Adaptive protection coordination scheme in microgrids using directional over-current relays with non-standard characteristics

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ABSTRACT

Protection coordination of AC microgrids (MGs) is a challenging task since they can operate either in grid-connected or islanded mode which drastically modifies the fault currents. In this context, traditional approaches to protection coordination, that only consider the time multiplier setting (TMS) as a decision variable may no longer be able to guarantee network security. This paper presents a novel approach for protection coordination in AC MGs that incorporates non-standard characteristic features of directional over-current relays (OCRs). Three optimization variables are considered for each relay: TMS, maximum limit of the plug setting multiplier (PSM) and standard characteristic curve (SCC). The proposed model corresponds to a mixed integer non-linear programming problem. Four metaheuristic techniques were implemented for solving the optimal coordination problem, namely: particle swarm optimization (PSO), genetic algorithm (GA), teaching-learning based optimization (TLBO) algorithm and shuffled frog leaping algorithm (SFLA). Numerous tests were run on an IEC MG as well as with the distribution portion of the IEEE 30-bus test system. Both systems incorporate distributed generation (DG) and feature several modes of operation. A comparison was made with other MG protection coordination approaches proposed in the specialized literature. In all cases, the proposed approach found reduced coordination times, evidencing the applicability and efficacy of the proposed approach.

1. Introduction

Massive implementation of renewable distributed generation (DG) is one of the promissory solutions for satisfying the worldwide growing energy demand [1]. MGs have an essential function in this transition by facilitating the integration of DG into distribution networks (DNs). However, there are still some technical issues to be discussed for their suitable incorporation such as the protection coordination problem. MGs are flexible systems that may have multiple operating modes which makes their protection coordination a challenging task [2, 3]; MGs also tend to grow in size and complexity and the fact of harboring DG introduces bidirectional power flows and variable short-circuit currents [4]. MG operation modes render inefficient the conventional design of protection coordination which considers fixed short circuit levels and unidirectional power flows; therefore, researchers around the world are in constant search of new models and methodologies regarding the protection coordination problem of MGs [5]. One of the new challenges in designing protection schemes for MGs, is to deal with their dynamic behavior resulting from the use of intermittent energy resources and the possibility of being connected and also disconnected to the main power network [6, 7].

Directional OCRs have become one of the most extended protections in DNs, and can also be configured for MGs for their easy and simple installation and also their performance. [8, 9]. Nonetheless, coordination of directional OCRs in MGs is an emerging research topic, requiring specialized knowledge and designing experience [10, 11]. Different approaches have been suggested in the literature on the optimal coordination of OCRs in MGs. The impact of DG plants within a MG depends on their type, location and capacity. In [9] the authors proposed a protection coordination index that aims at measuring the impact of DG plants in meshed distribution systems. A two-phase nonlinear programming optimization problem was developed to compute the proposed protection coordination index by optimally calculating changes of the maximum DG penetration level with variations in the protection coordination time interval. The authors in [12] present an approach for the optimal coordination of OCRs with inverse-time char-
acteristics in DNs with high penetration of DG. In this case, all types of short-circuit contributions are taken into account and therefore the coordination problem becomes a complex problem. Although many coordination problems are approached considering a fixed network topology, in [13] the authors solve the coordination problem taking into account the different topologies that result when considering security constraints. In [14] the authors resort to swarm optimization to approach the OCRs coordination in MGs. In [15], the authors proposed an online adaptive coordination protection scheme for directional OCRs by using intelligent electronic devices and a communication channel to obtain real-time information to update the configuration of the relays. Recently, various researchers have studied the effect of considering non-standard characteristics in the protection coordination of OCRs in MGs [16]. The growth of distribution systems and the incorporation of MGs make the coordination of protection an increasingly complex problem. In this context, non-standard features emerge as an alternative that must be explored to improve the performance of the protection scheme. In [17], the authors proposed a protection coordination approach considering the future installation of photovoltaic plants, with different locations along the distribution feeder. They modified the existing characteristic curve by changing its constants, keeping the dial and the relay pick-up current fixed. An option to guarantee the coordination protection in MGs is the use of optimization techniques combined with a novel setting of the characteristics for non-standard curves; reducing coordination times and keeping MG reliability and security as proposed in [18, 19]. Also, protection coordination can be improved by using multiples curves as proposed in [20]. In this case, several IEC curves are considered as decision variables, and the coordination is obtained by solving a mixed-integer nonlinear optimization problem. The authors of [18] recently proposed a novel constraint on the PSM (plug setting multiplier) to enhance the coordination of OCRs in MGs. They modeled the use of nonstandard curves by modifying the upper bound for the PSM, extending the tripping feature of OCRs. Later, after the possibility of using alternative limits on the PSM, authors in [19] proposed a different upper limit for this variable. Generally speaking, by adjusting the upper limit of the PSM, it is possible to change the tripping characteristic, altering the sensitivity of the protection which could improve timing or even cope with loss of coordination.

Furthermore, the proposed approach can be used to obtain a coordination with multiple parameters for each operational mode or a single set of parameters suitable for all operational modes. Table 1 shows the features of other research works in the field, evidencing the knowledge gap in the existing literature which is filled by the proposed approach.

For a proper selection of the PSM maximum value, authors in [21] proposed PSM upper limit a variable of decision; obtaining faster responses and guaranteeing a proper coordination scheme. Our paper complements and expands the research presented in [21] by also considering different standard characteristic curves. In this sense, our research question is whether it is possible to design a protection coordination approach for MGs that takes into account three optimization variables per relay and several operational modes. To answer this question, we propose a novel coordination methodology of OCRs in MGs that considers as decision variables the TSM, the upper limit of the PSM and the standard characteristic curve (SCC) while also considering several operational modes of the MG. In this way, this paper complements the researches presented in [18, 19, 21]. A number of tests were carried out on an IEC reference MG taking into account four operational modes for comparative purposes and a modified version of the IEEE 30-bus test system. It was found that the proposed coordination approach obtains better solutions than those presented in [18, 19, 21].

The main contribution of this paper is the use of two non-standard features in the optimal coordination of OCRs in MGs that feature several operational topologies or modes. The first one lies on considering the PSM maximum limit as a variable of decision, not as a constant, as previously reported in [14, 18]. The second one is the possibility of selecting among different types of curves presented in the IEEE and IEC standards, complementing the works presented in [20] and [21]. Furthermore, four different metaheuristic techniques (GA, PSO, TLBO and SFLA) were used for solving the proposed coordination model for comparative purposes.

### 2. Non-standard characteristics

This paper is divided into the following sections: Section 2 details the concepts related to non-standard characteristics considered in the proposed coordination approach. Section 3 presents the mathematical formulation for optimal coordination of OCRs. Section 4 describes the methodology for finding the optimal parameters for the OCRs coordination. Section 4 explains the four different metaheuristic techniques that are proposed to approach the optimal coordination problem. Section 5 shows a comparison of the performance of the metaheuristic techniques. Finally, conclusions are presented in Section 6.

