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ORIGINAL PAPER

# Various Metaheuristic-Based Algorithms for Optimal Relay Coordination: Review and Prospective

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**Abstract**
The coordinated or selective power system can be considered as a sequence procedure among two protective devices installed in series and having certain features. The coordination of protective devices in protection system is a very substantial procedure to guarantee a strength and reliable power system. Directional overcurrent relays coordination is considered as an optimization problem. Due to the difficulties that face this problem especially in multi-loop networks; it is a complicated challenge taking into account the problem constraints. An overview of various metaheuristic-based optimization methodologies is presented to get a proper solution for the coordination problem between each relay pairs to guarantee satisfactory relay settings. In addition, offering various methods of relay coordination, a comparison between earlier works is also performed. It's expected that this study will be helpful for researchers interested in this field.

## 1 Introduction

In an electric power system, protection is used widely in all various voltage levels. An overcurrent relay is frequently implemented due to its effective cost. Several abnormal conditions (faults, overload, overvoltage, etc.) may arise. These faults will make worthy changes in system quantities, which can be considered as an indication for acceptable or unacceptable system conditions. consequently, it is important to implement a robust protection system to separate only the faulty section or to disconnect the least possible part of the network without affecting the healthy part of the system. Without system protection, the power system itself which is planned to be of an advantage, would itself become a danger. When fault is up, a protective relay close to fault which is called a primary relay should operate as quick as possible and the corresponding circuit breaker takes an order to disconnect the faulted part. The backup relay should work after a certain duration named coordination time interval (CTI) only if its corresponding main relay fails to operate.

There are two forms of faults which can be classified as temporary or permanent outages. A temporary fault is considered to be a fault continuing from one second to one minute. After that, it is considered as a permanent fault. Any abnormal condition less than 1 s is a power quality problem.

The five basic requirements that must be fulfilled in a proper protection application are reliability, selectivity, speed of operation, simplicity and economics. So, the protective designers should consider these requirements as constraints for optimizing the protection system. As the fault current may circle in or out of the protective relays. So DOCRs must be used. DOCR is considered one of the popular protective devices used for transmission, sub-transmission and distribution systems. The main difficulty in completing the optimal coordination appears in multi loop power system while each relay is involved in more than one loop [1].

The objective of DOCRs coordination is to get the proper settings and characteristics of each protective relay. This leads to reduce the damage of equipment and interrupt the fault as rapidly as possible enhancing the operation time of DOCRs. To perform a good setting for a relay, it is a must to know each relay pairs in the network. DOCR has two main variables to be well-defined in coordination problem: Time dial (TD) and current setting multiplier (CSM) ranging from 50 to 200% in step of 25% which is selected by determining both the highest value for the load current and the least current fault [2]. Each relay pairs (Primary and back up relays) (P/b) must be coordinated for each possible fault location to fulfil the CTI which can be assumed to be 0.2 s [3].

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## 2 Various Methods of Relay Coordination

Relay coordination is considered an optimization problem solved by optimization techniques which can be classified as under: -

**2.1** Traditional techniques.
**2.2** Heuristic techniques.
**2.3** Hybrid techniques.

Work performed for DOCR coordination by the mentioned methods is proposed in the following sections.

### 2.1 Traditional (Conventional) Methods

Efforts have been done in the last decades to find the optimal settings for DOCRs. Pre-determining the fault study, system emergencies and the abnormal conditions is the concept of conventional methodologies. Trial and error technique has been used manually which produced low accuracy especially when applied to large and complex networks. The researchers used a computer with graphical user interface to solve the coordination problems in such complicated networks. Computer Aided Protection Engineering (CAPE) has been used in [4, 5] to provide easy implementation of the network, feeder relays and different types of faults are easy applied. Authors in [5–8] introduced Evolutionary algorithm and linear programming e.g. simplex, and dual simplex methods.

Overcurrent relay characteristics have been represented with the aid of Computer using curve fitting technique in [9, 10] at which the relay characteristics has been modeled to find the TD of the relay for selected values of currents. The authors in [11] introduced a new parallel processing algorithm based on linear programming to get the (TD) of (DOCR) and get the solution of the coordination problem. A comparison has been done with the other conventional linear programming techniques.

Since the coordination problem has multi-optimum points, evolutionary programming technique has been introduced in [12]. This technique provides an accurate relay grading which is able to check for appropriate coordination for all system constraints and configurations. The purpose in [13] is to optimize discrete values of pickup current, operation time curves of relays and discrete values of time multiplier using linear construction of the coordination problem. A comparison has been introduced among this technique performance with both linear and non-linear software design. A simplex algorithm has been used with aid of linear programming in [14] to provide a solution for the coordination problem after taking the duality of the optimization problem into consideration.

In ref [7], the dynamic changes of the network are considered for optimal relay coordination using linear programming. A methodology of considering instantaneous units and definite time backup relays effect has been introduced in the coordination of DOCR using linear programming [15]. Authors in [16] made some modifications in the coordination problem to find the best values of relay settings. The coordination problem has been presented as a constrained quadratic software design model by applying a graphical theory rule.

On other hand, a nonlinear random search algorithm has been performed in [17] to get the proper solution of the coordination problem. An acceptable speed of the main protection has been achieved by This method while trying to achieve the maximum relay pairs coordination. In ref [18], the optimal solution of coordination problem of DOCRs has been carried out using interior point linear programming considering definite time back up relays. The results of presolving study decrease the complexity and size of the linear programming problem.

