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A high-performance hybrid algorithm to solve the optimal coordination of overcurrent relays in radial distribution networks considering several curve shapes

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ABSTRACT

The coordination of overcurrent relays (OCRs) is essential for improving reliability and security indicators in electrical networks. This paper proposes a high-performance hybrid algorithm (HPHA) to solve the optimal coordination of OCRs in radial distribution networks (RDNs). The optimal coordination problem is formulated as a mixed-integer nonlinear problem (MINLP). We considering as decision variables: (1) the pickup current (Ip); (2) time dial setting (TDS); (3) relay type; (4) curve type. The HPHA is composed of a specialized genetic algorithm (SGA) and an efficient heuristic algorithm (EHA). Thus, the HPHA finds the optimum combination of Ip, TDS, relay types and curve types that minimize the relays operational times, ensuring the selectivity for several fault levels. The proposed algorithm considers discrete values of Ip and TDS. The simulation results showed that the proposed technique is efficient, fast, reliable and improves the coordination by decreasing the operational times of OCRs.

1. Introduction

The electrical system is not immune to failure, and its protection has a key role in the preservation of equipment (generators, switchgears, conductors, capacitors, transformers etc.). In addition, it is necessary to ensure maximum continuity of power supply to consumers. Interruptions cause damage both for users and for electric utilities. For these, interruptions can mean revenue losses, damage to the power utility image and fines [1]. In order to reduce the number of users affected by the interruptions, the protection devices must be coordinated. This allows a specific sequence of operations when a fault occurs. The main goals of the coordination are sensitivity, selectivity, reliability and speed [2].

During a fault condition, one of the main consequences for the electrical system is the elevation of current levels. Thus, it is natural to use these levels as parameters to determine if the system is faulty. The most common devices in this category are the overcurrent relays (OCR), fuses and circuit breakers. The OCR are typically used as backup protection, but in some cases, they may be the only type of protection available [3]. As most of the distribution systems are radial, the protection using non-directional OCR is suitable and is widely used because it is simple, effective and cheap. This paper focuses on the inverse definite minimum time overcurrent relay (IDMT OCR). These relays have two parameters: pickup current (Ip) and time dial settings (TDS). However, some relays can have their curve types modified (inverse, very inverse etc.). Wherein, each relay type (IEEE [4], IEC [5], IAC [6], U.S. [7] etc.) has a different set of standardized curves.

The coordination problem can be formulated as a mixed-integer nonlinear optimization problem. The main objective consists in minimizing the total operational times of the primary relays. These times rely on the values of Ip, TDS, curve types and relay types. Ip is treated as discrete but the variable TDS is often considered continuous. However, some OCR does not have steps of TDS small enough to be treated as continuous, and rounding them to the nearest possible values can lead to miscoordination [8].

To solve the OCR coordination problem, classical optimization techniques are used, such as linear programming (LP) [2,3,9] and nonlinear programming (NLP) [10–12]. As well as, metaheuristics algorithms (MHAs) have been used. The MHAs can find high-quality solutions and, in some cases, the global optimal solution with less computational effort [13]. In [14–16,8,17] genetic algorithms (GAs) were used to solve the OCR coordination problem. In [8], the author solved the problem with GA and considered Ip and TDS as discrete variables. In [18,19] the problem was solved using particle swarm algorithm. In [20,21] the artificial honey bee algorithms were used to solve the coordination problem. In [22,23], a hybrid algorithm that combines LP and evolutionary algorithms was used to solve the

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problem. A methodology that optimizes each parameter independently, considering discrete Ip and TDS, was proposed in [24]. The problem was also solved using binary integer programming, this way TDS and Ip were considered discrete [25]. In [26] there was an addition of the curve types as decision variables. The authors considered standardized and non-standardized curves types.

The electrical networks encouraged the industrial, commercial and technology development, but most of them are old and not technologically developed. Nowadays, governments have been encouraging the electrical utility to make investments in their networks to make them more reliable, safe and technological. This way, utilities are developing the smart grids. These are electrical grids that use advanced technologies to monitor and act based on the information about the behavior of end-users and generation sources. So, the smart grid coordinates the needs and capabilities of all generators, grid operators, consumers and electricity market stakeholders. With the objective of operating all parts of the system as efficiently as possible, minimizing costs and environmental impacts while maximizing system reliability, security and stability [27]. In the smart grids, the energy control centers need fast and reliable techniques or computational algorithms, to be used in real-time applications. Hence, there is a great interest of electric utilities to use techniques or computational algorithms to solve problems in their power grids. One of these problems is the optimal coordination of protection devices in real-time. In this paper we propose an efficient, fast and reliable methodology for the coordination of OCR in radial distribution networks (RDNs). Such procedures are essential for the optimal operation of the networks.

The Ip, TDS are usually considered as decision variables. This paper considers the addition of curve and relay types as decision variables. A high-performance hybrid algorithm (HPHA) is proposed to solve the coordination problem. This combines a GA with an efficient heuristic algorithm (EHA). The GA is responsible for solving the nonlinear optimization problem, which consists in determining the Ip, relay types and curve types. This way is possible to find the optimum TDS possessing these variables. If TDS are treated as continuous variables, the problem of finding its optimal values is linear. Thus, LP techniques such as simplex, dual simplex, two-phase simplex and interior points are usually used to solve it. In this paper, the EHA will be used instead of LP techniques. Since the TDS are not encoded in the chromosome of the GA, its search space is greatly reduced. The HPHA also ensure the selectivity for multiple fault levels.

This paper is organized as follows: Section 2, presents the characteristics of the OCR used in this paper. Section 4, the presents OCR coordination problem as an optimization problem. Section 5.5 presents the EHA for finding the optimal TDS, in RDN. Section 5, presents the HPHA. Section 6, presents the test systems used in this paper. Section 7 provides a critical analysis of the obtained results. Finally, Section 8 concludes the work presented in this paper.

2. Overcurrent relay characteristics

The OCR operates when the input current exceeds a predetermined value (Ip), sending a signal to the circuit breaker to interrupt the circuit. The non-directional IDMT OCR has an operation time that is inversely proportional to the intensity of the input current. Moreover, it does not take into account the direction of the current flow. One of its main applications is in the RDNs, where the directions of the current flows are always known [28]. These relays have their operational times (1) determined by international standards, such as IEEE (Institute of Electrical and Electronics Engineers) [4], IEC (International Electrotechnical Commission) [5], IAC (Inverse Alternate Current) [6], U.S. (United States) [7] etc. The operational time of a relay i (R_i) for each k fault inside the primary protection zone of R_j (Icc_j^k) is shown in (1), and it depends on the TDS of R_i (TDS_i) and $K_{i,j}^k$. The term $K_{i,j}^k$ varies with the standard of R_i, and it related to the values of Ip of R_i (Ip_i), Icc_j^k and the curve constants related to the curve types of R_i. For the IEEE, IEC, IAC and U.S. standards, $K_{i,j}^k$ is computed using (2)–(5), respectively. Tables 1–4 show the constants related to the curve types for the IEEE, IEC, IAC and U.S. standards, respectively. Where E.I, V.I, M.I, I, L.I and S.I refer to extremely, very, moderately, standard, long and short inverse curve types, respectively.

