IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 7 March 2023, accepted 19 March 2023, date of publication 24 March 2023, date of current version 30 March 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3261827

RESEARCH ARTICLE

Adaptive Protection for Active Distribution Networks: An Approach Based on Fuses and Relays With Multiple Setting Groups

ADRIÁN BARRANCO-CARLOS[1], **CESAR OROZCO-HENAO**[1], **JUAN MARÍN-QUINTERO**[2], **JUAN MORA-FLÓREZ**[3], **AND ANDRES HERRERA-OROZCO**[3]

[1]Department of Electrical and Electronic Engineering, Universidad del Norte, Barranquilla 38118, Colombia
[2]Energy Department, Universidad de la Costa, Barranquilla 80001, Colombia
[3]Department of Electrical Engineering, Universidad Tecnológica de Pereira, Pereira 11001, Colombia

Corresponding author: Cesar Orozco-Henao (chenaoa@uninorte.edu.co)

This work was supported by Universidad del Norte and Departamento Administrativo de Ciencia, Tecnología e Innovación—COLCIENCIAS (currently Colombian Ministry of Science, Technology, and Innovation—Minciencias), by call contest "Convocatoria 852—Conectando conocimiento de 2019"—Project Integra2023 under Grant 111085271060 and Grant 80740-774-2020.

ABSTRACT Protection schemes are essential in active distribution networks and microgrids' reliable, efficient, and flexible operation. However, the protection of these networks presents significant challenges due to operational changes, such as variations in topology, distributed energy resources connection/disconnection, and microgrid operating modes, among others. This paper proposes an adaptive protection scheme based on overcurrent devices with several setting groups based on artificial intelligence algorithms. The developed strategy is composed of two stages. In the off-line stage, a clustering technique is employed to group the active distribution network operating scenarios exhibiting similarities. The optimal settings for the protection devices are determined for each set of scenarios. On the other hand, in the on-line stage, the protection strategy's implementation and operation, considering the active distribution network's existing communication system, are defined. Furthermore, the approach formulates the overcurrent relay coordination as a mixed-integer non-linear optimization problem, and as a result, the optimal setting of the overcurrent protection devices is obtained. It aims to minimize the operating time, considering the transformers' thermal limits, fuse operating curves, and overcurrent relay settings. The solution is determined by using an Augmented Lagrangian genetic algorithm. The presented protection scheme is validated on the modified IEEE 34 node test feeder, considering the main operating scenarios of the active distribution networks, such as topology changes, distributed energy resource connection/disconnection, and microgrid operating modes (on-grid and off-grid). The results obtained and its easy implementation indicates the high potential for real-life applications.

INDEX TERMS Active distribution networks, microgrids, overcurrent devices, clustering, protection coordination scheme.

NOMENCLATURE

Acronyms

ADN	Active Distribution Network.
ALGA	Augmented Lagrangian Genetic Algorithm.
DER	Distributed Energy Resource.
DG	Distributed Generation.
EI	Extremely Inverse.
IED	Intelligent Electronic Device.
MG	Microgrid.
MI	Moderately Inverse.
OC	Overcurrent.
PDN	Power Distribution Network.
SI	Standard Inverse.
VI	Very Inverse.

The associate editor coordinating the review of this manuscript and approving it for publication was Akshay Kumar Saha.

Sub−and Super − Indices

F	Fuse.
m	Fuse number.
max	Maximum.
min	Minimum.
n	Relay number.
p	Primary.
ps	population size.
R	Relay.
s	Backup.

Parameters

α, β	Relay operation curve constants.
$\Delta C(\%)$	Demand growth factor.
ϵ	Lagrange multiplier estimates.
ρ	positive penalty parameter.
CTI	Coordination Time Interval.
G	Generation.
If	Fault current.
k	Number of clustering groups.
K_F	Load growth factor.
M	Number of primary and backup relay-relay pairs.
N	Number of primary and backup fuse-relay pairs.
na	Project life cycle (years).
s	nonnegative shifts.

Variables

CO	Relay operation curve.
I_{PU}	Pickup current.
t	Operation time.
TF	Fuse type.
TMS	Time multiplier setting.

I. INTRODUCTION

A. MOTIVATION

High penetration of Distributed Energy Resources (DERs) in Power Distribution Networks (PDNs) leads to operational issues requiring control and automation infrastructure to integrate DERs and ensure stable, reliable, and efficient system operation [1], [2]. As a result, PDNs are being modernized into Active Distribution Networks (ADNs) [3], changing the system's characteristics, including power flow direction and short-circuit levels. These changes are caused by several ADN operating scenarios, such as variations in network topology due to control and automation schemes and bidirectional flows due to the integration of DERs. The new ADN operating scenarios that result from these changes impact the effectiveness of traditional Overcurrent (OC) protection schemes used to protect PDNs [4]. This requires the development of new protection schemes that consider in their formulation the critical operating scenarios of the ADN, such as topology changes, DER connection/disconnection, among others.

B. LITERATURE REVIEW

Several proposals in the literature have addressed the adaptive protection challenges when integrating DERs in PDNs. As noticed in [5], [6], and [7], communication systems are essential for implementing these strategies. Nonetheless, protection strategies have been proposed to reduce the reliance on communication systems using local measurements to identify the different PDN 's operating scenarios and adjust protection device settings, as described in [8]. However, this approach does not consider the occurrence of topology changes, MG integration and does not minimize the operation time of the OC protection devices. In [4], an OC protection system without communication is proposed, which uses local measurements to evaluate ADN state changes, such as topological changes, and Distributed Generation (DG) disconnection. However, this approach does not consider other OC devices, such as fuses and minimization of operating times in the coordination formulation. In addition, it does not consider the presence of Microgrids (MGs) and their operating modes. Several research papers have proposed protection schemes that use devices with multiple setting groups. The paper in [9] presents a centralized strategy that employs communication systems and adaptive protection with local measurements. This approach allows the system's protection to update the configuration of protection devices based on the DG operating condition. Nevertheless, the operation strategy modes are limited to the groups of settings allowed by the relays, which are estimated off-line and stored in the protection devices. Similarly to the above work, this approach does not consider other OC devices, such as fuses and minimization of operating times in the coordination formulation. A programmable logic-based approach for developing an adaptive protection strategy was suggested in [10], which considers coordination between OC relays and fuses. However, it does not address the impact of changes in network topology or the integration of inverter-based DG technology.

Research in references [11] and [12] focus on determining the optimal settings for OC relays based on connection/disconnection of DG but does not ensure relay coordination. These studies do not address the effect of ADN topological changes or the MGs operation modes, such as off-grid/on-grid. In [13], a mathematical model for coordinating protection devices in PDN that include DG and MG was proposed. The model uses a genetic algorithm to estimate the optimal settings for OC relays. Although this model addresses the MG operation modes and DERs integration, it does not consider the occurrence of topology changes by reconfiguration and DERs connection/disconnection. In [14] and [15], adaptive protection methodologies implementing centralized communication systems are presented, which consider essential aspects in the implementation, such as the connection of multiple DERs of different technologies and their connection and disconnection. However, these depend on a robust communication system to update the settings of the OC devices. In addition, these do not consider coordination with other protective devices, such as fuses. On the other hand, a strategy based on OC devices such as reclosers and fuses is proposed in [16] to face the problem of fuse saving in PDN when DERs are integrated. However, the strategy does not consider topological changes and MGs operation modes, such as off-grid/on-grid.

Other studies have formulated strategies incorporating mathematical optimization for the optimal configuration of OC protection devices and implementing OC relays with multiple setting groups. In [17], an adaptive OC protection approach using artificial intelligence techniques was presented. This scheme employs a communication system and multi-setting relays and accounts for changes in network topology and the increased short-circuit current caused by the integration of DG. Nevertheless, the method's effectiveness is acceptable when the amount of ADN operating scenarios is less than or equal to the number of setting groups of relays. Additionally, its formulation does not consider integrating different DG technologies, DG status, and using other OC devices such as fuses and reclosers.

In [18] and [19], the authors presented the implementing OC relays using operating curves within the optimization problem but do not account for coordination with other OC devices or clustering techniques for different operating scenarios. Similarly, reference [20] proposes the coordination of OC relays with multiple setting groups but disregards topology changes, MG operating modes, or the presence of other OC devices, such as fuses. Besides, strategies proposed in [21], [22], and [23] use clustering techniques and relay setting groups for determining optimal settings for protective devices. However, these only consider using OC relays and do not consider coordination with fuses or integrating MGs into the PDN. Other research, such as that presented in [24] and [25], proposes adaptive protection strategies using optimization techniques to determine the best setting parameters for the coordination of inverse-time OC relays. In addition, these consider devices with multiple setting groups for different operating scenarios. However, the strategy is not validated in PDN with the integration of MG, and the coordination with fuses and different operating curves of the relays is not included in the optimization process.

More recent research, as in [26], presents the optimal coordination of OC protections while considering the probability of several topologies changes. The optimization is performed for groups of specific topologies to determine the optimal setting for each cluster. Whereas in [27], an adaptive coordination strategy of relays is formulated based on OC devices considering the MG operation modes. For this purpose, each protection device is assigned two tripping modes for each operating characteristic using an optimization algorithm and selection of appropriate settings. Both investigations, [26] and [27], are based on directional OC relays with multiple setting groups considering DG connection/disconnection. However, these do not consider the integration of a MG nor the operation of the relays with other protective devices, such as fuses.

Table 1 summarizes state-of-the-art main works and the aspects considered, as described above. This Table highlights the remaining challenges in formulating protection strategies for ADNs and MGs, mainly when using conventional protection devices like OC relays and fuses.

The challenges outlined in Table 1 primarily revolve around assessing the main ADN operating conditions in the protection formulation, coordinating fuse operating curves, transformer thermal limits, OC relay setting parameters, and minimizing the dependence on the protection strategy formulation on the communication system.

C. CONTRIBUTION

The approaches proposed in the technical literature partially address the protection coordination problem. Table 1 shows a protection scheme that simultaneously considers all relevant aspects of ADN protection, such as its critical operating scenarios, the use of protection devices commonly used in distribution networks, such as fuses, and the optimization of operation times has yet to be proposed. In addition, most of the proposed methods use robust communication systems, and the performance of the protection system depends on their availability. This study addresses these challenges by proposing an adaptive protection strategy that uses OC devices with multiple setting groups and artificial intelligence techniques. The proposed strategy uses several setting groups for directional OC protection relays, which limits the number of clusters. The protection coordination problem is formulated as a mixed-integer non-linear optimization algorithm to minimize the operating time while considering the thermal limits of transformers, the operating curves of fuses, and the parameters of directional OC protection devices. An Augmented Lagrangian Genetic Algorithm (ALGA) is used to solve this problem.

The methodology is segmented into two stages. In the off-line stage, a clustering technique is employed to group similar ADN operating scenarios, and the settings for the protective devices are determined for each set of operating scenarios. On the other hand, in the on-line stage, the implementation and operation of the protection strategy, considering the existing communication system of the ADN, are defined.

