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Optimal relay coordination in transmission and distribution system: a critical review

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This paper presents a state of art review of optimal relay coordination in transmission and distribution system. In power system properly coordinated scheme is designed to ensure that the only faulted zone of system will be disconnected when system faces abnormality. As the power system is complex and demand is continuously increasing, the utilities must improve the reliability using properly coordination techniques for relays. Many researchers have taken efforts to cater all techniques used for overcurrent relay coordination. Different methods have been used till date for coordination of distance and overcurrent relay. These techniques include some conventional methods; artificial intelligence (AI) & nature inspire algorithm (NIA) as well as some optimization techniques. Review of application of all these methods for optimum coordination of relays along with critical comments and future scope in this area are systematically presented in this paper.

Keywords: *Directional overcurrent relay (DCOR), Artificial Inteligence(AI), Evolutionary Programming(EP), Nature inspired algorithms(NIA), Distributed Generation(DG), Linear programming(LP.)*

1.0 INTRODUCTION

Power system protection is the heart of electrical power system engineering. It plays very important role is the power system stability and it is designed to continuously monitor the power system to ensure maximum continuity of electrical power supply without damaging equipment. Protective relay is a device which gives instruction to the circuit breaker to disconnect the faulty part of the system. Due to faults, overload, under frequency and overvoltage in power system there is interruption in power supply and which may harm the equipment's connected to the system [1].Due to requirement of power system security, the protective system must be well coordinated with each other. Distance relays and directional overcurrent relays are commonly used to protect transmission and sub-transmission systems [2]. Changes in power system operating conditions can affect both the reach point of distance relay and the coordination of distance and overcurrent relay. The aim of relay coordination in power system is to select suitable setting of relays, so that their fundamental protective function is met under the requirement of sensitivity, selectivity, reliability and speed. Every relay must operate to protect its primary zone, but if it fails to operate, and then only backup protection should come in action and should take over the tripping. If primary and backup protections are not coordinated then maloperation can occur, so relay coordination is major concern of power system engineers. The primary and backup relays must be coordinated together and coordination time interval (CTI) is the criteria to be considered for coordination[3]. This paper presents the review of different effective methodologies for optimal relay coordination. This will provide good starting point and reference to upcoming researchers in this area.

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2.0 OPTIMAL OVER CURRENT RELAY COORDINATION

Over current relay (OCR) is a type of protective relay that operates when load current exceeds to a specific value and sends trip signal to the circuit breaker. Usually they have current setting multiplier of 50% to 200% in steps of 25% which is known as plug setting (PS) [1]. PS depends upon two parameters minimum fault current and the maximum load current. To clear the faults properly in definite time, each protective relay has to be coordinated with other relays located at adjacent buses. This process is very important from stability point of view. Relay coordination is the process of determining sequence of relay operation for each fault location so that fault should be cleared in minimum possible time. For optimal coordination these parameters should fulfil all constrains. Overcurrent relay process for distributed system is as shown in Figure 1

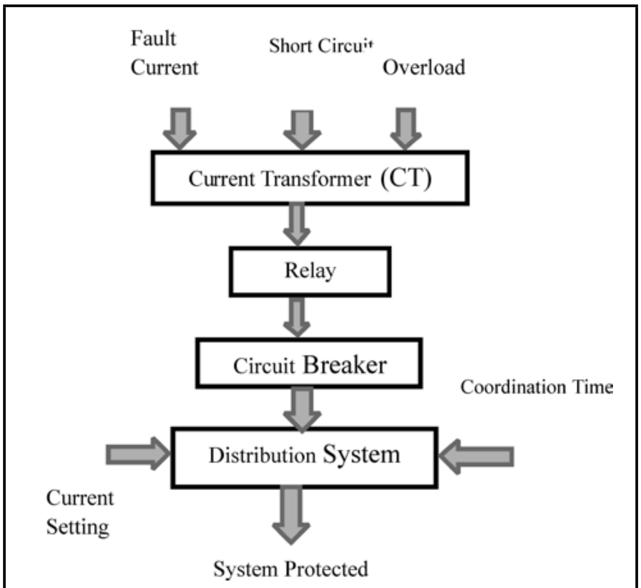

FIG. 1. PROCESS OF OVERCURRENT RELAY[4]

In distribution system, the OCR coordination problem can be can be defined as constrained optimization problem [4]. The objective function in this problem is to determine time setting multiplier (TSM) and plug setting multiplier (PSM) of each relay, so that the overall operating time of primary relays is minimized properly. For optimal coordination these parameters should fulfil all the constraints under the shortest operating time.

