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Smart Protection System for Microgrids with Grid-Connected and Islanded Capabilities Based on an Adaptive Algorithm

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Abstract: This work proposes a smart protection system for microgrids, which relies on an adaptive metaheuristic for the automatic calculation of optimal settings for directional overcurrent relays (DOCRs). The adaptive fuzzy directional bat algorithm (AFDBA) associated with a fuzzy inference system (FIS) is used for this purpose. A prominent advantage of this solution is that there is no need for an initial tuning of the parameters associated with the algorithm, unlike many traditional approaches reported in the literature. Such a metaheuristic is used in the conception of an adaptive protection system (APS) in the context of a microgrid while taking into account the connection status of distributed generation (DG) units under distinct scenarios. A performance comparison with a protection system with fixed optimal settings (PSFOS) is also presented. The results demonstrate that the proposed APS outperforms the PSFOS while providing faster response, higher reliability and less susceptibility to miscoordination. In other words, it presents a shorter trip time when compared with the PSFOS, with a reduction of 6.83% and 26.58% when considering the DG penetration and the islanded microgrid, respectively.

Keywords: adaptive protection systems; directional overcurrent relays; distributed generation; metaheuristics; microgrids

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1. Introduction

Distributed generation (DG) can be incorporated into modern power systems to provide several advantages, which include reduced losses, increase in reliability and stability, and improved voltage profiles, among many other benefits [1]. On the other hand, it will also result in other undesirable issues such as voltage unbalance caused by single-phase units, decrease in short-circuit levels that lead to higher fault currents, transients during changes in the connection status, and voltage fluctuations, as well as the need for more complex and effective protection systems [2].

The authors in [3] present a comprehensive overview of challenges, bottlenecks, and effective solutions for modern power systems, while highlighting the important role of automation in this scenario. In this sense, adaptive protection systems (APSs) present prominent advantages in terms of the capacity to adjust the relay settings according to the actual operating conditions of power networks on a real-time basis. They can be regarded as a quite cost-effective solution in the aforementioned new scenario, especially when compared with other conventional solutions that rely on fixed settings [4]. In this context, the literature presents several adaptive schemes for ensuring the efficient operation of protection relays.

A state-of-the-art analysis of relays and coordination techniques applied in microgrids is presented in [5]. Considering that the microgrid remains disconnected from the power grid in islanded mode, it will affect the protection system performance while causing miscoordination, blinding, malfunctioning, and false tripping of protection relays. The authors also clearly state that it is essential to determine the fault location in both operating modes of microgrids, as well as the influence on directional overcurrent relays (DOCRs).

According to [6], the protection coordination is highly influenced by the contribution of DG in fault currents, whereas the optimal placing of such units influences this behavior significantly, as demonstrated in [7]. In this context, the study in [6] presents a recloser-fuse coordination scheme based on the directional properties of a midline recloser for the proper coordination of upstream and downstream protection devices. The authors in [8] introduce a solution for the coordination of DOCRs in microgrids while taking distinct operating modes and the connection status of DG units into account. The main innovative aspect is the incorporation of the characteristic curves of relays as decision variables, considering that some works adopt the same type of curve for all devices. Unfortunately, this choice will inevitably lead to longer trip times and higher implementation complexity.

In turn, the coordination scheme proposed in [9] can shorten the operation time of relays because it will only update the setting groups (SGs) of the elements affected by contingencies and/or topological changes. Using unconventional curves provides the system with the flexibility to achieve the required time intervals for each location. The main limitation is that it relies on relay curves that are not traditionally used by commercial equipment.

The work developed in [10] addresses an adaptive protection coordination scheme that does not depend on existing infrastructures for communication among the relays. In turn, it relies on defining the penetration level of DG, this being a quite complex task in practical applications. The authors in [11] assess the protection of multiple interconnected microgrids. The SGs of DOCRs are obtained considering all possible configurations of the microgrids in the system, whereas the resulting topologies are represented in terms of vectors using the k-means clustering algorithm. An APS applied to microgrids is described in [12], considering that the designer should calculate the most adequate SGs as a function of the topology and connection status of the microgrid. The solution described in [13] relies on monitoring the network status and selecting the most appropriate SG employing fuzzy logic.

Although the authors discuss the possible adjustment of relay settings on an online basis in [14], the APS calculates optimized SGs using nonlinear programming (NLP) algorithms. In turn, a clustering technique relying on linear programming (LP) is employed in [15] to obtain proper SGs that provide optimal coordination for each operating mode of the power system. One can also treat the coordination of DOCRs as a nonlinear mixed-integer optimization problem using the hybrid LP algorithm introduced in [16].

The rule-based algorithm proposed in [17] calculates new settings whenever the microgrid status changes from islanded to grid-connected mode, and vice versa. A similar approach is presented in [18] while adopting active network management (ANM) schemes to assess the impact of the islanded operation on the protection system. New settings are also calculated in [19] using a multi-agent system (MAS) to adjust the SGs based on the control mode of wind turbines.

