currents both are continuous variables.
- Secondly, where the decision variables are both continuous as well as discrete that is, values of time multiplier settings is taken as continuous while values of plug setting multiplier is considered as discrete.
- Subjected to the various constraints and boundary conditions the problem uses the standard IEEE 8 bus and 9 bus test system for the implementation of both continuous and discrete coordination problem.

1.4. ORGANIZATION OF DISSERTATION

The dissertation named as "**Optimal Coordination of Directional Overcurrent Relay using Water Evaporation Optimization Algorithm**" has been presented in five chapters. The detailed introduction and the review of literature are mentioned in **Chapter 1**. The problem formulation for relay coordination for both discrete and continuous type is discussed in **Chapter 2**. The features and formulation of water evaporation optimization algorithm and its implementation for the optimal relay coordination problem is presented in **Chapter 3** and **Chapter 4** respectively. **Chapter 5** discusses the results for 8 and 9 bus test system for both continuous and discrete type coordination problem. The scope of future work and conclusion are mentioned in **Chapter 6** followed by the references and appendix.

CHAPTER 2

DIRECTIONAL OVERCURRENT RELAY COORDINATION

2.1. BACKGROUND

The directional overcurrent relay offers directly or indirectly protection to adjacent lines, measuring equipments, transformers, buses etc. The phase relationship of the voltage and current is being used for identifying the direction of a fault. DOCR are being designed so that they can sense the actual conditions of operation of a network and whenever the fault is detected it gives signal to trip the circuit breakers. Let us consider a situation when a symmetrical balanced three phase fault occurs, both relays would start the process and identify the situation at the same time. Thus to prevent the system from any disturbance or unbalance the relay settings must be set such as whenever any fault occurs the primary relay must operate first in every zones of protection and if due to some reason the operation fails then backup relay should work after a predefined time interval which is known as CTI. All the constraints when satisfied will provide a full protection scheme. Hence the primary and backup relay coordination is a complex coordination problem [47] . Therefore, the minimization of tripping time of relays formulated with the constraints related to CTI and the boundaries for tripping interval for each relay is to be done to get a feasible solution.

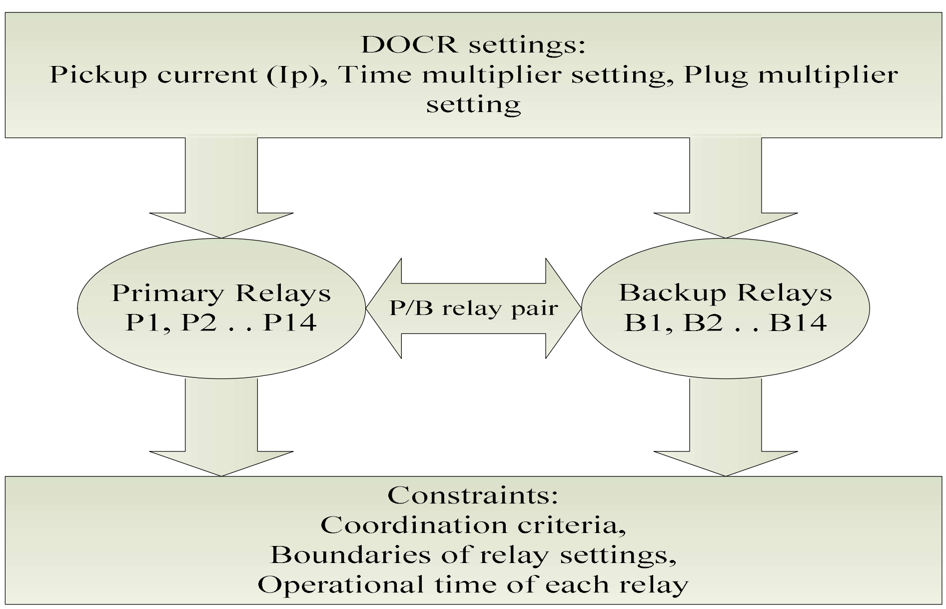

Fig 2.1: Schematic process of DOCR coordination problem

The problem of optimal coordination of DOCR by a schematic procedure is shown below in fig 2.1. Firstly, relay discriminates where the fault is located and the operation will not occur if fault is located behind the relay. But if the fault is located in front of the relay, a comparison of fault current and reference current (pickup current) will take place so that relay can decide whether to operate or not [48].

Thus incorporating the proper relay settings the operating time of overcurrent relay can be estimated. An inverse characteristic graph for the time of operation of relays is given by IEC as illustrated in fig 2.2. These curves are different for different types of relays like standard inverse, extremely inverse, IDMT or very inverse [49].

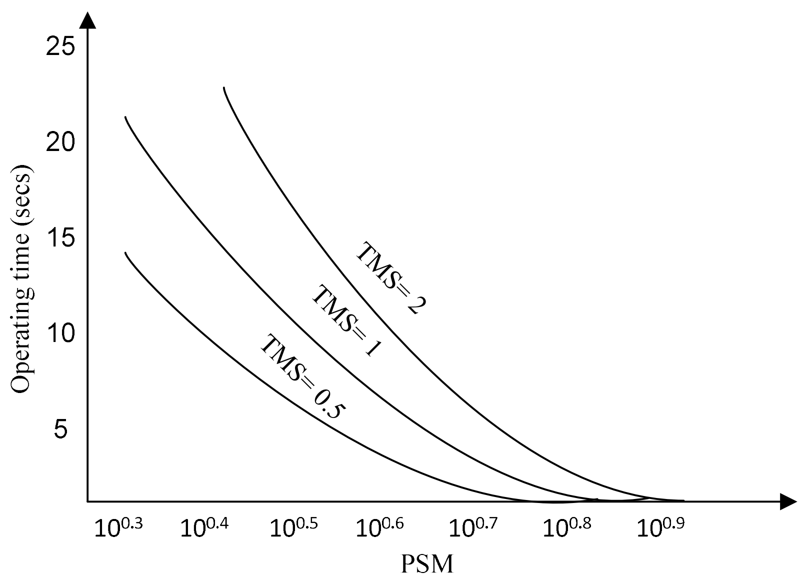

Fig 2.2: Inverse characteristic graph showing effect of TMS and PSM on relay operating time

The different relay settings like pickup current, plug setting and time multiplier setting are used to deal with different faults. The two settings which are considered here: “dial” which determines operating time of relay and “pickup currents” which determines the sensitivity and the time at which relay operation starts.

The IEEE 8 bus test system is being considered here for the validation of optimum relay settings. In the first system, TMS and pickup currents are assumed as the design variables and both of them are considered to have the continuous values. In the second system, TMS and PSM are assumed as the design variables and TMS is considered to have the continuous values while the PSM is considered to have discrete values.

The formulation for the stated problem is discussed below:

2.2. PROBLEM FORMULATION FOR CONTINUOUS COORDINATION

In the continuous coordination problem for optimizing the operating time of relays, the settings that are considered are pickup current settings and time multiplier settings. Both the decision variables considered are continuous in nature and the objective function with the various constraints are mentioned in the below section.

2.2.1. Objective Function

The fitness function for the problem of DOCRs coordination comprises the sum of tripping time of all the primary relays which needs to be minimized [48]. Thus fitness function is formulated as:

$$\text{Fitness Function:} \quad \sum_{i=1}^{m} w_i To_i \tag{2.1}$$

Where the operating time is To_i and the allocated weight is denoted by w_i for the i^{th} primary relay.

Here, we have considered value of w_i equal to 1 and the number of primary relays is represented by m.

The equation of operating time for inverse characteristic overcurrent relays as per IEEE C37.112-1996 is as follow [50] :

$$To_i = TMS_i \times \left(\frac{A}{\left(\frac{I_F^i}{I_P^i}\right)^B - C} \right) \tag{2.2}$$

Where, I_F^i denotes the fault current magnitude passing through i^{th} relay,

I_P^i denotes the pickup current value of the i^{th} relay,

To_i denotes the operating time of the i^{th} relay,

TMS_i denotes the time multiplier setting of the i^{th} relay,

A B and C are the coefficients of time inverse characteristics. In standard coordination strategies A and B are assumed to be fixed, but the values can be set specifically for each relay and thus the different curves for the relay which increases the probability of obtaining the desired operating time is created. But in non standard coordination approach A and B are considered as variables to be optimized. The standard inverse type is used in the work, so the values considered are A =0.14, B =0.02 and C =1.

2.2.2. Constraints

The objective of DOCR coordination problem is to minimize the operating time of all relays connected to the system and this purpose can be achieved by following the certain sets of constraint.

(1) Bounds on operating time of relay

To avoid the long operational time each relay require a certain amount of time to operate. Thus the constraint imposed is stated as:

$$To^i_{min} \le To^i \le To^i_{max} \tag{2.3}$$

Where To^i_{min} and To^i_{max} is the minimum and maximum operational time of i^{th} relay.

(2) Bounds on settings of relay

Since the TMS directly affects the operating time of relay, the limitations on the relay settings are stated as [40]:

$$TMS^i_{min} \le TMS^i \le TMS^i_{max} \tag{2.4}$$

$$IP^i_{min} \le IP^i \le IP^i_{max} \tag{2.5}$$

Where TMS^i_{min} and TMS^i_{max} are the minimum and maximum range of TMS for i^{th} relay, and IP^i_{min} and IP^i_{max} are the minimum and maximum magnitude of pickup current for i^{th} relay respectively.

The magnitude of pickup current is estimated with the help of two parameters that is the load current and the fault current. The highest value of load current must always be less than the pickup current value. Also, the pickup current magnitude should be less than the smallest value of the fault current. Thus, these boundary values must also be satisfied to get the feasible optimized solution.

(3) Relay coordination criteria

The coordinated working of both the primary relays and backup relays have a certain constraint to follow so as to avoid the mal operation in the protection system. On the occurrence of a fault whenever the primary relay operates and generate a trip signal to a circuit breaker, the backup relay must operate and takeover the tripping action only after a certain gap of time interval only if the primary relay fails to operate. This associated time gap is called as coordination time interval (CTI) which is the sum overshoot time and the operating time of circuit breaker associated with the primary relay. As illustrated in the fig 2.3, the second relay R_2 should operate after the certain time gap for the proper operation of first relay R_1.

