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Optimization of Impedance Relay Placement in Medium-Voltage Electrical Distribution Systems through Clustering Algorithms and Metaheuristics

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Abstract: This study explores the feasibility of using impedance relays in electrical distribution systems, a context where their application is not as common as in transmission systems. Given the dynamic nature and complex topology of medium-voltage distribution systems, this work proposes an innovative methodology integrating clustering algorithms and metaheuristic techniques to optimize the placement of impedance relays and enhance system reliability and resilience. Using CYME simulation and the Ant Colony Optimization (ACO) method, case studies were designed to validate the effectiveness of the proposed methodology. The results demonstrated that strategic placement of impedance relays reduces failure frequency and significantly improves the system's response to such failures. This approach allows for a more efficient configuration and quicker response, which is crucial for maintaining continuity and quality of power supply. A detailed analysis of system behavior under various fault scenarios illustrates the robustness and adaptability of the proposed solution, marking a significant advancement in the protection and optimization of electrical distribution systems.

Keywords: impedance relays; distribution systems; clustering; metaheuristic optimization; reliability; electrical protection

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1. Introduction

Electrical distribution systems constitute critical components of the electric service infrastructure, required to adhere to stringent quality and reliability standards to ensure continuous and safe power delivery to end-users [1]. Despite these standards, distribution systems remain susceptible to numerous natural failures and other incidents, such as the suboptimal placement of electrical equipment and the integration of renewable energy sources. The incorporation of renewable energy often introduces new challenges, particularly in protection schemes, as the fault current characteristics of renewable generation equipment differ significantly from traditional sources, potentially leading to protection malfunctions [2–4].

The effective planning and optimization of distribution systems are essential to mitigate these issues, aiming to prevent failures such as voltage drops, reduce network losses, and enhance overall system efficiency [5,6]. Various optimization methods and algorithms meet these objectives, minimizing energy and economic losses while optimizing system performance [7]. These methods are designed to reduce energy losses, lower investment costs, manage voltage levels, and determine the optimal placement of equipment [8–10].

Recent studies have proposed advanced multi-agent and multi-objective clustering methods to address the complexities of distribution system optimization, taking into account factors such as load growth over time [9,11,12]. Techniques such as K-means clustering [13] and particle swarm optimization combined with genetic algorithms have shown promise in enhancing system sensitivity and reliability [2,14]. These optimization strategies contribute to the development of intelligent tools for fault location and isolation, which are crucial for minimizing energy losses, reducing operating costs, and improving voltage profiles and the overall safety of distribution networks [12,14].

The use of impedance relays in electrical distribution systems, traditionally more common in transmission systems, offers a novel perspective for protection coordination studies [2]. Impedance relays monitor the system voltage and current, comparing these values against preset thresholds. When deviations are detected, the relay triggers corrective actions, such as opening a circuit breaker, to mitigate further damage [15,16]. These relays are crucial in maintaining system integrity during faults, ensuring that the network can withstand overvoltage, undervoltage, and short-circuit conditions, and maintaining an optimal power factor [17]. This research explores the potential of using impedance relays in distribution networks to enhance fault detection and isolation. Impedance relays feature three well-defined protection zones, which can be optimized using inverse K-medoids clustering to determine ideal relay positions. Following this, a directed graph is constructed with the Ant Colony Optimization (ACO) algorithm, and the optimal Minimum Spanning Tree is established to design the distribution network system. Ensuring correct operation involves verifying that end nodes meet voltage drop and technical loss principles. Generated faults and impedance relay responses are examined, necessitating symmetrical impedance in the system for accurate relay function. Variations in impedance can lead to operational errors, as detailed in the conclusions and case studies. This methodology underscores the potential of impedance relays to significantly improve fault detection efficiency and system reliability in distribution networks. Additionally, modern distribution networks' increasing complexity and dynamic nature, the need for more precise and rapid fault detection and isolation to maintain system stability, and the potential for integrating renewable energy sources present unique challenges in protection coordination. The enhanced focus on optimizing protection strategies in distribution systems aims to address these evolving requirements and improve overall system reliability and efficiency.

This study focuses on optimizing the placement of impedance relays within a distribution system. The objective of employing advanced optimization algorithms and clustering techniques is to identify the most effective relay locations to serve as primary protection devices. The methodology leverages the K-means clustering algorithm to delineate protection zones for impedance relays, ensuring enhanced system reliability and quality [15].

Using CYME simulation software (Version 9.0), a georeferenced medium-voltage distribution system was designed to validate the proposed methodology. Through various case studies, the performance of impedance relays was tested, employing clustering methods to determine the optimal number and placement of relays. This approach not only identifies the operational zones of impedance relays but also demonstrates the robustness and adaptability of the proposed solution in real-world scenarios. Figure 1 shows an overview of the proposed methodology, while Table 1 lists the nomenclature used in this study.

Table 1. Nomenclature and description of terms used in the study.

Nomenclature	Description	Nomenclature	Description
$LLL(S)$	Three-phase single fault	$LLL(Si)$	Simultaneous three-phase fault
$LLL(In)$	Interconnection three-phase fault	$LLLT(S)$	Three-phase single-earth fault
$LLLT(In)$	Interconnected three-phase ground fault	$LLLT(Si)$	Simultaneous three-phase to ground fault
$LL(S)$	Single two-phase fault	$LL(In)$	Two-phase interconnection fault
$LL(Si)$	Simultaneous two-phase fault	$LLT(S)$	Two-phase single-earth fault
$LLT(In)$	Two-phase to ground interconnection fault	$LLT(Si)$	Simultaneous two-phase to ground fault
X	Abscissa	Y	Ordinate
$Distance$	Manhattan distance	j	Imaginary unit
Vln	Phase neutral voltage	S/E	Substation
n	Nodes	GIS	Georeferenced system

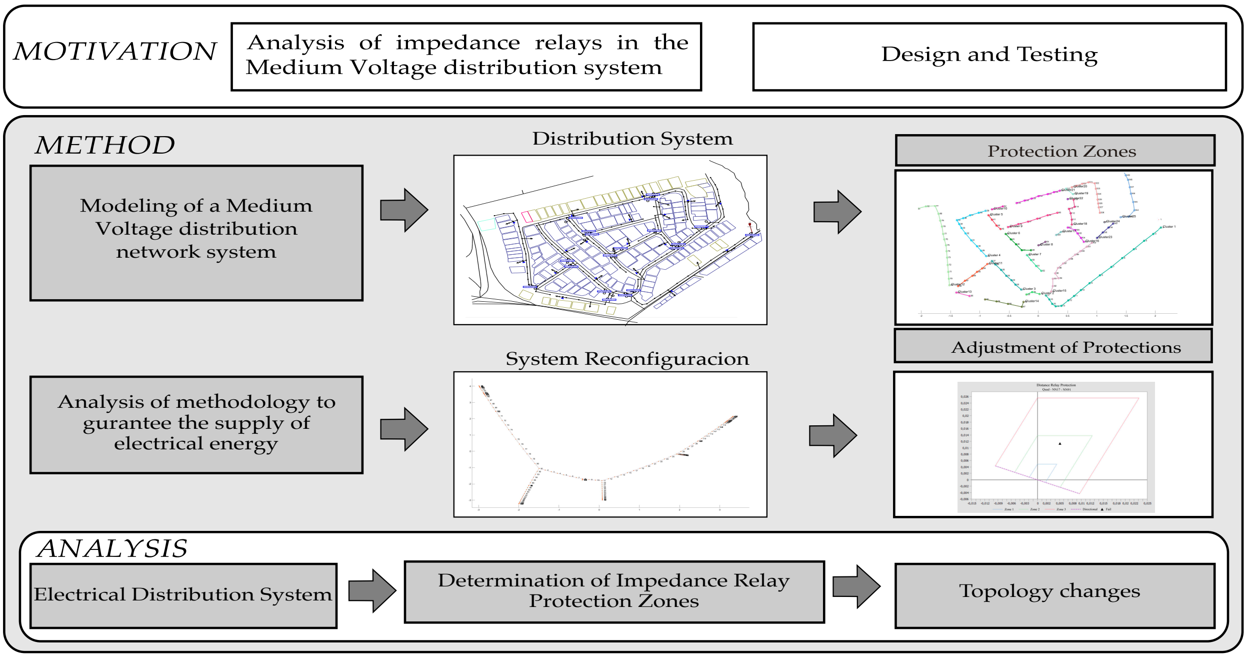


Figure 1. Illustration of the proposed methodology.