In this paper, we refer to non-standard characteristics as features that are not described within the IEC [22] and IEEE [23] standards which are currently used in protection coordination. The use of standard characteristics in protection coordination has been effective for many years to protect conventional DNs in which power flows are unidirectional. Nevertheless, the change of paradigm introduced by distributed energy resources (DERs) and their integration through MGs have rendered traditional protection coordination approaches inefficient. Seeking to overcome this drawback, this paper provides a new approach for OCRs protection coordination using the non-standard characteristics described below.

#### 2.1. Variable maximum limit of PSM

PSM is defined as the ratio between the relay fault current and their corresponding pick up current. The PSM upper limit corresponds to the highest current level programmed in the protective relay before the fault current enters the definite time region of the curve. Commercial relays use standard characteristic curves with predefined minimum and maximum PSM values. Nevertheless, the presence of DG plants significantly increases the short-circuit currents in the system. Hence, some faults may exceed the predefined maximum PSM value, which affects the sensitivity of the protection leading to loss of coordination. For this reason, in [18] a new constraint is proposed for the PSM by setting its maximum limit at 20.

In contrast, this work considers the maximum PSM value as a decision variable instead of a parameter. The range of the maximum PSM limit varies between default values α and β. This may result in a more complex optimization process; nonetheless, the search space is enlarged allowing to find better solutions to the coordination problem. Fig. 1 illustrates the non-standard feature described in this section. Although considering the maximum limit of the PSM as a variable makes the co-
ordination process more complex, it also expands the space search to look for new coordination alternatives.

### 2.2. Multiple characteristic curves

As stated in IEC [22] and IEEE [23] standards, the protection coordination only takes into account a single sort of characteristic curve. In some particular cases where the OCRs coordination cannot be guaranteed, some combinations of characteristic curve types of the same standard are used, all based on the experience of the protection engineer. Nevertheless, the model proposed in this paper considers multiple characteristic curves. In this case, the selection over the set of these curves (that includes both IEC and IEEE standards) is also considered as a decision variable. The relationship between operating time and input current for OCRs is defined in [22], which can be illustrated by means of a characteristic curve. This curve may adopt one of different shapes when selecting parameters $A$ and $B$ from Equation (1) as indicated in Table 2. In this case, for relay $i$, $t_{if}$ stands for the operating time when fault $f$ takes place, $TMS_i$ is the time multiplying setting, $ipickup_i$ is the pick up current and $t_{ii}$ indicates the fault current measured during the fault.

$$t_{if} = \frac{A \cdot TMS_i}{\left(\frac{ipickup_i}{TMS_i}\right)^B - 1} \quad (1)$$

IEEE C37.112-1996 standard [23] also defines another type of curve to represent the relationship between the input current and the operating time. The characteristics of this curve are presented in Equation (2). The point at which this characteristic differs from the one of the IEC standard is the parameter $C$. For actual protection coordination applications, the IEEE C37.112-1996 committee has defined several different characteristics which are similar to those of the IEC. Table 3 presents the values of $A$, $B$ and $C$ needed to obtain the characteristics of the IEEE standard relay.

$$t_{if} = \frac{A \cdot TMS_i}{\left(\frac{ipickup_i}{TMS_i}\right)^B - 1} + C \quad (2)$$

### 3. Mathematical formulation for optimal coordination of OCRs

#### 3.1. Objective function

The optimal coordination strategy consists on obtaining the minimum operating time for each OCR, guaranteeing the coordination of the protection scheme. The objective function is given by Equation (3) where $m$ corresponds to the number of relays while $n$ is the number of faults. $t_{if}$ is the operating time of relay $i$ during a fault $f$.

$$Min \sum_{i=1}^{m} \sum_{f=1}^{n} t_{if} \quad (3)$$

#### 3.2. Coordination criterion

In DNs, both backup and main OCRs detect the presence of a fault. Nonetheless, it must be ensured that the primary OCR acts first. This is the so called coordination criterion which is given by Equation (4). $t_{if}$ corresponds to the operating time of the backup relay $f$ when fault $f$ occurs. $t_{if}$ corresponds to the operating time of the primary relay $i$, for the same fault. In this case, the coordination time interval $CTI$ is defined as the time difference between the operation of the backup and main relays for the same fault. Typical values of this parameter range between 0.2 to 0.5 seconds. In this case, a value of 0.3 seconds was considered for comparative purposes.

$$t_{if} - t_{if} \geq CTI \quad (4)$$

#### 3.3. Relay characteristic and operating time

Equation (5) is a general expression of the IEC and IEEE standard characteristic curves described in Section 2.2. In this case, the expression $PSM_{if}$ is the relationship between $TMS_i$ and $ipickup_i$ as indicated in Equation (6). On the other hand, maximum and minimum values for operating times for relay $i$ are specified in Equation (7). Note that in equation (5) the expressions of the numerator and denominator of the first term are nonlinear. On the one hand, in the numerator there is a multiplication of two variables: TSM and ‘A’ which depends on the type of curve to be selected. On the other hand, in the denominator a variable that depends on the inverse of the pick up current is raised to the power of an unknown parameter ‘B’.

$$t_{if} = \frac{A \cdot TMS_i}{PSM_{if}} + C \quad (5)$$

$$PSM_{if} = \frac{t_{if}}{ipickup_i} \quad (6)$$

$$t_{imin} \leq t_{if} \leq t_{imax} \quad (7)$$

#### 3.4. Limits on TSM and pick up currents

Equation (8) indicates the limits of $TSM$ for relay $i$, which are indicated as $TMS_{imin}$ and $TMS_{imax}$. Note that $TSM$ is an unknown value that must be determined within the coordination. Equation (9) establishes the upper and lower limits of the pickup current $ipickup_i$. These limits are denoted as $ipickup_{imin}$ and $ipickup_{imax}$, respectively.

$$TMS_{imin} \leq TMS_i \leq TMS_{imax} \quad (8)$$

$$ipickup_{imin} \leq ipickup_i \leq ipickup_{imax} \quad (9)$$
3.5. Limits on PSM

One of the contributions of this paper is the inclusion of a variable upper limit of PSM as a non-standard characteristic in OCRs coordination as described in Section 2.1. Equation (10) represents the limits of the of \(PSM_\text{min} \) and \(PSM_\text{max}\). In traditional OCRs coordination, these limits are fixed. However, the upper limit of the \(PSM\) is considered here as a decision variable; being \(PSM_\text{max}\) a decision variable which range is defined between \(a\) and \(\beta\) as shown in Equation (11).