An analytical method has been proposed in [19] so that the impedance matrix for the network can be determined in case of abnormal condition so as to get the accurate critical fault point. A new subsystem coordination technique has been implemented in [20] to reach the best settings for DOCRs efficiently considering the network changes. An interior point method-based structures for protection coordination has been performed in ref [21] as a two-stage optimization-based method and a modern OF was developed for reducing the running time for both primary and backup relays simultaneously. The downside of conventional tools for optimization is that they take an initial guess which may lead to local minimum values.

### 2.2 Heuristic Techniques and (Artificial Intelligence Techniques)

Nowadays, researchers tend to use artificial intelligence techniques as an optimization tools to avoid the drawbacks of the conventional methods such as time consuming [22]. Neural network like fuzzy logic has been discussed in [23] for calculating optimally TD and the relay operating time. A method that was based on intelligent analysis has been used in [24] to find the settings of distance protection by initializing the parameters values and then coordination problem is solved. The coordination settings include the distance, optimum operating impedance characteristics, the fault detection settings and the minimum voltage and current relay sensitivities.

The routine of heuristic algorithms is known to be susceptible to the values assigned to its parameters, ref [25] is sample of empirical optimization technique in this case for a Particle Swarm Optimization (PSO) algorithm. In reference

[26], a modified genetic algorithm (GA) was suggested to provide a solution for coordination problem by adjusting the objective function (OF) of GA by inserting a new parameter to OF. This new term in (OF) solves the issue of main and back-up relays being mis-coordinated. Two test cases are introduced and the results obtained show the efficiency and usefulness of the above process.

A new OF has been formulated in [27] taking into consideration the priority of the constraints by the help of expert systems using GA. A new approach of GA including transformer protection in [28] has been proposed to get the optimal settings of DOCR. The relay curve type as Very Inverse (VI), moderate and Normal Inverse (NI) and the damage curves of transformer have been taken into consideration while coordination.

A Modified Adaptive PSO (MAPSO) for optimum coordination among distance relays and DOCRs was implemented in [29–31] including the series compensation influence on the relays in the system. One of the heuristics coordination techniques is Honey Bee algorithm that was performed for optimisation problem solution as linear programming and get the optimum settings [32, 33]. In reference [34], flower pollination algorithm (FPA) was used for optimization problem solution. The OF has been formulated to reduce the risk of Arc-flash while optimizing digital over current relays coordination.

The authors in [35] used PSO algorithm for solving the coordination problem of DOCR in radial networks which gives suitable coordination between each relay pairs. Using IEEE 15 nodes radial system, variables calculated from Dig SILENT software simulation. A modified Swarm Firefly Algorithm (MSFA) has been implemented in [36] taking the population size into consideration when solving the coordination problem. This methodology has been compared with the normal PSO and shows better results than PSO. Chaotic Firefly algorithm has been performed in [37, 38] for optimal time coordination.

In ref [39, 40], relay coordination in ring network system was implemented by means of Teaching Learning Based Optimization (TLBO) algorithm. In ref [41], efforts have been performed to optimally coordinate the optimization problem for DOCR using enhanced backtracking search algorithm.

An innovative tool for DOCR coordination based on post fault current has been implemented in [42]. The mentioned technique overcomes the problems of Conventional schemes. In ref [43], a new tool of optimization has been proposed based on cascade correlation neural network which deals with the nonlinearity of the characteristics. The mentioned method provides more efficiency and accuracy than the other neural network.

A new approach has been introduced in [44] to avoid relays malfunctioning in the network. The solution of this problem requires additional constraints using two phases which increase the complexity of the coordination problem. A new approach to reduce the effect of coordination constraints (ECC) has been presented in [45] by choosing the optimal value of pick up current by the aid of linear programming then the time dial of relays has been optimally coordinated.

The study of relay coordination in case of presence of distributed generators DGs has been reported in [46–50] where there are Three type of Fault Current Limiter (FCL) has been used for optimal coordination taking into consideration the relay curve type and the transformer damage curve. In ref [51], the setting of both timing distance relay second zone (as back up relay) and DOCR is optimally determined in complex protection system by the use of Multiple Embedded Crossover PSO (MECPSO).

An advanced method for solving the coordination problem was performed using break points like functional dependencies and graph theory for getting the starting points of relays in [52–54] taking into consideration the network configuration. This method reduces successfully both the CPU time and the number of constraints and. In ref [55], Pre-processing reduction constraints method has been used which gives a proper solution of coordination problem and decreases the processing time.

In [56] the authors introduced a new approach for solving the problem of coordination in distribution systems based on network splitting using GA. The obtained results show a superior operating time for each relay and reduce the chance of non-convexity of the problem. In [57], a new problem formulation has been introduced to minimize the number of miscoordination. The consequences of both close and far end faults are considered in addition to reducing the operating relay time compared with other algorithms. GA has been used as optimization tool.

New method for optimum coordination of DOCRs has been introduced in [58] using non-dominated sorting GA-II (NSGA-II). In this method, Multi-OF technique has been used which not only achieves minimum discrimination time between primary and back pairs but also reduces the operational time for relays. In ref [59], the DOCR coordination problem has been expressed as the problem of an interval linear programming (ILP) problem. The main objective of this method is to turn the inequality constraints for each relay pair into a restricted interval to avoid the drawbacks that may happen such as the single-line outage, repairs and system rearrangement that may produce miscoordination.