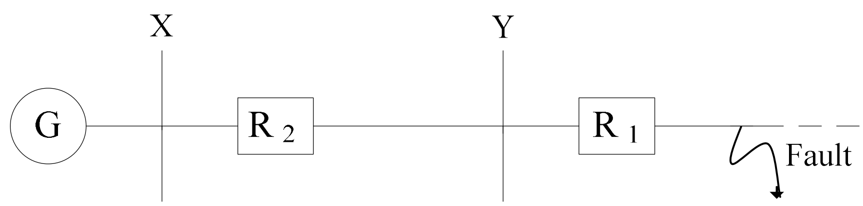

Fig 2.3: Representation of Primary/Backup relay pair

Here, CTI is the safety tool which needs to follow the stated constraint:

$$To_{BACK} - To_{PRI} \geq CTI \qquad (2.6)$$

Where, To_{PRI} represents the operating time of primary relay, and

To_{BACK} represents the operating time of backup relay,

Various system parameters, speed of the breakers and the type of relays decide the value of CTI. Generally it is selected in the order of 0.2 to 0.5 seconds for the electromagnetic relay and in range 0.1 to 0.2 seconds for the microprocessor based relays [51].

2.3. PROBLEM FORMULATION FOR DISCRETE COORDINATION

In this type of coordination problem, the problem is stated as the mixed integer type as it uses both discrete and continuous decision variables. Here, the plug setting multiplier values are considered in discrete steps and that of time multiplier setting as continuous.

2.3.1. Objective Function

The fitness function for the discrete problem is similar to the continuous problem as stated before in equation (2.1) that is the total tripping time of all the primary relays need to be minimized. But in this coordination problem, the equation for determining the operating time of each relay is different from continuous one. The continuous pickup current values are replaced by the discrete values of plug setting multiplier and the current transformer ratio and the equation for the operational time of each relay is stated below:

$$To_i = TMS_i \times \left(\frac{A}{\left(\frac{I_F^i}{CTratio^i \times PSM^i} \right)^B - C} \right) \tag{2.7}$$

Where, I_F^i denotes the fault current magnitude passing through i^{th} relay,

PSM^i denotes the plug setting multiplier of the i^{th} relay,

TMS_i denotes the time multiplier setting of the i^{th} relay,

To_i denotes the operating time of the i^{th} relay,

$CTratio^i$ denotes the current transformer ratio of the i^{th} relay.

2.3.2. Constraints

The constraints applied in continuous coordination problem of DOCR are also applied in discrete coordination problem such as the maximum and minimum tripping time of each relay.

(1) Bounds on settings of relay

The relay settings considered here are time multiplier setting and plug setting multiplier. The boundary conditions for TMS are similar to the boundary conditions of TMS for continuous problem as stated in equation (2.4).

$$PSM_{min}^{i} \leq PSm^{i} \leq PSM_{max}^{i} \tag{2.8}$$

Where, the minimum and maximum range of PSM for i^{th} relay is denoted by PSM_{min}^{i} and PSM_{max}^{i} respectively. The magnitude of PSM should be selected such that the value of PSM must be more than the highest value of load current and must be less than the lowest fault current value for each relay.

(2) Relay coordination criteria

The coordination criteria used in continuous problem is also applied for the discrete coordination problem and has the same relation as in equation (2.6).

CHAPTER 3

WATER EVAPORATION OPTIMIZATION ALGORITHM

3.1. INTRODUCTION

The metaheuristic optimization algorithms are widely studied and developed to overcome some drawbacks of conventional methods in non linear problems which are highly complex and the primary reason is that the global optimum is reached in less time.

One such metaheuristic algorithm recently developed is Water Evaporation Optimization (WEO) that follows the process of evaporation of small amount of water molecules with different wettability on a solid surface. This evaporation is studied by molecular dynamics solution [46] which depicts that as the surfaces changed to hydrophility from hydrophobicity the speed of evaporation increases first and after reaching a maximum value it starts decreasing. The geometrical shape of water accumulated decides the evaporation speed. Further, if the wettability of surface is not high then the water will congregate into the spherical cap form. But the geometric factor does not affect much when the wettability is quite high and thus the water molecule spread to a monolayer and the evaporation speed is now controlled by the energy barrier which is developed by the substrate.

The presence of positive as well as negative charges makes the substrate neutral. So the surface wettability can be changed by changing the value of charge. The simulations are done in a neutral substrate where charge (q) is taken between 0 to 0.7e where e has a value of 1.6×10^{-19} C. If q was less than 0.4e a sessile droplet is formed having the contact angle (θ) to the surface but as q is more than 0.4e then the water molecules spreads on the substrate. The liquid molecules and the wettability of surface can affect the contact angle [52]. The evaporation flux which decides the evaporation speed of the water molecules does not decreases monotonically with increasing value of charge. When q is less than 0.4e, as q increases the evaporation flux also increases but as the charge reach its maximum at 0.4e then the evaporation flux decreases as the q increases. This behavior is represented by:

$$J(q) \propto P_G\big(\theta(q)\big)P_E(E) \tag{3.1}$$

where, $P_E(E)$ represents the water molecule escape probability, The water molecule probability on liquid gas surface denoted by:

$$P_G(\theta) = P_O\left(\frac{2}{3} + \frac{\cos^3\theta}{3} - cos\theta\right)^{-2/3}(1 - cos\theta) \tag{3.2}$$

where, P_O is the constant parameter of diameter and volume of molecules. The energy provided by the neighboring water molecules (E_m) and by the interaction of substrate (E_{sub}) gives the average interaction energy$E$.

The contact angle (θ) decreases as the q increases and when it reaches 0.4e the contact angle becomes 0. For q less than 0.4e, the energy given by the neighboring water molecules is nearly constant and the energy provided by the interaction of substrate also does not change. Hence, the probability $P_E(E)$ is assumed to be constant.

Thus the evaporation flux is represented by the equation stated below:

$$J(\theta) = J_O P_G(\theta) \tag{3.3}$$

In analogy to the population based metaheuristic algorithm, water molecules are designated as algorithm individuals. The search space is the substrate with variable wettability. The water aggregates from a monolayer to a fixed droplet as the wettability of substrate decreases. The reducing wettability denotes the decrease of objective function of a optimization problem. Based on the results of molecular dynamic simulations, the evaporation rules are used to update the individuals globally and locally in two different phases, that is, droplet and monolayer evaporation phase. The most appropriate factor for updating the individual is the evaporation flux rate of the molecules. The local and global search ability of the algorithm and the fast convergence make this algorithm a simple algorithmic structure.

3.2. WEO ALGORITHM

In the WEO algorithm, the process follows three cycles which are stated as:

(i) Monolayer Evaporation Phase, this phase is considered as the global search ability of the algorithm

(ii) Droplet Evaporation Phase, this phase can be considered as the local search ability of the algorithm and

(iii) Updating the set of molecules, the water molecule is being updated each time it gets evaporated.

3.2.1. Monolayer Evaporation Phase

In this phase, as q increases energy consumed by the substrate will be more and thus less evaporation will take place. Thus, for q > 0.4e and up to half of the algorithm iterations, for each iteration let us assume the maximum and minimum value of the energy substrate as -0.5 and -3.5 respectively. The different values of substrate energy in this interval represented by the monolayer evaporation probability is shown in fig 3.1 [45].

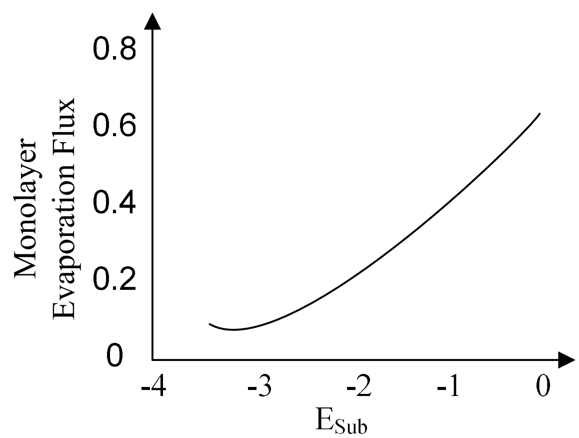

Fig 3.1: Monolayer evaporation probability for different energy substrate.

The objective function of the each individual obj_i^t is scaled to the interval [-3.5, -0.5] and the corresponding $E_{Sub}(i)^t$ inserted to each individual (substrate energy vector) with the following scaling function is represented by:

$$E_{Sub}(i)^t = \frac{(E_{Max}-E_{Min})\times\left(obj_i^t - Min(obj)\right)}{\left(Max(obj)-Min(obj)\right)} + E_{Min} \quad (3.4)$$

Where, E_{Max} and E_{Min} are the highest and lowest limits of E_{Sub} respectively.

The Monolayer evaporation matrix (MEP) is now constructed after the energy vector is created with the following equation:

$$MEP_{ij}^t = \begin{cases} 1\ if\ rand_{ij} \leq exp(E_{Sub}(i)^t) \\ 0\ if\ rand_{ij} \geq exp(E_{Sub}(i)^t) \end{cases} \quad (3.5)$$

Where, MEP_{ij}^t represent the updating probability of the i^{th}water molecule in the t^{th} iteration of the algorithm for the j^{th} variable. In this way an individual with better objective function is more likely to remain unchanged in the search space. The maximum and minimum values of MEP will be 0.6 and 0.03 respectively by which the best and worst candidate will get update.

3.2.2. Droplet Evaporation Phase

In the droplet evaporation phase, the evaporation flux is calculated by the following equation.

$$J(\theta) = J_O P_O \left(\frac{2}{3} + \frac{\cos^3\theta}{3} - cos\theta\right)^{-2/3}(1 - cos\theta) \quad (3.6)$$

where, $J_O\ and\ P_O$ are constant values. The evaporation flux value depends upon the contact angle θ. As the contact angle increases the evaporation will be less. The contact angle vector is represented by the following scaling function stated:

$$\theta(i)^t = \frac{(\theta_{Max} - \theta_{Min}) \times \left(obj_i^t - Min(obj)\right)}{\left(Max(obj) - Min(obj)\right)} + \theta_{Min} \quad (3.7)$$

where, the minimum and maximum functions are denoted by Min and Max respectively. The minimum and maximum values of θ_{Min} and θ_{Max} are chosen between$-50° < \theta < -20°$.

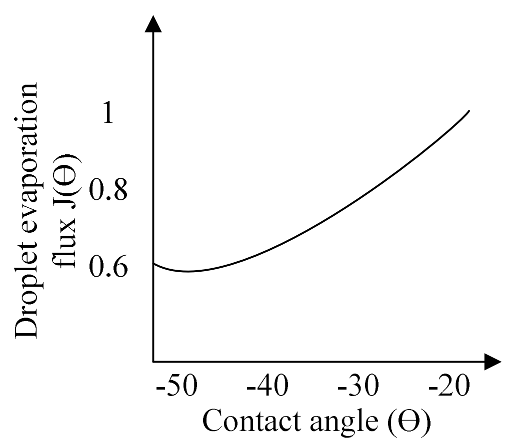

Fig 3.2: Droplet evaporation probability for various contact angles.

