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A New Method to Assess the Reliability and Security of Urban Electrical Substations

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Abstract: This paper presents the application of quantitative and qualitative methods to assess reliability and security in urban electrical substations. The method is a visual technique based on a conceptual analysis of the different substation configurations. We also performed a sensitivity analysis considering the effects of connecting and disconnecting various elements of a power system. The procedure considers evaluating the loadability levels of transformers, buses, and lines, as well as the current state of the individual elements and the number of connected elements. A new index was proposed for urban electrical substations, evaluating the non-attended demand risk. The technique was tested in a power system case study with a meshed subtransmission network and distribution circuits to supply power to the loads. The results showed that the proposed method is a useful qualitative method to obtain a quantitative description of the system during operation in critical cases and the non-attended demand risk. In addition, 30% of the electrical substations showed low reliability indicators for critical cases such as failures in transformers that connect different internal configurations. These findings could be of interest for utilities and operators, as this document provides a simplified and graphic method that can integrate components such as configurations, non-attended demand risk, and loadability indicators as key parameters to identify critical points that affect the reliability and security of power systems. The case study showed that the electrical substations with the highest non-attention demand risk, around 50%, were those with single- and double-bar configurations in their respective switchyards. On the other hand, the substations with the lowest risk of unmet demand, equal to or less than 20%, were electrical substations with a double-bar + bypass switch configuration, a double-bar and ring configuration in the 110 kV switchyard, and a single-bar configuration in the 13.8 kV switchyard. This study showed that those substations that had couplings had a higher probability of withstanding contingencies.

Keywords: reliability; security; power systems; electrical substation; $N - k$ contingency

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Citation: Silva-Ortega, J.; Ortíz, J.; Candelo-Becerra, J.E. A New Method to Assess the Reliability and Security of Urban Electrical Substations. *Electricity* **2024**, *5*, 991–1007. https://doi.org/10.3390/electricity5040050

Received: 9 September 2024
Revised: 13 November 2024
Accepted: 2 December 2024
Published: 5 December 2024

1. Introduction

Industrial cities require reliable electrical networks to supply power continuously and efficiently. However, blackouts result in high economic losses for retailers, manufacturers, and other businesses. These losses are related to service discontinuities, power quality issues, and disturbances that affect user equipment. The impact of power outages on users has been documented in numerous countries around the world [1–4]. Utility companies have applied smart technologies to improve the reliability and security of distribution networks. By adding smart technologies, low reliability levels improve and more relevant nodes in a distribution network are identified [5–7].

Various investigations and techniques have been presented in the literature to determine the reliability and security levels of a power system. In [8], a method to assess reliability is described by calculating the instantaneous failure rate, the average failure ratio, and various statistical tools. The study focused on the switches of substations and analyzed the failures using the Weibull distribution. Some researchers have analyzed reliability in power systems based on fault trees and Monte Carlo methods [9]. Furthermore, some researchers have evaluated the reliability of monitoring and measurement systems (PMUs), analyzing strategic points (buses or nodes) of a power system [10]. In [11], probabilistic relational models are used to analyze the reliability of power automation systems. Other studies, such as [12,13], have studied and analyzed the reliability of electrical substations considering the cybersecurity interface.

All of the research documents consulted have presented only recommendations to promote reliability. These documents do not consider methods for evaluating failures and only provide a guide for utilities to calculate reliability and conduct contingency analysis using simulation tools. Therefore, this paper proposes a method capable of performing quantitative and qualitative analyses of the most representative buses in a power system. The method carries out $N-1$ and $N-k$ contingencies, evaluating the reliability and security of the power system according to the configuration used for each bus.

In addition, conventional reliability indices require probabilistic and deterministic studies to identify critical nodes and parameters that help strengthen the subtransmission network. However, this procedure requires time, resources, and consulting activities, resulting in significant costs for utilities. Therefore, the proposed study presents a rapid analysis approach that does not require the application of stochastic methods or extensive simulation-based fundamental studies to determine the reliability and security of a power system.

This paper makes the following contributions:

- A new index is calculated for urban electrical substations, evaluating the non-attended demand risk. This index could be a subject of interest for utilities and operators.
- This paper presents a simplified and graphic method that integrates the system configuration, non-attended demand risk index, and loadability index. These are key parameters to identify critical points that affect the reliability and security of power systems.
- This study analyzes subtransmission networks to provide reliability for users and the probability of failure that can cause outages. This is a factor that affects users negatively, and previous studies only present a guide that users can employ to interpret the results [5].

2. Background

This section establishes a theoretical framework for determining the relationship between busbar configurations and their impact on reliability. In addition, this section includes the criteria for analyzing contingencies related to failures.

2.1. Urban Electrical Substations

An electrical substation is a facility formed of a set of elements that respond to requirements according to their responsibilities in an electrical power system. Urban substations are installed to connect the distribution circuits that supply electricity to the final users in the cities. In some countries, substations with subtransmission systems are constructed with voltages between 110 kV and 230 kV. Substations respond to power supply, power support (switching), transmission, interconnection, distribution, and combinations.

All elements in a busbar configuration respond to a set of requirements and the operation of the system. An electrical substation can have as many switchyards as voltage levels and responsibilities, or a commercial frontier (trade border) between utilities and operators [14]. The IEC 60038 standard establishes the classification of voltage levels, as presented in Table 1 [15]:

Table 1. Classification of voltage levels according to IEC 60038 standard [15].