2.1 Problem Formulation

Objective function of relay coordination (overcurrent to overcurrent) problem can be given as follows

$$\min z = \sum_{i=1}^{m} W_i . t_{i,k} \qquad ...(1)$$

Where

m is the number of relays,

t_{ik} is the operating time of the relay R_i, for fault at k, and

W_i is weight assigned for operating time of the relay R_i

In distribution system, since the lines are short and are of approximately equal length, equal weight (=1) is assigned for operating times of all the relays [4]

2.1.1 Constraint Set I – Coordination criteria

Fault is sensed by both primary as well as secondary relay simultaneously. To avoid mal-operation, the backup relay should take over the tripping action 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 can be stated as

$$t_{i,k} - t_{j,k} \geq \Delta t \qquad ...(2)$$

where,

$t_{j,k}$ is the operating time of the primary relay R_j, for fault at k $t_{j,k}$ is the operating time of the backup relay R_i , for the same fault (at k) Δt is the coordination time interval (CTI)

2.1.2 *Constraint Set II – Bounds on Relay Operating Time*

Constraint imposed because of restriction on the operating time of relays can be mathematically stated as

$$t_{i,\min} \leq t_{i,k} \leq t_{i,\max} \qquad ...(3)$$

where, $t_{i,min}$ is the minimum operating time of relay at location i for fault at any point in the zone of operation $t_{i,max}$ is the maximum operating time of relay at location *i* for fault at any point in the zone of operation

2.1.3 *Constraint Set III – Bounds on the TMS of Relays*

The bounds on *TMS* of relays can be stated as

$$TMS_{i,\min} \le TMS_i \le TMS_{i,\max} \quad ...(4)$$

where, $TMS_{i,min}$ is the minimum value of *TMS* of relay R_i $TMS_{i,max}$ is the maximum value of *TMS* of relay R_i

2.1.4 *Constraint Set IV – Bounds on the PS of Relays*

The bounds on *PS* of relays can be stated as

$$PS_{i,\min} \le PS_i \le PS_{i,\max} \quad ...(5)$$

where,

$PS_{i,min}$ is the minimum value of *PS* of relay R_i $PS_{i,max}$ is the maximum value of *PS* of relay R_i

2.1.5 Constraint Set V – Relay Characteristics

OCRs can have variety of characteristics as shown in equation (6)

$$t_{op} = \frac{\lambda(TMS)}{(I_{relay}/PS)^{\gamma} - 1} \quad ...(6)$$

where, t_{op} is relay operating time, I_{relay} is the current through the relay operating coil, and *PS* is plug setting.

3.0 DISTANCE RELAY COORDINATION

A failure of primary protection will usually result in operation of back up relay after some time span which is known as coordination time interval (CTI), in order to ensure proper sequence of operation of these relays [5]. In transmission and sub transmission systems directional OCR and distance relays are mainly used for protection. In such systems suitable settings of relays i.e. impedance of zones and related time delays for distance relays, time dial settings (TDS) and the pickup current (Ip) setting for directional overcurrent relays must be calculated correctly such that all relays should properly coordinated with each other. The arrangement of primary and backup relays is shown in Figure 2[2].

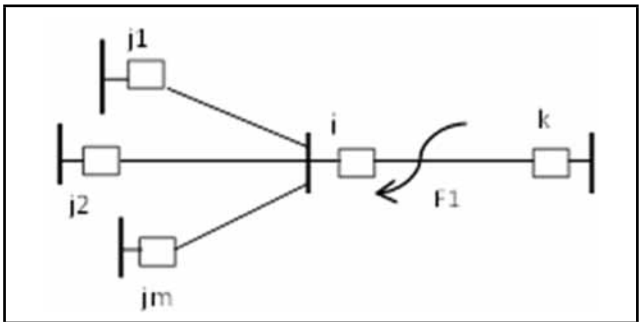

FIG. 2. PRIMARY AND BACKUP RELAYS

Directional overcurrent relays are best suited for local backup of distance relay from economical and technical point of view, but it is very complicated to coordinate these two relays together. So coordination is done in three ways [6].

1. Coordination of OCR with OCR
2. Coordination of distance relays with distance ones
3. Coordination of distance relays with OCR

Optimal coordination is done in such a way that all above cases are satisfied. For third case it is assumed that the distance relay is the main relay and the OCR is back up. So TMS of all OCR and the operating time of the second zone of all distance relays must be determined for critical condition [7].

When fault occurs at F, the discrimination time between the OCR and distance relay is minimum as shown in Figure 3[2] so

$$t_b(F) - t_{z2} > CTI$$

where t_b (F) is operating time of overcurrent relay at B, for fault at F, t_{z2} is operating time of zone two of the distance relay at M for fault at F and CTI is coordination time interval.

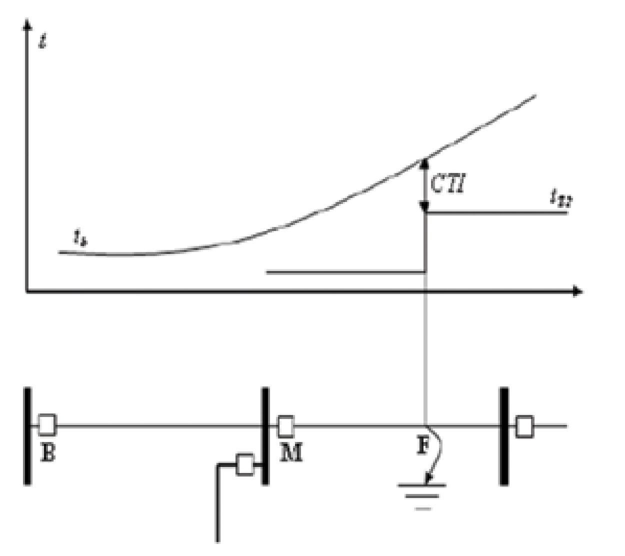

FIG. 3 CRITICAL FAULT LOCATION IN COORDINATION BETWEEN OVERCURRENT AND DISTANCE RELAYS [7]

4.0 METHODS USED TO ACHIEVE OCR COORDINATION

Many researchers are working on relay coordination problem and using different methods. Figure 4 shows the techniques they are using for relay coordination problem.