The droplet evaporation probability is presented in fig 3.2 for the various contact angles within this interval. Here, to bind the value of DEP to 1 we are considering the value of $J_O P_O$ equals to 0.3846. After the generation of contact angle vector $\theta(i)^t$ the Droplet Probability Matrix (DEP) is constructed by the following equation.

$$DEP_{ij}^{t} = \begin{cases} 1 \; if \; rand_{ij} < J(\theta(i)^t) \\ 0 \; if \; rand_{ij} \geq J(\theta(i)^t) \end{cases} \tag{3.8}$$

where, DEP_{ij}^{t} is the updating probability for the j^{th} variable of the i^{th}individual or water molecule in the t^{th} iteration of the algorithm.

3.2.3. Updating Water Molecules

The number of algorithm individuals or number of water molecules is considered constant in all iterations. To determine the evaporation phase and the stopping criterion we consider a maximum iterative value t_{max}.Whenever evaporation of a water molecule takes place it should be renewed. Thus by updating the water molecules we improve the objective function. The evaporated water molecules are generated using the current set of water molecules ($WM^{(t)}$). Thus a random permutation based step size provides the possible modification of individual:

$$S = rand\left(WM^{(t)}[perm1(i)(j)] - WM^{(t)}[perm2(i)(j)]\right) \tag{3.9}$$

Where, $rand$ represents a random number generated in the interval [0,1], $perm1$ and $perm2$ are rows of two different permutation functions.

$$WM^{(t+1)} = WM^{(t)} + S \times \begin{cases} MEP_{ij}^{t} & t \leq t_{max}/2 \\ DEP_{ij}^{t} & t > t_{max}/2 \end{cases} \tag{3.10}$$

The next set of water molecules $WM^{(t+1)}$ is obtained by using the above equation in which the random permutation based step size is multiplied with the corresponding probability and added to the previous set of molecules. Based on the fitness function every water molecule is first compared and then gets replaced by the best renewed molecule.

The step wise procedure of WEO algorithm is summarized below:

Step 1: Firstly, assign the value to all the algorithm parameters.

Step 2: Then initialize all the water molecules randomly.

Step 3: Generate the water evaporation matrix.

Generate the substrate energy vector E_{sub} using equation (3.4) and contact angle vector Θ by using equation (3.7). When $t \leq t_{max}/2$, based on monolayer evaporation matrix MEP generated by using equation (3.5) the water molecules are evaporated globally while for $t > t_{max}/2$, the water molecules get evaporated based on the droplet evaporation probability DEP by using equation (3.8).

Step 4: Generating random permutation based step size matrix S. A random permutation based step size matrix is developed as per the equation (3.9).

Step 5: Generating evaporated water molecules and update the new matrix of water molecules by using equation (3.10). The best water molecule is returned as the output of the algorithm.

Step 6: Check the condition for termination

Terminate the algorithm if the number of iteration of the algorithm (t) becomes larger than the maximum number of iterations (t_{max}) otherwise go again to step 3.

CHAPTER 4

WEO ALGORITHM FOR DIRECTIONAL OVERCURRENT RELAY SYSTEM

4.1. IMPLEMENTATION FOR CONTINUOUS COORDINATION

The procedure of implementing the water evaporation behavior for the continuous decision variables for coordination problem of directional overcurrent relays is discussed in the following steps.

4.1.1. Read the input values

Read the maximum and minimum values of the tripping time of each relay, pickup current, time multiplier settings, fault current for both primary and backup relays, and coordination time interval for each relay. Read the number of decision variables, and the maximum number of iterations. Then assign the maximum and minimum values for all the parameters used in the WEO algorithm.

4.1.2. Initialization

The search space consists of NP number of population where the technique is used to predict the best result. Initially, the decision variables, y= [TMS, I_P] are generated randomly for all the relays considering the boundary conditions. Thus the initial positions of water molecules are generated and based on the objective function of the problem the operating time of each primary and backup relay is calculated as per the following equation:

$$TMS_j^i = TMS_{min} + \left(TMS_{max}^i - TMS_{min}^i\right) \times random\ no \tag{4.1}$$

$$I_{P_j}^{\ i} = I_{P_{min}} + \left(I_{P_{max}}^{\ i} - I_{P_{min}}^{\ i}\right) \times random\ no \tag{4.2}$$

Where, $TMS_{max}^i$and $TMS_{min}^i$are the maximum and minimum parameters of TMS for i^{th} dimension respectively. TMS_j^i is the TMS for i^{th} dimension of j^{th} water molecule particle. $I_{P_{max}}^{\ i}$ and $I_{P_{min}}^{\ i}$ are the maximum and minimum parameters of pickup current for i^{th} dimension respectively. $I_{P_j}^{\ i}$ is the pickup current for i^{th} dimension of j^{th} water molecule particle. Thus, based on the objective function the operational time for each relay is calculated and using the algorithm the new sets are generated for each iterations.

4.1.3. Handling of constraints

The various methods are used for constraints handling and the method used in our work is the penalty method where a penalty term is added to the objective function so that the solutions which violate the constraints can be penalized.

4.1.4. Generating water evaporation matrix

The water evaporation matrix is generated in two phases. For the first half of the maximum no of iterations, the water evaporation matrix is formed when the algorithm searches globally and the matrix generated is Monolayer Evaporation matrix (MEP) which is used to update the new set of water molecules. Similarly for the second half of the maximum no of iterations, the water evaporation matrix is formed when the algorithm searches locally and the matrix generated is Droplet Evaporation matrix (DEP) which is used to update the new set of water molecules.

4.1.5. Updating the water molecules

The water evaporates as the algorithm progresses and therefore whenever the evaporation takes place the new set of water molecules need to be updated. The best strategy to achieve this purpose is by creating a random step size matrix S. The new updated set of water molecules is obtained by adding this random permutation based step size with their corresponding evaporation matrix to the previous set of water molecules.

$$S = rand\left(WM^{(t)}[perm1(i)(j)] - WM^{(t)}[perm2(i)(j)]\right) \quad (4.3)$$

Where, a random number is generated in the interval [0,1] by using $rand$, $perm1$ and $perm2$ represent the rows of two different permutation functions.

Here, the decision variables for the DOCR coordination problem are TMS and I_P. Thus, the new updated values of TMS and I_P are given by following equations:

For $t \leq t_{max}/2$

$$TMS_j^{i^{(t+1)}} = TMS_j^{i^{(t)}} + S \times MEP_{ij}^t \tag{4.4}$$

$$I_{P_j}^{i^{(t+1)}} = I_{P_j}^{i^{(t)}} + S \times MEP_{ij}^t \tag{4.5}$$

For $t > t_{max}/2$

$$TMS_j^{i^{(t+1)}} = TMS_j^{i^{(t)}} + S \times DEP_{ij}^t \tag{4.6}$$

$$I_{P_j}^{i^{(t+1)}} = I_{P_j}^{i^{(t)}} + S \times DEP_{ij}^t \tag{4.7}$$

Where, $TMS_j^{i^{(t)}}$ is the value of TMS for i^{th} dimension of t^{th} iteration. $TMS_j^{i^{(t+1)}}$ is the updated TMS for i^{th} dimension of j^{th} water molecule particle. $I_{P_j}^{i^{(t)}}$ is the value of pickup current for i^{th} dimension of t^{th} iteration. $I_{P_j}^{i^{(t+1)}}$ is the updated value of pickup current for i^{th} dimension of j^{th} water molecule particle. MEP_{ij}^t and DEP_{ij}^t represents the monolayer evaporation probability matrix and droplet evaporation probability matrix for i^{th} dimension of j^{th} water molecule. Finally, the results from all the sets of water molecules are compared and the best feasible solution considering the objective function fulfilling all the constraints is obtained.

The implementation of WEO algorithm for solving the DOCR coordination problem is represented by a flowchart given in fig 4.1.

4.2. IMPLEMENTATION FOR DISCRETE COORDINATION

The discrete optimization of the coordination problem of directional overcurrent relay uses both discrete as well as continuous variables. Thus, the procedure of implementing the water evaporation behavior for the discrete decision variables will almost remain similar. The procedure for implementing the coordination problem of DOCRs using water evaporation optimization algorithm is discussed in the following steps.

4.2.1. Read the input values

Read the maximum and minimum values of the tripping time of each relay, plug setting multiplier, time multiplier settings. The value of current transformer ratio (CTR) for each relay ,

