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ORIGINAL PAPER

Soft Computing Methods for Attaining the Protective Device Coordination Including Renewable Energies: Review and Prospective

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Abstract

The optimized coordination of directional over current relays (DOCRs) in power systems is still a challenging task. This optimization problem has been augmented in the literature through coping with various methodologies and the progress is not over yet. Thanks to the advance in technology, this task is mitigated in terms of time consuming and computational errors via applying different metaheuristic and nature inspired algorithms. Break points approach, distributed generations (DGs) penetration, mixed distance and DOCRs coordination, dual-setting DOCRs concept, transient stability constraint, and adaptive coordination represent most of the work performed by the researchers in the literature. However, some issues have not been tackled in this optimization process that deems a fertile ground needs tedious endeavors. This review article sheds the light on the most recently optimization approaches which are prevalent to deal with these highly constrained optimization problems. In the same context, many researchers are proposed various optimization frameworks to deal with coordination optimization problems aiming to have better performance and to define optimal relay settings. This review article is useful in the field of optimal relaying coordination of power systems with embedded DGs as it presents a comprehensive overview for many of the contributions of researchers in recent years. Detailed various formulations to represent the coordination problem with associated solution approaches are discussed and concluded.

List of Symbols

i	Relay identifier
r	Index of coordination pairs
M	Total number of fault locations
X	Total number of backup relays for each primary relay
I_{pi}	Pickup current of relay i
t_i	Operating time of ith relay
t_{ijl}	Operating time of ith relay at jth location for lth fault type
I_{fi}	Fault current passing through relay i
CTI	Coordination Time Interval
T_{mc}	Total number of miscoordinations
F_1	Near end fault
t_{piF_2}	Operating time of *i*th primary relay for fault F_2
k_i	Number of configurations in the kth SG
V_{fijl}	Per-unit phase fault voltage magnitude measured at ith relay at jth location for lth fault type
$I_{SC,backup^{2\Phi}}$	Minimum two-phase fault passing through the backup relay
t_{br}	Operating time of the backup relay for rth coordination pair
a, b, and w_i	Weighting factors
λ	Transient stability constraint penalty factor
I_{rvsi}	Inverse short circuit current seen by ith relay
j	Fault location identifier
x	Backup relay identifier
L	Total number of fault types
$t_{i,j}$	Operating time of ith relay at jth location
TDS_i	Time Dial Setting of relay number i
t_{pilj}	Operating time of ith primary relay at jth location for lth fault type
t_{pij}	Operating time of ith primary relay for jth fault
TDS_{fwi}	TDS of ith relay forward direction
TDS_{rvi}	TDS of ith relay reverse direction
I_{pfwi}	Pickup current of ith relay forward direction

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I_{prvi}	Pickup current of ith relay reverse direction
t_{fwi}	Operating time of ith relay forward direction
t_{rvi}	Operating time of ith relay reverse direction
A_{fwi}, B_{fwi}, C_{fwi}	TCC coefficients of ith relay forward direction
A_{rvi}, B_{rvi}, C_{rvi}	TCC coefficients of ith relay reverse direction
N_p	Number of primary relays
N_c	Number of close-in relays
F_2	Far end fault
t_{br}	Operating time of the backup relay for rth coordination pair
$I_{fault,min}$	Minimum fault current
$I_{load,max}$	Maximum load current
e^1	Exponential factor = 2.718
K_s	Sensitivity factor
OLF	Over Loading Factor
$t_{ij,phase}$	Operating time of the ith phase OCR for the jth fault
$E_{CTI_{L1}}$	CTI error in the rth coordination pair
l	Fault type identifier
N	Total number of relays
TP	Total number of coordination pairs
A, B, and C	TCC coefficients
Δt	Discrimination time
t_{bilj}	Operating time of ith backup relay at jth location for lth fault type
t_{bij}	Operating time of ith backup relay for jth fault
N_b	Number of backup relays
N_f	Number of far-bus relays
t_{piF_1}	Operating time of ith primary relay for fault F_1
$K1$	Constant parameter
k	Index of number of relays setting groups
m	Number of available relays setting groups
T_{z1}	First zone timing of distance relay
T_{z2}	Second zone timing of distance relay
T_{z3}	Third zone timing of distance relay
$I_{load,max}$	Maximum temporary load current
IE	Incident Energy
$t_{ij,earth}$	Operating time of the ith earth OCR for the jth fault

Abbreviations

DOCRs	Directional Over Current Relays
PS	Plug Setting
AI	Artificial Intelligence
IDMT	Inverse Definite Minimum Time
IEC	International Electrotechnical Commission
ANSI	American National Standard Institute
IEEE	Institute of Electrical and Electronics Engineers
NS-CCs	Non-Standard Characteristics
CADD	Connecting and Disconnecting of DGs
SBDGs	Synchronous-Based DGs
IBDGs	Inverter-Based DGs
ADNs	Active Distribution Networks
RESs	Renewable Energy Sources
DERs	Distributed Energy Resources
DTCC	Dual Time–Current Characteristics
PSO	Particle Swarm Optimization
EFO	Electromagnetic Field Optimization
NM-PSO	Nelder-Mead PSO
TLBO	Teaching Learning Based Optimization
CSA	Cuckoo Search Algorithm
BBO-DE	Biogeography Based Optimization DE
HPHA	High-Performance Hybrid Algorithm
EHA	Efficient Heuristic Algorithm
GSA-SQP	Gravitational Search Algorithm Sequential Quadratic Programing
EBSA	Enhanced Backtracking Search Algorithm
DC-HSS	Discrete-Continuous Hyper Sphere Search
FDMT	Fuzzy Decision-Making Tool
MOGWO	Multi-Objective GWO
ESA-DEMO	Enhanced Self Adaptive DE Multi-Objective
DFSA	Depth-First Search Algorithm
VNS	Variable Neighborhood Search
SFLA	Shuffled Frog Leaping Algorithm
MPSO-ILP	Modified PSO- Interval LP
SFLA	Shuffled Frog Leaping Algorithm
TVAC	Time-Varying Acceleration Coefficients
MATLAB	Matrix Laboratory
ETAP	Electrical Transient Analyzer Program
PSCAD	Power System Computer Aided Design
Fmincon	Built in function in the MATLAB optimization toolbox
SCADA	Supervisory Control And Data Acquisition
DGs	Distributed Generations
LP	Linear Programming
TMS	Time Multiplier Setting
TCCs	Time–Current Characteristics
NI	Normal Inverse
VI	Very Inverse
LI	Long Inverse
DI	Definite Inverse
CI	Classifying Index
SGs	Setting Groups
P/B	Primary/Backup

PV	Photo-Voltaic
FCL	Fault Current Limiter
PCC	Point of Common Coupling
DFIG	Doubly Fed Induction Generator
GA	Genetic Algorithm
LFA	Lightning Flash Algorithm
DE	Differential Evolution
RCGA	Real Coded GA
SOS	Symbiotic Organism Search
SGA	Specialized GA
CFA	Chaotic FA
HS	Harmony Search
RTO	Root Tree Optimization
SFSA	Stochastic Fractal Search Algorithm
WCA	Water Cycle Algorithm
IWO	Invasive Weed Optimization
EGWO	Enhanced GWO
MWCA	Modified WCA
ICGA	Integer Coded GA
C-DEPSO	Canonical DE PSO
RW-GWO	Random Walk GWO
MVO	Multi-Verse Optimizer
CPSO	Chaotic PSO
ALO	Ant Lion Optimizer
AIS	Artificial Immune System
SA	Seeker Algorithm
NSGA	Nondominated Sorting GA
AMFA	Adaptive Modified FA
BIP	Binary Integer Programming
GACB	Genetic Algorithm of Chu-Beasley
IFA	Improved FA
OF	Objective Function
EI	Extremely Inverse
MI	Moderately Inverse
SI	Short Inverse
CFP	Critical Fault Point
DIOCR	Doubly-Inverse OCR
MBPS	Minimum Break Point Set
MGs	Microgrids
CT	Current Transformer
CCT	Critical Clearing Time
SLGF	Single Line to Ground Fault
HPSO	Hybrid PSO
ABC	Artificial Bee Colony
MEFO	Modified EFO
FA	Firefly Algorithm
RL	Reinforcement Learning
FPA	Flower Pollination Algorithm
SAA	Simulated Annealing Algorithm
HWOA	Hybridized Whale Optimization Algorithm
GWO	Grey Wolf Optimization
IIWO	Improved IWO
C	Continuous
D	Discrete

1 Introduction

Power systems have to be protected from different types of faults to ensure the reliability, sensitivity, speed, and selectivity. Selectivity or coordination is the terminology of applying consecutive operation of protective devices to ensure the minimum outage of the network [1]. Since the over current relays (OCRs) are used as the main protection in distribution systems and backup protection in transmission and sub transmission systems, their coordination has become obligatory. The primary OCR is the responsible for detecting and isolating the fault first, and if it fails, its backup protection should act after a time margin called the Coordination Time Interval (CTI) [2].

