Online implementation of time augmentation of over current relay coordination using water cycle algorithm

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Abstract

In the present paper, a technique is presented for new investigations for the constrained type optimal coordination of over current relay problem using the water cycle algorithm (WCA). It is shown that the operating time of relay mainly depends upon the time dial setting (TDS) and plug settings. The paper introduces a novel metaheuristic optimizer algorithm, WCA, encouraged by the water sequence process and movements of rivers and flows on the way to the sea. Results are presented for the application of the methodology on a distribution system of single-end one loop system, Single-end multi-loop system and single-end multi-parallel feeder distribution system. Subsequently, the results find the minimal operating time of relay with optimized TDS for over current relay. The result reveals the effectiveness and superiority of the proposed WCA over the other techniques presented in the literature in terms of accuracy, input parameter and iterations.

Keywords Relay coordination · Time dial setting (TDS) · Water cycle algorithm (WCA)

1 Introduction

A continuous and uninterrupted power supply needs to be delivered safely to the consumers in order to assure that more revenue is generated and that the financial activities of the utility provider remain functioning smoothly. Power system protection plays a very vital role in making and maintaining such types of power transactions smooth and efficient. Proper installation and operation of power system protection devices leads to curtailment of harm to the network and helps sustain a more secure connection for power delivery. In a distribution network, over current (OC) relays are mainly employed for primary protection besides being employed for backup protection, whereas in transmission systems, it is applied for backup protection [1]. Due to its ease of use, sensitivity, selectivity, and consistency, OC relays are one of the most widespread relays in use today.

When an electrical network experiences a fault condition, the fault is sensed by both the primary and secondary relays. The primary relay is expected to execute the necessary action of activating the corresponding circuit breakers (CBs) and detach and isolate the faulty section of the network in order to limit the propagation of the fault and prevent any severe damages to the system. However, if for any reason the primary relay setup fails to activate, then after a set user-defined coordination time interval (CTI) from the instant of initial detection of the fault, the backup relay should activate and trip the required CBs and isolate the faulty section to effectively prevent any further damage. In order to avoid incorrect operation of the primary and backup relays such as the backup relay taking action before the primary relay or the backup relay failing to trigger after CTI has elapsed [1, 2], appropriate relay coordination procedures should be implemented.

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Relays have to be coordinated appropriately to avoid any malfunction and unnecessary downtime in other elements of the network. In the earlier days, relay coordination was executed manually and was thus a labor and time intensive process. But with the growth of the electricity network involving multiple sources and load points and the ever growing network complexity, the applicability of the straightforward old conventional methods proved to be a challenging task. Due to the difficulties involved and the lack of techniques in formulating an optimal solution for the coordination problem, power system operators had no choice but to accept the non-optimal coordination that met the protection system requirements at that time.

In order to achieve fast fault clearing time, an optimal coordination procedure is a necessity. This is more so for cases involving highly complex networks. In recent years, great efforts have been taken in the OC relay coordination problem to obtain the optimal relay setting. In [3] the authors have briefly discussed on the topological methods (graph theory) and optimization methods. Initially the trial and error method was applied in topological methods [4] but due to the requirements of a large number of iterations the rate of convergence is slow in the trial and error method. To achieve a faster rate of convergence at reduced iterations, techniques such as curve fitting method [5], graph theoretical method [6, 7] and analytical approach [8] were considered by different authors.

In 1988, Urdanta et al. [9] suggested the gauss–seidel iterative technique. The coordination of OC relay is a nonlinear problem since it involves simultaneous adjustment of the time dial setting (TDS) and plug setting (PS) values, however by considering a fixed plug setting (PS) value it can be treated and solved as a linear problem. The advantage of treating OC relay coordination as a linear problem lies in making the problem easier to solve and with less CPU time. Linear programming (LP) techniques including simplex [2, 10], dual simplex [11] and two-phase simplex [12] have been considered for solving the relay coordination problem when treating it as a linear problem. Although LP is simple, it still suffers from the possibility of being stuck in local optima. The major drawback in solving relay coordination by considering it as a linear problem is that only the TDS values can be calculated for fixed PS values. Though non-linear programming (NLP) approach is more complicated and takes more CPU time when compared to LP approaches, with OC relay coordination being a nonlinear problem at the roots, applying a nonlinear approach to solve it to obtain the optimal values for both the TDS and PS is a

much preferred choice. Since the NLP approach also suffers from the possibility of being stuck at local optima, some researchers proposed a mixed-integer linear program (MINLP) to solve the coordination problem [13–15]. Both NLP and MINLP approaches struggle with the selection of initial guess value.

In the past few years, to solve the relay coordination problem, many heuristic and evolutionary algorithms have been proposed by many researchers such as genetic algorithm (GA) [16], particle swarm optimization (PSO) [17], teaching learning-based optimization (TLBO) [18], ant colony optimization (ACO) [19], and differential evolution (DE) [20]. Some researchers further improved the GA approaches as continuous GA [21] and hybrid GA [22], which greatly reduced relay operating time. Further, researchers and scholars have also modified and improved the techniques mentioned in the literature, some of the modified versions of which are, adaptive DE [23], modified adaptive TLBO [24], and modified PSO [25].