It is also possible to use nonlinear optimizers for calculating the relay settings as in [20], in which the protection system is adjusted when significant changes occur in the operating conditions. Other solutions for the conception of APSs include employing the internal logic of relays for recalculating the pickup currents, as there is no need for a communication network associated with a centralized control system [21].

The APSs described thus far depend on rule-based or deterministic optimization methods. However, the coordination of DOCRs is a multimodal problem that may become quite complex depending on the number of existing relays. In this sense, several metaheuristics have been introduced in the literature, with good tradeoffs between performance and computational burden. However, there is no guarantee to find a globally optimal solution.

The first work to investigate the application of metaheuristics to such an optimization problem is reported in [22], which combines binary coding with a genetic algorithm (GA) to find a solution. An improved particle swarm optimization (PSO)-based solution is presented in [23], in which determining the settings is treated as an LP problem. A hybrid GA-LP solution is assessed [24], showing that this technique outperforms the traditional GA. This very same combination is also used in [25] to obtain initial solutions for an NLP algorithm. It is possible to allocate fault current limiters (FCLs) using GA as in [26] for minimizing the trip time of DOCRs. GA is also applied to a microgrid considering the islanded and grid-connected conditions. The results evidence that it is possible to obtain optimal relay settings. A microgenetic algorithm (μGA) is adopted in [27] to obtain the optimal coordination of DOCR based on monitoring the circuit breaker status and active power flow of DG units.

Two opposition-based chaotic differential evolution (OBCDE) algorithms are introduced in [28] and are applied in four test systems. The results clearly show that they outperform other traditional techniques. The hybrid metaheuristic called biogeography-based optimization with linear programming (BBO-LP) introduced in [29] resulted in low execution times, thus making it adequate for online applications.

The performance of GA, ant colony optimization (ACO), and differential evolution (DE) is assessed in [30] considering that the algorithms are applied in a test system. It is effectively demonstrated that DE outperforms its other counterparts in online applications. Three test systems are thoroughly evaluated in [31], showing that the hybrid gravitational search algorithm–sequential quadratic programming (GSA-SQP) algorithm can handle the coordination problem of DOCRs successfully.

The application of a fuzzy-logic-based GA is suggested in [32] to update the weight of a miscoordination penalty function associated with the objective function. It is compared with five other optimization methods while presenting the shortest trip time and no miscoordination among the pairs of primary relays (PRs) and backup relays (BRs). Distinct versions of DE algorithms applied to the coordination of DOCRs are evaluated in [33]. The enhanced DE technique is capable of improving the overall performance in terms of trip time, pattern deviation, and objective function.

The cuckoo optimization algorithm (COA) is combined with LP to provide the optimal coordination of DOCRs in microgrids and to determine the proper value of FCL at the point of common coupling (PCC) in [34]. The total trip time of DOCRs is reduced by 20% compared with that obtained with conventional GA, COA, and PSO algorithms. Sequential quadratic programming (SQP) is associated with the invasive weed optimization (IWO) algorithm in [35] to search for local solutions that eliminate the weaker weeds during the colonization process.

The authors in [36] state that GA, PSO, LP, and ACO do not require the optimization of relay settings according to the system loading and generation characteristics, this being a significant drawback. In this context, adaptive fuzzy-based techniques have become an important tool to update and optimize the coordination of DOCRs when the network topology changes [37]. For instance, the work proposed in [38] relies on simulating several fault conditions, whereas the results help to obtain fuzzy sets aiming to adjust the relay settings. An APS based on fuzzy logic for adjusting the pickup currents of DOCRs is assessed in [39]. The results prove that it increases the sensitivity of relays to high-impedance faults, while there is no need for communication among the devices.

In this context, the main contribution of the present work is the introduction of an APS for microgrids, which is capable of modifying the SGs of DOCRs whenever the connection statuses of both DG and the microgrid change. This solution relies on a modified metaheuristic based on the directional bat algorithm (DBA), which has an inherent self-tuning characteristic that does not require the setting of initial parameters owing to the incorporation of a fuzzy inference system (FIS). Thus, one can adjust the algorithm parameters on a real-time basis, also considering that BA-based techniques still remain little explored in the context of this optimization problem in particular. Such initial settings influence the performance of consolidated and traditional methods reported in the literature significantly, whereas the introduced approach presents improved performance versus other counterparts. It is effectively demonstrated that the introduced APS can provide faster response and low miscoordination when compared to a protection system with fixed optimal settings (PSFOS).

To the best of the authors' knowledge, other adaptive protective schemes associated with a self-adaptive optimization algorithm are not readily available in the literature. Other studies with a similar scope are reported in [26,34], but they present a methodology for calculating optimal settings associated with the allocation of FCLs instead. In turn, the present work introduces an APS that can adjust the relay settings in an online manner while presenting improved performance compared with the use of fixed optimal settings, which is not an efficient approach. The introduced architecture can benefit from existing communication and protection infrastructure associated with microgrids, with little hardware modification and impact on overall cost. However, the application of FCLs as suggested in [26,34] reduces both the short-circuit levels and the trip time of the protection system while also leading to increased cost due to the required additional equipment.