A comparative study has been proposed in [60] between the most popular metaheuristic-based algorithms such as GA, PSO, differential evolution (DE), harmony search (HS) and seeker optimization algorithm (SOA). By applying these five techniques in this study, DE technique has been found to be the best one between the other four tools.

In ref [61], an adaptive DE has been presented to determine the optimum settings of DOCRs. The two settings (TD and CSM) are considered as a discrete nature.

A new technique has been discussed in [62] depending on Monte Carlo simulation sequential to describe the reliability requirements of two applied relay coordination methods. For the results of the two "maximum path" and "dual simplex" methods of relay coordination, this technique was implemented for an actual network model. The obtained results display the effectiveness of dual simplex method than the maximum path method. Authors in [63, 64] presented an effective method for finding and resolving the issue of coordination characteristics intersection of overcurrent relays in sub transmission systems.

In order to increase the convergence rate, five mutation techniques based on DE have been used in [65, 66] to resolve the coordination problem of DOCR. Challenges of inserting distributed generators, active network management (ANM) and islanded modes of operation have been considered in [67] when solving the coordination problem of DOCRs. A new method for coordination problem in case of presence distributed generators has been illustrated in [68] using user-defined characteristics for the inverse time overcurrent relays that can specify a relay (time/current) characteristic.

The OF in [69, 70] has been formulated to resolve the problem of coordination for both overcurrent and distance relays using GA technique. A continuous GA (CGA) has been performed in [71] for optimum coordination problem in ring networks. Authors in [72] discussed the improvements in network configuration while achieving optimum settings for relay coordination using Binary GA.

In ref [73], the optimization problem has been solved for coordinating both overcurrent and earth fault relays by using GA, the traditional OF has been modified by adding new constraints for coordination problem in the network with various voltage levels. The condition of critical fault has been considered for the placed relays in both ends of transformers of network.

The optimization problem for directional overcurrent relay coordination has been resolved by both Lagrange generalized through the conditions of Karush–Kuhn–Tucker [74] and GA in [75] considering nonstandard tripping characteristic which achieves fault clearance with small tripping time. The thermal stress on every power system component has been considered. On other hand, an improved group search optimization IGSO tool has been proposed in [76] by adding some modification to the traditional GSO.

Authors in [77, 78] presented an optimization tool for coordination problem based on symbiotic organism search technique. Cuckoo Search Algorithm (CSA) has been presented in [79] to get the DOCRs coordination problem solution with highly nonlinear constraints. New modifications have been applied to the traditional Cuckoo Search in [80] by adding some information exchange among the best solutions.

An online coordination of directional overcurrent relays has been presented in [81] to satisfy customers using ant colony optimization (ACO), DE and GA. The advantages in addition to disadvantages of each algorithm has been discussed. Their performance is dependent on the operating time, superiority outcome, strength and convergence facility of each algorithm.

A comparison process among four metaheuristic tools such as (GA, PSO, Cuckoo Search Algorithm (CSA), Firefly Algorithm (FFA)) for optimum Overcurrent relay coordination has been applied in [82]. Various numbers of relays have been considered in a constrained power system. This comparison shows that FFA technique is the best between the other mentioned algorithms.

Authors in [83] used a lately advanced algorithm named Random Walk Grey Wolf Optimizer (RW-GWO) by which the optimal setting for DOCRs problem can be found. A comparison has been presented among the classical GWO, other unconventional algorithms and RW-GWO. This comparison showed the robustness of RW-GWO.

### 2.3 Hybrid Techniques

Hybrid techniques have been recently used by the researches for solving the coordination problem. The authors in [84, 85] gather between the benefits of (GA) and nonlinear programming (NLP) to get the optimal settings of OCR. Anew formulation of optimization problem has been introduced with nonlinearity. GA has been used to find TD and CSM values and then the nonlinear programming (NLP) was used to get the final optimum values of both variables so that the difficulties of both methods can be avoided. Hybrid PSO (HPSO) has been used in [86, 87] to optimally coordinated direction over-current relays DOCRs in micro grid. The optimal setting of pick up current is calculated using PSO and TD of each relay is calculated by the means of linear programming algorithm.

Another way of optimization using PSO has been developed in [88] named Laplace Crossover PSO (LXPSO) using Laplace distribution. Partial differential algorithm PDA has been used in [89] which achieve more accuracy than the conventional methods of optimization. The PDA selects the nearest point of the curves (VI or NI) to satisfy all the coordination constraints, GA has been implemented by considering different types of relay characteristics and the curves of transformer.

An efficient combination of two optimization tools called opposition based chaotic differential evolution (OCDE1 and OCDE2) was proposed for coordination problem in [90].

In ref [91, 92], the authors gather between the advantages of both Nelder-Mead (NM) simplex search with a quicker reach

the optimum settings and PSO to find globally optimum solution including gradient-based repair method for dealing with constrained optimization problems.

In [93], a hybrid technique based on PSO based differential evolution algorithm (PSO-DE) has been performed. The result of this method achieves the desired solution at a faster convergence speed. Authors in [94] used evolutionary algorithms and linear programming for coordinating DOCRs. The main advantages of the mentioned method are that the evolutionary algorithm and that of the linear programming are fast and achieve restrictions reduction.