Optimization techniques recently in use for solving the relay coordination problem include firefly algorithm (FA) [1], chaotic firefly algorithm (CFA) [26], harmony search algorithm (HAS) [27], symbiotic organism search (SOS) [28], root tree algorithm (RTA) [29], grey wolf optimization (GWO) [30] and most valuable player algorithm (MVPA) [31]. However, the drawback with most of these heuristic approaches in computing an optimal relay setting is that there is always a risk of convergence to local minima, requires a large population, have a slow rate of convergence and takes more computational time. Thus, there still exist possibilities for further improvement in finding an optimal relay setting that can help achieve reduced operating time and thereby minimize the fault clearing time.

The main objective of this paper is to find out the optimized TDS and minimize the overall operating time of relays installed on the system. The objective function is formulated by a linear equation considering TDS is a decision variable. The main contribution of this article is the application of novel metaheuristic WCA techniques for optimal OC relay coordination problems. WCA was first proposed and presented by Eskander et al. [33] as a new evolutionary algorithm (EA), and has been proven to be very competitive and fast compare to other EA techniques. The competency of the proposed WCA is evaluated with three case studies, and the comparison of the proposed method with GA, SM, FA, CFA, CGA, and RTA is presented. The rest of this article is organized as follows: Sect. 2 provides a detailed procedure for problem formulation of relay coordination. Water cycle algorithm is explained in brief in Sect. 3. Section 4 consists of the implementation of WCA on the relay coordination problem. The three case studies along with their computational results, comparison, and discussion with the existing

algorithm are provided in Sect. 5. Section 6 concluded the article.

2 Problem formulation

Consider an example of two bus radial distribution system is shown in Fig. 1. A fault k takes place on the system at point F beyond bus B . The relay R_2 acts first to take over this fault because R_2 is the adjacent relay to this fault. If, due to any reason R_2 fails to operate, R_1 comes in action after a predefined time delay. Hence, the relay R_1 performs a duty of backup protection. If the operating time of R_2 is set at 0.1 s, then the operating time of R_1 is set with the addition of time delay, which includes 0.1 s in addition to the operating time of CB at bus A and the overshoot time of R_1 .

The coordination of OC relay in the distribution network can be expressed as an optimization problem. Mathematically, it is stated as the sum of operating time of all installed relays ' z ' for a particular fault instant, which is to be minimized as follows:

$$\text{Minimize } z = \sum_{i=1}^n W_j \times T_{i_k} \quad (1)$$

where z denotes the objective function of this paper problem statement. n is the number of relays, T_{i_k} represents the operating time of relay i at fault location k . W_j is the weighting factor. The possible approach to using the weighting factor is to achieve the minimum system shock due to the faults would be to reduce a weighted the total operating time of all primary relays would be close to the minimum individual operating times that could be feasible. A fault may occur anywhere across the line since there are short lines in the distribution system and they have almost equal length and equal weights. W_j is therefore considered to be 1 ($W_j = 1$) for all relays. It is also a coefficient indicating the likelihood of fault occurrence. Therefore, since the length and weight of the lines are identical, the probability that the fault will occur on each line is equal. Because of this equal probability, usually W_j is set to 1 [2, 12, 18, 26, 35].

Fig. 1 A radial distribution system

2.1 Constraint criterion

Following constraints have to take into considerations which are as:

2.1.1 Operating time constraints

The load continuously varies at the distribution end. Due to these small disturbances which frequently come on the system, a relay has to wait for a few cycles and also not to take too long time to identify and register a fault condition.

Constraints on relay operating time can be written as:

$$T_{i_{kmin}} \leq T_{i_k} \leq T_{i_{kmax}} \quad (2)$$

where $T_{i_{kmin}}$ and $T_{i_{kmax}}$ is the lower and upper boundary for the i th relay at location k , respectively.

Typical values for $T_{i_{kmin}} = 0.1$ s and $T_{i_{kmax}} = 1.1$ s [28].

Sometimes $T_{i_{kmax}}$ may vary upon network configuration. This constraint indicate that lower the operating time constraints faster will be the relay response and hence lower will be the TDS.

2.1.2 TDS constraints

The fast response of relay depends upon the adequate selection of the TDS setting of the relay. Its bounds may be represented as:

$$TDS_{imin} \leq TDS \leq TDS_{imax} \quad (3)$$

where TDS_{imin} and TDS_{imax} is the lower and upper bounds of i th TDS, respectively.

In this paper, typical values for $TDS_{imin} = 0.025$ and $TDS_{imax} = 1.2$ are considered [2].

2.1.3 Coordination constraint

When a fault arises in the system both primary and backup relay sense this fault and may act simultaneously. Hence to avoid this false tripping, the backup relay should operate subsequently to predefined time interval known as CTI only when the primary relay fails.