The remainder of this work is organized as follows. Section 2 defines some relevant aspects related to the optimal coordination of DOCRs. Section 3 briefly reviews the adaptive fuzzy directional bat algorithm (AFDBA) as applied in the conception of the proposed APS. Section 4 compares the system performance with that of a PSFOS, whereas Section 5 discusses the concluding remarks.

2. Optimal Coordination of DOCRs

DOCRs are overcurrent relays with a directional unit that determines the direction of current flow with respect to a voltage reference. In complex distribution and subtransmission networks, such relays may be used to improve the coordination of protection systems. DOCRs often incorporate proper mechanisms that allow for the correct selection of devices among the PR/BR pairs. This is the main reason for using them to mitigate the possible miscoordination between PRs and BRs in power networks.

The quality of selectivity among protective devices is referred to as relay coordination. The proper coordination relies on the adequate selection of PRs to eliminate the in-zone faults. If any PR comes to fail, a corresponding BR will operate after a given time interval. This latter parameter must not be less than the coordination time interval (*CTI*) for which the BR must trip. The *CTI* is calculated as in (1).

$$CTI = t_{jk} - t_{ik}, \tag{1}$$

where t_{ik} and t_{jk} are the trip times of a relay i and a BR j, respectively, considering a fault k. Such a coordination time interval is a function of the operating time of circuit breakers, the operation criteria, the current transformer ratio (CTR), tripping errors, and other system parameters.

Besides the overcurrent parameters, DOCRs still require the parameterization of the maximum torque angle (MTA), which is responsible for changing the impedance plan and ensuring the proper current direction. For this purpose, the MTA must be as close as possible to the fault current angle. In electromechanical relays, the choice of such a parameter is somewhat limited, but it may vary between 0° and 90° in digital relays, thus allowing for an accurate adjustment. The latter issue is of major importance, because the fault current may leave the impedance plan after topological changes of the network, thus causing the miscoordination of DOCRs.

DOCRs incorporate two fundamental settings: the time multiplier setting or time dial setting (TDS); and the pick-up current setting, namely plug setting (*PS*). *PS* is the minimum current that flows through the relay, causing it to trip when this threshold is exceeded. This parameter is equal to the product among the rated current of the circuit I_{nom}, the overload factor (*OLF*), and the inverse of *CTR* as in (2).

$$PS = \frac{I_{nom} OLF}{CTR} \tag{2}$$

Considering that the pickup current is defined in terms of the minimum current that causes the relay to trip, it must be greater than the maximum current flowing through the relay to avoid untimely and/or false tripping. This aspect is of paramount importance because low fault currents on the order of the load current will often flow through power systems with a high penetration of inverter-based DG units or with high-impedance faults.

TDS is associated with the operation time t_i of the relay for each current I, often defined in terms of a time versus current curve. In general, overcurrent relays present a characteristic function similar to (3), whereas it is possible to calculate t_i from (4).

$$t = f(TDS, PS, I), \tag{3}$$

$$t_i = \frac{\beta \cdot TDS}{\left(\frac{1}{PS}\right)^{\alpha - 1}} + L, \tag{4}$$

where α is a constant that defines the slope of the curve, considering that the constants corresponding to α, β, and L can be obtained from ANSI/IEEE and IEC standards related to overcurrent relays. Furthermore, the ratio between I and PS is referred to as the time multiplier setting (TMS).

The calculation of TDS and PS is of paramount importance for the proper coordination of DOCRs and relies on reducing the overall trip time. The objective function OF shown in (5) takes into account a single same time versus current curve for all relays to reduce the problem complexity [40].

$$OF = \sum_{k=1}^{F} \sum_{i=1}^{N} \sum_{j=1}^{M_i} \left[\left({t_{ik}}^2 + {t_{jk}}^2 \right) + \beta \left(\Delta t_{ijk} - \left| \Delta t_{ijk} \right| \right)^2 \right] \tag{5}$$

where N represents the number of relays; F and M_i are the numbers of faults and BRs associated with a given relay i, respectively.

Analyzing the first term in (5) helps to conclude that it is necessary to reduce the total trip time. The weight of the penalty function used in the tests is β = 100. In turn, this parameter cannot ensure coordination, but it will only shorten the miscoordination time interval as much as possible. However, this aspect will not influence the obtained solution and provides the AFDBA with the capacity of determining SGs aiming to obtain a faster response while maintaining the CTIs only slightly less than the minimum threshold. Given the above, the AFDBA can determine optimal settings for the system while ensuring low miscoordination times and reducing the total trip time.

In the case of DOCRs, one can obtain the desired constraints considering the following issues:

(a) The coordination criteria that define the constraints of BRs and PRs for a given configuration can be described by (6).

$$\Delta t_{ijk} = CTI - CTI_{\min} > 0, \tag{6}$$

where Δt_{ijk} is the difference between the CTIs associated with relays i and j; and $CTI_{\min}$ corresponds to the minimum acceptable value of CTI.