In earlier days, protective devices coordination was attempted using several ways as trial and error, curve fitting and graphical and analytical methods. These traditional ways suffered from the slow rate of convergence and not necessarily computing the optimum solutions. Nowadays, DOCRs coordination has been implemented using optimization techniques that minimize the objective function (OF) subjected to set of coordination bounds. Conventional optimization techniques have been tackled to get the optimum solution using Linear Programming (LP) or Non-Linear Programming (NLP) techniques [3]. The coordination issue is solved using LP considering the Plug Setting (PS) fixed and the relay operating time is a function of Time Multiplier Setting (TMS). The simplex, two-phase simplex and dual simplex methods are the most common types of linear programming approaches [4]. Applying NLP or Mixed Integer NLP (MINLP) approaches increase the complexity of the problem but optimized the both settings of DOCRs (i.e. TMS and PS). The coordination dilemma is considered as a NLP if the Plug Setting Multiplier (PSM) is continuously changing. But, if PSM is discrete, the problem becomes a MINLP [2]. However, it requires an initial assumption and suffers from the snare of optimize the solution near the initial one. Currently, Artificial Intelligence (AI) based approaches have been proposed to get the optimal solution between randomly generated solutions which the quality of solution is improved every iteration [2].

There are three types of overcurrent protection addressed in the literature. In radial distribution networks, plain OCRs are deployed while in ring or meshed networks, the employment of the directionality feature has become necessary due to the bidirectional power flow [5]. DOCRs initiate a tripping command only when the fault current is in the forward direction by taking a reference voltage signal from voltage transformer as the polarized quantity.

Dual setting DOCRs are supplied with two inverse Time-Current Characteristics (TCCs). They significantly offer fast backup time by enabling the reverse direction of the relay. The advantage of dual-setting is that a single relay can carry out the function of two separate DOCRs [6]. Accordingly, the reverse feature of each relay is deployed as a backup mean for the next front line. This can be done by embedding a communication link between the reverse element of the relay and the forward element of the conventional backup DOCR. This communication link prevents the operation of the forward element in case of the reverse element operates. In this context, relay parameters shall be optimized in forward and reverse directions [7].

The operation behavior of DOCRs may either be instantaneous, definite time, or inverse time Characteristics (CCs). Instantaneous OCR operates without any intentional time delay while the definite time CCs can be adjusted. Inverse Definite Minimum Time (IDMT) OCRs mean that the operating time is inversely proportional to the amount of the fault current [7]. Mainly, OCRs have two parameters i.e. Time Dial Setting (TDS) and Pickup current $\left(\mathrm{I_p}\right)$ that represents the threshold above which the relay starts to operate. Previously, these two parameters are discrete and named as TMS and PS for traditional electromechanical relays. Conversely, they are continuous for digital relays. IDMT OCRs tripping CCs is described by the following equation:

$$t_i = \left(\frac{A}{\left(\frac{I_{fi}}{I_{pi}}\right)^B - 1} + C \right) TDS_i \tag{1}$$

where A, B, and C are constants depend on the relay curve type according to the most commonly used standards i.e. IEC 60255-3 [9] and ANSI/IEEE C37.112 [10] as listed in Table 1 and shown in Fig. 1a–b, respectively (just samples). On the other hand, the variations of TDS on the relay operating time is illustrated in Fig. 2. It can be seen that if TDS increases the relay operating time increases.

2 Formulation of OCRs Coordination Problem

OCRs coordination can be represented as a constrained optimization problem with selectivity and boundary constraints. The initial step of coordination is to create the possible relay pairs for fault scenarios. To illustrate how to prepare relay pairs, portion of power system is used for demonstration as depicted in Fig. 3. The near end fault of relay R3 is shown in Fig. 3 while that far end fault of the same relay occurs at the end of the line BC. The possible relay pairs of some fault scenarios occur at different portions of the network are listed in Table 2.

Table 1 Constants for various standardized IDMT curves

CCs type	Standard	A	B	C
NI	IEC	0.14000	0.02000	0.00000
VI	IEC	13.50000	1.00000	0.00000
EI	IEC	80.00000	2.00000	0.00000
LI	IEC	120.00000	1.00000	0.00000
Rectifier	UK	45900.00000	5.60000	0.00000
MI	IEEE	0.05150	0.02000	0.11400
VI	IEEE	19.61000	2.00000	0.49100
EI	IEEE	28.20000	2.00000	0.12170
Inverse	US-CO8	5.95000	2.00000	0.18000
SI	US-CO2	0.16758	0.02000	0.11858
Inverse	ANSI	8.93410	2.09380	0.17966
SI	ANSI	0.26630	1.29690	0.03393
LI	ANSI	5.61430	– 1.00000	2.18592
MI	ANSI	0.01030	0.02000	0.02280
VI	ANSI	3.92200	2.00000	0.09820
EI	ANSI	5.64000	2.00000	0.02434
DI	ANSI	0.47970	1.56250	0.21359

The OF can be formulated in many styles such as minimizing the operating time of main relays and/or of backup relays and etc. as shall be detailed later in this manuscript. Selectivity constraint is defined by Eq. (2) while boundary constraints are defined by Eqs. (3)–(5). The minimum relay operating time is decided by the relay manufacturer. However, the maximum relay operating time is decided based on the thermal damage curve of the equipment and the stability margin of the relay zone. To avoid the mal-functioning in case of transient overloading condition, the minimum pickup current should be set above maximum load current as stated in Eq. (6). Furthermore, to ensure the tripping of the relay, the maximum pickup current should be below the minimum fault current as stated in Eq. (7). Figure 4 proves that the correct coordination is achieved as there is no intersection between Primary/Backup (P/B) relays between minimum and maximum fault. There are some algorithms like Particle Swarm Optimization (PSO) deal with the unconstrained problems. So, penalty terms should be included in the OF regarding the discrimination time Δt declared in Eq. (8) to guarantee the coordination. The mis-coordination problem appears when Δt has negative values. However, the solution will be feasible if Δt has positive values and optimal when Δt is zero [8].