\[
\begin{align*}
PSM_\text{min} & \leq PSM_i \leq PSM_\text{max} \\
\alpha \leq PSM_\text{max} & \leq \beta
\end{align*}
\]

3.6. IEC/IEEE standard characteristic curve selection

Usually, only one type of curve is considered in traditional approaches of OCRs coordination. Nevertheless, in the proposed approach different type of curves might be selected in the protection coordination scheme. This fact is stated in Equation (12) where \(SCC_i\) is the \(i\)-th standard curve and \(\Omega\) is a set containing the IEC and IEEE standard characteristic curves described in Section 2.2.

\[
SCC_i \in \Omega
\]

4. Proposed metaheuristic techniques

According to the specialized literature, the model given by (3), (4), (5), (6), (7), (8), (9), (10), (11) and (12) can be solved by means of several methodologies. Nonetheless, as presented in [26], the so called metaheuristic techniques are the most effective strategies for approaching this type of problem. This is because they are well suited for solving complex optimization problems in reduced computational time. It should be noted that the main contribution of this work is not the adopted solution method, but lies in the consideration of several decision variables for the coordination of OCRs in MGs operating under different topologies. However, the performance of four metaheuristic techniques was evaluated, namely: GA, PSO, TLBO and SFLA.

4.1. Genetic algorithm

GAs are inspired in the natural selection process. They begin with an initial population in which every individual represents a candidate solution to the optimization problem. Once the initial population is defined, the individuals must go through the stages of selection, crossover and mutation to create a new generation. The flowchart of the implemented GA is presented in Fig. 2. It begins with the random generation of a population. Every element of this population represents an eventual solution to the coordination problem and must be represented by an array. Once the initial population is set up, the fitness (objective function) of every candidate solution is computed. After obtaining the fitness function, the individuals of the current population must go the tournament selection stage. In this case, a given number of individuals of the current generation is randomly chosen and the best one among them is selected as a parent. Every two tournaments create two parents that would produce two new offspring by means of recombination or crossover. In this stage the parents, exchange information of their corresponding vectors creating two new individuals. The offspring must go through the mutation stage. This stage adds diversification and allows the GA to avoid locally optimal solutions. The mutation is carried out by introducing small random changes in the vectors that represent the new offspring. When changes are introduced it must be validated that the affected variables remain within their limits. The fittest candidate solutions are selected in every generation to replace individuals of lower quality keeping the population size constant until a given number of generations is reached.

\[
\begin{align*}
\vec{v}_i(t + 1) & = w(t)\vec{v}_i(t) + c_1r_1 \left[\vec{x}_{g\text{Best}} - \vec{x}_i(t)\right] + c_2r_2 \left[\vec{x}_{p\text{Best}} - \vec{x}_i(t)\right] \\
\vec{x}_i(t + 1) & = \vec{x}_i(t) + \vec{v}_i(t + 1)
\end{align*}
\]

4.2. Particle swarm optimization

PSO is a stochastic optimization technique that solves a combinatorial problem using a population of candidate solutions or particles which move around the search-space according to simple rules over their position and velocity. Each particle’s movement is influenced by its local best known position, and is also guided toward the best known positions in the search-space [27]. The steps followed in the implementation of the PSO are illustrated in Fig. 3. This methodology begins with a random generation of potential solutions that are located in the search space. Every candidate solution features two vectors: one that describes its position and another one that accounts for its velocity. These two vectors are updated for each particle or candidate solution in every iteration. In this updating process the best own and global historical information is taken into account. The expressions for computing both velocity and position are provided in Equations (13) and (14), respectively.

In this case, \(i\) is the number of the iteration, \(\vec{v}_i\) and \(\vec{x}_i\) are the \(i\)-th particle’s velocity and position vector, respectively; \(w(t)\) is known as the inertia weight; \(\vec{x}_{g\text{Best}}\) and \(\vec{x}_{p\text{Best}}\), represent the historically best position of the entire swarm and particle \(i\), respectively; \(c_1\) and \(c_2\) are the personal and global learning coefficients, respectively, while \(r_1\) and \(r_2\) are uniformly distributed random numbers in the range \([0, 1]\).
4.3. Teaching-learning based optimization algorithm

This methodology mimics the dynamics and impact that a teacher has on the output of learners in a classroom [28]. It begins with a randomly generated population labeled as learners. Every learner has a given objective function or fitness. The so-called teacher is the best solution obtained so far. This methodology comprises two phases labeled as Teacher and Student phase. In the teacher phase, the potential solutions of the problem, labeled as students, acquire information from the teacher solution (learning process). In the student phase, the learners interact with themselves to further modify and improve their gained knowledge. Every solution candidate must go through both phases in every iteration. The main advantage of TLBO is that only two parameters are required: number of iterations and size of the population. The flowchart of the implemented TLBO is described in Fig. 4, where $X_i$ is the candidate solution i (also known as learner) while $r$ is a random number which is uniformly distributed. An interesting feature of TLBO is that it includes a greedy search in both phases, where the new solution is only acceptable if it outperforms the one that produces it.

4.4. Shuffled frog leaping algorithm

SFLA is an optimization technique that combines characteristics of memetic algorithms and PSO. It mimics the behavior of groups of frogs, particularly the way they seek for food. A virtual population of frogs is considered to be leaping in a swamp. Each leap of a frog produces a change of position within a space of solutions. The swamp has a number of stones at discrete locations where the frogs can find food. The frogs can communicate among them and the objective is to find the stone with the maximum amount of available food.

The algorithm begins with a randomly selected population of frogs in a swamp. Such initial population is divided into several parallel sets (named memeplexes) that can move and evolve independently to search the solution space in different regions. Within each memeplex, the frogs share other frogs information; hence, experiencing a memetic evolution. To ensure competitiveness, frogs with better memes contribute more to the development of new solutions than frogs with poor memes. During the evolution process, the frogs may change their memes using information from their own best memeplex or from the best of the entire population. After a given number of evolution time loops the memeplexes are mixed and new ones are formed through a shuffling process. Fig. 5 illustrates the SFLA algorithm. A detailed description of this methodology can be consulted in [29].

5. Comparative performance of metaheuristic techniques

Several runs of the proposed solution techniques were carried out with both test systems which data is available in [30] and [31]. Digis-
lent Power Factory was used to perform simulations in both systems and the metaheuristic techniques were developed in Matlab.

