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Optimal directional overcurrent relay coordination based on computational intelligence technique: a review

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Abstract: An exponential increase in diverse load demand in the last decade has influenced the integration of more power plants into the power system. This increases the fault current due to the bidirectional flow of current, resulting in unwanted tripping of the relays if not properly coordinated. Therefore, it is imperative to ensure the installation of relays in the grid being able to sense the fault current from any direction (i.e. upstream or downstream). This can be accomplished by introducing an optimal directional overcurrent relay (DOCR) coordination scheme into the system. This paper presents an in-depth review of the applications of various optimization techniques for optimal coordination of directional overcurrent relays (DOCRs) in integrated power networks. The review highlights the advantages and limitations of techniques implemented to mitigate the DOCR coordination issues. Furthermore, potential research directions for optimal DOCR coordination are also discussed in this paper.

Key words: Directional overcurrent relay, mathematical algorithm, artificial neural network, hybrid optimization, protection system

1. Introduction

The electrical power system network is prone to failure due to unavoidable fault occurrence in the system. The possibility of fault occurrence increases for a long line and in remote location. Hence, one of the most important aspects of the power system is to have an effective protection system. An effective protection system minimizes revenue loss by avoiding disruption of electricity supply and protecting expensive equipment such as generators, switchgear, conductors, condensers, and transformers from damage. For effective protection of the power system, the protection relays must be coordinated effectively and isolate the faulty area with adequate margins without unnecessary time delays [1–4].

1.1. Background and motivation

Conventional electric distribution networks (DNs) are radial in nature and supplied from one end via a central source. A protection scheme for this type of networks is simple because of the unidirectional power flow. To protect a radial DN, it only requires one overcurrent relay (OCR) at each line. The relay closest to the fault

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location will sense the large magnitude of fault current coming from the grid-connected generator. However, with the high penetration of distributed generation (DG) units into the DN, a conventional DN has substantially deteriorated specifically in terms of network protection [5–8]. Consequently, the relay sensitivity and selectivity have been disrupted due to the bidirectional current flow, which has ultimately caused the sympathetic tripping of the primary and backup protection and coordination failure with existing protection devices e.g., reclosure and fuse [9]. Moreover, it is alleged that the problems associated with DN protection are highly dependent on the network size and the type of integrated DGs. Since DG is an active asset, it transforms conventional radial systems into grid networks [10]. Due to this new network configuration, the existing protection scheme must be improved.

1.2. Literature review

The DOCR is the most commonly used protection relay to sense the bidirectional faults in an integrated network. In subtransmission or DN, DOCR is provided as a primary protection device, whereas in transmission lines, it is considered as a secondary protection device [11]. DOCR coordination problem can be characterized as a highly constrained optimization problem. The DOCR coordination problem aims to attain the time multiplier setting (TMS) and the plug setting current (PSC) of each relay to avoid miscoordination between primary-backup (B-P) relay and also to minimize the total operating time [12, 13]. Since the 1960s, researchers have made great efforts to resolve the DOCR coordination problem through computational approaches. The approaches adopted by the researchers for DOCR coordination can be divided into five categories, which are conventional approach, NIA-heuristic approach, mathematical approach, hybrids techniques, and artificial intelligence. Figure 1 shows the different techniques that have been used by most researchers.

In conventional techniques, three approaches had been used: trial and error, curve fitting technique, and graph theory. Previously, the trial-and-error approach was implemented to obtain the relay setting; however, the convergence rate of this technique is slow and may not provide suitable relay settings for large network protection [3, 14, 15]. On the other hand, the curve fitting technique has converted the DOCR characteristic into a mathematical model. The time multiplier setting (TMS) and relay operating time are determined based on these modelled time-inverse features. These methods start with a functional form like polynomials, which possesses a relay curve approximation. The functional coefficients that best suit the curves are then calculated using the computer [16, 17]. As for the graph theory approach, relay coordination is achieved by conducting the distribution network analysis to identify breakpoint relays (BPS). Appropriate BPS selection is important for rapid convergence of the relay coordination problem [17–19].

The NIA-heuristic technique is an iterative generation method for identifying the best quality solutions through learning strategies, integrating different ideas to scour the search space. Recently, more intelligent methods are utilized for relay coordination problems. These innovations were focused on observations of animal social behaviour, nature such as bird flocking, fish schooling, hydrological cycle, the creative process of music composition, human memory behaviour, Darwinian evolution concepts, and swarm theory [20, 21]. Evolutionary programming (EP), particle swarm optimization (PSO), genetic algorithm (GA), firefly algorithm (FA), artificial bee colony (ABC) algorithm, whale optimization algorithm (WOA), teaching learning-based optimization (TLBO) algorithm, electromagnetic field optimization (EFO), biogeography-based optimization (BBO) algorithm and gravitational search algorithm (GSA) belong to these techniques which possess random search technique that produces more feasible and near-optimal solutions [22–24].

Mathematically, the DOCR coordination problem is an analytic optimization method, such as linear (LP) and nonlinear programming (NLP). In an LP approach, only TMS values are considered as an optimized variable to achieve selectivity between the relays. Whereas, in the NLP approach, both the relay settings TMS and PSC are optimized simultaneously. These methods ensure the achievement of convergence and the result in near-optimum solutions, as it depends on the problem formulation. However, they require more computational effort than metaheuristics [25, 26]; therefore, its complexity increases [27, 28].

Subsequently, in attempting to address the limitations of conventional protection methods, metaheuristic, NLP, and LP techniques, researchers investigated ways for the DOCR coordination problem to be solved by a combination of metaheuristic techniques with NLP or LP. A hybrid gravitational search algorithm and sequential quadratic programming (GSA-SQP) is presented in [29] to solve the DOCR problem. Similarly, genetic algorithm (GA) with LP[30], differential evaluation (DE) with LP [31], NLP-based GA [32] and LP-based biogeography optimization [33] were utilized to achieve optimal coordination of DOCRs. While several hybrid approaches have been proposed to overcome optimal DOCR coordination, more combinations of metaheuristic techniques and mathematical programming can still be explored, which may result in more precise solutions efficiently.

2. Paper organization

This paper attended to provide a systematic review of optimal DOCR coordination. Numerous techniques are reviewed to recognize the gap behind the latest relevant research. The advantages and drawbacks of the techniques are discussed thoroughly. Based on the review, future works on optimal DOCR are presented. The paper is organized as follows: Section 2 describes the relay coordination problem formulation and constraints. Section 3 reviews the various computational intelligent techniques that have been proposed to mitigate the relay coordination issues and discusses their respective working principle, advantages, and disadvantages. Section 4 discusses the recommendations for future studies and Section 5 concludes the paper.

3. Coordination problem formulation and constraints

Generally, DOCRs coordination problem is highly constrained and nonconvex. The goal is to determine the optimal solution for DOCR setting, which minimizes the amount of their operational time while fulfilling various coordinated and borderline constraints[33–37]. Figure 1 depicts the overall methodology of optimal DOCR setting and coordination. The complete steps to explain the process flow to solve DOCR problem are as follows:

Step 1: The power system network to be incorporated with relays is selected. In this step, load flow analysis and fault analysis are conducted to determine the maximum load current and fault current for each line.

Step 2: System parameters for optimal relay setting and coordination are determined. The parameters are fault current value (from fault analysis in step 1), current transformer ratio, the primary and backup relay pairs. Meanwhile, specific (parameters to form the objective functions (total relay operating time) are TMS and PSC. In this step, the process of optimization is treated until it reaches to maximum number of iterations for the final value of TMS and PSC and for all relays in the system.

Step 3: The optimization technique is performed. In this step, optimization is carried out using any effective optimization approach to find the optimal solution for the TMS and PSC for each of the relays in the system. the solution must satisfy all constraints, mainly minimum coordination time between primary and backup relay.