2. Related Works

Various methods exist to determine optimal locations for network components to enhance reliability, mitigate voltage sags, and ensure continuous service to customers [1]. Incorrect placement of transformer stations can lead to numerous problems, including increased losses and voltage drops. The K-medoids method optimizes transformer locations, while the Multi-Objective Optimization Problem (MOOP) method addresses environmental gas emissions by optimally placing renewable generation plants [3]. The referenced study presents a novel approach for the distributed planning of renewable energy-distributed generators in active distribution networks and microgrids, starting with the creation of an electrical distance matrix (EDM) for the distribution system. This EDM is used to solve a maximization problem for optimal network clustering. Agents are then assigned to each cluster, and a MOOP is formulated for the optimal planning of renewable energy power plants, with objectives including annual energy losses and voltage improvement. The study's results show that this approach reduces losses and enhances the voltage profile in each cluster. The IEEE 37-node test feeder and two test cases demonstrate that this method improves energy efficiency and voltage stability, validating the effectiveness of the K-medoids and MOOP methods in optimizing renewable generation plant placement and overall system performance.

The placement of charging stations for electric vehicles also significantly impacts the grid. Poorly located charging stations can harm the grid's stability and efficiency. Modifying the Shuffled Frog Leaping Teaching–Learning-Based Optimization (SFL-TLBO) technique has been suggested to improve the placement of these stations [11]. Current distribution systems face substantial energy losses that utility companies must manage.

Distributed Generation (DG), such as small-scale power plants, can help address these losses when operated strategically [18]. However, incorrect installation can exacerbate the problem, leading to increased losses and voltage drops. The improved Particle Swarm Optimization (PSO) method has been proposed to optimize the installation and operation of DG units, enhancing system performance [14,19]. Furthermore, identifying critical points in the network through the Newton–Raphson method can improve the quality and safety of distribution systems by analyzing power flow and pinpointing areas of concern [20].

Energy storage systems are crucial in improving bus voltages and reducing operational costs. Proper placement of battery systems using the SFL method ensures timely restoration during power system failures [12]. Smart grids, which facilitate instantaneous recovery of energy supply, are recommended for their efficiency, particularly in managing the increasing loads from electric vehicles. The ACO method has been effectively used to locate DG units within the IEEE 33-bus system, demonstrating significant improvements in network performance [19,21]. The integration of batteries is particularly beneficial due to their efficiency and cost-effectiveness in handling the increased loads from electric vehicles [22].

The K-medoids method, known for its advantages in clustering energy inputs, offers a viable solution for optimizing the placement of DG units [13]. However, the sensitivity of the K-medoids algorithm to initial values significantly impacts its convergence and clustering quality. If initial medoids are poorly distributed or do not represent the data structure well, the algorithm may converge to suboptimal solutions. Like K-means, K-medoids can also settle in local minima, leading to inconsistent results across different initializations. Strategies such as multiple random initializations, intelligent initialization methods like K-medoids++ and Partitioning Around Medoids (PAM), metaheuristic optimization techniques, and cross-validation can mitigate this. These approaches enhance the likelihood of finding a globally optimal solution and ensure robust, high-quality clustering outcomes.

Combined with the Whale Optimization Algorithm (WOA), this method enhances distribution network performance by improving DG unit placement [23]. However, these techniques often fail to account for short distances and specific network configurations. The criterion of electrical configuration, discussed in [17], emphasizes the importance of considering the characteristics of maneuvering or control equipment and the sections they protect. Sections in distribution networks originate from a common point and branch out to other sections. Therefore, combining methods can effectively identify general points and divide sections with similar electrical configurations for optimal protection by relays.

Table 2 provides an extract of the state-of-the-art matrix, showcasing the most relevant manuscripts, optimization methods, research processes, and parameters. This comprehensive review highlights the various methodologies and their strengths and weaknesses, providing a foundation for further research and development in optimizing electrical distribution network systems.

Table 2. Summary of state-of-the-art articles on optimal allocation and reconfiguration in power distribution systems.

		Parameters Considered				**Topic**			
Author, Year	**Objectives**	**Clustering Techniques**	**Clustering Algorithm**	**Voltage**	**Graph Algorithm**	**Clustering**	**Georeferenced System**	**Electrical Network Software**	**Distribution System**
Ruiaz, 2019 [1]	Optimal allocation of transformers	-	✠	✠	✠	✠	✠	✠	-
Karaaom, 2020 [20]	Optimal distribution network Reconfiguration	-	✠	✠	-	✠	-	-	-
Zenhom, 2019 [17]	Optimal allocation of distributed generation	-	✠	✠	-	-	-	✠	✠
de Carvalho, 2018 [24]	Optimal allocation using Ant Colony Optimization	✠	✠	✠	✠	✠	✠	✠	-
Mehmood, 2018 [3]	A multi-agent clustering-based approach	-	✠	✠	✠	✠	-	✠	-
Battapothula, 2019 [5]	Multi-objective optimal planning of FCSs and DGs	✠	-	✠	-	✠	✠	-	-
Mirhoseini, 2020 [25]	Economic battery sizing and power dispatch	-	-	✠	✠	-	-	✠	✠
Present work	Analysis of impedance relays	✠	✠	✠	✠	✠	✠	✠	✠

3. Problem Formulation and Methodology

This study addresses the application of impedance relays in electrical distribution network systems, utilizing the CYME software to simulate relay operations. Impedance relays are traditionally used in transmission lines because they create instantaneous protection zones and timers for rapid fault detection and clearing. Given that the highest frequency of fault occurrences within an electrical system typically occurs at the distribution level, this research proposes using impedance relays in distribution systems to enhance fault detection and clearing effectiveness. By incorporating impedance relays into distribution networks, it is expected that the speed and accuracy of fault isolation can be significantly improved, minimizing system disruptions and enabling quicker restoration of normal operations.

The goal is to strategically place impedance relays within the network to separate subsystems and provide reliable protection effectively, following the logic sequenced in Figure 2.

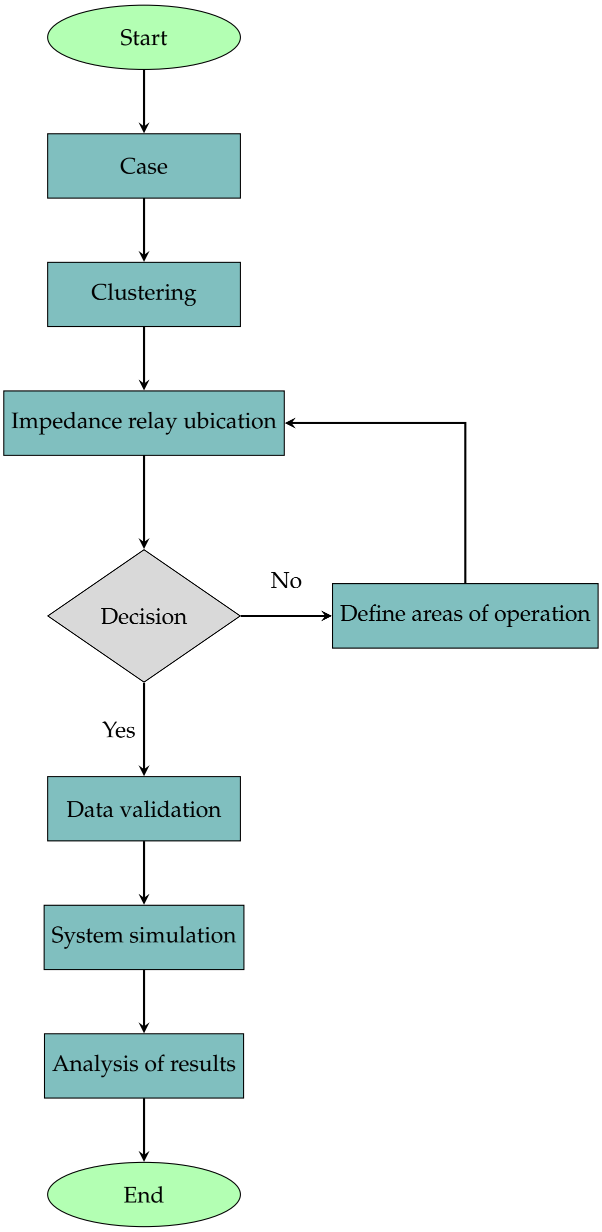


Figure 2. Flowchart describing the sequence of steps for the proposed methodology.