The main contributions of this work towards the state-of-the-art are:

- Considering critical operating scenarios of the ADN in formulating adaptive protection strategies, such as changes in topology, DER connection/disconnection, and MG operation modes.
- Using directional OC relays and fuses, commonly used in conventional distribution networks, to formulate an adaptive protection strategy for ADN and MG.
- Modeling the coordination problem as a mixed-integer non-linear optimization algorithm, considering the

TABLE 1. Adaptive protection scheme: state of the art review.

Analyzed aspect	References																							
	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[14]	[15]	[16]	[17]	[18]	[19]	[20]	[21]	[22]	[23]	[24]	[25]	[26]	[27]	Proposal
ADN aspects considered																								
Unbalance	✓	✓	✓	x	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Topological changes (switch commutation)	✓	✓	✓	x	x	✓	x	x	x	✓	x	x	✓	✓	x	✓	✓	x	✓	✓	✓	✓	✓	✓
DER Technology (IIDER and INIDER)	✓	x	x	✓	✓	✓	x	x	x	✓	✓	x	x	x	✓	x	x	✓	x	✓	x	x	✓	✓
Several DER connected	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	x	✓	x	✓	x	✓	✓	✓	✓	x	✓	✓
DER status (On/Off)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	x	x	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
MG operation (connected/isolated)	✓	x	✓	✓	✓	✓	✓	x	x	x	✓	x	✓	✓	x	x	x	✓	✓	✓	✓	x	✓	✓
MG integration	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	✓
Communication system																								
Centralized	x	✓	✓	✓	x	✓	x	✓	✓	✓	✓	✓	✓	x	✓	✓	x	✓	✓	✓	✓	✓	x	✓
Decentralized	x	x	x	x	x	✓	✓	x	x	x	✓	x	x	✓	x	x	✓	✓	x	x	x	x	✓	✓
No communication	✓	x	x	x	✓	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	✓
Protection devices																								
Relays	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	x	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Fuses	x	✓	x	x	x	x	✓	x	x	x	x	✓	x	x	x	x	x	x	x	x	x	x	x	✓
Recloser	x	✓	x	x	x	x	x	x	x	x	x	✓	x	x	x	x	x	x	x	x	x	x	x	x
Optimal setting																								
TMS	x	x	x	x	x	x	x	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	x	✓	✓
Ipu	x	x	x	x	x	x	x	✓	✓	✓	✓	✓	✓	✓	✓	x	x	✓	✓	✓	x	✓	✓	✓
Relay operation curve	x	x	x	x	x	x	x	x	x	x	✓	x	x	✓	x	x	x	x	x	x	x	✓	x	✓
Thermal limits of transformers and lines	x	x	x	x	x	x	x	x	x	✓	x	x	x	x	✓	x	x	x	x	✓	x	x	✓	✓
Fuse operation curve	x	x	x	x	x	x	x	x	x	x	x	✓	x	x	x	x	x	x	x	x	x	x	x	✓
Multi-setting relays	x	x	x	x	x	✓	✓	x	✓	x	x	x	✓	✓	x	✓	✓	✓	✓	✓	✓	✓	✓	✓
Clustering of scenarios	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	✓	✓	✓	x	✓	✓	✓	✓

✓: aspects considered, x: aspects not considered

thermal limits of transformers, fuse operating curves, and the parameters of directional OC protection relays.

- Offering support and flexibility to the system protection without dependence on the communication type. In this way, it would be adapted to operate when there are critical failures in the communication system.

The remainder of this paper is organized as follows: Section II presents the formulation of the coordination of OC devices as an optimization problem. Section III describes the proposed adaptive protection strategy. Then, Section IV outlines the case studies and operating scenarios. Results and discussions are reported in Section V. Finally, the conclusions of this research are documented in Section VI.

II. FORMULATION OF THE OPTIMAL COORDINATION PROBLEM

The coordination scheme is approached as a mixed-integer non-linear optimization problem to guarantee a minimal OC operating time, maintaining relay coordination. The proposed objective function and constraints are presented in Sections II-A and II-B.

A. OBJECTIVE FUNCTION

The objective function was formulated based on the expression stated in [11]. However, the function was modified to ensure the minimization of the operating time of each pair of relays (primary - backup) and also to reduce the times of each pair of relays with the respective fuse that provides backup protection to the scheme as given in (1).

$$min \quad \sum_{i=1}^{M}\left(t_i^{R_p}+t_i^{R_s}\right)+\sum_{j=1}^{N}\left(t_j^{R_s}+t_j^{F}\right) \tag{1}$$

where M is the number of relay pairs that must be coordinated, meanwhile N represents the number of fuse-relay pairs that provide primary and backup protection, respectively. $t_i^{R_p}$ and $t_i^{R_s}$ are the operating times of the primary and backup relays when a fault occurs in the primary relay R_p 's zone. Likewise, $t_j^{R_s}$ and t_j^{F} are the operating times of the backup protection relay and the operating time of the primary protection fuse, when a fault takes place in the fuse's zone. The operating times t^{R_p} and t^{R_s} are estimated using (2).

$$t^R=\left(\frac{\beta}{\left(\frac{I_f^R}{I_{PU}^R}\right)^{\alpha}-1}+L\right)TMS^R \tag{2}$$

where TMS^R is the time multiplier setting that controls the characteristic curve of the relay R, I_f^R is the fault current of relay R when there is a fault in zone f, and I_{PU}^R is the pickup current of relay R. The proposed strategy employs the constants α, β, and L in the relay operating curve as discrete variables within the optimization problem. These constants are defined according to the IEEE C37.112 [28] and IEC 60255 [29] standards. t_j^F represents the operating time of the fuse when a fault occurs in its protection zone. It is estimated by employing the operating curves of type "K" fuses from the company *S&C electric company* [30], and a piecewise linear interpolation method [31].

For relays with adaptive OC function 50/51, it is possible to consider the instantaneous operating characteristic in the proposed formulation. This does not affect the coordination between OC relays and fuses since the instantaneous function is set to operate as primary protection and not as a backup for any other protection device, such as fuses.

B. CONSTRAINTS AND BOUNDS

Inequations from (3) to (10) define the constraints and bounds of the proposed protection coordination problem.

$$CTI - t_i^{R_s} + t_i^{R_p} \leq 0, i = 1, 2, 3, \ldots .M \quad (3)$$

$$CTI - t_j^{R_s} + 1.15\, t_j^F \leq 0, j = 1, 2, 3, \ldots .N \quad (4)$$

$$TMS_n^{min} \leq TMS_n \leq TMS_n^{max} \quad (5)$$

$$I_{PU_n}^{min} \leq I_{PU_n} \leq I_{PU_n}^{max} \quad (6)$$

$$t_{min}^R \leq t^R \leq t_{max}^R \quad (7)$$

$$1 \leq CO \leq 6 \quad (8)$$

$$TF_m^{min} \leq TF_m \leq TF_m^{max} \quad (9)$$

where constraint (3) ensures coordination between the pair of relays providing primary and backup protection, with Coordination Time Interval (CTI) being the safety time the backup relay must wait if the primary relay does not operate. According to the IEEE 242 standard, the CTI should equal or exceed 0.2 s [32]. Similarly, constraint (4) ensures coordination between relays and fuses. A factor of 1.15 must be considered in this constraint since the fuse operation time varies 15% due to the material melting depending on the operating conditions immediately before the fault occurrence [33]. On the other hand, (5) establishes the lower and upper limits of the multiple time setting *TMS* defined as TMS_n^{min} and TMS_n^{max}, respectively. The inequation (6) indicates the pickup current limits for each directional OC relay, being $I_{PU_n}^{min}$ and $I_{PU_n}^{max}$ the minimum and maximum pickup current of relay n, respectively. Similarly, (7) represents the operation time restriction for each directional OC relay, and (8) represents the constrain for the inverse-time OC relays' operating curves. In this case, a single curve is selected for all relays to avoid curve crossing and miscoordination. Finally, (9) represents the limits for the fuse types considered according to the operating conditions of each of the protection devices. The lower limit TF_m^{min} is the minimum selection current for fuse m. It is estimated by multiplying the fuse's rated current by the demand factor K_F represented in (10).

$$K_F = \left(1 + \frac{\triangle C(\%)}{100}\right)^{na} \quad (10)$$

where $\triangle C(\%)$ is the demand growth factor and na is the project life cycle in years [34]. The upper limit, TF_m^{max}, is defined as 25% of the minimum short-circuit current seen by the fuse, which is the current seen by the fuse during a single-phase fault located at the farthest end of its protection zone.

III. PROPOSED ADAPTIVE PROTECTION SCHEME BASED ON ARTIFICIAL INTELLIGENCE TECHNIQUES

The adaptive protection strategy proposed in this study comprises two stages, as illustrated in Fig. 1.

Off-line Stage I involves determining the optimal setting parameters for each setting group's directional OC relays using artificial intelligence techniques as detailed in Section III-A. On-line Stage II updates the setting group of the directional OC relays in real-time. This stage is described in Section III-B and outlines how the strategy can be implemented based on the ADN control and automation infrastructure.

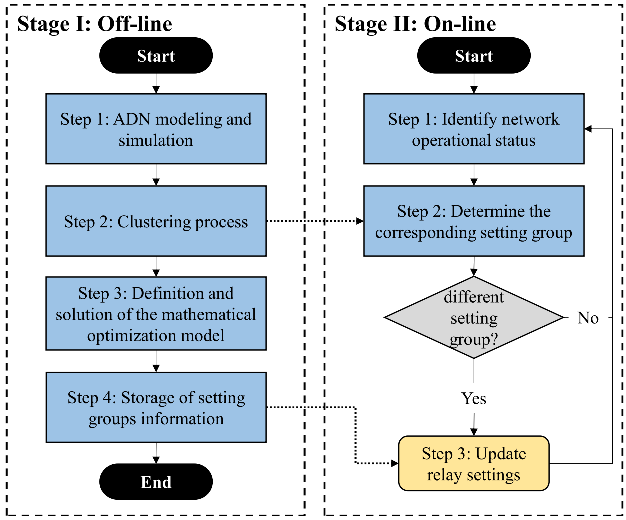

FIGURE 1. Flowchart of the proposed adaptive protection scheme.

A. OFF-LINE STAGE: DETERMINING THE OPTIMAL SETTING PARAMETERS FOR THE OC RELAYS

This stage aims to solve the optimal coordination problem presented in Section II while considering the optimal number of clusters of the operating conditions of the ADN clustered using a clustering technique. The protection system must estimate the ADN operating scenarios that impact it, specifically the operating normal and fault currents (step 1). Subsequently, the operating scenarios with similarities are clustered using a technique that implicitly minimizes the number of clusters needed to group the scenarios and, thus, the number of settings required for each relay (step 2). Once the optimal number of clusters is obtained, the optimal coordination problem, as presented in Section II, is solved for each group (step 3). Finally, the settings for each group and relay are stored for use in the on-line stage (step 4). These steps constitute the setting and coordination strategy for the off-line stage, as shown in the flowcharts of Fig. 1 and 2. Sections III-A1 to III-A4 provide a detailed explanation of each step.