(b) The boundaries involving the relay settings and operation times are defined according to (7).

$$PS_{\min} \leq PS_i \leq PS_{\max}, \tag{7}$$

where the pickup current of relay i is PS_i, which assumes the minimum and maximum values according to (8) and (9), respectively.

$$PS_{\min} = \max\left(PS_{\min}^{eq}, K_1 I_{\max}^{L} \right), \tag{8}$$

$$PS_{\max} = \min\left(PS_{\max}^{eq}, K_2 I_{\min}^{F} \right), \tag{9}$$

where the minimum and maximum pickup currents correspond to $PS^{eq}_{\min}$ and $PS^{eq}_{\max}$, respectively; $I^{L}_{\max}$ represents the maximum load current that flows through the device, which can be determined from a load flow analysis; whereas the minimum fault current through the relay under any condition is $I^{F}_{\min}$. It is also necessary to multiply coefficients $K_1 > 1$ and $K_2 < 1$ by $I^{L}_{\max}$ and $I^{F}_{\min}$ to adjust the pickup currents. To obtain the minimum and maximum values of TDS represented by $TDS_{\min}$ and $TDS_{\max}$ as in (10), respectively, it is only necessary to define the constraints associated with a given relay *i*.

$$TDS_{\min} \leq TDS_i \leq TDS_{\max} \tag{10}$$

3. AFDBA-Based APS

The authors in [41] proposed the traditional bat algorithm (BA), which can provide optimal solutions for non-convex problems. However, it may lead to a premature convergence in many conditions, as reported in [42]. In turn, the directional bat algorithm (DBA) corresponds to an improved version of BA that can eliminate such inconvenience [42].

The coordination of APSs is a rather complex problem in practice because the characteristics and solutions change whenever the operating conditions of the power system also change. In practice, many iterations and tests may be necessary to determine optimal SGs. Furthermore, an initial intervention is required by most APSs. To solve the aforementioned issues, the AFDBA was previously combined with an FIS in [40] to adjust the SGs in three reference test systems. The study also demonstrated that this issue can eliminate the need to define the execution parameters because the FIS is responsible for adjusting the algorithm parameters in an online manner. An in-depth description and performance assessment of AFDBA compared with other similar counterparts in terms of convergence issues and CTI is provided in [40] and will not be included here for simplicity.

The proposed APS can change the SGs of DOCRs based on the connection status of the network components, changes in the network topology, and the operation mode of microgrids. It relies on the centralized architecture shown in Figure 1, in which all devices are monitored and controlled by a single supervisory control and data acquisition (SCADA) system at the substation. This system also monitors the states of the switches, thus informing the APS whenever they change. Based on the new operating conditions of the network, the APS calculates new settings for the relays. The proposed architecture takes advantage of existing systems responsible for the automation of power networks. Therefore, integrating the APS into existing hardware becomes simple.

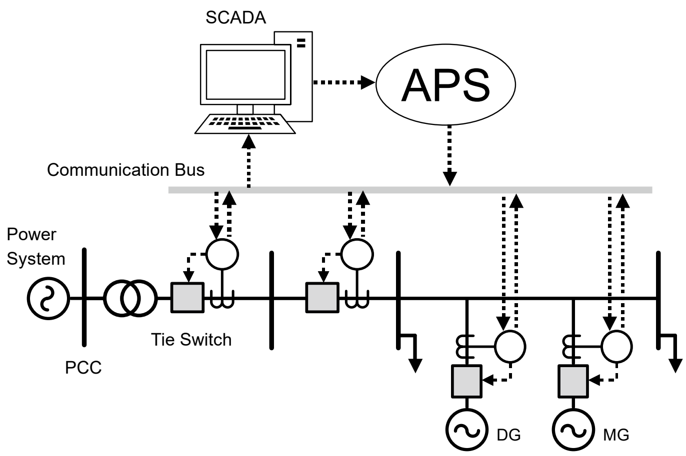

Figure 1. Architecture of the proposed APS.

Before the operation starts, it is necessary to provide the APS with some input parameters, which can be classified into protection and electrical data. Protection data include defining $PS_{\min}$, $PS_{\max}$, $TDS_{\min}$, and $TDS_{\max}$ for each relay; $CTI_{\min}$; the internet protocol (IP) address of each relay; and the values of CTR. Electrical data comprise the cable impedance;

load power; equivalent impedance of the power system; power and impedance of DG units; and impedance of each transformer. The APS also requires a data structure capable of representing the network topology for performing load flow and short-circuit calculations. MyGrid software was used for this purpose in this work [43].