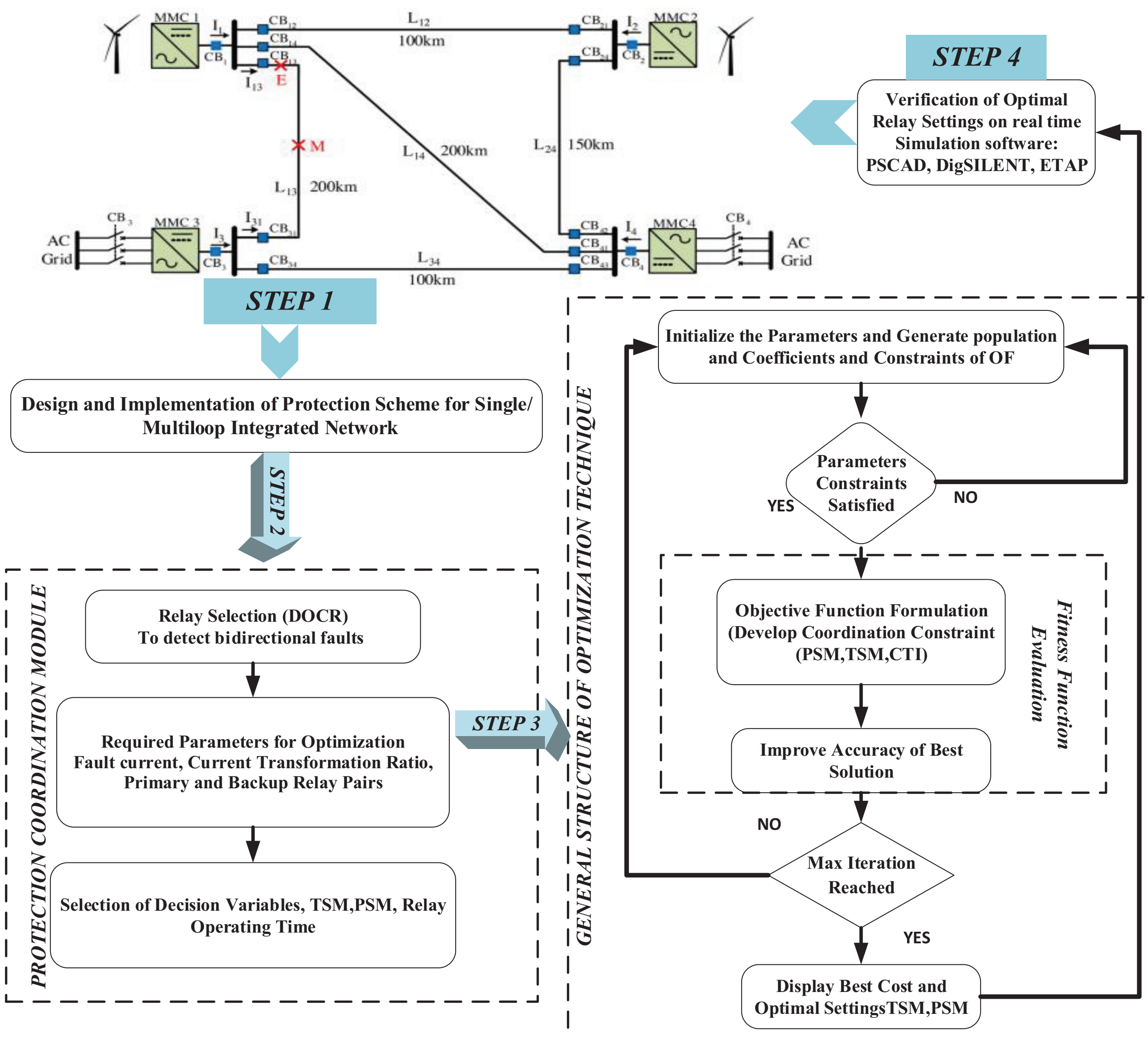

Figure 1. Protection strategy for integrated power networks.

Step 4: The optimal relay setting needs to be verified. In this step, the selected network can be modelled in any industrial power system software. Fault current is applied at the midpoint of different line in the network. The tripping time (tcc) curve is generated by the software. From this tcc, the overlapping or nonoverlapping between primary and backup can be observed. There should not be any overlapping between primary and backup and also fulfil the minimum coordination time.

3.1. Formulation of objective function

The relay coordination is defined as a nonlinear optimization problem where the minimization of the objective function (OF) is the total operating time of the primary relays which protect the faulted line. OF formulation is shown Eq. (1) as:

$$f_1 = \sum_{i=1}^{G} (W_p * T_p(Primary)), \tag{1}$$

where T_p denotes the operating period for relays, R_p in their primary area of protection, G is the total relay located in the specific network and W_p the probability constant for the occurrence of fault beyond the area of protection. W_p is typically set to one which means that each protection zone has an equal chance of failure[33, 34, 36, 38].

3.2. DOCR constraints

The emphasis on minimizing relay operating times is usually achieved within the five constraints as discussed below.

3.2.1. Coordination time interval

A specified time margin must be defined to ensure a safe operation of primary and backup relays. The backup relay would trip if the primary relay fails to clear the fault. Therefore, a duration is required to maintain proper selectivity between relays, generally referred to Coordination Time Interval (CTI). The CTI relies on the relay type, circuit breaker operating time, relay error, and safety margin[33–37, 39]. It can be indicated as:

$$ROT_{rk} - ROT_{hk} \leq CTI^{min} \qquad\qquad \forall k \in NPR \tag{2}$$

Here, NPR is the number of pairs relay. ROT_{hk} and ROT_{rk} are the operating time of the primary relay and the backup relay, respectively. CTI is usually selected within 0.2 s and 0.5 s[33–37, 39].

3.2.2. Limits of the TMS

The TMS tunes the operating time lagging prior to the relay trips every time the fault current magnitude reaching equal to or more than the plug setting current of the relay[33–37, 39]. The limits of the relay TMS are being specified as:

$$TMS^{min} \leq TMS_p \leq TMS^{max} \qquad\qquad \forall p \in G \tag{3}$$

where G is a set of relays, TMS^{min} and TMS^{max} are the minimum and maximum range of TMS for the R_p relay.

3.2.3. Limits of the PSC

The PSC specifies the secondary current range by considering two criteria; the relays are forbidden to operate within rated load current and in a minimum fault current circumstance. Additionally, the relays must react to the least fault current. The limits of the relay PSC can be specified as:

$$PSC_p^{min} \leq PSC_p \leq PSC_p^{max} \qquad\qquad \forall p \in G \tag{4}$$

where PSC_p^{min} and PSC_p^{max} are the minimum and maximum range of PSC for the R_p relay.

These are further determined as:

$$PSC_p^{min} = \frac{OLF * I_{L,p}}{CTR_p} = \frac{I_{PC}^{min}}{CTR_p} \tag{5}$$

$$PSC_p^{max} = \frac{2 * I_{L,p}^{min}}{3 * CTR_p} = \frac{I_{PC}^{max}}{CTR_p} \tag{6}$$

where OLF, $I_{L,p}$,and CTR_p are the current overload factors, the maximum of load current, the current transformer ratio of relay R_p, respectively. $I_{f,p}^m in$ is the minimum of fault current detected by R_p relay. I_{PC}^{min} and I_{PC}^{max} is the minimum current and the maximum current range at the primary side of current transformer(CT).

3.2.4. Relay operating time limits

The protective relaying is designed to operate in the desired time span, meaning it requires a threshold time to initiate the tripping action and that there is a limitation of maximum time to which it can keep operating[33, 35, 36, 40, 41]. It can be stated as:

$$ROT^{min} \leq ROT_p \leq ROT^{max} \qquad \forall p \in G \tag{7}$$

where $ROT_p^m in$ and $ROT_p^m in$ are the minimum and maximum range of operating time levels of the R_p.

3.2.5. Relay time characteristics

According to the IEC 60255-3 standard[42], the nonlinear formulation of time inverse characteristic of relay curve is represented by in Eqs. (**??**) which were addressed in [32–35, 38].

$$ROT_p = RCOT_p * TMS_p \tag{8}$$

$$RCOT_p = \frac{\alpha}{PSM_p^{\beta} - 1} \tag{9}$$

$$PSM_p = \frac{I_{f,p}}{PSC_p} \tag{10}$$

Eqs. (8) and (9), α and β are the coefficients of the time characteristic curve for any type of relays, $RCOT_p$ is the relay characteristic operating time, TMS_p is the time multiplier setting and PSM_p is the plug setting multiplier of relay R_p. In Eq. (10), PSC_p is the plug setting current and $I_{L,p}$ is the maximum three-phase fault current that flow through the R_p relay coil. Characteristic coefficients for IEC-60255-3 protection curves are specified in Table 1.

4. DOCR optimization technique

To solve the problem addressed in Section 2, many computational intelligent approaches for DOCR coordination were proposed by researchers. In general, all the techniques are aimed to minimise Eq.(1) to obtain the optimal solution of the relay settings. The techniques can be divided into two sections. Subsection 3.1 discusses

Table 1. IEC 60255-3 coefficient of time characteristic curve for DOCR.

Curve type	α	β
Standard inverse(IDMT)	0.14	0.02
Very inverse(VI)	13.5	1
Extremely inverse(EI)	80	2
Long time standard inverse(LTI)	120	1

conventional method protection by considering advantages and disadvantages of each approach. Meanwhile, subsection 3.2 discusses computational intelligent approaches, which consist of four techniques. Figure 2 summarizes the optimal DOCR coordination with different optimization techniques.