1) STEP 1: ADN MODELING AND SIMULATION

The ADN is modeled and simulated in this step to analyze the system's power flow and short circuit conditions under different operating scenarios. These studies aim to gather information for configuring and coordinating protection devices. Therefore, for each ADN configuration, a load flow and short circuit study are performed to determine the rated, maximum, and minimum short circuit currents for each relay in each scenario, as shown in step 1 of Fig. 2.

FIGURE 2. Flowchart of off-line stage: determining the optimal setting parameters for the OC relays.

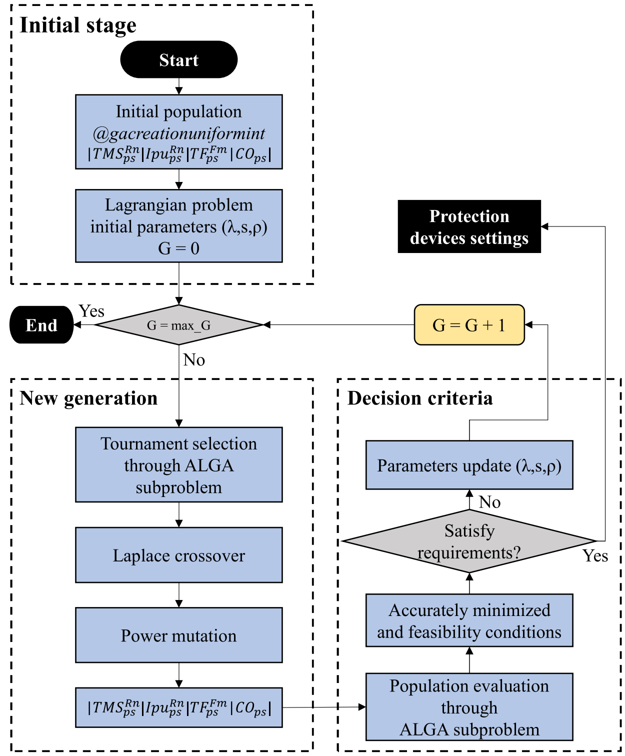

FIGURE 3. Flowchart of the genetic algorithm.

On the other hand, in [35], the authors present a study about clustering techniques performance for the coordination of adaptive OC protections by considering different combinations of features. From this study is determined that the maximum short-circuit currents for each relay are suitable to be used as features in clustering techniques. This research adopts this conclusion as shown in step 1 of Fig. 2.

2) STEP 2: CLUSTERING PROCESS

Once the ADN operating scenarios affecting the protection system have been estimated and characterized, the next step involves clustering the operating scenarios using an optimal clustering technique. Previous research work reported by the authors found that the k-means technique using the Manhattan distance yields satisfactory results for this task [35]. The optimal number of clusters (k) to group the scenarios is determined by the Silhouette Value evaluation metric [36], considering the limited number of setting groups available for each multi-setting relay. The Silhouette Value is estimated for all possible clusters, with k ranging from 2 to the maximum number of allowed settings per relay, as shown in Fig. 2. If a feasible problem solution cannot be found using the optimal value of k, the algorithm selects the next highest k with a higher Silhouette Value and repeats the process from step 2 until a feasible solution that satisfies all constraints is obtained.

3) STEP 3: FORMULATE AND SOLVE THE MATHEMATICAL OPTIMIZATION MODEL

The operating scenarios are assigned into clusters due to the grouping process. The mathematical optimization model described in Section II must be applied and solved for each of these groups. Since the coordination problem is formulated as a mixed-integer non-linear optimization algorithm, a meta-heuristic technique is employed to solve it due to the simplicity of representing these mathematical models through encoding [37], [38], [39]. In this research, an ALGA is implemented [40] as shown in Fig. 3, and its execution is based on the algorithm presented in [41].

ϵ is a nonnegative vector known as the Lagrange multiplier. s is a vector of nonnegative shifts and ρ is the positive penalty parameter. These values are defined by using the default initial penalty function. The genetic algorithm uses a series of approximate subproblems to find a solution to the original problem. When the accuracy and feasibility of a subproblem are sufficient, the algorithm updates its estimates. If not, it increases the penalty parameter and creates a new subproblem to minimize. This process is repeated until the stopping criteria are met [40].

4) STEP 4: STORAGE OF SETTING PARAMETER INFORMATION

After solving the mathematical optimization model in step 3, the setting groups parameters such as TMS, I_{PU}, CS for each relay, and fuses selected are stored. Additionally, the operating scenarios assigned to each group, determined in step 2, are stored for use in the on-line stage.

B. ON-LINE STAGE: ADN OPERATING SCENARIO IDENTIFICATION AND UPDATE OF RELAYS SETTING

In this stage, the ADN operating scenario is identified and compared with the scenarios clustered in step 2 to determine the group to which this operational condition belongs. Once the setting group is determined, it is compared with the current setting group held by the protection relays. If it is the same group, no action is taken. Otherwise, the relay setting parameters are updated to the parameters of the identified group for the current ADN operating state. This is summarized in the flowchart in Fig. 1. Nevertheless, the development of this process depends on the control and automation infrastructure of the ADN, mainly its communication system, which can be centralized, decentralized, or without communication, as detailed below.

1) CENTRALIZED COMMUNICATION SYSTEM

To identify the operating condition of the network using centralized communication schemes, a SCADA central control system [42] or another system based on the IEC 61850 protocol [43] or similar is required. These systems must constantly monitor the operating condition of the DG and the condition of interrupting and switching equipment to determine the operating scenario of the ADN. The communication system must allow access to the protection devices to change the preset setting groups when necessary [7]. Centralized communication systems are fast and reliable, but their implementation is expensive due to the need for a robust and redundant communication system to avoid communication failures. The main disadvantage of this architecture is that the protection system heavily depends on the availability of the communication system, even though the communication system is robust [6].

2) DECENTRALIZED COMMUNICATION SYSTEM

A decentralized architecture involves communication between adjacent substations or relays to exchange information about generation and component connection/ disconnection [21]. This process is performed from substation to substation to determine the system's operating condition and, in the same way, the protection devices settings are updated if the operating condition changes.

3) WITHOUT COMMUNICATION

The operation of protection schemes for ADN must not depend on the availability of the communication system. This implies that the protection devices must be able to detect faults within their protection zone with local information if the communication system is unavailable. The proposed protection scheme can be implemented without communication since directional OC relays with several setting groups were considered. However, the relay must be able to identify an operational change in the ADN with local information to change its setting group. In [44], the authors propose a data-driven topology detector for Intelligent Electronic Devices (IEDs) integrated into ADN. Each relay can use this strategy to determine the ADN operating condition with local information and whether to change its setting group. This solution is less reliable than the one previously presented since the protection scheme's performance depends on the accuracy of the topology detector. However, it can be used as a redundant system for a communication-based protection scheme to reduce its dependence on the availability of the communication system.

IV. STUDY CASE

The proposed protection scheme is validated on the modified IEEE 34 node test feeder, which is shown in Fig. 4. This system is located in Arizona and operates at a nominal voltage level of 24.9kV. The original test feeder is described in [45], and its parameters are presented. The system is composed of three-phase and single-phase lines, multiple laterals, non-homogeneous lines, and unbalanced loads and is modified by integrating five DERs: four DERs based on power electronics interfaces (photovoltaic systems) at nodes 812, 848, 854, 840 and one DER based on synchronous generators at node 834. In addition, four sectionalizing switches (SW1-SW3, SMR1) are included to perform different topology changes and the integration of a MG within the ADN.

On the other hand, twenty-four SIEMENS brand SIPROTEC 5 7SJ82 [46] directional OC relays with eight setting groups, and six fuses with S&C ELECTRIC COMPANY [30] specifications are taken into account in the proposed strategy. The fuse sizes considered are 6K, 8K, 10K, 12K, 15K, 20K, 25K, 30K, and 40K, labeled with integers from one to nine, respectively, for encoding within the optimization problem. The location of the protection devices is shown in Fig. 4. The criteria for the location of the protection devices are as follows:

- Directional OC relays: these are located at each end of the lines or set of lines that present bidirectional flows. Several lines can be grouped as a single-line section if they do not present bifurcations or are short lines.
- Fuses: these are located at the beginning of the laterals where no DER are connected, and their power flow is unidirectional.

Operating curve parameters α, β and L for directional OC relays are obtained from the standards IEEE C37.112 [28] and IEC 60255 [29] and are presented in Table 2. The limits of I_{PU} are determined according to [47], which states that the $I_{PU_n}^{min}$ should be selected as the relay I_{nom} multiplied by an overload factor that can be between 1.25 and 2.5 depending on the element to be protected. The $I_{PU_n}^{max}$ is estimated as one-third of the I_{cc}^{min}, where I_{cc}^{min} is the a double-phase fault current.

The maximum time limit depends on the equipment to be protected. A commonly used value is 4 s for line protection due to the thermal capacity of the conductors. However,

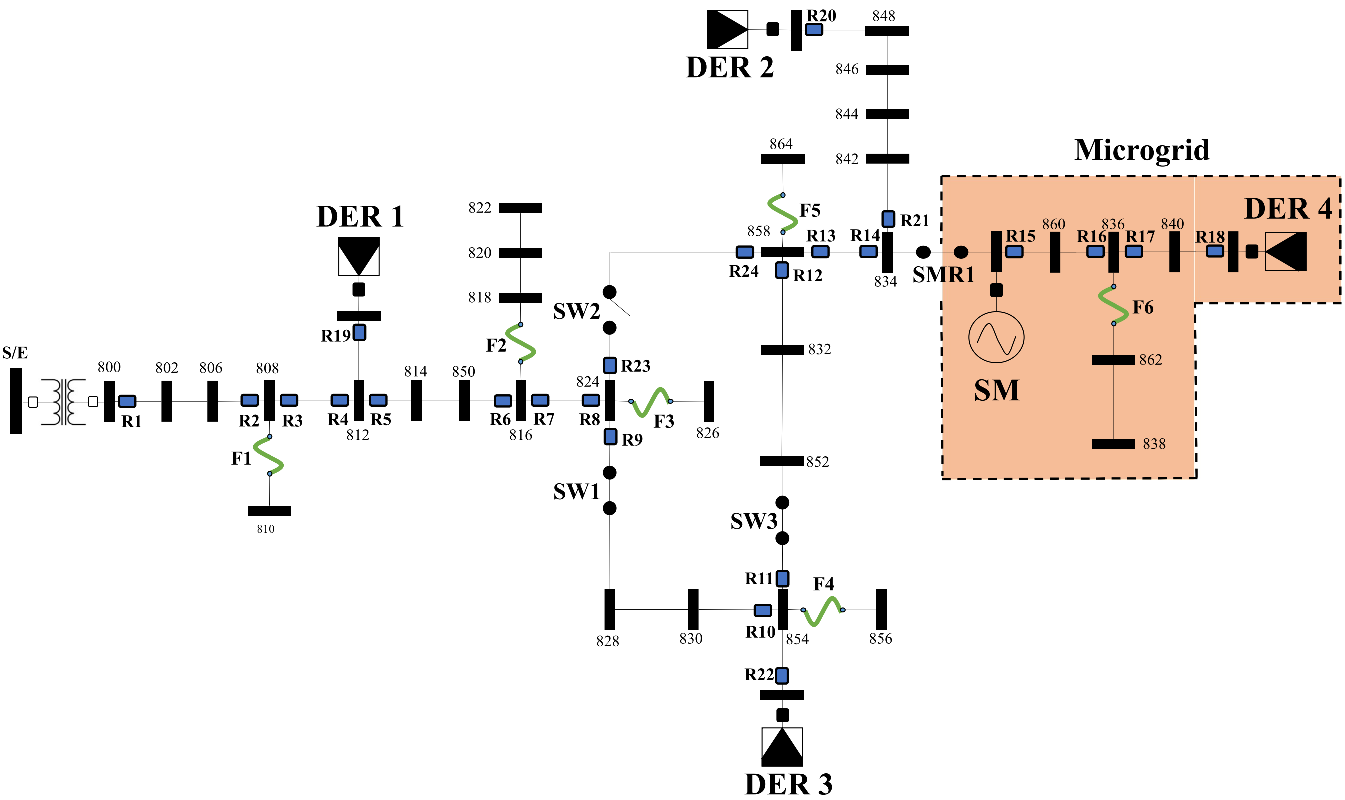

FIGURE 4. Modified IEEE 34 node test feeder and protection scheme implemented.