The flowchart that represents the APS is shown in Figure 2. After the SCADA system sends a message informing the topology change, the APS reconfigures the network and performs all required calculations. Thus, it is possible to obtain the load currents and the short-circuit currents flowing through the relays. Such data are used to define the coordination constraints applied to the AFDBA, which is responsible for solving the optimization problem. From the load currents, short-circuit currents, and input parameters of the system, it is possible to obtain new settings for the DOCRs using the adaptive fuzzy-based algorithm. Then, optimal settings are sent to the protection relays.

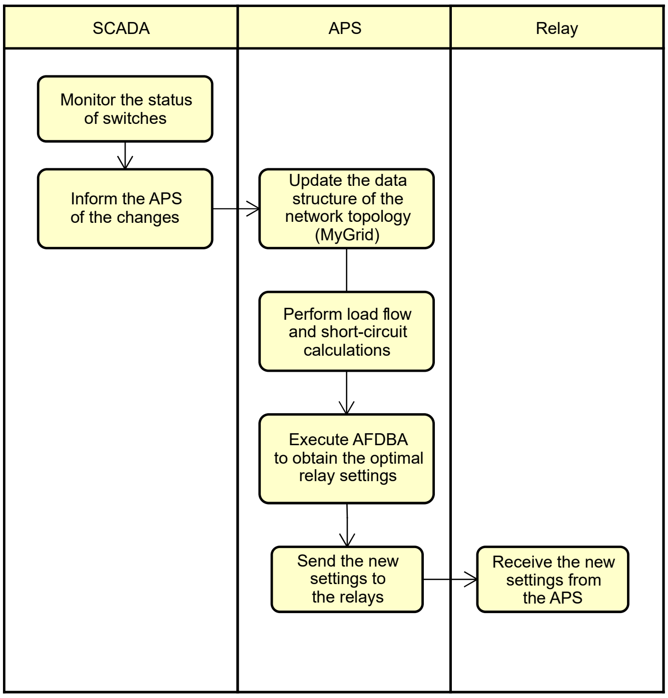

Figure 2. Flowchart of the proposed APS.

The APS associated with AFDBA can provide the proper coordination of the protection system when disturbances either internal or external to the microgrid occur. When there is a fault in the power distribution network, the APS should take into account the contributions of all sources, including the PCC to which the microgrid is connected. AFDBA is then initialized to adjust the settings accordingly. In turn, if the fault occurs in the microgrid while operating in grid-connected mode, the APS will be responsible for taking into account the contribution of the network in terms of the short-circuit power of the connection bus, as well as that of other sources that exist in the microgrid. To validate the performance of AFBDA, three test systems were assessed in [40], showing that the algorithm outperforms other conventional techniques widely used in the literature. This work focuses on the application of AFDBA considering microgrids operating in grid-connected and islanded modes.

4. Results and Discussion

Data obtained from the Canadian distribution network described in [34] were used to assess the proposed APS in a microgrid, whereas the topology is presented in Figure 3. The network is supplied at 115 kV, with a short-circuit power of 500 MVA, while bus 1 corresponds to the PCC. It is necessary to open switch 17 so that the microgrid operates in islanded mode while disconnecting it from the grid.

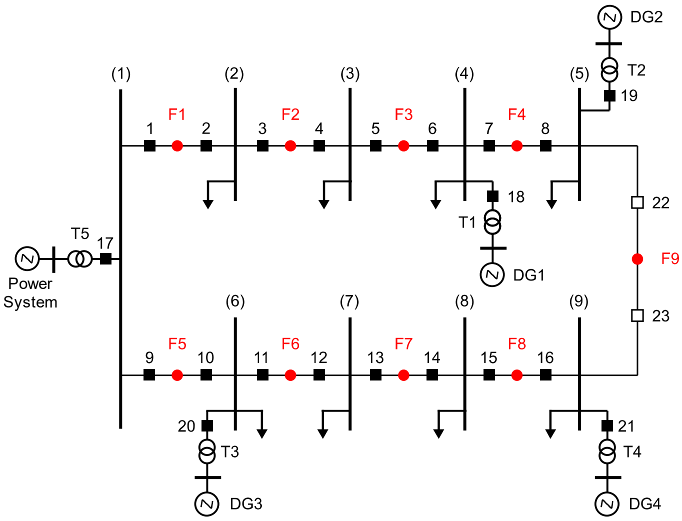

Figure 3. Canadian distribution network considered as a benchmark scenario in [26,34] and the present study.

Transformer T5, which is rated at 115–12.47 kV, 5 MVA, and an impedance X_{tr} = 0.1 pu, is responsible for connecting the network to the power system. The network also comprises four DG units (DG1 . . . DG4), each one rated at 3 MVA, 480 V, and an impedance X_d = 0.2 pu. Each unit is associated with a transformer (T1 . . . T4) rated at 0.48–12.47 kV, 5 MVA, and X_{tr} = 0.1 pu. The lines have an impedance of 0.1529 + j0.1406 ohm/km and a length of 500 m. Each load corresponds to an apparent power of 2 MVA and a lagging power factor of 0.9. The short-circuit currents were calculated from the fault points F1 . . . F9.