$$t_{bij} - t_{pij} \geq CTI \tag{2}$$

$$TDS_{i,min} \leq TDS_i \leq TDS_{i,max} \tag{3}$$

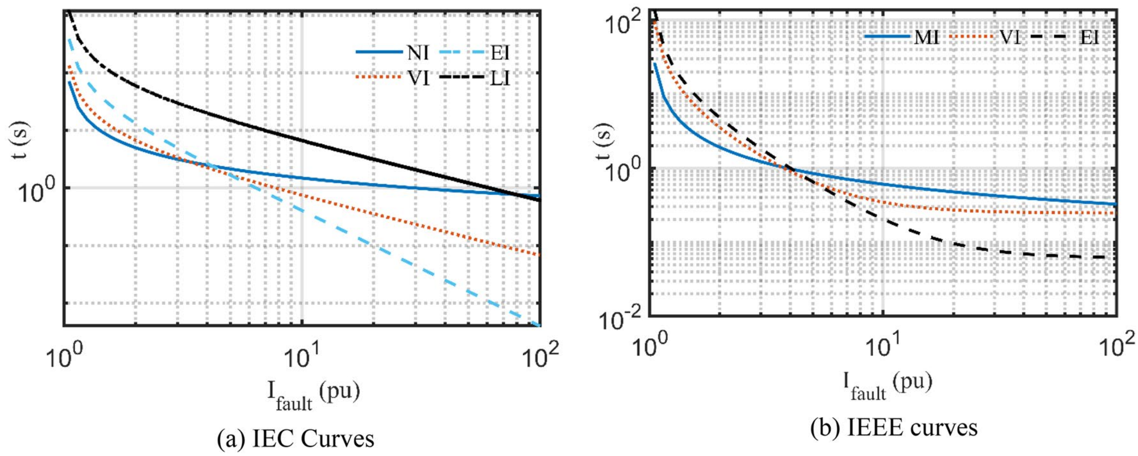


Fig. 1 Standardized IDMT curves based on IEC 60255-3 and IEEE C37.112

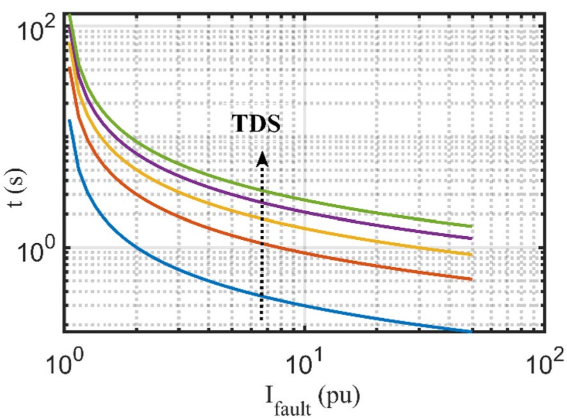


Fig. 2 The effect of TDS change

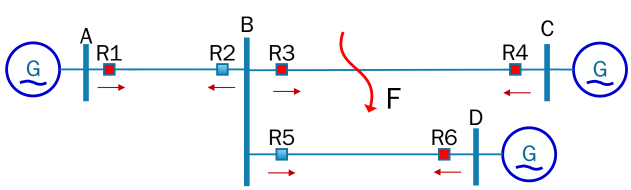


Fig. 3 Relay pairs scenarios

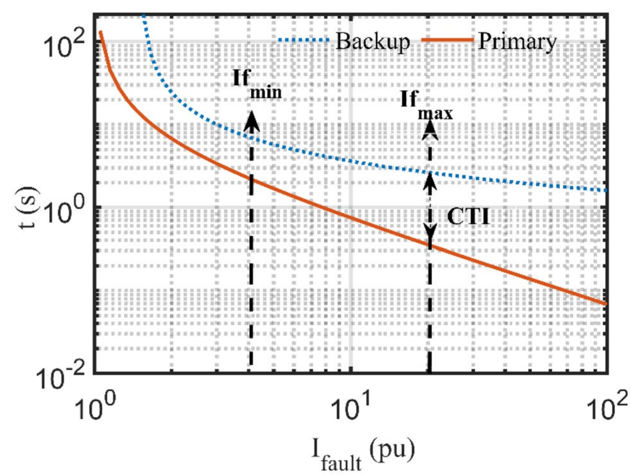


Fig. 4 Relay pair correct coordination

Table 2 Various relay pairs scenarios of Fig. 3

Primary relay	Backup relays
R2	R4, R6
R3	R1, R6
R5	R1, R4

$$I_{pi,min} \le I_{pi} \le I_{pi,max} \tag{4}$$

$$t_{i,min} \le t_{i,j} \le t_{i,max} \tag{5}$$

$$I_{pi,min} \ge I_{load,max} \tag{6}$$

$$I_{pi,max} \le I_{fault,min} \tag{7}$$

$$\Delta t = t_{bij} - t_{pij} - CTI \tag{8}$$

Some researchers include the relay type CCs in the optimization process as decision variables besides TDS and I_p as reported in [11–13]. It is not limited to the CCs but extended to optimize the coefficients in the tripping equation i.e. (A, B, and C) as reported in [14, 15]. Moreover, some papers offer the use of non-standardized tripping CCs as the formulation of new non-standard time–current-voltage characteristics that depend on the current and voltage magnitudes in Eq. (9) with additional setting of K1 which can be easily implemented in microprocessor based DOCRs [16]. In this context, the dynamic model of OCRs based on ANSI/IEEE C37.112 is utilized in [17–19] to consider the changes in network topology.

$$t_{ijl} = \left(\frac{1}{e^1 - V_{fijl}}\right)^{K1} \left(\frac{A}{\left(\frac{I_{fi}}{I_{pi}}\right)^B - 1}\right) TDS_i \quad (9)$$

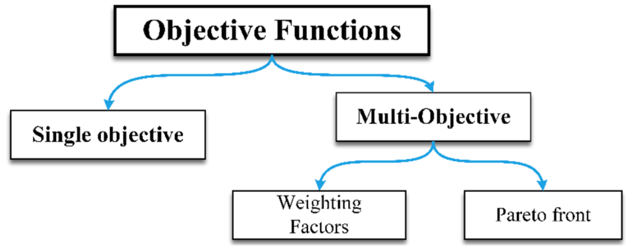


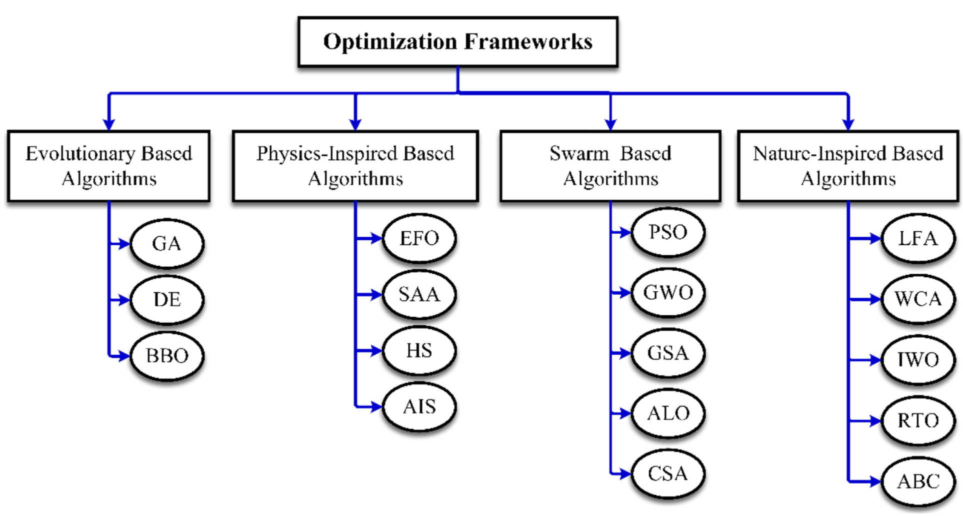
Fig. 6 Classification of OFs

3 Summary of the Nature of Some Optimization Algorithms

The nature of any optimization algorithm varies from one to another. There are many classifications for heuristic based frameworks such as evolutionary based, swarm based, physics based, and nature inspired based algorithms as revealed in Fig. 5 while classification of OFs is shown in Fig. 6.

Authors [20–29] present review articles about metaheuristic optimization algorithms and their applications in power systems optimization problems. Genetic Algorithm (GA) is one of the most popular evolutionary based algorithms which its basic concept is starting with population initialization called chromosomes and their fitness function is computed. Then, chromosomes with large fitness function undergo the crossover phase to produce new generation of chromosomes which are subjected to the power mutation phase [30]. On the other side, PSO is one of the most commonly used swarm-based algorithms in power system optimization. However, PSO has attractive CCs compared to the GA that it has a memory so that the previous knowledge is not destroyed when the population changes. In addition, PSO has no evolution operators like crossover and mutation [31]. In addition to PSO, Grey Wolf Optimization (GWO), Gravitational Search Algorithm (GSA), and Ant Lion Optimization (ALO) are also swarm-based type. One of the physics-based type is the Electromagnetic Field Optimization (EFO) algorithm which is inspired by attraction and repulsion forces occur due to the different polarities of electromagnets [32]. Firefly Algorithm (FA) is a swarm intelligent type that insufflated by the flashing of fireflies. The OF depends on the position of each firefly where the brightness intensity of each firefly is an indicator of its objective value [33]. There are also nature inspired algorithms like Lightning Flash Algorithm (LFA) proposed in [34] which is based on the movement of lightning strikes. According to the movement of cloud to ground lightning, the optimum value will be attained which is an indicator that the lightning strike arriving the surface. Water Cycle Algorithm (WCA) starts with initial population (raindrops) and the best candidate selected as the sea [13]. Invasive Weed Optimization (IWO) imitates the behaviour of weeds which invade crops to absorb the water to continue growing. The fitness function of each weed is calculated and each one is allowed to leave

Fig. 5 Classification of optimization tools



a seed based on its ranking [35]. Another nature inspired algorithm is the Root Tree Optimization (RTO) addressed in [36] which is inspired by the random movement of roots. The roots of a plant are combined together searching for water to get the best location. The roots having less wetness degree or far away from the combination are replaced by new ones randomly while the roots with higher wetness will maintain their orientation. The overall procedures of employing the optimization method to solve OCR's problem are summarized in the flow-chart illustrated in Fig. 7.

4 Metaheuristic Optimization Approaches for DOCRs Coordination

Different population-based optimization approaches have been tackled in the literature for the optimal coordination problem. [37–39] represent a review of OCR coordination from curve fitting techniques to the artificial intelligent based approaches. Inherently, the standard PSO is not used for the constrained optimization problems. Hence, a modified PSO is used in [40] to deal with the DOCR coordination without adding penalty terms to the OF. Nelder-Mead PSO (NM-PSO) algorithm has been utilized in [41] considering different network topologies and manifests its outperformance over the conventional PSO. A Hybrid PSO (HPSO) is used for the optimal coordination; the PSO is used to optimize the discrete pickup current and LP is used to optimize the continuous TMS [42].