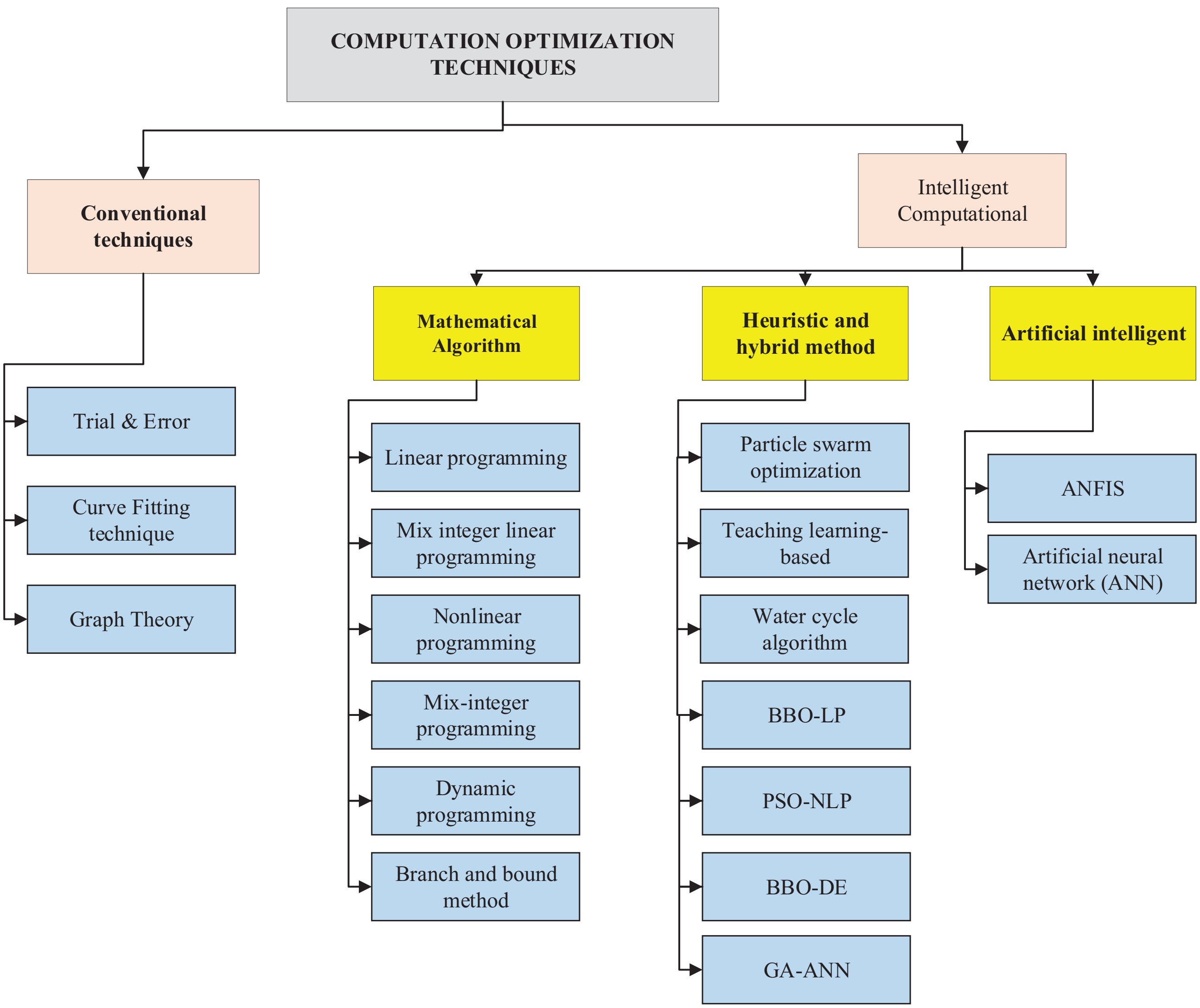

Figure 2. Optimal DOCR coordination with different optimization techniques.

4.1. Conventional method protection

Before the intensive use of computers, the change in relay settings was performed manually by the network operators [21]. Most distribution network operators were used to update the current settings to permit maximum full load current based on the network impedance and load. They also calculated the fault current and determined the allowable time margin for relay coordination by considering relay data (error, overshoot time.) and circuit breaker tripping time. Using this data, the current-time characteristics were plotted using log-log graph paper assuming a tentative time multiplier setting and adjusting whenever necessary to maintain the discrimination time. However, this method is an extremely painstaking task and needs a thorough check on the applicability of the settings required for a small changes made in the distribution network[36]. This approach was inaccurate practically and time-consuming [43]. To overcome these issues, various alternative computational techniques to address the DOCR coordination problem were proposed: try and error, curve fitting technique, graph theoretical technique.

In the early 1960s, the trial-and-error technique was performed using computers to obtain the optimal relay setting. The technique was able to address the coordination problem for a simple conventional network. However, this method experienced low convergence rates and required massive computational effort with the increment in size and complexity of the network [44]. In the late eighties, the curve fitting approach which relies on topological analysis, including techniques for graphical and functional dependencies was adopted. However, the curve-fitting technique is an easy technique for relays setting, but it is inaccurate for currents setting less than 1.3 times of the pick-up current [17–19].

Similarly, the graph theoretical technique which is based on the principle of the breakpoint was used [18, 45, 46]. In [18], the linear graph theory definition has been expanded to define and evaluate all simple network loops, concerning both the minimum breakpoint set and all main and backup relay pairs. The constraints upon these relay settings are formulated by the functional dependency approach, which is a systematic topological analytical technique [46]. Nevertheless, the technique is not effective for complex networks and high penetration of DG. Thus, the computer-aided approach is utilized to cater the coordination problem involving DOCRs in a multi-DG power network with a graphical user interface implemented [60, 61] but the approach is not optimal enough when multimiscoordination occurs. Among all these strategies, the optimization technique eliminates the need to find the breakpoints needed in curve fitting and graph-theoretical techniques. In addition, TMS and PSC found from the graph and curve theoretical methods are not optimal [47–49]. Due to the problems, several work started to explore the use of artificial intelligence (AI) and nature-inspired algorithms (NIA) to solve the optimal coordination of DOCR [34, 40, 50–52].

4.2. Computational intelligence approaches

In general, the techniques are broadly categorised into conventional and intelligent techniques. These optimization strategies are utilized in combination with protective devices to perform the most appropriate protection strategy for a particular DN. Figure 3 illustrates the percentage of citations for the past seven years in DOCR coordination research. It has been revealed that the hybrid technique and mathematical based optimization indicates increasing trend as compared to artificial intelligence techniques respectively in term of percentage. However, hybrid technique is preferred nowadays due to its superiority which is more robust, fast convergence and expediting time of searching for feasible solution in order to solve the optimization problems. Thus, this will result in an efficient DN protection based on the optimal setting of the relays [53]. Table 2 summarizes the advantages and limitations of the optimal DOCR coordination optimization techniques using hybrid, mathematical, and AI/ANN techniques.

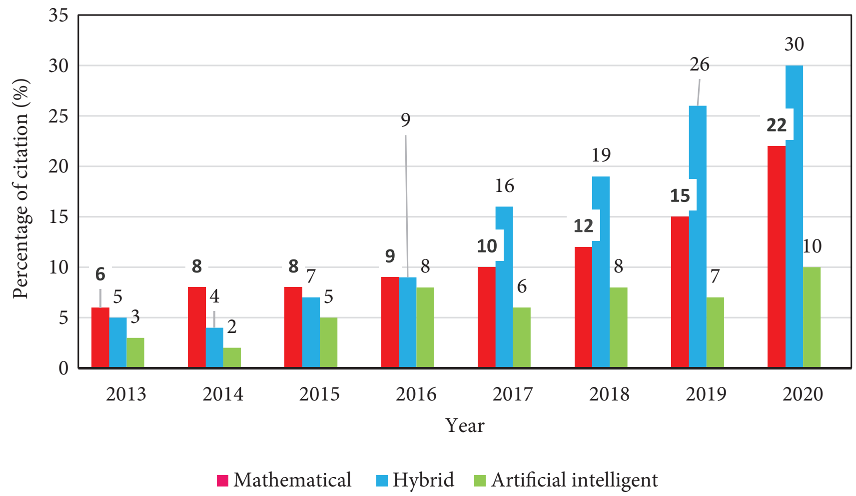

Figure 3. The percentage of citations in the research on the optimal DOCR coordination reported in this article.

Table 2. Summaries of advantages and disadvantages of optimal DOCR coordination optimization techniques using conventional, hybrid, mathematical and AI/ANN technique.

Type of techniques	AI/NIA techniques	Main feature	Advantages	disadvantages
Conventional technique	Trial and Error [44]	Transparent plate has been cut according to relay current-time characteristics	Good for simple power network	Time consuming when dealing with large network. This approach has a slow rate of convergence and the obtained TDS values of the relays are relatively high
	Curve fitting technique[17]	Time inverse operating characteristics are generated for various types of linear and nonlinear functions relay time operating curves	Method available at that time only	Poor accuracy which will lead to nonoptimal result and causing the setting violated
	Graph theory [18]	Break points relay are identified	fast to converge solution the best solution	Selection of break point is critical

Table 2. (Continued).

Type of techniques	AI/NIA techniques	Main feature	Advantages	disadvantages
NIA-heuristic	EP [70]	Optimize the relay setting and avoid the trapping in local optima	Constraint being handle very well	Miscoordination occur, longer computational time taken
	GA[95]	Modifying objective function (OF) by adding new terms to handle miscoordination	Very effective, flexible and accurate	Longer computational time taken
	CGA [96]	Reduce relay operating time and proposed continuous genetic algorithm	Satisfactory	All the constraint not fully satisfy
	CPSO [97]	Assimilation of PSO with the penalty method to enhance and improve the quality of the solutions the CPSO scheme	The population member of the CPSO more discriminative in finding the optimal solution	Consuming more time for each subproblem stage due to the iterations process
	MPSO [38]	Optimize DOCRs coordination by using PSO and 5 agents	Easy to implement and robust	Suffers from partial optimization in the system
Hybrid	IA-PSO [52]	Employed by coupling the immune information processing mechanism with the PSO	Fastest convergence rate, gives minimum CTI values	Not dealing with more complicated cases include conflicting objective functions and various systems topologies
	GA-PSO[53]	Accelerate the optimization process, manual tuning steps	A highly reliable coordination, able to identify the pairs in which the backup relays fail to react to faults	No result presented or validation being made for tested under network reconfigure cases
	NM-PSO [97]	Optimise the relay setting using PSO and implement melder mead to enhance the efficiency	Fast and better rate of convergence	Not considering continuous value

Table 2. (Continued).

