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Hybrid optimization algorithm applied to adaptive protection in distribution systems with distributed generation

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ABSTRACT

The expansion of distributed generation (DG) to supply the energy demand is a reality in the modern electricity sector. However, it may cause changes in the load current and short-circuit current levels of feeders and transmission lines, among other undesirable impacts, which impair the coordination of protection schemes that were formerly designed for a radial configuration. This work proposes a method for optimizing the coordination of overcurrent relays based on computational intelligence techniques applied to adaptive protection in the context of DG. The proposed hybrid algorithm uses fuzzy logic to control the setting currents and genetic algorithms (GAs) to obtain the time dials and curves of the relay. In order to validate the proposed technique, a case study based on a 13-bus test distribution system is analyzed to compare the proposed method with two other protection methods widely known in the literature. ATPDraw software is used for the system simulation and MATLAB software allows implementing the protection algorithms. By using the proposed solution, it is possible to obtain a protection system with improved response with respect to the power system dynamics, thus enabling improvements in sensitivity and minimizing the trip times of the relays without violating the selectivity criteria.

1. Introduction

The connection of distributed generation (DG) units to the power system is a modern trend that cannot be neglected. This is due to distinct factors, e.g., adoption of encouraging policies for the incorporation of renewable energy sources; possibility of reducing losses in transmission lines; improvement of reliability indexes associated with power energy supply, among others.

It is well known that a given protection system must comply with five basic requirements, that is, sensitivity, speed, selectivity, stability, and reliability [1]. Given the constant changes that occur in modern distribution systems, many works, such as [2–5], have proposed solutions for improving the protection schemes of power networks.

The frequent changes in the network topology due to the presence of DG represent a challenge to the traditional solutions for eliminating power system faults. Therefore, the adoption of novel protection schemes by the utilities is a must [6]. As a possible solution, the adaptive protection is a philosophy that allows adjustments to be made to the protection system to make it more suitable to the changing operating conditions of the power system [7].

The authors in [8] propose an adaptive protection algorithm for distribution systems with DG based on the selection of settings through the logic states of circuit breakers. The authors in [9] propose an adaptive protection method for feeders with DG that uses the load current measured continuously to change the setting currents of the relays, ensuring a better protection sensitivity compared with the conventional method.

Regarding the calculation of overcurrent relay settings, this is still an archaic problem, with little automation, which is strongly dependent on the expertise of qualified professionals. Therefore, the results may often not be the best solutions among the various existing possibilities [10]. In view of the above, some strategies were developed aiming to validate the use of optimization techniques for coordination of overcurrent relays.

Table 1 presents the main advantages and disadvantages of some relevant optimization techniques used in power system protection, that is, linear programming (LP), particle swarm optimization (PSO), ant colony optimization (ACO), genetic algorithm (GA), and fuzzy logic.

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Table 1
Comparison among some optimization techniques applied to the coordination of protection relays.

Method	Reference	Advantages	Disadvantages
LP	[12] a [14]	It treats the coordination optimization as a linear problem, that is, a low-complexity approach by (usually prefixing the curves and setting currents). Low computational burden when compared with other methods, that is, PSO, GA, and ACO.	Possibility of optimizing a single protection setting (time dial). The presented solution may not be within a set of feasible results. Reduced capacity to find solutions close to the global optimum when compared with PSO, GA, and ACO. The setting currents are not optimized in accordance with the loading and generation features of the power system.
PSO	[15] a [17]	Possibility of optimizing two parameters, that is, usually the setting currents and time dials. Higher capacity to find solutions close to the global optimum than LP. The provided solution is within a set of feasible results.	There is the need to adapt the algorithm to deal with restrictions imposed by the coordination of relays. Higher computational burden and convergence time than LP. Travel the trip curves are often prefixed, thus reducing the search space of the algorithm. The setting currents are not optimized in accordance with the loading and generation features of the power system.
ACO	[10] e [18]	Possibility of optimizing three parameters, that is, setting currents, time dials, and actuation curves. Higher capacity to find solutions close to the global optimum when compared with LP and PSO. Lower computational burden and convergence time than GA.	Lower capacity to find solutions close to the global optimum when compared with GA. The setting currents are not optimized in accordance with the loading and generation features of the power system.
GA	[19] a [22]	Possibilidade de otimização dos três parâmetros de ajuste (correntes de ajuste, diais de tempo e curvas). Higher capacity to find solutions close to the global optimum when compared with LP, PSO, and ACO. Simplicity with respect to the incorporation of constraints associated with the coordination problem.	Higher computational burden and convergence time than LP, PSO, and ACO. The setting currents are not optimized in accordance with the loading and generation features of the power system.
Fuzzy	[23] a [25]	Capacity to convert linguistic terms and expertise into numerical variables. Possibility of optimizing the setting currents in accordance with the loading and generation features of the power system. Possibility of adapting the weights according to the criteria involved in decision making.	The implementation of the fuzzy inference system may be a time-consuming and complex task.

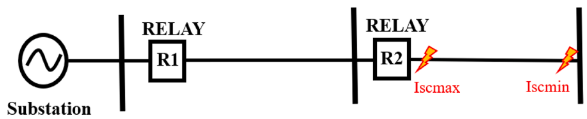

Fig. 1. Representation of a typical radial network.

Table 1 shows that LP, PSO, ACO, and GA do not require the optimization of setting currents for the relays in accordance with the system loading and generation features, this being a significant disadvantage. This is why fuzzy logic becomes an adequate choice for the application addressed in this work. This approach is then combined with GA so that it is possible to find solutions close to the global optimum similarly to LP, PSO, and ACO.

In recent years, the use of fuzzy logic in the context of relay coordination has drawn significant attention from researchers. The author in [11] proposes a method for coordinating directional overcurrent relays with distance relays in loop transmission systems. GAs are used to optimize the settings of the overcurrent function, whereas a fuzzy controller assists in decision making of the pilot protection system with respect to overrange setting permissive trip.

The authors in [23] associate an inference fuzzy block with a learning module based on artificial neural networks (ANNs) to obtain optimized protection settings in view of the system dynamics. The work developed by [24] employs a fuzzy system to obtain optimized settings for the pickup currents of the protection relays from voltage phasors and power injected by the DG.

The authors in [25] model an adaptive relay based on fuzzy logic for applications in distribution systems, in which the pick-up current is controlled from two inputs: the current prior to the fault and the current variation.

This work proposes an adaptive protection method based on fuzzy logic for optimizing the pick-up currents of overcurrent relays from variations in the loading and power injected by the DG. A GA is used for optimizing other relay settings, that is, the time dial and curve. As it will be further demonstrated, the combination of the aforementioned computational intelligence techniques presents advantages over other consolidated approaches previously used in the literature, such as the LINEAR method and the traditional solution based on the use of only GAs for the parameterization of the relays.

The main contribution of the present study includes the introduction of a protection method capable of incorporating variations in the loading and power injected by the DG into the adaptive optimization problem of overcurrent relays, aiming to obtain an improved performance in response to the dynamic behavior of the power network. By using the proposed technique, it is possible to obtain an automatic improvement in the sensitivity of relays for various scenarios, as well as reduce their respective operating times without violating any selectivity criteria.

2. Coordination of overcurrent relays

The coordination between two inverse time overcurrent relays using the classic method should be performed according to the criteria defined in [26]. From Fig. 1, the main steps can be described as follows.

Step 1: Choosing the curve type.

The time versus current curves of the relays are given by equation 1:

Table 2
Coefficients of the curves defined by IEC 60255.

Curve type	α	β
Normal inverse (NI)	0.14	0.02
Very inverse (VI)	13.5	1
Extremely inverse (EI)	80	2

Table 3
Errors and typical coordination margins for each relay technology.