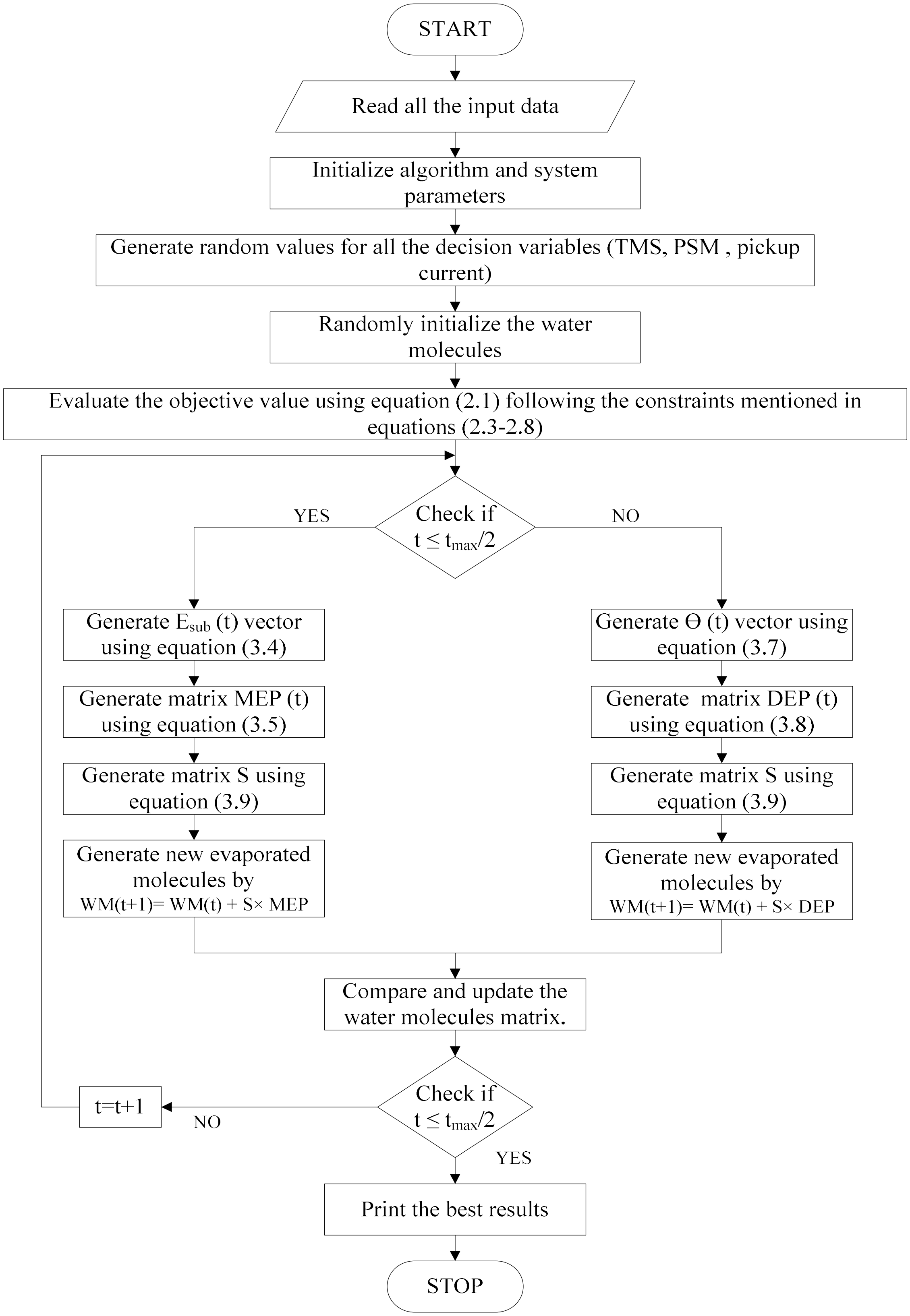

Fig 4.1: Flowchart for the WEO algorithm to solve DOCR coordination problem

step size for decision variables, fault current for both primary and backup relays, and coordination time interval for each relay is also defined. Read the number of decision variables, and the maximum number of iterations. Then assign the maximum and minimum values for all the parameters used in the WEO algorithm.

4.2.2. Initialization

Initially, the decision variables, y= [TMS, PSM] are generated randomly for all the relays considering the boundary conditions. Thus the initial positions of decision variables are generated and based on the objective function of the problem the operating time of each primary and backup relay is calculated as per the following equation:

$$TMS_j^i = TMS_{min} + \left(TMS_{max}^i - TMS_{min}^i\right) \times random\ no \tag{4.8}$$

$$PSM_j^i = PSM_{min} + \left(PSM_{max}^i - PSM_{min}^i\right) \times random\ no \tag{4.9}$$

Where, $TMS_{max}^i$and $TMS_{min}^i$are the maximum and minimum parameters of TMS for i^{th} dimension respectively. TMS_j^i is the TMS for i^{th} dimension of j^{th} water molecule particle. PSM_{max}^i and PSM_{min}^i are the maximum and minimum parameters of plug setting multiplier for i^{th} dimension respectively. PSM_j^i is the plug setting multiplier for i^{th} dimension of j^{th} water molecule particle.

4.2.3. Handling of constraints

The constraints handling used in our work is the penalty method that is used to penalized the violated constraints by adding a penalty term to the objective function to get a feasible result.

4.2.4. Generating water evaporation matrix

The process of generating the water evaporation matrix is similar as in continuous optimization problem that is generated in two phases, that is, Monolayer Evaporation matrix (MEP) and the Droplet Evaporation matrix (DEP) which is used to update the new set of water molecules whenever the evaporation process takes place.

4.2.5. Updating the water molecules

The water evaporates as the algorithm progresses and therefore whenever the evaporation takes place the new set of water molecules need to be updated. The best strategy to achieve this purpose is by creating a random step size matrix S. The new updated set of water molecules is obtained in a similar manner as illustrated for continuous problem in equation (4.3).

For discrete coordination problem, the decision variables for the DOCR coordination problem are TMS and PSM. Thus, the new updated values of TMS and PSM are given by following equations:

For $t \leq t_{max}/2$

$$TMS_j^{i^{(t+1)}} = TMS_j^{i^{(t)}} + S \times MEP_{ij}^t \tag{4.10}$$

$$PSM_j^{i^{(t+1)}} = PSM_j^{i^{(t)}} + S \times MEP_{ij}^t \tag{4.11}$$

For $t > t_{max}/2$

$$TMS_j^{i^{(t+1)}} = TMS_j^{i^{(t)}} + S \times DEP_{ij}^t \tag{4.12}$$

$$PSM_j^{i^{(t+1)}} = PSM_j^{i^{(t)}} + S \times DEP_{ij}^t \tag{4.13}$$

Where, $TMS_j^{i^{(t)}}$is the value of TMS for i^{th} dimension of t^{th} iteration. $TMS_j^{i^{(t+1)}}$is the updated TMS for i^{th} dimension of j^{th} water molecule particle. $PSM_j^{i^{(t)}}$is the value of plug setting multiplier for i^{th} dimension of t^{th} iteration. $PSM_j^{i^{(t+1)}}$ is the updated value of plug setting multiplier for i^{th} dimension of j^{th} water molecule particle. MEP_{ij}^t and DEP_{ij}^t represents the monolayer evaporation probability matrix and droplet evaporation probability matrix for i^{th} dimension of j^{th} water molecule. Comparing the best and worst molecule, the best water molecule is selected which provides the best feasible solution considering the objective function fulfilling all the constraints.

CHAPTER 5

RESULTS AND DISCUSSION

The water evaporation optimization algorithm is considered for solving the coordination problem of directional overcurrent relay where the optimized value of relay settings are determined so that the proper coordinated operation of primary and backup relay take place ensuring the reliable and protected system. To implement the water evaporation algorithm adopted, a certain set of program codes are written in the software MATLAB (version R2018a) and have been executed on the Intel(R) Core(TM)i3-3110M CPU at 2.40GHz and 4.00 GB RAM processor. For testing and validating the technique the standard IEEE bus system is considered.

5.1. TEST SYSTEM 1

The first system used for testing the continuous coordination problem is the standard IEEE 8-bus system network as illustrated in fig 5.1. The system comprises of eight buses, seven lines, two transformers, two generating sources, and fourteen directional overcurrent relays.

The fault currents for both the relays (primary and backup) are presented in table 3. The other settings of each relay like CT ratios and maximum and minimum value of pickup current is mentioned in table 1. Further, the time multiplier setting has minimum and maximum values selected as 0.05 and 1.1 respectively. The maximum time of operation (To_{max}) after which relay will trip is maintained at 2 seconds and the coordination time interval selected for this purpose is 0.3. Thus the problem will handle total 40 constraints, 20 each for both $CTI$and To_{max} and the total number of decision variables will be 28, 14 each for TMS and $I_p$respectively.

5.1.1. Parameters

The set of parameters considered for the water evaporation algorithm are stated below:

1. Population size = 20
2. No of algorithm iterations = 1000
3. No of decision variables = 28
4. $E_{Max} = -0.5$ and $E_{Min} = -3.5$
5. $J_O P_O$ = 0.384

6. $\theta_{Max} = -20°$ and $\theta_{Min} = -50°$

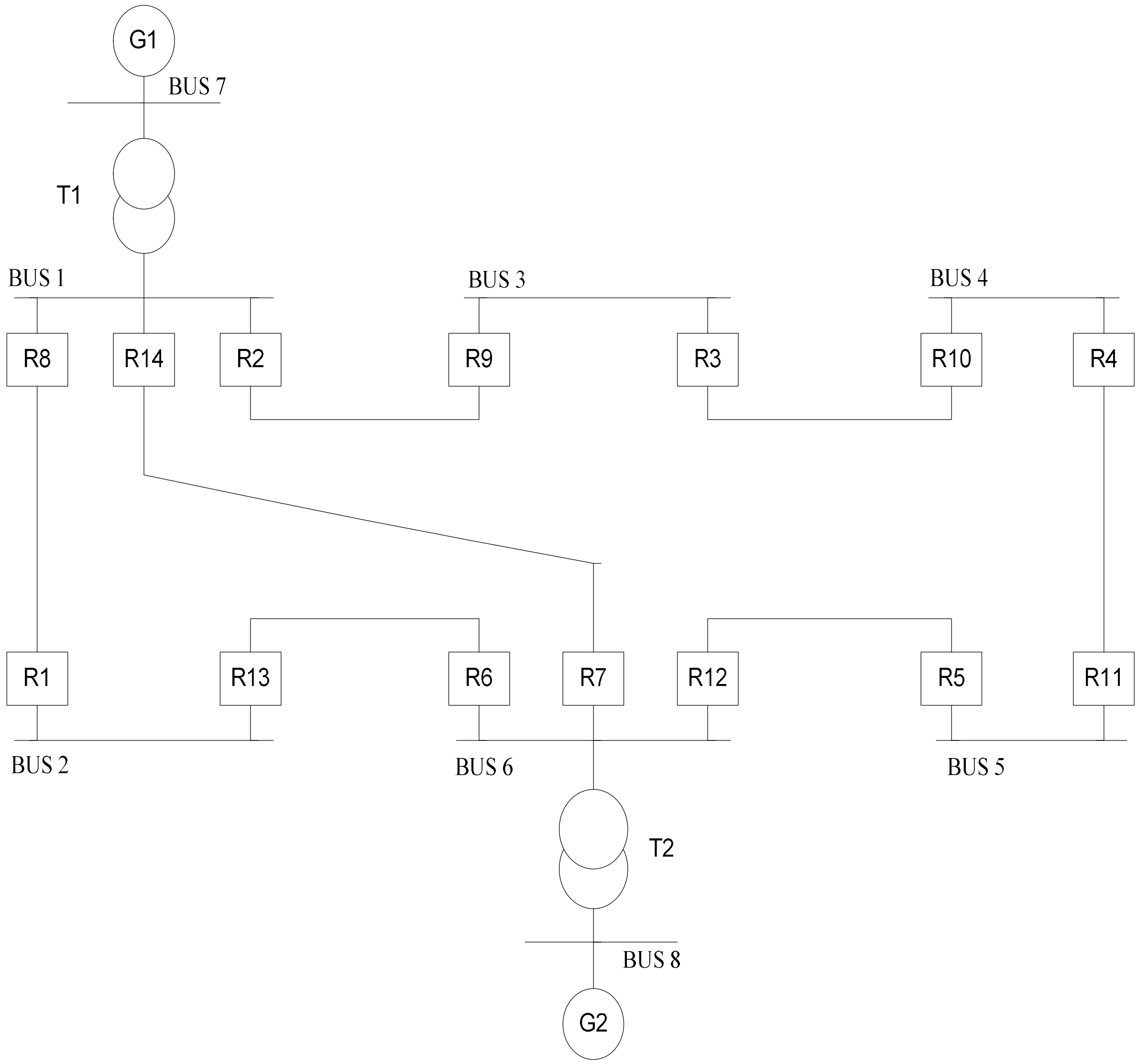

Fig 5.1: IEEE 8 bus network connection diagram [53]

5.1.2. Obtained results

Applying the water evaporation optimization algorithm with the mentioned parameters and boundaries, the optimized relay settings of pickup current and time multiplier is obtained so that the total tripping time of the primary relays is minimized. The table 5.1 shows the operating time of both primary as well as backup relays corresponding to their optimized values of pickup current and time multiplier setting. Table 5.2 shows the comparison of output for different algorithms used. The CTI obtained for the different relay pair is mentioned in table 5.3. The overall operating time for the each iteration is represented by a curve in fig 5.2. The different relay combination with their operating time and the corresponding CTI is illustrated in fig 5.3.