The system has 23 circuit breakers associated with DOCRs. Switches 22 and 23 were also added to the circuit for restoring the branches that are disconnected by the other feeder. Each relay has a normal inverse curve and a CTR of 500-1. According to Section 2, the limits corresponding to (11) and (12) were adopted.

$$\max\left(0.1, 3I^{L}_{\max}\right) \leq PS \leq \min\left(3.2, \frac{2}{3}I^{F}_{\min}\right) \quad (11)$$

$$0.05 \leq TDS_i \leq 1.5 \quad (12)$$

where 0.1, 3.2, 0.05, and 1.5 are associated with the maximum and minimum values of PS and TDS defined for the commercial relay model SEL-751 [44].

The APS was tested in multiple scenarios involving the microgrid operation, considering the connection status of DG, network topology, as well as the grid-connected and islanded operation of the microgrid. All possible combinations of the DG status are summarized in Table 1, where 0 and 1 denote that the DG unit remains disconnected and connected, respectively.

The conditions involving topology changes as shown in Table 2 comprise all the cases in which a branch under fault is isolated (or remains under maintenance) and de-energized loads are restored. In this work, a single line-to-line-to-line (LLL) fault occurs per line as in the studies presented in [26,34], which also rely on the test system shown in Figure 3. The analysis also takes into account all cases in which the microgrid is islanded and connected to the power system. However, when switch 17 is open and the microgrid operates in islanded mode, all conditions represented in Table 1 are analyzed, except for case P because no source would be connected to the power system. Therefore, the APS was tested for a total of 279 distinct cases. The tests were performed on a personal computer (PC) with an Intel®Core™i5-3210M processor, base frequency of 2.5 GHz, and 6 GB random access memory (RAM).

Table 1. Case studies involving the connection status of DG units.

Case	Connection Status			
	DG1	**DG2**	**DG3**	**DG4**
A	1	1	1	1
B	0	1	1	1
C	1	0	1	1
D	1	1	0	1
E	1	1	1	0
F	0	0	1	1
G	0	1	0	1
H	0	1	1	0
I	1	0	0	1
J	1	0	1	0
K	1	1	0	0
L	0	0	0	1
M	1	0	0	0
N	0	1	0	0
O	0	0	1	0
P	0	0	0	0

Table 2. Case studies involving topology changes.

Case	Connection Status			
	DG1	**DG2**	**DG3**	**DG4**
A	1	1	1	1
B	0	1	1	1
C	1	0	1	1
D	1	1	0	1
E	1	1	1	0
F	0	0	1	1
G	0	1	0	1
H	0	1	1	0
I	1	0	0	1
J	1	0	1	0
K	1	1	0	0
L	0	0	0	1
M	1	0	0	0
N	0	1	0	0
O	0	0	1	0
P	0	0	0	0

The APS was also compared with a PSFOS, which was obtained considering that the coordination problem was modeled while aggregating all the aforementioned case studies associated with a single objective function. Thus, the settings are optimized for every operating condition of the network and remain fixed. Since the PSFOS is a very large problem, the AFDBA was executed with an initial population of 300 individuals during 10,000 iterations. Therefore, one can ensure that the algorithm will converge to a satisfactory solution. Only the coordination constraints were taken into account while disregarding adjustments in the load current and minimum fault current. A weight $\beta = 500$ was also adopted for the penalty function associated with the objective function.

To evaluate each case defined in Tables 1 and 2, first it is necessary to collect data about the trip time of PRs, trip time of BRs, and resulting miscoordination associated with the APS and PSFOS. Figures 4 and 5 present the average trip times of the primary and backup protection systems, respectively, considering the grid-connected and islanded conditions. The dashed lines correspond to the average of all assessed cases.

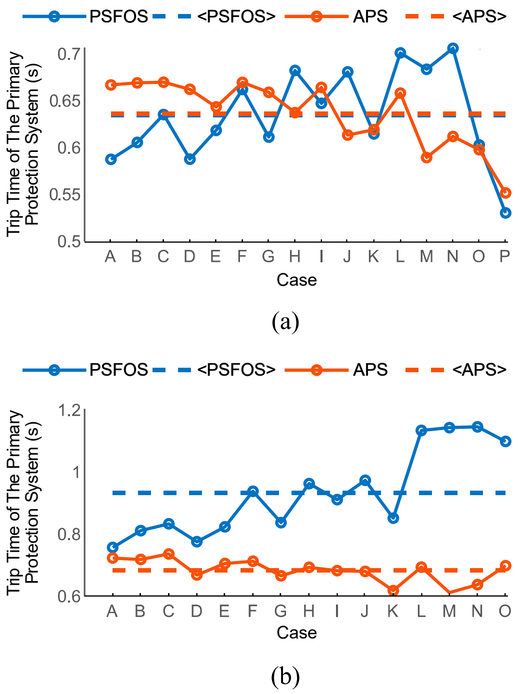

Figure 4. Average trip times of the primary protection system: (**a**) grid-connected mode, (**b**) islanded mode.