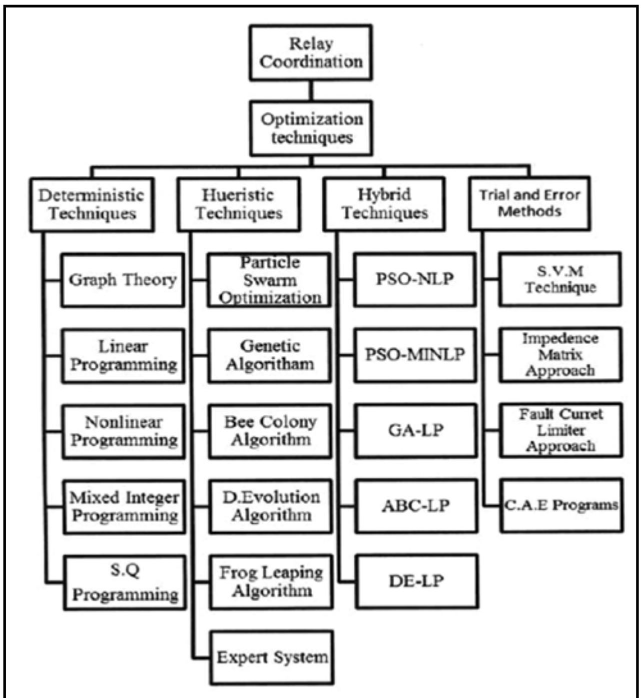

FIG.4. CLASSIFICATION OF RELAY COORDINATION TECHNIQUES [4]

In modern power system OCR is widely used for transmission line protection due to its simplicity and from economical point of view. Several methods have been proposed in past five decades since 1960s for the coordination of overcurrent and distance relays.

The comparison of conventional and advanced optimization techniques is presented in Table1.

TABLE 1
COMPARISON OF CONVENTIONAL AND ADVANCED OPTIMIZATION TECHNIQUES

Property	Advanced	Traditional
Search space	Population of potential solutions	Trajectory by a single point
Motivation	Natural selection and Social adaptation	Mathematical properties (gradient, Hessian)
Applicability	Domain independent, Applicable to variety of Problems	Applicable to a specific problem Domain
Point Transition	Probabilistic	Deterministic
Prerequisites	An objective function to be optimized	Auxiliary knowledge such as gradient vectors
Initial guess	Automatically generated by the algorithm	Provided by user
Flow of control	Mostly parallel	Mostly serial
CPU time	Large	Small
Results	Global optimum more probable	Local optimum, dependent of initial guess
Advantages	Global search, parallel, speed	Convergence proof

These methods can be categorized in to four classes as

4.1 Coventional Methods

i) Trial and Error ii) Topological Analysis . Trial and error approach has low convergence rate and hence required large number of iterations. To minimize the number of iterations required, a technique to break all the loops called breakpoint and locate the starting relays at these points is recommended. Finding the breakpoints is the significant part to initiate the coordination process. Topological methods which include functional and graph theory are used to determine breakpoints. Solution found using these methods are not global optimal. Due to complexity of system and large time consumption these methods became obsolete. The distribution system where more than one source is connected, directional overcurrent relays are more convenient choice.

Birla *et al.* in [8], classified the coordination techniques into three categories, curve fitting technique, graph theoretical technique and optimization techniques. For determining finest function to represent data, curve fitting techniques are used. The relay characteristic is modeled mathematically by polynomial form using curve fitting methods [9, 10]. Other technique is graph theoretical technique which was used in [11].