A novel method based on Optimized OF has been introduced in [95] using hybrid GA and PSO algorithm (HGAPSOA). The OF is enhanced during the optimization process so that the parameters of the traditional OF have been improved to determine the optimum settings of relays. The authors in [96] used a new approach called biogeography-based optimization (BBO) as an optimization tool for optimal relay coordination problem. Also, hybrid BBO with Linear Programming (BBO-LP) has been introduced for improving the conventional BBO algorithm performance which achieves a good and acceptable solution with little iteration and less CPU time.

A hybrid GA and LP have been introduced in [97] to coordinate both overcurrent and distance relays. New seeker technique has been introduced in [98] to resolve the optimization problem which is considered as mixed-integer nonlinear programming problem. The mentioned method can be applied for both continues and discrete variables and the same technique has been applied in [99] with high performance for solving the coordination problem considering the relay type and the curve type.

On other hand, the hybrid CSA–FFA technique has been formulated in [100] where the initial optimal values of TD and CSM were defined using CSA as an higher limit in FFA to ensure global best solution.

An efficient strategy based on PSO named Time Varying Acceleration Coefficient (PSO-TVAC) was established in [101] to resolve the optimum settings for $DOCR_s$. The robustness and efficiency of this technique has been clearly confirmed compared to the standard PSO and GA as well [102].

## 3 Comparison Between Some of the Mentioned References

The comparison between some of previous works mentioned in this paper is tabulated as under**:**

| Ref | Optimization tool | Objective function | Test case | Remarks |
|---|---|---|---|---|
| [2] | GA | $\alpha \sum_{i=1}^{N} t_i^2 + \beta \sum_{k=1}^{P} \left(\Delta t_{mbk-} \lvert \Delta t_{mbk} \rvert\right)^2$<br>$\Delta t_{mbk} = t_{bk} - t_{mk} - \mathrm{CTI}$<br>where $\Delta t_{mbk}$ refers to operation time difference with CTI for kth relays pair, N refers to the relays number, P is number of P/B current pairs, β refers to miscoordination parameter to be considered and the weight equation control is defined by α | IEEE 8 Buses and 30 Buses | Neglecting the damage curve of equipment |
| [6] | Two phase simplex method | $\min z = \sum_{i=1}^{m} W_i . t_{i,k}$,<br>where m refers to relays number, $t_{i,k}$ is the Ri relay operating time for a fault at k and Wi refers to operating time weight of Ri relay | A one-end-fed, multi-loop distribution system | Problems happen in interconnected systems are neglected |
| [32] | Honey Bee algorithm | $\alpha_1 \sum_{i=1}^{N} t_i^2 + \alpha_2 \sum_{k=1}^{P} [\Delta t_{mb} - \beta_2 (\Delta t_{mb}) - \lvert \Delta t_{mb} \rvert)$<br>Where $t_i$ refers to the operating time of a relay for fault clear the near bus and $\Delta t_{mb}$ is difference of operation time between backup and main relay | 8 bus system | Avoid miscoordination in relay operation and can be implemented in larger system |
| [34] | FPA | $minimize \left\{ \sum_j \sum_k IE(t_{k,j}) \right\}$,<br>$t = \frac{TD.\beta}{\left(\frac{I_f}{I_p}\right)^{\alpha} - 1}$, where t refers to the operational time of a relay, TD is the time dial/delay, $I_f$ is the short circuit current (A), $I_p$ is the pickup current (A) and α and β are coefficients for different overcurrent relay characteristics | 8-bus and 15-bus | Reducing the risk produced by arc-flash and providing the optimum settings of DOCRs |

| Ref | Optimization tool | Objective function | Test case | Remarks |
|---|---|---|---|---|
| [35] | PSO | $\text{Min} \sum_{i=1}^{n} W_i O_{ti}$, where, Oti refers to Ri relay operational time, and Wi is a factor that considered to be 1, that refers to the fault existence probability on transmission line and n is the whole relays number | IEEE 15 node distribution system | Applying on radial system which does not have the problems happens in case of ring or interconnected networks |
| [57] | GA | $\text{Min} \sum_{i=1}^{n} W_i t_{ik}$, where n is the number of relays, $t_{ik}$ is the Ri relay operational time at k position, and Wi is the weight factor given to all relays and is usually equal 1 | Nine-bus and IEEE 30bus distribution section | The established OF leads to minimize the miscoordination difficult |
| [84] | Hybrid GA-NLP Approach | $\text{Min} \sum_{i=1}^{m} W_i t_{ik}$, where m indicates the total relays number, tik refers to Ri relay operational time in case of fault at k | Nine-bus system and Single end fed distribution system | The relay type and relay curves have been taken into consideration but neglecting the effect of damage curve of equipment |

## 4 Conclusion and Recommendations for Future Scope

An overall review on over current relay coordination has been shown in this study using several types of optimization tools. Optimization techniques have been classified to traditional methods, heuristics methods and hybrid techniques. A comparison between some of the reviewed papers has been performed in Sect. 3. The future work for this study:

- Perform optimal relay coordination considering the damage(melting) curve of each equipment.
- Analysis of several fault scenarios and different operating arrangements.