	Relay Technology		
	Electromechanical	Static	Numeric
Typical basic timing error [%]	7.5	5	5
Inertia time	0.05	0.03	0.02
Safety margin	0.10	0.05	0.03
Margem de coordenação típica [s]	0.40	0.35	0.30

$$t_d = TD.\left(\frac{\alpha}{\frac{Isc}{Ip}^{\beta} - 1}\right) \tag{1}$$

where t$_d$ is the trip time [s]; TD is the time dial [s]; Isc is the short-circuit current [A]; Ip is the setting current [A]; and α, β are constants whose values depend on the curve type.

Table 2 presents the values of α and β as defined by IEC 60255 standard.

The choice of the curve type is often made based on practical criteria. For instance, the EI curve is the most common one for primary distribution systems [27]. Conservatively, the curve type chosen for relay R1 must be the same as that used for relay R2.

Step 2: Determining the setting current.

The setting current must be chosen so that the relay does not operate for the maximum expected value of the load current, but for a current less than or equal to the minimum fault current flowing through the branch to be protected as defined by equation (2).

$$ktxImax \leq Ip \leq Iscmin \tag{2}$$

where kt is the overload factor, chosen as 1.2 in this work, i.e., corresponding to an overload of 20%; Imax is the maximum load current [A]; and Iscmin is the minimum fault current through the branch protected by the relay [A].

An important issue that should be analyzed is the sensitivity factor, which is the ratio between the minimum fault current detected by the device and the setting current:

$$Sensitivity = \frac{Iscmin}{Ip} \tag{3}$$

Good sensitivity is achieved when the minimum fault current is at least 1.5 times the pick-up current. This is because the currents close to the vertical asymptotic region of the relay characteristic lead to a long trip time, which consequently implies a reduction or loss of sensitivity [18].

Step 3: Coordination and selectivity.

Based on Fig. 1, there are two options for choosing the time dial of R2: a minimum trip time can be established for a maximum fault current (Iscmax), as the time dial can then be calculated; or one can adopt the lowest available time dial. The first option was used in this work for a minimum trip time (R2tmin) greater than or equal to 0.1 s for R2.

To ensure the protection selectivity, one must maintain a minimum difference between the trip times of two cascaded relays, while taking into account the trip time of the circuit breaker, the tolerance established by the manufacturer, and the safety time of the project [1,27].

According to Table 3, the typical values used for the trip margin depend on the type of relay. In this work, the use of numerical relays was considered as a trend for the protection of modern power systems. Thus, the minimum margin for the trip time was set at 0.3 s.

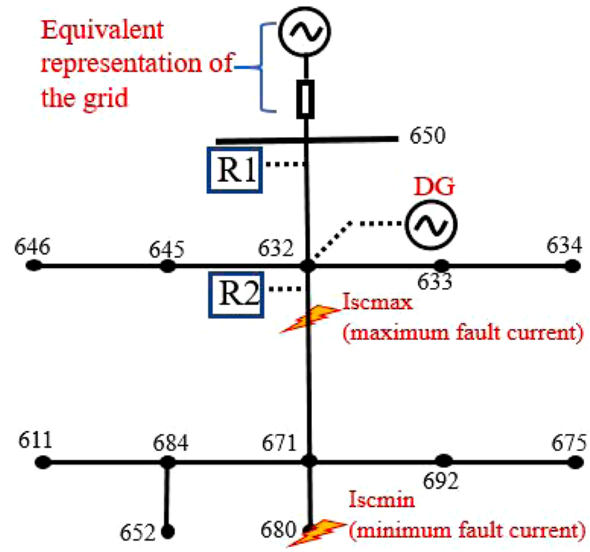

Fig. 2. 13-bus test system.

Determining the time dial of R1 should start from the following premise: the trip time of R1 for the maximum fault current detected by R2 must be greater than or equal to the trip time of R2 for the maximum fault current detected by relay plus 0.30 s, as represented by (4).

$$R1tmin \geq R2tmin\ +\ 0.30s \tag{4}$$

where R1tmin is the trip time of R1 for the maximum fault current measured by R2 [s]; and R2tmin is the trip time of R2 for the maximum fault current measured by R2 [s].

It is worth mentioning that the following criteria must be met: the values of TD must be within the range of settings as defined by the manufacturer; the curve of R1 must be above and to the left of the curve of R2; the setting current of R1 must be greater than or equal to that of R2; and the time interval between the curves should be at least 0.30 s at the maximum short-circuit current.

3. Case study and methodology

ATPDraw software was used in this work to perform the simulations, this being one of the most popular tools adopted in the analysis and modeling of power systems [28]. The test distribution system consists of a modified version of the well-known IEEE 13-bus model [29]. Figure 2 presents the feeder diagram.

The relays to be coordinated, namely R1 and R2, were added to buses 650 and 632, respectively. Relay R2 must protect the main branch of the feeder from the beginning of the line connecting bus 632 to bus 671 up to bus 680. Relay R1 is supposed to act as a backup for R2 in the event of incorrect tripping of the circuit breaker.

In this work, the maximum fault current Iscmax corresponds to a three-phase fault at the beginning of the line connecting bus 632 to bus 671. The minimum fault current Iscmin corresponds to a two-phase fault at the end of the feeder (bus 680). The DG unit, which is connected to bus 632, was modeled in terms of a voltage source and a series-connected (sub-transient) reactance of 0.2 pu. The maximum active power supplied by the source is 660 kW. An active power control block was used to vary the power injected by the DG (PDG), thus representing an intermittent source, e.g., a wind power plant, in which the power injected by the source varies according to the wind speed.

The impact of DG on protection systems is a topic widely explored in the literature [18,30,31]. From Fig. 2, it is possible to observe the following impacts caused by the DG:

Table 4
Case study scenarios.

Scenario	Pload	PDG[kW]	R1Imeas[A]	R2Imeas[A]
1	100%	0 (No DG)	551	508
2		220	494	508
3		440	472	508
4		660	451	508
5	75%	0 (No DG)	449	308
6		220	392	308
7		440	370	308
8		660	350	308
9	50%	0 (No DG)	280	135
10		220	232	135
11		440	213	135
12		660	196	135

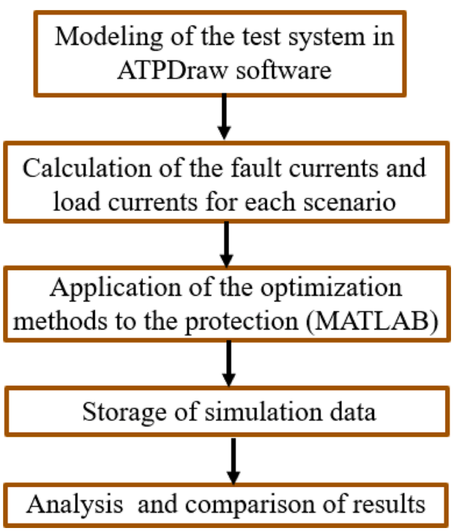

Fig. 3. Flowchart of the adopted methodology.

- For relay R1, which is upstream of the DG connection point, the measured load current will be less than the current demanded by the load, since part of such current is supplied by the new source. Thus, there is the possibility of reducing the pick-up current of R1 (Ip1) as PDG increases, improving the protection sensitivity;
- For relay R2, which is downstream of the DG connection point, the short-circuit currents in the protection zone will be significantly higher. Therefore, it is necessary to determine the logic level of the circuit breaker associated with the DG connection for calculating the short-circuit levels of the network topology.