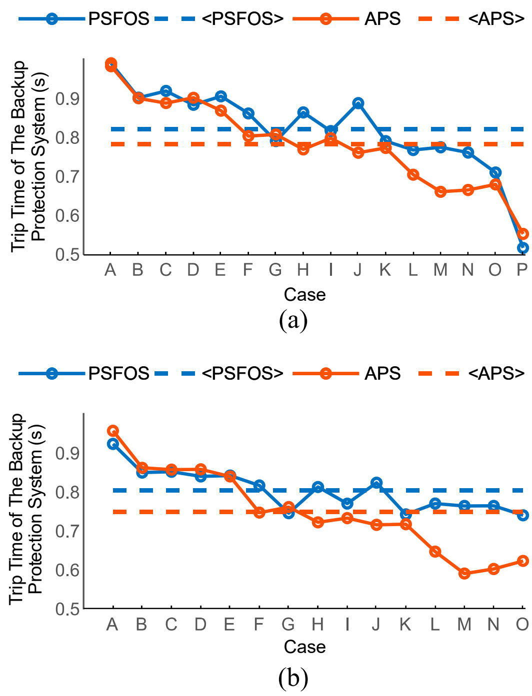

Figure 5. Average trip times of the backup protection system: (**a**) grid-connected mode, (**b**) islanded mode.

At least two fault conditions will not be associated with a backup protection for each case listed in Table 2. For instance, considering faults F2 and F5 in case 1, relays 1 and 2 will not provide backup protection, respectively. In either condition, the trip time of the backup relays t_{jk} was considered to be null, whereas the CTI is equal to $CTI_{\min}$. Thus, no penalty is applied to the objective function owing to the trip time of the backup protection system and/or miscoordination.

The performance of both protection systems with respect to the minimization of trip times of PRs is similar when the network is connected to the power system. As the penetration of DG increases and decreases, the PSFOS and APS tend to present the best results, respectively. The overall average trip time of PSFOS is only 0.2586% less than that of the APS.

The APS provides the relays with a very fast response in islanded mode. Figure 4b evidences that the average trip times are shorter in the cases comprising the existence of DG. The overall average trip time of APS is 26.58% less than that of PSFOS.

Both solutions present nearly the same trip times of the backup protection system in grid-connected mode. However, the APS presents the best results when there is little penetration of DG, resulting in a shorter overall average trip time of 4.77%. Once again, both systems present nearly the same results in islanded mode with the increasing penetration of DG, but the APS has an improved performance when the penetration of DG decreases. In other words, the APS presents a trip time reduction of 6.83%.

Since the PSFOS has fixed optimized SGs for all the assessed cases, it cannot achieve good performance in every operating condition. Furthermore, the higher the number of DOCRs, the higher the value assumed by the penalty function associated with the objective function. Therefore, the resulting settings are more adequate for cases in which the microgrid operates in grid-connected mode and with a higher penetration of DG. This issue explains why the APS outperforms the PSFOS when the microgrid operates in islanded mode with low penetration of DG.

Another issue incorporated into the analysis is miscoordination, which requires the collection of CTIs associated with the pairs of PRs and BRs for each one of the 279 cases, whereas $CTI_{\min} = 0.300$ was adopted in the tests. Figure 6 shows the frequency distribution of CTIs obtained by APS and PSFOS, as well as the respective mean μ and pattern deviation σ. Overall, both systems comply with the coordination constraints, resulting in CTIs above $CTI_{\min}$. However, the mean and pattern deviation of the APS are higher and lower than the respective values assumed by the PSFOS. In other words, the settings provided by the APS present a higher margin of CTI with respect to miscoordination, with a higher concentration around the mean. Furthermore, most CTIs, that is, 89.89% of the values remain within 0.2 and 0.3 s, as there are no values below this interval. Since the *CTI* can be between 0.2 and 0.5 s according to [45], the APS is capable of ensuring proper coordination in 91.3% of the cases. It would take more than 0.5 s for the operation of BRs in the remaining 8.7% of cases, which is a less severe condition than miscoordination. On the other hand, only 6.79% of *CTI*s associated with PSFOS remain between 0.2 and 0.3 s, whereas 35.16% of *CTI*s are between 0.2 and 0.5 s. Unfortunately, 45.68% of *CTI*s remain between -0.4 and 0.2 s, thus evidencing the miscoordination.

Based on the analysis of results, it is reasonable to state that the APS outperforms the PSFOS significantly. This is why the PSFOS cannot ensure coordination for every operating condition of the microgrid, resulting in miscoordination in some cases. The average execution times for one simulation of APS and PSFOS are 13.14 and 4473.5 s (one hour and 15 min), respectively. However, it is not fair to compare both approaches because they rely on distinct principles. Yet, the APS can provide good relay settings for DOCRs within a reasonable timeframe. Considering a maximum time interval of three minutes for the automatic reconfiguration, the APS would take only 7.3% of the total time for adjusting the settings and restoring the power system.