TABLE 2. Standard curve operation IEC 60255 and IEEE C37.112.

Standard	Curve	α	β	L	Label
	Standard Inverse (SI)	0.02	0.14	0	1
IEC	Very Inverse (VI)	1.0	13.5	0	2
	Extremely Inverse (EI)	2.0	80.0	0	3
	Moderately Inverse (MI)	0.02	0.0515	0.114	4
IEEE	Very Inverse (VI)	2.0	19.61	0.491	5
	Extremely Inverse (EI)	2.0	28.2	0.1217	6

TABLE 3. Design specifications of the protection system.

Design requirements	Value
Demand growth factor $\triangle C(\%)$	5%
Projected time of protection system	4 years
Overload factor for minimum current I_{min}	1.25
Minimum operation time of OC relays	2 cycles
Time Multiplier Setting (TMS)	0 a 2
Coordination Time Interval (CTI)	0.2s

if power transformers are upstream of it, the maximum operating time must be below the transformer's thermal capacity curve. A recommended value for this is 2 s [48]. The other design requirements for the protection system are presented in Table 3. These values will be the same for all operational scenarios.

A. OPERATIONAL SCENARIOS

ADN operating scenarios such as topology changes, DER connection/disconnection, and MG operating modes (on-grid and off-grid) are considered to demonstrate the robustness of the proposed protection approach. Topology changes are performed by opening/closing switches SW1, SW2, SW3, and SMR1. In total, studied ADN has six topologies. In addition, it has five DERs integrated, disconnected one at a time. Finally, the presence of a MG is also considered, and its on-grid/off-grid operation modes are evaluated by its connecting/disconnecting from the SMR1 switch. Table 4 summarizes the scenarios considered for the ADN under study, where "0" indicates that the component switch is open and "1" that the component switch is closed. The total number of operating conditions evaluated is 33. The number of simulated faults in the validation process is 2640; these faults are used to obtain the minimum and maximum currents of operating scenarios that will adjust the methodology. The currents are obtained by using the ATPDraw 7.2 software. Additionally, these faults were simulated for 33 operating scenarios and in 40 different locations of the study case.

On the other hand, cases during fault recovery are not included in the topology change scenarios. Nevertheless, these can be compared with the operation of the SW1, SW2, SW3, and SMR1 breakers after the occurrence of these events. After the occurrence of a fault, the system can be reconfigured by open/close switches to obtain a topology known by the protection system, even if the MG has been disconnected from the main network. However, the strategy developed is generally designed to include all cases or scenarios of the operability of the ADN studied. The N-1 analysis of

TABLE 4. Operational scenarios for studied ADN.

Scenario	DER1	DER2	DER3	DER4	SM	SW1	SW2	SW3	SMR1
1	1	1	1	1	1	1	0	1	1
2	0	1	1	1	1	1	0	1	1
3	1	0	1	1	1	1	0	1	1
4	1	1	0	1	1	1	0	1	1
5	1	1	1	0	1	1	0	1	1
6	1	1	1	1	0	1	0	1	1
7	1	1	1	1	1	1	1	0	1
8	0	1	1	1	1	1	1	0	1
9	1	0	1	1	1	1	1	0	1
10	1	1	0	1	1	1	1	0	1
11	1	1	1	0	1	1	1	0	1
12	1	1	1	1	0	1	1	0	1
13	1	1	1	1	1	0	1	1	1
14	0	1	1	1	1	0	1	1	1
15	1	0	1	1	1	0	1	1	1
16	1	1	0	1	1	0	1	1	1
17	1	1	1	0	1	0	1	1	1
18	1	1	1	1	0	0	1	1	1
19	1	1	1	1	1	1	0	1	0
20	0	1	1	1	1	1	0	1	0
21	1	0	1	1	1	1	0	1	0
22	1	1	0	1	1	1	0	1	0
23	1	1	1	0	1	1	0	1	0
24	1	1	1	1	1	1	1	0	0
25	0	1	1	1	1	1	1	0	0
26	1	0	1	1	1	1	1	0	0
27	1	1	0	1	1	1	1	0	0
28	1	1	1	0	1	1	1	0	0
29	1	1	1	1	1	0	1	1	0
30	0	1	1	1	1	0	1	1	0
31	1	0	1	1	1	0	1	1	0
32	1	1	0	1	1	0	1	1	0
33	1	1	1	0	1	0	1	1	0

line output should be carried out, and a study should be made of which scenarios are feasible, and these have to be included in the operational scenarios.

B. HARDWARE AND SOFTWARE SPECIFICATIONS

The developed protection strategy was implemented in Matlab 9.13.0.2049777 [49] software and was executed on a laptop computer with Intel Core i5- 8300H processor CPU@2.30GHz and 16 Gb of RAM memory. Load flows and short-circuit analysis of the modified IEEE 34-node test system exposed in Section IV are executed in the ATPDraw 7.2 software [50].

V. RESULTS AND DISCUSSION

Considering the scenarios exposed in Section IV-B, the proposed protection scheme is validated and compared to the conventional protection technique. Section V-A presents the application of stages shown in Fig. 2, and Section V-C presents a comparison with conventional protection strategy based on optimization.

A. PROPOSED ADAPTIVE OC PROTECTION STRATEGY IMPLEMENTATION

The application proposed scheme stages are presented in Fig. 2, and the results obtained are described below.

1) STEP 1: ADN MODELING AND SIMULATION

The modified IEEE 34-node test feeder is simulated in ATP-Draw. Power flow and short-circuit analysis are executed for operating scenarios of Table 4. Three-phase faults are simulated at the nearest end of their protection zone to gather information on the maximum short-circuit currents of each protection relay. This information is required for the clustering process and the coordination between the protection devices. On the other hand, the minimum short-circuit currents are determined by simulating two-phase faults at the farthest end of the protection zone of the devices, depending on whether they provide backup protection. This information and rated line currents obtained from load flow are used in the following steps.

2) STEP 2: CLUSTERING PROCESS

For the clustering of the operating scenarios, the maximum short-circuit currents observed by each relay are used, and silhouette value criteria estimate the optimum group's number. Table 5 presents the silhouette value for each group's number. Note that the maximum number of groups is eight since this is the number of setting groups that SIPROTEC 5 7SJ82 relays have [46]. The highest silhouette value is obtained for group number $k = 6$ as shown in Table 5.

TABLE 5. Silhoutte value metric for different values of k.

Valoration	0.864	0.824	0.806	0.759	0.608	0.607	0.472
k-value	6	7	5	8	4	3	2

TABLE 6. Clustering of operating scenarios.

Cluster	Scenarios					
1	1	2	3	4	5	6
2	13	14	15	16	17	18
3	19	20	21	22	23	
4	7	8	9	10	11	12
5	29	30	31	32	33	
6	24	25	26	27	28	

TABLE 7. Genetic algorithm fitting parameters.

Parameter	Value
PopulationSize	1000
MaxGenerations	Variables*150
CrossoverFraction	0.9
EliteCount	0.1*Population
Tolerance	1e-3

Once the optimal group number k is determined, the k-means clustering technique with Manhattan distance is applied. The results are shown in Table 6, showing how the 33 scenarios are distributed within the six groups.

As presented in Section III-A2, if any optimization model solutions of Section II is infeasible for the groups obtained by the clustering technique, the number of groups is increased to the next k with the highest silhouette value, which for this case is $k = 7$.

Note that k not only defines the number of settings each relay will have but also the number of control actions the ADN operator will execute for the 33 operating scenarios of the system under study. For example, as shown in Table 4 for the case study, all relays are set with the parameters of setting group N°1 to scenarios 1 to 6.

In conventional distribution systems, frequent network control is impossible because the automation and control infrastructure is insufficient for this purpose. However, the proposed approach aims at ADN with advanced distribution infrastructure. This infrastructure has intelligent electronic devices such as the numerical relay SIPROTEC 5 7SJ82 that can be controlled remotely from the control center to change their setting group.

3) STEP 3: SOLUTION TO THE OPTIMIZATION PROBLEM

Once the operating scenarios are clustered in the previous step, the coordination problem for each group is formulated by obtaining the optimization model presented in Section II. These models are solved using the ALGA presented in Section III-A3. Table 7 [51] presents the ALGA fitting parameters.

This technique successfully estimates a solution for each optimization problem without violating constraints. Table 8 presents the estimated setting parameters for each relay in

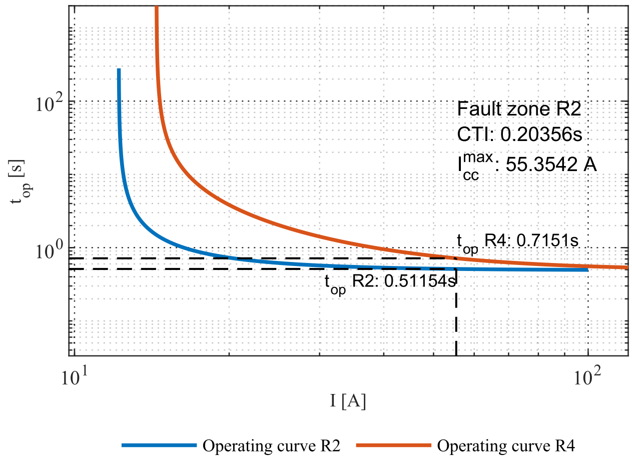

FIGURE 5. Coordination diagram of relays 2 and 4: Operating scenario 1.

each group, and Table 9 contains the fuse dimension for the adaptive protection scheme.

In addition, to verify that the determined settings satisfy the problem constraints, the coordination diagrams are analyzed for three situations. In the first situation, the coordination of the main grid relays is analyzed under operation scenario 1. Fig. 5 to Fig. 8 show the coordination diagrams of all pairs of primary and backup protection devices of the main grid belonging to operation scenario 1, which is part of setting group 1 according to Table 6. These figures show how the constraint (3) is satisfied between directional OC relays since the coordination time between them is higher than 0.2 s.