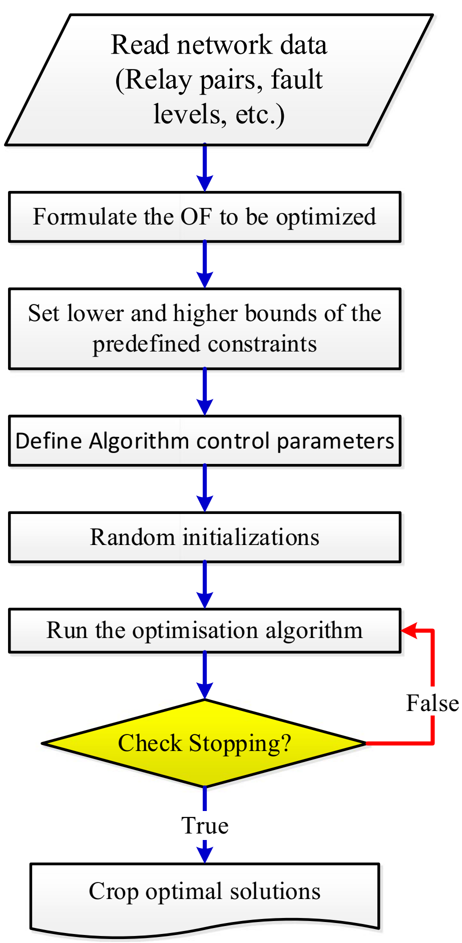


Fig. 7 General procedures of OCRs and optimization method

On the other side, a new iterative algorithm is proposed for optimal OCR coordination for reducing the total operating time by optimizing the both settings of the OCR simultaneously [43]. Afterwards, the optimal coordination problem is solved using Teaching Learning Based Optimization (TLBO) in [44] and Differential Evolution (DE) algorithm in [45]. Moreover, Artificial Bee Colony (ABC) algorithm is the optimization tool in [46] for the coordination of electromechanical relays to attain the optimized discrete values of the relay settings.

The optimal coordination is performed using Real Coded GA (RCGA) in [4], Modified EFO (MEFO) in [32], Cuckoo Search Algorithm (CSA) in [47], Symbiotic Organism Search (SOS) algorithm in [2] and FA in [48]. Hybrid Biogeography Based Optimization DE (BBO-DE) algorithm is tested in [49] by using a feasible checker unit to check the feasibility of the solution. The coordination problem in [1] is formulated as a MINLP by optimizing the discrete decision variables using a High-Performance Hybrid Algorithm (HPHA). This hybrid algorithm consists of a Specialized GA (SGA) with an Efficient Heuristic Algorithm (EHA). There are four decision variables need to be optimized; pickup current, time dial setting, relay type, and curve type. In [50], a hybrid GSA Sequential Quadratic Programing (GSA-SQP) algorithm performance has been evaluated on three different test systems considering various fault scenarios. Enhanced Backtracking Search Algorithm (EBSA) and Discrete–Continuous Hyper Sphere Search (DC-HSS) algorithm are used in [51] and [52] respectively for optimizing both relay characteristics and TDS of each OCR. TLBO is found to be an efficient algorithm in terms of total operating time and coordination constraints more than PSO [53]. Chaotic FA (CFA) is applied in [33] and a hybrid BBO-LP algorithm in [54] to consolidate the performance of optimal DOCR coordination with respect to the simplicity and speed rather than the original BBO. The Q-learning algorithm is proposed to solve the coordination problem which can be seen as Reinforcement Learning (RL) approach. This approach is a machine learning approach that depends on the interaction of agents (i.e. TDS) with the environment (i.e. power system) [55].

CSA is used to attain the initial optimal values of TDS and Ip that are employed in FA as upper bounds to obtain the global optimal solution [56]. The optimization problem is formulated as linear programming to optimize TDS of OCR using Flower Pollination Algorithm (FPA) in [57].

Stochastic Fractal Search Algorithm (SFSA) has been investigated in [58] which was found as a promising algorithm in power system optimization. The coordination problem is formulated as MINLP by considering both TDS and I_p as continuous values and the relay characteristic as a discrete variable. The optimized settings of DOCRs have been assessed using hybrid GA-LP approach. Firstly, LP stage optimizes the TDS value then GA stage optimizes the pickup current to complete the coordination process [59]. RTO addressed in [60] and GWO in [61] optimize the TDS of each relay by minimizing the sum of the primary relays operating time. A Hybridized Whale Optimization Algorithm (HWOA) has been applied to 5 test systems to prove its outperformance over the traditional WOA. The hybridization technique is done by employing the Simulated Annealing Algorithm (SAA) incorporated with WOA to augment the best-found solution after each iteration [62].

The performance of a multi-objective algorithm has been evaluated for the DOCRs coordination based on multi-objective PSO and Fuzzy Decision-Making Tool (FDMT). The presented OFs are optimized separately and independently evaluated by using the FDMT in the proposed algorithm. Therefore, the proposed algorithm has proven its efficiency in solving the problem of miscoordinations in addition to the large relay operating time [63]. However, miscoordinations may occur as topological and parametric uncertainties are not included in the optimization problem formulation. These uncertainties include unplanned outages, maintenance activities, CT ratio errors, CT saturation, and line parameters measurement errors [64]. The optimization dilemma presented in [65] achieves optimal relay coordination besides network reconfiguration using DE algorithm. The objective is to minimize the relay operating time concurrently with maximizing the load restoration so that the network remains radial as possible. The proposed Modified WCA (MWCA) reduces the search space by updating the C-value of the traditional WCA to achieve the balance between the exploitative and explorative phases [66].

A hybrid Improved IWO (IIWO) is proposed in [67] for optimal DOCRs coordination to ameliorate the slow convergence rate of the conventional IWO and IFA is proposed in [68]. This has been done by involving SQP as a subroutine in the main algorithm for searching for the best local solutions. Enhanced GWO (EGWO) is proposed in [69] instead of the standard GWO to improve the computation time and convergence rate by balancing between exploitation and exploration phases. Moreover, the obtained results are validated using DIgSILENT PowerFactory software achieving notable reduction in the relays operating time. Hybrid Integer Coded GA (ICGA) and NLP approach has been utilized in [70] by optimizing the PSM using the ICGA and the TDS using the NLP. In addition, a hybrid GA-NLP proves its efficacy in the combination coordination between electromechanical and numerical OCRs [71]. A hybrid WOA-GWO approach is proposed for optimal DOCRs coordination by enhancing the WOA exploitation phase to obtain the best optimal solution [72]. The proposed Multi-Objective GWO (MOGWO) is suggested to solve the coordination problem with Fuzzy Logic decision making to attain the compromise solution between diverse optimal solutions [73]. Enhanced Self Adaptive DE Multi-Objective (ESA-DEMO) algorithm proves its consistency and reliability for solving non-linear non-convex highly constrained DOCRs coordination problem. This parameter tune free approach gets rid of the headache of tuning both the OF weighting factors and algorithm parameters [74]. The application of multi-objective Canonical DE PSO (C-DEEPSO) approach paves the way for vast improvement in DOCRs results especially in the large networks like the IEEE 30 buses test case [75].

5 Break Points Concept

Break points are the inception points of OCR coordination that determine the sequence of operation of P/B relay pairs. It has been discovered that the break points affect the optimization process and vanish conflicting inequality constraints [76]. Accordingly, the determination of Minimum Break Point Set (MBPS) is very essential especially in large scale power systems to locate the starting point of the coordination [77]. To detect the directional loops in the network, the implementation of Depth-First Search Algorithm (DFSA) is proposed in [77]. Consequently, the determination of the MBPS has been assessed using the Variable Neighborhood Search (VNS) heuristic-based algorithm and tested on various test cases.

6 Impact of Distributed Generation on DOCRs Coordination

Since DG penetration causes variations in fault currents level, the coordination process should be tackled in the presence of it [78]. Figure 8 shows that installing a DG on bus C

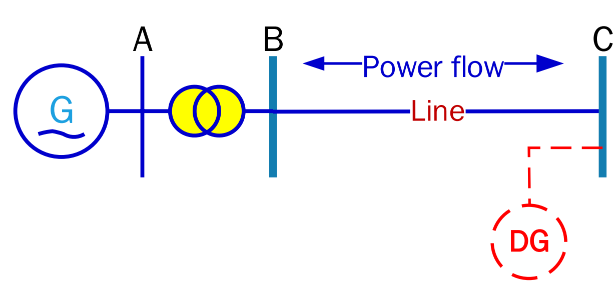


Fig. 8 Impact of DG on power flow and fault level

will change the fault current level and make the power flow bidirectional. The impact of DGs penetration on the relay coordination process depends on its type, size, installation location and distribution system nature (radial or meshed) [6]. Inverter-Based DGs (IBDGs) are fault limiter types by restricting the fault current value from 1 to 2 per unit. In contradiction, Synchronous-Based DGs (SBDGs) significantly increase the short circuit level [5, 6]. In renewable based DGs, connection and disconnection events of these units frequently occur as the power flow changes due to variations in environmental conditions like solar irradiation and wind speed [78, 79].

Different sizes and locations of DGs are investigated in [80] for minimizing the relays operating time besides suppression of miscoordinations using GA. In addition to the mentioned earlier, technologies of DGs (SBDGs and IBDGs) have been tested in [6] and some cases of near-end faults, far-end faults, and fault resistance effect on the proposed approach have been investigated. By using the built in MATLAB optimization function; Fmincon in [81], the OCR coordination problem is formulated under variable sizes of DGs. This new OF offers the optimal settings of OCRs considering different penetration levels of DGs at specific bus. Also, various fault types without and with different sizes of DGs are investigated to solve the optimal OCR coordination using GSA [82]. It has been proven that the proposed approach in [16] achieves significant reduction in DOCR tripping time with various implementation techniques of DGs compared to the conventional characteristics. The coordination of Active Distribution Networks (ADNs) which include DGs with uncertainties has been examined using hybrid CSA-LP approach. The uncertainties in ADNs include changes in operating and fault conditions, measuring equipment errors, and DG outages. Besides the optimization of TDS and I_p, both A and B parameters are also optimized [83].