Therefore the coordination criteria between backup and primary relay mathematically expressed as [28]:

$$T_{bi_k} - T_{pj_k} \geq CTI \quad (4)$$

where T_{bi_k} is the functioning time of i th backup relay at fault k and T_{pj_k} is the functioning time of primary j th relay at the same fault k . CTI is the coordination time interval.

Table 1 Values for α and β of different over current relay characteristics [28]

Relay type	β	α
Inverse definite minimum time	0.14	0.02
Very inverse	13.5	1
Extremely inverse	80	2
Instantaneous	Fixed operating time	
Definite time	Predefined and fixed operating time	

CTI can be taken as 0.1 to 0.5 s, which depends upon the speed of the circuit breaker [26].

2.2 Relay characteristics

In OC relay family, different relays are available. These different relays characteristics constants are given in Table 1. Mostly preferred OC relay is inverse definite minimum time (IDMT) relay because of its elegant features this can be expressed by the following equation [32].

$$T_{op} = \frac{\beta \times TDS}{(PSM)^\alpha - 1} = \frac{0.14 \times TDS}{(PSM)^{0.02} - 1} \quad (5)$$

where T_{op} the operating time of relay, β , and α are standard constant for IDMT relay characteristics. TDS is the time dial setting, and PSM is the plug setting multiplier.

The nature of Eq. (5) is nonlinear, but keeping PSM is fixed with predetermine pick up current value Eq. (5) can be converted into a linear equation [2].

$$T_{Op} = a_i \times (TDS) \quad (6)$$

where

$$a_i = \frac{0.14}{(PSM)^{0.02} - 1} \quad (7)$$

Substitute the Eq. (7) into Eq. (1) to get the objective function of relay coordination problem and can be rewritten as:

$$\text{Minimize } z = \sum_{i=1}^n a_{ik} \times TDS \quad (8)$$

where a_{ik} is the constant term of the i th relay at location k .

3 Water cycle algorithm

Inspired by the natural water cycle process, Eskander et al. [33]. proposed the meta-heuristic water cycle algorithm (WCA). WCA can find the best minimum or maximum

value of a given function with higher accuracy in less time. The author in [37] applied the WCA technique to solve an optimal reactive power dispatch problem considering the standard IEEE 30 bus test system and obtained encouraging results. Jabbar et al. [38] also used WCA to the rough set theory for attribute reduction problems. Based on their findings, the WCA performed just as well or even better than other methods to detect optimal selection of attributes. The optimal relay coordination problem is a constrained type of optimization problem that cannot be addressed effectively using traditional approaches. Therefore, the motivation is developed to use the WCA to solve the over current relay coordination problem for the various distribution network.

Mathematical Model for water cycle algorithm is described below in the following stages as:

3.1 Initial Population

In this algorithm, the population is called raindrops. For each raindrop is an array of $1 \times N_{var}$.

This array can be represented as follows:

$$\text{Raindrops} = X_i = [x_1, x_2, x_3, \dots, x_{N_{var}}] \quad (9)$$

where N_{var} is the number of variables. For optimization, the array is represented in a matrix form

$$\text{Raindrops} = \begin{bmatrix} \text{raindrop1} \\ \text{raindrop2} \\ \vdots \\ \text{raindrop3} \end{bmatrix} \quad (10)$$

where N_{pop} is the number of population for raindrops as an initialization.

Cost function obtained by the following equation

$$C_i = f(x_1^i, x_2^i, \dots, x_{N_{var}}^i) \quad \text{Where, } i = 1, 2, \dots, N_{pop} \quad (11)$$

3.2 Streamflow to the river or river flow to the sea

Streams are produced from the raindrops and join to the river. Sometimes the stream may directly join the sea. All streams and river flow ended up in the sea. The mathematical expression is given in Eqs. (12) and (13).

$$\text{location}_{\text{newstream}} = \text{location}_{\text{stream}} + \text{rand} \times C \\ \times (\text{location}_{\text{river}} - \text{location}_{\text{stream}}) \quad (12)$$

$$location_{newriver} = location_{river} + rand \times C \times (location_{stream} - location_{river}) \quad (13)$$

where $rand$ is the random number evenly distributed between 0 and 1. C is the number between 1 and 2. If the updated stream location gives the solution, then no need to connect it to the river. The location of stream and river interchange (i.e. streams becomes the river and vice versa). Perhaps, such an interchange can occur for the river and the sea.

3.3 Condition for evaporation and raining

It is assumed that this condition will avoid being deceived in local optima. The evaporation condition end if

$$|location_{stream} - location_{river}| < d_{max} \quad (14)$$

where d_{max} is close to zero. After evaporation process value of d_{max} start decreases as:

$$d_{max}^{new} = d_{max} - \left(\frac{d_{max}}{iter.max} \right) \quad (15)$$

where $iter.max$ is the maximum iterations.

So, when this evaporated water goes into the atmosphere to appear as a cloud, the raining cycle will begin. The cloud becomes cold due to the condensation process and releases water back to earth. Such raindrops create a new stream flowing into the river and winding up in the sea. These new locations of streams can be expressed as follows:

$$location_{newstream} = lb + rand \times (ub - lb) \quad (16)$$

where lb and ub are lower and upper bounds assigned for the given problem.