5.1. Comparative performance with an IEC MG

The proposed model was tested on a MG that integrates different types of DG. The benchmark MG is presented in Fig. 6 and its parameters are presented in [30]. Table 4 summarizes the four operational modes (OMs) that were considered; nonetheless, the proposed approach allows the inclusion of other ones. These OMs refer to different conditions or topologies under which the MG is expected to operate. Although modern distribution networks may feature several OMs, these are usually limited to a handful and can be defined beforehand by the network operator. For OM1, the DG plants are disconnected and the load of the MG is only fed using the main power supply; in contrast, for OM2, all DG plants are connected and the load is fed using not only the DG plants but also the main power supply. For OM3, DG3 and DG4 plants are disconnected, so the load is supplied through the main power supply and also from DG1 and DG2 plants. For OM4, the MG is disconnected from the main power supply being the load only fed using the MGs own DG plants.

Table 5 describes the three-phase faults considered in this research obtained through simulations using DIgSILENT PowerFactory software.

The short circuit (SC) values for each OMs are also presented. The simulations of the faults were carried out in compliance with the recommendations of IEEE Standard 242 [32]. The three-phase faults of Table 5 were considered for comparative purposes; nevertheless, faults in other locations and of other type can also be evaluated according to the criteria of the system operator, which may result in different settings of the OCRs.

Fig. 5. Implemented Shuffle Frog Leaping Algorithm.

Fig. 6. Benchmark IEC MG.

Table 4. Operational modes.

| Operational Mode | Power supply | OM1 | OM2 | OM3 | OM4 |
|------------------|--------------|-----|-----|-----|-----|
| DG1              | ON           | OFF | OFF | OFF | OFF |
| DG2              | ON           | ON  | ON  | ON  | ON  |
| DG3              | ON           | ON  | ON  | OFF | OFF |
| DG4              | OFF          | ON  | ON  | ON  | ON  |

Table 5. Description of the faults under analysis.

| Fault | Location | SC OM1 [kA] | SC OM2 [kA] | SC OM3 [kA] | SC OM4 [kA] |
|-------|----------|-------------|-------------|-------------|-------------|
| Fault 1 | Line DL-5  | 3.69        | 6.29        | 4.29        | 3.94        |
| Fault 2 | Line DL-4  | 5.13        | 8.72        | 6.36        | 4.15        |
| Fault 3 | Line DL-2  | 8.37        | 11.89       | 10.11       | 3.55        |
| Fault 4 | Line DL-1  | 5.13        | 6.98        | 6.42        | 3.18        |
| Fault 5 | Line DL-3  | 3.69        | 5.90        | 4.29        | 3.59        |
Table 6. RCT and $i_{pu,kap}$ for each relay.

| Relay  | $R_{pu}$  | $i_{pu,kap}$ |
|--------|-----------|--------------|
| Relay1 | 400       | 0.50         |
| Relay2 | 400       | 0.50         |
| Relay3 | 400       | 0.50         |
| Relay4 | 400       | 0.50         |
| Relay5 | 400       | 0.50         |
| Relay6 | 400       | 0.50         |
| Relay7 | 1200      | 1.00         |
| Relay8 | 400       | 0.50         |
| Relay9 | 400       | 0.50         |
| Relay10| 400       | 0.50         |
| Relay11| 400       | 0.65         |
| Relay12| 400       | 0.50         |
| Relay13| 400       | 0.88         |
| Relay14| 400       | 0.65         |
| Relay15| 400       | 0.55         |

Table 7. Metaheuristics parametrization (IEC MG).

| Parameters | GA | PSO | TLBO | SFLA |
|------------|----|-----|------|------|
| Iterations | 2000 | 2000 | 2000 | 2000 |
| Size of the Population | 200 | 200 | 200 | 230 |
| Crossover Rate | 0.7 | - | - | - |
| Mutation Rate | 0.3 | - | - | - |
| Inertia Weight | - | 1 | - | - |
| Inertia Weight DR | - | 0.99 | - | - |
| Personal LC | - | - | 1.5 | - |
| Global LC | - | - | 2.0 | - |
| Memeplex Size | - | - | - | 46 |
| Number of Memeplexes | - | - | - | 5 |

Fig. 7. Comparison of results with different techniques (IEC MG).

Table 7 presents the parameters that resulted in the best solutions for each methodology, where DR stand for damping ratio and LC stand for learning coefficient.

A direct comparison of the performance of each implemented technique can be inferred from Fig. 7. In this case, the X and Y axes correspond to the value of the objective function and the computation time, respectively. Therefore, the best solutions in terms of both criteria are those closer to the origin. It can be seen that the GA outperforms the other technique in all operational modes, followed closely by PSO. Based on this outcome, the results of the GA were chosen for comparative purposes with [18], [19] and [21]. Furthermore, the convergence of the metaheuristic techniques is illustrated in Fig. 8. For the sake of simplicity only two tests are considered in OM1. Note that all techniques present a quick convergence; however, SFLA is trapped in a locally optimal solution. This is inferred by the fact that its objective function is worse than that of the other techniques.

Fig. 8. TLBO, GA, PSO and SFLO Convergence for different tests in OM1.

5.2. Comparative performance using a modified version of the IEEE 30-bus test system

Different tests were performed on the test system illustrated in Fig. 9, which comprises the distribution section of the IEEE 30-bus test system. This system is able to operate in both grid-connected and islanded modes. The test system considers several phase-line failures described in Table 8. Note that short-circuit currents are provided for both operational modes. The allocation of several DG units is also illustrated in Fig. 9. Such generation units have 10 MVA of capacity and are connected to the system through 480 V/33 kV transformers.

Several tests were also carried out in this test system to assess the performance of the proposed solution techniques. Table 9 presents the parameters that resulted in the best results for each metaheuristic. A comparison of the performance among the proposed techniques can be inferred from Fig. 10. In this case, it was found that the GA outperforms...
Table 8. Short circuit levels (in kA) for the IEEE 30-bus test system.

| Fault | Grid-connected mode | Islanded mode |
|-------|---------------------|---------------|
| Fault 1 | 12.97 | 6.03 |
| Fault 2 | 3.46 | 2.22 |
| Fault 3 | 6.34 | 3.76 |
| Fault 4 | 9.42 | 5.31 |
| Fault 5 | 12.25 | 5.76 |
| Fault 6 | 6.26 | 5.12 |
| Fault 7 | 8.36 | 6.13 |
| Fault 8 | 13.29 | 9.04 |
| Fault 9 | 7.14 | 5.17 |
| Fault 10 | 11.49 | 5.49 |
| Fault 11 | 6.07 | 2.71 |
| Fault 12 | 3.71 | 1.89 |
| Fault 13 | 3.33 | 1.87 |
| Fault 14 | 1.75 | 1.27 |
| Fault 15 | 7.38 | 5.24 |
| Fault 16 | 9.72 | 6.10 |
| Fault 17 | 13.40 | 5.86 |
| Fault 18 | 7.96 | 6.33 |
| Fault 19 | 11.56 | 8.01 |
| Fault 20 | 9.04 | 5.27 |

Table 9. Metaheuristics parametrization (modified IEEE 30-bus test system).