Table 5.1: Operating time for primary and backup relay and the optimal relay settings for test system 1

Relay No.	$T_O^{Primary}$ (sec)	T_O^{Backup} (sec)	TMS	I_P(Amp)
1	0.5092	0.8719	0.2195	141.6999
2	0.1090	0.1294	0.0500	220.4075
3	1.0060	1.1705	0.4381	162.5816
4	0.2752	0.3350	0.1181	120.0000
5	1.2922	2.0000	0.4555	120.0000
6	1.6646	2.0000	0.7356	247.3293
7	0.3771	0.5437	0.1900	130.7459
8	1.5065	1.8668	0.8321	120.0000
9	2.0000	2.0000	0.9077	175.4894
10	0.8289	1.2071	0.1892	470.1970
11	1.0003	1.1424	0.4907	120.0000
12	1.3661	1.5502	0.7710	120.0000
13	1.1143	2.0000	0.4174	182.4544
14	0.3705	0.6177	0.1404	310.1970

Table 5.2: Results obtained using different algorithms for test system 1

Algorithm Used	Operating time (sec)
WEO	13.419
EM [38]	18.489
PSO [19]	20.797

Table 5.3: Coordination time interval corresponding to different primary and backup relay pairs for test system 1

Relay Pairs		Coordination Time Interval (seconds)
Backup Relay	Primary Relay	
6	1	1.4908
1	2	0.7629
7	2	0.4347
2	3	0.8765
3	4	0.8952
4	5	0.9720
5	6	0.3354
14	6	1.0469
5	7	1.6229
13	7	1.6229
7	8	0.9628
9	8	0.4935
10	9	0.7929
11	10	0.3135
12	11	0.5499
13	12	0.6339
14	12	0.7484
8	13	0.7525
1	14	0.5014
9	14	1.6295

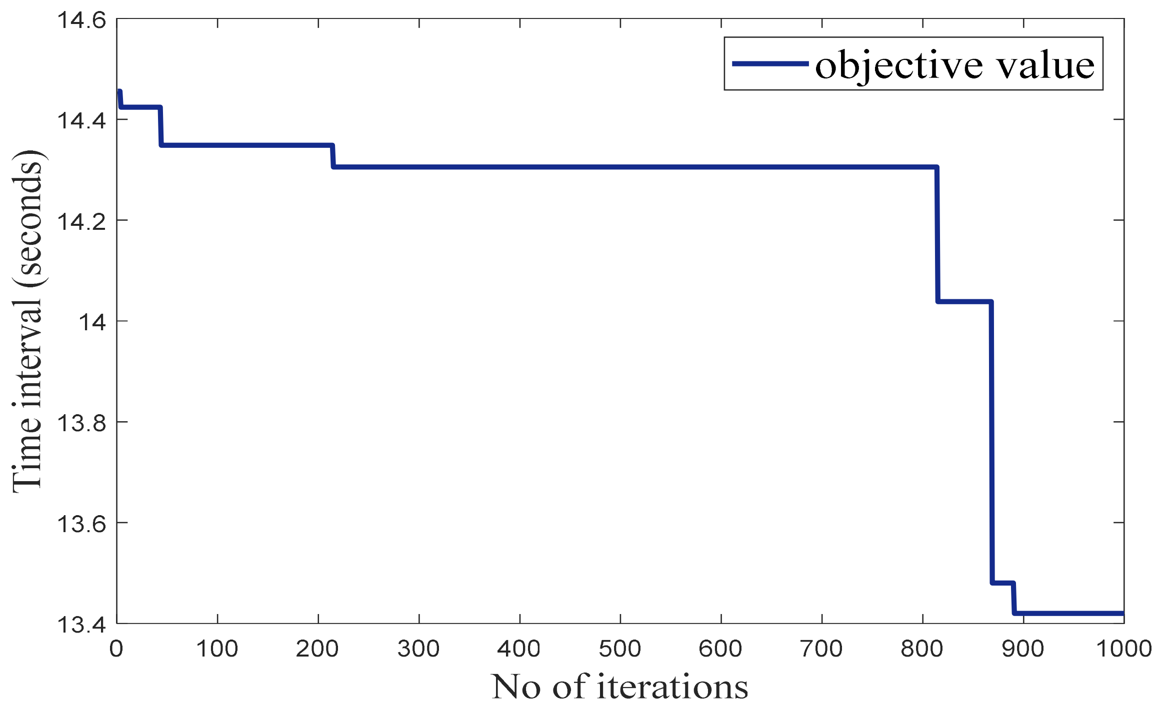

Fig 5.2: Total operating time for each iteration for test system 1

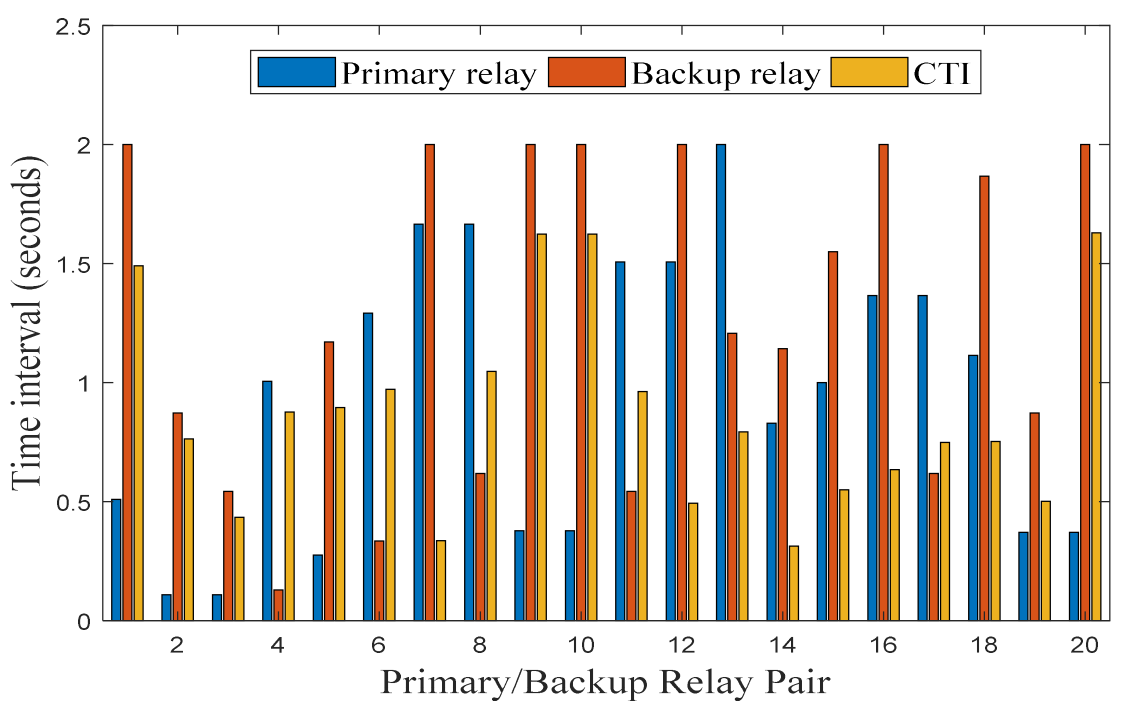

Fig 5.3: Different relay combination and their corresponding CTI for test system 1

5.2. TEST SYSTEM 2

The second system used for testing the continuous coordination problem is the standard IEEE 9 bus system network as illustrated in fig 5.4. The system comprises of nine buses, twelve lines, one generating source connected to bus 1, and twenty four directional overcurrent relays in which four relays 17,19,21,23 have no backup protection.

The settings of each relay like CT ratios and maximum and minimum value of pickup current is mentioned in table 4**.** The fault currents for both the primary and backup relays are presented in table 5**.** Further, the maximum and minimum values of the time multiplier setting are selected as 1.20 and 0.025 respectively. The higher and lower boundary limit for time of operation (To_{max}) after which relay will trip is maintained at 2 seconds and 0.2 seconds respectively. The coordination time interval selected for this purpose is 0.3. Thus the problem will handle total 104 constraints, 36 each for both To_{min} and To_{max}, and 32 for $CTI$and the total number of decision variables will be 48, 24 each for TMS and $I_p$respectively.

5.2.1. Parameters

The set of parameters considered for the water evaporation algorithm are stated below:

1. Population size = 20
2. No of algorithm iterations = 1000
3. No of decision variables = 48
4. $E_{Max} = -0.5$ and $E_{Min} = -3.5$
5. $J_O P_O$ = 0.384
6. $\theta_{Max} = -20°$ and $\theta_{Min} = -50°$

5.2.2. Obtained results

The CTI obtained for the different relay combination after applying the water evaporation optimization algorithm for system 2 with the mentioned parameters and boundaries is mentioned in table 5.4. The optimized relay settings of pickup current and time multiplier is obtained so that the overall operating time of the relays is minimized. The table 5.5 shows the operating time of both primary and backup relays corresponding to their optimized values of TMS and pickup current. The table 5.6 shows the comparison of output for different algorithms used. The overall operating time for the each iteration is represented by a curve in fig 5.5. The different relay pair for this 9 bus system with their operating time and the corresponding CTI is illustrated in fig 5.6.