Additionally, regarding the coordination between relays and fuses, Fig. 9 shows the coordination diagram between fuse 1, which provides primary protection for the lines from node 808 to 810, and relays R1 and R4, which provide it backup protection. As in previous cases, these figures show how the constraint (3) is satisfied between directional OC relays and fuse F1 since the coordination time between them is higher than the CTI, being the difference between the operating time R4 and F1 of 0.634 s and between R1 and F1 of 1.219 s.

On the other hand, the second situation analyzes the coordination of primary and backup relays considering several ADN operating scenarios. Fig. 10 to 15 show the coordination diagrams for relays 15 and 17 for scenarios 6, 11, 16, 21, 25, and 29. These scenarios present different topologies, DER disconnection, and conditions 21, 25, and 29 have the MG disconnected. Relays R15 and R17 are located in the MG; therefore, the topological changes of the ADN and the operation of the MG in off-grid mode significantly affect the short circuit levels observed by these relays and, therefore, their operation.

The above coordination diagrams show no loss of coordination between relays R15 and R17 for the operation scenarios evaluated since the difference between their operating times is higher than 0.2 s. However, it is observed that for scenarios 6, 11, and 16, where the MG is connected to the

TABLE 8. Setting parameters of the overcurrent relays with several setting groups.

Relay	Cluster 1 Curve: IEEE VI		Cluster 2 Curve: IEEE VI		Cluster 3 Curve: IEC SI		Cluster 4 Curve: IEEE VI		Cluster 5 Curve: IEEE VI		Cluster 6 Curve: IEC SI	
	TMS	I_{PU} [A]	TMS	I_{PU} [A]	TMS	I_{PU} [A]	TMS	I_{PU} [A]	TMS	I_{PU} [A]	TMS	I_{PU} [A]
R1	1.056	101.196	1.171	91.510	1.041	62.918	1.289	86.168	1.302	88.324	1.018	57.303
R2	0.021	12.189	0.017	11.212	0.002	7.122	0.056	10.730	0.028	6.666	0.010	6.747
R3	1.097	78.267	1.317	71.960	1.093	35.083	1.065	78.672	0.887	82.377	0.963	33.512
R4	0.157	12.062	0.206	11.304	0.107	7.214	0.252	10.632	0.144	6.762	0.118	6.842
R5	0.931	71.060	1.063	67.126	0.852	40.221	1.178	62.279	0.939	64.601	0.729	37.701
R6	0.738	7.409	0.861	7.044	0.371	2.396	0.794	7.295	1.688	2.208	0.370	2.417
R7	1.051	57.308	1.201	53.149	0.699	33.340	1.275	50.758	1.073	49.368	0.622	26.553
R8	0.781	7.782	0.824	7.392	0.412	2.578	0.742	7.673	0.697	2.364	0.407	2.588
R9	1.216	45.040	1.345	0.000	0.632	21.943	0.911	2.226	0.680	0.000	0.283	2.216
R10	0.551	7.977	1.000	2.090	0.432	2.674	0.102	4.473	1.802	2.080	0.168	4.450
R11	0.839	43.353	0.295	2.900	0.346	28.978	1.421	0.000	0.381	2.856	1.051	0.000
R12	1.543	5.007	0.910	25.746	1.065	0.406	1.439	1.031	0.661	26.982	0.017	1.023
R13	0.702	36.181	0.950	40.208	0.201	21.767	0.760	45.109	0.736	32.000	0.224	20.613
R14	1.103	6.573	1.809	5.288	0.345	3.684	1.597	5.346	0.429	2.723	0.353	2.763
R15	0.588	30.595	0.953	31.544	0.495	10.098	0.838	32.736	0.399	9.801	0.501	10.058
R16	1.206	2.087	1.059	2.020	0.019	1.165	1.099	1.916	0.054	1.165	0.015	1.165
R17	0.374	12.041	0.844	7.759	0.023	4.646	0.063	10.219	0.176	2.600	0.012	3.591
R18	0.265	4.307	0.198	4.505	0.073	4.402	0.183	4.512	0.046	4.402	0.074	4.402
R19	0.109	4.639	0.108	4.604	0.298	4.610	0.101	4.606	0.104	4.584	0.259	4.586
R20	0.230	4.309	0.171	4.508	0.370	4.250	0.155	4.515	0.172	4.480	0.275	4.480
R21	0.042	24.314	0.105	31.123	0.014	32.514	0.101	36.952	0.105	23.020	0.017	24.509
R22	0.160	4.547	0.093	4.844	0.232	4.510	0.133	4.457	0.109	4.817	0.225	4.433
R23	0.786	0.000	1.224	42.803	0.889	0.000	1.200	44.083	0.968	39.243	0.439	20.395
R24	0.934	0.000	0.636	7.551	0.761	0.000	1.054	5.227	0.563	2.421	0.295	2.669

TABLE 9. Fuse for protection scheme.

	Fuse 1	Fuse 2	Fuse 3	Fuse 4	Fuse 5	Fuse 6
Type	12K	25K	6K	8K	8K	6K

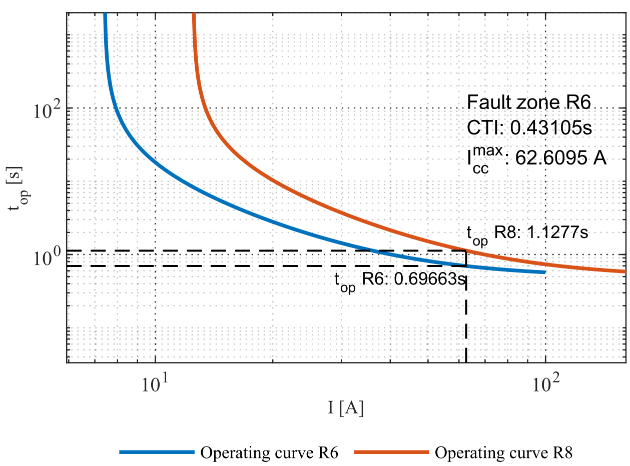

FIGURE 6. Coordination diagram of relays 6 and 8: Operating scenario 1.

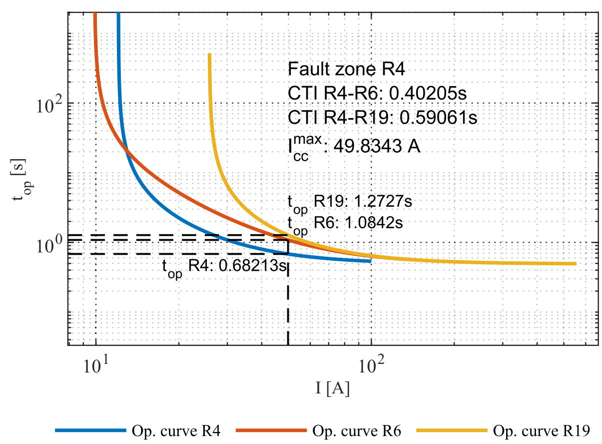

FIGURE 7. Coordination diagram of relays 4, 6 and 19: Operating scenario 1.

main grid, the relays operate in less time than for scenarios 21, 25, and 29, where the MG operates in isolated mode from the main grid. This behavior is expected since the short circuit levels are reduced in the MG when it operates in off-grid mode; then, the operating times of the directional OC relays increase.

Finally, the third situation analyzes the coordination between the devices protecting the MG when operating in off-grid mode. This case is analyzed because the short-circuit currents decrease significantly since the main grid has no short-circuit current contribution. This situation can lead to a loss of coordination between the protection devices. From Fig. 16 to 181, we show the coordination diagrams of relays 15, 16, 17, 18, and fuse 6.

As in the previous cases, it is verified that the operating time difference between the primary and backup pair of devices is higher than 0.2s for the maximum short-circuit current occurring in the primary protection zone. For relay pairs R16-R18 and R17-R15, the estimated CTIs are 0.24s and 1.574s, respectively, higher than the CTI specified in constraint (3). Likewise, it is also fulfilled for fuse-relay pairs F6-R15 and F6-R18, where the estimated CTI is 0.483s and 0.308s, respectively.

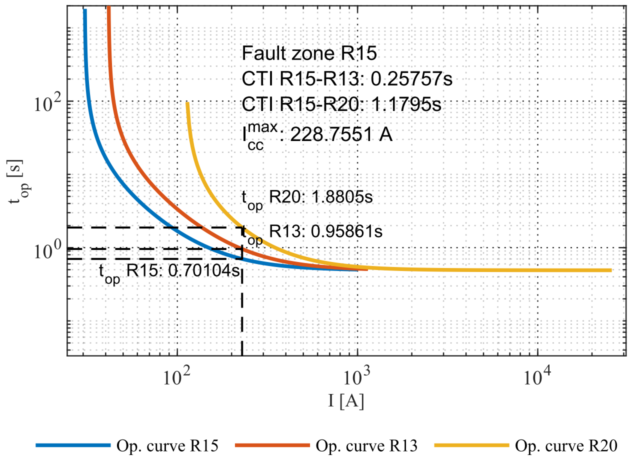

FIGURE 8. **Coordination diagram of relays 15, 13, and 20: Operating Scenario 1.**

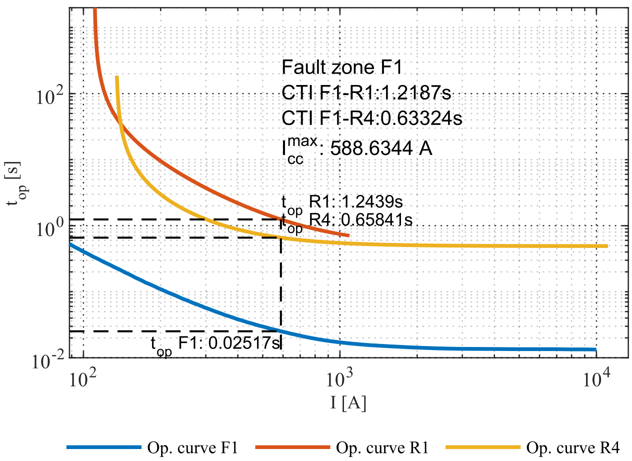

FIGURE 9. **Coordination diagram of fuse 1 with relays 1 and 4: Operating Scenario 1.**

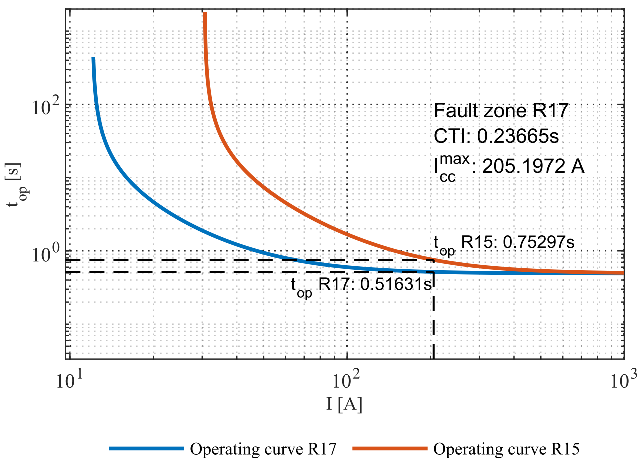

FIGURE 10. **Coordination diagram of relays 17 and 15: Operating Scenario 6 - Cluster 1.**