| Parameters | GA | PSO | TLBO | SFLA |
|------------|----|-----|------|------|
| Iterations | 2000 | 2000 | 2000 | 2000 |
| Population | 600 | 600 | 600 | 600 |
| Crossover Rate | 0.7 | - | - | - |
| Mutation Rate | - | 0.3 | - | - |
| Inertia Weight | - | - | 1 | - |
| Inertia Weight DR | - | - | 0.99 | - |
| Personal LC | - | - | 1.5 | - |
| Global LC | - | - | 2.0 | - |
| Memeplex Size | - | - | - | 120 |
| Number of Memeplexes | - | - | - | 5 |

Fig. 10. Comparison of results with different metaheuristics (modified IEEE 30-bus test system).

the other metaheuristic techniques (in both cases on and off grid), being PSO the second best technique. The convergence of the algorithms is illustrated in Fig. 11 for two independent runs in grid-connected mode. It was found that SFLA is the technique with the worst performance, being trapped in locally optimal solutions.

6. Detailed results obtained with the GA

Given the fact that the best performance was achieved with the GA for both test systems, a detail description of the results with this approach is presented in this section.

6.1. Results with the IEC MG

A comparison was performed with the results found in [18], [19] and [21] and those obtained by the proposed GA. Standard IEEE 242 [32] suggests that the coordination time established for main and backup relays labeled as CTI must be greater than or at least equal to 0.2 seconds. A CTI of 0.3 seconds has been chosen with the objective of performing comparisons. The relays denoted by letter R are numbered from 1 to 15. Fig. 6 depicts the allocation of each relay. For each fault under analysis the label MR is assigned for the main relays, while the label BR is assigned for backup relays. The works presented in [18], [19] and [21] use normally inverse IEC curves. Nevertheless, as previously indicated, the selection of a characteristic curve is considered as decision variables in this work.

Several tests were performed to adjust the GA parameters. The parameters that showed the best performance were: population of 200, number of generations of 2000, crossover rate of 0.7 and mutation rate of 0.3. CB-LOOP1 and CB-LOOP2 were open for all the scenarios considered. Table 10 presents the total operating time $T(s)$ obtained with the GA and those reported in [18], [19] and [21]. For all scenarios, the proposed coordination shows lower $T(s)$ than the ones reported in [18], [19] and [21]. It is important to highlight that what makes our proposed better is not only the fact of providing a proper coordination; but also finding it in a lower operational time.

6.1.1. Results for operational mode 1

For OM1, all DG plants are disconnected and the power is obtained from the main power supply. The five faults described in Table 4 were simulated. The simulation results were used as input data for the proposed coordination model, thus obtaining the results presented in Tables 11 and 12. Table 11 shows the results of $TMS$, $SCC$, and $PSM_{max}$ obtained with the proposed model for each relay. Table 12 shows the operating times of the relays using the proposed method. Note that the information provided in Table 12 provides the operating times for main and back up relays. If the operating time is not specified is because there is no fault current seen by the relay in this OM. It was observed that in all cases the GA guaranteed coordination between main and back up relays.

6.1.2. Results for operational mode 2

For OM2, both the main power supply and all DG plants are available to supply the demand. The coordination results obtained for this
operational mode are presented in Tables 13 and 14. The values obtained for variables $T_M S$, $SCC_i$, and $PSM_{max}$ are specified for each relay in Table 13. The operating time of main and back up relays under consideration is presented in Table 14. For all scenarios, our approach presented coordination between main and backup relays.

### 6.1.3. For OM3, DG3 and DG4 plants are offline; therefore, the load of the MG can be supplied through the main power supply as well as DG1 and DG2. Solutions of the protection scheme using GA are presented in Tables 15 and 16. Table 15 presents the results of the optimization variables $T_M S$, $SCC_i$ and $PSM_{max}$ for each relay. Table 16 details the operating times obtained with the proposed model. The information reported in Table 16 provides the operating times of main and back up relays. If the operating time is not specified is because there is no fault current seen by the relay in this OM. For all scenarios, our approach ensures coordination scheme.

### 6.1.4. For OM4, the MG is operating disconnected from the main power supply while the load is only fed by the DG plants. Tables 17 and 18 summarize the results concerning the protection coordination. Table 17 details the results of the optimization variables $T_M S$, $SCC_i$ and
Table 17. Coordination parameters for OM4.

| Relay | $T_{M_i}$ | $P_{S M_{max}}$ | $S C_i$ |
|-------|-----------|----------------|--------|
| Relay1 | 0.3892 | 30.216 | IEEE EI |
| Relay2 | 0.05 | 85.2371 | IEC STI |
| Relay3 | 0.05 | 45.8544 | IEC STI |
| Relay4 | 0.5289 | 64.1675 | IEEE EI |
| Relay5 | 0.8621 | 82.2638 | IEEE EI |
| Relay6 | 0.6446 | 67.271 | IEEE EI |
| Relay7 | 0.4961 | 85.0166 | IEEE EI |
| Relay9 | 0.05 | 10.6396 | IEEE EI |
| Relay10 | 0.05 | 43.8229 | IEC STI |
| Relay11 | 1.1169 | 24.244 | IEC STI |
| Relay12 | 0.05 | 80.3194 | IEC STI |
| Relay13 | 2.0614 | 33.493 | IEEE EI |
| Relay14 | 0.1179 | 10.4433 | IEEE MI |
| Relay15 | 0.05 | 31.2988 | IEC STI |

$P_{S M_{max}}$ for each relay obtained with the GA. Table 18 presents the operational times obtained with the proposed model. The information reported in Table 18 includes main and back up operating times for each fault; for all scenarios, our approach guarantees a proper coordination scheme.

6.2. Results with the modified version of the IEEE 30-bus test system

To show the applicability of the proposed approach a modified version of the IEEE 30-bus test system was also considered [33]. This system comprises 20 main feeders and 29 over-current relays (R1 to R29). It also has three distribution substations at 132/33 kV. Several tests were initially carried out in DigSILENT for twenty faults. In this case, all simulations were computed in compliance with the IEEE Standard 242 [32].

6.2.1. Results considering grid-connected mode

This OM allows the simultaneously operation of DG plants and the main power supply to fed the load. Table 19 presents the values of $T_{M_i}$, $S C_c$, and $P_{S M_{max}}$ for each relay. The resulting operating times of both main and back up relays are presented in Tables 20 (parts a and b), for each fault under consideration. If the operating time is not specified is because there is no fault current seen by the relay in this operational mode. Feasible operating times were obtained in all cases guaranteeing coordination scheme.