To improve the effectiveness of the protection scheme, the selectivity must be guaranteed for a range of fault currents. For selectivity purposes, is considered p fault current levels inside each primary protection zone, as shown in (6). For instance, if $p=2$, the selectivity is guaranteed, for each OCR, for two expected fault levels: the minimum and maximum. For $p>2$, more fault levels between the expected minimum and maximum are considered for the selectivity. Eq. (7) shows the size of the discretization steps of the selectivity interval (ΔIcc_j^k), for faults within the primary protection of R_j.

For phase OCRs, the maximum and minimum expected fault currents are usually the close-in three-phase and the far-end two-phase faults, respectively. For ground OCRs, the close-in phase-to-ground and the far-end phase-to-ground (through a contact impedance) faults might be used as maximum and minimum expected fault currents.

$$T_{i,j}^k = TDS_i \cdot K_{i,j}^k \quad (1)$$

$$K_{i,j}^k = \frac{A_i}{\left(\frac{Icc_j^k}{Ip_i}\right)^{P_i} - 1} + B_i \quad (2)$$

Table 1
Constants of curve types for the IEEE relay [4].

Curve type	A	B	P
E.I	28.20	0.122	2.00
V.I	19.61	0.491	2.00
M.I	0.05	0.114	0.02

Table 2
Constants of curve types for the IEC relay [5].

Curve type	A	N
I	0.14	0.02
V.I	13.50	1.00
E.I	80.00	2.00
L.I	120.00	1.00

Table 3
Constants of curve types for the IAC relay [6].

Curve type	A	B	C	D	E
E.I	0.004	0.638	0.620	1.787	0.246
V.I	0.090	0.796	0.100	−1.289	7.959
I	0.208	0.863	0.800	−0.418	0.195
S.I	0.043	0.061	0.620	−0.001	0.022

Table 4
Constants related to the curve types for the U.S. relay [7].

Curve type	A	B	N
M.I	0.023	0.010	0.020
V.I	0.097	3.880	2.000
S.I	0.003	0.003	0.020
I	0.180	5.950	2.000
E.I	0.035	5.670	2.000

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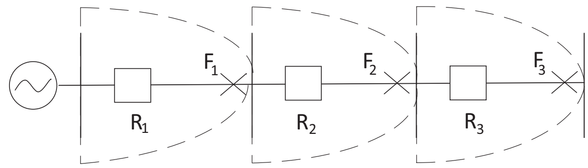

Fig. 1. Radial system with three relays and their respective primary protection zones.

$$K_{i,j}^{k}=\frac{A_i}{\left(\frac{Icc_j^k}{Ip_i}\right)^{N_i}-1} \quad (3)$$

$$K_{i,j}^{k}=A_i+\frac{B_i}{\frac{Icc_j^k}{Ip_i}-C_i}+\frac{D_i}{\left(\frac{Icc_j^k}{Ip_i}-C_i\right)^2}+\frac{E_i}{\left(\frac{Icc_j^k}{Ip_i}-C_i\right)^3} \quad (4)$$

$$K_{i,j}^{k}=A_i+\frac{B_i}{\left(\frac{Icc_j^k}{Ip_i}\right)^{P_i}-1} \quad (5)$$

$$Icc_j^k=Icc_{\min}^j+(k-1)\cdot\Delta Icc_j^k \quad (6)$$

$$\Delta Icc_j^k=\frac{Icc_{\max}^j-Icc_{\min}^j}{p-1},\quad p>1 \quad (7)$$

where $T_{i,j}^k$ is the operation time of R_i for Icc_j^k. TDS_i is the TDS of R_i. $K_{i,j}^k$ is related to the relay operational time and it varies with the standard of R_i. Icc_j^k is the k level of short-circuit where R_j act as primary protection. $A_i, B_i, C_i, D_i, E_i, N_i$ and P_i are constants related to the curve types for, R_i. ΔIcc_j^k is the size of the discretization step of the selectivity interval. $Icc_{\max}^j$ and $Icc_{\min}^j$ are the maximum and minimum short-circuit currents inside the primary protection zone of R_j, respectively.

3. Coordination problem

In Fig. 1 is shown a RDN. Where R_1, R_2 and R_3 refer to relays 1, 2 and 3, respectively. F_1, F_2 and F_3 correspond to the faults location in the system. For the fault in F_3, R_3 and R_2 will act as primary and back-up protection (PP and BP), respectively. For the fault in F_2, R_2 and R_1 will act as PP and BP, respectively. Finally, for the fault in F_1, R_1 will act as PP and it is the only protection available. The areas bounded by dotted lines are the protection zones of each relay.

As the fault is sensed by both BP and PP simultaneously, the difference between their operational times must be greater or equal than the coordination time interval (ΔT_{relay}), to guarantee the selectivity. This way, the PP will have sufficient time to clear the fault, wherein the BP must act only if the PP fails in clearing the fault. Usually, is adopted ΔT_{relay} = 0.4 s because the circuit breaker operating time, the manufacturing tolerances and the design of safety time are approximately 0.13, 0.10 and 0.17 s, respectively [1].

4. Mathematical model

In this section, the coordination problem of OCRs is formulated as an optimization problem, containing an objective function (OF), responsible for minimizing the operating times of the relays, and a set of constraints. This problem is formulated as a nonlinear and non-convex optimization problem, with a high number of restrictions [23,29]. In this paper, Ip, TDS, curve type, and relay type are considered as variables. If any of these parameters is treated as a discrete, the problem becomes mixed-integer, which has a greater complexity. The addition of curve and relay types as decision variables is supported by the fact that some microprocessor-based OCRs accept several curve types and standards. For instance, the SEPAM Series 20 (Schneider Electric) [30] and the 735/737 (General Electric) [6] accept multiple curve standards, such as IEEE, IEC and IAC.

4.1. Objective function

In a fault situation, one of the consequences for the electrical system is the sudden increase in current levels to dangerous values. The faster the fault is isolated, the lower is the thermal and mechanical efforts in the system. In the optimal coordination of OCRs, the objective is to obtain the settings (Ip, TDS, curve types and relay types) that minimize the operational time of the primary protection OCRs [3,31–33]. The optimal settings are directly related to the speed criteria. The OF consists of minimizing the sum of all operational times of the OCRs, for all the p fault levels considered within its primary protection zone, as shown in (8).

$$\min \quad z=\frac{1}{p}\sum_{k=1}^{p}\sum_{i=1}^{m}T_{i,i}^{k} \quad (8)$$

where m, k and p are the number of OCRs, the index related to the fault level analyzed and the number of fault levels considered within the primary protection zones, respectively. $T_{i,i}^k$ is the operational time of R_i for a fault inside its primary protection zone, and it can be computed by setting $j = i$ in (1).