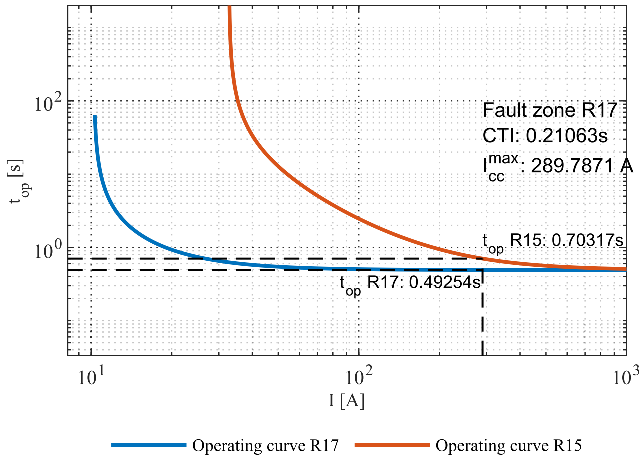

FIGURE 11. **Coordination diagram of relays 17 and 15: Operating Scenario 11 - Cluster 4.**

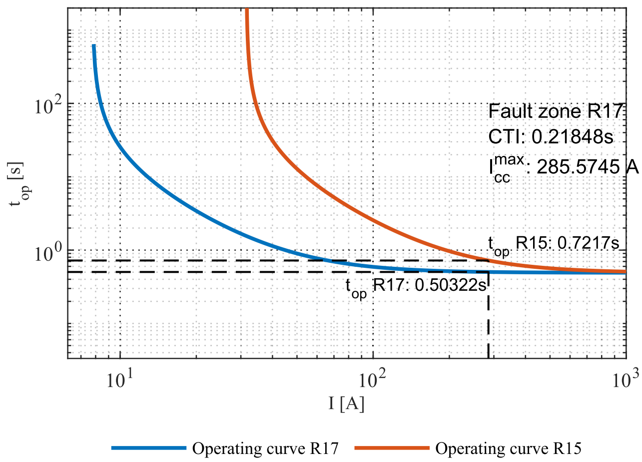

FIGURE 12. **Coordination diagram of relays 17 and 15: Operating Scenario 16 - Cluster 2.**

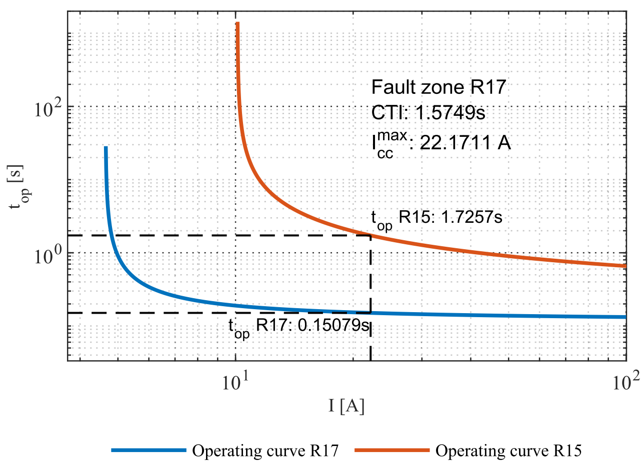

FIGURE 13. **Coordination diagram of relays 17 and 15: Operating Scenario 21 - Cluster 3.**

4) STEP 4: SETTING DATA STORAGE

The results stored by the proposed protection scheme for on-line operation are the operation scenarios for each group as shown in Table 6 and the estimated protection device settings for each group presented in Table 8.

Their on-line storage and operation depend on the architecture of the protection scheme. In an ADN with centralized automation and control architecture, the settings can be estimated each time the ADN configuration changes through

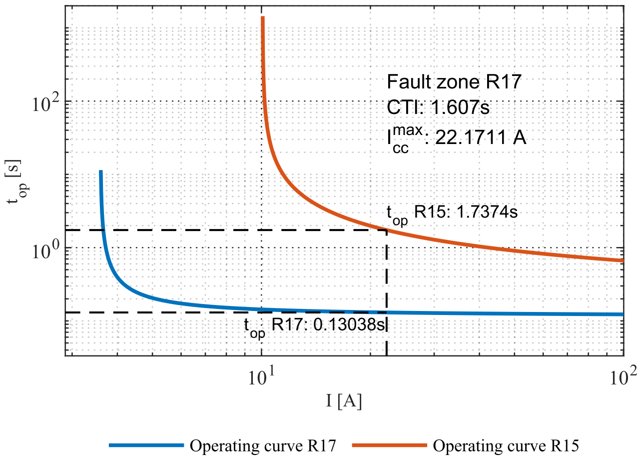

FIGURE 14. Coordination diagram of relays 17 and 15: Operating Scenario 25 - Cluster 6.

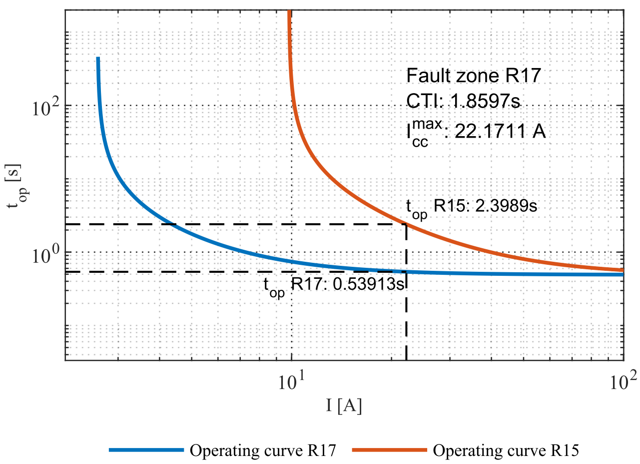

FIGURE 15. Coordination diagram of relays 17 and 15: Operating Scenario 29 - Cluster 5.

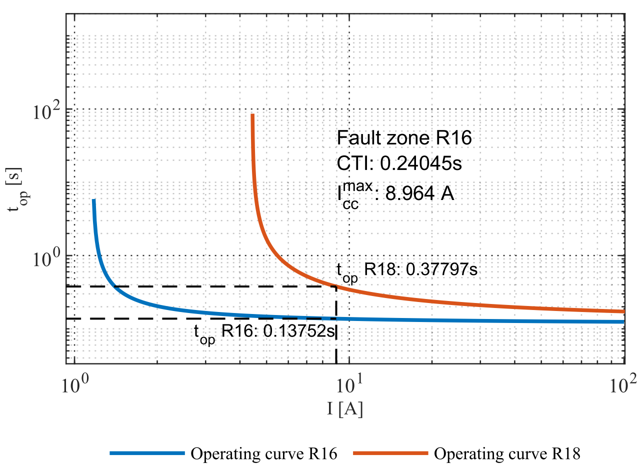

FIGURE 16. Coordination diagram of relays 16 and 18: Operating Scenario 19.

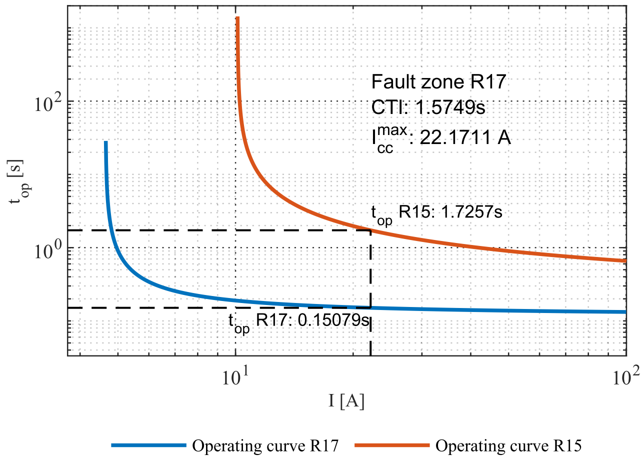

FIGURE 17. Coordination diagram of relays 17 and 15: Operating Scenario 19.

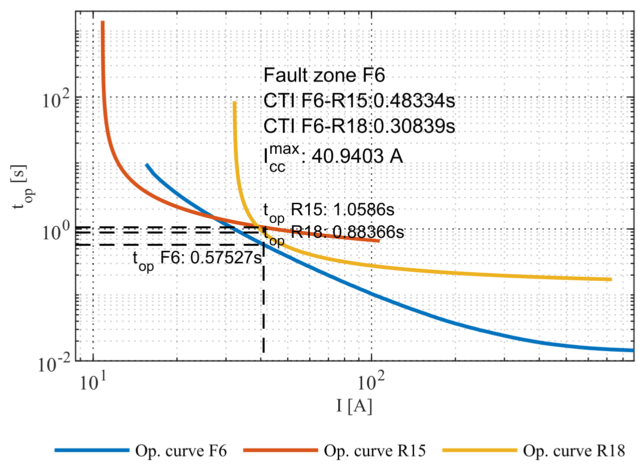

FIGURE 18. Coordination diagram of fuse 6 with relays 15 and 18: Operating Scenario 19.

the off-line stage proposed in Section III-A and update the settings of the protection devices through their communication system. Also, in any ADN configuration change for the operating scenarios considered by the setting groups, the control center will only send a signal to change the setting group to all relays since each relay will already have loaded its settings for each group.

On the other hand, for a decentralized automation and control architecture, the operating scenarios for each group shown in Table 6 and the estimated settings for each group presented in Table 8 are stored in each substation. Then, the automation and control architecture continuously monitors the system configuration and determines the operating scenario in real-time. This process can be slower than in a centralized architecture because each substation must use local information and query information from adjacent substations to determine if the system configuration has changed. Once the operating scenario is identified, it is compared to the scenarios listed in Table 6 to determine the setting group changed. If the setting group changes concerning the group in which the relays are set, a signal is sent from each substation control center to update the relay setting group.

Finally, if the automation and control architecture lacks communication or is not available when the system

TABLE 10. Setting parameters of the overcurrent relays 3 and 5 for cluster 1.

Relay	Cluster 1 Curve: IEEE VI	
	TMS	I_{PU} [A]
R3	1.097	78.267
R5	0.931	71.060

configuration changes, the operating scenarios for each group in Table 6 and the estimated settings for each group in Table 8 are stored in the relays if they allow it, or in external hardware with local connection to each relay. The relay or external hardware must have functionalities that determine the operating condition of the ADN with the local information recorded by the relays as presented in [44]. Once the operating scenario is determined, it is compared with the scenarios listed in Table 6 to determine the setting group to which the relay should be set; if the setting group changes concerning the current configuration, a setting group change signal is sent. Since this process is performed on each relay, the protection devices' performance depends on the strategy's performance for determining the ADN operating scenario.

B. PROTECTION SCHEME APPLICATION

To illustrate the operation and applicability of the developed strategy, in the case of a change in the ADN operating scenario, the IEEE 34-node test network described in Section IV and relays 3 (main relay) and 5 (backup relay) are taken as references. These two relays are used to describe the protection scheme application since these are affected by the presence of a DER connected at the connection point of relay 3. Under normal conditions or with traditional strategies, coordination may be lost between these relays. Initially, the network is supposed to operate under the operating state number 1 since all the DER are connected, and the switches SW1, SW3, and SMR1 are closed, as shown in Table 4. According to the results of the clustering process recorded in Table 10, the setting group is 1 for relays 3 and 5 configurations. These settings are those shown in Table 8 and extracted directly from the settings parameters in Table 8.