Type	Rated Voltage (kV)		Operation Frequency 50 Hz	60 Hz
Secondary distribution	3.3	3	x	x
	6.6	6	x	x
	11	10	x	x
	15		x	x
	22	20	x	x
	33		x	x
	35		x	x
	4.16			x
	12.47			x
	13.2			x
	13.8			x
Primary distribution	24.94			x
	34.5			x
	45		x	x
	66	69	x	x
	110		x	x
Subtransmission	115		x	x
	132	138	x	x
	150		x	x
	220		x	x
	230		x	x

All specified voltages have a nominal value, as identified in Table 1. The IEC 60038 standard classifies voltage levels according to the values that are used in power networks. The medium voltages are classified between 1 kV and 52 kV. The high voltages are classified between values higher than 52 kV and those equal to 230 kV. Additionally, extra high voltages are classified between values higher than 230 kV and equal to 550 kV. Finally, ultra-high voltage includes voltages higher than 550 kV [15]. Distribution networks operate at voltage levels below 110 kV, and subtransition networks are classified between 110 kV and 135 kV [15].

2.2. Relationship Between Reliability and Non-Attended Demand Risk

The fundamental principle underlying the reliability of electrical distribution networks installed within urban areas is the provision of an uninterrupted electrical power supply. The operation must guarantee good quality of service [16]. The main requirements of an electrical substation are the reliability and security of supporting loads connected to the electrical substations. They must be designed with configurations that adapt to fault conditions, as well as alternative paths for the supply of electrical energy [17]. Electrical substations in urban areas must offer security and dynamic reliability, with the capacity to respond to the conditions of the power system, such as faults, power quality issues, and network imbalances [8,18].

Basic indices help estimate the reliability of electrical substation elements in a power system. Some indices include the frequency of failures, unavailability, and the expected energy not served [19]. In distribution networks, the average interruption time and average interruption frequency indices measure the number of interruptions in a system [20]. The failure rate is a reliability index that is used to measure the ratio between the number of verified failures in each period and the product between the number of unavailable pieces of equipment. For the time to be evaluated, the total failure rate is measured as the sum of all failure rates of a certain number of elements to be evaluated. The average duration of failure is calculated as the sum of all the products of the repair time of an element and the number of interruptions of the element in the period to be evaluated [21].

Some indicators that also fulfill the functionality of measuring the quality and reliability of the service provided to users are oriented toward efficient evaluation. The following are some useful indicators found in local and international standards: the System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), Customer Average Interruption Duration Index (CAIDI), Customer Average Interruption Frequency Index (CAIFI), Average Service Availability Index (ASAI), Average Service Unavailability Index (ASUI), Average System Interruption Frequency Index (ASIFI), and Average System Interruption Duration Index (ASIDI) [22,23].

Equation (1) presents the SAIDI, as the total duration of interruption for the customer at a given time [22,23]. This term is measured in the local distribution system of the network operator j during the year t, and it is measured in hours per year (hours/year). The term $D_{i,u,m}$ is the duration in minutes of the event i which occurred during the month m, affecting the asset u belonging to the local distribution system of the network operator j. The term $NU_{(i,u,m)}$ refers to the number of users affected by the event i which occurred during the month m, connected to the asset u. The term $UT_{(j,m)}$ is the total number of users connected to the local distribution system of the network operator j during the month m.

$$\mathrm{SAIDI}_{j,t} = \sum_{m=1}^{12} \frac{\sum_{i=1}^{n}(D_{i,u,m} * NU_{i,u,m})}{UT_{j,m}} / 60 \quad (1)$$

The SAIFI, defined in Equation (2), is the relationship between the number of customers interrupted and the total number of users served [22,23]. This index is measured as the number of events that occur per user in the local distribution system of the network operator j during the year t, and is measured in occurrences per year [occurrences/year].

$$\mathrm{SAIFI}_{j,t} = \sum_{m=1}^{12} \frac{\sum_{i=1}^{n}(NU_{i,u,m})}{UT_{j,m}} \quad (2)$$

The CAIDI measures the average time required to restore the electricity service and is expressed as in Equation (3). This mathematical expression shows that the CAIDI is a relation between the SAIDI and SAIFI.

$$\mathrm{CAIDI}_{j,t} = \frac{\mathrm{SAIDI}_{j,t}}{\mathrm{SAIFI}_{j,t}} \quad (3)$$

In addition, the CAIFI is the relation between the total number of customers interrupted N_i and the total number of distinct customers interrupted CN [22]. The mathematical formulation is expressed as in Equation (4).

$$\mathrm{CAIFI} = \frac{\sum N_i}{CN} \quad (4)$$

The ASAI represents the fraction of time during which the user has received electricity and can be calculated as in Equation (5). The term N_t is the total number of users served, r_i is the restoration time for each interruption event, and L_i is the connected kVA load interrupted for each interruption event [22].

$$\mathrm{ASAI} = \frac{\text{Customer Hours Service Availability}}{\text{Customer Hours Service Demand}} = \frac{N_t(\text{hours/year}) - \sum r_i L_i}{N_t(\text{hours/year})} \quad (5)$$