A linear programming method presented by Luis G. Perez *et al.* [12] , shows that the influence of considering second zone distance relays and breaker failure relay imposed important requirement for the determination of time dial setting of directional overcurrent relays. The application of linear programming techniques for the time coordination of directional overcurrent relays considering definite time backup relaying proved to be a very useful tool for detecting and solving specific problems in realistic power systems with combined protection schemes. A method to automatically determine the optimum timing for the second zone of distance relays in mixed scheme with directional overcurrent relays has been proposed by Luis G. Perez *et al.* [13]. It has been shown that when the line protection schemes are composed of distance relays and directional overcurrent relays the settings of the relays must be computed considering both relays. Separate relay computations would lead to loss of selectivity. Trial and error approach was used but it has low convergence rate and number of iterations are more. A nonstandard tripping characteristic for over current relays and its advanced method for optimized coordination were presented by Timo Keil *et al.* [14]. The characteristic is based on the logarithmic function of and the optimization task has been solved using method of Lagrange generalized with the Karush-Kuhn-Tucker conditions. These results in noticeable reduction of the maximum and effective average tripping times in relation to the conventional definite time overcurrent (DTOC) & inverse definite minimum time (IDMT) grading. Birla *et al.* [15] considered that weight factor and far end faults in the directional overcorrect relay coordination problem formulation do not affect the optimal solution. The use of fault current limiter (FCL) is proposed in [16] to limit the effect of distributed generation (DG) on the coordinated relay protection scheme in a radial system during a fault. Result shows that a novel hybrid electrical / mechanical fault current limiter is able to reduce the impact of DG on the existing coordinated relay protection. Additionally it is shown that the FCL can maintain the stability and reduce stresses on DG during a ground fault. The presence of DG units in distribution systems affects system protection. This problem is solved by Aslinezhad *et al.* in [17, 18]. The FCL makes no change on system operation in normal condition and limits DG current at faulty conditions. In this method the effect of DG on CTI is compensated by changing the amount of FCL.

The pre-processing reduction constrains a method introduced in [19], by reducing number of constrains, the feasibility of the optimization is increase and run time of program is decreased. The obtained result from 8-bus showed that number of constraints are reduced by 60% which results into reduction of system processing time and required memory.

To improve the performance of protective system, an adaptive scheme of relay setting is proposed by E. Orduna [20]. A combined algorithmic-knowledge-based mythology is used. Hossein Askrian Abyaneh *et al.* [21] proposed a new method based on only constraints. Minimization is inherently included by setting the time dials to minimum and increasing their values gradually. This method does not need any initial solution. It can consider both linear and nonlinear relay characteristics model. Proposed method proves to be superior to previous technique as it has fast convergence due to smaller matrix dimensions.

An efficient method for optimal relay coordination is proposed by Mansour Ojaghi *et al.* in [22]. They proposed full adaptive technique for setting all overcurrent relays in HV substation. This technique can be used online and there is no need of telecommunication infrastructure. Using this method, the problems in the operation of the OC relays due to change in the topology of the grid is totally solved.

The effect of superconducting fault current limiter (SFCL) on the optimal sizing of a wind turbine generator system (WTGS) has been analyzed in [23], when the WTGS is connected to a radial distribution system, the level of fault current during contingency is increased which can reduce coordination time interval (CTI) between multiple overcurrent relays.

In [24] the time setting is performed using probabilistic faults trees with time dependencies (PFTTD). PFTTD is built for the hazards like remote circuit breaker tripping, provided local circuit breaker can be opened. PFTTD are used in selection of time delays of primary (local) and backup (remote) protections. The outcomes presented in the paper related to protection scheme based only on distance relays, where neither local backup protection nor breaker failure logic is taken into account.

B. Ravikumar *et al.*[25] aims at evaluating the methods of multiclass support vector machines (SVMs) for effective use in distance relay coordination. In this paper one step multiclass classification, one against all and all against one multiclass methods are compared for their performance with respect to accuracy, number of iterations, number of support vectors, training and testing time. The results show that the one-step multiclass SVM classification approach has the potential to discriminate the zones based on the apparent impedance characteristics observed for various operating conditions of the practical Indian Western grid system. It takes less time to classify all the testing data. Transmission system distance relaying coordination using detailed simulation studies of the apparent impedance loci as seen from the relaying location considering various operating conditions including fault resistance was presented by B. Ravikumar *et al.* [26]. The results demonstrate that the SVM have the potential to obtain a reliable transmission line distance protection. An approach using support vector machines for distance relay coordination in transmission systems is proposed by B. Ravikumar [27]. The scheme utilises the apparent impedance values observed during fault as inputs. The results demonstrate that the SVMs have the potential to obtain a reliable transmission line distance protection.

4.2 Optimization Method

The solution obtained from conventional coordination techniques are very far away from the global optimal solution. Optimization techniques generally overcome the conventional approach in which relays are arranged in a sequence before coordination [28] and due to this major advantage, it becomes popular among researchers. Urdaneta *et al.* were the first to describe the application of optimization theory in coordination of directional overcurrent relay [29]. They calculated value of TSM using linear programming model and simplex method for a given values of pickup current Ip. In distribution system the overcurrent relays are the major protection devices used. The relays in the power system must be coordinated properly for providing proper primary as well as back up protection, and at the same time mal-operation should be avoided and hence avoid the unnecessary disconnection of healthy part of the power system. The overcurrent relay coordination in ring fed distribution networks is a highly constrained optimization problem. As the pickup currents of the relays are predetermined from the system requirements, the optimization can be formulated as linear program problem. Naghobi *et al.* [30] proposed a new approach based on the interval analysis to solve the DOCR coordination problem considering uncertainty in network topology. The basic idea is to convert the set of inequality constraints corresponding to each relay pair to an interval constraint. Hence the relay coordination problem is formulated as an interval linear programming (ILP) problem. Result shows that number of coordination constraints significantly reduced, and DOCR problem becomes robust against uncertainty. P. P. Bedekar *et al.* [31] presented the simplex method for optimum time coordination of directional overcurrent relays. In this paper author applied the simplex algorithm to the dual of problem. It reduces number of iterations and memory required. A comparison with other variants of the simplex algorithm and the genetic algorithm is also presented. Result shows that proposed method is applicable for finding the optimum coordination even when a variety of OCR is present in the system.