Correspondingly to obtain an improved convergence rate and computational time for the constrained type of problem an Eq. (17) is written for a stream which directly connected to the sea. This Equation helps to enhance the exploration near the sea in the feasible region [33, 36].

$$location_{newstream} = location_{sea} + \sqrt{\mu} \times randn(1, N_{var}) \quad (17)$$

where μ is the coefficient of searching region range nearby sea, $randn$ is the normally distributed random number. The suitable value of μ is taken as 0.1 because the larger value of μ increases the probability to escape from the feasible region. Hence, the smaller value is considered which leads to exploring in the smaller region near to the sea. The term $\sqrt{\mu}$ represent the standard deviation.

3.4 End of loop

The most exceptional result is computed when the termination condition comes with the maximum number of iterations. The end of the loop in WCA is continued till the convergence criterion is satisfied.

4 Implementation of WCA for Relay Coordination

The proposed WCA approach used for relay coordination to find the optimal value of TMS and to reduce the operating time of installed relay in the system. WCA takes the following steps to compute the given problem. Flow-chart depicted in Fig. 2 helps to understand the implementation procedure of the proposed WCA on the relay coordination problem.

- Stage 1: Select the initialization parameters such as N_{pop} , N_{sr} , d_{max} , and maximum iterations. Where N_{sr} is the number of streams and rivers
- Stage 2: Create random initialization population matrix by Eq. (10)
- Stage 3: Calculate the cost function of relay coordination for each raindrop by Eq. (11)
- Stage 4: Determine the streams and river flow by using Eqs. (12) and (13)
- Stage 5: Interchange the location of the river with stream and vice versa for the best solution
- Stage 7: Decrease the defined d_{max} value by Eq. (15)
- Stage 8: Check for convergence criterion using Eq. (17) If it is satisfied and reached up to the maximum iteration algorithm will stop otherwise, go to stage 4 and repeat the above procedure

5 Result and discussion

The proposed WCA program has been developed in MATLAB software to find the optimal TDS value of OC relay in a single and multi-loop distribution network. The execution of WCA is implemented on three different network configurations and it was observed that the proposed WCA gives a better solution in all the contextual analysis. The detailed system descriptions of all three cases can be found in [2, 26, 29]. The purpose behind considering a single loop and multi-loop network is that depending upon different networks, the number of constraints, CTI and complexity varies. Therefore, the viability of the proposed WCA must be reviewed and evaluated with the simple as well as complicated network to evaluate its computational time and

Fig. 2 Flowchart of WCA algorithm

number of iterations. Besides the reason behind choosing the three case studies presented in the paper is that these case studies are already discussed in the literature. So, the results obtained from the proposed WCA results can be compared and validated with the other existing technique.

5.1 Case study I

In this case, a single end loop distribution system consists of seven OC relays, as depicted in Fig. 3. Relays 1 and 5 are non-directional OC relay, and other relays are directional over current relay. Table 2 consists of CT ratios and plug settings of relays. Primary/back up relation is tabulated in Table 3. different fault locations, current sensing relays, and a_i constant are given in Table 4.

In this case study, twelve constraints are taken into consideration. Seven constraints are taken for minimum operating time, and five constraints are due to the coordination criterion. CTI is considered as 0.2 s. The TDS of seven OC relays are represented by x_1 to x_7 in Eq. (25). ($x_1, \dots, x_7$ subscripts indicates the relay numbers).

The following calculations are useful to model the objective function for case study I. In the following Eqs. (18)–(24), the value of a_i constant is taken from Table 4.

Relay 1 sense the fault locations M and N as shown in Fig. 3 and Table 4. It can be written in mathematical form as:

$$a_1 = 3.252 + 6.872 = 10.124 \quad (18)$$

Fig. 3 A single-end loop distribution system

Table 2 CT ratios and plug settings of seven relays [2]

Relay	CT ratios (A: A)	Plug settings
1	1000:1	0.8
2	1000:1	0.8
3	500:1	0.8
4	500:1	0.8
5	1000:1	0.8
6	1000:1	0.8
7	500:1	0.5

Relay 2 sense only one fault point M. It also can be written in mathematical form as:

$$a_2 = 43.776 \quad (19)$$

Relay 3 sense the fault locations K, L, and N as shown in Table 4 and can be written in mathematical form as:

$$a_3 = 6.872 + 5.809 + 4.044 = 16.725 \quad (20)$$

Relay 4 also senses the fault locations like relay 1 i.e. M and N and represented in mathematical form as:

$$a_4 = 8.159 + 5.811 = 13.97 \quad (21)$$

Like relay 3, similarly relay 5, also sense the same fault locations K, L, and N and can be written in mathematical form as:

$$a_5 = 4.811 + 5.809 + 14.01 = 24.63 \quad (22)$$

Relay 6 sense only one fault location K and can be expressed in mathematical form as:

$$a_6 = 22.165 \quad (23)$$

Relay 7 also sense the single fault location L and can be written in mathematical form as:

$$a_7 = 4.145 \quad (24)$$

Table 3 Primary/backup relationship and fault current through relay [2]