Another important variable to be considered in the problem is the loading of the distribution system (Pload), because the load power demanded by consumer units varies constantly in a real case. According to Table 4, 12 different scenarios were simulated by varying the feeder loading by 50%, 75%, and 100%; as well as varying the power injected by the DG by 0 (no DG), 220, 440, and 660 kW. The values of R1Imeas and R2Imeas correspond to the load currents measured by the relays for each scenario.

Two protection methods already consolidated in the literature were chosen to perform a fair comparison with the proposed approach. The first one was presented in [8] and will be called hereafter as the LINEAR method, which coordinates the relays every time the state of the circuit breaker associated with the DG changes. It aims at optimizing only the time dials of the relays so that it is possible to achieve the selectivity criteria.

The second method is simply called GA. Every time the state of the circuit breaker changes, it employs a simple genetic algorithm to provide the optimized protection settings. This metaheuristic is suitable for solving nonlinear problems and often presents good performance for coordination optimization tasks as reported in [20] and [21].

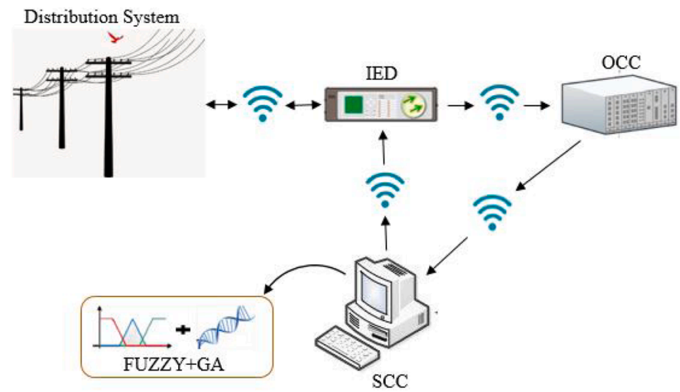

Fig. 4. Architecture of the adaptive protection system (adapted from [21]).

The use of GA enables a protection coordination that optimizes both the time dial and the type of trip curve. Because of the larger search space, this method is capable of providing better solutions when compared with the LINEAR one, as it will be further demonstrated. When using either of the aforementioned solutions, the setting currents of the relays (Ip1 and Ip2) are conservatively fixed at a value that corresponds to the maximum load current multiplied by an overload factor of 1.2. The proposed solution, hereafter called FUZZY+GA, aggregates the prominent advantages of GA. Besides, by means of fuzzy logic, it can perform an optimized and dynamic adjustment of pickup currents according to changes in Pload and PDG, thus enabling improvements in the sensitivity and trip time of the protection system. Figure 3 shows the flowchart representing the methodology employed in the analysis.

4. Proposed adaptive protection approach

Adaptive protection is a method that allows adjustments to be made in the protection system so that it becomes less susceptible to the ever-changing conditions of the power system [32]. This work proposes an adaptive protection system based on the one described in [33], which is characterized by a distributed architecture consisting of three layers:

- Intelligent Electronic Devices (IEDs) - such devices perform the traditional tasks of a basic relay, also allowing the settings to be modified during the normal monitoring condition;
- Operation Control Center (OCC) - this layer is responsible for monitoring and identifying changes in the network;
- Substation Control Center (SCC) - it is responsible for calculating new parameters for the overcurrent relays.

This very same model was used in [21], but associated with a radial distribution system, where an GA was employed in the SCC to calculate the relay settings. In the present work, the model is used in the context of DG, while combining fuzzy logic and GA in the SCC to obtain the relay settings (Fig. 4).

It is assumed that the protection system monitors electrical quantities continuously, while also monitoring distinct digital signals, e.g., the logical state of circuit breakers; and analog signals, e.g., the voltages and currents measured by the IEDs. Many modern relays are currently capable of measuring electrical quantities and communicating with SCCs on an online basis. However, in order to make the approach proposed in this work feasible for practical applications, the devices should still allow the automatic change of respective settings on a real-time manner, analogously to the relay proposed in [34].

The variables used as inputs for the proposed algorithm are: the currents measured by R1 and R2, namely R1Imeas and R2Imeas,

Table 5
Fault currents according to the DG status (DJ_DG).

Status	R1		R2	
	Iscmin [A]	Iscmax [A]	Iscmin [A]	Iscmax [A]
DJ_DG=0	2378	3750	2378	3750
DJ_DG=1	2084	3748	3108	5913

respectively; the minimum and maximum short-circuit currents represented by Iscmax and Iscmin, respectively, which were previously calculated for cases with and without considering the DG operation; the logic level of the DG breaker (DJ_DG), where 0 and 1 denote that the DG is enabled and disabled, respectively; the power injected by the DG (PDG); and the system loading (Pload).

A change in the logical level of DJ_DG denotes a change in the DG status, which implies changes in the short-circuit levels as shown in Table 5. Therefore, the algorithm interprets this event as a need to change the protection settings, also adopting the fault currents corresponding to the current topology.

Variations in the DG power injection (ΔPDG) and system loading (ΔPload) also point to the need for changing the protection settings. Maximum limits of 5% were previously defined for such variations. Such values were determined so that the protection system allows the loading or power injected by the DG to be reduced by 5% without the need for changes in the relay settings. From this premise, it becomes evident that the network operation profile has changed significantly, thus pointing to the need to change the protection settings. After that, parameters PDG and Pload are used as inputs to the fuzzy block aiming to control the pick-up currents (Ip1 and Ip2), which are then applied to the GA block to determine the time dials and relay curves. Figure 5 shows the flowchart of the proposed technique.

4.1. Fuzzy logic block

Fuzzy logic was proposed by Zadeh [35], this being a technique widely used to derive mathematical models of complex problems. Based on the prior knowledge of an expert, it is possible to obtain adequate answers in the form of solutions. Basic concepts associated with fuzzy sets are not part of the scope of this work, but an in-depth explanation can be easily found in the literature [36,37]. Figure 6 shows a schematic of the process involving the development of a conventional fuzzy inference system.

A fuzzy routine was implemented in this work using MATLAB to control the setting currents of relays R1 and R2 in Fig. 2. The inputs for the block are the system loading in pu and the power injected by DG in kW. The output variables of the fuzzy block (Ip1 and Ip2) are defined based on the following membership rules:

1. IF (PDG Is VeryLow) AND (Pload Is Light) Then (Ip1 Is Low3)
2. IF (PDG Is Low) AND (Pload Is Light) Then (Ip1 Is Low2)
3. IF (PDG Is Normal) AND (Pload Is Light) Then (Ip1 Is Low1)
4. IF (PDG Is VeryLow) AND (Pload Is Average) Then (Ip1 Is Average3)
5. IF (PDG Is Low) AND (Pload Is Average) Then (Ip1 Is Average2)
6. IF (PDG Is Normal) AND (Pload Is Average) Then (Ip1 Is Average1)