Table 18. Operating times for OM4.

| Fault location | Operating times of OCRs (s) |
|----------------|---------------------------|
| Fault 1        | MR1 | BR13 |
|                | 0.2858 | 0.5858 |
|                | MR4 | BR4 |
|                | 0.0244 | 0.3244 |
| Fault 2        | MR3 | BR1 |
|                | 0.0392 | 0.3301 |
|                | MR4 | BR6 | BR15 |
|                | 0.2347 | 0.5347 | 0.5505 |
| Fault 3        | MR5 | BR15 |
|                | 0.2626 | 0.5869 |
|                | MR6 | BR7 | BR8 |
|                | 0.5109 | 0.8109 |
| Fault 4        | MR8 | BR11 |
|                | 0.7157 | 1.0157 |
|                | MR12 | BR5 | BR7 |
|                | 0.0248 | 0.3249 |
| Fault 5        | MR9 | BR14 |
|                | 0.0378 | 0.3379 |
|                | MR10 | BR6 | BR15 |
|                | 0.0221 | 0.55 | 0.6267 |

Table 19. Results for grid-connected mode.

| Relay | $T_{M_i}$ | $P_{S M_{max}}$ | $S C_c$ |
|-------|-----------|----------------|--------|
| Relay1 | 0.5977 | 58.71593943 | IEEE EI |
| Relay2 | 0.2792 | 21.83563429 | IEEE MI |
| Relay3 | 0.2548 | 76.07391895 | IEEE EI |
| Relay4 | 0.4298 | 68.89495385 | IEEE VI |
| Relay5 | 0.3465 | 81.03742671 | IEEE MI |
| Relay6 | 0.05 | 81.84831403 | IEEE EI |
| Relay7 | 2.5998 | 60.9482788 | IEEE EI |
| Relay8 | 0.2935 | 81.83046956 | IEEE MI |
| Relay9 | 0.0847 | 41.11140493 | IEEE MI |
| Relay10 | 0.4565 | 62.96774207 | IEEE EI |
| Relay11 | 0.2232 | 84.62581851 | IEC SI |
| Relay12 | 0.4051 | 54.69255405 | IEEE EI |
| Relay13 | 0.1591 | 71.92315302 | IEEE SI |
| Relay14 | 0.4548 | 64.90205492 | IEEE MI |
| Relay15 | 0.05 | 67.8518301 | IEC STI |
| Relay16 | 0.05 | 36.80876621 | IEEE VI |
| Relay17 | 0.05 | 11.6696892 | IEEE MI |
| Relay18 | 0.05 | 52.37199665 | IEEE EI |
| Relay19 | 0.69 | 49.08059592 | IEEE EI |
| Relay20 | 1.6696 | 56.55888329 | IEEE EI |
| Relay21 | 1.9561 | 71.32852908 | IEEE EI |
| Relay22 | 1.0226 | 74.71217476 | IEEE EI |
| Relay23 | 0.3816 | 58.26667558 | IEEE MI |
| Relay24 | 1.3782 | 61.59071976 | IEEE EI |
| Relay25 | 0.05 | 89.1997948 | IEEE EI |
| Relay26 | 0.2771 | 42.8499888 | IEEE SI |
| Relay27 | 0.4097 | 62.23443162 | IEEE EI |
| Relay28 | 0.1248 | 72.81405532 | IEEE SI |
| Relay29 | 0.7587 | 71.38238422 | IEEE EI |

Table 20. Operating times of OCRs for grid-connected mode.

| Fault location | Operating times of OCRs (s) |
|----------------|---------------------------|
| (part a)       |                           |
| Fault 1        | MR1 | BR23 | BR21 | BR20 | BR19 |
|                | 0.1535 | 1.49 | 2.25 | 1.63 | 1.21 |
|                | MR15 | BR13 |
|                | 0.5290 | 0.8290 |
| Fault 2        | MR24 | BR21 | BR11 | BR4 |
|                | 0.323 | 4.37 | 2.15 |
|                | MR25 | BR29 |
|                | 0.7320 |
| Fault 3        | MR24 | BR21 | BR11 | BR4 |
|                | 0.1561 | 0.9218 | 0.9764 | 0.4560 |
|                | MR25 | BR29 |
|                | 0.6634 |
| Fault 4        | MR23 | BR11 |
|                | 0.2822 | 0.8513 |
|                | MR21 | BR25 | BR3 |
|                | 0.5557 | 0.8558 | 2.36 |
|                | MR4 | BR15 | BR20 | BR19 |
|                | 0.2162 | 1.13 | 0.6129 |
| Fault 5        | MR23 | BR11 |
|                | 0.8151 | 1.11 |
|                | MR21 | BR25 | BR3 |
|                | 0.4669 | 1.03 | 0.7569 |
|                | MR4 | BR15 | BR20 | BR19 |
|                | 0.1983 | 0.7025 | 2.34 | 1.4 |
| Fault 6        | MR8 | BR16 | BR6 | BR22 |
|                | 0.1245 | 0.6413 | 0.766 | 1.101 |
| Fault 7        | MR10 | BR6 | BR22 |
|                | 0.3023 | 0.6022 | 0.9816 |
|                | MR16 | BR18 |
|                | 0.4394 | 0.7394 |
| Fault 8        | MR9 | BR16 | BR22 |
|                | 0.2225 | 0.5326 | 0.5325 |
|                | MR6 | BR12 |
|                | 0.1177 | 0.4177 |
| Fault 9        | MR11 | BR16 | BR6 |
|                | 0.5764 | 0.9335 | 1.24 |
|                | MR22 | BR21 | BR4 | BR25 |
|                | 0.2087 | 1.06 | 0.7270 | 1.08 |
Table 20 (continued)

| Fault location | Operating times of OCIs (s) |
|----------------|-----------------------------|
| (part b)       |                             |
| Fault 10       | MR23 | BR11 | 1.06 | 1.38 |
|                | MR21 | BR25 | BR3  | 0.6804 | 1.22 | 6.36 |
|                | MR4  | BR15 | BR20 | BR19 |
|                | 0.1779 | 7 | 1 | 0.7999 | 1.36 |
| Fault 11       | MR24 | BR21 | BR11 | BR4  |
|                | 0.2244 | 1.79 | 1.45 |
|                | MR25 | BR29 |
|                | 0.5556 |
| Fault 12       | MR27 | BR24 | BR29 |
|                | 0.0230 | 0.6054 |
| Fault 13       | MR26 | BR24 |
|                | 0.4994 | 0.7993 |
|                | MR29 |
|                | 2.48 |
| Fault 14       | MR28 | BR26 |
|                | 0.1587 | 0.5252 |
| Fault 15       | MR17 | BR10 |
|                | 0.3309 | 0.6309 |
|                | MR18 | BR2 |
| Fault 16       | MR14 | BR1 |
|                | 0.2375 | 0.5375 |
|                | MR13 | BR7 |
|                | 0.3654 | 0.6655 |
| Fault 17       | MR20 | BR23 |
|                | 0.6607 | 0.9695 |
|                | MR3  | BR15 | BR23 | BR21 | BR19 |
|                | 0.3379 | 0.6380 | 0.9695 | 0.6379 | 1.0667 |
| Fault 18       | MR5  | BR9  | BR12 |
|                | 0.1287 | 0.4287 | 0.5294 |
| Fault 19       | MR12 | BR14 |
|                | 0.2113 | 0.5113 |
|                | MR7  | BR9  |
|                | 0.1498 | 0.4953 |
| Fault 20       | MR19 | BR17 |
|                | 0.5786 | 0.8788 |
|                | MR2  | BR15 | BR23 | BR21 | BR20 |
|                | 0.2788 | 1.13 | 4.22 |