4.2. Constraints

The constraint shown in (9) refers to the ΔT_{relay} needed to ensure the selectivity between BP and PP. The constraint shown in (10) prevents that the relay takes a long time to operate, avoiding the equipment damage and the instability of the power system. The constraints related to the minimum and maximum boundaries of TDS and Ip are shown in (14) and (11), respectively. The relays must not act during the normal operation of the system, as it is shown in (12). R_i cannot act as BP if the minimum short-circuit current inside its protection zone ($Icc_{\min}^{protected,i}$) is less or equal than Ip_i, as shown in (13).

$$T_{BP_i,i}^{k}-T_{i,i}^{k}\geq\Delta T_{relay} \quad (9)$$

$$T_{i,j}^{k}\leq T_{\max} \quad (10)$$

$$Ip_i^{\min}\leq Ip_i\leq Ip_i^{\max} \quad (11)$$

$$Ip_i>LGF\cdot I_{load}^{i} \quad (12)$$

$$Ip_i<Icc_{\min}^{protected,i} \quad (13)$$

$$TDS_i^{\min}\leq TDS_i\leq TDS_i^{\max} \quad (14)$$

where $T_{BP_i,i}^k$ is the operational time for the BP of R_i, for Icc_i^k. $TDS_{i,min}$ and $TDS_{i,max}$ are the minimum and maximum possible TDS for R_i, respectively. T_{max} is the maximum operational time of the OCR, for Icc_j^k. $Ip_i^{\min}$ and $Ip_i^{\max}$ are the minimum and maximum possible Ip for R_i, respectively. $Icc_{\min}^{protected,i}$ is the minimum short-circuit inside the protection zone of R_i. LGF is the load growth factor that includes a possible increase on the system demand. I_{load}^i is the maximum expected load current in the system.

5. The high performance hybrid algorithm

The proposed algorithm is based in the main ideas of the GA presented in [34], which was initially developed to solve the

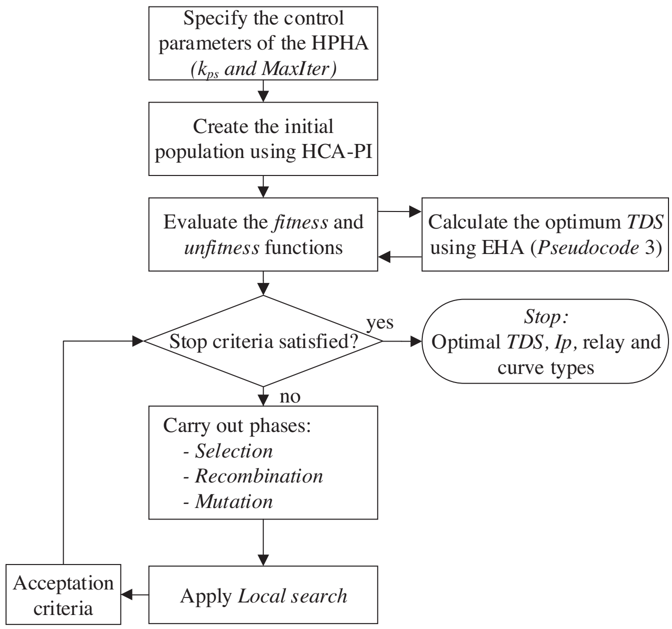

Fig. 2. Flowchart of the proposed HPHA.

generalized assignment problem. This algorithm has several differences when compared to the classical GA: (1) in each generation cycle, only one *offspring* is generated and it can enter in the current population if it satisfies the acceptation criteria; (2) the OF is composed by *fitness* and *unfitness* functions; (3) a local search is used to improve the OF of the *offspring*.

Some modifications in the GA proposed in [34] were made to adapt it to the coordination problem. The codification, population initialization, OF computation and local search are performed in a different way. The proposed method combines EHA with a GA, in order to reduce the dimension of the problem, making this a hybrid technique. The flowchart for the HPHA is shown in Fig. 2. The parameters k_{ps} and *MaxIter* refers to the size of the initial population and the stop criteria, respectively. The HPHA stops if the incumbent solution does not change after *MaxIter* generation cycles.

5.1. Codification

In this paper, the *TDS*, *Ip*, relay and curve types are considered decision variables. The TDS are not coded in the chromosome because its optimal values are determined using the EHA. An example of a chromosome for a system containing five OCR is shown in Fig. 3. Where Ip_{gene}, $Relay_{gene}$ and $Curve_{gene}$ are *Ip*, relay type and curve types genes, respectively. Each chromosome is divided into three parts: one for selecting Ip, one for curve types, and the other for relay types. A decimal codification is considered. Each gene assigned in Ip_{gene} will correspond to a feasible *Ip* value accepted by the respective OCR. Each value $Relay_{gene}$ is related to one relay type (IEEE, IEC, IAC or U.S.), so it vary from one to four. Each value of $Curve_{gene}$ is related to one standardized curve type of the respective OCR and it may vary from one to five.

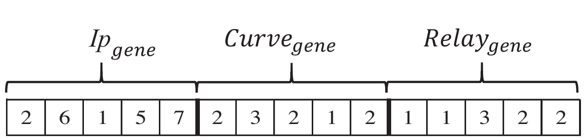

Fig. 3. Example of a chromosome of the proposed algorithm.

5.2. Initial population

The initial population of HPHA can be created randomly, but this can lead to having a population of poor quality (very high operational times of the relays or unfeasible proposals). To solve this issue, the initial population can be created using a heuristic algorithm that takes some characteristics of the problem to be solved. In this paper, is proposed a heuristic constructive algorithm for the population initialization (HCA-PI). This algorithm is shown in Pseudocode 1, where Ip_{gene} are limited by (12) and (13), and the $Curve_{gene}$ are limited by the respective $Relay_{gene}$. The main idea of this algorithm consists in to eliminate some infeasible proposals in the population initialization.

Pseudocode 1. Heuristic constructive algorithm for the population initialization (HCA-PI).

for (All individuals on the population) **do**
  for (i = 1 to number of relays) **do**
    $Ip_{gene}(i) \leftarrow$ random integer value that correspond to a Ip that satisfies $I^{i}_{load} \cdot LGF < Ip < Icc^{protected,i}_{min}$;
    $Relay_{gene}(i) \leftarrow$ random integer value that vary from 1 to 4;
    $Curve_{gene}(i) \leftarrow$ random integer value that vary from 1 to the number of available curve types of R_i;
  end for
end for

5.3. Objective function

First, it is necessary to decode the information of Ip, relay types and curve types of the chromosome, in order to compute the TDS using the EHA (more details in Section 5.5). This way, the *fitness* function is evaluated using (8). The *unfitness* function is proportional to the number of constraints (11)–(14) violated, multiplied by a penalization factor. The *fitness* and *unfitness* functions are combined and form the OF. During the iterative process of the HPHA, the OF is computed several times. Therefore, the EHA is interesting due to its speed.

5.4. Local search

After the phases of selection, recombination and mutation, a new offspring is generated and it can be feasible or infeasible. In both cases, a local search is performed to improve its OF by performing a neighborhood search in Ip_{gene} and $Curve_{gene}$. The algorithm is shown in Pseudocode 2.