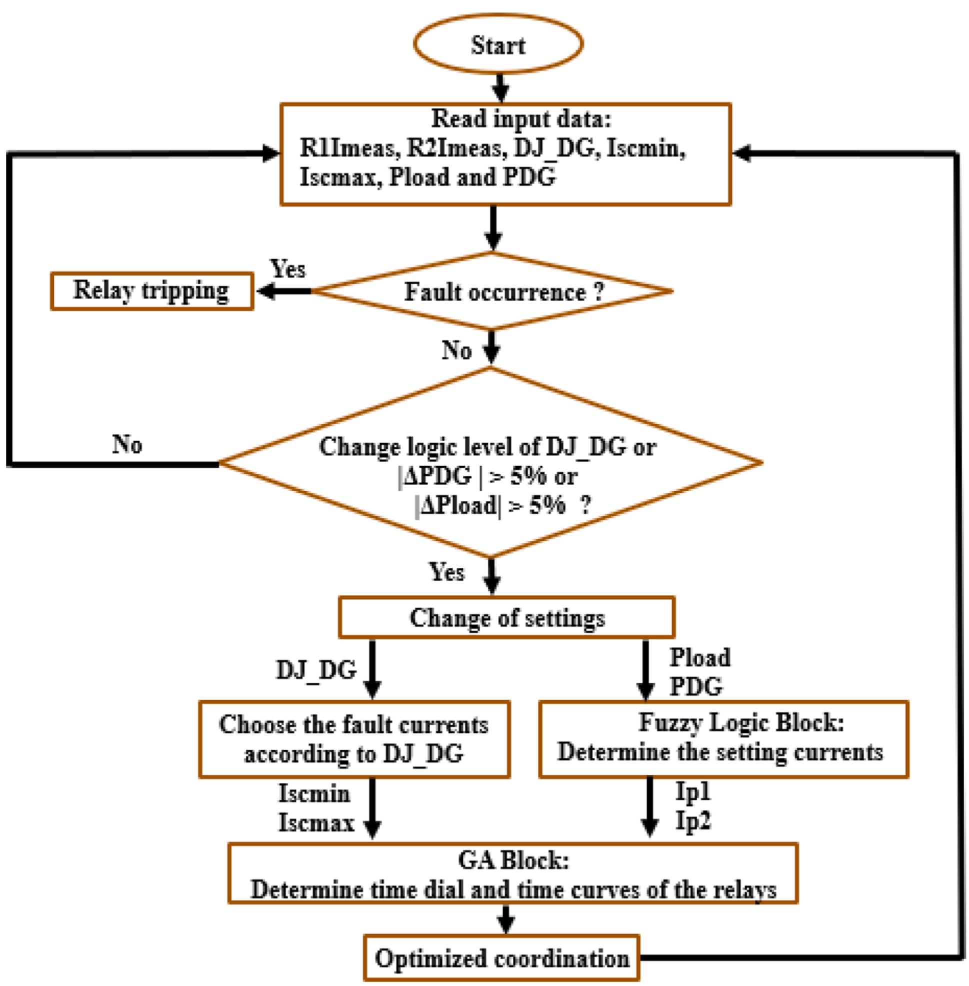

Fig. 5. Flowchart of the proposed method.

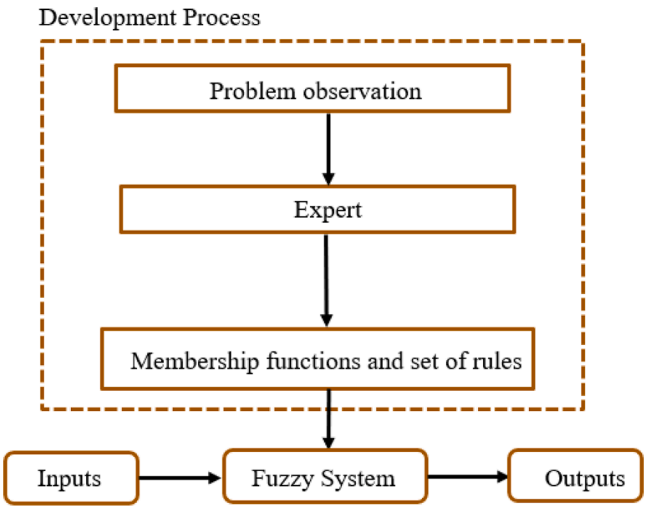

Fig. 6. Conventional fuzzy inference system (adapted from Bertho Junior [38]).

7. IF (PDG Is VeryLow) AND (Pload Is High) Then (Ip1 Is High3)
8. IF (PDG Is Low) AND (Pload Is High) Then (Ip1 Is High2)
9. IF (PDG Is Normal) AND (Pload Is High) Then (Ip1 Is High1)
10. IF (Pload Is Light) Then (Ip2 Is Low)
11. IF (Pload Is Average) Then (Ip2 Is Average)
12. IF (Pload Is High) Then (Ip2 Is High)

It is worth mentioning that, as relay R2 is downstream of the DG, controlling the pick-up current Ip2 depends only on the system loading. As for relay R1, the higher the power supplied by the DG, the lower the load current measured at the installation point. Thus, it means that the setting current Ip1 can also be modified according to the value of PDG, implying a greater number of rules for the control implementation.

Figure 7 shows the membership functions associated with the power injected by the DG (PDG) and the system loading (Pload). Figure 8 presents the membership functions for the pick-up currents of R1 and R2. A Mamdani controller is used, whereas defuzzification is performed using the centroid method.

4.2. GA block

GAs consist of metaheuristic methods based on Darwin's theory of evolution. Figure 9 shows the block diagram of a simple GA algorithm.

First, a set of individuals representing possible solutions, called the initial population, is generated randomly. Then, each individual is evaluated, receiving an aptitude value according to the objective function (OF) used in the problem. Individuals with better skills are more likely to survive in the next generations. Then, a selection is performed to choose the parent chromosomes, which will be used in the next steps to generate a new population. The selected individuals go through the genetic operators, called crossing and mutation, thus generating a new population of more fit individuals, as the previous population is replaced. This process is repeated until the final population is composed of individuals who represent optimized solutions for the problem. [39].

A GA block was used in this work to optimize the settings, namely the time dial and curve of two relays as shown in Figure 2. Table 6 presents the parameters used in the implementation of the GA, which were determined on an empirical basis based on previous works reported in the literature [7,18].

Figure 10 shows an example of the OF versus the number of generations for 100 executions in one of the simulated cases. A population of 1000 individuals was necessary to provide a search space large enough for the GA to be able to find an optimized solution in a reasonable number of generations. The stop condition is achieved when all individuals in the population converge to the same solution, which means that this is the optimal solution. It is observed that the GA does not find the best global solution in some conditions. However, for all cases, there was a minimum hit rate of 95% and a maximum standard deviation of 0.0412, thus denoting high accuracy and little dispersion of solutions obtained by the algorithm.

4.2.1. Individual coding

According to Figure 11, the binary encoding of each individual is obtained from a chromosome made up of 18 genes (bits), which contains the type of curve and the time dial of relays R1 and R2. The curves can be of three types as previously mentioned in Table 2. Therefore, they can be encoded with only two bits. On the other hand, the time dial varies from 0.05 to 1 with a step of 0.01. Therefore, seven bits are required for its binary representation.