Type of techniques	AI/NIA techniques	Main feature	Advantages	disadvantages
	PSO-DE [77]	Use two different evolutionary algorithms by exploring the search space first globally and then locally	able to find superior TDS and PS and thus minimum operating time of the relays and minimum CTI	Not robust
	SA-SOS [98]	Proposed new objective function by incorporating the summation of time operating for far end and near end DOCR relay to clear fault	minimum function evaluations required by the algorithm to reach the optimum	Applicable only for small bus system, need extensive statistical analysis and parameters tuning can further highlight and improve the efficiency of SASOS
Mathematical	MINLP solver [99]	Two-stage analytical approach	remove infeasibility of the MINLP coordination problem and converge to an optimal solution in a few iterations	Consuming more time for each subproblem stage due to the iterations process
	Analytic approach [100]	Proposed new optimal relay setting procedure, an iterative numerical solution	fast convergence, small run time, initial values independence, insensitiveness to coordination order	No mathematical formulation has been proposed to assure the convergence of the proposed algorithm
	Interval linear programming [54]	Convert the set of inequality constraints corresponding to each relay pair to an interval constraint, modelling topology uncertainty in the large-scale coordination problem	number of coordination constraints is significantly reduced	The result has not been verified

Table 2. (Continued).

Type of techniques	AI/NIA techniques	Main feature	Advantages	disadvantages
	AMPL [101]	Utilizing a mathematical programming language (AMPL) based interior point optimization (IPOPT) solver	Good results in reasonably small time and thus suitable for the adaptive protection scheme	No comparison being made to justify the efficiency of the method
	LP-interior point algorithm [55]	Use the variation of the primal-dual approach that uses multiple correctors of centrality	capable to reduce the dimension of the coordination problem and the number of constraints	No comparison with other technique to justified the efficiency of the method
ANN,AI	Fuzzy (FLDM)-Fast recursive discrete Fourier transform (FRDFT) [102]	FRDFT algorithm is used for efficient fundamental tracking of varying power system signals and embedded with an FLDM for obtaining optimal protection settings for different topology	Easily coordinated with other numerical relays, computationally effective	The identification of all potential network topologies are difficult.
	ANN [102]	Used in the prediction of miscoordination time of relay operations.	Able to find the minimum solution for medium size of radial network	Still produce miscoordination
	Adaptive neuro-fuzzy [103]	Proposed the adjustment of the overcurrent relay's pick-up currents with instantaneous and current-voltage based inverse-time units	Develop in time characteristic curve,TCC relay	Still limited on the radial system network

Table 2. (Continued).

Type of techniques	AI/NIA techniques	Main feature	Advantages	disadvantages
	Cascade forward neural network (CFNN) [104]	It is modelled using cascade neural network by comparing the number of neurons and learning rates in the learning and testing processes	Applied to the loop system network, maximizes the weight in the iteration process to achieve the suitable error value based on the setting goal	The complication of DG fault current affects the reliability of the sampling rate
	Levernberg–Marqurdt ANN based [105]	User defined characteristic curve applied to the DOCR	Convenient alternative on curve selection to the conventional DOCR particularly on the implementation phase	Not considering miscoordination issues, not validated on the network system

4.2.1. Mathematical techniques

Mathematical techniques are derived from the numerical formulas based on the mathematical formulation. Researchers have explored new DOCR setting techniques that rely on protective devices and objective functions that are optimally designed. The motivation behind implementing optimization techniques to achieve the exact and reliable setting to all protection schemes in the DN dealing with DG [54–56].

Some researchers have formulated the relay coordination as a nonlinear programming problem and it is solved by implementing various optimization techniques. However, those proposed techniques are complicated and time-consuming [48, 51]. In [34, 35, 51] the relay coordination problem was formulated as a mixed-integer nonlinear programming (MINLP) and was determined using the general algebraic modelling system (GAMS) software. Nevertheless, considering the discrete PSC, the use of binary variables increased the difficulty of the coordination problem [47]. Due to the difficulty of the technique, linear programming (LP) such as simplex, dual simplex, and simplex two-phase methods occasionally were used to coordinate the overcurrent relays [20, 34, 57, 58]. The techniques were based on an initial prediction and can be stuck in the local optima [59]. These techniques specified PSC and each relay operating time is expected to be a linear mathematical function for the TMS setting. In [60], the big M-method was proposed in determining the optimal TMS value of overcurrent relays which assumes that the PS is specified and fixed. Following the proposed techniques in LP and Big-M, the proceeding paper in [61] demonstrated the comparison among the proposed techniques using LP-technique, the big-M technique, and the dual-simplex process.

Linear programming (LP), nonlinear programming (NLP), mixed-integer programming (MIP), mixed-integernonlinear programming (MINLP), branch and bound were already commonly used to deal with the relay coordination problem optimally. High dimensionality and low computational problems of these methods are major disadvantages [14, 62, 63]. The articles in [40, 65] formulated the mixed integer programming problem

(MIP) for directional overcurrent relay coordination. The chances of getting stuck in local optima can be reduced by updating global best (Gbest) and position vector (Pbest) values for each iteration [66]. On-line risk evaluation is implemented in this approach to identify areas of susceptibility, and the probabilities of relay miscoordination are estimated using the event tree approach [67]. Pourtandorost et al. in [68] used LP to perform the optimization towards TMS setting by predetermining the PSC. Birla et al. in [1] carried out sequential quadratic programming (SQP) to discover the solution to the coordination problem of a DOCR based only on the location of fault at the near end which will maintain its optimality. On the other hand, Gholinezhad et al. in [69] has applied additional constraints of near-end selectivity and remote end selectivity to prevent blinding trip. Two phases were designed to address this challenging issue. Regular coordination technique is used in the first stage to classify sympathy tripping. Additional constraint proposed for handling sympathetic tripping obtained from the previous stage are included in the second stage. By relaxing the constraints, this method is able to avoid constraint violation but consumes more time due to the complexity of the network.

Mathematical approaches are effective for simple distribution networks. However, for interconnected power networks, the number of relay coordination pairs is quite large, which leads to the complexity of the matrix coordination constraint. Since the mathematical approach tends to be stuck in local minima in searching space, this gap led the researchers to explore the application of NIA-heuristic and the combination of NIA-heuristic and mathematic approaches to attain the global optimum solution for the coordination problems.

4.2.2. NIA-heuristic and hybrid approach

Metaheuristic techniques known as deterministic and multipoint search optimization have been applied to obtain an optimal global completed in a short computational time and are most widely used to coordinate relays [51]. In the year 2000, So et al. introduced the EP implementation to the protection scheme in [70]. However, two main issues were encountered; relay miscoordination and TSM variable selection. Gupta et al. in [60] identified the relay operating time by using GA for both linear and nonlinear objectives functions. Similarly, L. Yinhong et al. in [71] suggested GA for the optimal coordination of the overcurrent relay, and the constraint interval coding technique were used to improve the performance and accuracy of GA. Asadi and Kouhsari, and Hussain et al. [72, 73] assured that PSO is able to resolve the problems of miscoordination compared to the EP- and the GA-algorithm ways of solving for continuous and discrete TSM and PSC settings. Later, three groups of the researchers, Zieneldin et al., Mansur et al., and Rathniam et al., proposed a modified particle swarm optimization (PSO) to attain the optimum relay settings [39, 74, 75]. However, the optimal outcomes of coordination cannot be sustained. This DOCRs problem is developed as MINLP by the well-established differential evolution (DE) algorithm[76, 77].

New and more comprehensive algorithms such as the hybridation approach have used classical and nature-inspired approaches [21] which have enhanced the convergence and effectiveness of the NIA-heuristic technique. The hybrid type algorithms in general divides the optimization problem into the subproblems, where each subproblem is solved by using a specific algorithm [78]. These techniques are the combination of mathematical and NIA-heuristic or double NIA-heuristic optimization methods, which are widely used to counter a highly constraint DOCR problem [37, 39–41]. The problem of optimum DOCR coordination is normally being formulated as an LPP, whenever current pick-up settings are predetermined. The formulation for each relay operation time is likely to be a linear feature function of its TMS. Bedekar and Bhide et al. have come out with the combination of the GA-NLP method in[35]. The problem of obtaining the optimum setting of TMS and PS of DOCRs is formed as a nonlinear programming issue (NLP). The function adopted a sequential quadratic programming (SQP) approach to gain an optimal global solution for the NLP problem. However, their convergence speed is slow; algorithms become more complex for implementation and require high computation time.

