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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.

$$T_{i,j}^k = TDS_i \cdot K_{i,j}^k \tag{1}$$

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

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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