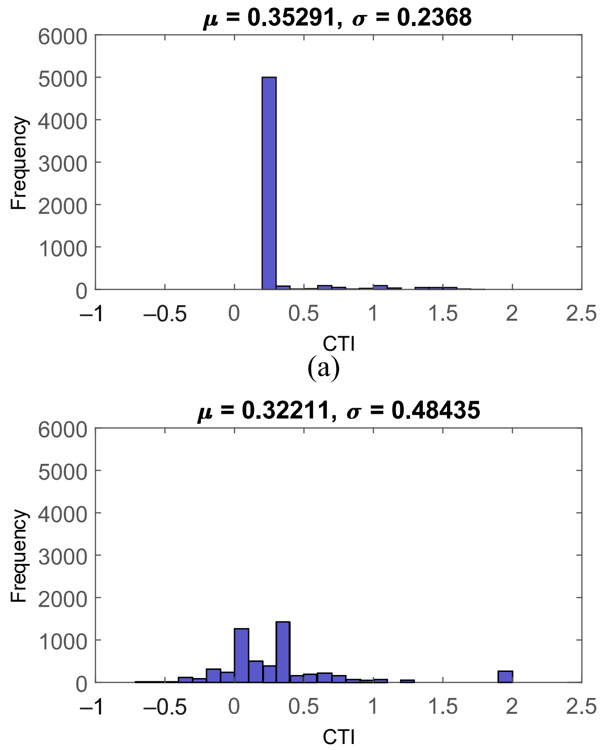

Figure 6. Frequency distribution of CTIs obtained by (**a**) the APS and (**b**) the PSFOS.

Table 3 presents a qualitative comparison among several APSs reported in the literature. Even though the schemes proposed in [4,10] relying on machine learning (ML) and the non-dominated sorting genetic algorithm (NSGA), respectively, do not require a communication structure, both of them will inevitably lead to high implementation complexity. While ML can be an incredibly powerful tool capable of handling multidimensional and multivariate data, it requires massive datasets for training, as well as some time for training and evolving the solution, unlike metaheuristics, while also requiring additional computational resources for this purpose.

Table 3. Comparison among the proposed APS and other similar solutions available in the literature.

Characteristic	[4]	[8]	[9]	[10]	[20]	[26]	[34]	Proposed APS
Network reconfiguration	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
Microgrid status (on-grid/off-grid)	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
Technique	ML	GA	DE	NSGA	AMPL	GA	Cuckoo algorithm	AFDBA + FIS
Communication	No	Yes	Yes	No	Yes	Yes	Yes	Yes
Additional hardware	No	No	No	No	No	FCLs	FCLs	No

A mathematical programming language (AMPL) is used in [20] for determining optimal settings for DOCRs, but the influence of DG is not assessed. As for other approaches based on consolidated algorithms, such as [8,9,26], GA may converge to local minima as demonstrated in [40]. As previously mentioned, solutions similar to the proposed APS are reported in [26,34], but additional hardware is often associated with budget constraints in practical applications.

5. Conclusions

This work has presented an APS capable of providing optimal settings for DOCRs and outperforming a PSFOS while providing the protection scheme with a fast response and higher reliability. It relies on an adaptive algorithm for calculating the settings, requiring only 13.14 s for adjusting 23 DOCRs in a power network with DG units.

The APS presents improved performance in terms of the trip time when compared with the PSFOS, with a reduction of 6.83% and 26.58% when considering the DG penetration and the islanded microgrid, respectively. Furthermore, the APS contributed significantly to eliminate miscoordination in all assessed fault conditions, whereas 45.68% of the cases resulted in the miscoordination when fixed optimal settings are employed. This is because the PSFOS is not capable of ensuring proper coordination for every operating condition of the power grid.

The proposed approach requires a communication network associated with protection relays, as well as the monitoring of switches and DG units. Modern substations often comprise supervisory systems for this purpose, and therefore, it is easy to incorporate this concept into existing networks with little hardware modification.

The APS was thoroughly tested in a microgrid considering multiple scenarios of DG penetration, topology changes, and connected/islanded mode. It has been demonstrated that it presents an improved performance compared with the PSFOS in terms of faster response and no miscoordination. This is due to the AFDBA, which presents fast convergence, good compliance with coordination constraints, acceptable computational burden, and high robustness, thus making this solution adequate for real-time practical applications.

It is reasonable to state that future smart grids will inevitably rely on adaptive and dynamic solutions that can ensure a continuous power supply associated with high reliability and enhanced performance. This scenario comprises the evolution of intelligent electronic devices (IEDs), development of improved optimization techniques, and investments in infrastructure of existing networks. Given the above, the proposed APS is a prominent solution for distribution networks comprising the increasing penetration of DG and microgrids based on renewable and intermittent energy resources.

Future work includes the possibility of assessing the APS in a more realistic scenario involving a communication architecture similar to the one described in [46], which relies on a conventional optical fiber network for the communication with the relays using Telnet protocol.

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