The initial step involved identifying the number of connections at each node, as outlined in Expression (1). The system topology, critical for implementing the Ant Colony

Optimization (ACO) metaheuristic method, was analyzed to ensure robust routing and enhanced fault tolerance. This approach guaranteed improved organization of the electrical distribution network and faster response times. Various methods for determining relay placement include K-means, K-medoids, MOOP, SFL, and Newton–Raphson. Impedance relays operate directionally, protecting their location at a predefined endpoint. The complexity of their operation arises from varying system conditions, changes in topology, and the presence of subsystems with single-phase and three-phase configurations. Nodes downstream of the impedance relay cluster may remain unprotected due to the relay's directional nature. To address this, a proposed algorithm identified optimal relay locations, separated subsystems based on phase configurations, and grouped nodes according to load flow direction. Equation (2) standardizes scalability from 0 to 1 based on distance.

$$\sum_{n=1}^{N} n \geq 2 \tag{1}$$

$$Z_i = \frac{x_i - \bar{X}}{\sigma} \tag{2}$$

In the equations above, x_i represents the coordinate data of the node from n_i to n_j. Z_i is the scaled data. In the context of a radial topology distribution network, node j is defined as the node contiguous to node i. This sequential relationship is established by incrementing the index of node i by one, i.e., $j = i + 1$. This approach ensured logical progression in the network's topology. Determining the minimum input data required for the electrical distribution network system was necessary to establish the node distances, as shown in Equation (3).

$$|A - B| = \sum_{j=1}^{p} |a_{1j} - b_{2j}| \tag{3}$$

The methodology, while effective, presented specific challenges. Impedance relays are dispersed throughout the electrical distribution network system, requiring a robust routing solution. The Depth-First Search (DFS) algorithm addressed this by routing from an initial node n_i to an end node n_j, ensuring convergence and optimal routing in subsequent iterations. This process guaranteed the identification of trunk branches in secondary branches.

The optimal placement of impedance relays considers the length between nodes, allowing for clustering in operational zones using the K-medoids technique. This technique found the best inter-cluster distances, and an algorithm was implemented to divide the zones of impedance relay operation. A startup node n_i was fixed for the distribution of actuation zones.

Figure 3 shows the topology of the distribution network system taken as a reference in the study. This urban electrical network includes a structure of 150 nodes, nineteen three-phase transformers, and five single-phase transformers connected across different phases with varying power capacities with the details shown in Table 3. An installed capacity of 30 MVA is expected at the substation. Case studies were conducted to analyze the algorithm's behavior in defining protection zones for impedance relays. Scenarios included simultaneous failures and variable topology conditions, comprehensively evaluating the algorithm's performance.

Figure 3. Georeferenced area created with QGIS, including system nodes in an actual urban distribution network.

Table 3. Flow data summary: (a) summary of load flow data in normal system conditions (b) data summary of load flow for interconnection scenarios.

Distribution Network Parameters			
(a)		(b)	
S/E Capacity	30 MVA	S/E Capacity	30 MVA
Total Load		Total Load	
Real Power Ractive Power Apparent Power	402.97 kW 130.9 kVAR 423.69 kVA	Real Power Ractive Power Apparent Power	402.97 kW 130.9 kVAR 423.69 kVA
Load Used		Load Used	
Real Power Ractive Power Apparent Power	402.97 kW 130.90 kVAR 423.69 kVA	Real Power Ractive Power Apparent Power	402.97 kW 130.90 kVAR 423.69 kVA
Total Losses		Total Losses	
Max ΔV Length	2.82% 6872.9 m	Max ΔV Length	2.95% 6630.9 m

To standardize the data, the Universal Transverse Mercator (UTM) format was used, scaling the data between 0 and 1, as specified in Algorithm 1. After defining the new normalized data, the network was created with all nodes to construct the electrical distribution system. The Manhattan criterion was applied to determine the distances between nodes, and the Kruskal theorem was used to identify the Minimum Spanning Tree (MST), as instructed in Algorithm 2. The normalization process resulted in a random enumeration of the nodes. For better organization and presentation, the nodes were re-routed using the

Depth-First Search (DFS) method, which traverses a network path from a start node to an end node, changing the path if no further nodes are available (Figure 4).

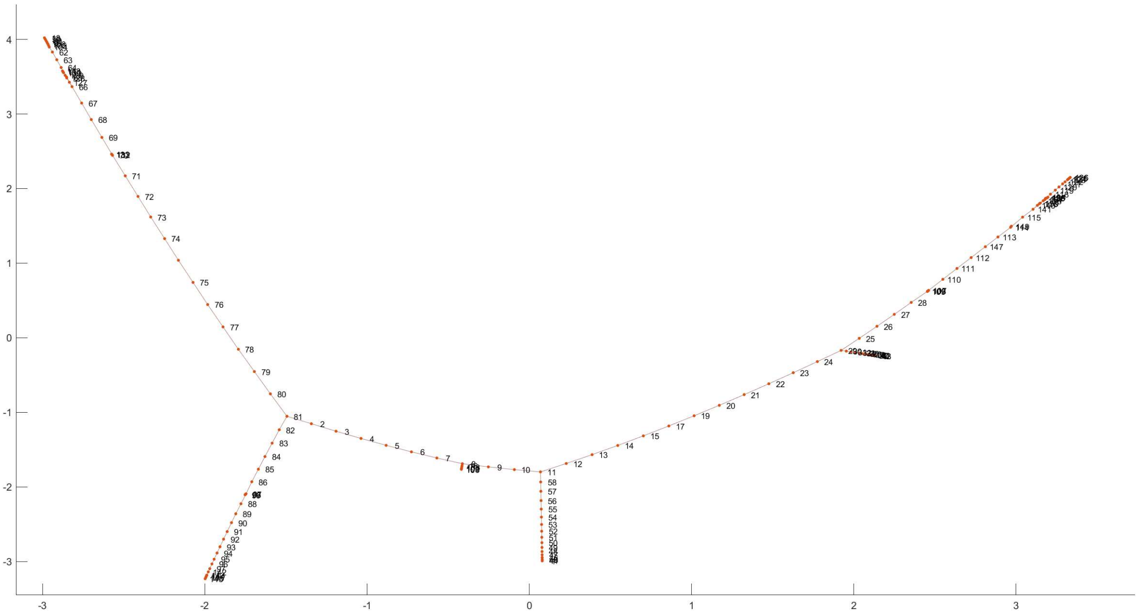


Figure 4. Kruskal's algorithm resulting in the proposed 150-node system without data reorganization as a result of implementing Algorithms 1 and 2.

Algorithm 1. Data normalization

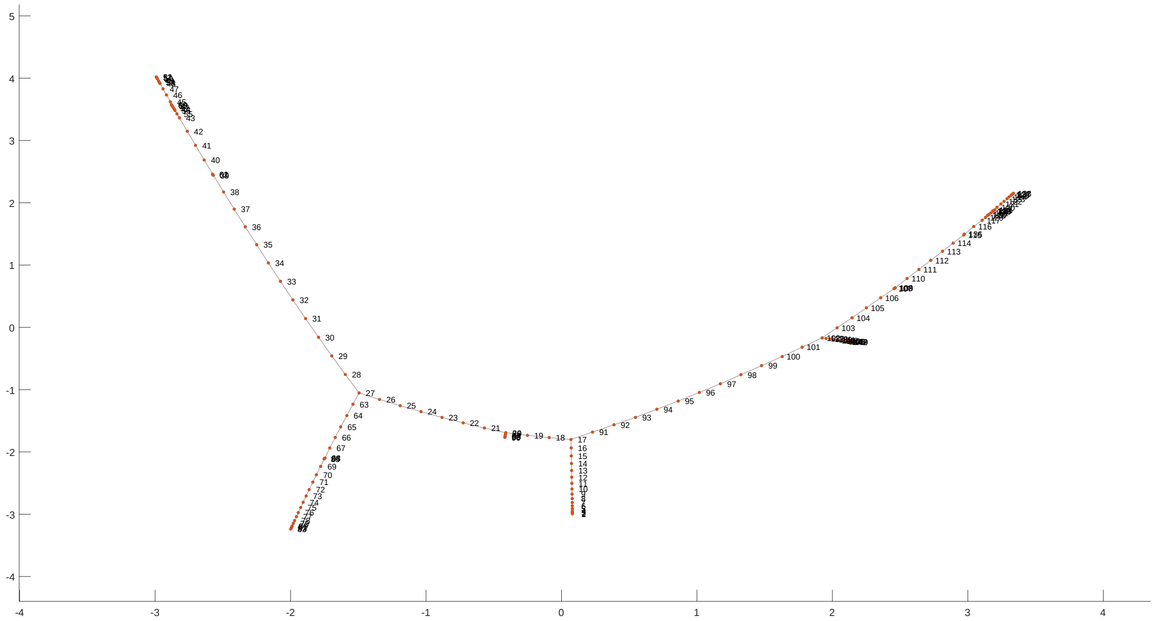
```
for c = k:length(X)
X_esc(j,1) = (X(c)-a)/b;
Y_esc(j,1) = (Y(c)-n) /d;
j = j + 1;
end
for c = k:length(SubstationX)
SubstationX_esc(j,1) = (SubstationX(c)-a)/b;
SubstationY_esc(j,1) = (SubstationY(c)-n)/d;
j = j + 1;
end
```