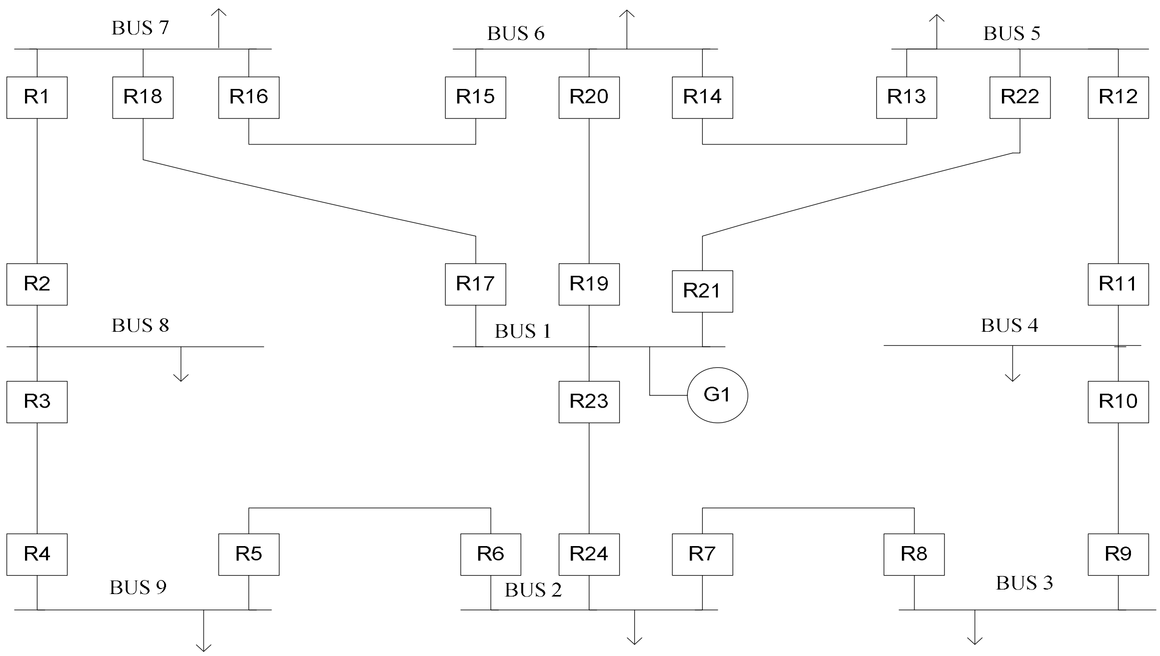

Fig 5.4: IEEE 9 bus network connection diagram [54]

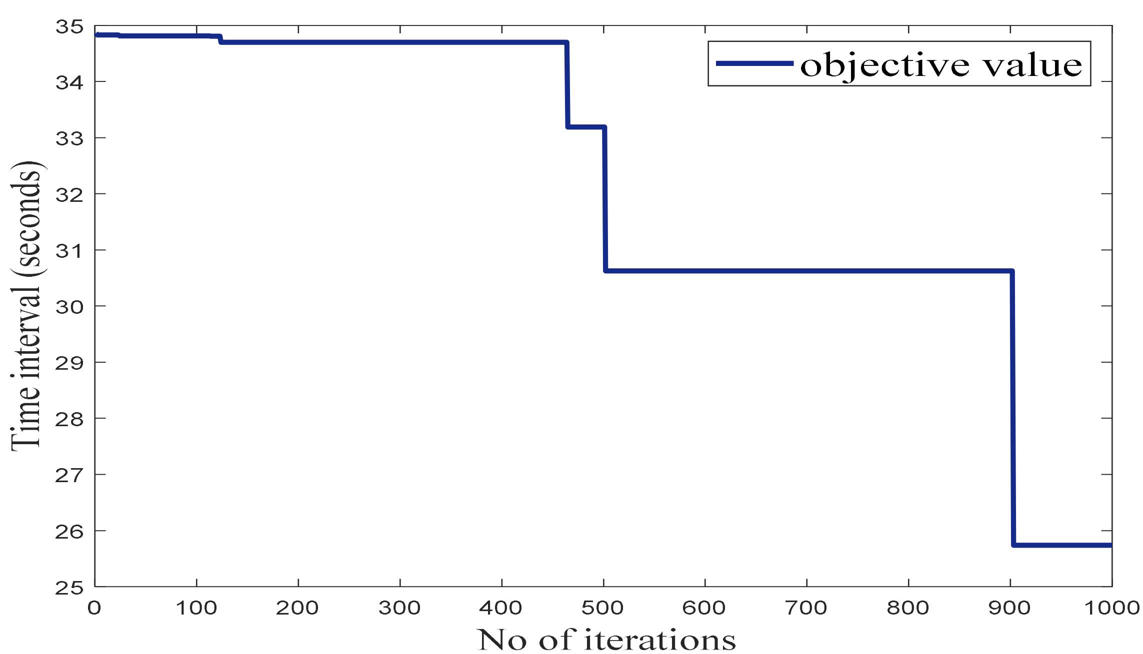

Fig 5.5: Total operating time for each iteration for test system 2

Table 5.4: Coordination time interval corresponding to different primary and backup relay pairs for test system 2

Relay Pairs		Coordination Time Interval (seconds)
Primary Relay	**Backup Relay**	
1	15	1.4145
1	17	0.6197
2	4	1.6577
3	1	1.0624
4	6	0.4642
5	3	0.3794
6	8	0.9772
6	23	1.0222
7	5	1.8000
7	23	1.8000
8	10	0.8903
9	7	0.3589
10	12	1.0489
11	9	0.6476
12	14	0.7650
12	21	0.3697
13	11	1.8000
13	21	0.6653
14	16	0.7647
14	19	0.8897
15	13	1.4301
15	19	0.3699
16	2	0.4977
16	17	1.0051
18	2	0.8023
18	15	0.5000
20	13	1.8000
20	16	1.6544
22	11	1.7788
22	14	1.7788
24	5	0.6055
24	8	0.5605

Table 5.5: Operating time for primary and backup relay as per the optimal relay settings for test system 2

Relay No.	T_O ^{Primary} (sec)	T_O ^{Backup} (sec)	TMS	I_P(Amp)
1	0.5855	0.9376	0.3001	152.1500
2	0.3423	0.6977	0.0904	265.9500
3	2.0000	2.0000	1.1263	445.1559
4	2.0000	2.0000	1.1469	430.0951
5	1.6206	2.0000	0.5075	208.0951
6	0.9778	1.5358	0.5192	121.4370
7	0.2000	0.2000	0.0343	315.9139
8	1.1097	1.9550	0.3475	208.0951
9	0.5589	1.1468	0.1466	430.0951
10	0.9511	2.0000	0.2434	483.5451
11	1.7944	2.0000	0.5940	169.6951
12	1.2350	2.0000	0.4311	258.7451
13	0.2000	0.2000	0.0250	147.4995
14	1.1103	2.0000	0.3396	512.7951
15	1.6301	2.0000	1.1469	38.0500
16	0.2000	0.3456	0.0446	421.7451
17	0.3600	1.2051	0.1343	596.5451
18	1.5000	1.6813	0.3076	551.6500
19	2.0000	2.0000	0.8890	513.6000
20	2.0000	2.0000	1.1469	513.6000
21	0.2585	0.8653	0.0965	596.5451
22	0.2212	0.2743	0.0250	1036.400
23	0.9893	2.0000	0.3661	633.1500
24	1.3945	1.6844	0.1775	688.7951

Table 5.6: Results obtained using different algorithms for test system 2

Algorithm Used	Operating time (sec)
WEO	25.2394
BH [38]	25.8840
BBO [33]	28.8341

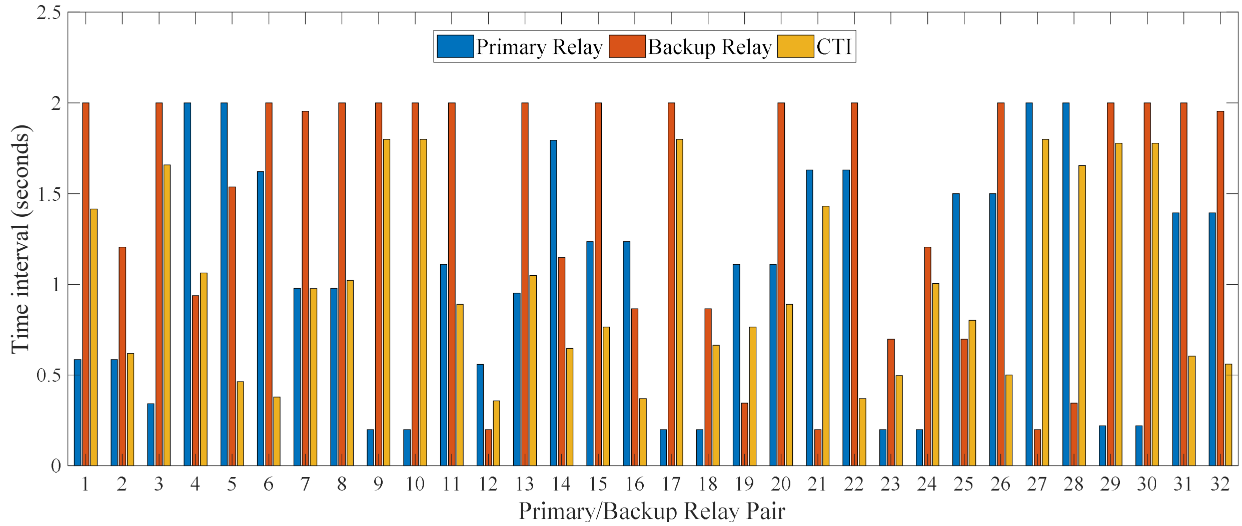

Fig 5.6: Different relay combination and their corresponding CTI for test system 2

5.3. TEST SYSTEM 3

The system used for testing the discrete coordination problem is the standard IEEE 8 bus system network as illustrated in fig 5.1 consisting of eight buses, seven lines, two transformers, two generating sources, and fourteen directional overcurrent relays [55].

The fault currents for both the primary and backup relays are presented in table 7 and the CT ratios are same as mentioned in table 1**.** The minimum and maximum values of the time multiplier setting selected are 0.1 and 1.1 respectively. The lower and higher limit of plug setting multiplier is 0.5 and 2.5 respectively with discrete step size of 0.1. The coordination time interval selected for this purpose is 0.3 and the maximum time of operation (To_{max}) after which relay will trip is maintained at 2 seconds. Thus the problem will handle total 40 constraints, 20 each for both $CTI$and To_{max} and the total number of decision variables will be 28, 14 each for TMS and PSM respectively.

5.3.1. Parameters

The set of parameters considered for the water evaporation algorithm are stated below:

1. Population size = 20
2. No of algorithm iterations = 1000
3. No of decision variables = 28

4. $E_{Max} = -0.5$ and $E_{Min} = -3.5$
5. $\theta_{Max} = -20°$ and $\theta_{Min} = -50°$
6. PSM_{min}= 0.5 and PSM_{max}= 2.5

5.3.2. Obtained results

The operating time of both primary and backup relays obtained corresponding to their optimized values of TMS and PSM are mentioned in table 5.7. After applying the water evaporation optimization algorithm with the mentioned parameters and boundaries, the CTI obtained for the different relay pair is stated in table 5.8. The table 5.9 shows the comparison of output for different algorithms used. The fig 5.7 show the overall operating time obtained for all iterations and the relay combination with their operating time and the corresponding CTI is illustrated in fig 5.8.