The integration of Renewable Energy Sources (RESs) in distribution networks like Solar Photo-Voltaic Panels (PV) has a profound impact on the relay coordination [84]. In [78], the incorporation of DG with the study of the effect of environmental conditions on OCR coordination has been investigated. PV and wind energy systems have been modelled using PSCAD software. It is found that fault current increases with DG penetration, and thus, relay operating time decreases. In [85], OCR coordination is simulated in radial network with the presence of DG (wind turbine generator) and solved using MFA. This algorithm is examined on 4 test cases with different combinations between DG, generator, and the grid. Random Walk GWO (RW-GWO) approach is employed in [86], tested for optimization, and its performance is validated against different approaches in the literature. In addition, different modes of operation are analyzed based on connecting and disconnecting the Distributed Energy Resources (DERs). DOCRs are coordinated in the presence of Wind Farms to show the effect of these weather dependent sources on the currents flow in the network. The coordination problem is formulated as a mixed integer optimization problem and solved using PSO by optimizing the relay type CCs [87].

Since OCR coordination in radial distribution networks is highly affected by DG penetration, optimal protective devices coordination is assessed using hybrid GA-LP approach. Therefore, a multi-objective optimization function is used to lessen the protective devices operating time (e.g. OCRs, fuses, and reclosers) besides determining the optimal size of Fault Current Limiter (FCL) [88]. A novel optimization technique is proposed in [89] based on constraints reduction concept for distribution systems with high penetration level of DGs. Furthermore, variable sizes and locations of DGs are considered and the proposed method performance is tested on the IEEE 38-bus radial and ring networks.

7 Various Coordination Concepts and Applications

7.1 Mixed Coordination Between Distance and DOCRs

In sub-transmission systems, mixed coordination between Distance and DOCR as shown in Fig. 9 is a key solution of determining primary and backup relay pairs. First, the distance relay impedance settings of the three zones are calculated and then the timing of the second zone (T_{z2}) is optimized in conjunction with DOCR settings [14]. Three different zones at least are considered in the distance relay impedance settings. The first zone is set to protect 80% to 90% of the primary forward line and operates instantaneously without any intentional time delay. The second zone is

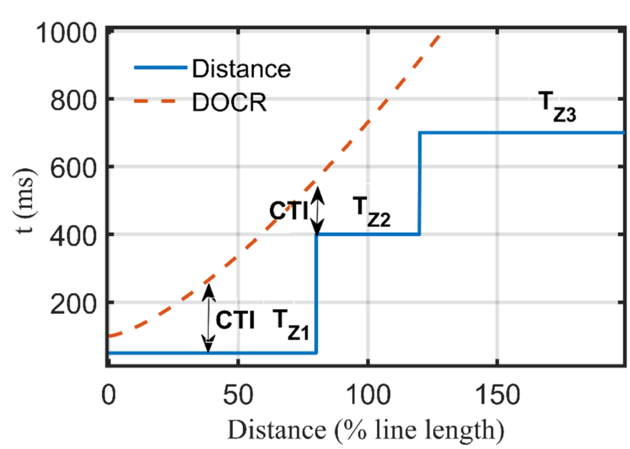


Fig. 9 Mixed coordination between distance and DOCR

set at 120% of the forward line with a safety sufficient time margin from the first zone from 15 to 40 cycles. The third zone is set to protect the primary line plus the longest forward line with time margin from the second zone above 40 cycles [90–92]. If the effect of in-feed and out-feed currents is not considered in the relay coordination dilemma, the distance relay will suffer from maloperation in the form of over-reaching and under-reaching. So, these currents should be included in the process to locate the critical fault point which represents the end of the second zone [91].

A mixed coordination process between distance and DOCRs should follow three different selectivity scenarios; coordination between two distance relays, coordination between two DOCRs, and coordination between DOCR and distance relay [90–92]. Dual TCCs (DTCCs) can be formed using inverse characteristics as the first stage accompanied by definite or inverse characteristics as the second stage. Deployment of numerical DOCRs with DTCCs instead of conventional DOCRs should be optimized to tackle the coordination process in a cost-effective manner. Furthermore, this optimal replacement in conjunction with different TCCs minimize the total operating time of the relays and eliminate the miscoordination [90]. In [93], a new non-standard operating characteristic of distance relays is developed to minimize the overall operating time of P/B relay pairs. This is achieved by dividing the second zone tripping time into two sections. The first section is to protect the remaining of the main line with time delay of T_{z2n1} and the second section is to protect 50% of the adjacent line with time delay of T_{z2n2}.

7.2 DOCRs Coordination in Microgrids

It is cleared that the fault current level varies between grid connected and islanded operating modes of Microgrids (MGs). The purpose of FCL in MGs is limiting the effect of DGs on OCR coordination. FCL is one of the best approaches to solve the problem of variation of short circuit level in MGs in both modes of operation [94]. Optimal value of FCL is attained using a hybrid Shuffled Frog Leaping Algorithm (SFLA) incorporate with relay coordination accompanied by load flow and short circuit studies in [95] and CSA in [94]. The analysis is performed in two phases, in phase-1, relay settings have been attained only in grid-connected mode. Then, due to some miscoordinations, relay settings have been obtained in both modes of operation in phase-2 [96].

The optimization process is formulated as a non-linear problem and solved using GA to obtain optimal settings of DOCRs besides optimal sizing of FCLs. Optimum values are attained simultaneously in both modes of MGs. FCLs have a profound impact on DOCRs coordination especially in grid-connected mode [97]. A new hybrid CSA-LP is proposed in [98] for optimal coordination of DOCRs in MGs for both modes besides hybrid Modified PSO- Interval LP (MPSO-ILP) in [99] in which Ip is optimized using MPSO and TDS is optimized using ILP. Moreover, the optimal size of FCL is attained and optimal unique settings of relays for both modes are also attained. Furthermore, different changes in population size have been analyzed and the best attempt is considered. In addition, the optimal setting of Directional FCL that is installed at the Point of Common Coupling (PCC) between the upstream network and the MG is calculated preserving the coordination of OCRs [100]. A heuristic Multi-Verse Optimization (MVO) algorithm is proposed also for solving the coordination problem in MGs [101].

A novel GA optimization technique is developed to improve the protection of Doubly Fed Induction Generator (DFIG) for OCRs coordination in wind farms considering various fault types and locations [103]. A new approach is presented in [102] to reduce the sympathetic tripping in MGs is implemented by utilizing the hybrid coordination between the phase and earth OCR. The earth OCR will be the backup protection of the phase OCR, which are located on the same digital OCR in case of phase faults without the need of communication. The optimized values of TMS are calculated based on the Single Line to Ground Fault (SLGF) calculations [102]. Protection coordination is verified using grid-connected and islanded modes of MG and is solved using Fmincon. Both relays on the same line will communicate with each other so that the reverse CCs of one relay will prevent the operation of the forward CCs of the other. In this context, this blocking signal exists during backup protection operation only using low bandwidth communication [104].

7.3 Dual-Setting DOCRs Coordination

DTCCs means that activating the reverse direction of DOCRs as shown in Fig. 10 and both tripping time equations of Eqs. (10) and (11) are involved in the optimization process. In [5], the proposed approach aims to optimize the parameters A, B, C, TDS, and I_p in both directions by minimizing the overall operating time of primary and backup relays.

$$t_{fwi} = \left(\frac{A_{fwi}}{\left(\frac{I_{fi}}{I_{pfwi}} \right)^{B_{fwi}} - 1} + C_{fwi} \right) TDS_{fwi} \tag{10}$$

$$t_{rvi} = \left(\frac{A_{rvi}}{\left(\frac{I_{fi}}{I_{prvi}} \right)^{B_{rvi}} - 1} + C_{rvi} \right) TDS_{rvi} \tag{11}$$

Parameter C is optimized to guarantee the minimum operating time in case of near end fault especially when it has