The coordination of DOCR poses serious problems in the modern complex power system network. Ralhan *et al.* [32] formulated coordination of DOCR using Linear programming two phase simplex methods and intervals. Here objective function is defined as sum of time dial setting of all the relays. By this technique the size of optimization problem is greatly reduced. The optimal values of the operating time of the relays are bounded as well as objective function is also bounded. Dual simplex technique Bedekar *et al* [33] is used for optimum coordination of OC relays in a ring fed distribution system. A brief comparison with two phase simplex method is also given. From the result it is concluded that the method gives satisfactory results even for multi loop system. There are new challenges in coordination of protective relays in microgrids, due to variation of fault current levels, bidirectional fault current and changing of microgrid operation modes.

Bedekar *et al* presented big-M (penalty) method for optimum time coordination of overcurrent relays [34] which is based on the simplex algorithm. This method is used to find optimum solution of linear programming problem. The method introduces artificial variables in the objective function to get an initial basic feasible solution. It shows that depending upon the system requirements and breaker and relay specifications the constraints can be formed and the optimum coordination can be obtained. The number of iteration to be performed is less than that of simplex method.

Ahmad Razani Haron[35] presented a new protection strategy with systematic coordination approach using combination of three different types of relays namely overcurrent, directional and differential relays. Result shows that by combining OC, DOC and DIF relays, it is possible to successfully protect the micro grid with topology changes.

Electrical engineering power coordination problem has been solved by K. Deep *et al.* [36] by modeling it as constrained nonlinear optimization problem. The results obtained by RST algorithm are compared with that of MATLAB toolbox, and it is found that results of RST are superior to MATLAB.

A new approach for planning the overcurrent relay coordination has been proposed by Ekta Purwar *et al* [37]. The proposed method is capable of mitigating the problem of miscoordination of relays due to the anticipated proliferation in DG's size at a given bus. The results produced demonstrate that the relay settings obtained by proposed method remains unchanged and properly coordinated even if DG size is changed within the specified upper limit. Thus the proposed method adapts the future changes in DG's size. Big-M method for determination of optimum values of TMS and PS of OCRs is presented by P. P. Bedekar *et al* [38]. The problem is formulated as an NLPP. As Big-M method is a method of solving LPP, the constrained NLPP is converted into a constrained LPP by selecting a set of PS of OCRs at a time. The method introduces artificial variables in the objective function to get an initial basic feasible solution (IBFS). Artificial variables are removed using iterative process which also leads to an optimum solution. The program was tested for various systems, and was found to give satisfactory results in all the cases. P. P. Bedekar *et al* [39] formulated problem of determining the optimum values of TMS and PS of OCRs is as a constrained nonlinear optimization problem and nonlinear programming (NLP) method is used for determination of optimum values of TMS and PS of OCRs. The algorithm gives satisfactory results in all the cases.

4.3 Artificial elligence Method

Since relay coordination is backbone of transmission line protection, it is extensively studied by many researchers. But due to some major drawbacks of conventional and optimization relay coordination methods such as convergence time, dependability on initial guess , types of constraints, type of system and optimal global solution etc., the artificial intelligence based optimization methods are applied to solve relay coordination problems. They are classified as follows.

4.3.1 Genetic Algorithms

Some researchers used genetic algorithm (GA) based approaches to analyze this problem. The OC relay coordination in ring fed distribution networks is a highly constrained optimization problem. The purpose is to find an optimum relay setting to minimize the time of operation of relays and at the same time, to avoid the miscoordination of relays. GA technique is used for optimum coordination of OC relays in a ring fed distribution system [40]. Constraints are incorporated in the fitness function making use of the penalty method. Shayestch *et al*. [41] presented a powerful optimal coordination method based on GA. In this paper new computer program for distance and overcurrent relay coordination based on GA has been developed. In the proposed method the objective function has been modified by adding a new term which presents the constraint for distance and overcurrent relay coordination. The obtained result shows that the new method is successful and accurate. Various relay characteristics have been considered for each OCR relay and the best of them have been selected by GA to make optimal coordination easier. It has been shown that the proposed method is successful and efficient. Bedekar *et al*. [42] introduced continuous genetic algorithm (CGA) technique for optimum coordination of a ring fed distribution system. Constraints are incorporated in the fitness function making use of penalty function. This method is found to be faster than GA and advantage of requiring less storage space than binary GA. Hybrid genetic algorithm (GA) and nonlinear programming (NLP) approach was presented by Bedekar *et al.* [43] for determination of optimal values of TMS and PS of OCRs. GA has been applied to find the initial solution of this problem, which was then used by NLP method to find global optimal solution. Thus the proposed method makes use of advantages of both methods and at the same time overcomes the drawbacks of these methods.