In[79], Zellagui and Abdelaziz adopted numerical relay into a small system. A year later, Al-Roomi et al. proposed a hybrid approach BBO/DE to obtain optimal relay settings by considering numerical and electromechanical DOCR relays [80]. The static DOCR is used, which needs feasible search space, very confined, less accurate time, and is difficult to be feasibly optimized. In [81], the authors proposed an improved hybrid BBO/DE algorithm for the numerical relays to overcome the miscoordination and avoid violation of the relay constraints. Khurshaid et al. in [82] presented a better solution by combining WOA and SA. The literature adopted convex optimization and problem relaxation techniques to coordinate DOCRs, which contributes to a low relay operating time for a complex network. Nevertheless, the technique generated miscoordination in the system.

Generally, NIA-heuristic and hybrid have the potential to mitigate the common issues related to relay coordination with large integrated networks and can easily achieve the optimal global solution. However, it works only for fixed network topology because of the incapability to store many load profile data. Due to this limitation, the researchers had also explored the artificial intelligent approach to address such limitations [106–108].

4.2.3. ANN and AI

Artificial intelligence (AI) is an approach that imitates the humanoid rational of thinking mode and makes a duplication into the computer application that could be utilized to reconfigure networks such as those applied in expert systems [53]. Karupiah et al., with the use of the artificial neural network (ANN) in[83], recommended a new efficient relay operation time which has the capabilities to forecast the possibilities of relay miscoordination in the network; however, the operation of this scheme has not been experimentally validated. Similarly, Emmanuel et al. proposed a novel GA-ANN hybrid approach to determine the time-current characteristics curve for forecasting the actual optimal operating time for each protective relay of different station buses by using the valid experimental result output from the MOF in the GA solution, which addresses the global optimal parameter settings determination as to the input training data to the ANN. However, miscoordination elimination among relay pairs was not improved effectively [84].

In all the aforementioned solutions, the main obstacle is storing and using numerous data related to different groups of protection settings in the computer memory. If the network is extended or more DGs are installed, it would require collecting an immense quantity of data resulting from the hugeness of the set of additional conditions to be considered. Moreover, if the prevailing condition of the microgrid does not match any of the stored protection settings, then consequently, the interpretation of the proposed structure becomes essential. Consequently, to find a solution for the issue related to a conventional system, a flexible approach is required. In [85], Daryani et al. proposed a flexible approach based on fuzzy logic and artificial neural network (ANN), namely adaptive neuro-fuzzy interface system (ANFIS). In the proposed system, the ANFIS structure is incorporated into the developed protection relay model, and the ANFIS structure of each relay is optimally aligned to the DG-connected topological state. The entire relay has perfect performance for post contingency and precontingency conditions. Regardless, network selection is less complicated, and the number of topological changes is very minimal. However, the approach only employed a single inverse type of relay into consideration.

Figure 4 shows the adaptive relaying scheme using ANFIS [85]

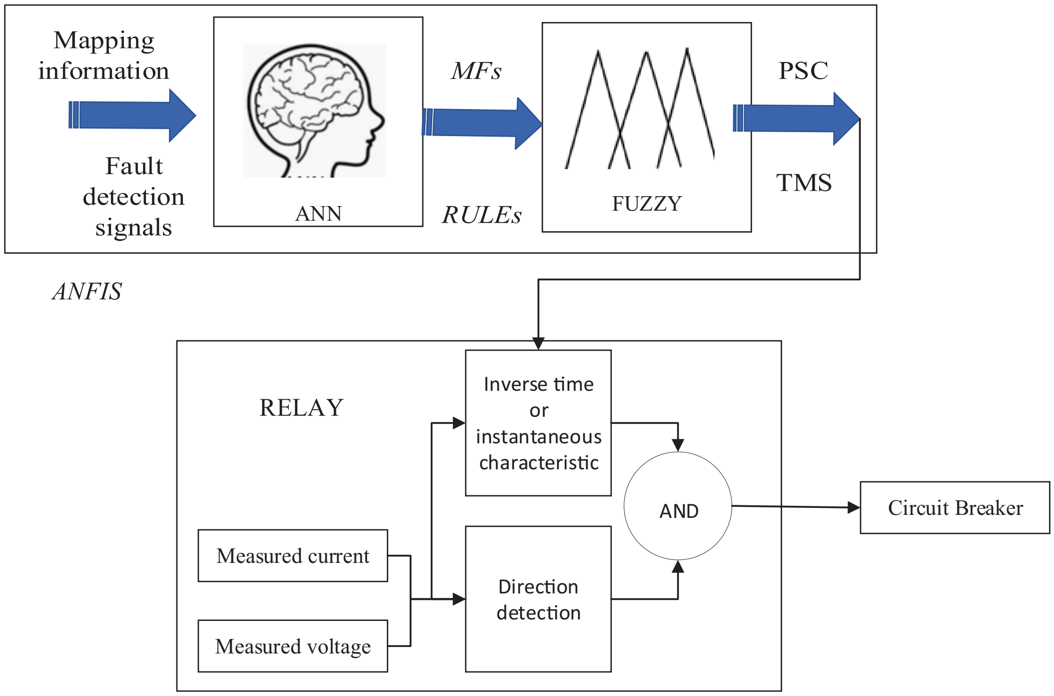

Figure 4. Flow diagram of adaptive relaying scheme using ANFIS.

5. Recommendations for future studies

Future smart grid capabilities promise to leverage network technologies to revolutionize the electricity production, transmission, distribution, and utilization[109]. With the increase of generator assembly capacity, the abundance of power types, and the increasingly close AC-DC hybrid connection of the power grid, the operation characteristics of the power grid are becoming more complex [86, 87]. Therefore, the expansion of power grid-scale and construction of ultrahigh voltage (UHV) power grid that leads to a variation in fault current capacity due to the integration and disintegration of the utility grid, needs to be addressed [88–90]. Based on the reviews presented in this paper, changes in power grids such as high DG penetration and dynamic changing of the load cause erratic to coordinate the relay to address network issues. In this section, future recommendations are made according to the gaps identified from the literature, and a directional relay for future studies is recommended. The key topics related to the hybrid intelligent computerized method that should gain further consideration in future studies include:

i) Removing or reducing the impact of handling constraints as much as possible is a promising solution to achieve major operating time reduction. Thus, a veritable minimization in TMS of relays can be attained without violating any coordination constraint. The motivation behind this is to increase the feasible solution area and reduce the relay coordination problem dimension using the strategies given in [91, 92, 108]. Nonetheless, both approaches should satisfy the inequality coordination constraints, which are related to different network topologies.

ii) Devising a criterion to select relay decision variables or characteristics curves from the standard ones such as IEC, IAC, IEEE and U.S type. Moreover, a new user-defined relay characteristics curve should be considered to obtain more optimal solutions for the relay coordination problem.

iii) Utilizing the hybrid artificial neural network and fuzzy logic into numerical relay coordination to deal with ill-defined and uncertain systems, especially with the IBDG. Furthermore, the modeling of DOCRs using a specific neural network model is likely to generate an accurate outcome. Most of the mathematical based model requires large memory, thus by incorporating the special microprocessor to store the protection algorithm with a variety of settings is the best solution.

iv) It should be emphasised that by minimizing the impact of CTI on the relay operating time in its main protection zone with the increase of the integration of flexible AC transmission system (FACTS) in the distribution network [110], the issue of coordinating protective relays becomes more difficult. Some methods have lately been carried out to counter the effect of the controlled series FACTS device, i.e. TCSC and GCSC, on optimal coordination of DOCRs problem. Therefore, in future studies, the usage of optimization techniques to gain the optimal coordination of DOCRs in the transmission network in the presence of dynamic FACTS is worth to be considered.

v) The difficulties of protection schemes in modern power systems are tackled well by the multiple metaheuristic methods with major improvements such as the use of variation coefficients or the combination of more than one steps of the standard technique. Nevertheless, it is worth establishing a range for each coefficients so that there is no risk of divergence, particularly in large networks exposed to heavy DG penetration and dynamic load redeployment.

6. Conclusion

This paper presents a timely review of the cutting-edge techniques for optimal DOCR coordination protection. Multiple approaches have been proposed in the literature to reduce the complexity of the nonconvex and the nonlinear problems with the highly-constrained and numerous objectives. This paper gives an in-depth review of the hybrid techniques, mathematical algorithms, and AI/ANN approaches. Furthermore, recommendation work is also suggested to enhance the DOCR coordination technique to improve grid operation, security and reliability. It can be observed that conventional methods to solve protection issues corresponding to the modern interconnected DN have almost been replaced by computational intelligence techniques. The research in optimal DOCR coordination is ongoing despite many techniques or methods that have been proposed. This is due to new challenges in power system networks such as the increase in network size, DG penetration and smart grid technology. In addition, the introduction of more advanced optimization techniques also encourages researchers to explore them to obtain improvement in optimal DOCR coordination. Hence, continuous research remains a substantial requirement towards establishing an efficient protection scheme to overcome future challenges.

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References

[1] Birla D, Maheshwari RP, Gupta HO. A new nonlinear directional overcurrent relay coordination technique, and banes and boons of near-end faults based approach. IEEE Transactions on Power Delivery 2006; 21 (3): 1176-1182. doi: 10.1109/TPWRD.2005.861325

[2] Paithankar YG, Bhide S. Fundamentals of Power System Protection. New Delhi, India: PHI Learning Pvt. Ltd, 2011.