## References


1. Birla D, Maheshwari RP, Gupta HO (2005) Time-overcurrent relay coordination: a review. International Journal of Emerging Electric Power Systems; 2(2), Article 1039
2. Mohammadi R, Abyaneh HA, Razavi F, Al-dabbagh M, Sadeghi SHH (2010) Optimal relays coordination efficient method in interconnected power system. Electr Eng 61(2):75–83
3. Singh D. K., Gupta, S., "Optimal coordination of directional overcurrent relays: A genetic algorithm approach " in 2012 IEEE Students' Conference on Electrical, Electronics and Computer Science: Innovation for Humanity, SCEECS 2012, India 2012.
4. Hairi M, Alias K, Aras M, Basar M, Fah S (2010) Inverse definite minimum time overcurrent relay coordination using computer aided protection engineering. In the proceedings of the 2010 power engineering and optimization conference (PEOCO), 2010 4th International, Malaysia, pp: 304-307
5. Wagner JK, Trutt FC (1981) Interactive relay coordination using microcomputer graphics. Electric Power System Res 4(2):129–134
6. Sueiro JA, Diaz-Dorado E, Míguez E, Cidrás J (2012) Coordination of directional overcurrent relay using evolutionary algorithm and linear programming. Int J Electr Power Energy Syst 42(1):299–305
7. Bedekar PP, Bhide SR, Kale VS (2010) Optimum coordination of overcurrent relay timing using simplex method. Electric Power Compon Syst 38(10):1175–1193
8. Bedekar PP, Bhide SR, Kale VS (2009) Coordination of overcurrent relays in distribution system using linear programming technique proceedings of the international conference on control automation communication and energy conservation (INCACEC-2009), Kongu Engineering College, Erode (India), June 2009, pp. 905–908
9. Braga AS, Saraiva JT (1996) Coordination of directional overcurrent relays in meshed networks using the simplex method, IEEE mediterranean on electro technical conference (MELECON) Bari–Italy 3 13 16
10. Zocholl SE, Akamine JK, Hughes AE, Sachdev MS, Scharf L (1989) Computer representation of overcurrent relay characteristics. IEEE Trans Power Deliv 4(3):1659–1667
11. Smooolleck H (1979) A simple method for obtaining feasible computational models for time characteristics for industrial power system protective. Electric Power Syst Res 2(1):65–69
12. Elrefaie HB, Irving MR, Zitouni S (1994) A parallel processing algorithm for coordination of directional overcurrent relays in interconnected power systems. In: Generation, transmission and distribution, IEE proceedings, 141(5), 514–520
13. So CW, Li KK (2000) Overcurrent relay coordination by evolutionary programming. Electric Power Syst Res 53(2):83–90
14. Ezzeddine M, Kaczmarek R (2011) A novel method for optimal coordination of directional overcurrent relays considering their available discrete settings and several operation characteristics. Electric Power Syst Res 81(7):1475–1481
15. Urdaneta AJ, Perez LG, Restrepo H (1997) Optimal coordination of directional overcurrent relays considering dynamic changes in the network topology. IEEE Trans Power Del Oct 12(4):1458–1464
16. Perez LG, Urdaneta AJ (1999) Optimal coordination of directional overcurrent relays considering definite time backup relaying. IEEE Trans Power Deliv 14(4):276–284
17. Papaspiliotopoulos VA, Korres GN, Maratos NG (2015) A novel quadratically constrained quadratic programming method