4.2.2. Objective function

Aiming to minimize the trip time of the relays, the lowest possible

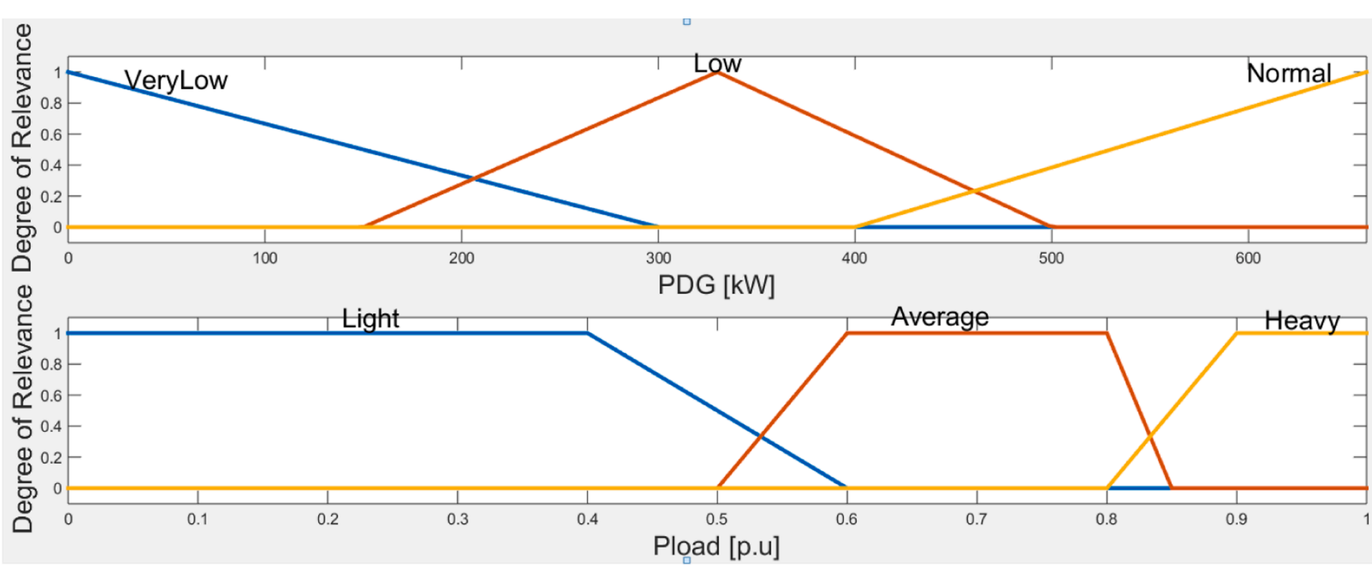

Fig. 7. Membership functions of PDG and Pload.

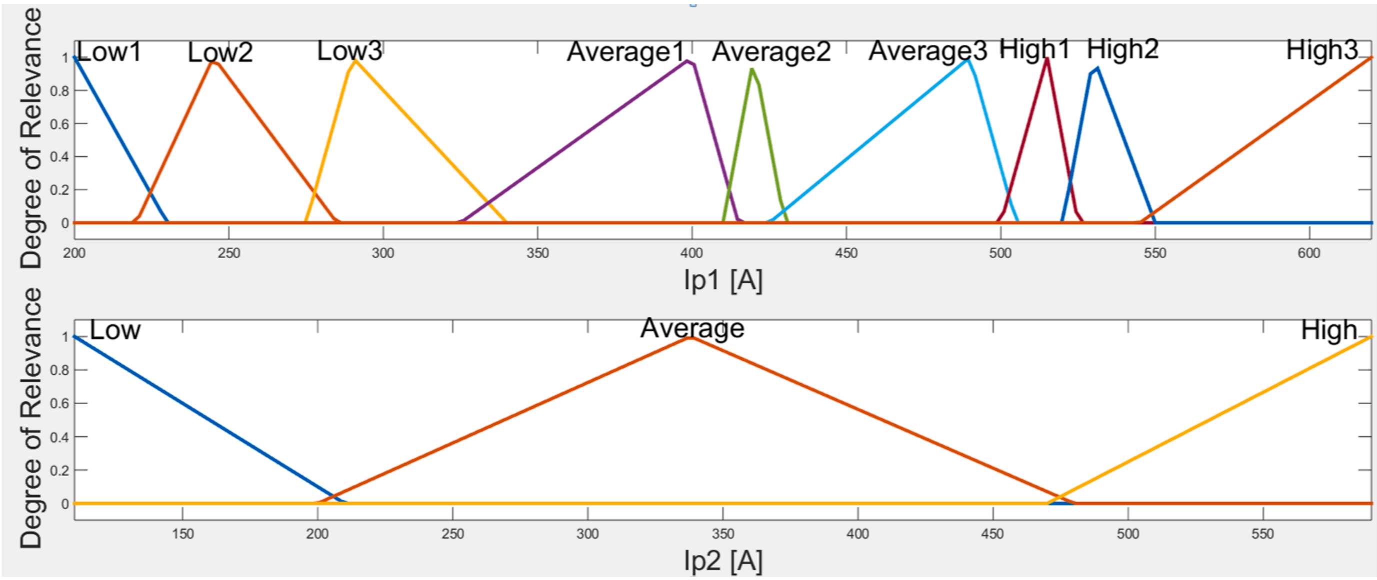

Fig. 8. Membership functions of the pick-up currents of relays R1 and R2.

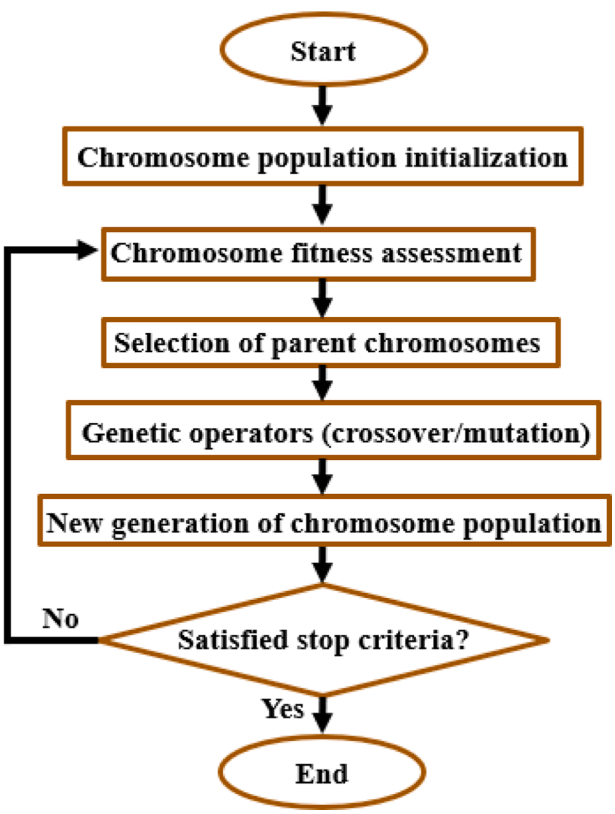

Fig. 9. Conventional block diagram of a simple GA.

Table 6
Parameters used in the implemented GA.

Population Size	1000
Number of Genes	18
Crossover Rate	90%
Mutation Rate	4%
Tournament Size	4

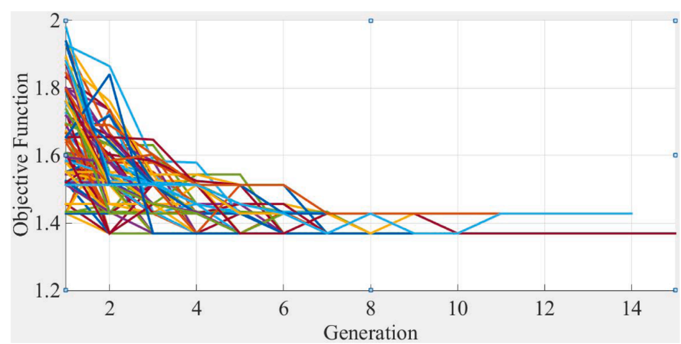

Fig. 10. OF versus number of generations of the GA.

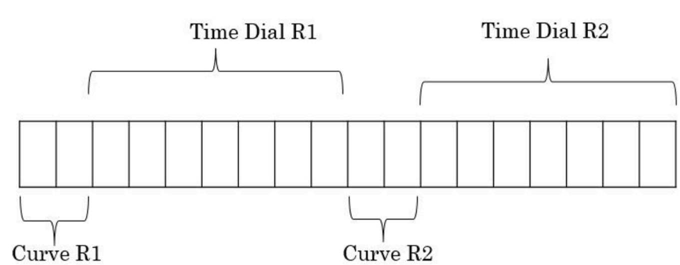

Fig. 11. Chromosome structure used in the proposed GA.

value of the following OF must be determined:

$$OF = \sum tmin_i + \sum tmax_i + \sum P\Delta t + \sum T \quad (5)$$

where $\sum tmin_i$ is the sum of the minimum trip times of the relays; $\sum tmax_i$ is the sum of the maximum trip times of the relays; $\sum P\Delta t$ is the sum of penalties for the individual who violates the selectivity criterion (0.3 s); $\sum T$ is the sum of penalties for the individual who violates the minimum trip time criterion of 0.05 s.