[3] Thangaraj R, Pant M, Deep K. Optimal coordination of over-current relays using modified differential evolution algorithms. Engineering Applications of Artificial Intelligence 2010; 23 (5): 820-829. doi: 10.1016/j.engappai.2010.01.024

[4] Feizifar B, Usta Ö. A new failure protection algorithm for circuit breakers using the power loss of switching arc incidents. Turkish Journal of Electrical Engineering & Computer Sciences 2019; 27: 1982-1997. doi: 10.3906/elk-1805-84

[5] Tarsi IK, Sheikholeslami A, Barforoushi T, Sadati SMB. Investigating impacts of distributed generation on distribution networks reliability: A mathematical model. In: IEEE 2010 Electric Power Quality and Supply Reliability Conference; Kuressaare, Estonia; 2010. pp. 117-124.

[6] Tailor J, Osman A. Restoration of fuse-recloser coordination in distribution system with high DG penetration. In: IEEE 2008 Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century; Pittsburgh, PA, USA; 2008. pp. 1-8.

[7] Chaitusaney S, Yokoyama A. Prevention of reliability degradation from recloser–fuse miscoordination due to distributed generation. IEEE Transactions on Power Delivery 2008; 23 (4): 2545-2554. doi: 10.1109/TPWRD.2007.915899

[8] Chaitusaney S, Yokoyama A. Reliability analysis of distribution system with distributed generation considering loss of protection coordination. In: IEEE 2006 International Conference on Probabilistic Methods Applied to Power Systems; Stockholm, Sweden; 2006. pp. 1-8.

[9] Khan AU, Hong Q, Dyśko A, Booth C. Review and evaluation of protection issues and solutions for future distribution networks. In: IEEE 2019 54th International Universities Power Engineering Conference (UPEC); Bucharest, Romania, Romania; 2019. pp. 1-6.

[10] Razavi SE, Rahimi E, Sadegh Javadi M, Nezhad AE, Lotfi M et al. Impact of distributed generation on protection and voltage regulation of distribution systems: a review. Renewable and Sustainable Energy Reviews 2019; 105: 157-167. doi: 10.1016/j.rser.2019.01.050

[11] Elmore WA. Protective Relaying: Theory and Applications. Madison Avenue, NY, USA: CRC Press, 2003.

[12] Abdelaziz AY, Talaat H, Nosseir A, Hajjar AA. An adaptive protection scheme for optimal coordination of overcurrent relays. Electric Power Systems Research 2002; 61 (1): 1-9. doi: 10.1016/S0378-7796(01)00176-6

[13] Hussain M, Musirin I, Rahim S, Abidin AF. Computational intelligence based technique in optimal overcurrent relay coordination: a review. The International Journal of Engineering And Science (IJES) 2013; 2 (1): 01-09. doi: 10.1016/j.proeng.2013.02.043

[14] Urdaneta A, Perez L, Gomez J, Feijoo B, Gonzalez M. Presolve analysis and interior point solutions of the linear programming coordination problem of directional overcurrent relays. International Journal of Electrical Power & Energy Systems 2001; 23 (8): 819-825. doi: 10.1016/S0142-0615(00)00097-1

[15] Urdaneta AJ, Restrepo H, Marquez S, Sanchez J. Coordination of directional overcurrent relay timing using linear programming. IEEE Transactions on Power Delivery 1996; 11 (1): 122-129. doi: 10.1109/61.484008

[16] Zocholl S, Akamine J, Hughes A, Sachdev M, Scharf L. Computer representation of overcurrent relay characteristics. In: IEEE 1089 committee report; New York, USA; 1989. pp. 1659-1667.

[17] Singh M. Protection coordination in distribution systems with and without distributed energy resources-a review. Protection and Control of Modern Power Systems 2017; 2 (1): 1-17. doi: 10.1186/s41601-017-0061-1

[18] Damborg MJ, Ramaswami R, Venkata SS, Postforoosh JM. Computer aided transmission protection system design part I: Alcorithms. IEEE Transactions on Power Apparatus and Systems 1984; (1): 51-59. doi: 10.1109/TPAS.1984.318576

[19] Shah KR, Detjen ED, Phadke AG. Feasibility of adaptive distribution protection system using computer overcurrent relaying concept. IEEE Transactions on Industry Applications 1988; 24 (5): 792-797. doi: 10.1109/28.8981

[20] Rashtchi V, Gholinezhad J, Farhang P. Optimal coordination of overcurrent relays using Honey Bee Algorithm. In: IEEE 2010 International Congress on Ultra Modern Telecommunications and Control Systems; Moscow, Russia; 2010. pp. 401-405.

[21] Korashy A, Kamel S, Youssef AR, Jurado F. Modified water cycle algorithm for optimal direction overcurrent relays coordination. Applied Soft Computing 2019; 74: 10-25. doi: 10.1016/j.asoc.2018.10.020

[22] Raza SA, Mahmood T, Bukhari SBA, Nawaz MK. Application of optimization techniques in overcurrent relay coordination-a review. World Applied Sciences Journal 2013; 28 (2): 259-265. doi:10.5829/idosi.wasj.2013.28.02.12400

[23] Uthitsunthorn D, Pao-La-Or P, Kulworawanichpong T. Optimal overcurrent relay coordination using artificial bees colony algorithm. In: IEEE 2011 The 8th Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI); Khon Kaen, Thailand; 2011. pp. 901-904.

[24] So C, Li K, Lai K, Fung K. Application of genetic algorithm for overcurrent relay coordination. In: IET 1997 6th International Conference on Developments in Power Systems Protection; Nottingham, UK; 1997. pp. 66-69.

[25] Birla D, Maheshwari RP, Gupta H. A new nonlinear directional overcurrent relay coordination technique, and banes and boons of near-end faults based approach. IEEE Transactions on Power Delivery 2006; 21 (3): 1176-1182. doi: 10.1109/TPWRD.2005.861325

[26] Gokhale S, Kale V. Application of the Firefly algorithm to optimal over-current relay coordination. In: IEEE 2014 International Conference on Optimization of Electrical and Electronic Equipment (OPTIM); Bran, Romania; 2014. pp. 150-154.

[27] Amraee T. Coordination of directional overcurrent relays using seeker algorithm. IEEE Transactions on Power Delivery 2012; 27 (3): 1415-1422. doi: 10.1109/TPWRD.2012.2190107

[28] Papaspiliotopoulos VA, Kurashvili T, Korres GN. Optimal coordination of directional overcurrent relays in distribution systems with distributed generation based on a hybrid PSO-LP algorithm. In: IET 2014 MedPower; Athens, Greece; 2014. pp. 64-66.

[29] Radosavljević J, Jevtić M. Hybrid GSA-SQP algorithm for optimal coordination of directional overcurrent relays. IET Generation, Transmission Distribution 2016; 10 (8): 1928-1937. doi: 10.1049/iet-gtd.2015.1223

[30] Noghabi AS, Sadeh J, Mashhadi HR. Considering different network topologies in optimal overcurrent relay coordination using a hybrid GA. IEEE Transactions on Power Delivery 2009; 24 (4): 1857-1863. doi: 10.1109/TPWRD.2009.2029057

[31] Costa MH, Saldanha RR, Ravetti MG, Carrano EG. Robust coordination of directional overcurrent relays using a matheuristic algorithm. IET Generation, Transmission Distribution 2017; 11 (2): 464-474. doi: 10.1049/iet-gtd.2016.1010

[32] Bedekar PP, Bhide SR. Optimum coordination of directional overcurrent relays using the hybrid GA-NLP approach. IEEE Transactions on Power Delivery 2010; 26 (1): 109-119. doi: 10.1109/TPWRD.2010.2080289

[33] Albasri FA, Alroomi AR, Talaq JH. Optimal coordination of directional overcurrent relays using biogeography-based optimization algorithms. IEEE Transactions on Power Delivery, 2015; 30 (4): 1810-1820. doi: 10.1109/TPWRD.2015.2406114

[34] Noghabi AS, Sadeh J, Mashhadi HR. Considering different network topologies in optimal overcurrent relay coordination using a hybrid GA. IEEE Transactions on Power Delivery 2009; 24 (4): 1857-1863. doi: 10.1109/TPWRD.2009.2029057

[35] Bedekar PP, Bhide SR. Optimum coordination of directional overcurrent relays using the hybrid GA-NLP approach. IEEE Transactions on Power Delivery 2010; 26 (1): 109-119. doi: 10.1109/TPWRD.2010.2080289

[36] Rajput VN, Pandya KS. Coordination of directional overcurrent relays in the interconnected power systems using effective tuning of harmony search algorithm. Sustainable Computing: Informatics and Systems 2017; 15: 1-15. doi: 10.1016/j.suscom.2017.05.002

[37] Damchi Y, Dolatabadi M, Mashhadi HR, Sadeh J. MILP approach for optimal coordination of directional overcurrent relays in interconnected power systems. Electric Power Systems Research 2018; 158: 267-274. doi: 10.1016/j.epsr.2018.01.015

[38] Amraee T. Coordination of directional overcurrent relays using seeker algorithm. IEEE Transactions on Power Delivery 2012; 27 (3): 1415-1422. doi: 10.1109/TPWRD.2012.2190107

[39] Mansour MM, Mekhamer SF, El-Kharbawe N. A modified particle swarm optimizer for the coordination of directional overcurrent relays. IEEE Transactions on Power Delivery 2007; 22 (3): 1400-1410. doi: 10.1109/TPWRD.2007.899259

[40] Urdaneta AJ, Nadira R, Jimenez LP. Optimal coordination of directional overcurrent relays in interconnected power systems. IEEE Transactions on Power Delivery 1988; 3 (3): 903-911. doi: 10.1109/61.193867

[41] Yadav P, Kumar R, Panda SK, Chang CS. An intelligent tuned harmony search algorithm for optimisation. Information Sciences 2012; 196: 47-72. doi: 10.1016/j.ins.2011.12.035

[42] Moravej Z, Adelnia F, Abbasi F. Optimal coordination of directional overcurrent relays using NSGA-II. Electric Power Systems Research 2015; 119: 228-236. doi: 10.1016/j.epsr.2014.09.010

[43] Pabla AS. Electric Power Distribution. New York, USA: Tata McGraw-Hill Education, 2012.