Pseudocode 2. Local search algorithm.

for $i = 1$ to number of relays **do**
  Perform a neighborhood search in the $Ip_{gene}(i)$ by incrementing and decrementing one unit;
  If the neighborhood search in the $Ip_{gene}(i)$ improved the OF, update the Ip_{gene};
  Perform a neighborhood search in the $Curve_{gene}(i)$ by incrementing and decrementing one unit;
  If the neighborhood search in the $Curve_{gene}(i)$ improved the OF, update the $Curve_{gene}$;
end for

5.5. Efficient heuristic algorithm (EHA) to calculate the optimum TDS

The LP is a well known technique used to find the optimal TDS [2]. In this paper, is proposed an alternative method entitled “efficient heuristic algorithm (EHA)” to find the optimal TDS in RDN. This algorithm can work with discrete and continuous TDS, unlike the LP techniques.

The proposed algorithm is divided into two steps: relay numbering and iterative process. In the first step, the branches where OCR are located are arranged in layers. In the next step the optimal *TDS* is computed.

5.5.1. Relay numbering

In [35] is proposed a methodology for branches numbering based in layers to solve the three-phase power flow. The same ideas are applied for the OCR numbering. This way, the OCR in one layer is numbered only after all OCR from the previous layer was numbered. In Fig. 4 is shown an example of a system with ten OCR after the numbering. In the case of R_{10}, R_9,. . ., R_1 were analyzed in that particular order, the PP will always be analyzed before the BP. This methodology allows a systematic way to analyze the OCR only once, during the EHA. This procedure is performed only once for a fixed RDN.

5.5.2. Iterative process

The algorithm is showed in Pseudocode 3. In this step, it is assumed that all the OCR are previously numbered as shown above. The variables $K^k_{i,i}$ and $K^k_{BP_i,i}$ are computed with (2)–(5), depending on the type of R_i and R_{BP_i}, respectively. Moreover, it is necessary to check if the new TDS does not violate the bound of TDS_{max} in the steps 10 and 12.

In this algorithm, each backup OCR has the minimum TDSs necessary to be coordinated with their primary protections. This condition is achieved with the step 6 of the Pseudocode 3. The process begins in the relays further from the substation and ends in it. When are considered discrete settings, it is necessary to perform rounding as shown in step 10 of Pseudocode 3 to avoid miscoordination.

Pseudocode 3. Efficient heuristic algorithm (EHA).

1: Initialize all relays with TDS_{min};
2: **for** $i = m$ to 0 **do** ▷ m is the number of relays.
3: **if** R_i has a backup relay **then**
4: $R_{BP_i} \leftarrow$ backup relay of R_i;
5: **for** $k = 1$ to p **do** ▷ p is the number of faults inside each protection zone.
6: $T_{aux} \leftarrow TDS_i \cdot K^k_{i,i} + \Delta T_{relay}$; ▷ the minimum operational time required of R_i for the considered fault level plus ΔT_{relay}.
7: $TDS_{aux} \leftarrow T_{aux}/K^k_{BP_i,i}$; ▷ TDS_{BP_i} required for R_{BP_i} to have an operational time of T_{aux} for the considered fault level.
8: **if** $TDS_{aux} > TDS_{BP_i}$ **then**
9: **if** TDS is considered discrete **then**
10: $TDS_{BP_i} \leftarrow$ round TDS_{aux} to the next available setting;
11: **else** ▷ for continuous TDS.
12: $TDS_{BP_i} \leftarrow TDS_{aux}$;
13: **end if**
14: **end if**
15: **end for**
16: **end if**
17: **end for**

6. Methods

The proposed HPHA is applied in two test systems: I (Fig. 4) and II (Fig. 5). The maximum current load, current transformer ratio (CTR), the initial relay and curve types and the maximum/minimum short-circuit currents inside the protection zone of each OCR, for both systems, are shown in Tables 5 and 6, respectively. Initially, all OCR are IEC with inverse curve type. It is assumed that all relay and curve types can be changed (either by replacement or input parameters). It is considered TDS_{min} = 0.1, TDS_{max} = 10, T_{max} = 5 s, LGF = 150% and p = 2. The TDS steps is 0.05 and 0.01 for the test systems I and II, respectively. The Ip varies from 50 to 200% of the CTR, with steps of 15%. Also, the GA parameters k_{ps} and $MaxIter$ are set to 100 and 1500, respectively.

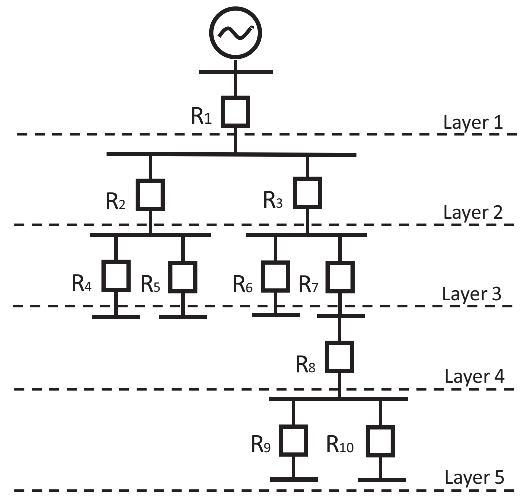

Fig. 4. OCRs renumbering in a RDN (test system II).

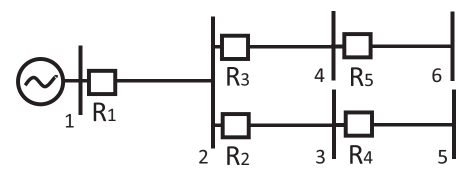

Fig. 5. Test system I.

Table 5
OCR data for the test system I.

	R_1	R_2	R_3	R_4	R_5
$I_{load}(A)$	199.5	130.8	68.7	100.7	50.0
CTR	300/5	300/5	100/5	200/5	100/5
$Icc_{max}(A)$	3115.0	2010.7	2010.7	1512.5	878.4
$Icc_{min}(A)$	1510.5	1046.3	975.1	500.3	325.1

16	16	31	7	7
Ip_1	Ip_2	Ip_3	Ip_4	Ip_5

Fig. 6. Chromosome used for example.

7. Results and discussions

7.1. An example of the HPHA

An example of the procedure used for calculation of the TDSs and OF of the proposed algorithm in the test system I is shown as follows. This procedure takes place in stages for the creation of initial population, mutation, recombination and local search. For simplicity, only the values of *Ip* are decision variables. Thus, the curve and relay types are fixed, where all relays are IEC with inverse curve type. The chromosome of the GA used in this example is shown in Fig. 6. Each gene corresponds to Ip available in the corresponding relay. For example, as the gene related to Ip_1 is 16, so Ip_1 gets the 16th available Ip available at R_1[1] ($Ip_1 \leftarrow 375\,A$). The remaining decoded Ips are $Ip_2 = 375, A$, $Ip_3 = 200, A$, $Ip_4 = 160, A$ and $Ip_5 = 70, A$.

[1] The Ips available at R_1 are {150, 165, 180, 195, . . ., 600A}.

Table 6
OCR data for the test system II.