Algorithm 2. Network creation and Kruskal algorithm

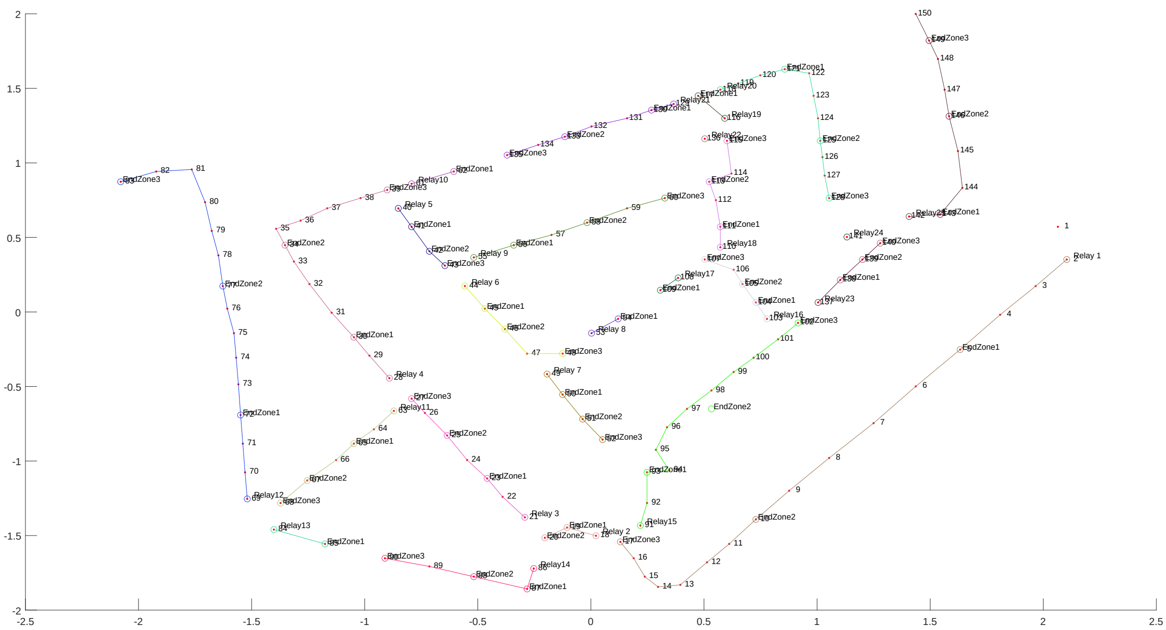
```
for c = k:length(X)-1;
for c = z:length(X)-1;
ReceiveNode(c,k) = c + 1;
a = X(k);
a1 = X(c + 1);
b = Y(k);
b1 = Y(c + 1);
distance(c,k) = sqrt((a-a1)^2  + (b-b1)^2);
distance1 = sqrt((a-a1)^2 + (b-b1)^2);
z = z + 1;
ShippingNode(c,k) = k;
WeightArray(mxy,1) = distance1;
Shipping(mxy,1) = k;
Resive(mxy,1) = c + 1;
Weight(k,c) = distance1;
Weight(k,c) = distance1;
Send2(k,c) = k;
Receive2(k,c) = c + 1;
Nodes = k;
mxy = mxy + 1;
end
end
for c = k:3;
if c == 1;
FinalData = WeightArray;
else if c == 2;
FinalData = Shipping;
else c == 3;
FinalData = Resive;
end
end
FinalExcel(:,c) = FinalData;
end
```

In Algorithm 3, the data and the node enumeration from Algorithm 2 were processed. This proposal analyzed the existing network to identify the number of vertices emerging from each node and the minimum distance to the subsequent nodes in Algorithm 3.

Algorithm 3 works with Algorithm 4, which reorganizes the numbering assigned to each node based on the shortest path identified by Algorithm 3. With the system ordered, relay locations were determined using the electrical configuration criterion in Algorithm 4. Zones were characterized by the number of nodes (single-phase, two-phase, or three-phase). Figure 5 shows the results of applying Algorithms 3 and 4.



(**a**)



(**b**)

Figure 5. Results of implementing Algorithms 3 and 4: (**a**) change in the numbering of the nodes belonging to the network, same structure shown in previous graph, and (**b**) locations of the relays that make up the system and the zone divisions of each relay reorganization.

Algorithm 3. DFS method

```
for i in range(1,n):
B.append(tuple([V_Nodo_i[i], V_Nodo_j[i]]))
n = n_nodos-2
for j in range(1,(n_nodos-1)):
A.append(V_Nodo_j[j])
D = {'A':A, 'B':B}
grafo = D
class Graph:
def __init__(self, edges, n):
self.adjList = [[] for _ in range(n)]
for (src, dest) in edges:
self.adjList[src].append(dest)
self.adjList[dest].append(src)
def iterativeDFS(graph, v, discovered):
stack = deque()
stack.append(v)
while stack:
vs. = stack.pop()
camino.append(v)
if discovered[v]:
continue
discovered[v] = True
adjList = graph.adjList[v]
for i in reversed(range(len(adjList))):
u = adjList[i]
if not discovered[u]:
stack.append(u)
```

Algorithm 4. Reorganization algorithm

```
for i = 1:length(Path1)
NewPath = Path1(i,1)
X1 = TotalX(NewPath,1)
Y1 = TotalY(NewPath,1);
NewX(i,:) = X1
NewY(i,:) = Y1;
end
for c = k:length(X)-1;
m = m + 1;
z = m;
for c = z:length(X)-1;
ReceiveNode(c,k) = c + 1;
a = X(k);
a1 = X(c + 1);
b = Y(k);
b1 = Y(c + 1);
distance(c,k) = sqrt((a-a1)^2 + (b-b1)^2);
distance1 = sqrt((a-a1)^2 + (b-b1)^2);
z = z + 1;
ShipNode(c,k) = k;
WeightArray(mxy,1) = distance1;
Ship(mxy,1) = k;
Resive(mxy,1) = c + 1;
Weight(k,c) = distance1;
Send2(k,c) = k;
Receive2(k,c) = c + 1;
Nodes = k;
mxy = mxy + 1;
end
end
for c = k:3;
if c == 1;
FinalData = WeightArray;
else if c == 2;
FinalData = Shipping;
else c == 3;
FinalsData = Receive;
end
end
FinalExcel(:,c) = FinalsData;
end
for c = k:length(X)-1;
m = m + 1;
z = m;
for c = z:length(X)-1;
ReceiveNode(c,k) = c + 1;
a = X(k);
a1 = X(c + 1);
b = Y(k);
b1 = Y(c + 1);
distance(c,k) = sqrt((a-a1)^2 + (b-b1)^2);
distance1 = sqrt((a-a1)^2 + (b-b1)^2);
z = z + 1;
ShipNode(c,k) = k;
WeightArray(mxy,1) = distance1;
Ship(mxy,1) = k;
Resive(mxy,1) = c + 1;
Weight(k,c) = distance1;
Send2(k,c) = k;
Receive2(k,c) = c + 1;
Nodes = k;
mxy = mxy + 1;
end
end
for c = k:3;
if c == 1;
FinalData = WeightArray;
else if c == 2;
FinalData = Shipping;
else c == 3;
FinalsData = Receive;
end
end
FinalExcel(:,c) = FinalsData;
end
```

Algorithm 5, consisting of two parts, identifies nodes where relays can be implemented if outgoing vertices are greater than or equal to two. The second part of Algorithm 5 applies a simplified method based on the Ant Colony Optimization (ACO) algorithm. This part takes the nodes where the relays and final nodes of the system are located to analyze possible routes from node to relay and from relay to final node, resulting in the determination of relay locations and their respective protection sections.