The ASUI is the average index of system unavailability. It can be calculated as in Equation (6).

$$\mathrm{ASUI} = 1 - \mathrm{ASAI} \quad (6)$$

Another index focused on load and energy is the ASIFI, which is the ratio between the power interrupted and the total power served. The mathematical formulation is expressed in Equation (7).The term L_t is the total connected kVA load served [22].

$$\text{ASIFI} = \frac{\sum \text{Total Connected kVA of Load Interrupted}}{\text{Total Connected kVA Served}} = \frac{\sum L_i}{L_t} \quad (7)$$

Moreover, the ASIDI is the ratio between the power per hour interrupted and the total time duration [21]. The mathematical expression is defined as in Equation (8).

$$\text{ASIDI} = \frac{\sum \text{Connected kVA Duration of Load Interrupted}}{\text{Total Connected kVA Served}} = \frac{\sum r_i L_i}{L_t} \quad (8)$$

Reliability indicators are based on the number of failures presented and the duration, the time, and the frequency of failures. Other indicators also measure their impact and the power not delivered, thus highlighting reliability, such as the capacity of a system or sets of elements responsible for uninterruptedly supplying electrical energy. The system must have the capacity to recover electrical service rapidly following a failure (reliability), supporting permanent or transitory failures, and presenting an effective backup during the duration of the failure (security). Reliability has a relation to the unavailability of the non-attended demand and the interruption time. Therefore, a detailed reliability analysis is required in electrical substations, in addition to a large-scale analysis including all elements of the power system. A load flow study allows us to understand the behavior of a power system, which is variable and can have a topology that provides greater or less reliability. Therefore, the loadability of the elements affects the reliability, and it is crucial to identify these critical points and elements of the power system [24].

Electrical substations serve as critical interfaces between energy users and the distribution network. They also connect complex systems where the energy flow can change directions. These substations are essential nodes where actions can be monitored, controlled, and adjusted to ensure the proper operation of the electrical energy system [24]. The reliability of electrical substations, in addition to their change capacity and redundancy that they may have in their elements [24], also depends on their physical layout, electrical substation technology, and switch technology, and the alternation of their elements [25]. According to [26], about 60% of the faults that occur in an electrical substation originate from failures in the power equipment; 20% from failures in the protection, control, and supervision equipment; and 20% from human factors.

In the research carried out in [25], gas-insulated substations with ring configurations are the most reliable systems. This type of system is even better than the one-and-a-half-breaker configuration. According to the author, higher reliability can be obtained with a simple or poor configuration in terms of robustness, but with good technology. Likewise, good technology with a robust configuration can generate unnecessary investments if there are loadability problems in an electrical substation. Good technology and configuration will not guarantee reliability, and poor technology with poor electrical substation configuration will cause unacceptable reliability problems in the electrical substation and consequently in the power system [25].

2.3. Applicable Technologies and Configurations with Distribution Networks

Each substation configuration is particularly studied as a physical configuration that provides three important components for transmission and distribution networks. These components are security, reliability, and flexibility. However, the latter is the least relevant for studying distribution substations in urban areas. Table 2 summarizes the relationship between these components [27].

Table 2. List of configurations evaluated for distribution networks in urban electrical substations.

Configurations	Reliability	Security
Single bar	This configuration does not have backup.	This configuration goes out of service under contingencies.
Double bar	This configuration has backup for faults in the busbar but not in the camp.	This configuration goes out of service under contingencies.
Main and transfer bus	This configuration has backup under fault conditions in the busbar and breaker, losing protection in a second failure event.	This configuration goes out of service under contingencies.
Double bar + bypass switch disconnector	This configuration has backup for faults in the busbar, switch, and breaker, losing protection in a second failure event if the breaker is under fault conditions.	This configuration only has fault events on busbars if both are energized.
Double bar and transfer switch disconnector	This configuration has backup under faults in the busbar, camp's switch, and breaker, losing protection in a second failure event if the breaker is under fault conditions.	This configuration only has fault events on busbars if both are energized.
H configuration	This configuration does not have backup if one breaker has a fault. It can be energized in two ways.	Under fault conditions, this configuration goes out of service.
Double bar and transfer single bar	This configuration has backup for faults in the busbar, camp's switch, and breaker, losing protection in a second failure event if the breaker is under fault conditions.	This configuration only has fault events on the busbar, switch, or breaker if the transfer bar is coupled and energized in that fault event.
Ring bus	This configuration has backup under any fault event associated with the configuration, losing reliability when the ring opens.	This configuration is secure under any fault event.
One and a half breaker	In a failure scenario, all circuits continue to operate, and in the worst case, only the failed and the adjacent circuits can go out of service.	This configuration supports failure scenarios in busbars and central bays without suspending the power supply and in the event of a failure in a line bay. It does not affect another circuits.

2.4. Criteria and Contingency Analysis for Reliability Evaluation

A contingency is an event that occurs when an element of an electrical network goes out of service due to an unexpected event [28]. The $N-1$ contingency criterion is frequently applied in failure contingency analysis. This criterion is used to assess the reliability of an electrical system by evaluating the capacity of an electrical system before the output of an element that is part of the system [29].