Reza Mohammadi *et al.* [44] presented an efficient method for optimal relay coordination in interconnected power systems based on Genetic Algorithm (GA). In the proposed method objective function is developed to solve the problem of miscoordination for six pair's short circuit fault currents. Redundant term is removed so objective function becomes more optimal. Result shows that the proposed technique is more optimal, flexible, efficient and successful.

DOCR coordination problem is always studied based on a fixed network topology and formulated as optimization problem, but system topology may vary which is function of transmission line outage, transformer and generating units. This problem is addressed and solved by Abbas Saberi Naghabi in [45] using hybrid GA. The proposed method has added advantage of improved computational efficiency. The main contribution of this research work is introducing concept of robust coordination.

Adaptive coordination scheme is applied by Margo Pujiantara [46] *et al* to create optimal protection coordination with different coordination in each radial distribution system configuration. Genetic algorithm is used to calculate values of TMS & PS. Simulation results demonstrates that values of TMS & Ps are lower than conventional methods and it also maintain coordination in them.

4.3.2 Particle Swarm Optimization

Bashir *et al.* come out with a better solution compared to GA and EP method as reported in [47]. Vijaykumar *et al.*[48] presented a Modified Particle Swarm Optimization method for DOCR coordination. Author presented NLP problem approach for Ip calculation which results in I_p value rounded to nearest values of discrete available I_p setting values. With I_p value fixed LP approach is used to solve TDS setting of coordination problem. The proposed MPSO technique shows that it is suitable for Linear as well as Nonlinear programming problem.

To determine the abilities and limitations of different algorithms used for relay coordination problem a comprehensive comparison is done by Hosseinian *et al.* [49]. Different algorithms include Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and Immune Genetic Algorithm (IGA). The results show that GA has best convergence speed and PSO is most reliable in convergence.

Mansour *et al.* [50] proposed Particle Swarm Optimization (PSO) for the coordination of DOCR. This optimizer uses the swarm behaviour searching for in searching for an optimum. DOCR is highly constrained optimization problem which is solved here as a linear programming (LP) problem. For dealing such constraints standard PSO is modified. Here author presented three case studies, and the results are compared to those of LP technique to demonstrate the effectiveness of the proposed method.

Moravej *et al.*[6] presented modified adaptive particle swarm optimization (MAPSO) method for optimal coordination between distance relays and directional overcurrent relays in series compensated systems. It is concluded that with the use of MAPSO method the fault current level reduces in compensated system than in uncompensated systems.

Magdi El- Saadawi *et al.* [51] proposed adaptive optimal relay coordination scheme for distributed generation. This adaptive methodology to determine optimal relay setting uses modified PSO technique in distribution system with DGs. Result shows that proposed methodology succeed to converge to the optimal setting found by conventional methods. As any change occurs in the system, the program is applied to redesign the optimal time delay for every relay pair in every faulted bus in the system.

A new method named LP-PSO has been suggested by A. Akbar Motie Birjandi *et al.* [52] for optimal OCR and distance relay coordination. This model is combination of Linear programming (LP) and Particle Swarm Optimization (PSO). In the proposed method number of constraints can be added to coordination problem as search space reduces. All discrimination time values between main and backup overcurrent relays are positive and have no miscoordination. Mixed PSO is compared with GA method, and it is found that mixed PSO succeeded in finding optimal solution than GA.

Asadi *et al.*[53] convinced that PSO can handle miscoordination problems much better for both continuous and discrete TSM and PSM rather than EP and GA.

Particle Swarm Optimization algorithm efficiency has been investigated for overcurrent relay coordination problem. The obtained optimum values of PS and TMS come to confirm that this useful optimization technique carefully implemented in MATLAB software is feasible for overcurrent relays protection coordination in radial networks. However, Mostafa Kheshti *et al* [54] found that the calculation time of PSO algorithm is a big issue especially in very large scale networks.

4.4 Evolutionary methods

Other optimization technique which is reliable to solve the optimization problem is Evolutionary programming (EP). EP application in protection system was first introduced by So *et al.* [55], but it has two problems; miscoordination between relays and discrete TSM changed to continuous. PSO has been recently adopted by a lot of researcher due to its superiority to other evolutionary algorithms (EA) regarding its memory and computational time requirement as it relies on very simple mathematical operations and also it requires very few lines of computer code to implement. Modified differential evolution algorithms were presented by Radha Thanaraj *et al*[56]. Five improved versions viz MDE1, MDE2, MDE3, MDE4 and MDE5 are suggested and used to solve the IEEE 3-buns, IEEE 4-bus and IEEE 6-bus problem. The study shows that the MDE scheme requires only one control parameter where as other techniques have more than one parameters. The author concludes that MDE4 and MDE5 schemes are more effective.