	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}
$I_{load}(A)$	399.5	120.8	278.7	50.7	70.1	79.2	199.5	199.5	100.7	99.2
CTR	600/5	200/5	500/5	100/5	150/5	600/5	200/5	500/5	100/5	150/5
$Icc_{max}(A)$	3115.0	2010.7	2010.7	1512.5	1512.5	1190.0	1190.0	950.4	780.1	780.1
$Icc_{min}(A)$	1510.0	1046.3	975.1	630.3	599.1	510.5	699.3	519.1	398.3	372.1

First, all relays are initialized with TDS_{min}. The counters i and k are initialized with the number of relays ($i \leftarrow 5$) and ($k \leftarrow 1$), respectively.

7.1.1. Step 1 – coordination between R$_3$ and R$_5$

The coordination is performed for 325.1 A (Icc_5^1), which is one of the considered fault levels inside the primary protection zone of R_5. In this case, $R_i \leftarrow R_5$ and $R_{BP_i} \leftarrow R_3$. T_{aux} is computed as the minimum operational time of R_3 for faults inside its protection zone plus ΔT_{relay}, as shown in (15).

$$T_{aux} = TDS_5 \cdot K_{5,5}^1 + \Delta T_{relay} = 0.1 \cdot 4.9228 + 0.4 = 0.8923\,\text{s} \tag{15}$$

The variable T_{aux} has the minimum operational time required for the backup protection (R_3) to be coordinated with the primary protection (R_5). The necessary TDS for the backup protection have an operational time of T_{aux} is TDS_{aux}, and it is calculated as shown in (16).

$$TDS_{aux} = \frac{T_{aux}}{K_{3,5}^1} = \frac{0.8923}{14.3389} = 0.0622 \tag{16}$$

Since $TDS_{aux} < TDS_3$, the TDS_3 is not updated. The counter k is increased ($k \leftarrow 2$) and the coordination is held for 878.4 A (Icc_5^2), for the same pair of OCRs, as shown in (17) and (18).

$$T_{aux} = TDS_5 \cdot K_{5,5}^2 + \Delta T_{relay} = 0.1 \cdot 2.8520 + 0.4 = 0.6852\,\text{s} \tag{17}$$

$$TDS_{aux} = \frac{T_{aux}}{K_{3,5}^2} = \frac{0.6852}{4.6608} = 0.1470 \tag{18}$$

The $TDS_{aux} > TDS_3$, so $TDS_3 \leftarrow 0.15$, because 0.1470 is not available at the relay.[2] The coordination between R_3 and R_5 is finished, the counter i is decremented ($i \leftarrow 4$) and ($k \leftarrow 1$).

7.1.2. Step 2 – coordination between R$_2$ and R$_4$

The coordination is realize for the fault level of 500.3 A (Icc_4^1), $R_i \leftarrow R_4$ and $R_{BP_i} \leftarrow R_2$. The variables T_{aux} and TDS_{aux} are computed as shown in (19) and (20).

$$T_{aux} = TDS_4 \cdot K_{4,4}^1 + \Delta T_{relay} = 0.1 \cdot 6.0704 + 0.4 = 1.0070\,\text{s} \tag{19}$$

$$TDS_{aux} = \frac{T_{aux}}{K_{2,4}^1} = \frac{1.0070}{24.2119} = 0.0416 \tag{20}$$

As $TDS_{aux} < TDS_2$, the TDS_2 is not updated. The counter k is increased ($k \leftarrow 2$) and the coordination is held for 1512.5 A (Icc_4^2), for the same pair of OCRs. The T_{aux} and TDS_{aux} are computed as shown in (21) and (22).

$$T_{aux} = TDS_4 \cdot K_{4,4}^2 + \Delta T_{relay} = 0.1 \cdot 3.0467 + 0.4 = 0.7047\,\text{s} \tag{21}$$

$$TDS_{aux} = \frac{T_{aux}}{K_{2,4}^2} = \frac{0.7047}{4.9497} = 0.1424 \tag{22}$$

In this case, $TDS_{aux} > TDS_2$, so $TDS_3 \leftarrow 0.15$. The coordination between R_2 and R_4 is ended and the counter i is decremented ($i \leftarrow 3$) and ($k \leftarrow 1$).

7.1.3. Step 3 – coordination between R$_1$ and R$_3$

The coordination is performed for 975.1 A (Icc_3^1), $R_i \leftarrow R_3$ and $R_{BP_i} \leftarrow R_1$. The variables T_{aux} and TDS_{aux} are computed as shown in (23) and (24).

$$T_{aux} = TDS_3 \cdot K_{3,3}^1 + \Delta T_{relay} = 0.15 \cdot 4.3489 + 0.4 = 1.0523\,\text{s} \tag{23}$$

$$TDS_{aux} = \frac{T_{aux}}{K_{1,3}^1} = \frac{1.0523}{7.2554} = 0.1450 \tag{24}$$

As $TDS_{aux} > TDS_1$, so $TDS_1 \leftarrow 0.15$. The counter k is increased ($k \leftarrow 2$) and the coordination is performed for 2010.7 A (Icc_3^2), for the same pair of OCRs. The variables T_{aux} and TDS_{aux} are computed as shown in (25) and (26).

$$T_{aux} = TDS_3 \cdot K_{3,3}^2 + \Delta T_{relay} = 0.15 \cdot 2.9636 + 0.4 = 0.8445\,\text{s} \tag{25}$$

$$TDS_{aux} = \frac{T_{aux}}{K_{1,3}^2} = \frac{0.8445}{4.0988} = 0.2060 \tag{26}$$

Once again, the $TDS_{aux} > TDS_1$, so $TDS_1 \leftarrow 0.25$. The coordination between R_3 and R_1 is finished and the counter i is decremented ($i \leftarrow 2$) and ($k \leftarrow 1$).

7.1.4. Step 4 – coordination between R$_1$ and R$_2$

The coordination is realized for 1046.3 A (Icc_2^1), $R_i \leftarrow R_2$ and $R_{BP_i} \leftarrow R_1$. The T_{aux} and TDS_{aux} are computed as shown in (27) and (28).

$$T_{aux} = TDS_2 \cdot K_{2,2}^1 + \Delta T_{relay} = 0.15 \cdot 6.7523 + 0.4 = 1.4128\,\text{s} \tag{27}$$

$$TDS_{aux} = \frac{T_{aux}}{K_{1,2}^1} = \frac{1.4128}{6.7523} = 0.2092 \tag{28}$$

As $TDS_{aux} < TDS_1$, the TDS_1 is not updated. The counter k is increased ($k \leftarrow 2$) and the coordination is held for 2010.7 A (Icc_2^2), for the same pair of OCRs. The T_{aux} and TDS_{aux} are computed as shown in (29) and (30).

$$T_{aux} = TDS_2 \cdot K_{2,2}^2 + \Delta T_{relay} = 0.15 \cdot 4.0988 + 0.4 = 1.0148\,\text{s} \tag{29}$$

$$TDS_{aux} = \frac{T_{aux}}{K_{1,2}^2} = \frac{1.0148}{4.0988} = 0.2476 \tag{30}$$

Due to $TDS_{aux} < TDS_1$, the TDS_1 is not updated. The coordination between R_1 and R_2 is finished and the counter i is decremented ($i \leftarrow 1$) and ($k \leftarrow 1$). As $R_i \leftarrow R_1$ and it does not have backup protection, the iterative process ends. The optimum TDSs are $TDS_1 = 0.25$, $TDS_2 = 0.15$, $TDS_3 = 0.15$, $TDS_4 = 0.10$ and $TDS_5 = 0.10$. The OF in this case is 3.231 s.