for optimal coordination of directional overcurrent relays. IEEE Trans Power Deliv 32(1):3–10
18. Birla D, Maheshwari RP, Gupta HO, Deep K, Thakur M (2006) Application of random search technique in directional overcurrent relay coordination. Int J Emerg Electric Power Syst 7(1):1–14
19. Urdaneta AJ, Pérez LG, Gómez JF, B Feijoo; M González, (2000) Presolve analysis and interior point solutions of the linear programming coordination problem of directional overcurrent relays. Electr Power Energy Syst 23(8):819–825
20. Alkaran DS, Vatani MR, Sanjari MJ, Gharehpetian GB, Yatim AH (2015) Overcurrent relays coordination in interconnected networks using accurate analytical method and based on determination of fault critical point. IEEE Trans Power Deliv 30(2):870–877
21. Ramaswami R, Damborg MJ, Venkata SS (1990) Coordination of directional overcurrent relays in transmission systems-a subsystem approaceh. IEEE Trans Power Deliv 5(1):64–71
22. Alam MN, Das B, Pant V (2016) An interior point method based protection coordination scheme for directional overcurrent relays in meshed networks. Electr Power Energy Syst 81:153–164
23. Hussain MH, Rahim SRA, Musirin I (2013) Optimal overcurrent relay coordination: a review. Procedia Eng 53:332–336
24. Abyane HA, Faez K, Karegar HK (1997) A new method for overcurrent relay (O/C) using Neural network and fuzzy logic TENCON '97 Brisbane–Australia. Proceedings of IEEE TENCON, Speed and image technologies for computing and telecommunications, pp. 407–410
25. El-Arroudi K, Joos G, McGillis DT, Brearley R (2005) Comprehensive transmission distance protection settings using an intelligent-based analysis of events and consequences. IEEE Trans Power Deliv 20(3):1817–1824
26. Harrison KR, Ombuki-Berman BM, Engelbrecht AP (2017) Optimal parameter regions for particle swarm optimization algorithms. IEEE Congr Evol Comput 2017:349–356
27. Razavi F, Abyaneh HA, Al-dabbagh M, Mohammadi R, Torkaman H (2008) A new comprehensive genetic algorithm method for optimal overcurrent relays coordination. Electric Power Syst Res 78(4):713–720
28. Mohammadi R, Abyaneh HA, Rudsari HM, Fathi SH, Rastegar H (2011) Overcurrent relays coordination considering the priority of constraints. IEEE Trans Power Deliv 26(3):1927–1938
29. Chen CR, Lee CH, Chang CJ (2013) Optimal overcurrent relay coordination in power distribution system using a new approach. Int J Electr Power Energy Syst 45(1):217–222
30. Moravej Z, Jazaeri M, Gholamzadeh M (2012) Optimal coordination of distance and overcurrent relays in series compensated systems based on MAPSO. Energy Convers Manage 56:140–151
31. Benabid R, Zellagui M, Boudour M, Chaghi A (2013) Considering the series compensation in optimal coordination of directional overcurrent protections using PSO technique, IEEE Jordan conference on applied electrical engineering and computing technologies, AEECT
32. Benabid R, Zellagui M, Chaghi A, Boudour M (2013) Optimal coordination of IDMT directional overcurrent relays in the presence of series compensation using differential evolution algorithm, In: 2013 3rd International Conference on Systems and Control (ICSC), 29–31 October, ALGIERS, Algeria, pp. 1049–1054
33. Rashtchi V, Gholinezhad J, Farhang P (2010) Optimal coordination of overcurrent relays using honey bee Algorithm. Ultra modern telecommunications and control systems and workshops (ICUMT); October p. 401–405
34. Hussain MH, Musirin I, Abidin AF, Rahim SRA (2014) Solving directional overcurrent relay coordination problem using artificial bees colony. Int J Electr Electron Sci Eng 8(5):705–710
35. El-Fergany AA (2016) Optimal directional digital overcurrent relays coordination and arc-flash Hazard assessments in meshed networks. Int Trans Electr Energy Syst 26(1):134–154
36. Kheshti M, Tekpeti BS, Kang X (2016) The Optimal coordination of over-current relay protection in radial network based on particle swarm optimization. IEEE PES Asia-Pacific power and energy conference. p.604–608
37. Hussain MH, Musirin I, Abidin AF., Rahim SRA (2014) Directional overcurrent relay coordination problem using modified swarm Firefly algorithm considering the effect of population size, 2014 IEEE 8th international power engineering and optimization conference (PEOCO 2014), Langkawi, Malaysia, pp. 591-596
38. Gokhale SS, Kale VS (2016) An application of a tent map initiated chaotic firefly algorithm for optimal overcurrent relay coordination. Electr Power Energy Syst 78:336–342
39. Gokhale SS, Kale VS (2014) An application of the Firefly algorithm for optimal overcurrent relay coordination. In: The proceedings of OPTIM 2014 conference, Bran, Romania, May. p. 150–154
40. Singh M, Panigrahi B, Abhyankar A (2013) Optimal coordination of directional over-current relays using teaching learning-based optimization (TLBO) algorithm. Int J Electr Power Energy Syst 50:33–41
41. Kalage AA, Ghawghawe ND (2016) Optimum coordination of directional overcurrent using modified adaptive teaching learning based optimization algorithm. Intell Ind Syst 2(1) 55 71
42. Othman AM, Abdelaziz AY (2016) Enhanced backtracking search algorithm for optimal coordination of directional overcurrent relays including distributed generation. Electr Power Compono Syst 44(3):278–290
43. Jalilian A, Hagh M, Hashemi S (2014) An innovative directional relaying scheme based on post fault current. IEEE Trans Power Del 29(6):2640–2647
44. Meshkin M, Faez K, Abyaneh HA, Kanan HR, Application of cascade correlation neural network in modelling of overcurrent relay characteristics, In: 2006IEEE GCC Conference (GCC), 20–22 March, Manama, Bahrain 2006, pp. 1–6
45. Birla D, Maheshwari RP, Gupta HO (2007) An approach to tackle the threat of sympathy trips indirection overcurrent relay coordination. IEE Trans Power Deliv 22(2):851–858
46. Ezzeddine M, Kaczmarek R (2008) Reduction of effect of coordination constraints in the linear optimization of operating times of overcurrent relays MELECON, The 14th IEEE Mediterranean electro technical conference Ajaccio France pp 707 712
47. Javadi H, Ali Mousavi SM, Khederzadeh M (2013) A novel approach to increase FCL application in preservation of overcurrent relays coordination in presence of asynchronous DGs. Int J Electri Power Energy Syst 44:810–815
48. Ebrahimi E, Sanjari MJ, Gharehpetian GB (2014) Control of three-phase inverter-based DG system during fault condition without changing protection coordination. Int J Electri Power Energy Syst 63:814–823
49. Yazdanpanahi H, Xu W, Li YW (2014) A novel fault current control scheme to reduce synchronous dg's impact on protection coordination. IEEE Trans Power Deliv 29(2):542–551
50. El-Khattam W, Sidhu TS (2009) Resolving the impact of distributed renewable generation on directional overcurrent relay coordination: a case study. IET Renew Power Gener 3(4):415–425
51. Chabanloo RM, Abyaneh HA, Agheli A et al (2011) Overcurrent relays coordination considering transient behaviour of fault current limiter and distributed generation in distribution power network. IET Gener Transm Distri 5(9):903–911