Table 21. Results for islanded mode.

| Relay | TMS | PSM | SCC |
|-------|-----|-----|-----|
| Relay1 | 0.9889 | 87.89584935 | IEC EI |
| Relay2 | 0.6733 | 18.80898118 | IEEE VI |
| Relay3 | 0.05 | 59.55473475 | IEEE VI |
| Relay4 | 0.4458 | 81.72180744 | IEEE VI |
| Relay5 | 0.5233 | 84.71859435 | IEEE MI |
| Relay6 | 0.05 | 58.38804672 | IEEE EI |
| Relay7 | 0.0728 | 65.22041587 | IEC LI |
| Relay8 | 0.3942 | 82.44370797 | IEC SI |
| Relay9 | 0.1114 | 79.15522085 | IEC SI |
| Relay10 | 0.8793 | 57.07956311 | IEE VI |
| Relay11 | 0.7254 | 73.14385439 | IEEE MI |
| Relay12 | 0.1635 | 84.0799661 | IEEE EI |
| Relay13 | 0.05 | 70.00726825 | IEC SI |
| Relay14 | 0.1416 | 66.57834766 | IEEE SI |
| Relay15 | 0.05 | 49.94163202 | IEEE EI |
| Relay16 | 0.0966 | 57.12540558 | IEEE EI |
| Relay17 | 0.05 | 92.4990564 | IEEE MI |
| Relay18 | 0.05 | 32.17442206 | IEEE SI |
| Relay19 | 0.0566 | 73.72275025 | IEC LTI |
| Relay20 | 0.1791 | 72.04918235 | IEC EI |
| Relay21 | 0.2213 | 83.42672247 | IEEE EI |
| Relay22 | 1.3257 | 55.66450373 | IEC EI |
| Relay23 | 0.1708 | 56.43170046 | IEEE MI |
| Relay24 | 0.6733 | 64.45362651 | IEEE MI |
| Relay25 | 0.05 | 64.45914557 | IEEE EI |
| Relay26 | 0.05 | 51.63005233 | IEC SI |
| Relay27 | 0.4054 | 80.67585509 | IEC EI |
| Relay28 | 0.416 | 74.21713113 | IEEE MI |
| Relay29 | 0.1637 | 42.63076827 | IEEE EI |

Table 22. Operating times of OCIs for islanded mode.

| Fault location | Operating times of OCIs in seconds |
|----------------|----------------------------------|
| (part a)       |                                  |
| Fault 1        | MR1 | BR23 | BR21 | BR20 | BR19 |
|                | 0.2418 | 1.5541 | 3.66 | 0.7742 | 1.33 |
| Fault 2        | MR24 | BR21 | BR11 | BR4  |
|                | 0.5146 | 1.9 | 2.01 | 2.44 |
| Fault 3        | MR27 | BR21 | BR11 | BR4  |
|                | 0.4984 | 1.96 | 1.36 |
| Fault 4        | MR23 | BR11 |
|                | 0.5938 | 1.21 |
| Fault 5        | MR23 | BR11 |
|                | 1.17 | 1.49 |
| Fault 6        | MR8  | BR16 | BR6  | BR22 |
|                | 0.1259 | 0.4817 | 0.9496 | 0.6138 |
| Fault 7        | MR10 | BR6  | BR22 |
|                | 0.5917 | 0.8922 | 0.8918 |
| Fault 8        | MR9  | BR16 | BR22 |
|                | 0.2621 | 0.5620 |
| Fault 9        | MR1 | BR16 | BR6  |
|                | 0.8615 | 1.21 |
| Fault 10       | MR22 | BR21 | BR4  | BR25 |
|                | 0.3261 | 2.73 | 3.41 |

6.2.2. Results considering islanded mode

Under this topology it is the DG plants the sole responsible for meeting the network demand. The resulting values of $T_{M.S.}$, $SCC_i$, and $PSM_{max}$ are shown for each OCR in Table 21. Table 22 (parts a and b) show the operating times, for each fault, for both main and backup relays. If the operating time is not specified is because the relay does not see the fault current in this mode. Note that the proposed methodology always presented feasible operating times. It should also be noted that coordination scheme is guaranteed in all cases.

7. Conclusions

MGs are expected to exhibit different modes of operation, so conventional approaches to over-current relay coordination might not be suitable for some of their topologies. Furthermore, the presence of DG makes the protection coordination even more complex. Bearing this in mind, this paper proposes a novel approach for optimal coordination of OCIs in MGs that harbor DG and that may operate under different topologies. As a novelty, there are simultaneously considered TMS, PSM and SCC as optimization variables which increases the search space for coordination alternatives, enhancing the overall protection scheme’s performance. In traditional coordination approaches, TMS is the sole variable that is set for protection coordination; nonetheless, this paper
also considers the maximum limit of the DSM and the SCC as decision variables, resulting in a more versatile approach, differentiated from other methodologies. TLBO, GA, PSO and SFLO techniques were implemented for solving the optimal coordination problem. GA proved to be the best approach in terms of solution quality and computation time, followed by PSO and TLBO, while SFLO was trapped in locally optimal solutions. In consequence, GA was selected for performing the results with a benchmark IEC MG under different operating modes. A comparison was carried out with other approaches proposed in the specialized literature, which demonstrated that the proposed approach is applicable and effective in MGs which include DG scenarios. The results obtained evidenced that the proposed methodology allows obtaining lower operating times in the coordination of protections of the test MGs.

**Declarations**

**Author contribution statement**

Sergio D. Saldarriaga-Zuluaga: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Jesús M. Lopez-Lezama & Nicolas Munoz-Galeano: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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**Data availability statement**

Data will be made available on request.

**Declaration of interests statement**

The authors declare no conflict of interest.

**Additional information**

No additional information is available for this paper.

**References**

[1] C. Gambaro, J.M. Guerrero, Computational optimization techniques applied to microgrids planning: a review, Renew. Sustain. Energy Rev. 48 (2015) 413–424.