The companies that supply electricity must guarantee the stability of the system after the occurrence of one fault [5]. In this case, an $N-k$ contingency analysis is applied to study the behavior of the power system, evaluating the possible faults that can occur. The term N is the total number of elements that support the operation, and k is the number of faults that can occur and cause the output of an element of the electrical power supply network.

As a power system is dynamic, companies responsible for supplying electrical energy must guarantee reliable operation it terms of both the static and dynamic behavior of the network [30]. Thus, contingency analysis based on an $N-k$ scenario is not only to used evaluate the reliability of a system. It is also employed to size a system and, in this way, provide energy supply alternatives from different points, making the system redundant [24,31]. The $N-1$ contingency criterion is designed to prevent the system from reaching the thermal limits of the loads and the stress limits at the nodes [24]. Table 3 highlights previous related research considering contributions and applications. The literature often reports evaluations, as presented in the table, based on requirements such as reliability (R), security (S), and evaluation using methods such as qualitative (Ql) and quantitative (Qn) methods.

Table 3. Related research: applications and contributions.

Ref.	Requirement		Evaluation		Application	Contribution
	R	S	Ql	Qn		
[32]		X		X	Integration of wind renewable energy systems	This paper presents a system configuration based on real-time measurements using a theory-based approach to quantify the redundancy and vulnerability of transmission lines.
[33]	X	X		X	Power system	A reliability evaluation quantifies the controllability and vulnerability components of the security and stability control system.
[34]	X			X	Power systems	This paper presents a review of an optimization methodology to solve the optimal issues of power systems under the background of energy Internet.
[35]	X	X		X	Power distribution	This research focuses on the enhancement of situational awareness through fault location using fault passage indicators to improve nominal impedance-based methods in distribution networks and promote reliability and security.
[36]	X	X		X	Substation	This paper evaluates the criticality of electrical substations considering their possible operating states, associate probabilities, and consequences on the static and dynamic performance of the electric power system.
[37]	X	X		X	Power systems	This paper presents novel mathematical algorithms, considering that the key issue in security calculations is the number of simultaneously failed elements.
[38]	X	X	X		Power systems	This method, developed for substation post-fault operations, uses failure events and fault trees to enable the possibility of calculating different importance measures for substation components and for the parameters of the model.
[39]	X			X	Power systems	This paper evaluates the N-1 and N-2 contingency criteria in a real scenario.

3. Research Method

This paper proposes a qualitative method capable of measuring the level of reliability of electrical substations according to the following considerations:

- The level of importance within the network.
- The electrical substation configuration.
- The amount of protection and transformation equipment.
- The continuity of electrical service energy in $N-k$ contingency events in a schematic and visual way.

Each of these considerations will be evaluated and quantified to compare the levels of reliability.

3.1. Assessment of the Level of Importance Within the Distribution Network

This evaluation was carried out according to the number of connections with other electrical substations. In this case, $N-k$ contingency events were evaluated to validate the continuity of service in the system. Events were carried out for each line that connects substations. This process was carried out iteratively, as presented in Equation (9). The term N refers to the set of elements to evaluate; for example, a set of 1 or more lines, or a set of 1 or more transformers. The term k increased iteratively until F_k became zero.

$$F_k = N - k \tag{9}$$

3.2. Analysis and Evaluation of Failure Based on the Configuration of the Electrical Substation

For each failure scenario, the decision process was considered to involve a simple answer, yes or no. For example, fault events evaluated for two buses corresponded to the evaluation of a fault in bus 1, bus 2, and finally, bus 1 + bus 2. This process was employed to identify whether an electrical substation can remain in service. The analysis was carried out in the same way as the switches of each connection between electrical substations, considering an $N - k$ contingency event until the affected line or circuit was out of service.

3.3. Analysis and Evaluation of Fault in Internal Transformers of Electrical Substations

Within each electrical substation, various voltage levels were present among the different configurations. These configurations had to be analyzed to assess the system's capacity to withstand the failure of a single transformer or any related fault that may lead the transformer to go out of service. This evaluation was performed with an $N - k$ contingency scenario in the power transformers located within the electrical substation bay. An assessment of the operational continuity capacity of the electrical substation was conducted. In the absence of data related to the loadability of the elements, it was assumed that each transformer can withstand the load in an $N - k$ contingency scenario. The loadability is a determining factor in considering the reliability level of electrical substations.

Equation (10) presents the mathematical expression for calculating the non-attended demand risk (NADR). The supported $N - k$ contingency events must be registered and divided between 1 and the result multiplied by 100%.

$$\text{NADR} = 1/(N - k) * 100\% \tag{10}$$

3.4. Processing and Comparison of Results

The analysis was carried out by using the probability of an event and evaluating the behavior of the power system under this scenario. The frequency was defined as the number of events that occur among the total number of events [40]. Here, an analysis was performed on transformers, switches, busbars, and connections with electrical substations of the local distribution system. These elements can influence the reliability of the electrical substation during a failure event.

Figure 1 illustrates the process and provides instructions to apply the method proposed in this document. The process starts by defining the case studies for the power system to be evaluated, and a unifilar diagram is obtained and represented in an admittance matrix; from this matrix, the power system scheme is obtained, the electrical substation configurations are identified, and the connections are determined between electrical substations (lines), transformers, and other connection elements between electrical substations or configurations in each electrical substation. Once the previous parameters are defined, the $N - k$ contingency scenarios are calculated, as is the the non-attention demand risk. If it is not possible to perform the calculation, this is the end of the cycle without success; if the calculations are performed according to the methodology, the procedure is successfully completed.