Algorithm 5. Relay locations

```
[unique_valuesShipping,ind_uniqueShipping] = unique(s);
ind_repeatedShipping = setdiff(1:length(s) ...
          ,ind_uniqueShipping);
values_repeatedShipping = s(ind_repeatedShipping, 1);
ShippingArray = [];
for i = 1:length(values_repeatedShipping);
Shipping = find(s == repeated_valuesShipping(i));
ShippingArray = [ShippingArray;Shipping];
end
ReceivedArray = [];
for i = 1:length(values_repeatedShipping)
Receipt = find(t == values_repeatedShipping(i));
MatrixReceived = [MatrixReceived;Received];
end
[Column,Row] = size(System);
MatrixTotal = sort([MatrixReceived;MatrixShipping]);
TotalMatrix = sort([ShippingMatrix]);
for i = 1:length(TotalMatrix)
NewPath = TotalMatrix(i,1);
Relays = System(NewPath,1:Row);
NewX(i,:) = Relays;
end
RelayGoingNode = [System(1,1:Row);NewX];
[~,s] = classify(RelayGoingNode(:,2));
Orderedrelaythatisworth = RelayGoingNode(s,:);
RelayPath = [Orderedrelaythatisworth =  ...
          RelayGoingNode(:,2)-1;length(TotalX)];
RelayPath2 = [Orderedrelaythatisworth =
          RelayGoingNode(:,2)]
for i = 1:length(RelayPath)-1
Number = RelayPath2(i);
Number2 = RelayPath(i + 1);
for j = Number:Number2
m = m + 1;
SeparationMatrix(m,i) = j;
end
for i = 1:length(RelayPath)-1
Data = SeparationMatrix(:,i)
Data(Data == 0) = [];
for j = 1:length(Data)
m = m + 1;
FinalX(m,i) = TotalX(Data(j),1);
FinalY(m,i) = TotalY(Data(j),1);
end
end
```

The final step involved dividing the relay operating zones based on various characteristics. For this case, a relay with three zones of operation was selected, and the position of a cluster, which could be a start- or endpoint, was determined. In this scenario, the endpoint was selected, and the remaining clusters were identified, as shown in Figure 4. Algorithm 6 applies the modified K-means method to determine the operating zones for each relay. This algorithm processes the data from Algorithm 5, dividing the sections handled by each relay. The sequence of Algorithm 6 is shown in Figure 6.

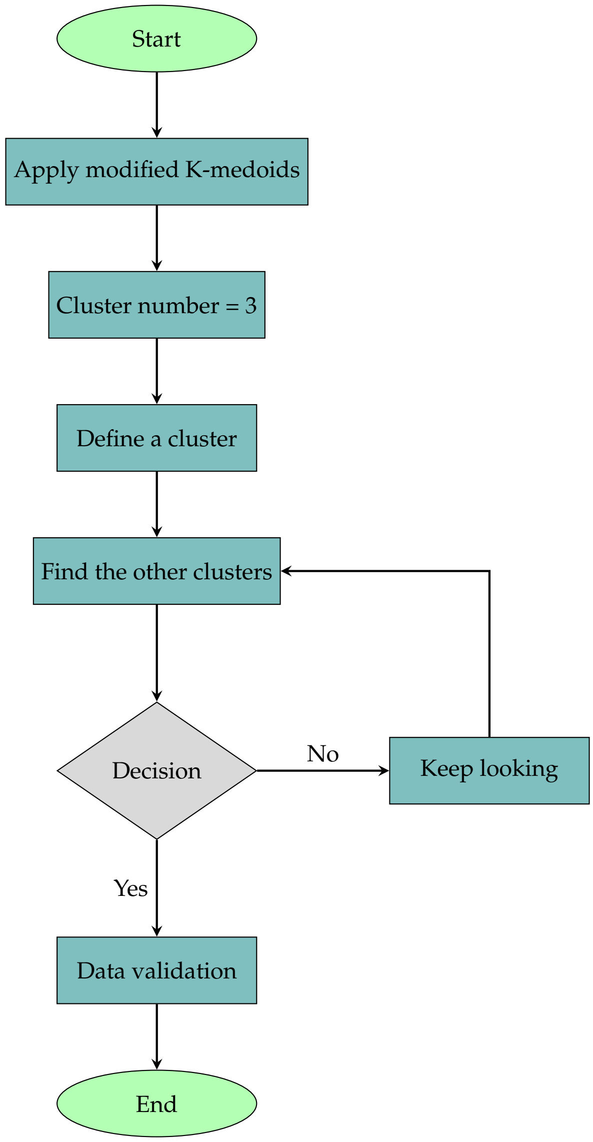
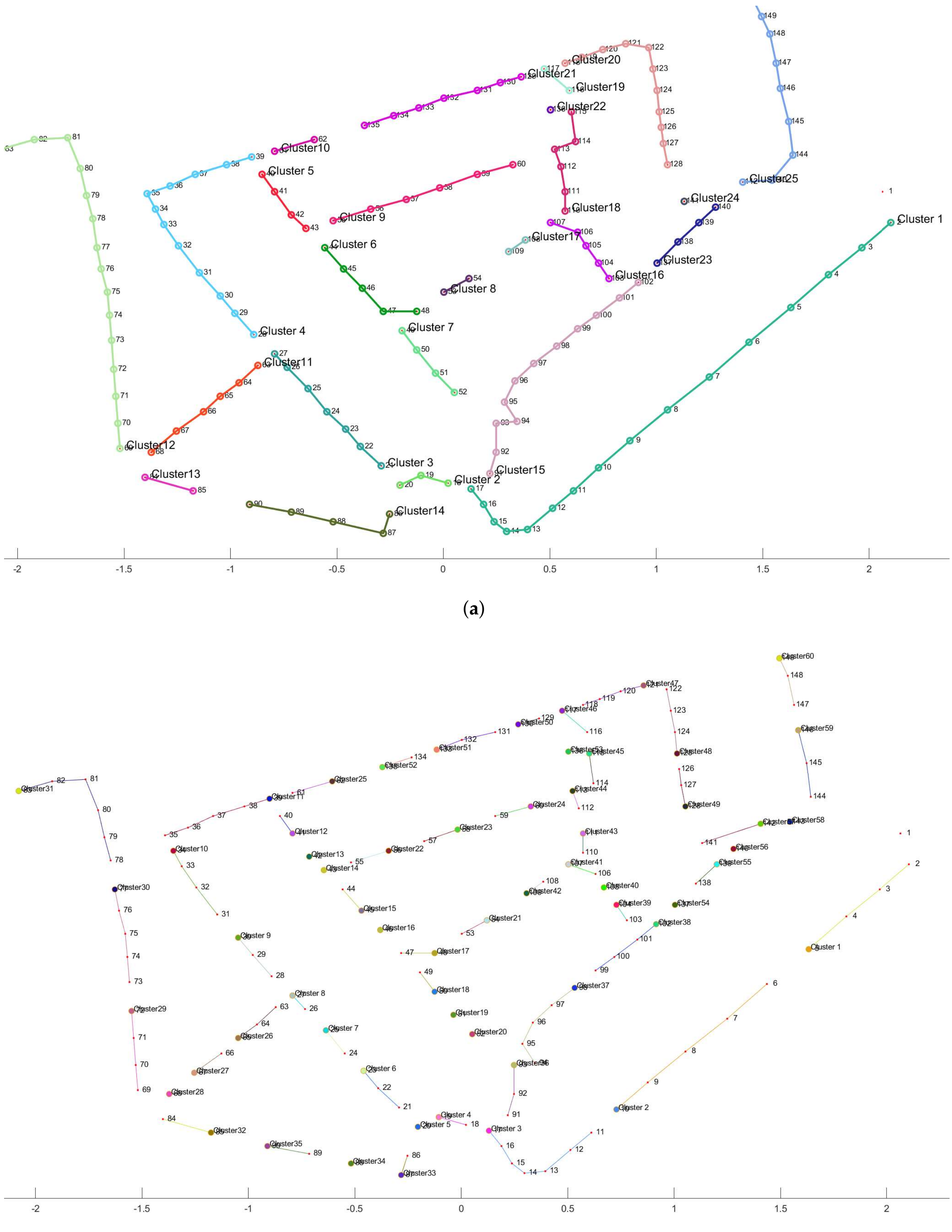


Figure 6. Flowchart for implementing Algorithm 6.

The operation zone was defined, starting with an initial or final zone, and the remaining zones were identified, culminating in the results shown in Figure 7. This comprehensive approach ensured the optimal placement and operation of impedance relays within the electrical distribution network, enhancing protection and reliability.