[44] Singh M, Panigrahi B, Abhyankar AR. Optimal coordination of directional over-current relays using teaching learning-based optimization (TLBO) algorithm. International Journal of Electrical Power & Energy Systems 2013; 50: 33-41. doi: 10.1016/j.ijepes.2013.02.011

[45] Dwarakanath M, Nowitz L. An application of linear graph theory for coordination of directional overcurrent relays. In: SIAM 1980 Electric Power Problems-The Mathematical Challenge; Seattle, WA, USA; 1980. pp. 104-114.

[46] Jenkins L, Khincha H, Shivakumar S, Dash PK. An application of functional dependencies to the topological analysis of protection schemes. IEEE Transactions on Power Delivery 1992; 7 (1): 77-83. doi: 10.1109/61.108892

[47] Birla D, Maheshwari RP, Gupta HO. Time-overcurrent relay coordination: a review. International Journal of Emerging Electric Power Systems 2005; 2 (2). doi: 10.2202/1553-779X.1039

[48] Hussain MH, Rahim SRA, Musirin I. Optimal overcurrent relay coordination: a review. In: Procedia 2012 Engineering Malaysian Technical Universities Conference on Engineering & Technology(MUCET); Penang,Malaysia; 2012. pp. 332-336.

[49] Hussain M, Musirin I, Abidin A, Rahim SA. Solving directional overcurrent relay coordination problem using artificial bees colony. Engineering and Technology International Journal of Electrical, Electronic Science and Engineering 2014; 8: 766-771. doi: 10.5281/zenodo.1092584

[50] Ezzeddine M, Kaczmarek R. A novel method for optimal coordination of directional overcurrent relays considering their available discrete settings and several operation characteristics. Electric Power Systems Research 2011; 81 (7): 1475-1481. doi: 10.1016/j.epsr.2011.02.014

[51] Abyaneh HA, Al-Dabbagh M, Karegar HK, Sadeghi SHH, Khan RJ. A new optimal approach for coordination of overcurrent relays in interconnected power systems. IEEE Transactions on power delivery 2003; 18 (2): 430-435. doi: 10.1109/TPWRD.2002.803754

[52] Ezzeddine M, Kaczmarek R, Iftikhar MU. Coordination of directional overcurrent relays using a novel method to select their settings. IET Generation, Transmission & Distribution 2011; 5 (7): 743-750.doi: 10.1049/iet-gtd.2010.0603

[53] Norshahrani M, Mokhlis H, Bakar A, Halim A, Jamian JJ, Sukumar S. Progress on protection strategies to mitigate the impact of renewable distributed generation on distribution systems. Energies 2017; 10 (11): 1864. doi: 10.3390/en10111864

[54] Ehrenberger J, Švec J. Protection settings optimization in distributed generation system. In: IEEE 2016 International Energy Conference (ENERGYCON); Leuven, Belgium; 2016. pp. 1-6.

[55] Bouchekara H, Zellagui M, Abido MA. Optimal coordination of directional overcurrent relays using a modified electromagnetic field optimization algorithm. Applied Soft Computing 2017; 54: 267-283. doi: 10.1016/j.asoc.2017.01.037

[56] Sharaf HM, Zeineldin H, Ibrahim DK, Essam EL. A proposed coordination strategy for meshed distribution systems with DG considering user-defined characteristics of directional inverse time overcurrent relays. Applied Soft Computing 2015; 65: 49-58. doi: 10.1016/j.ijepes.2014.09.028

[57] Razavi F, Abyaneh HA, Al-Dabbagh A, Mohammadi R, Torkaman HA. A new comprehensive genetic algorithm method for optimal overcurrent relays coordination. Electric Power Systems Research 2008; 78 (4): 713-720. doi: 10.1016/j.epsr.2007.05.013

[58] Singh M, Panigrahi B, Abhyankar A. Optimal overcurrent relay coordination in distribution system. In: IEEE 2011 International Conference on Energy, Automation and Signal; Bhubaneswar, Odisha, India; 2011. pp. 1-6.

[59] Moravej Z, Jazaeri M, Gholamzadeh M. Optimal coordination of distance and over-current relays in series compensated systems based on MAPSO. Energy Conversion and Management 2012; 56: 140-151. doi: 10.1016/j.enconman.2011.11.024

[60] Bedekar PP, Bhide SR, Kale VS. Optimum time coordination of overcurrent relays in distribution system using big-M (penalty) method. WSEAS Transactions on Power Systems 2009; 4 (11): 341-350.

[61] Bedekar PP, Bhide SR, Kale VS. Determining optimum TMS and PS of overcurrent relays using linear programming technique. In: IEEE 2011 The 8th Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI); Khon Kaen, Thailand; 2011. pp. 700-703.

[62] Noghabi AS, Mashhadi HR, Sadeh J. Optimal coordination of directional overcurrent relays considering different network topologies using interval linear programming. IEEE Transactions on Power Delivery 2010; 25 (3): 1348-1354. doi: 10.1109/TPWRD.2010.2041560

[63] So C, Li KK. Time coordination method for power system protection by evolutionary algorithm. IEEE Transactions on Industry Applications 2000; 36 (5): 1235-1240. doi: 10.1109/28.871269

[64] Zeienldin H, El-Saadany E, Salama M. A novel problem formulation for directional overcurrent relay coordination. In: IEEE 2004 Large Engineering Systems Conference on Power Engineering; Halifax, NS, Canada; 2004. pp. 48-52.

[65] Aggarwal C, Mangalvedekar H, Chaudhari H. Effect of fault location on optimal coordination of directional over current relay. In: IEEE 2008 TENCON 2008-2008 IEEE Region 10 Conference; Hyderabad, India; 2008. pp. 1-5.

[66] Gholinezhad J, Mazlumi K, Farhang P. Overcurrent relay coordination using MINLP technique. In: IEEE 2011 19th Iranian Conference on Electrical Engineering; Tehran, Iran; 2011. pp. 1-6.

[67] Perez LG, Urdaneta AJ. Optimal coordination of directional overcurrent relays considering definite time backup relaying. Electric Power Systems Research 81 1999; 14 (4): 1276-1284. doi: 10.1109/61.796218

[68] Jamali S, Pourtandorost M. New approach to coordination of distance relay zone-2 with overcurrent protection using linear programming methods. In: IEEE 2004 39th International Universities Power Engineering Conference; Bristol, UK; 2004. pp. 827-831.

[69] Birla D, Maheshwari RP, Gupta HO. An approach to tackle the threat of sympathy trips in directional overcurrent relay coordination. IEEE Transactions on power delivery 2007; 22 (2): 851-858. doi: 10.1109/TPWRD.2007.893587

[70] So C, Li KK. Overcurrent relay coordination by evolutionary programming. Electrical Power System Research 2000; 53 (2): 83-90. doi: 10.1016/S0378-7796(99)00052-8

[71] Yinhong L, Dongyuan S, Xianzhong D. A study on optimal coordination of definite-time relay based on genetic algorithm. In: IEEE PES 2003 Transmission and Distribution Conference and Exposition; Dallas, TX, USA; 2003. pp. 279-284.

[72] Asadi M, Kouhsari S. Optimal overcurrent relays coordination using particle-swarm-optimization algorithm. In: IEEE/PES 2009 Power Systems Conference and Exposition; Seattle, WA, USA; 2009. pp. 1-7.

[73] Hussain M, Musirin I, Rahim, Abidin A, Azmi A. Optimal overcurrent relay coordination using particle swarm optimization. In: InECCE 2013 International Conference on Electrical, Control and Computer Engineering (InECCE 2013); Pahang, Malaysia; 2013, pp. 42-47.

[74] Zeineldin H, El-Saadany EF, Salama MMA. Optimal coordination of overcurrent relays using a modified particle swarm optimization. Electric Power Systems Research 2006; 76 (11): 988-995. doi: 10.1016/j.epsr.2005.12.001

[75] Rathinam A, Sattianadan D, Vijayakumar K. Optimal coordination of directional overcurrent relays using particle swarm optimization technique. International Journal of Computer Applications 2010; 10 (2): 43-47. doi: 10.5120/1451-1762

[76] Yang H, Wen F, Ledwich G. Optimal coordination of overcurrent relays in distribution systems with distributed generators based on differential evolution algorithm. International transactions on electrical energy systems 2013; 23 (1): 1-12. doi: 10.1002/etep.635

[77] Yang M, Luo C. Optimization Theory, Method and Solution Software. Beijing: Science Press, 2006.