3.5. Case Study

A power system that includes a meshed subtransmission network and distribution circuits was selected as a case study. A real system to evaluate this case is the Caribbean coast power system in Colombia. Figure 2 presents a one-line diagram of the proposed case study.

This system is powered by different thermal energy generators distributed in different cities and connected to the regional transmission system and the local distribution system. Ten substations are responsible for distributing electricity to urban areas. Table 4 describes these electrical substations.

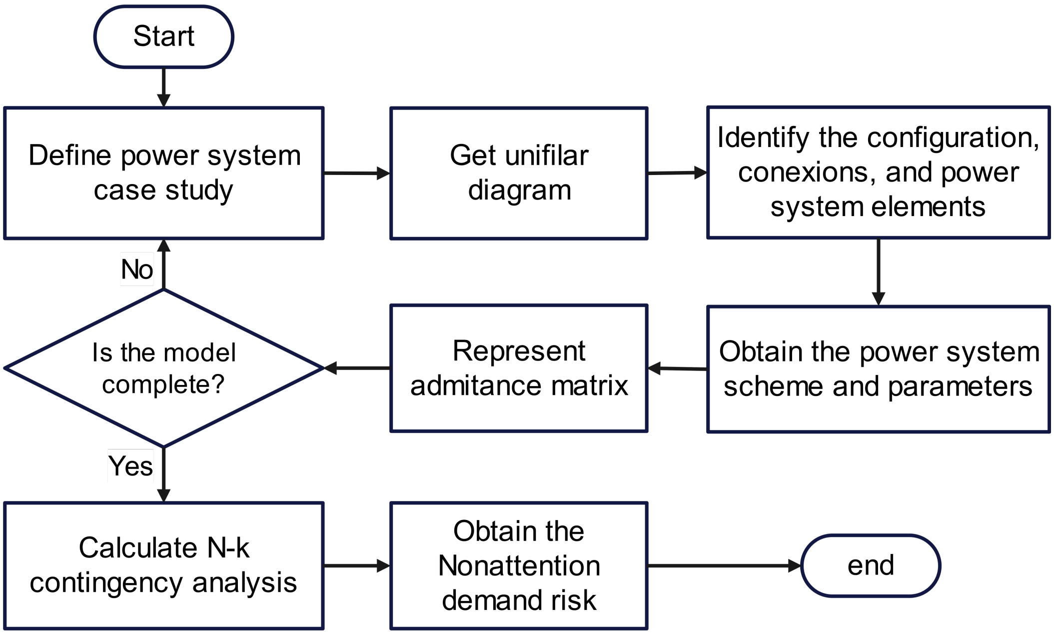

Figure 1. A flowchart of the methodology.

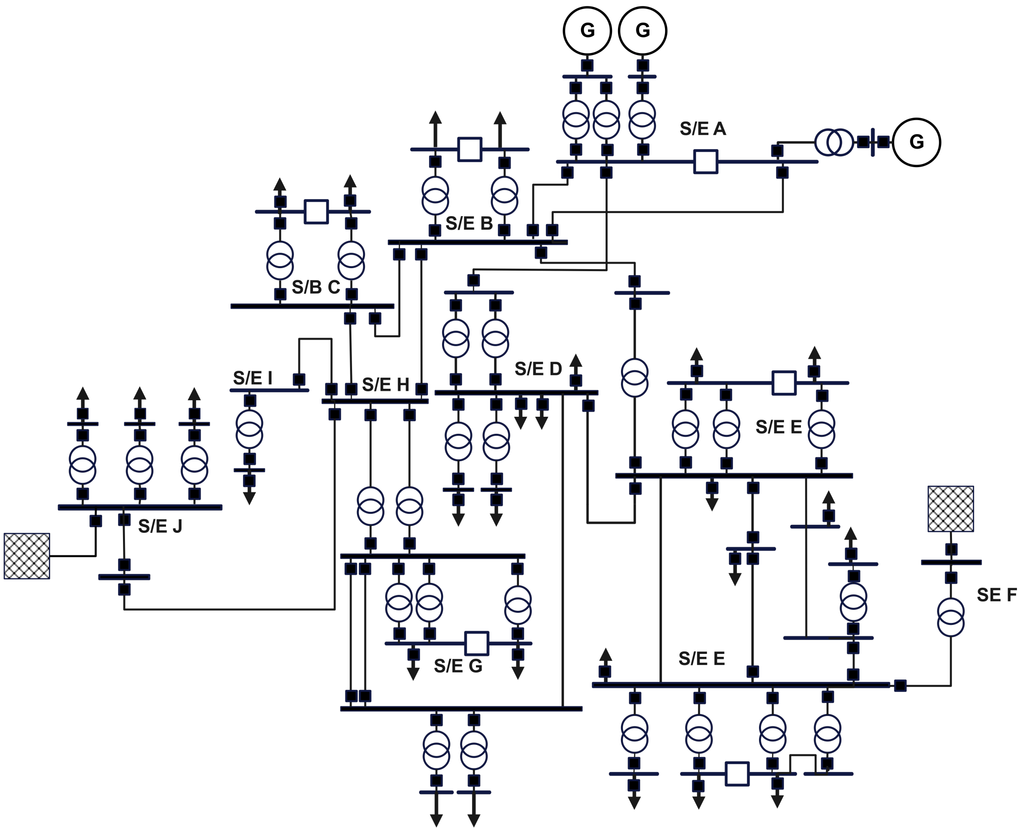

Figure 2. Power system case study.