7.2. Results for test systems I and II

For both systems, the OCR coordination will be done for three cases: A, B and C. In the case A, TDS and Ip are considered decision variables. In case B, there is an addition of the curve types as decision variables. In case C, there is an addition of the relay types as decision variables. The results are shown in Tables 7 and 8.

When the results of cases A and B are confronted, the addition of curve types as decision variables improved the OF by 25.63 and 35.74% for the systems I and II, respectively. When the results of

[2] The TDS available at the relay are 0.1, 0.15, 0.20, 0.25, ..., 10.

Table 7
Results for test system I.

	Case A				Case B				Case C			
	Ip (A)	TDS	Relay	Curve	Ip (A)	TDS	Relay	Curve	Ip (A)	TDS	Relay	Curve
R_1	375	0.25	IEC	I	375	0.20	IEC	I	420	6.15	U.S.	S.I
R_2	375	0.15	IEC	I	375	0.10	IEC	I	240	2.35	IAC	E.I
R_3	200	0.15	IEC	I	170	0.15	IEC	E.I	125	0.25	IEC	E.I
R_4	160	0.10	IEC	I	160	0.10	IEC	E.I	160	0.10	IAC	S.I
R_5	80	0.10	IEC	I	80	0.10	IEC	E.I	80	0.10	IAC	S.I
OF		3.231 s				2.403 s				1.394 s		

Table 8
Results for test system II.

	Case A				Case B				Case C			
	Ip (A)	TDS	Relay	Curve	Ip (A)	TDS	Relay	Curve	Ip (A)	TDS	Relay	Curve
R_1	440	0.28	IEC	I	500	0.17	IEC	E.I	500	2.02	U.S.	M.I
R_2	160	0.21	IEC	I	160	0.14	IEC	I	160	8.14	IAC	S.I
R_3	370	0.21	IEC	I	310	0.18	IEC	I	250	3.17	IAC	E.I
R_4	80	0.10	IEC	I	80	0.10	IEC	V.I	80	0.10	IAC	S.I
R_5	80	0.10	IEC	I	80	0.10	IEC	E.I	80	0.10	IAC	S.I
R_6	65	0.10	IEC	I	65	0.10	IEC	E.I	65	0.10	IAC	S.I
R_7	250	0.19	IEC	I	130	0.47	IEC	E.I	160	0.30	IEC	E.I
R_8	280	0.10	IEC	I	130	0.20	IEC	E.I	160	1.59	IAC	E.I
R_9	65	0.10	IEC	I	65	0.10	IEC	E.I	65	0.10	IAC	S.I
R_{10}	65	0.10	IEC	I	65	0.10	IEC	E.I	65	0.10	IAC	S.I
OF		6.539 s				4.202 s				3.465 s		

Table 9
Relay operational times (case C), for the test system I.

PP	BP	Icc_{min}				Icc_{max}			
		T_{PP}	T_{BP}	$T_{BP}-T_{PP}$	$Icc(A)$	T_{PP}	T_{BP}	$T_{BP}-T_{PP}$	$Icc(A)$
R_1	–	0.827	–	–	1510.5	0.531	–	–	3115.0
R_2	R_1	0.722	1.158	0.436	1046.3	0.274	0.677	0.404	2010.7
R_3	R_1	0.334	1.254	0.920	975.1	0.078	0.677	0.600	2010.7
R_4	R_2	0.007	3.175	3.168	500.3	0.005	0.406	0.401	1512.5
R_5	R_3	0.006	3.470	3.464	325.1	0.005	0.413	0.409	878.4

cases B and C are confronted, the addition of relay types as decision variables improved the OF by 41.99 and 17.54% for the systems I and II, respectively. A greater improvement happened when confronted cases A with C, which the addition of relay and curve types as decision variables improved the OF by 56.86 and 47.01% for the systems I and II, respectively. The results showed that the addition of more decision variables into the problem greatly reduced the OCR operational times. The consideration of the relays and curves types as decision variables, result in a wide range of curves shapes that can be chosen. This flexibility improved the coordination of OCR.

For the case C, the coordination graphics for the OCR for the test system I and II are shown in Fig. 7. Also, the operational times for both PP and BP are shown in Tables 9 and 10. The selectivity was achieved for the considered fault levels, because of the differences between T_{BP} and T_{PP} are greater than ΔT_{relay}, for all OCRs pairs. Also, the OCR did not take too long to operate, since all the T_{BP} and T_{PP} are less than T_{max}.

Table 10
Relay operational times (case C), for the test system II.

PP	BP	Icc_{min}				Icc_{max}			
		T_{PP}	T_{BP}	$T_{BP}-T_{PP}$	$Icc(A)$	T_{PP}	T_{BP}	$T_{BP}-T_{PP}$	$Icc(A)$
R_1	R_0	0.985	–	–	1510.5	0.609	–	–	3115.0
R_2	R_1	0.432	1.457	1.024	1046.3	0.389	0.789	0.400	2010.7
R_3	R_1	1.177	1.607	0.430	975.1	0.389	0.789	0.400	2010.7
R_4	R_2	0.005	0.501	0.496	630.3	0.004	0.404	0.400	1512.5
R_5	R_2	0.005	0.512	0.506	599.1	0.004	0.404	0.400	1512.5
R_6	R_3	0.005	4.507	4.502	510.5	0.004	0.842	0.838	1190.0
R_7	R_3	1.325	2.212	0.886	699.3	0.441	0.842	0.400	1190.0
R_8	R_7	0.827	2.519	1.692	519.1	0.300	0.700	0.400	950.4
R_9	R_8	0.005	1.421	1.416	398.3	0.004	0.406	0.401	780.1
R_{10}	R_8	0.005	1.656	1.651	372.1	0.004	0.406	0.401	780.1