52. Farzinfar M, Jazaeri M, Razavi F (2014) A new approach for optimal coordination of distance and directional over-current relays using multiple embedded crossover PSO. Int J Electr Power Energy Syst 61:620–628
53. Meskina M, Domijan A, Grinberg I (2015) Optimal co-ordination of overcurrent relays in the interconnected power systems using break points. Electric Power Syst Res 127:53–63
54. Yue Q, Lu F, Yu W, Wang J (2006) A novel algorithm to determine minimum break point set for optimum cooperation of directional protection relays in multiloop networks. IEEE Trans Power Del 21(3):1114–1119
55. Gajbhiye RK, Anindya. De, Soman SA (2007) Computation of optimal break point set of relays—an integer linear programming approach, IEEE Trans Power Del, Oct 22(4):2087–2098
56. Karegar HK, Abyaneh HA, Ohis V, Meshkin M (2005) Preprocessing of the optimal coordination of overcurrent relays. Electric Power Syst Res 75:134–141
57. Azari A, Akhbari M (2014) Optimal coordination of directional overcurrent relays in distribution systems based on network splitting. Int Trans Electr Energ Syst 25(2310):2324
58. Adelnia F, Moravej Z, Farzinfar M (2013) A new formulation for coordination of directional overcurrent relays in interconnected networks. Int Trans Electr Energ Syst 25(1):120–137
59. Moravej Z, Adelnia F, Abbasi F (2015) Optimal coordination of directional overcurrent relays using NSGA-II. Electric Power Syst Res 119:228–236
60. Noghabi AS, Mashhadi HR, Sadeh J (2010) Optimal coordination of directional overcurrent relays considering different network topologies using interval linear programming. IEEE Trans Power Deliv 25(3):1348–1354
61. Alam MN, Das B, Pant V (2015) A comparative study of metaheuristic optimization approaches for directional overcurrent relays coordination. Electric Power Syst Res 128:39–52
62. Moirangthem J, Krishnanand KR, Dash SS et al (2013) Adaptive differential evolution algorithm for solving non-linear coordination problem of directional overcurrent relays. IET Gener Transm Distrib 7(4):329–336
63. Mazlumi K, Abyaneh HA (2009) Relay coordination and protection failure effects on reliability indices in an interconnected sub-transmission system. Electric Power Syst Res 79:1011–1017
64. Lu Y, Chung J-L (2013) Detecting and solving the coordination curve intersection problem of overcurrent relays in sub transmission systems with a new method. Electr Power Syst Res 95:19–27
65. Chung J-L, Lu Y, Kao W-S, Chou C-J (2008) Study of solving the coordination curve intersection of inverse-time overcurrent relays in sub transmission systems. IEEE Trans Power Del 23(4):1780–1788
66. Thangaraj R, Pant M, Abraham A (2010) New mutation schemes for differential evolution algorithm and their application to the optimization of directional over-current relay settings. Appl Math Comput Mar 216(2):532–544
67. Thangaraj R, Pant M, Deep K (2010) Optimal coordination of overcurrent relays using modified differential evolution algorithms. Eng Applicat Artificial Intell 23(5):820–829
68. Coffele F, Booth C, Dysko A (2015) An adaptive overcurrent protection scheme for distribution networks. IEEE Trans Power Deliv 30(2):561–568
69. Sharaf HM, Zeineldin HH, Ibrahim DK, El-Zahab EEA (2015) A proposed coordination strategy for meshed distribution systems with DG considering user-defined characteristics of directional inverse time overcurrent relays. Electr Power Energy Syst 65:49–58
70. Chabanloo RM, Abyaneh HA, Kamangar SSH, Razavi F (2011) Optimal combined overcurrent distance relay coordination incorporating intelligent overcurrent relay characteristic selection. IEEE Trans Power Deliv 26(3):1381–1391
71. Abyaneh HA, Kamangar SSH, Razavi F, Chabanloo RM, F. Razavi (2008) A new genetic algorithm method for optimal coordination of O/C relays in a mixed protection scheme with distance relays, presented at the UPEC Conf., Padova, Italy, 1_4 Sep. 2008
72. Bedekar PP, Bhide SR (2011) Optimum coordination of overcurrent relay timing using continuous genetic algorithm, expert systems with applications, Elsevier 38: 11286-11292
73. Bhattacharya SK, Goswami SK (2008) Distribution network reconfiguration considering protection coordination constraints. Electric Power Compon Syst 36:1150–1165
74. Kamangar S, Abyaneh H, Chabanloo R, Razavi F, A new genetic algorithm method for optimal coordination of overcurrent and earth fault relays in networks with different levels of voltages, In: proceedings of the 2009 IEEE Bucharest power tech, Bucharest, Romania, 2011, pp. 1–5
75. Timo K, Johann J (2008) Advanced coordination method for overcurrent protection relays using nonstandard tripping characteristics. IEEE Trans Power Deliv 23(1):52–57
76. Salazar CAC, Enríquez AC, Schaeffer SE (2015) Directional overcurrent relay coordination considering non-standardized time curves. Electric Power Syst Res 122:42–49
77. Alipour M, Teimourzadeh S, Seyedi S (2015) Improved group search optimization algorithm for coordination of directional overcurrent relays. Swarm Evolut Comput 23:40–49
78. Saha D, Datta A, Das P (2016) Optimal coordination of directional overcurrent relays in power systems using symbiotic organism search optimisation technique. IET Gener Transm Distrib 10(11):2681–2688
79. Cheng MY, Prayogo D (2014) Symbiotic organisms search: a new metaheuristic optimization algorithm. Comput Struct 139:98–112
80. Darji GU, Patel MJ, Rajput VN, Pandya KS (2015) A tuned cuckoo search algorithm for optimal coordination of directional overcurrent relays, IEEE 2015 International conference on power and advanced control engineering,12_14 Aug 2015, Bengaluru, India pp 162–167
81. Walton S, Hassan O, Morgan K, Brown MR (2011) Modified cuckoo search: a new gradient free optimisation algorithm. Chaos, Solitons Fractals 44(9):710–718
82. Shih MY, Enríquez AC, Trevi˜no LMT, (2014) On-line coordination of directional overcurrent relays: performance evaluation among optimization algorithms. Electr. Power Syst Res 110(2014):122–132
83. Ralhan S, Goswami R, Ray S (2018) Comparative study of optimal overcurrent relay coordination using metaheuristic techniques. Comput Intell Data Min. https://doi.org/10.1007/978-981-10-8055-5_30
84. Gupta S, Deep K (2019) Optimal coordination of overcurrent relays using improved leadership-based grey wolf optimizer. Arab J Sci Eng. https://doi.org/10.1007/s13369-019-04025-z
85. Bedekar PP, Bhide SR (2011) Optimum coordination of directional overcurrent relays using the hybrid GA-NLP approach. IEEE Trans Power Deliv 26(1):109–119
86. Noghabi AS, Sadeh J, Mashhadi HR (2009) Considering different network topologies in optimal overcurrent relay coordination using a hybrid GA. IEEE Trans Power Del 24(4):1857–1863
87. Damchi Y, Mashhadi HR, Sadeh J, Bashir M (2011) Optimal coordination of directional overcurrent relays in a microgrid system using a hybrid particle swarm optimization, IEEE, the international conference on advanced power system automation and protection, APAP, pp. 1135–1138
88. Zeineldin HH, EI-Saadany EF, Salama MM (2006) Protective relay coordination for Micro-grid operation using particle swarm optimization, lEEE large engineering systems conference