Fault location	Primary relay	Backup relay	Fault current (A)
K	5	–	3289
	6	3	1096.5
L	7	3	1315.8 through relay 3 and 5
	–	5	2631.6 through relay 7
M	3	1	2193
	4	5	1315.5
N	1	–	6579
	2	4	939

Table 4 a_i constant and relay current (A) for case study I [2]

Fault location		Relay						
		1	2	3	4	5	6	7
K	Relay current	–	–	2.741	–	4.111	1.370	–
	a_i	–	–	6.872	–	4.881	22.165	–
L	Relay current	–	–	3.289	–	3.289	–	5.263
	a_i	–	–	5.809	–	5.809	–	4.145
M	Relay current	8.223	1.1737	–	2.347	–	–	–
	a_i	3.252	43.776	–	8.159	–	–	–
N	Relay current	2.741	–	5.482	3.288	1.644	–	–
	a_i	6.872	–	4.044	5.811	14.01	–	–

Therefore, the calculations made in Eqs. (18)–(24), gives the objective function for a case study I and can be shaped as:

$$\text{Min } z = 10.24x_1 + 43.77x_2 + 16.725x_3 + 13.97x_4 + 24.63x_5 + 22.16x_6 + 4.145x_7 \quad (25)$$

According to Sect. 2.1.1, the constraints for minimum operating time is considered as 0.1 s. The requested data for Eqs. (26)–(32) is taken from Table 4. Therefore the constraints subject to the minimum operating time are as follows:

$$3.255x_1 \geq 0.1 \quad (26)$$

$$43.77x_2 \geq 0.1 \quad (27)$$

$$4.044x_2 \geq 0.1 \quad (28)$$

$$5.811x_4 \geq 0.1 \quad (29)$$

$$4.881x_5 \geq 0.1 \quad (30)$$

$$22.165x_6 \geq 0.1 \quad (31)$$

$$4.14x_7 \geq 0.1 \quad (32)$$

The constraints given in Eqs. (27)–(32) disobey the constraint for the minimum value of TDS as mentioned in Sect. 2.1.2 TDS constraint. Therefore, these constraints are set to minimum TDS at 0.025 and rewritten as follows:

$$x_2 \geq 0.025 \quad (33)$$

$$x_3 \geq 0.025 \quad (34)$$

$$x_4 \geq 0.025 \quad (35)$$

$$x_5 \geq 0.025 \quad (36)$$

$$x_6 \geq 0.025 \quad (37)$$

$$x_7 \geq 0.025 \quad (38)$$

Moreover, the coordination constraint must have to take into consideration as mentioned in Sect. 2.1.3 coordination constraint. For these coordination constraints, primary/backup relay pair details are required which is taken from Table 3. In this case, the CTI is assumed as 0.2 s. Hence, the coordination criterion constraint with CTI expressed as follows:

$$43.77x_2 - 8.159x_4 \geq 0.2 \quad (39)$$

$$6.872x_1 - 4.044x_3 \geq 0.2 \quad (40)$$

$$14.01x_5 - 5.811x_4 \geq 0.2 \quad (41)$$

$$6.872x_3 - 22.165x_6 \geq 0.2 \quad (42)$$

$$5.809x_3 - 13.998x_7 \geq 0.2 \quad (43)$$

5.1.1 Application of WCA

In this case, the lower and upper limits for TDS are set as 0.025 and 1.2 respectively. The constraints for minimum operating time are given in Eqs. (26)–(32). The coordination constraints are provided in Eqs. (39)–(43). The proposed technique, WCA has been tested in case I with 50 initial population size and 100 iterations. The WCA code has been run for 30 times, and the minimum value of the objective function was observed as 4.20 s. The optimized TDS for all seven relays and total operating time are given in Table 5 (TDS 1, TDS 2 subscripts indicates the relay number). Table 5 also provides a comparative analysis of the proposed method with the existing methods. The Convergence characteristic for case study 1 of the proposed WCA is depicted in Fig. 4.

Table 5 Optimized TDS and total operating time for case study I

Time dial settings	Simplex method [2]	Root tree algorithm [29]	Proposed water cycle algorithm
TDS 1	0.238	0.085	0.059
TDS 2	0.12	0.025	0.025
TDS 3	0.36	0.095	0.052
TDS 4	0.031	0.025	0.025
TDS 5	0.027	0.025	0.025
TDS 6	0.025	0.025	0.025
TDS 7	0.08	0.025	0.025
Total operating time(z) in second	15.70	5.17	4.20
Net time gain in seconds with WCA	11.50	0.97

Fig. 4 Convergence characteristic for a case study I **Fig. 5** Multi-loop single end distribution network

5.1.2 Comparison of WCA with simplex method and root tree algorithm

The results obtained with the proposed WCA show the better quality performances of the suggested algorithm.