Table 5.7: Operating time for primary and backup relay as per the optimal relay settings for test system 3

Relay No.	$T_O^{Primary}$ (sec)	T_O^{Backup} (sec)	TMS	PSM
1	0.3731	1.0462	0.1000	2.1
2	0.5720	0.6845	0.3018	0.7
3	1.1262	1.3645	0.4456	1.5
4	0.8421	0.9744	0.4298	0.5
5	2.0000	2.0000	0.4847	2.2
6	1.2306	1.5300	0.6077	0.9
7	1.2648	1.7603	0.6956	0.8
8	0.2346	0.3132	0.1000	1.4
9	0.8909	1.1515	0.4526	0.5
10	1.2765	1.5482	0.4870	1.2
11	0.2393	0.2866	0.1000	0.9
12	0.9000	1.0686	0.4001	1.2
13	2.6585	2.0000	0.6688	0.8
14	2.0000	2.0000	0.9332	1.6

Table 5.8: Coordination time interval corresponding to different primary and backup relay pairs for test system 3

Relay Pairs		Coordination Time Interval (seconds)
Backup Relay	Primary Relay	
6	1	1.1569
1	2	0.4742
7	2	1.1883
2	3	0.4418
3	4	0.5224
4	5	1.0256
5	6	0.7694
14	6	0.7694
5	7	0.7352
13	7	0.7352
7	8	1.5257
9	8	0.9169
10	9	0.6573
11	10	0.9899
12	11	0.8293
13	12	1.1000
14	12	1.1000
8	13	1.3452
1	14	0.9538
9	14	0.8485

Table 5.9: Results obtained using different algorithms for test system 3

Algorithm Used	Operating time (sec)
WEO	14.61
GAMS [28]	17.25
MPSO [28]	17.33

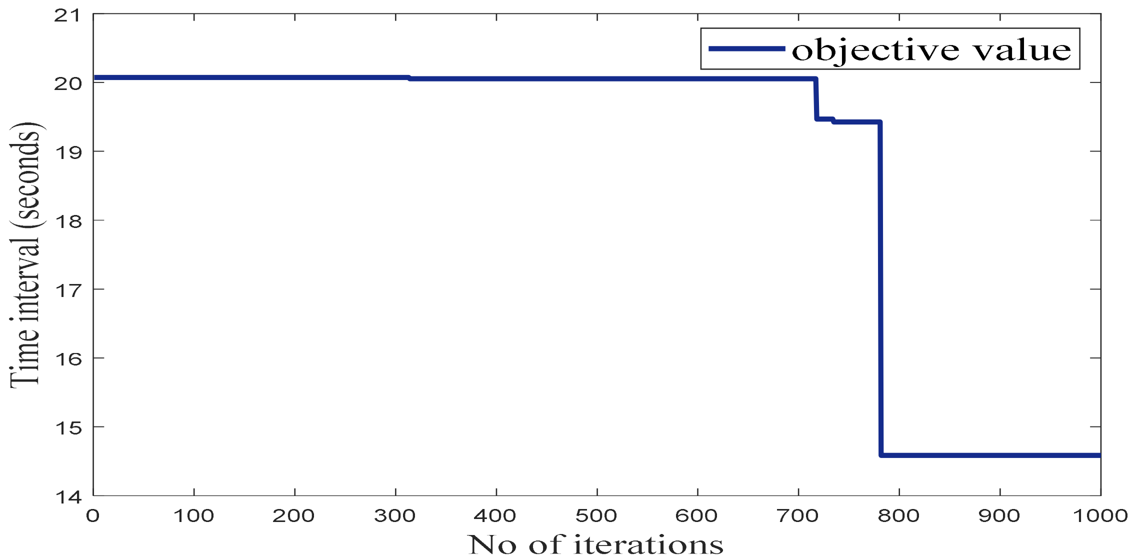

Fig 5.7: Total operating time for each iteration for test system 3

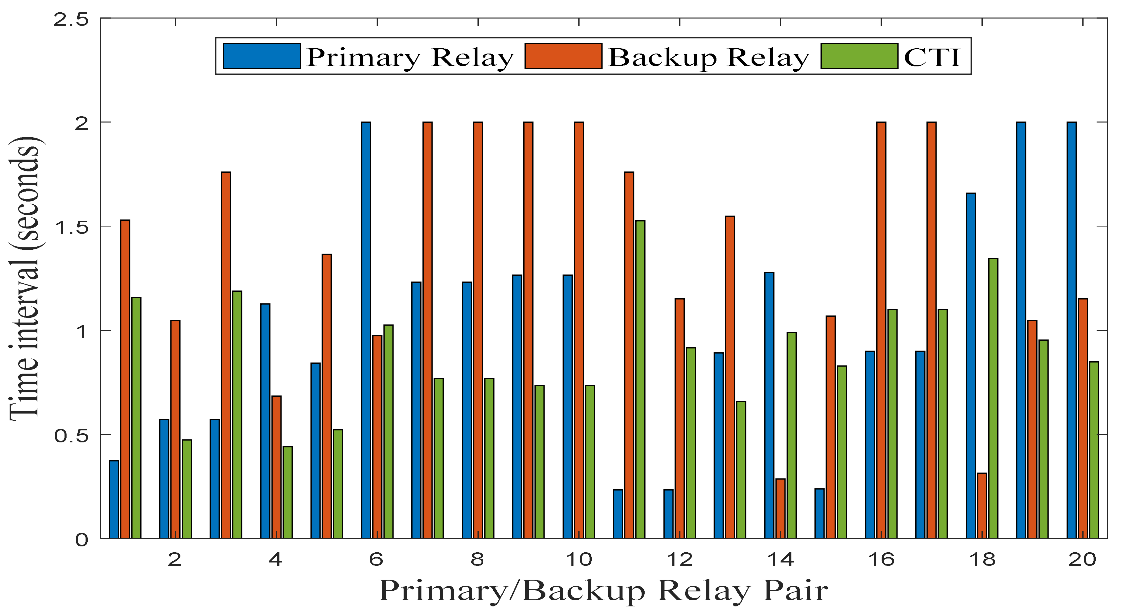

Fig 5.8: Different relay combination and their corresponding CTI for test system 3

5.4. TEST SYSTEM 4

The second system used for testing the discrete coordination problem is the standard IEEE 9 bus system network as illustrated in fig 5.4. With no backup protection at four relays, system comprises of one generating source connected to bus 1, nine buses, twelve lines and twenty four directional overcurrent relays.

The maximum and minimum values of the time multiplier setting are selected as 1 and 0.01 respectively and the higher and lower limit of plug setting multiplier is 0.5 and 2.5 respectively.. The fault currents for all the backup and primary relays and CT ratios are presented in table 5 and table 4 respectively**.** The higher and lower boundary limit for time of operation (To_{max}) after which relay will trip is maintained at 2 seconds and 0.2 seconds respectively. The coordination time interval selected for this purpose is 0.3. Thus the problem will handle total 104 constraints, 36 each for both To_{min} and To_{max}, and 32 for $CTI$and the total number of decision variables will be 48, 24 each for TMS and PSMrespectively.

5.4.1. Parameters

The set of parameters considered for the water evaporation algorithm are stated below:

1. Population size = 20
2. No of algorithm iterations = 1000
3. No of decision variables = 48
4. $E_{Max} = -0.5$ and $E_{Min} = -3.5$
5. $\theta_{Max} = -20°$ and $\theta_{Min} = -50°$
6. PSM_{min}= 0.5 and PSM_{max}= 2.5

5.4.2. Obtained results

The table 5.10 shows the operating time of both primary and backup relays with the optimized values of relay settings, that is, time multiplier setting and plug multiplier setting. The CTI obtained for the different relay pair after applying the water evaporation optimization algorithm with the mentioned parameters and boundaries is mentioned in table 5.12. The table 5.11 shows the results for the same problem using different algorithms. The overall operating time for the each iteration is represented by a curve in fig 5.9. The different relay combination with their operating time and the corresponding CTI is illustrated in fig 5.10.

Table 5.10: Operating time for primary and backup relay as per the optimal relay settings for test system 4

Relay No.	T_O ^{Primary} (sec)	T_O ^{Backup} (sec)	TMS	PSM
1	0.7114	2.0000	0.1633	2.0
2	0.2000	0.5456	0.0100	0.7
3	1.1069	1.7981	0.3921	0.5
4	0.6899	1.5625	0.1656	1.0
5	0.2000	2.0000	0.0100	0.6
6	0.3866	1.5600	0.0955	1.6
7	0.2000	2.0000	0.0100	1.0
8	2.0000	2.0000	0.7786	0.8
9	1.0198	1.6891	0.3499	0.5
10	0.2000	1.0876	0.0100	0.5
11	2.0000	0.2000	0.3841	1.8
12	1.0102	2.0000	0.3578	0.5
13	1.4872	0.2000	0.2919	1.9
14	2.0000	2.0000	0.7620	1.1
15	2.0000	2.0000	0.7395	1.3
16	0.2000	1.1884	0.0100	1.2
17	0.6685	2.0000	0.2576	1.1
18	0.2000	1.5511	0.0100	1.7
19	0.2045	1.5000	0.0613	1.9
20	2.0000	2.0000	0.3825	1.4
21	1.1930	2.0000	0.4042	1.5
22	1.6101	1.9258	0.2149	1.8
23	1.4114	2.0000	0.6202	0.8
24	1.4320	1.6037	0.2960	0.8