5. Results and discussion

This section presents the results involving the comparison of the FUZZY+GA method with the LINEAR and GA ones. Table 7 shows the

Table 7
Setting currents of the relays obtained by methods.

Scenario	LINEAR and GA		FUZZY+GA	
	Ip1[A]	Ip2[A]	Ip1'[A]	Ip2'[A]
1	662	596	597	552
2	662	596	570	552
3	662	596	528	552
4	662	596	514	552
5	662	596	474	340
6	662	596	457	340
7	662	596	387	340
8	662	596	380	340
9	662	596	304	148
10	662	596	274	148
11	662	596	245	148
12	662	596	211	148

prefixed pick-up currents of the relays for the LINEAR and and GA methods (Ip1 and Ip2), as well as the parameters determined by the FUZZY+GA solution (Ip1' and Ip2').

Table 7 shows that there are cases involving the application of the fuzzy controller for which the pick-up current of the rear relay (R1) may be less than that of the main relay (R2), e.g., scenarios 3 and 4.

When using the conventional coordination method, this should be avoided so that the curves do not cross each other, which may lead to the loss of selectivity. With the use of GA as an optimization tool in this work, this is not a concern, since the algorithm itself penalizes individuals who present loss of selectivity.

Tables 8 and 9 represent the time dials (R1TD and R2TD), trip curves (R1Curve and R2Curve), minimum trip times (R1tmin and R2tmin), maximum trip times (R1tmax and R2tmax), as well as the minimum and maximum coordination margins (Δtmin and Δtmax) obtained with the LINEAR, GA and FUZZY+GA methods for each scenario, respectively.

The plots in Figs. 12 and 13 show the behavior of the load currents measured by the relays (R1Imeas and R2Imeas), the pick-up currents of the relays determined without the fuzzy logic block (LINEAR and GA methods), and the pick-up currents of the relays determined by the fuzzy logic block (FUZZY+GA method) for each scenario.

It is important to note that, without the use of fuzzy logic, there are situations in which the pick-up currents can be extremely high with respect to the load currents measured by the protection devices. For instance, Ip1 is about 3.38 times R1Imeas (Figure 12) and Ip2 is about 4.42 times R2Imeas (Fig. 13) in scenarios 9 to 12.

This difference means that there is a wide operating margin of the protection system, resulting in low sensitivity, which may cause the protection devices not to be enabled by low fault currents.

With the use of the introduced technique, the setting currents follow the behavior of the load currents detected by the relays. Such parameters are then automatically adjusted to values close to the load currents, thus adapting the protection sensitivity for each distinct condition.

It is not desirable for the sensitivity to exceed a reasonable limit that occurs when the setting current becomes less than or equal to the load current of the feeder. To avoid this situation, the fuzzy controller associated with the setting currents was implemented based on the load current values obtained from the simulations multiplied by a factor of 1.05, thus providing a minimum overload margin of 5%.

In this way, it was possible to keep the values of the setting currents of the relays very close (but always higher by at least 5%) of the load current values measured for each scenario, preventing the relays from acting unnecessarily.

The plots in Figs. 14 and 15 show the values of the sensitivity factor for the relays with (FUZZY+GA method) and without (LINEAR and GA methods) the application of fuzzy logic. These values were calculated from Eq. (3).

By using the proposed technique, it is possible to obtain a sensitivity up to 3.13 times greater for R1 (Fig. 14, scenario 12) and up to 4.00 times greater for R2 (Fig. 15, scenarios 10 to 12).

Figure 16 shows the optimal value of the OF for each scenario as obtained with the optimization methods. The objective function of the LINEAR method was considered as equal to the sum of the minimum and maximum trip times of the relays. By fixing the setting currents, the LINEAR and GA methods have the characteristic of changing the settings only when there is a change in the status of DG operation, that is, only when the logical value of DJ_DG is changes, thus denoting the connection or disconnection to the power system.

Table 8
Results for applying the LINEAR and GA methods.

LINEAR										
Scenario	R1TD	R2TD	R1Curve	R2Curve	R1tmin[s]	R2tmin[s]	Δtmin[s]	R1tmax[s]	R2tmax[s]	Δtmax[s]
1, 5, and 9	0.13	0.05	NI	NI	0.5157	0.1868	0.3289	0.7026	0.2494	0.4532
2-4, 6-8, 10-12.	0.12	0.05	NI	NI	0.4762	0.1491	0.3271	0.7241	0.2084	0.5157
GA										
Scenario	R1TD	R2TD	R1Curve	R2Curve	R1tmin[s]	R2tmin[s]	Δtmin[s]	R1tmax[s]	R2tmax[s]	Δtmax[s]
1, 5, and 9	0.11	0.05	NI	MI	0.4363	0.1276	0.3087	0.5945	0.2258	0.3687
2-4, 6-8, 10-12.	0.11	0.07	NI	MI	0.4365	0.1059	0.3206	0.6638	0.2242	0.4396

Table 9
Results for applying the FUZZY+GA method.

FUZZY + GA										
Scenario	R1TD	R2TD	R1Curve	R2Curve	R1tmin[s]	R2tmin[s]	Δtmin[s]	R1tmax[s]	R2tmax[s]	Δtmax[s]
1	0.12	0.05	NI	MI	0.4488	0.1165	0.3323	0.5994	0.2041	0.3953
2	0.12	0.08	NI	MI	0.4377	0.1112	0.3265	0.6396	0.2332	0.4064
3	0.12	0.08	NI	MI	0.4203	0.1112	0.3091	0.6035	0.2332	0.3703
4	0.12	0.08	NI	MI	0.4145	0.1112	0.3033	0.5917	0.2332	0.3585
5	0.13	0.08	NI	MI	0.4309	0.1077	0.3232	0.5552	0.1802	0.3750
6	0.13	0.05	NI	NI	0.4234	0.1191	0.3043	0.5907	0.1547	0.4360
7	0.14	0.05	NI	NI	0.4219	0.1191	0.3028	0.5723	0.1547	0.4176
8	0.14	0.13	NI	MI	0.4184	0.1071	0.3113	0.5661	0.2156	0.3505
9	0.16	0.05	NI	NI	0.4347	0.1048	0.3299	0.5334	0.1226	0.4108
10	0.16	0.06	NI	NI	0.4171	0.1097	0.3074	0.5409	0.1338	0.4071
11	0.17	0.06	NI	NI	0.4245	0.1097	0.3148	0.5441	0.1338	0.4103
12	0.18	0.06	NI	NI	0.4255	0.1097	0.3158	0.5377	0.1338	0.4039