(**a**)

(**b**)

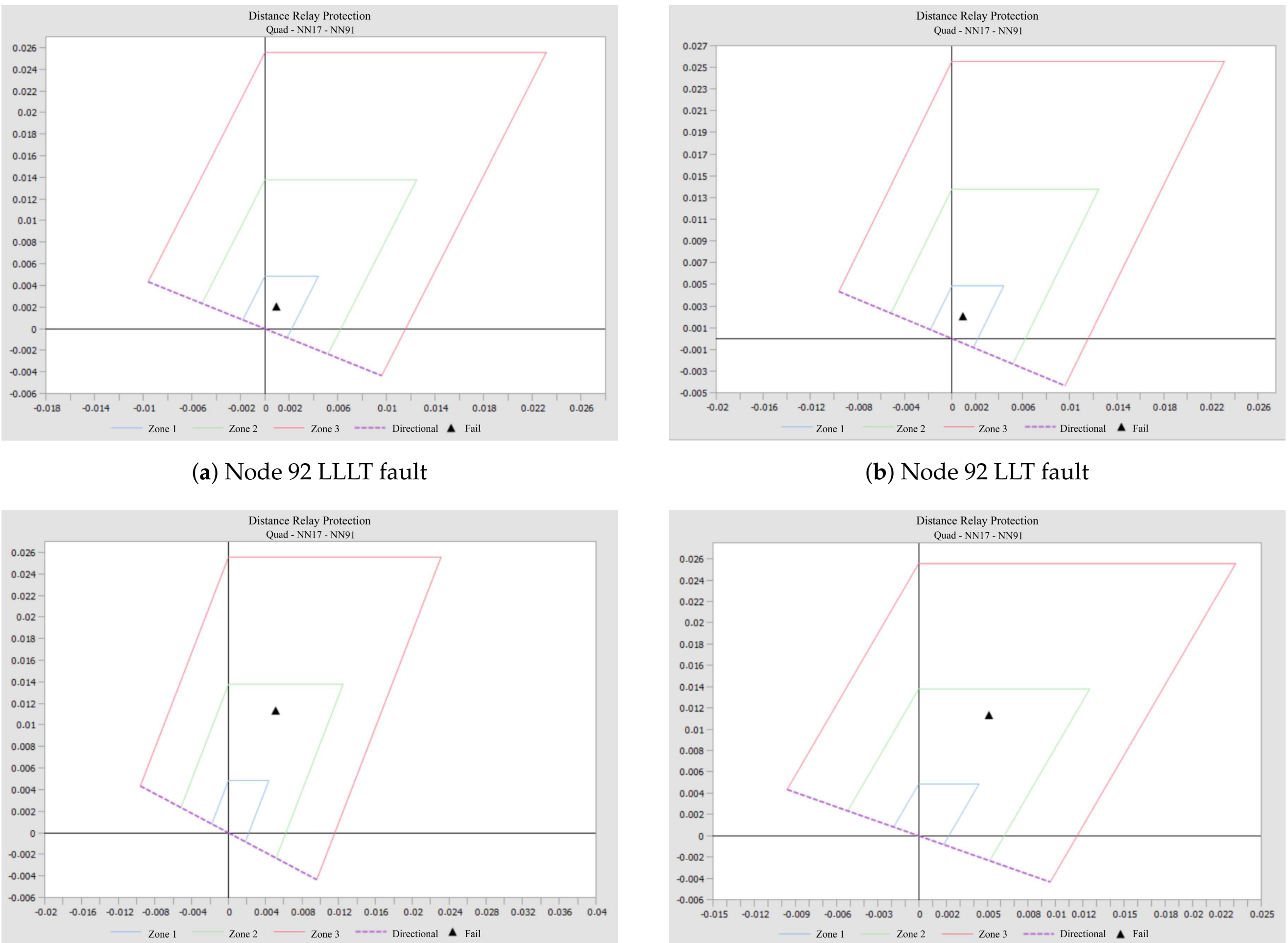
Figure 7. Results of implementing Algorithms 5 and 6 for identifying distribution system clusters: (**a**) cluster of relays in the distribution system, and (**b**) georeferenced area that includes the nodes of the system and the clustering of zones.

4. Results

The georeferenced system data extract, see Figure 7b, and the scaled data of the graph were in the range of 0 to 1, which the Kruskal algorithm, the optimal configuration of the electrical distribution network, determined, as seen in Figure 7, thus finding the MST of the system.

Algorithm 5 allowed locating the impedance relays in the distribution system and, through clustering techniques such as modified K-medoids as shown in Figure 5, the effectiveness and reliability were analyzed through case studies; the metaheuristic technique, called ACO, separated the impedance relays by protection sectors with restrictions of system configurations; see Figure 3.

In case one, each node belonged to an impedance relay and a zone; a simple fault was applied to nodes 92, 96, 101, 101, 104, 105, and 106, checking if the impedance relay was detected, identifying in which zone the fault was located, and which impedance relay identified it; see Figure 8; furthermore, the operating points of relays 92 and 96 were observed in front of a three-phase and two-phase fault with arc; the operating point was maintained in the impedance line that was programmed to the relay, indicating that the fault was detected effectively; in Table 4, the results of currents and voltages during the fault event are exposed.



(**a**) Node 92 LLLT fault (**b**) Node 92 LLT fault

(**c**) Node 96 LLLT fault (**d**) Node 96 LLT fault

Figure 8. Charts illustrating single failures in nodes 92 and 96 of the distribution system.

Table 4. Short-circuit currents and fault voltages for the studied scenarios.

Types of Failure	Phases Affected	V_A (KV)	I_A (A)	V_B (KV)	I_B (A)	V_C (KV)	I_C (A)
LLLT	ABC	0.01 − 0.0j	295.2 − 1907.54j	−0.01 − 0.01j	1799.58 + 698.12j	−0.0 + 0.01j	1504.38 + 1209.42j
LLT	AB	0.01 + 0.0j	1047.38 − 1302.85j	−0.01 − 0.0j	−1047.4 + 1302.81j	−9.53 + 16.5j	0.0 + 0.02j

(a) Short-circuit currents and fault voltage at node 92

Types of Failure	Phases Affected	V_A (KV)	I_A (A)	V_B (KV)	I_B (A)	V_C (KV)	I_C (A)
LLLT	ABC	0.06 − 0.02j	296.4 − 1900.35j	−0.04 − 0.04j	1793.78 + 693.8j	0.01 + 0.06j	1497.73 + 0206.56j
LLT	AB	0.05 + 0.01j	1044.91 − 1297.1	−0.05 − 0.01j	−1044.92 + 1297.05j	−9.53 + 16.5j	0.0 + 0.02j

(b) Short-circuit currents and fault voltage at node 96

Types of Failure	Phases Affected	V_A (KV)	I_A (A)	V_B (KV)	I_B (A)	V_C (KV)	I_C (A)
LLLT	ABC	0.12 − 0.03j	297.14 − 1890.82j	−0.09 − 0.09j	−1786.07 + 688.08j	−0.03 + 0.12j	1488.92 + 1202.74j
LLT	AB	0.1 + 0.03j	1041.6 − 1289.47j	−0.1 − 0.03j	−1041.61 + 1289.42j	−9.53 + 16.5j	0.0 + 0.02j

(c) Short-circuit currents and fault voltage at node 101

Types of Failure	Phases Affected	V_A (KV)	I_A (A)	V_B (KV)	I_B (A)	V_C (KV)	I_C (A)
LLLT	ABC	0.01 − 0.0j	297.65 − 1886.28j	−0.01 − 0.01j	−1782.39 + 685.36j	−0.0 + 0.01j	484.74 + 1200.91j
LLT	AB	0.01 + 0.0j	1040.02 − 1285.84j	−0.01 − 0.0j	−1040.03 + 1285.8j	−9.53 + 16.5j	0.0 + 0.0j

(d) Short-circuit currents and fault voltage at node 104

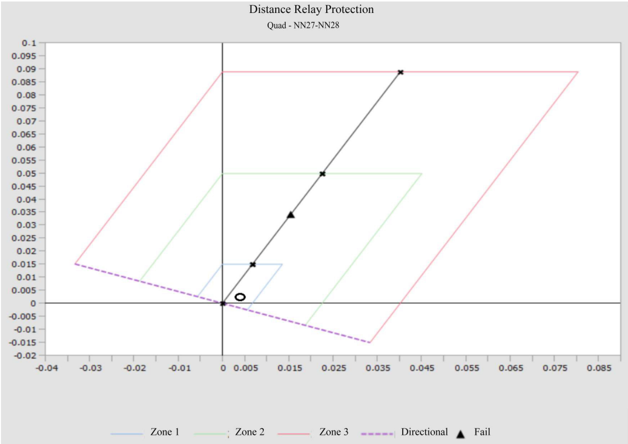
Types of Failure	Phases Affected	V_A (KV)	I_A (A)	V_B (KV)	I_B (A)	V_C (KV)	I_C (A)
LLLT	ABC	0.02 − 0.0j	297.82 − 1884.82j	−0.01 − 0.01j	−1781.21 + 684.49j	−0.0 + 0.02j	1483.4 + 1200.33j
LLT	AB	0.02 + 0.0j	1039.51 − 1284.68j	−0.02 − 0.0j	−1039.52 + 1284.64j	−9.53 + 16.5j	0.0 + 0.0j