Distributed generation can bring many benefits in economical, technological, and environmental but it affects coordination of protective relays. The optimal coordination problem of protective relays in distribution system with distributed generations is formulated as an MINLP problem [57] by Hui Yang *et al.* and solved by differential evolution algorithm. It is found that the method is efficient and feasible. Comparison of all these AI based optimization methods is given in Table 2.

TABLE 2

COMPARISON OF AI BASED TECHNIQUES

Sr. No.	Meth-od	Stan-dard Param-eters	Pros and Cons	
			Pros	Cons
1	EP	popula-tion size, number of genera-tions	As a power-ful and gen-eral global optimization tool con-ventionally very simple. works on real value coded strings.	- more research needed in the mathematical foundation for the EP or its variants with regard to experimental and empirical research - more parameter tun-ing is required. -require more compu-tational time in most cases. - heavily involved programming skills are required to develop and modify competing algorithms to suit different classes of optimization prob-lems.
2	GA	cross-over prob-ability, muta-tion prob-ability, popula-tion size	GAs can provide a globally op-timal solu-tion. - GAs use probabilistic transition rules, -GAs can handle the Integer or discrete variables. - GAs can be eas-ily coded to work on parallel computers.	- are stochastic algo-rithms and solution is not guaranteed to be optimum. -The execution time and the quality of the solution, deteriorate with the increase of the chromosome length, i.e problem size. If the size of the power system is increasing, the GA approach can produce more in fea-sible off springs which may lead to wastage of computational efforts.
3	PSO	swarm size, cogni-tive pa-rameter, social param-eter	Robust, sim-ple , easy implementa-tion, - fast convergence speed, can handle mis-coordination problem - suitable for linear as well as nonlinear problem -flexible enough to allow hy-bridization and integra-tion with any other method	-Large computational time is required for large scale network

4.5 Nature Inspired Algorithms

Ghaffarzadeh *et al.*[58] proposed a new optimization black hole algorithm for optimal coordination of digital overcurrent relays in a standard 33-bus radial system. It is found that the Black Hole (BH) algorithm is faster and more accurate than (PSO) algorithm.

A novel approach of Artificial Bees Colony (ABC) algorithm [59] in solving DOCR coordination problem is presented by M. H. Hussain *et al.* The effectiveness of ABC was demonstrated and tested on 8 bus test system. Results imply that the proposed ABC technique gives best results to solve DOCRs coordination problem and to avoid misscoordination in relay operation compared to PSO.

A new era of decentralized control and efficiency demands has led to an environment demanding efficiency and reliability that pushes some legacy methods to their limits.

An adaptive multiagent approach to protection relay coordination with DG is proposed by Hui Wan *et al.* [60]. The validity of proposed method is demonstrated by applying it to an agent based JADE platform. This method has ability to self-check and self-correct. Biogeography based optimization (BBO) algorithms for optimal coordination of DOCRs is suggested by Fadhel A. Albasri *et al.*[61] and the performance of ten types of constraint –handling techniques is evaluated. In addition a new hybrid BBO with Linear Programming (BBO-LP) is proposed to enhance the performance of the1conventional BBO algorithm. The result shows the effectiveness of the proposed algorithm as compared to various EAs such as Seeker, PSO, MPSO, MDE, TLBO, GA, GA-LP, and GA-NLP algorithms.

Barzegari *et al*. used Harmony Search Algorithm [62] which gives better solution compared to GA and LP method while Rashtchi *et al*. proposed Honey Bee Algorithm [63] which results in less TSM. One year later, uthisunthorn *et al*. showed that, Artificial Bees Colony (ABC) can converge towards better solution slightly faster than PSO [64]. Davood Solati *et al* [65] presented OCR coordination in interconnected network using accurate analytical method and based on determination of fault critical point. This method quickly modifies the impedance matrix of the network using the analytical approach. The accurate setting of primary and backup relays has been determined by solving the optimization problem. Simulation results show that compared to other methods proposed method results in accurate settings.

A new time-current-voltage tripping characteristics proposed by Khaled A. Saleh *et al*.[66] for optimal coordination of DOCR. Here protection coordination problem is formulated as a constrained nonlinear programming problem to determine the optimal relay settings. The result shows that the utilization of the proposed time-current-voltage characteristics for each DOCR in a meshed distribution network can achieve a significant reduction in the total relay operating time in the absence and presence of synchronous based and inverter based DG.

Debashree Saha *et al* [67] presented an efficient optimization technique called TLBO. It is used for determination of optimum values of time dial settings and pickup current settings of DOCRs. Results represent notable reduction in total relays' operating time and coordination time interval (CTI) in comparison with other techniques. Optimum protection coordination is tested in WSCC 9-bus system and it is found that all the TDS and Ip settings are within the range.

The numbers of methods have been used by researchers to solve relay coordination problem and they have shown the effectiveness as well as limitations of different methods. To summarize this it has been presented in tabular form as shown in table 3.

TABLE 3
REVIEW OF OPTIMAL RELAY COORDINATION AT A GLANCE.