According to the data in Table 4, the voltage levels 110 kV, 34.5 kV, and 13.8 kV were identified within the local distribution system. Voltages identified as 110 kV are considered subtransmission systems, and buses of 34.5 kV have internal connections with industrial circuits. In addition, commercial and residential circuits are connected to 13.8 kV, and they include some small industrial companies. Table 4 shows that the local distribution system is mostly predominant in double-bar and single-bar configurations, with some electrical substations with other configurations.

Table 4. Configuration and voltages of electrical substations evaluated in this research.

Substation	Configuration	Voltage (kV)
A	Double bar + bypass switch disconnector	110
B	Double bar	110 - 13.8
C	Double bar	110 - 13.8
D	Double bar Single bar	110 - 13.8 34.5
E	Single bar	110 - 34.5 - 13.8
F	Double bar Single bar	13.8 110 - 34.5
G	Single bar	34.5 - 13.8
H	Ring bus Double bar Single bar	110 13.8 34.5
I	Ring bus Single bar	110 13.8
J	Double bar Single bar	110 - 13.8 13.8

The system can be represented in an admittance matrix, as presented in Figure 3, which provides an alternative perspective on the diagram. This matrix demonstrates how the various nodes within the system should be connected. The admittance matrix establishes a relationship between all electrical substations and connections. The shaded parts in the admittance matrix are those that represent the electrical substations and the nodes and are the sum of the admittances of all the connections that interact with each node.

2Yab+Yab+Yad	2Yab		Yad						
2Yba	2Yba+Ybe+Ybc+Ybh	Ybc		Ybe			Ybh		
	Ycb	Ycb+Ych					Ych		
Yda			Yda+Ydg+Yde	Yde		Ydg			
	Yeb		Yed	Yeb+Yed+Yef+Yeg	Yef	Yeg			
				Yfe	Yfe				
			Ygd	Yge		Ygd+Yge+2Ygh	2Ygh		
	Yhb	Yhc				2Yhg	Yhb+Yhc+2Yhg+Yhi+Yhj	Yhi	Yhj
							Yih	Yih	
							Yjh		Yjh

Figure 3. An admittance matrix of the study case.

This representation can also be presented as in Figure 4. In this new representation, instead of the connections of substations, the name of each node and the corresponding voltage levels are utilized. This approach replaces the original representation and provides a matrix-based representation of the one-line diagram derived from the admittance matrix.

The connection matrix of the electrical substations represents a simplified version of a unifilar diagram. This matrix provides a concise and organized way to understand the interconnections within the electrical substation network. Information is synthesized for analysis by omitting transformers, lines, and buses, illustrating the connection between electrical substations using blocks. Each electrical substation is represented in a different color. This is independent of the voltage level, as its purpose is to give an illustrative color to each electrical substation.

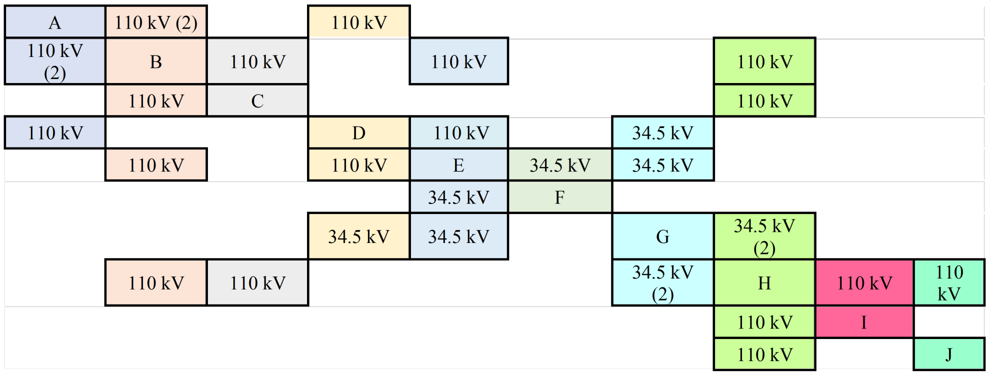

Figure 4. The power system scheme. A matrix representing the unifilar diagram of the electrical substation of the urban area.

Figures 1 and 4 show that substation B is connected to substations A, C, E, and H. In these figures, a double connection with substation A is identified with the number two (2) and a voltage of 110 kV (see Table 4). Figure 4 shows that lines, buses, and transformers were omitted to perform this analysis. The matrix can be interpreted and structured by placing cells where the electrical substations intersect. Therefore, in the column of substation A and in the column of substation B, the connection is placed where substation B intersects substation A. The same analysis can be performed with the other substations.

The electrical system comprises a combination of different substation configurations. Figure 5 presents the percentage of configurations utilized in the case study. According to this figure, 81% of the electrical substation configurations are single-bar and double-bar. Approximately 13% of the substations are arranged in a ring configuration, while 6% utilize a double-bar and bypass disconnector setup.