Under this network operation scenario, Fig. 19 shows the coordination diagram for relays 3 and 5. This figure shows that in the most critical scenario, where relay 3 senses the maximum current value, the coordination between these two relays is ensured by the CTI value. The difference between the relays' operating time is higher than 0.2 s, established as a CTI reference criterion.

Suppose a fault leads the system to perform a reconfiguration where DER 1 went out of operation. In that case, switch SW2 is closed and switches SW3 and SMR1 are opened, leaving the MG isolated (Operating scenario 25). It must be identified if it is necessary to change the relay settings; then, the network operating status, as indicated in Section V-A4, should be identified from the operating status of the DER and switches. The operating mode is identified, belonging to setting group 6, using the results of the clustering process in Table 6. Since the new setting group is different from the

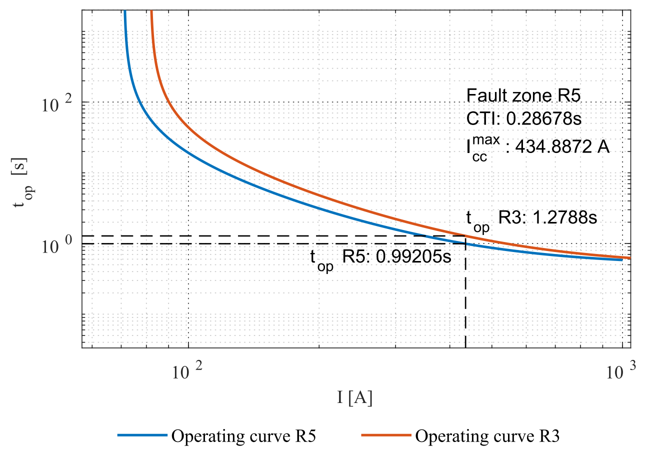

FIGURE 19. Coordination diagram of relays 5 and 3: Operating Scenario 1.

TABLE 11. Setting parameters of the overcurrent relays 3 and 5 for cluster 6.

Relay	Cluster 6 Curve: IEC SI	
	TMS	I_{PU} [A]
R3	0.963	33.512
R5	0.729	37.701

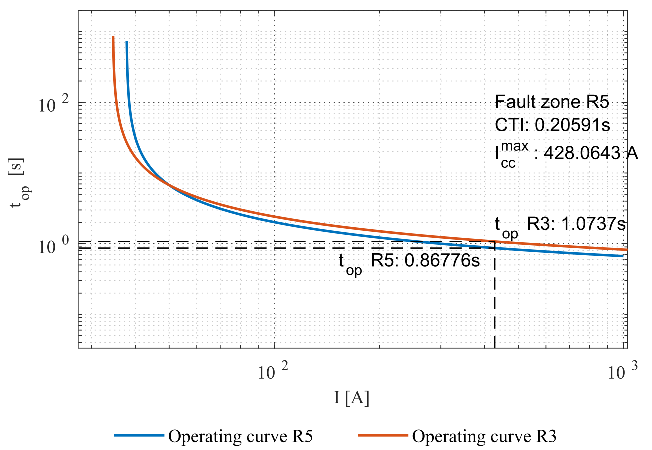

FIGURE 20. Coordination diagram of relays 5 and 3: Operating Scenario 25.

previous one (Group 1), the setting change signal must be sent to all the protection devices to operate correctly in case of any new fault in the system. Internally in the OC relays, each setting receives a binary activation signal, and only one can be activated at a time.

The settings corresponding to relays 3 and 5 for this group would be those shown in Table 11; the respective coordination curves for these devices are shown in Fig. 20, demonstrating their correct operation when complying with the CTI greater than 0.2 s in the primary protection zone of relay 3.

C. COMPARISON TEST

The proposed protection scheme is compared with conventional OC protection scheme based on optimization

TABLE 12. Operating time and violation results.

Repetition	$\sum t_{op}$ [s]	Violation
1	4096.3	191
2	4519.9	56
3	4846.2	42
4	4524.2	191
5	4764.2	54
6	4346.9	187
7	4367.8	189

TABLE 13. Sum of operating times of the overcurrent devices of each group.

Cluster	$\sum t_{op}$ [s]
1	546.5
2	484.6
3	260.6
4	499.4
5	378.3
6	225.8
Total	**2395.2**

techniques such as those proposed in [11], [12], and [17]. For this purpose, the protection problem is initially presented as an optimization problem, as described in Section II. The genetic algorithm presented in [23] solves the optimization problem, considering the 33 operational scenarios in a single group listed in Table 4. The method's performance is evaluated by the sum of operating times and the number of constraint violations, as shown in Table 12.

This Table summarizes the results obtained from seven iterations of the genetic algorithm. It can be seen that the optimization technique failed to find a feasible solution, as all of its generations violated constraints. The average sum of the operating times for the devices is 4495.1 s. This value is used as a reference for comparing the results obtained with the proposed protection technique.

Similarly, the proposed protection scheme is applied to the same operating scenarios evaluated in the conventional protection strategy. As the operating scenarios evaluated are the same as those used for applying the proposed scheme in Section V-A, the results obtained are the same as those presented in the previous section. The results obtained in the previous section show that the coordination problem is successfully solved, estimating the settings for each group without violating any constraint. Table 13 shows the sum of the operating times of all protective devices for each setting group. Also, the sum of all the relay operating times considering the setting groups equals 2395.2 s.

This time is significantly less than the total operating time obtained by the conventional protection scheme, approximately half. Moreover, no constraints are violated for the solution obtained with the proposed scheme, compared to the 42 constraints violated in the best solution obtained with the conventional strategy. This comparison allows quantifying the reduction of the proposed strategy's mean operating time compared to the conventional strategy. Also, the constraint violations could be seen as events that the conventional strategy is unable to cover and, consequently, these events will generate improper operation of protection devices that the proposed strategy does solve.

VI. CONCLUSION

This paper presents an adaptive protection scheme based on OC devices with several settings groups and artificial intelligence techniques. This scheme is composed of two stages. In the off-line stage, a clustering technique is used to group the ADN operating scenarios that exhibit similarities to each other, and the setting of the protection devices is determined for each set of operating scenarios by an ALGA. In the on-line stage, the implementation process of the proposed protection strategy and its operation according to the existing communication system in the ADN is defined.

The proposed protection scheme is validated on the modified IEEE 34 node test feeder, considering the main operating scenarios of the ADN, such as topology changes, DER connection/disconnection, and MG operating modes (on-grid and off-grid).

The results obtained for the case study show that the off-line stage successfully groups the 33 scenarios considered in the ADN operation into six groups, using the silhouette value criteria. It is also observed that the eight setting groups available in the relays are not used, showing an optimal number of groups in the clustering process.

In addition, the ALGA successfully estimates a solution for each optimization problem without violating the constraints. The coordination diagrams of the primary and backup protection device pairs verify this. The coordination times between relay-relay and relay-fuse pairs are determined at the maximum short-circuit current to verify compliance with the constraints of the coordination problem.

Finally, the proposed protection scheme is compared with a conventional OC protection scheme based on optimization techniques. The results show that the conventional protection scheme fails to obtain a solution for the proposed case study without violating at least 42 constraints of the coordination problem. In contrast, the proposed scheme determines a solution without violating any constraint. Moreover, the sum of the operating times for the solution estimated by the proposed scheme is approximately half of the sum of the operating times obtained with the conventional strategy.

REFERENCES

[1] British Petroleum. (2022). *BP Energy Outlook: 2022 Edition*. [Online]. Available: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2022.pdf

[2] Y. D. B. Ramirez, "Metodología de diseño conceptual de la automatización de red de distribución de energía que permita la integración de recursos energéticos distribuidos (der) e implementación de estrategias de gestión de demanda (DSM)," *Ingeniería Eléctrica*, to be published.

[3] C. D'Adamo, S. Jupe, and C. Abbey, "Global survey on planning and operation of active distribution networks–update of CIGRE C6.11 working group activities," in *Proc. IET Conf. Publications*, 2009, pp. 1–4.

[4] C. Liu, Z. Chen, and Z. Liu, "A communication-less overcurrent protection for distribution system with distributed generation integrated," in *Proc. 3rd IEEE Int. Symp. Power Electron. Distrib. Gener. Syst. (PEDG)*, Jun. 2012, pp. 140–147.

[5] S. M. Brahma and A. A. Girgis, "Development of adaptive protection scheme for distribution systems with high penetration of distributed generation," *IEEE Trans. Power Del.*, vol. 19, no. 1, pp. 56–63, Jan. 2004.

[6] F. Coffele, C. Booth, and A. Dysko, "An adaptive overcurrent protection scheme for distribution networks," *IEEE Trans. Power Del.*, vol. 30, no. 2, pp. 561–568, Apr. 2015.

[7] Y. Ates, A. Boynuegri, M. Uzunoglu, A. Nadar, R. Yumurtacı, O. Erdinc, N. Paterakis, and J. Catalão, "Adaptive protection scheme for a distribution system considering grid-connected and islanded modes of operation," *Energies*, vol. 9, no. 5, p. 378, May 2016.

[8] P. Mahat, Z. Chen, B. Bak-Jensen, and C. L. Bak, "A simple adaptive overcurrent protection of distribution systems with distributed generation," *IEEE Trans. Smart Grid*, vol. 2, no. 3, pp. 428–437, Sep. 2011.

[9] B. P. Bhattarai, B. Bak-Jensen, S. Chaudhary, and J. R. Pillai, "An adaptive overcurrent protection in smart distribution grid," in *Proc. IEEE Eindhoven PowerTech*, Jun. 2015, pp. 1–6.

[10] E. C. Piesciorovsky and N. N. Schulz, "Comparison of programmable logic and setting group methods for adaptive overcurrent protection in microgrids," *Electr. Power Syst. Res.*, vol. 151, pp. 273–282, Oct. 2017.

[11] V. A. Papaspiliotopoulos, G. N. Korres, and N. D. Hatziargyriou, "Protection coordination in modern distribution grids integrating optimization techniques with adaptive relay setting," in *Proc. IEEE Eindhoven PowerTech*, Jun. 2015, pp. 1–6.

[12] M. Y. Shih, C. A. C. Salazar, and A. C. Enríquez, "Adaptive directional overcurrent relay coordination using ant colony optimisation," *IET Gener., Transmiss. Distrib.*, vol. 9, no. 14, pp. 2040–2049, Nov. 2015.

[13] C. Reiz and J. B. Leite, "Optimal coordination of protection devices in distribution networks with distributed energy resources and microgrids," *IEEE Access*, vol. 10, pp. 99584–99594, 2022.

[14] A. Conde and M. Y. Shih, "An adaptive overcurrent coordination scheme withstanding active network operations," *IEEE Access*, vol. 10, pp. 104270–104284, 2022.