(e) Short-circuit currents and fault voltage at node 105

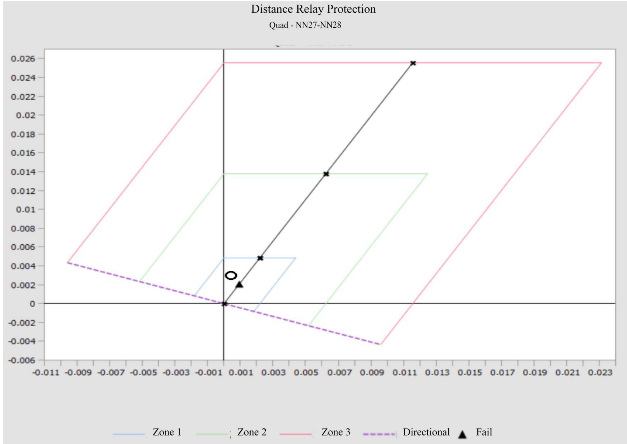
Types of Failure	Phases Affected	V_A (KV)	I_A (A)	V_B (KV)	I_B (A)	V_C (KV)	I_C (A)
LLLT	ABC	0.03 − 0.01j	297.96 − 1883.51j	−0.02 − 0.02j	−1780.15 + 683.71j	−0.01 + 0.03j	1482.19 + 1199.8j
LLT	AB	0.02 + 0.01j	1039.05 − 1283.63j	−0.02 − 0.01j	−1039.06 + 1283.59j	−9.53 + 16.5j	0.0 + 0.0j

(f) Short-circuit currents and fault voltage at node 106

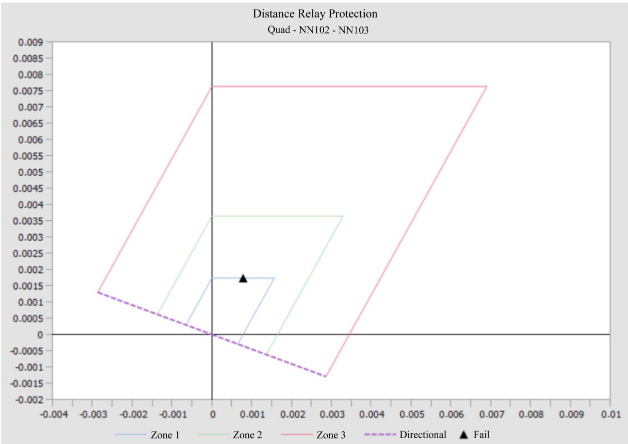
As a second case study, simultaneous faults were considered. The simulation was performed at nodes 130-143 and 32-92, see Figure 9, where the impedance relays used the positive sequence impedance of the system; when faults occurred, its value changed for all relays, which caused them not to detect it, since the new impedance generated by this fault tended to oscillate, due to the contributions of the currents of all the nearby nodes and the multiple references to the fault nodes, which generated a disconnection of the distribution system and, as a consequence, the reliability was reduced from 100 to 0; in addition, the reliability referred to providing a quality service without interruptions. The fault ran through the system, causing the substation protection to be activated to avoid internal damage to the substation; however, by performing this action, the substation went out of operation, causing there to be no capacity to meet the demand; however, to maintain system reliability, secondary equipment must be used to respond at the time the event is generated, or the impedance relay becomes as secondary protection.



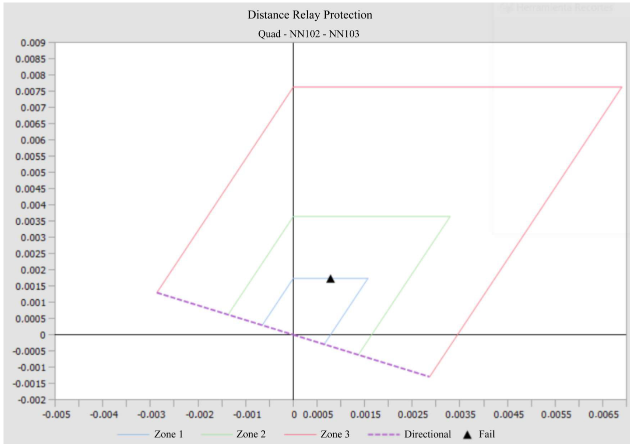
(**a**) Single and simultaneous failure for node 32



(**b**) Single and simultaneous failure for node 92



(**c**) Node 104 LLLT fault



(**d**) Node 104 LLT fault

Figure 9. Charts illustrating simultaneous failures within the distribution system.

If the system is subject to interconnections, caused by the maintenance of a section, isolation of a fault, or load balancing, among others, it is mandatory to perform the reconfiguration and determine the MST; this scenario is called case three.

This topology change provoked the output of some impedance relays due to the direction that the power flow took; on the other hand, the inclusion of new impedance relays for the sections that were not protected implied an increase in costs; its analysis was the result of subjecting the interconnected system to failures in nodes 104, 105, 106, 92, 96, and 98, see Figure 9, which caused the distribution system to be subject to a reconfiguration.

The results of the simulations and the conditions of the distribution system (previously presented in Table 3b) maintained system restrictions such as standard load conditions, technical losses due to energy transport, and adequate voltage levels at terminal nodes. The resulting values from the failure scenarios are detailed in Table 5, providing comprehensive insights into the system's performance under different fault conditions. This analysis underscores the importance of strategic impedance relay placement and advanced optimization techniques to enhance the reliability and efficiency of electrical distribution networks.

Table 5. Summary table of short circuits in the case of simultaneous failure.

Types of Failure	Phases Affected	V_A (KV)	I_A (A)	V_B (KV)	I_B (A)	V_C (KV)	I_C (A)
LLLT	ABC	0.01 − 0.0j	295.2 − 1907.54j	−0.01 − 0.01j	−1799.58 + 698.12j	−0.0 + 0.01j	1504.38 + 1209.42j
LLT	AB	0.01 + 0.0j	1047.38 − 1302.85j	−0.01 − 0.0j	−1047.4 + 1302.81j	−9.53 + 16.5j	0.0 + 0.0j
(a) Short-circuit currents and fault voltage at node 92							
Types of Failure	**Phases Affected**	V_A **(KV)**	I_A **(A)**	V_B **(KV)**	I_B **(A)**	V_C **(KV)**	I_C **(A)**
LLLT	ABC	0.06 − 0.02j	296.04 − 1900.35j	−0.04 − 0.04j	−1793.78 + 693.8j	−0.01 + 0.06j	1497.73 + 1206.56j
LLT	AB	0.05 + 0.01j	1044.91 − 1297.1j	−0.05 − 0.01j	−1044.92 + 1297.05j	−9.53 + 16.5j	0.0 + 0.0j
(b) Short-circuit currents and fault voltage at node 96							

5. Discussion

The application of clustering methods to impedance relays was demonstrated through various case studies, showing how their coordination can vary when subjected to different types of faults. In a radial network, it is necessary to find the optimal location for the impedance relays and the shortest paths and ensure the system's overall efficiency.

The methodology applied to the electrical network necessitates the presence of circuit breakers for the corresponding tripping actions. The more elements the system includes, the more efficient and protected the circuit becomes. Therefore, the primary objective is to strategically locate impedance relays within the distribution system. This study focused on a three-phase electrical distribution network system; however, the configuration of single-phase systems must be considered for future research.

Technological advances enable reducing the number of impedance relays required in the distribution system, lowering direct and indirect costs. The efficiency of the relays in detecting faults has been demonstrated, and the introduction of bidirectional impedance relays could further enhance system performance. Currently, unidirectional relays necessitate the addition of relays and equipment repositioning during interconnections. Bidirectional relays would eliminate the need for such procedures, allowing for more flexible configuration profiles, especially in the case of multiple faults, where the relay's response depends on the line impedance value during the fault.

Modified clustering algorithms efficiently determine the location of impedance relays and divide the operational zones, enabling circuit breakers to open and isolate faults. In case study one, under single fault conditions, the relays operated correctly, detecting changes in line impedance and disconnecting the affected zones.

However, in the presence of simultaneous faults, the impedance relays struggled to interpret the generated line impedances accurately, leading to non-tripping. This is due to the highly variable nature of the impedances, which the relays could not detect reliably, as shown in Figure 9.

In three-phase distribution systems, impedance relays can divide the network into smaller groups, enhancing fault detection efficiency. These relays can isolate the faulted zone and, through network transfer or reconfiguration, continue to provide service to unaffected sections until the fault is resolved.

Reconfiguration is necessary when interconnections occur, requiring the determination of impedance relay locations for each possible configuration to maintain network reliability. In short, topologies, such as impedance relays alone, cannot guarantee system protection, and their functionality becomes limited. The more derivations or reconfigurations occur, the more impedance relays are needed, as observed in the third case study.

A fault detector can identify and isolate faults, providing additional functionality to the relay. Network expansion does not affect operation efficiency if the system contains medium- and low-voltage loads across different branches. However, in reconfiguration scenarios, such as case three, most relays cease to function optimally due to changes in flow direction. Thus, additional impedance relays must be added or replaced to protect the reconfigured zones effectively.

6. Conclusions

Implementing impedance relays in medium-voltage distribution systems significantly impacts system reliability, as the case studies show. These studies reveal that reliability remains at 100% for single-fault detection but drops to 0% for multiple faults. This issue arises from the difficulty in accurately determining the line impedance where the event occurred due to the current supplied by the faults.