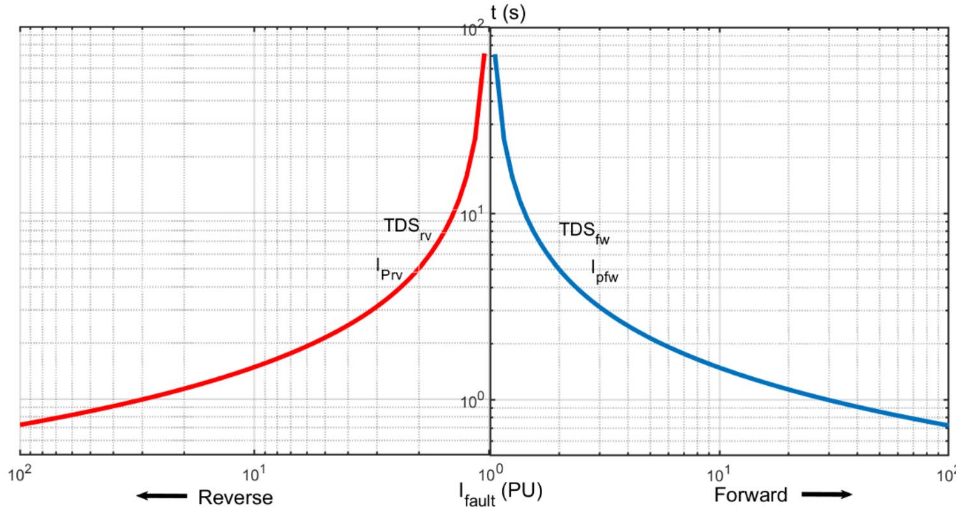


Fig. 10 Dual Time Current Characteristics DTCC

a negative value. In addition, the discrimination time Δ*t* is involved into the optimization function by applying a penalty term to it to reduce the miscoordination as possible. A multi-objective optimization approach is proposed to minimize the total relays operating time, in addition to optimizing the deployment of dual-setting DOCRs. In other words, since high penetration of dual-setting DOCRs becomes meaningless due to the saturation in operating time reduction. Therefore, the percentage of dual-setting DOCRs will be optimized by deploying augmented ε-constraint approach and then pick out the optimal Pareto solution that compromises these two conflicting objectives. Furthermore, non-standard inverse time current characteristics and multi-point fault approach have been interrogated to improve the optimized functions [105]. The coordination model presented in [106] has been conducted using multiple fault locations in addition to the exploit of dual-setting DOCRs and notable reduction in operating time is achieved. A novel approach is proposed for the combined coordination between communication-based dual-setting DOCRs and distance relays for N-1 contingency analysis in sub transmission systems. The applied algorithm is Chaotic PSO (C-PSO) which is tested on the IEEE 14 bus system besides the optimization of the relay tripping equation coefficients in both directions [107].

7.4 DOCRs Coordination with Stability Constraint

Critical Clearing Time (CCT) is the maximum time below it the network transient stability is ensured. CCT values of each relay are determined before the optimization process begins. If any relay violates the transient stability constraint, it will be equipped with instantaneous characteristics to guarantee the lowest operating time and the optimization is performed again [108]. This time is involved as a constraint in the optimization problem by ensuring that the relay operating time is lower than it. In other words, the relay time curve should below the CCT curve to ensure the DG stability. In [109], the transient stability is checked by implementing a hybrid protection scheme. One is considering two stage OCR (i.e. inverse and definite time) to avoid the intersection between OCR curve and DG CCT curve and the other is inserting a communication channel between relays for intersection points outside the primary zone. ALO has proven its superiority over Artificial Immune System (AIS) and PSO in optimal DOCR coordination with different DGs penetration level considering the transient stability constraint [110]. The transient stability besides selectivity constraints are embraced in [111] and the reduction in the relay tripping time is noticed. The Seeker Algorithm (SA) is conducted along with the concept of using user-defined CCs of dual-setting DOCRS. Doubly-Inverse OCR (DIOCR) characteristic has been utilized to maintain DGs stability while providing proper coordination between OCRs. DIOCR composes of two curves; the main curve for the optimal coordination and the auxiliary curve for preserving the DGs stability especially during high fault currents [112].

7.5 Adaptive and Online Coordination

Optimal OCR coordination has been investigated using a full online adaptive technique without deploying any telecommunication infrastructure. This online technique depends on the online calculations of the power system equivalent circuit parameters then fault calculations to set the OCRs correctly [113].

Adaptive protection scheme automatically readjusts the relay settings based on network topology, configuration, and operating conditions [79, 114]. To overcome the problem of network topology changes, two solutions are offered for protective coordination. The first is to update the settings of the relays for each change but the probability of applying incorrect settings increases. The second is to use the concept of Setting Groups (SGs) by reducing the possible scenarios of network topologies to optimize the number of the available SGs [115]. A new adaptive method in [116] is proposed to obtain adaptive optimized settings of the relays based on connecting and disconnecting of DGs (CADD) states and available SGs of relays. A Classifying Index (CI) is considered to determine the similar states that can be adapted with the same SGs as the possible CADD states is larger than the available SGs of relays. For further clarification, as the number of SGs available for each digital OCR is much lower than the probable network topologies [115], adaptive OCR coordination is implemented using k-means clustering technique [117]. Hence, the network topologies under the same cluster are assigned to the same SG and activated based on the current network state [117].

Adaptive overcurrent relay protection system with two units based on Fuzzy Logic has been proposed in [118]. The first OCR unit is instantaneous and the other is a current–voltage based inverse time characteristic to select the suitable values of I_p based on the type of the fault. The two-phase adaptive approach developed in [119] determines the optimized on-line settings of the relays considering several network scenarios regarding DGs operation. In this regard, Adaptive Modified FA (AMFA) has been investigated and tested on radial network with five different test cases [120].

Online coordination approach has been investigated in [60]. The first step is using SCADA system to perform load flow, short circuit, and reset each relay remotely for each network topology change. The second step is conducting Binary Integer Programming (BIP) model to formulate the DOCR coordination. Local online adaptive methodology has been investigated in [121] for optimal OCR coordination under various network topologies by implementing Shuffled Frog Leaping Algorithm (SFLA). The GA is applied in [122] taking into account the variations in load and DGs output and then SCADA system is used to attain the online measurements with Advanced Meter Infrastructure system. The on-line DOCR coordination has been utilized to reduce the execution time using the improved GWO. Moreover, a weighted multi-objective GWO is proposed to minimize the primary and backup relays operating time in addition to the CTI. Sensitivity analysis test is performed to exclude the uncoordinated coordination pairs due to network topology changes [123]. The aforementioned metaheuristic algorithm is tested on the IEEE 14 bus and 30 bus test systems using the standardized IEEE VI curves [123].

7.6 DOCRs Coordination with User Defined and Non-standard Tripping Characteristics

The built-in MATLAB function uses the flexibility feature of digital DOCRs that offers the capability of using user defined time–current curves by optimizing A and B parameters [124]. The proposed coordination strategy developed in [14] guarantees secure and fast protection scheme by optimizing the auxiliary variable C in the TCC equation. A new OF is modeled to reduce the overall relays operating time along with minimizing the number of miscoordinations by considering penalties. Two goals are achieved in [125] by resolving false tripping of non-directional OCRs and minimizing the relays operating time. The first goal is fulfilled by adding the false tripping constraint into the optimization problem and the second by selecting the optimized values of both the pickup current and the characteristic curve type.

Authors [126] present a review of the Non-Standard Characteristics (NS-CCs) types which were used in the optimal coordination of overcurrent relays. The formulation of these NS-CCs can be either by including electrical magnitudes, manipulating the standard curves, mathematical approaches, and applying different constant values of the tripping equation. The NS-CCs presented in [127] depend on the logarithmic function and the optimization task is solved using the generalized Lagrange method. Optimal DOCR coordination has been performed using non-standardized time current curves and considering two different levels of short circuit current by optimizing the constants of the tripping time equation instead of the selection of an optimized standardized curve [128]. Each relay pair is coordinated also for the maximum 3-phase fault and the minimum 2-phase fault. Hybrid BBO-LP is used for extracting the best TCC curve among standard curves for optimizing the primary relays operating time [129]. Moreover, the performance of GSA presented in [3] is evaluated for three various test systems for different fault locations with user defined relay characteristics.

In [130], a new constraint of current multiplier setting $\left(CMS_{max} i.e. CMS = \frac{I_f}{I_p}\right)$ has been introduced in the OCR coordination formulation to compensate the negative impact of the excessive fault currents. In addition, NS-CCs have been utilized and the problem is solved using GA and tested on a benchmark IEC microgrid with different DG types [130]. The proposed approach deployed in [131] increases the flexibility of the coordination by employing NS-CCs via optimizing additional parameters in the tripping equation. Moreover, the stability constraint is considered to ensure the stability especially in low inertia time constant synchronous-based DERs. IWO algorithm proposed in [114] which accompanied by NS-CCs has proven its outstanding performance considering various fault locations.

7.7 Coordination Using the Dynamic Model of OCRs

Since the injection of the DGs alters the short circuit levels, FCLs are applied to limit these high fault currents. The exploit of the dynamic model of the OCR has been utilized to deal with the transient behavior of DGs and FCLs and the coordination is performed using GA [132]. The optimal coordination between Over-Current Protection Devices including OCRs and fuses using GA is proposed in [18]. The utilizing of multistage OCRs provides more efficient coordination than single-stage OCRs. Furthermore, the proposed algorithm is implemented to select the optimized curve type along with I_p and TMS for each stage of the OCR TCCs. Eventually, it safeguards the relays from malfunctioning due to transient over currents like motor starting by utilizing the dynamic model of the OCR. A new proposed numerical approach is presented in [133] based on hybrid GA-LP considering the transient behavior of the fault current due to the presence of synchronous generators. Therefore, the TCC curve of the OCR has become meaningless and the dynamic model of the OCR becomes imperative for the parameters setting. Due to the operation of the remote side relay, the fault current passing through the primary-backup pair alters causing miscoordination. The proposed method presented in [17] utilizes the dynamic model of the OCR considering two level-fault current for optimal coordination due to transient network topology changes. The implementation of LP to optimize TMS has been performed on the IEEE 8 bus and the distribution portion of the IEEE 30 bus.