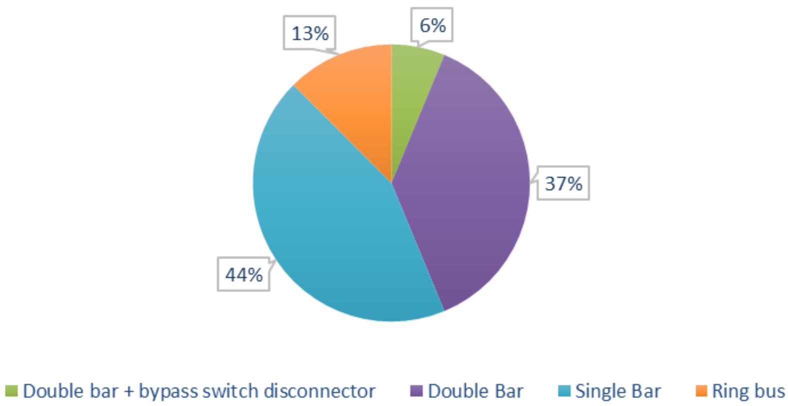

Figure 5. Percentages of substation configurations in the case study.

Table 5 shows the circuits associated with each electrical substation. In this table, the term 'General' means the number of connections that each substation has, including circuits with loads. The term 'Between Substations' refers to the links used to connect each substation to other substations.

Table 5. Number of associated circuits per electrical substation.

Substation	General	Between Substations
A	8	5
B	17	5
C	13	2
D	17	3
E	11	5
F	15	2
G	15	4
H	18	6
I	16	2
J	18	3

4. Results and Analysis

Analysis of the Case Study

Tables 6–8 present the results of the reliability analysis according to the qualitative method in combination with a failure probability analysis. These results allow us to determine the reliability level of each electrical substation.

Table 6 shows the percentage of non-attended demand risk (NADR) for each electrical substation, the $N-k$ contingency scenario supported, and the transformer loadability in the $N-k$ contingency scenario. The term LDB refers to the percentage of loadability in a maximum-demand scenario. The transformer loadability in a maximum-demand scenario according to the available information of the electric system presented in the study case is summarized in the column named LDB (%) in Table 6. It shows that in a maximum-demand scenario, the transformers of electrical substations A, C, and G are overloaded above 125%. In addition, Table 6 has information on the connection of the transformer voltage level from the primary winding to the secondary winding.

Table 6. Internal connection via power transformers between connections in the Electrical Substation and $N-k$ contingency events in power transformers of connections between configurations.

Substation	Voltage (kV) From	Voltage (kV) To	NADR (%)	$N-k$	LDB (%)
A	13.8	110	100	0	165.96
B	34.5	13.8	50	1	78.16
C	34.5	13.8	100	0	131.13
D	110	34.5	50	1	114.38
	34.5	13.8	50	1	43.61
E	110	34.5	100	0	0
	34.5	110	33.3	2	97.67
F	34.5	13.8	33.3	2	107.74
G	34.5	13.8	100	0	181.1
H	110	34.5	50	1	114.77
	34.5	13.8	50	1	113.28
I	34.5	13.8	100	0	0
	34.5	13.8	100	0	0
J	34.5	13.8	100	0	0
	34.5	13.8	100	0	0
	34.5	13.8	100	0	0

For example, substation A has a connection from a busbar energized with 13.8 kV and it is connected to a busbar energized with 100 kV. Therefore, it is considered to have the highest power demand and loadability of transformers connected between configurations of the same electrical substation. Table 7 presents the calculation of NADR for the different substations.

Table 7. The probability of interruption of the power supply in the event of failure in the connection lines between the electrical substations.

Substation	NADR (%)	$N-k$
A	20	4
B	20	4
C	50	1
D	33	2
E	25	2
F	50	1
G	25	3
H	16.7	5
I	50	1
J	33.3	2

Table 8 shows the probability ratio of power supply interruption in the event of a failure in the interconnection lines. The term PSC refers to the percentage of service continuity. Substation H has a lower probability of interruption in the event of failure. Substations A, B, and E have a probability of non-attended demand risk of 20% in failure events. Substations D and J have a probability of 33.3%. Substations G and E have a probability of 25%. Finally, the electrical substations with the highest probability of failure are substations C and I. The reliability of these electrical substations is $1-(P_f/100)$. Therefore, the electrical substation with the highest reliability is substation H with a reliability of 83.3%.

Table 8. The probability of service continuity in the event of bar failure in the local distribution system of urban substations, evaluating non-attended demand risk.