Table 6 Primary/backup relation of relay and maximum fault current for case study 3 [29]

Fault location	Primary relay	Backup relay	Maximum fault current (A)
K	3, 7	-, 4	2330
L	3, 4	-, 1, 2	1200
M	4, 8	1, 2, 3	1400
N	1, 5	-, 8	2800
O	2, 6	-, 8	2800
P	1, 2, 8	-, -, 3	2330

It reduces minimum operating time by 11.50 s and 0.97 s in comparison with the simplex method and root tree algorithm, respectively. It is found that WCA provides slightly improved net time gain relative to RTA, but as oppose to RTA, WCA takes fewer iterations [29]. The WCA gave less operating time and improved the performance of seven OC relay with optimized TDS. It can be seen from Fig. 4 if carefully observed that the convergence has been started only before 10th iterations, even though 100 iterations are taken. Even though 100 iterations are taken. This shows the superiority of WCA in terms of smoothness and fast convergence in relay coordination problems.

5.2 Case study II

Figure 5 demonstrated, a multi-loop single-ended distribution network with eight over current relays. Relays 1, 2, and 3 are considered as a non-directional relay, whereas the remaining five relays are directional over current relay. Six fault points K, L, M, N, O, and P are marked in Fig. 5. Primary-backup relation among all eight relays and maximum fault current is given in Table 6. The details of a_i constant and relay current for case study II are given in Table 7. All eight relays have a CT ratio 100:1. Eight constraints are taken for a minimum operating time of relay, and furthermore, eight constraints are taken into consideration for coordination

Table 7 a_i constants and relay currents (A) for case study II [29]

Fault location		Relay							
		1	2	3	4	5	6	7	8
K	Relay current	2	2	10	4	–	–	4	–
	a_i	10.035	10.035	2.971	4.9804	–	–	4.9804	–
L	Relay current	3.45	3.45	5.1	6.9	–	–	–	–
	a_i	5.584	5.584	4.227	3.551	–	–	–	–
M	Relay current	5	5	4	10	–	–	–	4
	a_i	4.281	4.281	4.9804	2.971	–	–	–	4.9804
N	Relay current	20	6	2	–	8	–	–	2
	a_i	2.267	3.837	10.035	–	3.297	–	–	10.035
O	Relay current	6	20	2	–	–	8	–	2
	a_i	3.837	2.267	10.035	–	–	3.297	–	10.035
P	Relay current	10	10	3.3	–	–	–	–	3.3
	a_i	2.971	2.971	5.749	–	–	–	–	5.749

criterion. This system is quite complicated as compared with the previous case; therefore, the CTI is taken as 0.6. The TDS of eight OC relay is represented by x_1 to x_8 in Eq. (44).

The calculation is made to build the objective function for case study II is close to the case study I described. The requested data for Eq. (44) is taken from Table 7. Therefore, the objective function can be written as:

$$\text{Min } z = 28.975x_1 + 28.975x_2 + 37.736x_3 + 11.502x_4 + 3.297x_5 + 3.297x_6 + 4.9804x_7 + 30.799x_8 \quad (44)$$

According to Sect. 2.1.1, the constraint for minimum operating time is considered as 0.1 s. The data for Eqs. (45)–(52) are taken from Table 7. Therefore, the constraints subject to the minimum functioning time of relay are stated as follows:

$$2.97x_1 \geq 0.1 \quad (45)$$

$$2.97x_2 \geq 0.1 \quad (46)$$

$$5.584x_3 \geq 0.1 \quad (47)$$

$$4.980x_4 \geq 0.1 \quad (48)$$

$$3.297x_5 \geq 0.1 \quad (49)$$

$$3.297x_6 \geq 0.1 \quad (50)$$

$$4.980x_7 \geq 0.1 \quad (51)$$

$$10.035x_8 \geq 0.1 \quad (52)$$

The constraints are given in Eqs. (47), (48), (51) and (52) disobey the constraints for the minimum TDS value of relay.

Therefore, these constraints set at minimum TDS value at 0.025 and rewrite as follows:

$$x_3 \geq 0.025 \quad (53)$$

$$x_4 \geq 0.025 \quad (54)$$

$$x_7 \geq 0.025 \quad (55)$$

$$x_8 \geq 0.025 \quad (56)$$

In this case study, the CTI is assumed as 0.6 s and the data for primary/backup relay pair is taken from Table 6. Hence, the coordination criterion constraint with CTI expressed as follows:

$$5.749x_3 - 5.749x_8 \geq 0.6 \quad (57)$$

$$5.584x_1 - 3.551x_4 \geq 0.6 \quad (58)$$

$$5.584x_2 - 3.551x_4 \geq 0.6 \quad (59)$$

$$4.980x_4 - 4.980x_7 \geq 0.6 \quad (60)$$

$$4.281x_1 - 2.971x_4 \geq 0.6 \quad (61)$$

$$4.980x_3 - 4.980x_8 \geq 0.6 \quad (62)$$

$$10.035x_8 - 3.297x_5 \geq 0.6 \quad (63)$$

$$10.035x_8 - 3.297x_6 \geq 0.6 \quad (64)$$

Table 8 Optimized TDS and total operating time for case study II

Time dial setting	Genetic algorithm [34]	Root tree algorithm [29]	Water cycle algorithm
TDS 1	0.297	0.252	0.194
TDS 2	0.297	0.252	0.145
TDS 3	0.227	0.20	0.030
TDS 4	0.173	0.151	0.145
TDS 5	0.06	0.03	0.030
TDS 6	0.06	0.03	0.030
TDS 7	0.04	0.025	0.025
TDS 8	0.113	0.08	0.069
Total operating time(z) in seconds	31.883	26.681	24.141
Net time gain in seconds with WCA	9.742	2.5

Fig. 6 Convergence characteristic for case study II

5.2.1 Application of WCA

Case study II consists of a multi-loop system with eight over current relays. The TDS constraint with lower and upper bound is varied from 0.025 to 1.2. The constraints for the minimum functioning time of relay are given in Eqs. (45)–(52). Due to the multi-loop, coordination constraint has been increased which leads to a more constrained optimization problem and the proposed WCA effectively works on constrained optimization problems as mentioned in Sect. 3. In this case, CTI is considered as 0.6 s between primary and backup relay, which are given in Eqs. (57)–(64). The proposed WCA is applied in case II with 50 initial populations of raindrops with 100 iterations. The WCA code has been run for 30 times to check the feasibility of the algorithm and the minimum value of objective function was observed as 24.41 s with a few number of iterations. Table 8 demonstrates the optimized TDS value of the proposed WCA and was compared to other existing algorithms. Figure 6 displays the smooth convergence characteristics for case study II.

5.2.2 Comparison of the WCA with exiting algorithms

The results obtained by the proposed WCA is compared with GA and RTA are given in Table 8. This shows from

Fig. 7 A single-end multi-parallel feeder distribution network**Table 9** Line data for case study III [26]

Line	Impedance (Ω)
1–2	$0.08 + j1$
1–3	$0.16 + j2$
2–3	$0.08 + j1$

Table 10 Primary/backup relay pair [26]

Fault location	Primary relay	Backup relay
K	5	–
	6	3
L	3	1
	5	–
M	3	1
	4	5
N	1	–
	2	4

Table 11 CT ratios and plug settings of relay for case study III [26]

Relay	CT ratio (A)	Plug setting
2	300:1	1
4	600:1	1
3	600:1	1
6	600:1	1
1	1000:1	1
3	1000:1	1

Table 8 that the TDS value of all relay optimally improved. The performance of the WCA gives the advantage of net time gain with a large margin of 9.742 s over the genetic algorithm. The advantage of net time gain shows the improvement in overall minimum operating time for all relays. Also, it gives the advantage of 2.5 s over the recently introduced root tree algorithm. The best part of the proposed WCA is that it takes fewer iterations compared to both techniques GA and RTA as cited in the paper. It can be observed from Fig. 6 that the convergence towards minimum operating time has been started only between 40th and 45th iterations. The results achieved by the WCA must meet the coordination constraints for all relays. Besides, no violation of the coordination constraint has been found.

5.3 Case study III

In this case, a single end multi-parallel feeder distribution network demonstrates in Fig. 7. The given system consist of six OC relays with neglecting the line charging admittances. Relays 1 and 5 are non-directional relay and the remaining relays are the directional OC relays. The four fault locations, K, L, M, and N are considered on the different feeders. The line data for this case is provided in Table 9. For different fault locations the primary-backup relay pair is depicted in Table 10. CT ratios and plug settings are given in Table 11. The data for a_i Constant and relay sensing current is tabulated in Table 12. In this case, six constraints come into consideration due to the

minimum relay operating time and five constraints are due to the coordination criteria. CTI is considered as 0.3 s. The TDS of six relays are denoted by x_1 to x_6 in Eq. (65).

The calculation to model the objective function for case study III is made similarly as explained in the case study I. Therefore, it can be constructed from Table 12 as:

$$\text{Min } z = 102.40x_1 + 6.06x_2 + 98.76x_3 + 24.40x_4 + 35.32x_5 + 11.54x_6 \quad (65)$$

The a_i value given in Eqs. (66)–(70) are taken from Table 12. As stated in Sect. 2.1.1, the minimum operating time limit is 0.1 s. So, keeping this constraint in mind, the constraints were formulated subject to the minimum operating time specified in Eqs. (66)–(71) will be as follows:

$$3.646x_1 \geq 0.1 \quad (66)$$

$$6.055x_2 \geq 0.1 \quad (67)$$

$$8.844x_3 \geq 0.1 \quad (68)$$

$$8.844x_4 \geq 0.1 \quad (69)$$

$$4.044x_5 \geq 0.1 \quad (70)$$

$$11.539x_6 \geq 0.1 \quad (71)$$

The constraints given in Eqs. (67)–(71) violate the limit as stated in Sect. 2.1.2 for the minimum value of TDS. Therefore, these constraints are set to minimum TDS 0.025 and rewrite as follows:

$$x_2 \geq 0.025 \quad (72)$$

$$x_3 \geq 0.025 \quad (73)$$

$$x_4 \geq 0.025 \quad (74)$$

$$x_5 \geq 0.025 \quad (75)$$

Table 12 a_i constant and relay current (A) for case study III [26]