The application of impedance relays offers several advantages, such as improved network organization. The network is divided into smaller groups, as illustrated in Figure 5b. Using algorithms, it is possible to detect the location of faults precisely. Each relay protects its section and is configured with three impedance zones, allowing for the determination of the fault location with minimal error.

Despite these benefits, some authors recommend using impedance relays as secondary protection rather than primary. This recommendation stems from the fact that, when a fault occurs, the feeder may be left without a power supply until the fault is isolated. This isolation can leave a feeder section without service during interconnection or transfer situations, necessitating system reconfiguration for optimal operation. New impedance relays must be implemented within the system to address this.

Future research should explore the integration of artificial intelligence with impedance relays to enhance their functionality. Additionally, the development of metaheuristic methods for implementing these relays in electrical distribution systems should be investigated. An alternative approach is to analyze impedance relays as fault analyzers.

Further studies could focus on designing protection devices that combine the advantages of impedance relays and disconnectors for exclusive use in electrical distribution systems. This combination could offer a more robust and efficient solution for fault detection and system protection, ultimately improving the reliability and stability of electrical distribution networks. While a comparative study is essential for evaluating the performance and limitations of this proposal, current constraints did not allow for a direct comparison with other methodologies using the same real urban distribution system segment. Most existing techniques for optimal impedance relay placement are tailored for transmission networks. Therefore, adapting and redesigning these techniques for distribution networks would be necessary and is suggested as a direction for future work. Comprehensive comparisons with other methodologies in similar distribution systems will be crucial to validate further and refine the proposed approach.

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References

1. Ruiz, M.; Pinzón, S.; Yánez, S. Optimal Allocation of Transformers in Electrical Distribution Systems Considering Attenuation and Capacity Constraints. In Proceedings of the 2019 International Conference on Information Systems and Computer Science (INCISCOS), Quito, Ecuador, 20–22 November 2019; pp. 230–237. [CrossRef]
2. Gallardo, J.L.; Ahmed, M.A.; Jara, N. Clustering Algorithm-Based Network Planning for Advanced Metering Infrastructure in Smart Grid. *IEEE Access* **2021**, *9*, 48992–49006. [CrossRef]
3. Mehmood, K.K.; Khan, S.U.; Haider, Z.M.; Kim, C.H. A Multi-Agent Clustering-based Approach for the Distributed Planning of Wind Generators. *IFAC-PapersOnLine* **2018**, *51*, 132–142. [CrossRef]
4. Mehmood, K.K.; Kim, C.H.; Khan, S.U.; Haider, Z.M. Unified planning of wind generators and switched capacitor banks: A multiagent clustering-based distributed approach. *IEEE Trans. Power Syst.* **2018**, *33*, 6978–6988. [CrossRef]
5. Battapothula, G.; Yammani, C.; Maheswarapu, S. Multi-objective optimal planning of FCSs and DGs in distribution system with future EV load enhancement. *IET Electr. Syst. Transp.* **2019**, *9*, 128–139. [CrossRef]
6. Alasali, F.; El-Naily, N.; Zarour, E.; Saad, S.M. Highly sensitive and fast microgrid protection using optimal coordination scheme and nonstandard tripping characteristics. *Int. J. Electr. Power Energy Syst.* **2021**, *128*, 106756. [CrossRef]
7. Valenzuela, A.; Montalvo, I.; Inga, E. A decision-making tool for electric distribution network planning based on heuristics and georeferenced data. *Energies* **2019**, *12*, 4065. [CrossRef]
8. Lamberti, L.; Parmakovic, A.; Krsman, V. FLISR with field devices and distribution management system. In Proceedings of the 11th IET International Conference on Advances in Power System Control, Operation and Management (APSCOM 2018), Hong Kong, China, 11–15 November 2018; Volume 2018, pp. 1–2. [CrossRef]
9. Gokhale, S.S.; Kale, V.S. On the significance of the plug setting in optimal time coordination of directional overcurrent relays. *Int. Trans. Electr. Energy Syst.* **2018**, *28*, e2615. [CrossRef]
10. Liu, G.; Kang, L.; Luan, Z.; Qiu, J.; Zheng, F. Charging station and power network planning for integrated electric vehicles (EVs). *Energies* **2019**, *12*, 2595. [CrossRef]
11. Syed, D.; Abu-Rub, H.; Ghrayeb, A.; Refaat, S.S.; Houchati, M.; Bouhali, O.; Banales, S. Deep Learning-Based Short-Term Load Forecasting Approach in Smart Grid with Clustering and Consumption Pattern Recognition. *IEEE Access* **2021**, *9*, 54992–55008. [CrossRef]
12. Zambrano-Asanza, S.; Chumbi, W.; Franco, J.F.; Padilha-Feltrin, A. Multicriteria Decision Analysis in Geographic Information Systems for Identifying Ideal Locations for New Substations. *J. Control Autom. Electr. Syst.* **2021**, *32*, 1305–1316. [CrossRef]
13. Hatata, A.; Lafi, A. Ant Lion Optimizer for Optimal Coordination of DOC Relays in Distribution Systems Containing DGs. *IEEE Access* **2018**, *6*, 72241–72252. [CrossRef]
14. Grover-Silva, E.; Girard, R.; Kariniotakis, G. Optimal sizing and placement of distribution grid connected battery systems through an SOCP optimal power flow algorithm. *Appl. Energy* **2018**, *219*, 385–393. [CrossRef]
15. Alghassab, M. Adaptive Protection of Distribution Networks Integrated with DG Units. In Proceedings of the 2019 2nd International Conference on Computer Applications & Information Security (ICCAIS), Riyadh, Saudi Arabia, 1–3 May 2019; pp. 1–6. [CrossRef]
16. Keihan Asl, D.; Seifi, A.R.; Rastegar, M.; Mohammadi, M. Multi-objective optimal operation of integrated thermal-natural gas-electrical energy distribution systems. *Appl. Therm. Eng.* **2020**, *181*, 115951. [CrossRef]
17. Zenhom, Z.M.; Boghdady, T.A. Optimal Allocation of Distributed Generation in A Part of The Egyptian Electrical Network Using Whale Optimization Algorithm. In Proceedings of the 2019 21st International Middle East Power Systems Conference (MEPCON), Cairo, Egypt, 17–19 December 2019; pp. 365–370. [CrossRef]
18. Chabla-Auqui, L.; Ochoa-Correa, D.; Villa-Ãvila, E.; Astudillo-Salinas, P. Distributed Generation Applied to Residential Self-Supply in South America in the Decade 2013–2023: A Literature Review. *Energies* **2023**, *16*, 6207. [CrossRef]
19. Ruan, H.; Gao, H.; Liu, Y.; Wang, L.; Liu, J. Distributed voltage control in active distribution network considering renewable energy: A novel network partitioning method. *IEEE Trans. Power Syst.* **2020**, *35*, 4220–4231. [CrossRef]
20. Karaaom, C.; Jirapong, P.; Thararak, P. Optimal Distribution Network Reconfiguration Implemented with Tie Line and Capacitor Using Improved Particle Swarm Optimization. In Proceedings of the 2020 International Conference on Power, Energy and Innovations (ICPEI), Chiangmai, Thailand, 14–16 October 2020; pp. 61–64. [CrossRef]
21. Pérez Hernández, L.P. Load Restoration in Primary Distribution Networks Using the Binary Particle Swarm Optimization. In Proceedings of the 2019 IEEE Electrical Power and Energy Conference (EPEC), Montreal, QC, Canada, 16–18 October 2019; pp. 1–6. [CrossRef]
22. Jin, X.; Han, J. *K-Medoids Clustering*; Springer: Boston, MA, USA, 2017. [CrossRef]
23. Azizivahed, A.; Ghavidel, S.; Ghadi, M.J.; Li, L.; Zhang, J. Multi-Objective Energy Management Approach Considering Energy Storages in Distribution Networks with Respect to Voltage Security. In Proceedings of the 2019 IEEE International Conference on Industrial Technology (ICIT), Melbourne, Australia, 13–15 February 2019; pp. 661–666. [CrossRef]

24. de Carvalho, T.L.A.; Ferreira, N.R. Optimal allocation of distributed generation using ant colony optimization in electrical distribution system. In Proceedings of the 2018 Simposio Brasileiro de Sistemas Eletricos (SBSE), Niteroi, Brazil, 12–16 May 2018; pp. 1–6. [CrossRef]
25. Mirhoseini, P.; Ghaffarzadeh, N. Economic battery sizing and power dispatch in a grid-connected charging station using convex method. *J. Energy Storage* **2020**, *31*, 101651. [CrossRef]