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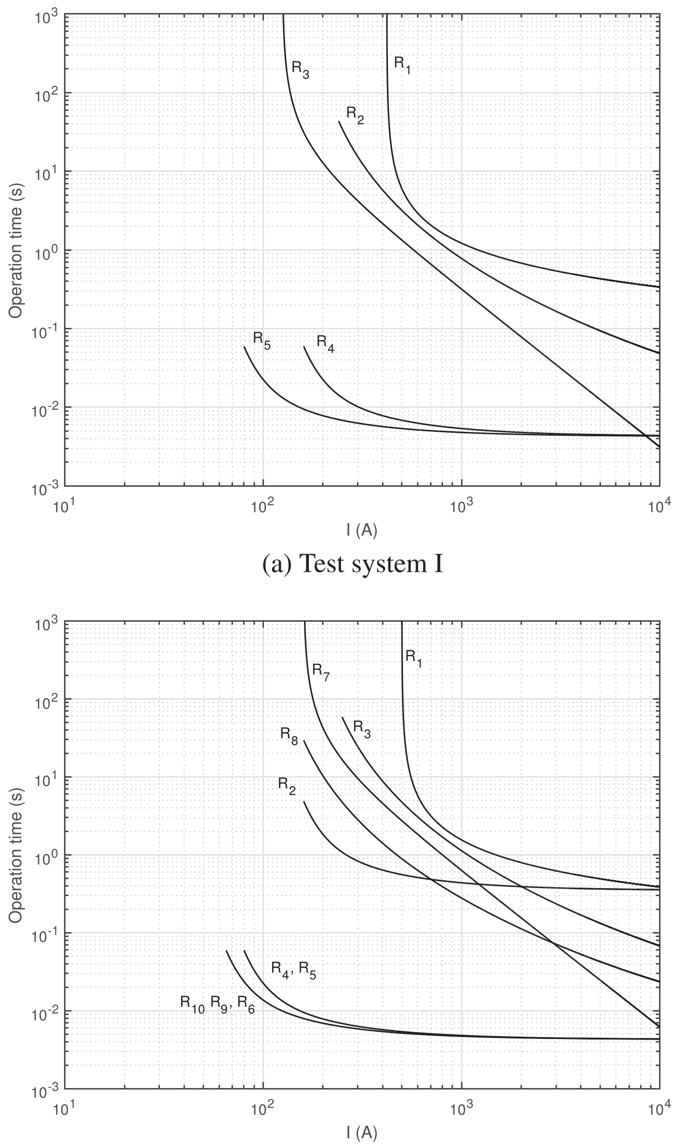
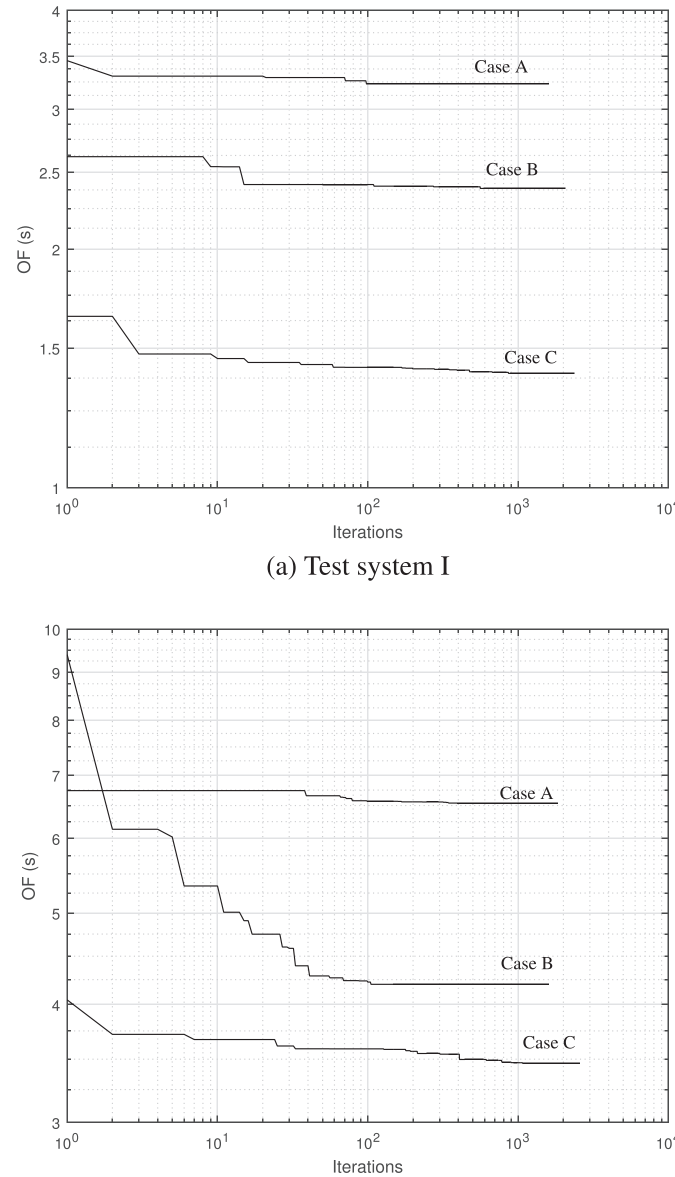


(a) Test system I

(b) Test system II

Fig. 7. Coordination graphics for the case C.



(a) Test system I

(b) Test system II

Fig. 8. Convergence of the HPHA.

A performance benchmark between EHA and LP techniques was realized, thus, the TDS were treated as continuous values. Two LP solvers were utilized: the state-of-the-art CPLEX® and the optimization tool of Matlab®. The tests were done in a Intel® Core™ i5-3317U CPU@1.7 GHz, and the results are shown in Table 11. The EHA and the LP solvers provided the same answers, but they demanded different computational times. In the worst case scenario (test system II), the EHA was 2.69 times faster than the fastest LP solver (CPLEX®). The Matlab® solver was the slowest alternative to solve this problem. In addition, the EHA can handle discrete TDS differently from LP techniques. This way, the EHA showed to be a superior technique to find the optimum TDS in RDN (Fig. 8).

Table 11
Time comparison for finding the optimum TDS for the case A (considering continuous TDS).

Test system	EHA (ms)	PL (CPLEX®) (ms)	PL (Matlab®) (ms)
I	0.39	1.21	15.25
II	0.58	1.56	15.87

8. Conclusion

This paper presented a high-performance hybrid algorithm (HPHA) to solve the problem of overcurrent relays (OCRs) coordination in radial distribution networks (RDNs). The HPHA combines a genetic algorithm (GA) with an efficient heuristic algorithm (EHA) to decrease the search space of the GA, as the optimum time dial settings (TDS) are computed with the EHA. Several advantages are obtained using the EHA: (1) it can handle discrete and continuous TDS; (2) it does not depend on commercial solvers; (3) it is faster than the linear programming (LP) techniques and (4) it has a simple implementation. The EHA showed to be a more interesting approach than LP techniques for RDN.

Several decision variables are considered in the optimization problem: TDS, pickup current (Ip), curve types and relay types. For each decision variables added to the problem, the OCR operational times were reduced. Therefore, it is interesting to consider in the optimization problem the adjusts that do not imply additional costs, like TDS, Ip and curve types. The addition of relay types as decision variable can be held in a system which lies in the design phase or if the relays accept multiple curve standards. Otherwise, a cost-benefit analysis must be held. When the relay types are considered as decision variables, more curve shapes are available to choose. Results showed that the added flexibility significantly improved the coordination.