Table 5.11.: Results obtained using other algorithm for test system 4

Algorithm Used	Operating time (sec)
WEO	24.1315
GA [15]	32.6058

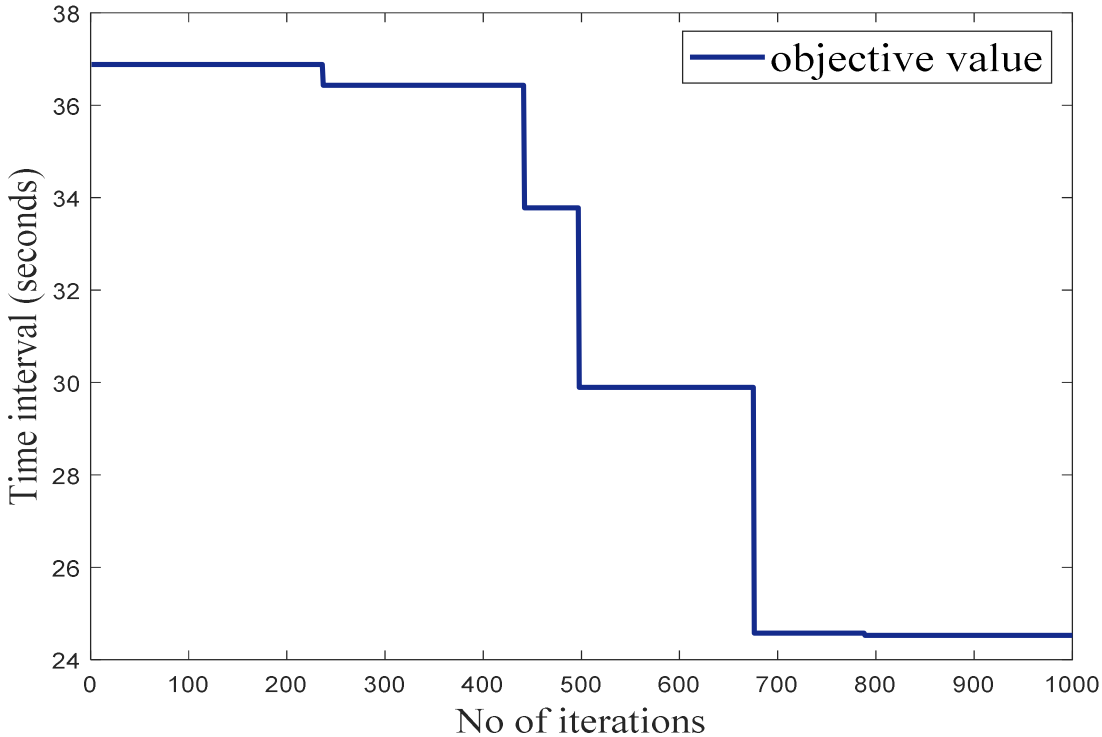

Fig 5.9: Total operating time for each iteration for test system 4

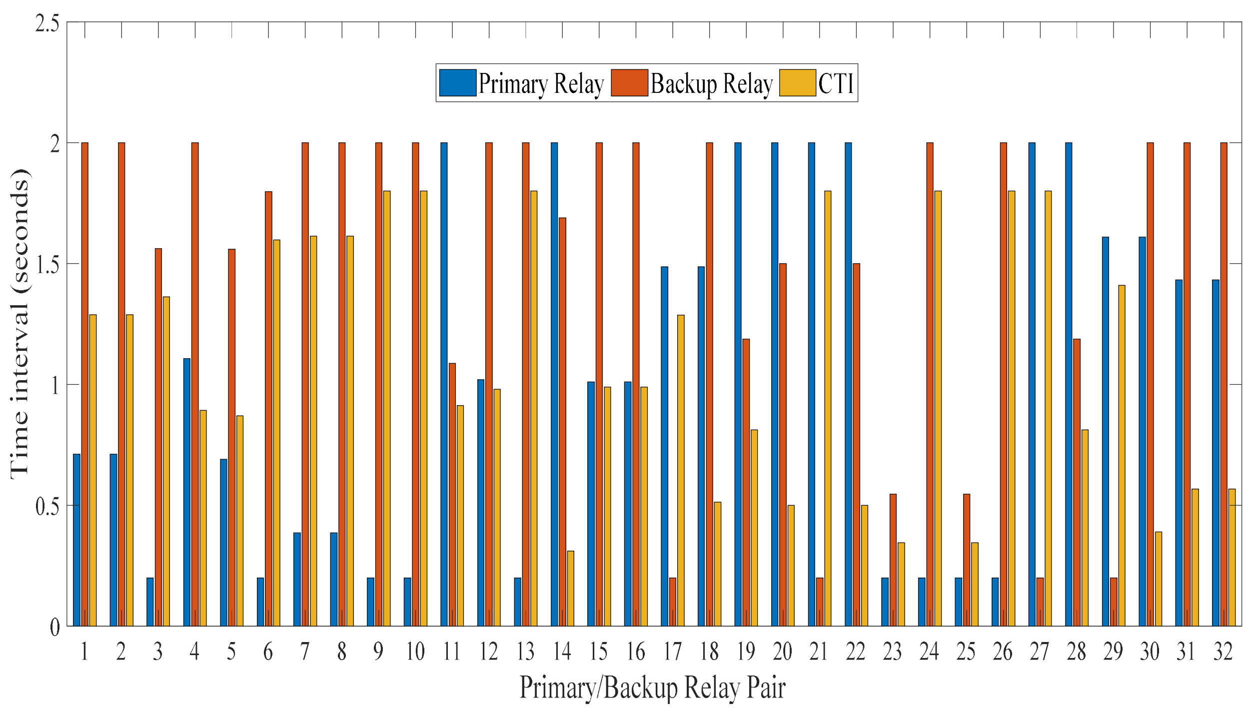

Fig 5.10 : Different relay combination and their corresponding CTI for test system 4

Table 5.12.: Coordination time interval corresponding to different primary and backup relay pairs for test system 4

Relay Pairs		Coordination Time Interval (seconds)
Backup Relay	Primary Relay	
15	1	1.2886
17	1	1.2886
4	2	1.3625
1	3	0.8931
6	4	0.8701
3	5	1.5981
8	6	1.6134
23	6	1.6134
5	7	1.8000
23	7	1.8000
10	8	0.9124
7	9	0.9802
12	10	1.8000
9	11	0.3109
14	12	0.9898
21	12	0.9898
11	13	1.2872
21	13	0.5128
16	14	0.8116
19	14	0.5000
13	15	1.8000
19	15	0.5000
2	16	0.3456
17	16	1.8000
2	18	0.3456
15	18	1.8000
13	20	1.8000
16	20	0.8116
11	22	1.4101
14	22	0.3899
5	24	0.5680
8	24	0.5680

CHAPTER 6

CONCLUSION AND SCOPE FOR FUTURE WORK

6.1. CONCLUSION

Various approaches and metaheuristic algorithm used previously by the researchers, the water evaporation optimization algorithm is being presented in the work and has been validated successfully. The global and local search ability of the algorithm helped to provide a optimized solution for the optimal coordination problem of directional overcurrent relay which is a highly non linear and a highly constrained problem.

In the work presented, the algorithm is implemented by testing on the IEEE 8 bus system and IEEE 9 bus system. The two approaches of optimization are considered: 1) Continuous optimization approach and 2) discrete optimization approach. The problem of minimizing the overall operating time of primary relays is achieved well by using the water evaporation optimization algorithm. The algorithm was tested for different system and give satisfactory results in all cases which show that the proposed method gives better results than the other methods.

6.2. FUTURE SCOPE OF WORK

- The approach used can be implemented to solve constrained and high dimension problem.
- By using other optimization techniques with WEO technique, the performance can be improved further.
- The discrete settings of plug setting multiplier can also be considered for time multiplier settings to obtain further results.

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APPENDIX

Table 1: Relay settings for the test system 1

Relay	CT Ratio	Pickup Current(amperes)	
		Minimum	Maximum
1	1220/5	120	480
2	1200/5	120	480
3	800/5	80	320
4	1200/5	120	480
5	1200/5	120	480
6	1200/5	120	480
7	800/5	80	320
8	1200/5	120	480
9	800/5	80	320
10	1200/5	120	480
11	1200/5	120	480
12	1200/5	120	480
13	1200/5	120	480
14	800/5	80	320

Table 2: Limits for the decision variables for test system 1 and test system 3

CTI	0.3
TMS_{min} (continuous)	0.05
TMS_{min} (discrete)	0.1
TMS_{max}	1.1
PSM_{min}	0.5
PSM_{max}	2.5

Table 3: Fault currents corresponding to their primary/backup relay pair for the test system 1

Primary relay	Backup relay	I_F (primary)	I_F (backup)
1	6	2666.3	2663
2	1	5374.8	804.7
2	7	5374.8	1531.5
3	2	3325.6	3325.6
4	3	2217.1	2217.1
5	4	1334.3	1334.3
6	5	4975	403.6
6	14	4975	1533
7	5	4247.6	403.6
7	13	4247.6	805.5
8	7	4973.2	1531.5
8	9	4973.2	403.2
9	10	1420.9	1420.9
10	11	2313.5	2313.5
11	12	3474.3	3474.3
12	13	5377	805.5
12	14	5377	1533
13	8	2475.7	2475.7
14	1	4246.4	804.7
14	9	4246.4	403.2

Table 4: Relay settings for the test system 2 and 4

Relay	CT Ratio	Pickup Current	
		Minimum	Maximum
1	500	152.15	907.75
2	500	265.95	435.75
3	500	27.15	749.60
4	500	27.15	696.15
5	500	97.85	474.15
6	500	97.85	817.35
7	500	97.85	817.35
8	500	97.85	474.15
9	500	27.15	696.15
10	500	27.15	749.60
11	500	152.15	435.75
12	500	152.15	524.80
13	500	38.05	687.80
14	500	38.05	778.85
15	500	38.05	778.85
16	500	38.05	687.80
17	500	551.65	862.60
18	500	551.65	1302.45
19	500	513.6	842.75
20	500	513.6	1504.55
21	500	551.65	862.60
22	500	551.65	1302.45
23	500	633.15	897
24	500	633.15	954.85

Table 5: Fault currents corresponding to their primary and backup relay for the test system 2 and 4

Primary Relay	Fault Current	Backup Relay	Fault Current
1	4863.6	1	1361.6
2	1634.4	2	653.6
3	2811.4	3	1124.4
4	2610.5	4	1044.2
5	1778	5	711.2
6	4378.5	6	1226
7	4378.5	7	1226
8	1778	8	711.2
9	2610.5	9	1044.2
10	2811.4	10	1124.4
11	1634.4	11	653.6
12	2811.4	12	787.2
13	3684.5	13	1031.7
14	4172.5	14	1168.3
15	4172.5	15	1168.3
16	3684.5	16	1031.7
17	7611.2	17	1293.9
18	2271.7	18	1953.7
19	7435.8	19	1264.1
20	2624.2	20	2256.8
21	7611.2	21	1293.9
22	2271.7	22	1953.7
23	7914.7	23	1345.5
24	1665.5	24	1432.3

Table 6: Limits for the decision variables for test system 2

CTI	0.3
TMS_{min}	0.025
TMS_{max}	1.20
$T_{O\ min}$	0.2
$T_{O\ max}$	2

Table 7: Fault currents corresponding to their primary/backup relay pair for the test system 3

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

Table 8: Limits for the decision variables for test system 4

CTI	0.3
TMS_{min}	0.01
TMS_{max}	1
$T_{O\ min}$, $T_{O\ max}$	0.2,2
PSM_{min}, PSM_{max}	0.5,2.5