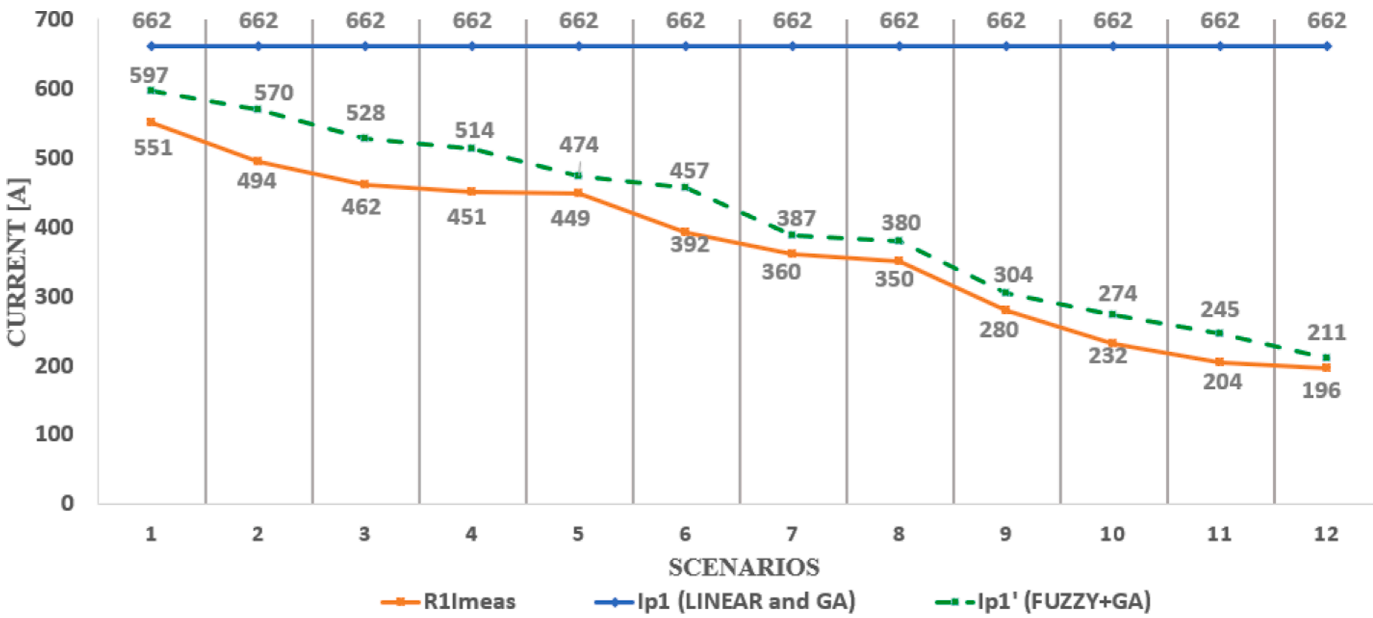

Fig. 12. Measured values of the load current and setting current of R1 using distinct methods.

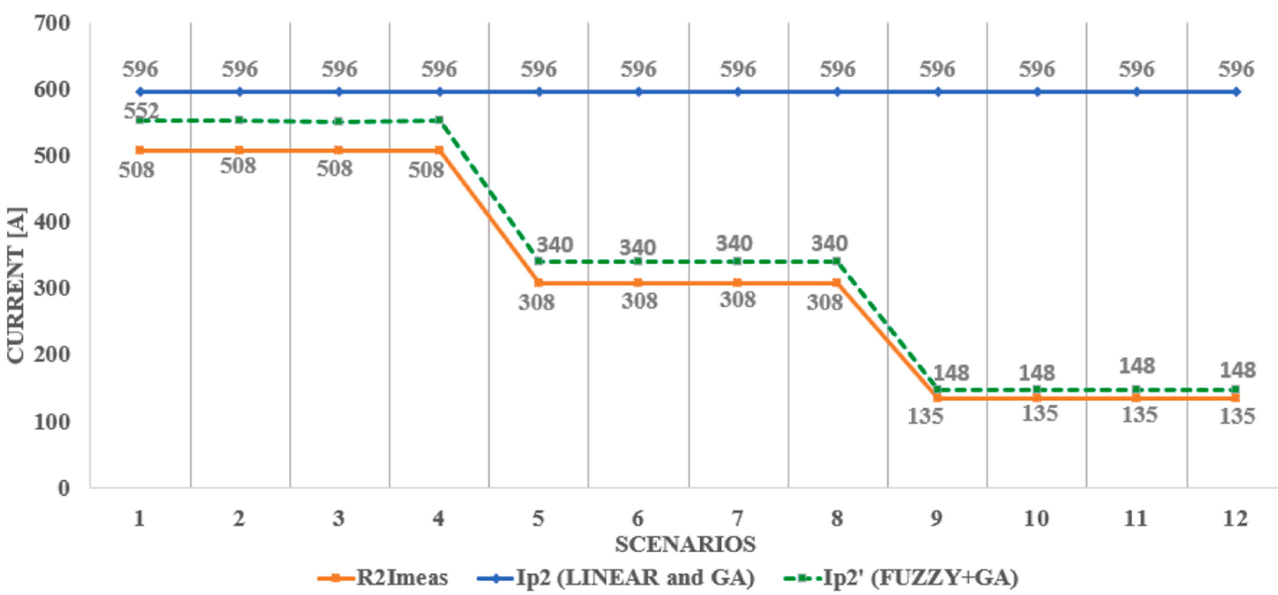

Fig. 13. Measured values of the load current and setting current of R2 using distinct methods.

It is observed that the GA method could find smaller values of the OF than the LINEAR one, but they did not vary much in the simulated scenarios. For all scenarios, the FUZZY+GA solution determines smaller values of the OF than the other two ones. This is because the use of fuzzy logic enables significant reductions in the setting currents of the relays, causing the values in the trip curves of the OF to be shifted to the left on the abscissa axis. Thus, it provides the GA with a search space that includes regions where the optimal solutions present shorter trip times, also making the protection faster.

The GA method is capable of improving the OF by up to 16 in scenarios 1, 5, and 9, corresponding to an increase of 16.34%when compared with the LINEAR solution. On the other hand, the FUZZY+GA technique improved the OF obtained by the LINEAR and GA methods by 27.74% (scenario 9) and up to 16.00% (scenario 10), respectively.

A possible drawback of the FUZZY+GA method lies in the fact that the adjustment of membership functions and definition of fuzzy sets on a manual basis depend on the observation and knowledge of an expert on the problem, which can be a quite laborious and time-consuming task.

Fixing the pick-up currents while always considering the maximum load and a given overload factor makes the adjustment of this parameter a simpler and faster solution for the GA method. However, the results denote the superior performance achieved by the novel method with regard to the optimization of protection coordination in view of the power system dynamics.

6. Conclusion

The protection of distribution systems is a topic that has been widely discussed in recent years. This is because several changes occur daily in power networks, such as changes in load profiles and increased penetration of DG units, which make the coordination of protection devices an increasingly complex problem.

In this context, this work has presented a hybrid algorithm that uses fuzzy logic and GAs incorporated into an adaptive protection scheme to

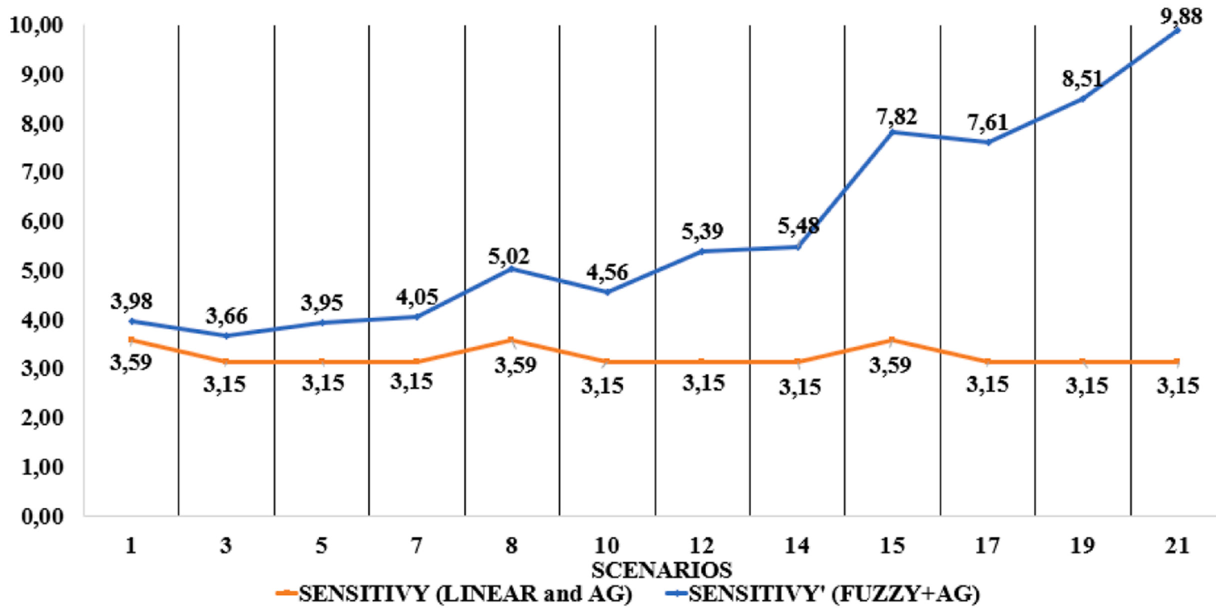

Fig. 14. Sensitivity of R1 using the LINEAR, GA, and FUZZY+GA methods for 12 simulated scenarios.