on power engineering, Halifax, NS, Canada ,26_28 July, pp. 152–157
89. Deep Kusum, Bansal Jagdish Chand (2009) Optimization of directional overcurrent relay times using Laplace crossover particle swarm optimization (LXPSO). In: Proc nature & biologically inspired computing. NaBIC 2009. World Congress; December 2009.p. 288–293
90. Chen CR, Lee CH, Chang CJ (2011) Overcurrent relay coordination optimization with partial differentiation approach for the validation of coordination violation. Electr Power Compon Syst 39:933–947
91. Chelliah TR, Thangaraj R, Allamsetty S, Pant M (2014) Coordination of directional overcurrent relays using opposition based chaotic differential evolution algorithm. Int J Electr Power Energy Syst 55:341–350
92. Yang MT, Liu A (2013) Applying hybrid PSO to optimize directional overcurrent relay coordination in variable network topologies. J Appl Math Hindawi Publ Corp 39:1–9
93. Liu An, Yang Ming-Ta (2012) Optimal coordination of directional over-current relay using NM-PSO technique. In: IEEE transactions on international symposium on computer and Control, p. 678–681
94. Zellagui M, Abdelaziz AY (2015) Optimal coordination of directional overcurrent relays using Hybrid PSO-DE algorithm. Int Electr Eng J (IEEJ) 6(4):1841–1849
95. Sueiro JA, Diaz-Dorado E, Míguez E, Cidrás J (2012) Coordination of directional overcurrent relay using evolutionary algorithm and linear programming. Int J Electr Power Energy Syst 42:299–305
96. Motlagh MSH, Mazlumi K (2014) Optimal overcurrent relay coordination using optimized objective function. SRN Power Eng 2014:1–10
97. Albasri FA, Alroomi AR, Talaq JH (2015) Optimal coordination of directional overcurrent relays using biogeography-based optimization algorithms. IEEE Trans Power Deliv 30(4):1810–1820
98. Sadeh J, Aminotojari V, Bashir M (2011) Optimal coordination of overcurrent and distance relays with hybrid genetic algorithm, in Proc., 10th international conference on environment and electrical engineering (EEEIC - 2011), Rome, Italy, 8_5 may, 2011 pp 1–5.
99. Amraee T (2012) Coordination of directional overcurrent relays using seeker algorithm. IEEE Trans Power Del Jul 27(3):1415–1422
100. Kida AA, Gallego LA (2016) A high-performance hybrid algorithm to solve the optimal coordination of overcurrent relays in radial distribution networks considering several curve shapes. Electric Power Syst Res 140:464–472
101. Rajput VN, Pandya KS, Kevin Joshi (2015) Optimal coordination of directional overcurrent relays using hybrid CSA-FFA method, IEEE 2015 12th international conference on electrical engineering/electronics, Hua Hin, Cha-am, Thailand ,24_26 June 2015, 1–6
102. Mancer N, Mahdad B, Srairi K, Hamed M, Hadji B (2015) Optimal coordination of directional overcurrent relays using PSO-TVAC. Energy Procedia 74:1239–1247