7.8 Various Ideas for Optimal DOCRs Coordination

By using Nondominated Sorting GA-II (NSGA-II) in [12], the operating times of both primary and backup relays are minimized separately. Besides attaining lower values of discrimination times between P/B relay pairs, the headache of selecting suitable values of weighting factors is eliminated. The application of GA of Chu-Beasley (GACB) for optimal coordination of DOCRs is conducted on typical 11 bus test system to validate its performance over the traditional GA. The innovative OF includes the faults evaluation at 99% and 1% of the line length to optimize both TDS and the curve type [134].

When a series capacitor is installed in power systems, the fault currents passed through P/B relay pairs will change. So, a new adaptive variant of PSO is proposed to solve the optimal coordination of DOCRs named as PSO-TVAC (Time-Varying Acceleration Coefficients) considering the effect of series compensation [135, 136].

The presented OF in [15] has used the average operating time of OCRs not the sum of the operating time as mentioned before. A fuzzy-based GA is used to solve the coordination problem by adjusting the weighting factors of the multi-terms OF depending on fuzzy rules. In [137], the coordination process has not been tackled by minimizing the OF but by solving the coordination constraints equations without composing any OF. In other words, the optimal settings of DOCRs have been obtained by minimizing the value of TMS of the relays.

7.9 Unique Ideas for Optimal DOCRs Coordination

In [11], network splitting approach is used to split the under-study network into smaller subnetworks to reduce the computational time and increase the solution feasibility. The main optimization program will be executed on every subnetwork and then complementary algorithm is applied to the disregarded relays on the tie lines. The challenge that faces the researcher is to determine the splitting points location on the main network based on a proposed criterion. A new analytical approach is presented to determine the exact Critical Fault Point (CFP) for optimal coordination instead of the traditional close-in fault. The impedance matrix in fault conditions is assessed to determine the CFPs which have the priority of P/B pairs coordination [138].

The implementation of WCA for optimal OCR coordination in large complex networks proves how efficient it can be compared to other algorithms. It is applied on the detailed IEEE 30 bus (i.e. 333 decision variables and 726 inequality constraints) besides selecting the optimized TCC curve [124]. The sensitivity constraint is added to the problem formulation to guarantee that the backup relay will operate for the minimum fault at the far end of the primary relay. The sensitivity factor K_s in Eq. (12) shall be equal or more than 1.5 to ensure the sensitivity condition [74].

$$K_s = \frac{I_{SC,backup^{2\Phi}}}{OLF \times I_{load,max}} \tag{12}$$

The novelty of this article is to propose a new OF that integrates the relay coordination with arc flash hazard assessments studies simultaneously. By applying FPA, the amount of Incident Energy (IE) is reduced below the critical value; 40 Cal/cm^2 and the relay settings are optimized to ensure the selectivity. Moreover, the value of CTI is achieved at the maximum fault current incorporate with validating the discrimination between P/B relay pairs at the minimum fault current [139]. As it is known that during a fault, induction motors are converted into generators which in turn contribute in short circuit currents affecting the OCR coordination. Therefore, the employment of the OCR dynamic model has become necessary to deal with these transient fault currents. GA is implemented and tested on an industrial power grid taking into account the induction motors contribution to avoid the false tripping of non-directional OCRs [19].

Table 3 Optimization methods in DOCRs coordination with DGs (CNST: Constraints, C: Continuous, and D: Discrete)

Optimization method	OF	CNST		Test systems	Remarks
		C	D		
(MEFO) [32]	$\sum_{i=1}^{N} t_i$	✓		IEEE 8, 9, and 15 bus	NI curve
(PSO) [140]	Ditto	✓		IEEE 15 bus, and radial network	NI curve
FPA [57]	Ditto	✓		Radial feeder, and Parallel feeder	I_p is predetermined and not optimized
Hybrid GA-LP [59]	Ditto		✓	Real power transmission system	NI curve
GACB [134]	Ditto		✓	Typical 11 bus test system	NI curve
Hybrid GA-LP [133]	Ditto	✓		IEEE 8, 14, and 39 bus	Considering transient fault currents
MILP [141]	Ditto		✓	IEEE 3, 8, 14, and 30 bus	NI curves, both near-end and far-end faults
EGWO [69]	Ditto	✓		IEEE 8, 9, 15, and 30 bus	NI curve
ER-WCA [142]	Ditto	✓		IEEE 15 bus	NI curve
Hybrid ICGA-NLP [70]	Ditto		✓	IEEE 8 bus	NI curve
Hybrid WOA-GWO [72]	Ditto	✓		IEEE 8, 9, 15, and 30 bus	NI curve
MWCA [66]	Ditto	✓		IEEE 8, 9,15, and 30 bus	NI curve
RW-GWO [86]	Ditto	✓		IEEE 4 bus	NI curve
PSO, GA, SQP [84]	Ditto	✓		IEEE 4 bus	NI curve, I_p is predetermined and not optimized
WCA [124]	Ditto	✓		IEEE 15, and detailed 30 bus	Optimize relay type CCs
LFA [128]	Ditto	✓		6 bus ring network, IEEE 9 bus, 15 bus radial network	NI curve
PSO [87]	Ditto	✓		IEEE 8 bus	Optimize relay type CCs
PSO-GSA [78]	$\sum_{i=1}^{N} t_{i,j}$	✓		IEEE 13 bus radial distribution system with DG	NI curve, Non-directional OCR, and Considering SLGF
PSO-TVAC [135]	Ditto	✓		IEEE 8 bus	NI curve
AMFA [120]	Ditto	✓		Radial network with DG	NI curve
CFA [33]	Ditto	✓		Parallel feeder system, and multi-loop system (3 bus)	NI curve, I_p is predetermined and not optimized
Hybrid CSA-FFA [56]	Ditto	✓		IEEE 8 bus	NI curve, near-end faults
SQP [143]	Ditto	✓		Two bus parallel feeder, and three bus loop system	NI curve
GSA [82]	Ditto	✓		4 bus radial system	NI curve
GSA [3]	Ditto		✓	IEEE 8, 15, and 30 bus	Optimize relay characteristic coefficients
RTO [60]	Ditto	✓		Different test distribution systems	I_p is predetermined and not optimized
CPSO [144]	Ditto	✓		Various test systems	NI curve, I_p is predetermined and not optimized
FA [145]	Ditto		✓	IEEE 3, 8, and 9 bus	NI curve
HWOA [62]	Ditto	✓		IEEE 3, 8, 9, 15, and 30 bus	NI curve
WOA [146]	Ditto	✓		IEEE 3, 8, 9, 14, 15, and 30 bus	NI curve
PSO-TVAC [113]	Ditto	✓		IEEE 8 bus	NI curve
IDE [147]	Ditto	✓	✓	IEEE 9, and 30 bus	NI curve
DE [45]	Ditto		✓	Simple distribution system	NI curve
NSGA [12]	$\sum_{i=1}^{N} t_{pi} + \sum_{r=1}^{TP} t_{br}$	✓		IEEE 3, 8, and 30 bus	Both near-end and far-end faults, Optimize relay type CCs
Expert rule [76]	Ditto		✓	IEEE 8 bus, 36 bus real network	NI curve
Hybrid BBO-LP [54]	Ditto		✓	IEEE 3, 4, 8, and 9 bus	NI curve

Table 3 (continued)