[2] J.S. Giraldo, J.A. Castiellon, J.C. López, M.J. Rider, C.A. Castro, Microgrids energy management using robust convex programming, IEEE Trans. Smart Grid (2018).

[3] R.H. Laseter, P. Pägi, Microgrid: a conceptual solution, in: IEEE Power Electronics Specialists Conference, vol. 6, Citeeseer, 2004, pp. 4285–4291.

[4] S. Katarya, L. Staszewski, Z. Leonowics, Protection coordination of properly sized and placed distributed generation-methods, applications and future scope, Energies 11 (10) (2018) 2672.

[5] J.d.J. Jaramillo Serna, J.M. López-Lezama, Alternative methodology to calculate the directional characteristic settings of directional overcurrent relays in transmission and distribution networks, Energies 12 (19) (2019).

[6] S.A. Hoseiní, H.A. Abyaneh, S.H.H. Sadeghi, F. Razavi, A. Nastari, An overview of microgrid protection methods and the factors involved, Renew. Sustain. Energy Rev. 64 (2016) 174–186.

[7] V. Telukunta, J. Pradhan, A. Agrawal, M. Singh, S.G. Srivani, Protection challenges under bulk penetration of renewable energy resources in power systems: a review, CSEE J. Power Energy Syst. 3 (4) (2017) 365–379.

[8] A.C.Z. de Souza, M. Castilla, Microgrids Design and Implementation, Springer, 2019.

[9] H.H. Zeinelidin, Y.A.-R.I. Mohamed, V. Khadkikar, V.R. Pandi, A protection coordination index for evaluating distributed generation impacts on protection for meshed distribution systems, IEEE Trans. Smart Grid 4 (3) (2013) 1523–1531.

[10] D.M. Bui, S.-L. Chen, Fault protection solutions appropriately proposed for ungrounded low-voltage ac microgrids: review and proposals, Renew. Sustain. Energy Rev. 75 (2017) 1156–1174.

[11] E. Sortomme, G. Mapes, B. Foster, S. Venkata, Fault analysis and protection of a microgrid, in: 2008 40th North American Power Symposium, IEEE, 2008, pp. 1–5.

[12] J. Ehrenberger, J. Švec, Directional overcurrent relays coordination problems in distributed generation systems, Energies 10 (10) (2017) 1452.

[13] K.A. Saleh, H.H. Zeinelidin, E.F. El-Saadany, Optimal protection coordination for microgrids considering n = 1 contingency, IEEE Trans. Ind. Inform. 13 (5) (2017) 2270–2279.

[14] H.R. Baghaee, M. Mirsalim, G.B. Gharehpetian, H.A. Talebi, MOPSO/FDFT-based Pareto-optimal solution for coordination of overcurrent relays in interconnected networks and multi- DER microgrids, IET Gener. Transm. Distrib. 12 (12) (2018) 2871–2880.

[15] M.N. Alam, Adaptive protection coordination scheme using numerical directional overcurrent relays, IEEE Trans. Ind. Inform. 15 (1) (2018) 64–73.

[16] H.C. Kilikciar, I. Şengür, H. Aldemir, B. Kekezoglu, Ö. Erdinç, N.G. Paterakis, Power system protection with digital overcurrent relays: a review of non-standard characteristics, Electr. Power Syst. Res. 164 (2018) 89–102.

[17] B. Farid, H. Bisheeh, I. Sadeghkhani, Protection coordination scheme for distribution networks with high penetration of photovoltaic generators, IET Gener. Transm. Distrib. 12 (8) (2017) 1802–1814.

[18] S.M. Saad, N. El-Naily, F.A. Mohamed, A new constraint considering maximum DSM of industrial over-current relays to enhance the performance of the optimization techniques for microgrid protection schemes, Sustain. Cities Soc. 44 (2019) 445–457.

[19] N. El-Naily, S.M. Saad, T. Hussein, F.A. Mohamed, A novel constraint and non-standard characteristics for optimal over-current relays coordination to enhance microgrid protection scheme, IET Gener. Transm. Distrib. 13 (6) (2019) 780–793.

[20] M.N. Alam, Overcurrent protection of ac microgrids using mixed characteristic curves of relays, Comput. Electr. Eng. 74 (2019) 74–88.
[21] S.D. Saldarriaga-Zuluaga, J.M. López-Lezama, N. Muñoz-Galeano, Optimal coordination of overcurrent relays in microgrids considering a non-standard characteristic, Energies 13 (4) (2020) 922.
[22] I. Std. 60255-3, Electrical relays-Part 3: Single input energizing quantity measuring relays with dependent or independent time, 1989.
[23] I. Std. C37. 112-1996, IEEE standard inverse-time characteristic equations for overcurrent relays, 1997.
[24] SIEMENS, Siprotec 5 overcurrent protection 7sj82/7sj85, https://new.siemens.com/global/en/products/energy/energy-automation-and-smart-grid/protection-relays-and-control/siprotec-5.html, 2020.
[25] AREVA, K range – series 1 overcurrent and directional overcurrent relays, https://www.se.com/ww/en/doc/FAC270672/, 2020.
[26] M. Singh, B. Panigrahi, A. Abhyankar, Optimal coordination of directional overcurrent relays using teaching learning-based optimization (TLBO) algorithm, Int. J. Electr. Power Energy Syst. 50 (2013) 33–41.
[27] J. Kennedy, R. Eberhart, Particle swarm optimization, in: Proceedings of ICNN’95 - International Conference on Neural Networks, vol. 4, 1995, pp. 1942–1948.
[28] R. Rao, V. Savsani, D. Vakharia, Teaching-learning-based optimization: a novel method for constrained mechanical design optimization problems, Comput. Aided Des. 43 (3) (2011) 303–315.
[29] M. Eusuff, K. Lansey, D. Pasha, Shuffled frog leaping algorithm: a memetic meta heuristic for discrete optimization, Eng. Optim. 38 (2006) 129–154.
[30] S. Kar, S.R. Samantaray, M.D. Zadeh, Data-mining model based intelligent differential microgrid protection scheme, IEEE Syst. J. 11 (2) (2017) 1161–1169.
[31] LINES, Power systems test case archive-30 bus power flow test case, http://labs.ece.uw.edu/pstca/index.html, 2020.
[32] IEEE, IEEE recommended practice for protection and coordination of industrial and commercial power systems (IEEE buff book), in: IEEE Std 242-2001 (Revision of IEEE Std 242-1986) [IEEE Buff Book], 2001, pp. 1–710.
[33] H.M. Sharaf, H.H. Zeineldin, E. El-Saadany, Protection coordination for microgrids with grid-connected and islanded capabilities using communication assisted dual setting directional overcurrent relays, IEEE Trans. Smart Grid 9 (1) (2016) 143–151.