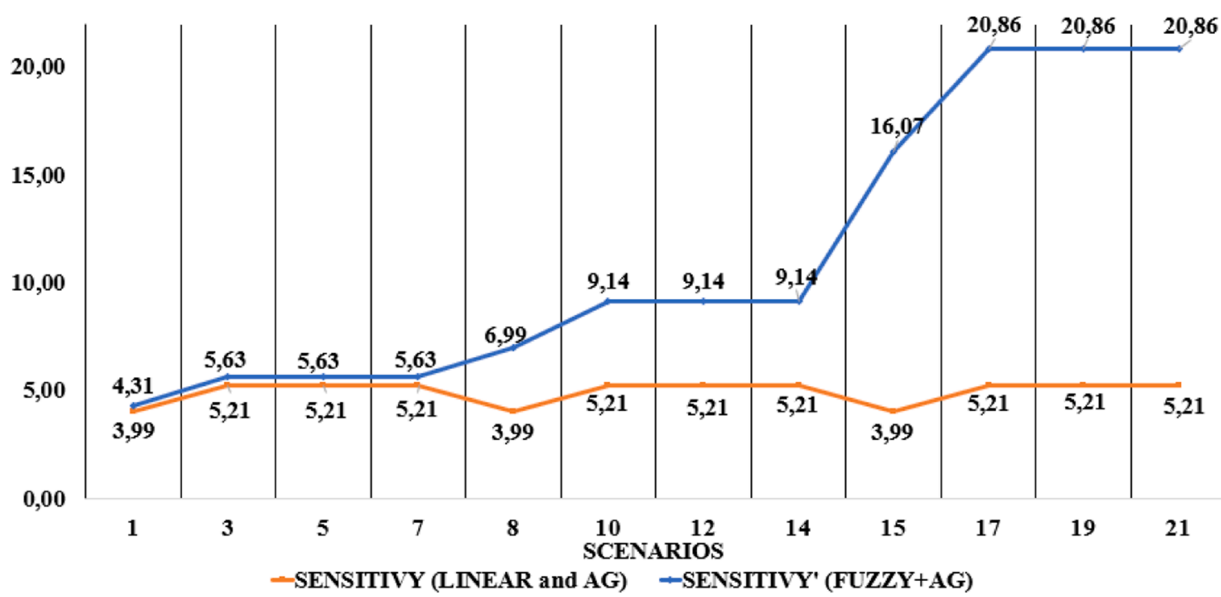

Fig. 15. Sensitivity of R2 using the LINEAR, GA, and FUZZY+GA methods for 12 simulated scenarios.

optimize the coordination of relays in power systems with DG units. The main contribution of the study comprises the combined application of two computational intelligence techniques aiming to obtain the benefits that both of them can provide in the search for optimal solutions. To validate the proposed method, a case study was analyzed, comprising a feeder in a test distribution system that contains DG. The performance of two other protection methods available in the literature was also assessed to perform a fair comparison with the introduced technique.

It is observed that the present method has a greater implementation complexity, but it is capable of providing better solutions than other consolidated approaches reported in the literature. Besides, it allows controlling the pick-up currents, improving the protection sensitivity and optimizing the relay trip times. Overall, it is reasonable to state that the technique is very promising for optimizing the coordination of overcurrent relays in an adaptive way. It also provides utilities with prominent solutions toward more efficient protection systems, aiming to avoid high economic losses and ensure proper reliability indices associated with power supply.

Future work includes the application of the algorithm to larger power distribution systems (complex mesh and tree structure), with a greater number of relays and DG units, these being more complex problems. The simulation analysis is supposed to be validated by means of a small-scale experimental prototype as well.

CRediT authorship contribution statement

Luis Henrique Pereira Vasconcelos: Conceptualization, Methodology, Software, Validation, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Aryfrance Rocha Almeida:** Conceptualization, Software, Investigation, Visualization. **Bartolomeu Ferreira dos Santos:** Methodology, Validation, Investigation, Validation, Supervision. **Nelber Ximenes Melo:** Conceptualization, Methodology, Data curation. **José Genilson Sousa Carvalho:** Conceptualization, Methodology, Software. **Danillo de**

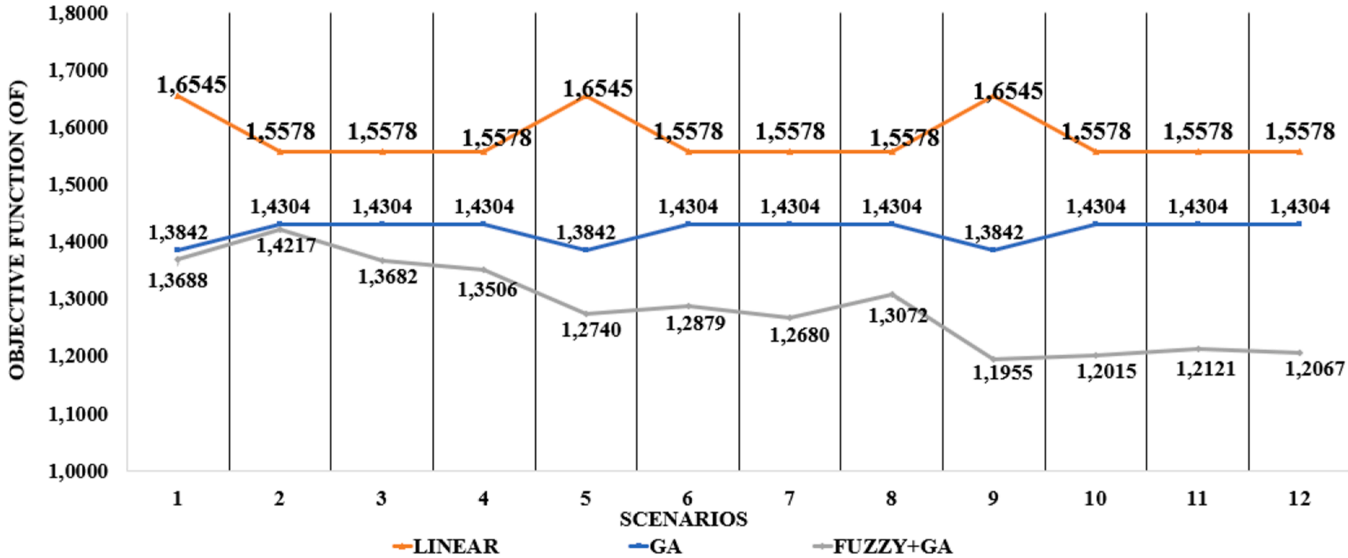

Fig. 16. Values assumed by the OF for the best individual in each scenario.

Oliveira Sobreira: Validation, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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