[15] A. H. El-Hamrawy, A. A. M. Ebrahiem, and A. I. Megahed, "Improved adaptive protection scheme based combined centralized/decentralized communications for power systems equipped with distributed generation," *IEEE Access*, vol. 10, pp. 97061–97074, 2022.

[16] M. Yousaf, A. Jalilian, K. M. Muttaqi, and D. Sutanto, "An adaptive overcurrent protection scheme for dual-setting directional recloser and fuse coordination in unbalanced distribution networks with distributed generation," *IEEE Trans. Ind. Appl.*, vol. 58, no. 2, pp. 1831–1842, Mar. 2022.

[17] N. El Naily, S. M. Saad, T. Hussein, and F. A. Mohamed, "Minimizing the impact of distributed generation of a weak distribution network with an artificial intelligence technique," *Appl. Sol. Energy*, vol. 53, no. 2, pp. 109–122, Apr. 2017.

[18] A. Ataee-Kachoee, H. Hashemi-Dezaki, and A. Ketabi, "Optimized adaptive protection coordination of microgrids by dual-setting directional overcurrent relays considering different topologies based on limited independent relays' setting groups," *Electr. Power Syst. Res.*, vol. 214, Jan. 2023, Art. no. 108879. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378779622009324

[19] M. N. Alam, "Adaptive protection coordination scheme using numerical directional overcurrent relays," *IEEE Trans. Ind. Informat.*, vol. 15, no. 1, pp. 64–73, Jan. 2019.

[20] A. Samadi and R. M. Chabanloo, "Adaptive coordination of overcurrent relays in active distribution networks based on independent change of relays' setting groups," *Int. J. Electr. Power Energy Syst.*, vol. 120, Sep. 2020, Art. no. 106026. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S014206151933532X

[21] M. Ojaghi and V. Mohammadi, "Use of clustering to reduce the number of different setting groups for adaptive coordination of overcurrent relays," *IEEE Trans. Power Del.*, vol. 33, no. 3, pp. 1204–1212, Jun. 2018.

[22] S. M. E. Ghadiri and K. Mazlumi, "Adaptive protection scheme for microgrids based on SOM clustering technique," *Appl. Soft Comput.*, vol. 88, Mar. 2020, Art. no. 106062. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1568494620300028

[23] S. D. Saldarriaga-Zuluaga, J. M. López-Lezama, and N. Muñoz-Galeano, "Optimal coordination of over-current relays in microgrids using unsupervised learning techniques," *Appl. Sci.*, vol. 11, no. 3, p. 1241, Jan. 2021. [Online]. Available: https://www.mdpi.com/2076-3417/11/3/1241

[24] P. Naveen and P. Jena, "Adaptive protection scheme for microgrid with multiple point of common couplings," *IEEE Syst. J.*, vol. 15, no. 4, pp. 5618–5629, Dec. 2021.

[25] M. Ghotbi-Maleki, R. M. Chabanloo, H. H. Zeineldin, and S. M. H. Miangafsheh, "Design of setting group-based overcurrent protection scheme for active distribution networks using MILP," *IEEE Trans. Smart Grid*, vol. 12, no. 2, pp. 1185–1193, Mar. 2021.

[26] E. Sorrentino and J. V. Rodríguez, "Optimal coordination of directional overcurrent protections considering the occurrence probability of different configurations and the effect of grouping cases," *Electr. Power Syst. Res.*, vol. 218, May 2023, Art. no. 109163. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378779623000524

[27] A. K. Soni, A. Kumar, R. K. Panda, A. Mohapatra, and S. N. Singh, "Adaptive coordination of relays in AC microgrid considering operational and topological changes," *IEEE Syst. J.*, early access, Dec. 19, 2022, doi: 10.1109/JSYST.2022.3227311.

[28] *IEEE Standard Inverse-Time Characteristic Equations for Overcurrent Relays*, Standard IEEE c37.112-1996, I. Power and E. Society, 1996.

[29] *Measuring Relays and Protection Equipement—Part 151: Functional Requirments for Over/Under Current Protection*, International Electrotechnical Commission (IEC), Geneva, Switzerland, 2008.

[30] SANDC. (1986). *Sc 'k' Speed Minimum Melting Time-Current Characteristic Curves*. Positrol Fuse Links. [Online]. Available: https://www.sandc.com/en/products–services/products/positrol-fuselinks/

[31] A. M. Bayen and T. Siauw, "Interpolation," in *An Introduction to MATLAB Programming and Numerical Methods for Engineers*, A. M. Bayen and T. Siauw, Eds. Boston, MA, USA: Academic, 2015, pp. 211–223. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780124202283000142

[32] *Protection and Coordination of Industrial and Commercial Power Systems*, Standard IEEE 242-2001, Institute of Electrical and Electronics Engineers, 2001.

[33] V. S. Madureira and T. C. Vieira, "Coordination of inverse-time overcurrent relays with fuses using genetic algorithm," in *Proc. Simposio Brasileiro de Sistemas Eletricos (SBSE)*, May 2018, pp. 1–6.

[34] G. D. Ferreira, "Cuaderno didáctico de subestaciones eléctricas y protecciones de sistemas eléctricos," Tech. Rep., 2012, pp. 1–123.

[35] A. B. Carlos, C. O. Henao, J. M. Quintero, J. M. Florez, and A. H. Orozco, "Clustering techniques performance for the coordination of adaptive overcurrent protections," in *Proc. IEEE ANDESCON*, Nov. 2022, pp. 1–6.

[36] H. Belyadi and A. Haghighat, "Unsupervised machine learning: Clustering algorithms," in *Machine Learning Guide for Oil and Gas Using Python*, H. Belyadi and A. Haghighat, Eds. London, U.K.: Gulf Professional Publishing, 2021, pp. 125–168. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780128219294000020

[37] M. N. Alam, "Overcurrent protection of AC microgrids using mixed characteristic curves of relays," *Comput. Electr. Eng.*, vol. 74, pp. 74–88, Mar. 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0045790618313181

[38] R. M. Chabanlooa, M. G. Maleki, S. M. M. Agah, and E. M. Habashi, "Comprehensive coordination of radial distribution network protection in the presence of synchronous distributed generation using fault current limiter," *Int. J. Elect. Power Energy Syst.*, vol. 99, pp. 214–224, Jul. 2018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0142061517314023

[39] A. E. Dahej, S. Esmaeili, and H. Hojabri, "Co-optimization of protection coordination and power quality in microgrids using unidirectional fault current limiters," *IEEE Trans. Smart Grid*, vol. 9, no. 5, pp. 5080–5091, Sep. 2018.

[40] MATLAB. (2022). *Nonlinear Constraint Solver Algorithms Augmented Lagrangian Genetic Algorithm*. [Online]. Available: https://la.mathworks.com/help/gads/description-of-the-nonlinear-constraint-solver.html

[41] MATLAB. (2019). *GA Find Minimum of Function Using Genetic Algorithm*. [Online]. Available: https://la.mathworks.com/help/gads/ga.html

[42] A. Almalawi, Z. Tari, A. Fahad, and X. Yi, *SCADA-Based Security Testbed*, 2021, pp. 25–62.

[43] M. Singh, T. Vishnuvardhan, and S. G. Srivani, "Adaptive protection coordination scheme for power networks under penetration of distributed energy resources," *IET Gener., Transmiss. Distrib.*, vol. 10, no. 15, pp. 3919–3929, Nov. 2016.

[44] J. Marin-Quintero, C. Orozco-Henao, and J. Mora-Florez, "Data-driven topology detector for self-healing strategies in active distribution networks," *Energy Rep.*, vol. 9, pp. 377–385, May 2023. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352484723000057

[45] (2001). *IEEE 34 Node Test Feeder*, Distribution System Analysis Subcommittee. [Online]. Available: https://site.ieee.org/pes-testfeeders/resources/
[46] S. AG. *Overcurrent and Feeder Protecion Siprotec 7SJ82*. [Online]. Available: https://cache.industry.siemens.com
[47] S. Horowitz and A. Phadke, *Power System Relaying*. Hoboken, NJ, USA: Wiley, 2008. [Online]. Available: https://books.google.com.br/books?id=4A3Kw3fgNusC
[48] N. A. E. R. Corporation. (2015). *Considerations for Power Plant and Transmission System Protection Coordination*. [Online]. Available: https://www.nerc.com/comm/PC/System%20Protection%20and%20Control%20Subcommittee%20SPCS%2020/SPCS%20Gen%20Prot%20Coordination%20Technical%20Reference%20Document.pdf
[49] *MATLAB Version 9.13.0.2049777 (R2022b)*, Mathworks, Inc., Natick, MA, USA, 2022.
[50] H. K. Hoidalen, *ATPDraw Windows Version 7.2*. Rueil-Malmaison, France: Schneider Electric, 2020.
[51] MATLAB. (2022). *Mixed Integer Ga Optimization*. [Online]. Available: https://la.mathworks.com/help/gads/mixed-integer-optimization.html

ADRIÁN BARRANCO-CARLOS received the B.S. degree in electrical engineering from Universidad del Norte, Barranquilla, Colombia, in 2020, where he is currently pursuing the M.Sc. degree in electrical engineering. His research interests include adaptive protections, smart grids, and the operation of microgrids.

CESAR OROZCO-HENAO received the B.S. and M.S. degrees in electrical engineering from Universidad Tecnológica de Pereira (UTP), Colombia, in 2010 and 2012, respectively, and the Ph.D. degree in electrical engineering from the Federal University of Rio Grande do Sul (UFRGS), Porto Alegre, Brazil, in 2016. He is currently a Professor with the Department of Electrical and Electronic Engineering, Universidad del Norte, Barranquilla, Colombia. His research interests include adaptive protection, fault location, power quality, and smart grids.

JUAN MARÍN-QUINTERO received the B.S. and M.S. degrees in electrical engineering from Universidad Tecnológica de Pereira (UTP), Pereira, Colombia, in 2010 and 2013, respectively, and the Ph.D. degree in electric and electronic engineering from Universidad del Norte, Barranquilla, Colombia. Currently, he is a full-time Professor with the Energy Department, Universidad de la Costa. His research interests include adaptive protection, machine learning in power systems, operation and control of active distribution networks, and microgrids.

JUAN MORA-FLÓREZ received the B.Sc. and M.Sc. degrees in electrical engineering from Universidad Industrial de Santander (UIS), Colombia, in 1996 and 2001, respectively, and the M.Sc. and Ph.D. degrees in information technologies from the University of Girona (UdG), Spain, in 2003 and 2006, respectively. He is an Associate Professor with the Electrical Engineering School, Universidad Tecnológica de Pereira (UTP). His research interests include power systems, protective relaying, and soft computing techniques. He is a member of ICE3.

ANDRES HERRERA-OROZCO received the B.Sc. and M.Sc. degrees in electrical engineering from Universidad Tecnológica de Pereira (UTP), Colombia, in 2010 and 2013, respectively, and the Ph.D. degree from Universida de Federal do Rio Grande do Sul (UFRGS), Brazil, in 2017. Currently, he is a Professor with the Electrical Engineering School, UTP. He is a member of ICE3-UTP and CAFE-UTP Research Groups. His research interests include smart electrical grids, microgrid protection, power quality, fault analysis, and power system operation.