Fault location		Relay					
		1	2	3	4	5	6
K	Relay current	1.096	–	1.096	–	5.482	1.827
	a_i	75.91	–	75.91	–	4.044	11.539
L	Relay current	1.644	–	1.644	–	2.741	–
	a_i	13.99	–	13.99	–	6.872	–
M	Relay current	2.193	–	2.193	2.193	2.193	–
	a_i	8.844	–	8.844	8.844	8.844	–
N	Relay current	6.579	3.13	–	1.565	1.565	–
	a_i	3.646	6.065	–	15.55	15.558	–

Table 13 Optimized TDS and total operating time for case study III

Time dial settings	Firefly algorithm [1]	Continuous genetic algorithm [23]	Chaotic firefly algorithm [26]	Root tree algorithm [29]	Proposed water cycle algorithm
TDS1	0.027	0.0765	30.027	0.059	0.0589
TDS2	0.13	0.034	0.221	0.025	0.025
TDS3	0.025	0.0339	0.025	0.025	0.025
TDS4	0.025	0.036	0.025	0.029	0.029
TDS5	0.025	0.0711	0.029	0.065	0.0626
TDS6	0.489	0.0294	0.363	0.025	0.025
Total operating time (z) in seconds	16.25	15.58	14.39	11.93	11.86
Net time gain in seconds with WCA	4.39	3.72	2.53	0.07

Fig. 8 Iteration characteristic for case study III

$$x_6 \geq 0.025 \quad (76)$$

Furthermore, as stated in Sect. 2.1.3, the coordination constraint must be taken into account. Therefore, for these coordination constraints, the primary-backup relay pair data requested which is taken from Table 10. In this case, the CTI is assumed as 0.3 s. Hence, the coordination criterion constraints with CTI are expressed as follows:

$$15.55x_4 - 6.065x_2 \geq 0.3 \quad (77)$$

$$8.844x_1 - 8.844x_3 \geq 0.3 \quad (78)$$

$$8.844x_5 - 8.844x_4 \geq 0.3 \quad (79)$$

$$75.91x_3 - 11.53x_6 \geq 0.3 \quad (80)$$

$$13.998x_1 - 13.998x_3 \geq 0.3 \quad (81)$$

5.3.1 Application of WCA

In this case, the performance of the WCA is evaluated in a single-end loop system with six OC relay. The linear objective function for this case is given in Eq. (65). The lower and upper bound of TDS is taken as 0.025 and 1.2, respectively. To find the optimized TDS value for a given system, various constraints are considered from Eqs. (66) to (81) for simulation purposes. To check the feasibility and strength of the proposed WCA for a relay coordination problem, simulation has been run for 30 times, with the initial populations of 50 raindrops for 100th iterations. In all 30 runs, the average minimum objective function was observed as 11.86 s. Table 13 demonstrates the optimized TDS for all six relays with the proposed algorithm and it also elaborates the comparison with other metaheuristic techniques as cited in the literature. The Convergence characteristic for case study III is illustrated in Fig. 8.

5.3.2 Comparison of the proposed WCA with the existing algorithms

To analyze the execution of the proposed WCA, this method has been contrasted with other metaheuristic techniques such as FA, CGA, CFA, and RTA techniques as demonstrated in Table 13. In terms of the total net time gain, the WCA outstripped the FA, CGA, CFA, RTA and provides the advantages of 4.39, 3.72, 2.53, and 0.07 s respectively over this process. In the case of RTA, however, the difference is less just 0.07 s but for the convergence, the RTA technique requires to adjust more input parameters, also it takes more computational effort. RTA takes 200 iterations to converge [29] but for the same WCA takes only 100 iterations. Instead, for convergence towards optimal TDS value, WCA requires to adjust only the initial population and it takes less number of iterations compared to RTA and other techniques. The advantage of even 0.07 s makes the protective system fast and

reliable under abnormal conditions. It can be observed from Fig. 7 that convergence towards the optimal solution has been started from only between 10th to 20th iterations. So, it is revealed from Table 13 and above discussion, the proposed WCA technique shows the faster response over the trending evolutionary algorithms with improved TDS and total operating time with fewer iteration.

6 Conclusion

Water cycle algorithm has been recommended to investigate the coordination problem of over current relays in mesh type power distribution network to calculate the time dial setting (TDS) for a certain pickup current. The study exposes that the suggested method can convey the overall operating time of the over current relay using the present technique is reduced. The proposed idea has been adequately examined and contrasted with other up to date techniques on three different test systems, and it has been observed that the overall operating time of the Over current relay using the present method is reduced, and the algorithm could successfully work for over current relay coordination.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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