Substation	Configuration	PSC in B1	PSC in B2	PSC in B1 + B2
A	Double bar + bypass switch disconnector	100%	100%	50%
B	Double bar	100%	100%	0%
	Double bar	100%	100%	50%
C	Double bar	100%	100%	0%
	Double bar	100%	100%	50%
D	Double bar	100%	100%	0%
	Double bar	100%	100%	50%
	Single bar	50%	50%	0%
E	Single bar	50%	50%	0%
	Double bar	100%	100%	0%
F	Double bar	100%	100%	50%
	Single bar	50%	50%	0%
G	Ring bus	N/A	N/A	N/A
	Double bar	100%	100%	50%
	Single bar	50%	50%	0%
H	Ring bus	N/A	N/A	N/A
	Single bar	0%	0%	0%
I	Double bar	100%	100%	0%
	Single bar	0%	0%	0%
J	Single bar	0%	0%	0%
	Single bar	0%	0%	0%

For this scenario, the loadability of the transformers was not considered, assuming that they support the load of the circuits associated with the electrical substation and the electrical substation connected to each one. The results show that 30% of the electrical substations have zero reliability when performing failures in transformers that connect different internal configurations of the electrical substations. In addition, 60% of the electrical substations are prepared for $N-1$ contingency scenarios of transformer failure, presenting a reliability of 50%. Furthermore, 30% of the electrical substations use an additional component to improve reliability, such as more transformers; for instance, substation E obtained a reliability of 66.7%. Moreover, substation F compensates for the reliability of the configurations located at 34.5 kV and 13.8 kV with greater reliability in the transformers, this being 75%.

Table 9 identifies the $N-1$ and $N-2$ contingency scenarios for all the configurations associated with the electrical substations. Although the single bar configurations are composed of one bar, these have a coupling in their bar that allows them to isolate the failed bar section and continue with the operation and supply energy to the fields associated with the unfailed section of the bus. Therefore, they have a 50% probability of service continuity under $N-1$ contingency scenarios in B1 or B2.

Table 9. $N-k$ contingency scenario on switch under fault conditions in line bay.

Substation	Configuration	Voltage (kV)	$N-k$
A	Double bar + bypass switch disconnector	110	1
B	Double bar Double bar	110 13.8	0 0
C	Double bar Double bar	110 13.8	0 0
D	Double bar Double bar Single bar	110 34.5 13.8	0 0 0
E	Single bar Double bar	34.5 13.8	0 0
F	Single bar Single bar	34.5 13.8	0 0
G	Ring bus Double bar Single bar	110 13.8 34.6	1 0 0
H	Ring bus Single bar	110 13.8	1 0
I	Double bar Single bar	110 13.8	0 0
J	Single bar Single bar	13.8 34.5	0 0

Table 8 shows the $N-k$ contingency scenarios supported by the line bays associated with the interconnection between the electrical substations. The results show that under fault conditions in a switch of any line bay, the electrical substation does not have backup except electrical substations with a ring bus configuration.

5. Conclusions

The configurations were identified at the general level of the local distribution network case study. In this study, the results show that the system has a low reliability level, as 44% are single-bar configurations and 37% double-bar configurations. Reliability analysis showed that electrical substations that had some type of double-bar or single-bar configuration presented greater robustness within their protection and transformation elements, in such a way that their reliability can be increased. Within the local distribution system, important connections and supply points were identified, such as electrical substations E, I, H, D, and B. For some of the electrical substations, such as electrical substations F and G, the number of loads and the types of connected users were less important.

In the event of a transformer failure, the probability of loss of service (non-attended demand risk) was calculated and analyzed according to the loadability of these transformers to each electrical substation. The results show that the electrical substations A, C, G, I, and J do not have options to fulfill the demand due to a fault event that causes the transformer to be disconnected as the loadability overcomes technical limits. Substation E does not provide security when a fault occurs, as the connection between 110 kV and 34.5 kV is supported by a single transformer.

The electrical substations that showed better reliability were F and E at voltage levels between 34.5 kV and 13.8 kV. The connected lines were an alternative way to supply power to the connected loads, as the purpose was to evaluate the security of the transformer elements due to a fault event or disconnection. The system had only 30% service continuity in 50% of failure events when applying the $N-2$ contingency scenario in the buses. Regarding interconnections, electrical substation H is one of the most important electrical substations, with a probability percentage of operating output of 16.7% and 83.5% less non-attended demand risk, without considering the loadability of the local distribution system of urban areas.

The case study showed that those substations with busbar couplings increased the probability of withstanding contingency scenarios, reducing the risk of unmet demand to between 25 and 20%. The results also showed that a more robust configuration is not always the best solution to reduce the probability of unattended demand, as was observed in substation G, which has a ring configuration, with the same non-attention demand risk as substation E, which has simpler configurations but with a greater number of connections to electrical substations.

The proposed method is a visual technique based on a conceptual analysis of electrical substation configurations. Important data were omitted from the reliability and security analyses within the local distribution system, specifically urban substations, such as the number of failures per year, the time of use of equipment and conductors, the loadability of the power transformers, and the connection lines between the electrical substations. The power switches of the circuits of the customers were not considered in the analysis, since they were not considered part of the 13.8 kV distribution network; the fields of the associated circuits only have one switch, except for electrical substations B, C, D, and J, which have a double switch in their field that supports an $N-1$ contingency scenario in the distribution circuits where customers are served. An analysis of the stochastic method is recommended to compare the accuracy and effectiveness of the proposed method.

The authors hope to test the accuracy of this methodology and compare the results based on historical data of the proposed power system. This can be performed based on the hours of unavailability, the average repair times per event, and the number of annual unavailability events.

Author Contributions: Conceptualization, investigation, methodology, software, formal analysis, writing—review and editing, J.S.-O., J.O. and J.E.C.-B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: The authors thank the Universidad de la Costa and Universidad Nacional de Colombia, Sede Medellín, for the support provided to perform this research.

Conflicts of Interest: The authors declare no conflicts of interest.

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