Optimization method	OF	CNST C	CNST D	Test systems	Remarks
GA [116]	Ditto plus	✓		IEEE 30 bus	MI curves No pickup current constraint
Hybrid GA-LP [115]	$\frac{1}{m}\sum_{k=1}^{m}\left[\frac{1}{k_i}\sum_{i_i}^{k_i}\left(\frac{1}{N}\sum_{i=1}^{N}t_{pi}\right)\right]$	✓		Radial network, and IEEE 30 bus	NI curve
RCGA [4]	$\sum_{i=1}^{N_c}t_{piF_1}+\sum_{i=1}^{N_f}t_{piF_2}$	✓		IEEE 3, 4, 6, and 14 bus	The selectivity constraint for both near and far end faults
ALO [110]	Ditto	✓		IEEE 30 bus, and practical 11 bus distribution system	Transient stability constraint
OCDE [7]	Ditto	✓		IEEE 4 bus	Investigate the results with different CCs
NM-PSO [41]	Ditto	✓		IEEE 8 bus	IEEE EI curve
TLBO [44]	Ditto	✓		IEEE 3, 4, and 6 bus	NI curve
ABC [46]	Ditto		✓	8 bus system, and IEEE 14 bus	NI curve
GA [11]	$\sum_{i=1}^{N}a\times(t_{piF_1}+t_{piF_2})$		✓	IEEE 30 bus	Optimize relay type CCs
Fuzzy-based GA [15]	$a\frac{\sum_{i=1}^{N}t_i}{N}$		✓	IEEE 6, 8, and 30 bus	Optimizing the coefficients of TCC curve
GSA-SQP [50]	$\sum_{i=1}^{N}\sum_{j=1}^{M}t_{pij}$	✓		IEEE 3, 9, and 30 bus	NI curve, consider near end, far end, and mid-point faults
EBSA [51]	Ditto	✓		IEEE 3, 8, and 15 bus	Optimize relay type CCs
MVO [101]	Ditto	✓		IEEE 3, and 9 bus	NI curve
BIP [60]	Ditto		✓	IEEE 6, and 8 bus	NI curve
GWO [61]	$\sum_{j=1}^{M}\sum_{i=1}^{N}t_{pij}$	✓		IEEE 6, and 30 bus	NI curve
IFA [68]	Ditto	✓		IEEE 6, 9, and 30 bus	I_p is predetermined and not optimized
SA-LP [148]	Ditto		✓	IEEE 3, 6, 8, 15 and 30 bus	NI curve
DE [96]	$\sum_{j=1}^{M}\sum_{i=1}^{2}t_{pij}$		✓	IEEE 9 bus, and radial distribution system with DG	NI curve, mid-point 3-phase fault only
(SOS) [2]	$\sum_{i=1}^{N}\sum_{j=1}^{M}(t_{pij}+t_{bij}).w_i$	✓		IEEE 6 bus, and WSCC 9 bus	NI curve
PSO & TLBO [53]	Ditto	✓		IEEE 6 bus, WSCC 9 bus, and IEEE 14 bus	$w_i=1$ NI curve
(TLBO) [149]	Ditto	✓		WSCC 9 bus	NI curve
ER-WCA [103]	$\sum_{i=1}^{N}\sum_{j=1}^{M}(t_{ij,earth}+t_{ij,phase})$	✓		IEC Microgrid implemented on ETAP	NI curve
Hybrid Fuzzy rules- GA [119]	$\sum_{i=1}^{N}\sum_{j=1}^{M}(t_{pij}+\sum t_{bij})$	✓		Modified distribution portion of IEEE 14 bus and 30 bus	Considering different DG types, locations, and sizes
Hybrid CSA-LP [83]	Ditto		✓	Practical 9 bus radial network, and IEEE 14 bus	Optimizing A and B
Q-learning algorithm [55]	Ditto	✓		IEEE 14 bus	I_p is predetermined and not optimized
GA [80]	Ditto	✓		IEEE 30 bus	considering different DGs locations and sizes
SFSA [58]	$\sum_{i=1}^{TP}(t_{pi}+t_{bi})$	✓		EEE 8, 9, and 15 bus	Optimize relay type CCs

Table 3 (continued)

Optimization method	OF	CNST		Test systems	Remarks
		C	D		
Fmincon [124]	$\sum_{j=1}^{M}\sum_{i=1}^{N}\left(t_{pij}+\sum t_{bij}\right)$ $\sum_{i=1}^{N}\left\{\begin{array}{c}\sum_{j=1}^{F_1}\left(t_{pij}+\sum t_{bij}\right)\\ +\sum_{j=1}^{F_2}\left(t_{pij}+\sum t_{bij}\right)\end{array}\right\}$	✓		IEEE 30 bus	considering different DGs locations and sizes and various fault locations
Hybrid PSO-LP&KNITRO solver [114]	$\sum_{j=1}^{M}\sum_{i=1}^{N}\left(t_{pij}+t_{bij}\right)$	✓		5 bus, and 15 bus distribution networks	NI curve
HPHA [1]	$\frac{1}{M}\sum_{i=1}^{N}\sum_{j=1}^{M}t_{pij}$		✓	Two radial distribution systems	Using non-directional OCR
PSA [108]	$a\sum_{i=1}^{N}\left(t_i\right)^2+\lambda(\Delta t+\lvert\Delta t\rvert)$ $\Delta t=t_i-CTI_i$	✓		Power Delivery System (PDS) of the IEEE 30 bus	Transient stability constraint, NI curve
GA [128]	$T_{mc}\times a+b\sum_{i=1}^{N}t_{pi}+w_i\sum_{r=1}^{TP}t_{br}$	✓		EEE 14, and 30 bus	IEEE equation
PSO [14]	$\sum_{j=1}^{M}a\sum_{i=1}^{N}\left(t_{ij}\right)^2$	✓		EEE 8, and 14 bus	Optimizing A, B, and C
GA [8]	$a\sum_{i=1}^{N}t_i^2$	✓		EEE 14, and 30 bus	Considered near end and far end faults
GA [138]	Ditto		✓	6 bus system	NI curve
MOPSO-FDMT [63]	Ditto	✓		IEEE 8, 30, 34 bus, and Wood and Woolenberg 6-bus	Optimizing A and B
GA [150]	Ditto	✓		9 bus network, and IEEE 30 bus	Considered near end and far end faults, Optimize relay type CCs
DC-HSS [52]	Ditto	✓		6 bus system	I_p is predetermined and not optimized
MSFA [151]	Ditto		✓	IEEE 8, and 9 bus	NI curve
GA [53]	Ditto		✓	Simple 8 bus network, and IEEE 6 bus	Adding penalty terms to the OF
FPA [139]	$\sum_{j}\sum_{i}IE\left(t_{i,j}\right),\forall j\in M,i\in N$	✓		IEEE 8, and 15 bus	Optimize relay type CCs
Fmincon [16]	$\sum_{i=1}^{N}\sum_{l=1}^{L}\sum_{j=1}^{M}\left(t_{pilj}+\sum_{x=1}^{X}t_{bilj}\right)$	✓		IEEE 14, and 30 bus	I_p is predetermined and not optimized
QCQP [152]	$\sum_{j=1}^{M}\sum_{i=1}^{N}\left(t_{pij}+\sum_{x=1}^{X}t_{bij}\right)$	✓		IEEE 3, 8, and 30 bus	NI curve
GA [112]	Ditto	✓		IEEE 33 bus distribution portion	Transient stability constraint
Hybrid IIWO [67]	Ditto	✓		IEEE 9, and 30 bus	NI curve
SQP [106]	Ditto	✓		IEEE 14, and 24 bus	Multiple fault locations (every 10% of the line)
MOGWO [73]	$OF1=\sum_{i=1}^{N_p}t_{pi}+\sum_{i=1}^{N_b}t_{bi}$ $OF2=t_b-t_p-CTI$	✓		IEEE 8, and 30 bus	NI curve

Table 3 (continued)

Optimization method	OF	CNST		Test systems	Remarks
		C	D		
ESA-DEMO [74]	$OF1 = \sum_{i=1}^{TP} t_{pi}$ $OF2 = \sum_{i=1}^{TP} t_{bi}$ $OF3 = \sum_{r=1}^{TP} E_{CTI_r}$	✓	✓	IEEE 6, 14, and 30 bus	IEEE VI curve, the coordination constraint for both near and far end faults, and sensitivity constraint
HGA-LP [93]	$\sum_{i=1}^{n} t_i + \sum_{j=1}^{m} \left(T_{z2n1j} + T_{z2n2j}\right)$	✓		8 bus system, IEEE 14, and 30 bus	VI curve, T_{z2n1} is kept fixed at the minimum typical value of 0.3 s, considering network topology change due to single line outages

8 Various OFs and Associated Constraints in the Literature

The general procedures to carry out protection co-ordination overall the literature can be summarized here for the reader's convenience. Table 3 announces various constrained OFs handled in the literature which are minimized using different algorithms. In which, the type of constraints and applied systems are illustrated as well.

9 Conclusion and Future Work

This paper has presented a review of metaheuristic optimization algorithms addressed in the literature for optimal coordination of DOCRs. Advantages and drawbacks of each method have been Interrogated through its implementation in different distribution networks. Moreover, diverse methodologies like DGs penetration, dual-setting concept, the dynamic model of OCRs, and more have been illustrated. Furthermore, some researchers develop unique ideas which in turn manifest how their approach is precise and brilliant although the complexity of the problem inflates. In addition, modified and hybrid algorithms prove their proficient performance over the traditional ones and how the convergence of the solution and results validity are improved. Eventually, the resilience of this approach and the Proliferation of metaheuristic algorithms pave the way for more progress and resplendent ideas to deal with. Transformer inrush current and equipment damage curves represent the new constraints to the DOCRs coordination problem as the future work. This paper is a contribution to comprehensive understands for relaying coordination. New area to increase the degree of non-linearity by including more constraints is highlighted.

Compliance with Ethical Standards

Conflict of interest The author confirms that there is no any kind of conflict of interest.

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