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References

[1] J.M. Filho, D.R. Mamede, Proteção de Sistemas Elétricos de Potência, 1st ed., LTC, Rio de Janeiro, 2011.
[2] A.J. Urdaneta, R. Nadira, L.G. Perez Jimenez, Optimal coordination of directional overcurrent relays in interconnected power systems, IEEE Trans. Power Deliv. 3 (No. 3) (1988) 903–911.
[3] P.P. Bedekar, S.R. Bhide, V.S. Kale, Optimum coordination of overcurrent relays in distribution system using dual simplex method, in: 2009 Second International Conference on Emerging Trends in Engineering & Technology, 2009, pp. 555–559.
[4] IEEE, IEEE Standard Inverse-Time Characteristic Equations for Overcurrent Relays, IEEE Std C37.112-1996, 1997, i-.
[5] IEC, IEC 60255-151 – Measuring Relays and Protection Equipment – Part 151: Functional Requirements for Over/under Current Protection, 2009.
[6] G. Multilin, 735/737 Feeder Protection Relay Instruction Manual, 2010 https://www.gegridsolutions.com/multilin/manuals/735737.htm.
[7] Schweitzer Engineering Laboratories, Inc., SEL-587-0, -1 Relay, Current Differential Relay, Overcurrent Relay – Instruction Manual, 2012.
[8] F. Razavi, H.A. Abyaneh, M. Al-Dabbagh, R. Mohammadi, H. Torkaman, A new comprehensive genetic algorithm method for optimal overcurrent relays coordination, Electr. Power Syst. Res. 78 (4) (2008) 713–720.
[9] S. Niyomphant, U. Leeton, T. Kulworawanichpong, N. Chomnawang, Application of linear programming for optimal coordination of directional over-current relays, in: 2012 9th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology, 2012, pp. 1–4.
[10] J. Gholinezhad, Overcurrent relay coordination using MINLP technique, in: 2011 19th Iranian Conference on the Proceedings of the 2011 Electrical Engineering (ICEE), 2011, pp. 6–11.
[11] D. Birla, R.P. Maheshwari, H.O. Gupta, A new nonlinear directional overcurrent relay coordination technique, and banes and boons of near-end faults based approach, IEEE Trans. Power Deliv. 21 (3) (2006) 1176–1182.
[12] H.A. Abyaneh, M. Al-Dabbagh, H.K. Karegar, S.H.H. Sadeghi, R.a.J. Khan, A new optimal approach for coordination of overcurrent relays in interconnected power systems, IEEE Trans. Power Deliv. 18 (2) (2003) 430–435.
[13] S.A. Raza, T. Mahmood, S. Basit, A. Bukhari, M.K. Nawaz, Application of optimization techniques in overcurrent relay coordination – a review, World Appl. Sci. J. 28 (2) (2013) 259–265.
[14] C. So, Application of genetic algorithm for overcurrent relay coordination, in: 6th International Conference on Developments in Power Systems Protection, Vol. 1997, IEE, 1997, pp. 66–69.
[15] H. Zeineldin, E. El-Saadany, M. Salama, Optimal coordination of directional overcurrent relay coordination, in: IEEE Power Engineering Society General Meeting, 2005, pp. 737–742.
[16] C.H. Lee, C.R. Chen, Using genetic algorithm for overcurrent relay coordination in industrial power system, in: 2007 International Conference on Intelligent Systems Applications to Power Systems (ISAP), IEEE, 2007, pp. 1–5.
[17] R. Thangaraj, M. Pant, K. Deep, Optimal coordination of over-current relays using modified differential evolution algorithms, Eng. Appl. Artif. Intell. 23 (5) (2010) 820–829.
[18] D. Vijayakumar, R.K. Nema, A novel optimal setting for directional over current relay coordination using particle swarm optimization, World Acad. Sci. Eng. Technol. 2 (5) (2008) 674–679.
[19] J. Teresa, T. Ríos, J. Sebastián, C. Tamayo, R. Alberto, H. Isaza, Coordinación óptima de relés de sobrecorriente usando Partículas(Swarm Optimal coordination of overcurrent relays using particles swarm optimization), Scientia et Technica Año XVII (52) (2012) 8–15.
[20] V. Rashtchi, J. Gholinezhad, P. Farhang, Optimal coordination of overcurrent relays using Honey Bee Algorithm, in: 2010 International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT), 2010, pp. 401–405.
[21] D. Uthitsunthom, T. Kulworawanichpong, N. Ratchasima, Optimal overcurrent relay coordination using artificial bees colony algorithm, in: The 8th Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI) Association (2), 2011, pp. 901–904.
[22] J.A. Sueiro, E. Diaz-Dorado, E. Míguez, J. Cidrás, Coordination of directional overcurrent relay using evolutionary algorithm and linear programming, Int. J. Electr. Power Energy Syst. 42 (1) (2012) 299–305.
[23] A.S. Noghabi, J. Sadeh, H.R. Mashhadi, Considering different network topologies in optimal overcurrent relay coordination using a hybrid GA, IEEE Trans. Power Deliv. 24 (4) (2009) 1857–1863.
[24] M. Ezzeddine, R. Kaczmarek, A novel method for optimal coordination of directional overcurrent relays considering their available discrete settings and several operation characteristics, Electr. Power Syst. Res. 81 (7) (2011) 1475–1481.
[25] R. Corrêa, G. Cardoso, O.C. de Araújo, L. Mariotto, Online coordination of directional overcurrent relays using binary integer programming, Electr. Power Syst. Res. 127 (2015) 118–125.
[26] C.A. Castillo, A. Conde, S. Elisa, Directional overcurrent relay coordination considering non-standardized time curves 122 (2015) 42–49.
[27] S. Grids, Technology roadmap, in: SpringerReference, Springer-Verlag, Berlin/Heidelberg, 2011, pp. 52.
[28] P. Anderson, Power System Protection, The Institute of Electrical and Electronics Engineers, Inc., United States of America, 1999.
[29] V.N. Rajput, K.S. Pandya, K. Joshi, Optimal coordination of directional overcurrent relays using hybrid CSA-FFA method, in: 2015 12th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), Vol. 119, IEEE, 2015, pp. 1–6.
[30] S. Electric, Manual de Utilizaç ao SEPAM Série 20.
[31] B. Chattopadhyay, M.S. Sachdev, T.S. Sidhu, An on-line relay coordination algorithm for adaptive protection using linear programming technique, IEEE Trans. Power Deliv. 11 (1) (1996) 165–171.
[32] A. Koochaki, M.R. Asadi, M. Mahmoodan, R.A. Naghizadeh, Optimal overcurrent relays coordination using genetic algorithm, in: 11th International Conference on Optimization of Electrical and Electronic Equipment, OPTIM 2008, IEEE, 2008, pp. 197–202.
[33] T. Amraee, Coordination of directional overcurrent relays using seeker algorithm, IEEE Trans. Power Deliv. 27 (3) (2012) 1415–1422.
[34] P. Chu, J. Beasley, A genetic algorithm for the generalised assignment problem, J. Oper. Res. Soc. 48 (8) (1997) 804–809.
[35] D. Shirmohammadi, H.W. Hong, A. Semlyen, G.X. Luo, Compensation-based power flow method for weakly meshed distribution and transmission networks, IEEE Trans. Power Syst. 3 (2) (1988) 753–762.

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