[78] Kida AA, Rivas AEL, Gallego LA. An improved simulated annealing–linear programming hybrid algorithm applied to the optimal coordination of directional overcurrent relays. Electric Power Systems Research 2020; 181: 106197. doi: 10.1016/j.epsr.2020.106197

[79] Zellagui M, Abdelaziz AY. Optimal coordination of directional overcurrent relays using hybrid PSO-DE algorithm. International Electrical Engineering Journal (IEEJ) 2015; 6 (4): 1841-1849.

[80] Al-Roomi AR, El-Hawary ME. Optimal coordination of directional overcurrent relays using hybrid BBO/DE algorithm and considering double primary relays strategy. In: IEEE 2016 Electrical Power and Energy Conference (EPEC); Ottawa, ON, Canada; 2016. pp. 1-7.

[81] Al-Roomi AR, El-Hawary ME. Optimal coordination of double primary directional overcurrent relays using a new combinational BBO/DE algorithm. Canadian Journal of Electrical and Computer Engineering 2019; 42 (3): 135-147. doi: 10.1109/CJECE.2018.2802461

[82] Khurshaid T, Wadood A, Farkoush SG, Yu J, Kim CH et al. An improved optimal solution for the directional overcurrent relays coordination using hybridized whale optimization algorithm in complex power systems. IEEE Access 2019; 7: 90418-90435. doi: 10.1109/ACCESS.2019.2925822

[83] Karupiah S, Hussain M, Musirin I, Rahim SRA. Prediction of overcurrent relay miscoordination time using urtificial neural network. Indonesian Journal of Electrical Engineering and Computer Science 2019; 14 (1): 319-326. doi: 10.11591/ijeecs.v14.i1.pp319-326

[84] Emmanuel O, Othman ML, Hizam H, Rezaei N, Othman MM. Time-current characteristic curve prediction for directional overcurrent relays in interconnected network using artificial neural network. ARPN Journal of Engineering and Applied Sciences 2015; 10 (1): 10679-10685.

[85] Daryani MJ, Karkevandi AE, Usta Ö. A Hybrid Approach for Microgrid Protection System Based on Neural Network and Fuzzy Logic. In: IEEE 2019 PES Innovative Smart Grid Technologies Europe (ISGT-Europe); Bucharest, Romania; 2019. pp. 1-5.

[86] Fucai L, Tao C, Qiuting G, Yuchen Q, Wei H. Design and implementation of intelligent dispatching operation strategy platform for power grid with UHV. In: IEEE 2019 Innovative Smart Grid Technologies-Asia (ISGT Asia); Chengdu, China; 2019. pp. 3788-3792.

[87] Ross KJ, Hopkinson KM, Pachter M. Using a distributed agent-based communication enabled special protection system to enhance smart grid security. IEEE Transactions on Smart Grid 2013; 4 (2): 1216-1224. doi: 10.1109/TSG.2013.2238261

[88] Lu J, Xie D, Ai Q. Research on smart grid in China. In: IEEE 2009 Transmission & Distribution Conference & Exposition: Asia and Pacific; Seoul, Korea; 2009. pp. 1-4.

[89] Gellings C. Using a smart grid to evolve a reliable power system. In: IEEE 2010 International Reliability Physics Symposium; Anaheim, CA, USA; 2010. pp. 1-2.

[90] Sun DQ, Zheng JW, Zhang T, Zhang ZJ, Liu HT et al. The utilization and development strategies of smart grid and new energy. In: IEEE 2010 Asia-Pacific Power and Energy Engineering Conference; Chengdu, China; 2010. pp. 1-4.

[91] Karegar HK, Abyaneh HA, Ohis V, Meshkin M. Pre-processing of the optimal coordination of overcurrent relays. Electric Power Systems Research 2005; 75 (2-3): 134-141. doi: 10.1016/j.epsr.2005.02.005

[92] Ezzeddine M, Kaczmarek R. Reduction of effect of coordination constraints in the linear optimization of operating times of overcurrent relays. In: IEEE 2008 The 14th IEEE Mediterranean Electrotechnical Conference; Ajaccio, France; 2008. pp. 707-712.

[93] Tjahjono A, Anggriawan DO, Priyadi A, Pujiantara M, Purnomo MH. Digital overcurrent relay with conventional curve modeling using Levenberg-Marquardt backpropagation. In: IEEE 2015 International Seminar on Intelligent Technology and Its Applications (ISITIA); Surabaya, Indonesia; 2015. pp. 171-176.

[94] Bougouffa L, Chaghi A. Optimal coordination time interval for DOCRs in presence of D-FACTS. In: IEEE 2018 5th International Congress on Information Science and Technology (CiSt); Marrakech, Morocco; 2018. pp. 477-480.

[95] Singh DK, Gupta S. Optimal coordination of directional overcurrent relays: A genetic algorithm approach. In: IEEE 2012 Students' Conference on Electrical, Electronics and Computer Science; Bhopal, Madhya Pradesh, India; 2012. pp. 1-4.

[96] Bedekar PP, Bhide SR. Optimum coordination of overcurrent relay timing using continuous genetic algorithm. Expert Systems with Applications 2011; 38 (9): 11286-11292. doi: 10.1016/j.eswa.2011.02.177

[97] Wadood A, Kim CH, Khurshiad T, Farkoush SG, Rhee SB. Application of a continuous particle swarm optimization (CPSO) for the optimal coordination of overcurrent relays considering a penalty method. Energies 2018; 11 (4): 869. doi: 10.3390/en11040869

[98] Zellagui M, Hassan HA. A hybrid optimization algorithm (IA-PSO) for optimal coordination of directional overcurrent relays in meshed power systems. WSEAS Transactions on Power Systems 2015; 10: 240-250.

[99] Darabi A, Bagheri M, Gharehpetian GB. Highly accurate directional overcurrent coordination via combination of Rosen's gradient projection–complex method with GA-PSO algorithm. IEEE Systems Journal 2019; 14 (1): 1171-1182. doi: 10.1109/JSYST.2019.2904383

[100] Liu A, Yang MT. A new hybrid nelder-mead particle swarm optimization for coordination optimization of directional overcurrent relays. Mathematical Problems in Engineering 2012; 18: 1-18. doi: 10.1155/2012/456047

[101] Sulaiman M, Ahmad A, Khan A, Muhammad S. Hybridized symbiotic organism search algorithm for the optimal operation of directional overcurrent relays. Complexity 2018; 11: 1-11. doi: 10.1155/2018/4605769

[102] Saberi H, Amraee T. Coordination of directional over-current relays in active distribution networks using generalised benders decomposition. IET Generation, Transmission & Distribution 2017; 11 (16): 4078-4086. doi: 10.1049/iet-gtd.2017.0434

[103] Mahari A, Seyedi H. An analytic approach for optimal coordination of overcurrent relays.IET Generation, Transmission & Distribution 2013; 7 (7): 674-680. doi: 10.1049/iet-gtd.2012.0721

[104] Alam M. Adaptive protection coordination scheme using numerical directional overcurrent relays. IEEE Transactions on Industrial Informatics 2018; 15 (1): 64-73. doi: 10.1109/TII.2018.2834474

[105] Kumar DS, Srinivasan D, Reindl T. A fast and scalable protection scheme for distribution networks with distributed generation. IEEE Transactions on Power Delivery 2015; 31 (1): 67-75. doi: 10.1109/TPWRD.2015.2464107

[106] Tjahjono A, Anggriawan DO, Priyadi A, Pujiantara M, Purnomo MH. Overcurrent relay curve modeling and its application in the real industrial power systems using adaptive neuro fuzzy inference system. In: IEEE 2015 IEEE International Conference on Computational Intelligence and Virtual Environments for Measurement Systems and Applications (CIVEMSA); Shenzhen, China; 2015. pp. 1-6.

[107] Sahrin A, Tjahjono A, Pujiantara M, Purnomo MH. The modeling of directional overcurrent relay in loop system using cascade forward neural network. In: IEEE 2017 International Seminar on Intelligent Technology and Its Applications (ISITIA); Surabaya, Indonesia; 2017. pp. 69-74.

[108] Anggriawan DO, Prasetyono E, Fahrisi F, Budikarso A, Tjahjono A et al. Digital overcurrent relay implementation with non-standard inverse curve modelling using adaptive neuro fuzzy inference system. In: IEEE 2019 International Conference of Artificial Intelligence and Information Technology (ICAIIT); Yogyakarta, Indonesia; 2019. pp. 327-330.

[109] Zare O, Galvani S, Farsadi M. Robust optimal operation of smart distribution grids with renewable based generators. Turkish Journal of Electrical Engineering & Computer Sciences 2020; 28: 799-820. doi: 10.3906/elk-1901-182

[110] Ahmad AS, Adamu SS, Buhari M. Available transfer capability enhancement with FACTS using hybrid PI-PSO. Turkish Journal of Electrical Engineering & Computer Sciences 2019; 27: 2881-2897. doi:10.3906/elk-1812-54