Sr. No.	Refer-ences	Major Findings
1	8,12,13, 14,15	Trial and error approach, the pre-processing reduction constraints and Karush-Kuhn-Tucker conditions were used and it is found that it has low convergence rate and number of iterations are more, there is noticeable reduction of the maximum and effective average tripping times in relation to the conventional DTOC and IDMT grading and the feasibility of the optimization is increase, run time of program is decreased and fast convergence due to smaller matrix dimensions.

2	16-18	Use of fault current limiter (FCL) is proposed to limit the effect of distributed generation (DG) on the coordinated relay protection scheme. This hybrid electrical / mechanical fault current limiter is able to reduce the impact of DG on the existing coordinated relay protection.
3	19-27	Use of pre-processing reduction constraints, SVM and some adaptive methods. The result shows that as number of constraints reduces processing time and memory reduces. SVM have potential to obtain a reliable transmission line distance protection.
4	28-39	Use of optimization methods such as Linear Programming, simplex method for optimal relay coordination. These techniques reduce no. of iterations and memory required. The operating time of the relays are bounded as well as objective function is also bounded.
5	9,10,11	Use of curve fitting methods and graph theory. But these methods are time consuming and solution is not global optimal.
6	40-46	Use of Genetic algorithm, Continuous genetic algorithm, and hybrid GA-NLP. The result is accurate and fast and it improves computational efficiency.
7	47-54	Use of Particle swarm optimization and modified adaptive particle swarm optimization. It is suitable for Linear as well as Nonlinear programming problem and more reliable in convergence. PSO can handle miscoordination problems much better for both continuous and discrete TSM and PSM rather than EP and GA
8	55-57	Use of evolutionary programming and differential evolution algorithm. Memory and computational time require is less, as it relies on very simple mathematical operations and also it requires very few lines of computer code to implement. It gives feasible and efficient solution.
9	58-67	Use of other nature inspired methods like ANN, ABC, Black hole, Honey Bee algorithms etc. These methods leads to better solution compared to GA and LP method as well can converge to better solution slightly faster than PSO.

5.0 CRITICAL COMMENTS

1] Though the optimal OCR coordination algorithms are fast and robust, they are very difficult to use practically, because practical power system consists combination of numerical relays and electromagnetic relays.

2] Most of the researchers have considered the system having only one generating source, but practically there may be n number of sources connected to the system.

3] All evolutionary and swarm intelligence based algorithms require proper tuning of algorithm specific parameter in addition to controlling parameter.

4] Improper tuning of algorithm specific parameters gives local optimal solution or increases computational efforts, so efforts should be done to eliminate algorithm specific parameters.

5] Result of some of the algorithms are based on initial guess of variables if the initial guess is not proper there are chances of getting local optimum solution instead of global.

6] The connection of DG increases the maximum fault current of relays so it may affect the current coordinated range.

7] Proper selection of random variables in ABC, Jaya algorithms and selection of social variables in PSO algorisms i..e algorism specific variable selection is a big issue from optimum solution point of view.

6.0 FUTURE SCOPE

1] Future work may be carries out to improve the overcurrent relay coordination in presence of the smart grid.

2] Relay coordination in micro grid implementation imposes many challenges; those should be addressed in future.

3] Aggressive simulations of different test systems are still needed to verify the effectiveness of protection scheme and coordination algorithm.

4] Relay coordination in series compensated transmission line is big issue as it affects the selectivity and original coordination of relays. Very few researchers have worked on this, so remarkable efforts should be taken to solve this issue.

7.0 SUGGESTED MODIFICATION IN COMPUTATIONAL INTELLIGENCE TECHNIQUES FOR OCR COORDINATION

All the papers discussed above, have used different techniques for relay coordination. Some of them are GA, PSO, Modified PSO, hybrid GA-PSO. Short circuit current may vary due to penetration of DG in system. To avoid this adaptive online method for setting may be employed which can adjust the necessary settings on the relays that are appropriate for the current topology of the grid.

8.0 CONCLUSIONS

A detail and systematic review on overcurrent and distance relay coordination techniques is presented in this paper and the same is summarized in Table 3. Many researchers have presented and implemented different techniques for the past five decades. It is observed that the proper selection of primary and backup protection and maintain a small time delay between primary and backup relays operation reduces the mal-operation of relays. Conventional, optimization, hybrid, AI, NIA based and trial and error methods are used to solve the relay coordination problem. Critical comments based on the review and future scope in the area of relay coordination has been presented in this paper. The trial and error method predicts a solution for given problem and check the results if it does not work then it look for another possible solution and so on. For large complicated practical systems this method is slow and very time consuming and less optimal also. Therefore, many researchers approached to optimization methods to solve the relay coordination problem. Deterministic methods have a problem of high dimensionality. Large computational time and memory is necessary to solve the relay coordination problem by such techniques. Therefore, different heuristic approaches have been introduced to solve relay coordination problem solution and to reduce the computational time and the search space but the solution obtained from these techniques is far away from the global optimal solution. AI based techniques have been developed to obtain a global optimal solution in a reasonable computational time, and most widely used in relay coordination. These techniques results in optimal solutions. To meet the present day requirements, optimization methods based on AI and NIA seems too reliable and fast.

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